Chapter 9

Freshwater Environment Characterisation

DISCLAIMER

This disclaimer applies to and governs the disclosure and use of this Environmental Impact Statement ("EIS"), and by reading, using or relying on any part(s) of the EIS you accept this disclaimer in full.

This Environmental Impact Statement, including the Executive Summary, and all chapters of and attachments and appendices to it and all drawings, plans, models, designs, specifications, reports, photographs, surveys, calculations and other data and information in any format contained and/or referenced in it, is together with this disclaimer referred to as the "**EIS**".

Purpose of EIS

The EIS has been prepared by, for and on behalf of Wafi Mining Limited and Newcrest PNG 2 Limited (together the "**WGJV Participants**"), being the participants in the Wafi-Golpu Joint Venture ("**WGJV**") and the registered holders of exploration licences EL 440 and EL1105, for the sole purpose of an application (the "**Permit Application**") by them for environmental approval under the Environment Act 2000 (the "**Act**") for the proposed construction, operation and (ultimately) closure of an underground copper-gold mine and associated ore processing, concentrate transport and handling, power generation, water and tailings management, and related support facilities and services (the "**Project**") in Morobe Province, Independent State of Papua New Guinea. The EIS was prepared with input from consultants engaged by the WGJV Participants and/or their related bodies corporate ("**Consultants**").

The Permit Application is to be lodged with the Conservation and Environment Protection Authority ("**CEPA**"), Independent State of Papua New Guinea.

Ownership and Copyright

The EIS is the sole property of the WGJV Participants, who reserve and assert all proprietary and copyright ©2018 interests.

Reliance and Use

The EIS is intended and will be made available to CEPA, for review by CEPA and other applicable agencies of the Government of the Independent State of Papua New Guinea ("**Authorised Agencies**"), for the purpose of considering and assessing the Permit Application in accordance with the Act ("**Authorised Purpose**"), and for no other purpose whatsoever.

The EIS shall not be used or relied upon for any purpose other than the Authorised Purpose, unless express written approval is given in advance by the WGJV Participants.

Except for the Authorised Purpose, the EIS, in whole or in part, must not be reproduced, unless express written approval is given in advance by the WGJV Participants.

This disclaimer must accompany every copy of the EIS.

The EIS is meant to be read as a whole, and any part of it should not be read or relied upon out of context.

Limits on investigation and information

The EIS is based in part on information not within the control of either the WGJV Participants or the Consultants. While the WGJV Participants and Consultants believe that the information contained in the EIS should be reliable under the conditions and subject to the limitations set forth in the EIS, they do not guarantee the accuracy of that information.

No Representations or Warranties

While the WGJV Participants, their Related Bodies Corporate and Consultants believe that the information (including any opinions, forecasts or projections) contained in the EIS should be reliable under the conditions and subject to the limitations set out therein, and provide such information in good faith, they make no warranty, guarantee or promise, express or implied, that any of the information will be correct, accurate, complete or up to date, nor that such information will remain unchanged after the date of issue of the EIS to CEPA, nor that any forecasts or projections will be realised. Actual outcomes may vary materially and adversely from projected outcomes.

The use of the EIS shall be at the user's sole risk absolutely and in all respects. Without limitation to the foregoing, and to the maximum extent permitted by applicable law, the WGJV Participants, their Related Bodies Corporate and Consultants:

- do not accept any responsibility, and disclaim all liability whatsoever, for any loss, cost, expense or damage (howsoever arising, including in contract, tort (including negligence) and for breach of statutory duty) that any person or entity may suffer or incur caused by or resulting from any use of or reliance on the EIS or the information contained therein, or any inaccuracies, misstatements, misrepresentations, errors or omissions in its content, or on any other document or information supplied by the WGJV Participants to any Authorised Agency at any time in connection with the Authorised Agency's review of the EIS; and
- expressly disclaim any liability for any consequential, special, contingent or penal damages whatsoever.

The basis of the Consultants' engagement is that the Consultants' liability, whether under the law of contract, tort, statute, equity or otherwise, is limited as set out in the terms of their engagement with the WGJV Participants and/or their related bodies corporate.

Disclosure for Authorised Purpose

The WGJV Participants acknowledge and agree that, for the Authorised Purpose, the EIS may be:

- copied, reproduced and reprinted;
- published or disclosed in whole or in part, including being made available to the general public in accordance with section 55 of the Act. All publications and disclosures are subject to this disclaimer.

Development of Project subject to Approvals, Further Studies and Market and Operating Conditions

Any future development of the Project is subject to further studies, completion of statutory processes, receipt of all necessary or desirable Papua New Guinea Government and WGJV Participant approvals, and market and operating conditions.

Engineering design and other studies are continuing and aspects of the proposed Project design and timetable may change.

NEWCREST MINING LIMITED DISCLAIMER

Newcrest Mining Limited ("**Newcrest**") is the ultimate holding company of Newcrest PNG 2 Limited and any reference below to "Newcrest" or the "Company" includes both Newcrest Mining Limited and Newcrest PNG 2 Limited.

Forward Looking Statements

The EIS includes forward looking statements. Forward looking statements can generally be identified by the use of words such as "may", "will", "expect", "intend", "plan", "estimate", "anticipate", "continue", "outlook" and "guidance", or other similar words and may include, without limitation, statements regarding plans, strategies and objectives of management, anticipated production or construction commencement dates and expected costs or production outputs. The Company continues to distinguish between outlook and guidance. Guidance statements relate to the current financial year. Outlook statements relate to years subsequent to the current financial year.

Forward looking statements inherently involve known and unknown risks, uncertainties and other factors that may cause the Company's actual results, performance and achievements to differ materially from statements in this EIS. Relevant factors may include, but are not limited to, changes in commodity prices, foreign exchange fluctuations and general economic conditions, increased costs and demand for production inputs, the speculative nature of exploration and project development, including the risks of obtaining necessary licences and permits and diminishing quantities or grades of reserves, political and social risks, changes to the regulatory framework within which the Company operates or may in the future operate, environmental conditions including extreme weather conditions, recruitment and retention of personnel, industrial relations issues and litigation.

Forward looking statements are based on the Company's good faith assumptions as to the financial, market, regulatory and other relevant environments that will exist and affect the Company's business and operations in the future.

The Company does not give any assurance that the assumptions will prove to be correct. There may be other factors that could cause actual results or events not to be as anticipated, and many events are beyond the reasonable control of the Company. Readers are cautioned not to place undue reliance on forward looking statements. Forward looking statements in the EIS speak only at the date of issue. Except as required by applicable laws or regulations, the Company does not undertake any obligation to publicly update or revise any of the forward looking statements or to advise of any change in assumptions on which any such statement is based.

Non-IFRS Financial Information

Newcrest results are reported under International Financial Reporting Standards (IFRS) including EBIT and EBITDA. The EIS also includes non-IFRS information including Underlying profit (profit after tax before significant items attributable to owners of the parent company), All-In Sustaining Cost (determined in accordance with the World Gold Council Guidance Note on Non-GAAP Metrics released June 2013), AISC Margin (realised gold price less AISC per ounce sold (where expressed as USD), or realised gold price less AISC per ounce sold divided by realised gold price (where expressed as a %), Interest Coverage Ratio (EBITDA/Interest payable for the relevant period), Free cash flow (cash flow from operating activities less cash flow related to investing activities), EBITDA margin (EBITDA expressed as a percentage of revenue) and EBIT margin (EBIT expressed as a percentage of revenue). These measures are used internally by Management to assess the performance of the business and make decisions on the allocation of resources and are included in the EIS to provide greater understanding of the underlying performance of Newcrest's operations. The non-IFRS information has not been subject to audit or review by Newcrest's external auditor and should be used in addition to IFRS information.

Ore Reserves and Mineral Resources Reporting Requirements

As an Australian Company with securities listed on the Australian Securities Exchange (ASX), Newcrest is subject to Australian disclosure requirements and standards, including the requirements of the Corporations Act 2001 and the ASX. Investors should note that it is a requirement of the ASX listing rules that the reporting of Ore Reserves and Mineral Resources in Australia comply with the 2012 Edition of the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (the JORC Code) and that Newcrest's Ore Reserve and Mineral Resource estimates comply with the JORC Code.

Competent Person's Statement

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

HARMONY GOLD MINING COMPANY LIMITED DISCLAIMER

Harmony Gold Mining Company Limited ("**Harmony**") is the ultimate holding company of Wafi Mining Limited and any reference below to "Harmony" or the "Company" includes both Harmony Gold Mining Company Limited and Wafi Mining Limited.

Forward Looking Statements

These materials contain forward-looking statements within the meaning of the safe harbor provided by Section 21E of the Securities Exchange Act of 1934, as amended, and Section 27A of the Securities Act of 1933, as amended, with respect to our financial condition, results of operations, business strategies, operating efficiencies, competitive positions, growth opportunities for existing services, plans and objectives of management, markets for stock and other matters. These include all statements other than statements of historical fact, including, without limitation, any statements preceded by, followed by, or that include the words "targets", "believes", "expects", "aims", "intends", "will", "may", "anticipates", "would", "should", "could", "estimates", "forecast", "predict", "continue" or similar expressions or the negative thereof.

These forward-looking statements, including, among others, those relating to our future business prospects, revenues and income, wherever they may occur in this EIS and the exhibits to this EIS, are essentially estimates reflecting the best judgment of our senior management and involve a number of risks and uncertainties that could cause actual results to differ materially from those suggested by the forward-looking statements. As a consequence, these forward-looking statements should be considered in light of various important factors, including those set forth in these materials. Important factors that could cause actual results to differ materially from estimates or projections contained in the forward-looking statements include, without limitation: overall economic and business conditions in South Africa, Papua New Guinea, Australia and elsewhere, estimates of future earnings, and the sensitivity of earnings to the gold and other metals prices, estimates of future gold and other metals production and sales, estimates of future cash costs, estimates of future cash flows, and the sensitivity of cash flows to the gold and other metals prices, statements regarding future debt repayments, estimates of future capital expenditures, the success of our business strategy, development activities and other initiatives, estimates of reserves statements regarding future exploration results and the replacement of reserves, the ability to achieve anticipated efficiencies and other cost savings in connection with past and future acquisitions, fluctuations in the market price of gold, the occurrence of hazards associated with underground and surface gold mining, the occurrence of labour disruptions, power cost increases as well as power stoppages, fluctuations and usage constraints, supply chain shortages and increases in the prices of production imports, availability, terms and deployment of capital, changes in government regulation, particularly mining rights and environmental regulation, fluctuations in exchange rates, the adequacy of the Group's insurance coverage and socio-economic or political instability in South Africa and Papua New Guinea and other countries in which we operate.

For a more detailed discussion of such risks and other factors (such as availability of credit or other sources of financing), see the Company's latest Integrated Annual Report and Form 20-F which is on file with the Securities and Exchange Commission, as well as the Company's other Securities and Exchange Commission filings. The Company undertakes no obligation to update publicly or release any revisions to these forward-looking statements to reflect events or circumstances after the date of this EIS or to reflect the occurrence of unanticipated events, except as required by law.

Competent Person's Statement

The Wafi-Golpu Joint Venture is an unincorporated joint venture between a wholly-owned subsidiary of Harmony Gold Mining Company Limited and a wholly-owned subsidiary of Newcrest Mining Limited.

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

9. FRESHWATER ENVIRONMENT CHARACTERISATION

This chapter describes the baseline characteristics of the freshwater environment in the Project Area, including hydrology, surface water and sediment quality and aquatic ecology.

The key focus of the freshwater environment characterisation is on watercourses in the Mine Area located in the Lower Watut River catchment (i.e., from near the Wafi-Watut River confluence to the Markham-Watut river confluence), which is commensurate with the scale and duration of Project activity proposed in this area. The characterisation of watercourses along the section of the proposed Infrastructure Corridor located on the Lower Markham River floodplain (from Yalu village to the Outfall Area) has been completed at targeted locations as impacts in these areas will largely be temporary and restricted to the construction period only.

Baseline surveys were designed and targeted to capture representative freshwater ecological values across the Project Area based on previously collected data and an understanding of the Project configuration.

The descriptions for the freshwater environment characterisation are based primarily on information provided in the following reports:

- Wafi-Golpu Project EIS – Surface Water and Freshwater Aquatic Ecology Characterisation, BMT WBM, 2017 (Appendix G). This report describes Mine Area watercourses, including the Lower Watut River catchment, as shown in Figure 9.1.
- Surface Water and Freshwater Aquatic Ecology Characterisation, Coffey and Waterbug Company, 2017 (Appendix H). This report characterises Infrastructure Corridor watercourses between Yalu and the Coastal Area on the Lower Markham River floodplain as shown in Figure 9.2.

The methods, results and discussions in the following sections have been separated with respect to the two geographical survey areas (i.e., the Lower Watut River catchment and Lower Markham River floodplain), the level and duration of Project activity proposed and the respective differing levels of survey effort undertaken in each area.

9.1. Study Methods

The study methods used to characterise the freshwater environment for the Lower Watut River catchment and Lower Markham River floodplain are described below.

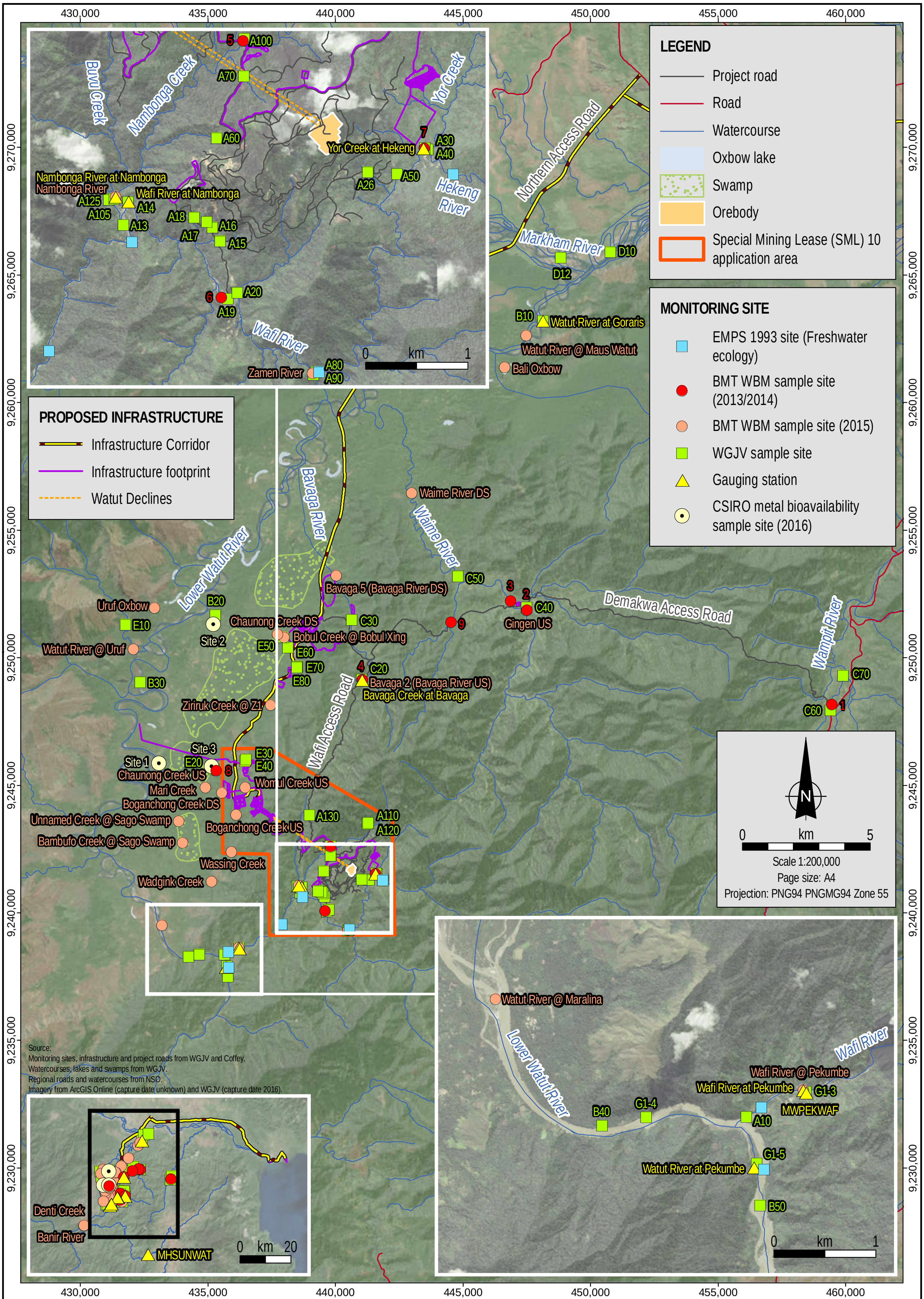
9.1.1. Hydrology, Water Quality and Sediment Quality

9.1.1.1. Data Collection

A summary of the hydrology, water and sediment quality data collected for each of the geographical areas is presented below.

9.1.1.1.1. Lower Watut River Catchment

Water and sediment quality, sediment transport, hydrology and geomorphology studies have been carried out in the Watut River catchment since the 1980s. The description of surface water resources in the Lower Watut River catchment in this area is primarily drawn predominantly from existing information including previous studies (see Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River, Powell and Powell (2000) and EMPS (1993)) and Wafi-Golpu Joint Venture (WGJV) environmental databases.



MXD Reference: 0520DD_10_GIS015_v0_9

coffey
A TETRA TECH COMPANY

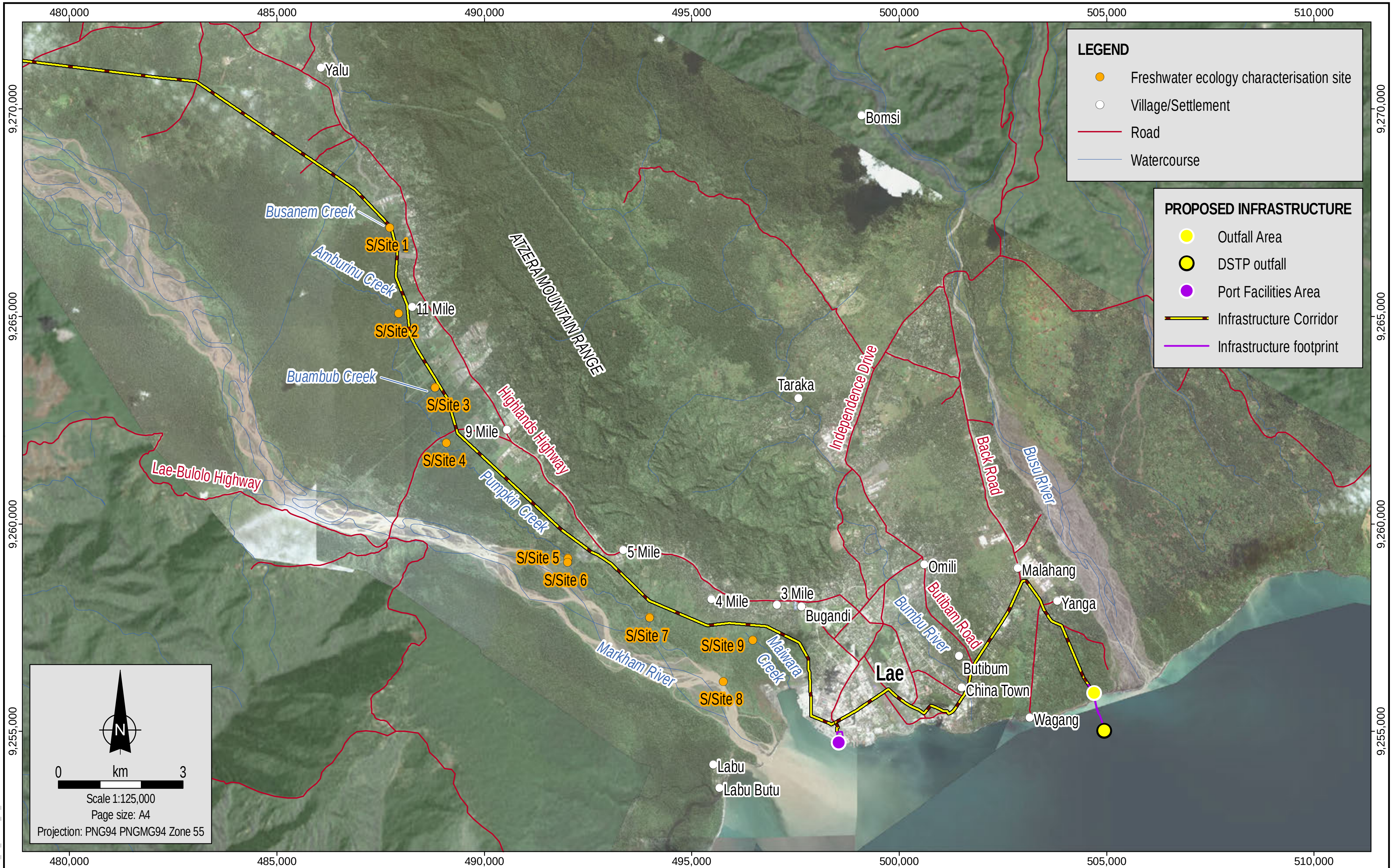
Date: 13.06.2018
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.01_GIS

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Monitoring sites and stream gauging stations in the Lower Watut River catchment

Figure No: 9.1



Source:
Freshwater ecology characterisation sites from Coffey.
Villages/Settlements and infrastructure from WGJV and Coffey.
Roads and watercourses from NSO.
Imagery from ArcGIS Online (capture date unknown) and WGJV (capture date 2016).

coffey
A TETRA TECH COMPANY

Date: 13.06.2018
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.02_GIS

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Water quality sampling sites in the Lower Markham River floodplain

Figure No: 9.2

The assessment of the baseline flow regime and water quality conditions in the Lower Watut River catchment considered historical flow and water quality data collected by WGJV, including water quality data collected between January 2006 and December 2016 across six catchments and further water quality data from monitoring programs undertaken by BMT WBM from 2013 to 2016. The majority of the WGJV water quality samples were collected during scheduled monthly sampling campaigns, which, for logistical and safety reasons, typically occur when stream flows are low. This ‘low-flow’ sampling bias does not capture the higher-flow periods during which water flow and water quality conditions are likely to be substantially different (e.g., higher sediment loads).

The assessment of baseline sediment quality considered data captured by WGJV between July 2006 and October 2016 from various sites across the Lower Watut River catchment.

To supplement the available historical water and sediment quality data, three targeted field sampling campaigns were carried out by BMT WBM in March 2015, June 2015 and December 2016. Sampling sites were chosen with a particular focus on characterisation of surface waters potentially affected by the Project that had not previously been surveyed. Both in-situ and laboratory-based analyses of water quality were undertaken and sediment samples were only analysed in laboratories. The BMT WBM water and sediment quality data, collected at the same time as the BMT WBM aquatic ecological surveys, is presented separately to the WGJV data to allow direct association of water quality and aquatic ecology.

Additional water quality sampling was undertaken by WGJV in March 2016 at two sites in the Watut River and one site in the Watut River floodplain to inform metal bioavailability assessments, which were undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), (Appendix G of Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River).

The water and sediment quality monitoring sites in the Lower Watut River catchment, along with stream gauging stations, are shown in Figure 9.1.

9.1.1.1.2. Lower Markham River Floodplain

Nine sampling sites in the Lower Markham River floodplain were surveyed in the vicinity of the Infrastructure Corridor from Yalu to the Coastal Area (see Figure 9.2) in June 2017. Data collected from nine additional sites north of the Atzera Mountain Range that were sampled for an infrastructure option that is no longer part of the Project in March 2017 is presented in Appendix H, Surface Water and Freshwater Aquatic Ecology Characterisation - Yalu to Wagang, but has not been discussed in the following sections.

The characteristics of the major Coastal Area watercourses, such as the Busu and Bumbu rivers, in relation to hydrology and sediment transport are presented in Chapter 11, Offshore Marine Environment Characterisation, and are not discussed further herein.

9.1.1.2. Data Analysis

The following analyses were undertaken in both geographical areas, i.e., the Lower Watut River catchment and the Lower Markham River floodplain:

- Physico-chemical and analytical water quality parameters, including pH, electrical conductivity, alkalinity, total suspended solids (TSS), dissolved and total metals, major ions and nutrients.

The following analyses were undertaken in the Lower Watut River catchment only:

- Sediment quality parameters, including moisture content, particle size distribution, particle density, total metals and total organic carbon.

Additional assessments undertaken for the Lower Watut River catchment area are described below.

9.1.1.2.1. Metal Bioavailability Assessments

Consistent with the tiered assessment framework of the ANZECC guidelines, sampling and analysis of water from the Watut River (two sites) and Watut River floodplain (one site in Chaunong Creek) was undertaken to assess metal bioavailability and potential ecotoxicological risks associated with potential contaminants of concern, namely copper, nickel and zinc. These metals were selected based on their potential toxicity to aquatic biota. As described by Angel et al. (see Appendix G of Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River), CSIRO undertook laboratory analysis, which included assessment of:

- Copper, zinc and nickel speciation and complexation capacity.
- Copper, zinc and nickel partitioning between dissolved and particulate phases to assess adsorption capacity.

Metal speciation and the natural complexing capacity of Lower Watut River catchment watercourses were assessed (using the Chelex-column method) to provide information on the fraction of the dissolved metals that are:

- Bound to organic matter, forming stable metal complexes in solution. Metals bound to organic matter generally render the metals less bioavailable and therefore potentially less toxic to aquatic biota.
- In a labile and potentially bioavailable form. This 'free' unbound form of dissolved metal is potentially more toxic to aquatic biota.

In addition to speciation and complexation capacity assessments, the partitioning of metals between dissolved and particulate phases (suspended solids) was determined to assess the adsorption capacity of the natural suspended particulate matter in the Watut River and floodplain.

9.1.1.2.2. Numerical Modelling

Numerical modelling was undertaken to assist characterisation of the baseline environment in terms of flooding and hydrology. A flood model was developed by BMT WBM using TUFLOW-GPU based on a flood frequency analysis and hydrologic modelling. Full details of model development are provided in Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River and Appendix I, Catchment and Receiving Water Quality Modelling.

The highly variable and dynamic nature of the Watut River has resulted in a number of periods where gauging stations have been washed away or compromised by changes in channel morphology. These factors have introduced uncertainty in the estimated design discharges at longer recurrence intervals (1:10 year Average Exceedance Probability (AEP) flood event and above) due to the recurrence interval of the design event being more than the length of the data record used to generate the design discharge. Given this uncertainty, the flood modelling likely overestimates the frequency of flooding and flood breakouts from the Watut River main channel onto the eastern side of the floodplain. This has been supported by the conclusions made by Hydrobiology (see Appendix I of Appendix I, Catchment and Receiving Water Quality Modelling).

The flood assessment is based on a desktop theoretical analysis of potential flooding, with reliance on numerical flow models and empirical equations. Nevertheless, the flood assessment is suitable to support description of the existing surface water environment.

9.1.1.3. Assessment Criteria

In the sections below, baseline water and sediment quality is compared with various guidelines including:

- Ambient water quality criteria applicable to dissolved metals (<0.45µm filtered):
  - State of Papua New Guinea Environment (Water Quality Criteria) Regulation 2002 (PNG ER)
  - State of PNG Environmental Code of Practice for the Mining Industry (PNG ECoP) (Office of Environment and Conservation, 2000)
  - The Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ, 2000) water quality guidelines (ANZECC guidelines)
- Drinking water guidelines applicable to total metals:
  - State of PNG Public Health (Drinking Water) Regulation 1984
  - World Health Organisation (WHO) Guidelines for Drinking Water Quality (WHO, 2011)
- Sediment quality guideline:
  - Australian sediment quality guideline values specified in ANZECC/ARMCANZ (2000) and Simpson et al. (2013)

9.1.1.3.1. Water Quality Guidelines

Water quality data are compared to guideline values in the documents described above to assess the general condition of watercourses. Table 9.1 provides a summary of the various water quality guideline values used.

The first priority in assessing water quality was to use guideline values provided in the PNG ER and the PNG ECoP. The PNG ER and PNG ECoP criteria provided in Table 9.1 are based on protection of aquatic life in freshwater in PNG.

The ANZECC guideline values were also used to assess whether the existing water quality of the surface water resources is sufficient for aquatic ecosystem protection, within the context that they provide a robust set of criteria and allow for consideration of site-specific conditions. The ANZECC guidelines provide a starting point to enable consideration of whether further detailed investigation of local area water quality should be undertaken. It is notable that the ANZECC guideline values for a number of elements are hardness-dependent, and the ANZECC guidelines indicate that such values should be adjusted to the site-specific hardness. Consistent with the tiered assessment framework of the ANZECC guidelines, bioavailability testing was carried out to further evaluate certain water quality parameters (discussed in Section 9.1.1.2.1).

Drinking water standards including the State of PNG Public Health (Drinking Water) Regulation 1984 and WHO drinking water guidelines (2011) are included in Table 9.1 and were used as a reference point in the description of surface water resources in relation to total metals data.

Table 9.1: Water quality guideline values

Parameter	Units	Guideline Values				
		PNG ER	PNG ECoP	Drinking Water Standards		ANZECC[1]
				PNG	WHO (2011)	
Temperature	°C	No alteration >2°C	No alteration >2°C	-	-	-
Dissolved Oxygen (DO)	% sat	-	>80-90	-	-	85 – 120
	mg/L	>6	> 6	-	-	-
Turbidity	NTU[2]	No alteration >25	<10% change from background seasonal mean	-	-	-
Electrical Conductivity (EC)	µs/cm	-	<1,500	-	-	-
pH	-	No alteration to natural pH	6.5 – 9.0	-	-	6.0 – 8.0
Total Suspended Solids (TSS)	mg/L	-	<10% change from background seasonal mean	-	-	-
Potassium (K)	mg/L	5	-	-	-	-
Sulphate (SO_4^{2-})	mg/L	400	-	400	-	-
Silver (Ag)	mg/L	0.05	0.0001	0.05	-	0.00005
Arsenic (As)	mg/L	0.05	0.05	0.05	0.01	0.024
Boron (B)	mg/L	1	0.5	-	0.5	0.37
Beryllium (Be)	mg/L	-	0.004	-	-	-
Cadmium (Cd)	mg/L	0.01	0.0007 *	0.01	0.003	0.0002 *
Chromium (Cr)	mg/L	0.05	0.01	-	0.05	0.001
Cobalt (Co)	mg/L	Limit of detection	0.00024	-	-	-
Copper (Cu)	mg/L	1	0.007 *	-	2	0.0014 *
Iron (Fe)	mg/L	1	1	-	-	-
Mercury (Hg)	mg/L	0.0002	0.0001	0.001	0.006	0.00006^
Manganese (Mn)	mg/L	0.5	-	0.5	0.4	1.9

Parameter	Units	Guideline Values				
		PNG ER	PNG ECoP	Drinking Water Standards		ANZECC[1]
				PNG	WHO (2011)	
Zinc (Zn)	mg/L	5	0.18 *	-	-	0.008 *
Selenium (Se)	mg/L	0.01	0.005	0.01	0.01	0.005^
Lead (Pb)	mg/L	0.005	0.0013 *	0.1	0.01	0.0034 *
Nickel (Ni)	mg/L	1	0.056 *	-	0.07	0.011 *
Aluminium (Al)	mg/L	-	0.1 (if pH >6.5) 0.005 (if pH <6.5)	-	-	0.055 (if pH >6.5) Not Detectable (if pH <6.5)
Antimony (Sb)	mg/L	-	0.03	-	0.02	-
Tin (Sn)	mg/L	0.5	-	-	-	-
Ammonia**	mg/L	3.6	1.04	-	-	0.9
Nitrate	mg/L	-	-	-	-	0.7

Note: Guideline values for metals/metalloids are for dissolved metals/metalloids.
[1] ANZECC values are not hardness-modified and are based on a 95% level of species protection for metals/metalloids in typical slightly–moderately disturbed systems, and slightly disturbed lowland river in tropical Australia for other parameters except: ^ mercury and selenium values are for protection of 99% of species in typical slightly–moderately disturbed systems.
[2] Nephelometric Turbidity Units.
* Guideline values for Cd, Cu, Pb, Ni, Zn are dependent on water hardness in PNG ECoP and ANZECC –PNG ECoP values presented are based on a hardness of <50 milligrams per litre (mg/L) of $CaCO_3$ while ANZECC values are based on a hardness mid-range value of 30mg/L $CaCO_3$.
** Ammonia guideline values are dependent on temperature and pH – guideline value listed is based on temperature of 25°C and pH of 7.

9.1.1.3.2. Sediment Quality Guidelines

The ‘interim sediment quality guidelines’ are presented in ANZECC/ARMCANZ (2000) for sediment assessment in Australia and New Zealand. These guidelines have been reviewed by Simpson et al. (2013) and updated to incorporate a revision to the guideline for silver. The sediment quality guidelines in Simpson et al. (2013) are presented as two guideline values:

- Sediment Quality Guideline Value (SQGV): threshold concentration level below which there is a low probability that biological effects could occur.
- SQGV-High: threshold concentration level above which there is a high probability that biological effects could occur.

These guidelines were developed for assessing potential risks to organisms in contact with benthic sediment rather than suspended solids in river waters. The guidelines were used in the analysis of the existing benthic sediment quality of the surface water resources. A summary of the guidelines is provided in Table 9.2.

Table 9.2: Sediment quality guideline values

Parameter	Units	ANZECC and Simpson et al. (2013) Sediment Quality Guidelines	
		SQGV	SQGV-High
Ag	mg/kg	1.0	4.0
As	mg/kg	20	70
Cd	mg/kg	1.5	10
Cr	mg/kg	80	370
Cu	mg/kg	65	270
Hg	mg/kg	0.15	1.0
Ni	mg/kg	21	52
Pb	mg/kg	50	220
Sb	mg/kg	2.0	25
Zn	mg/kg	200	410

9.1.2. Aquatic Ecology

The aquatic ecology study methods are presented in the sections below.

9.1.2.1. Data Collection

A summary of the aquatic ecological data collected for each of the geographical areas is presented below.

9.1.2.1.1. Lower Watut River Catchment

The description of freshwater aquatic ecology values provided herein (refer to Section 9.6) for the Lower Watut River catchment was predominantly drawn from surveys and studies conducted since the 1990s as identified in Table 9.3. In addition, the following databases and sources were reviewed:

- International Union of Conservation of Nature (IUCN) database of threatened species.
- Study into endemism and richness of freshwater biota by Polhemus et al. (2004).

Table 9.3: Key historical freshwater aquatic ecology data sources

Data Source	Sampling Locations	Flora	Aquatic Habitats	Aquatic Macroinvertebrates	Fish	Aquatic Reptiles	Tissue Metals/ Metalloids
EMPS (1993)	Wafi River and tributaries Watut River	-	-	Aquatic macroinvertebrate community survey (1993)	Fish community survey (1993)	-	Fish (1993)
Powell and Powell (2000)	Wafi River Upper, Middle, Lower Watut, Markham, Wampit, Bulolo rivers	-	-	Review only	Review only	-	Review only
Mallard and Hugman (in Powell and Powell 2000)	Bulolo River, Lower Watut River	-	-	-	-	-	Fish (1986)
BAAM (Appendix C, Terrestrial Ecology Characterisation - Mine Area to Markham River)	Mine Area and part of Infrastructure Corridor	Vegetation mapping	-	-	-	-	-
Coffey (2012) – including unpublished chapter by Alluvium	Part of Project Area	-	Physical habitat characterisation	-	-	-	-
BMT WBM (Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River)	Wampit River, Waime River, Kendrik Creek, Bavaga River, Womul Creek, Nambonga Creek, Wafi River, Hekeng Creek	Aquatic vegetation community survey (2012)	Aquatic habitat survey (2012)	Aquatic macroinvertebrate community survey (2012)	Fish community survey (2012)	Incidental records from other surveys (2012)	Fish and prawns (2012)
	Womul, Ziriruk, Boganchong creeks	Aquatic vegetation community survey (2012)	Aquatic habitat survey (2012)	Aquatic macroinvertebrate community survey (2012)	Fish community survey (2012)	Incidental records from other surveys (2012)	-
	Wafi River catchment and Lower Watut River	Aquatic vegetation community survey (2013)	Aquatic habitat survey (2013)	Aquatic macroinvertebrate community survey (2013)	Fish community survey (2013)	Incidental records from other surveys (2013)	-

Note: - denotes no relevant information

To supplement available historical data, targeted field sampling campaigns were conducted as part of the EIS in March 2015 (Campaign 1), June 2015 (Campaign 2) and December 2016 (Campaign 3). Sampling sites are shown in Figure 9.1 and listed in Table 9.4, with the latter including sampling parameters.

The sampling sites were selected in order to:

- Provide representative examples of aquatic ecosystem types within, downstream and upstream of (or in adjacent sub-catchments to) the Lower Watut River catchment.
- Characterise aquatic environments in areas potentially affected by the Project that have not previously been surveyed.
- Assess temporal variability at representative sampling sites.

An assessment of structural habitat characteristics, aquatic and riparian[1] vegetation was conducted at all sites using a modified version of the AUSRIVAS sampling protocol (DNRM, 2001; Tiller and Metzeling, 1995; Tiller and Metzeling, 2002). Periphytic diatom[2] assemblages were sampled at the sites visited in March 2015 using standard watercourse bio-assessment and bio-monitoring methods (Chessman et al., 2015). Aquatic macroinvertebrates, which include aquatic insects and other invertebrates dwelling within watercourses, were sampled using methods targeted for each habitat type. Fish and macro-crustaceans (i.e., freshwater shrimp and crayfish) were collected from each site, with the main sampling methods including backpack electrofishing, baited box traps, gill netting and fyke nets. Fish and prawn samples were collected for metal analysis and to inform baseline characterisation and assessment described in Section 9.6.3. Water and sediment quality data was also recorded at each of the aquatic ecology sites, as described in sections 9.4 and 9.5

Table 9.4: Field sampling sites and freshwater ecology sampling parameters (Lower Watut River catchment)

Habitat	Site	Habitat Assessment	Diatoms	Macro-invertebrates (incl. Chironomids*)	Fish Communities	Tissue Burden Analysis
Tributary watercourse (high to moderate gradient tributary stream)	Bavaga River 1	C3	NS	C3	C3	NS
	Bavaga River 2 (Upstream)	C1, C3	C1	C1, C3	C1, C3	C1
	Bavaga River 3	C3	NS	C3	C3	NS
	Bavaga River 4	C3	NS	C3	C3	NS
	Bavaga River 5 (Downstream)	C1, C3	C1	C1, C3	C1, C3	C1
	Zamen River	C1	C1	C1	C1	C1
	Nambonga River	C1	C1	C1	C1	C1
	Womul Creek Upstream	C1	C1	C1	C1	C1
	Wafi River at Pekumbe	C1	C1	C1	C1	C1
	Gingen River Upstream	C1	C1	C1	C1	C1
	Banir River	C1	C1	C1	C1	C1

[1] Stream or river bank

[2] A group of algae that live on the surface of submerged plants or other underwater objects

Habitat	Site	Habitat Assessment	Diatoms	Macro-invertebrates (incl. Chironomids*)	Fish Communities	Tissue Burden Analysis
	Waime River Downstream	C1	C1	C1	C1	C1
	Denti Creek	C1	C1	C1	C1	C1
	Ziriruk Creek	C1	C1	C1	C1	C1
	Boganchong Creek Upstream	C2	NS	NS	C2	NS
	Wassing Creek	C2	NS	NS	C2	NS
	Wadgink Creek	C2	NS	NS	C2	NS
Floodplain watercourse (low gradient floodplain streams and wetlands)	Bavaga River 6	C3	NS	C3	C3	NS
	Bavaga River 7	C3	NS	C3	C3	NS
	Bobul Creek at Bobul Xing	C1	C1	C1	C1	C1
	Chaunong Creek Upstream	C1	C1	C1	C1	C1
	Chaunong Creek Downstream	C2	NS	NS	C2	NS
	Mari Creek	C2	NS	NS	C2	NS
	Bambufo Creek at Sago Swamp	C2	NS	NS	C2	NS
	Unnamed Creek at Sago Swamp	C2	NS	NS	C2	NS
	Boganchong Creek Downstream	C2	NS	NS	C2	NS
Oxbow lake	Bali Oxbow	C1	C1	C1	C1	C1
	Uruf Oxbow	C1	C1	C1	C1	C1
Watut River (Unconfined, turbid major river systems)	Watut River at Uruf	C1	C1	C1	C1	C1
	Watut River at Maralina	C1	C1	C1	C1	C1
	Watut River at Maus Watut	C1	C1	C1	C1	C1

Note: C1 = campaign 1 (March 2015), C2 = campaign 2 (June 2015), C3 = campaign 3 (December 2016) NS = no sample,
* Chironomid specimens were picked from macroinvertebrate samples taken at edge and riffle habitat at each site sampled in campaign 1 only

9.1.2.1.2. Lower Markham River Floodplain

As mentioned above, the baseline characterisation for the Lower Markham River floodplain has been more targeted and less comprehensive in comparison with the Lower Watut River catchment, commensurate with the level and duration of Project activities occurring in this area (i.e., impacts will largely be restricted to the construction period only).

Representative watercourses surveyed in the Lower Markham River floodplain in June 2017 are listed in Table 9.5 and shown in Figure 9.2. The survey data represents a 'snapshot' of the sites at the time of sampling and cannot be used for analysis of temporal variation (see Appendix H, Surface Water and Freshwater Aquatic Ecology Characterisation - Yalu to Wagang).

The survey characterised the streams in terms of water quality, stream habitat and riparian condition. High-level aquatic flora observations were made; however, species identification was not completed. The deeper, swampy nature of the streams in the vicinity of the

Infrastructure Corridor precluded sampling of fish (by electrofishing) and macroinvertebrates (kick-netting in riffle habitat).

Table 9.5: Aquatic ecology field sampling sites (Lower Markham River floodplain)

Sites	Watercourse	Date	Instream Habitat and Riparian Condition Assessment
S/Site 1	Busanem Creek	7/06/2017	X
S/Site 2	Amburinu Creek	7/06/2017	X
S/Site 3	Buambub Creek	6/06/2017	X
S/Site 4	Pumpkin Creek	6/06/2017	X
S/Site 5	Pumpkin Creek	7/06/2017	X
S/Site 6	Pumpkin Creek	7/06/2017	X
S/Site 7	Pumpkin Creek	6/06/2017	X
S/Site 8	Markham River	6/06/2017	X
S/Site 9	Maiwara Creek	7/06/2017	X

X denotes assessment undertaken.

9.1.2.2. Data Analysis

Aquatic ecological data analysis for each of the Lower Watut River catchment and Lower Markham River floodplain areas are described below.

9.1.2.2.1. Lower Watut River Catchment

Diatom samples were transported to the University of Adelaide (Australia) for analysis. Multivariate statistical analysis was used to assist evaluation of the diatom data, and to investigate whether measured environmental variables explained patterns in the diatom assemblages (Ter Braak and Prentice, 1988).

Analysis was conducted on aquatic macroinvertebrate samples collected during March 2015 and December 2016, and patterns of variability in communities among sites were explored using multivariate statistical techniques. Chironomid specimens isolated from macroinvertebrate samples taken during the March 2015 sampling were sent to the South Australian Museum for identification of morphological deformities[3].

All captured fish and macro-crustaceans were retained for identification, counted, weighed and measured. Voucher macro-crustacea specimens were transported to a laboratory (Dardanus Scientific, Mt Tamborine) in Australia for identification. Catch data were used to generate a variety of metrics (e.g., richness, abundance, proportion of exotics) that describe the biodiversity values of fish and macro-crustaceans at each site. Multivariate statistical techniques were used to describe patterns in community structure.

Fish and prawn samples obtained during the March 2015 sampling were retained for analysis of concentrations of trace metals and metalloids in tissues. Three types of tissue samples were collected: fish whole body; macro-crustacean flesh tissue; and macro-crustacean cephalothorax. Frozen samples were transported to the National Measurement Institute (NMI) in Australia for tissue metal analysis. Seafood tissue trace metal/metalloid concentrations identified by the Australia and New Zealand Food Authority (ANZFA)

[3] Chironomids (the family Chironomidae) exhibit morphological deformities when exposed to environmental pollutants (Madden et al., 1995; Warwick, 1985) and prevalence of these deformities is a useful tool for detecting disturbance (Bird, 1994; Warwick, 1980)

(ANZFA, 2000) and the United States Food and Drug Administration (USFDA) (USFDA, 2001) were used as a reference when assessing fish tissue metal concentrations.

9.1.2.2.2. Lower Markham River Floodplain

No aquatic flora, macroinvertebrate or fish sampling was undertaken for the sites in the vicinity of the Infrastructure Corridor located on the Lower Markham River floodplain.

9.1.2.3. Assessment Criteria

Assessment of the Lower Watut River catchment area, which included species of conservation significance, likelihood of species occurrence, habitat modification and critical habitat assessments, were more comprehensive than those of the Lower Markham River floodplain, which included a simple riparian condition assessment. These assessments were proportionate with the proposed level and duration of Project activities in the respective study areas.

9.1.2.3.1. Conservation Conventions and Assessment Criteria

For the purposes of this assessment, species of conservation significance include:

- Species of international conservation priority, listed as threatened (Critically Endangered, Endangered or Vulnerable) or Near Threatened in the IUCN Red List of Threatened Species (IUCN Red List).
- Species of national conservation priority, listed as Protected or Restricted under the *Papua New Guinea (PNG) Fauna (Protection and Control) Act 1966*.
- Species endemic to the Lower Watut River catchment.

The State of PNG does not have a system in place for the categorisation of threatened ecological communities. As such, this assessment was conducted with consideration of features of high biodiversity significance, including habitat types, defined under International Finance Corporation (IFC) Performance Standard (PS) 6 (IFC, 2012).

The IFC PS 6 distinguishes between natural and modified habitats, as well as a subset of these habitats, known as critical habitats. The criteria for distinguishing these habitat types are set out in IFC PS 6 and its associated guidance notes. Habitat types are distinguished based on their condition and biodiversity values, and each are subject to differing management requirements.

For the purposes of the freshwater aquatic ecology assessment, the following approach was adopted in defining these habitat types:

- Categorisation of habitat areas into natural habitat and modified habitat, based on a list of criteria.
- Identification of areas of natural or modified habitat that are critical habitat, based on a list of criteria.

The assessment of each habitat type was based on discrete habitat units (as detailed in Section 9.6.3), i.e., high and moderate gradient tributary watercourses, low gradient floodplain tributary watercourses and wetlands, unconfined, turbid major river systems and oxbow lakes.

9.1.2.3.2. Natural and Modified Habitat

Criteria distinguishing between modified and natural habitat is provided in Table 9.6, and is primarily based on:

- Occurrence of non-native plants and/or animal species.
- Occurrence of substantial anthropogenic modification of ecological functions or species composition.

In distinguishing between these habitat types, the following study method was applied:

- All habitat types were assumed in the first instance to be natural habitat.
- Habitat was considered to be modified habitat where one or more of the following were present:
  - Habitat is not capable of supporting a viable population of native aquatic flora and/or fauna species.
  - Habitat has been subject to anthropogenic modification that causes impacts to ecological functions and species composition that exceeds naturally occurring landscape processes or changes within the range of natural variability.

Table 9.6: Modified and natural habitat criteria

Habitat Type	Criteria
Modified habitat	Areas that may contain a large proportion of plant and/or animal species of non-native origin
	Areas where human activity has substantially modified an area's primary ecological functions and species composition
Natural habitat	Areas composed of viable assemblages of plant and/or animal species of largely native origin
	Areas where human activity has not modified an area's primary ecological functions and species composition

9.1.2.3.3. Critical Habitat

A modified or natural habitat is considered to be critical habitat where it meets at least one of the criteria listed in Table 9.7. This table includes thresholds associated with each criterion, with specific breakdown of Tier 1 and Tier 2 critical habitats for Criteria 1 to 3 per IFC PS 6 guidance notes. The following definitions are relevant to the interpretation of Table 9.7:

- Critically Endangered and Endangered species are those listed in these categories in the IUCN Red List.
- Endemic species are those that have greater than 95% of their global range inside the island of New Guinea (i.e., Papua and PNG).
- Restricted-range flora species are all those listed as endemic species; restricted-range fauna species were determined on a case-by-case basis.
- Migratory species are those species of which a significant proportion of its members cyclically and predictably move from one geographical area to another.
- Congregatory species are those species whose individuals gather in large groups on a cyclical or otherwise regular and/or predictable basis.

- Species with a regular occurrence in habitat refers to species that occur continuously in the habitat, seasonally or cyclically or episodic but does not include vagrancies, marginal occurrence and historical records or unconfirmed anecdotal evidence.

Specific subsets of endemic species were defined, based on their range within the island of New Guinea:

- Category 1a – Restricted to the island of New Guinea but recorded in at least three basins, including the Markham River Basin.
- Category 1b – Restricted to the island of New Guinea but recorded in at least three basins; not known from the Markham River Basin.
- Category 2a – Restricted to an area of northern PNG including the Markham River Basin.
- Category 2b – Restricted to an area of northern PNG outside the Markham River Basin.
- Category 3 – Restricted to the Markham River Basin but not recorded in the Watut River catchment.
- Category 4 – Restricted to the Watut River catchment only.

9.1.2.3.4. Riparian Condition

Riparian condition can strongly influence instream ecology in tropical freshwater ecosystems (Dudgeon, 1994). At each site on the Lower Markham River floodplain in the vicinity of the Infrastructure Corridor, observations were recorded in relation to:

- Riparian vegetation condition (i.e., level of modification).
- Natural erosion along the stream banks in the riparian zone.
- Anthropogenic influences such as the presence of gardens, urban developments or nearby dwellings/settlements as well as roads and tracks.

An overall rating of low, medium or high level of modification was given for each site located in the Lower Markham River floodplain based on visual observation and review of Google Earth aerial imagery from July 2016.

Observations of instream habitat were also recorded.

Table 9.7: Critical habitat assessment criteria

Criteria	Description of Criteria	Descriptor	Threshold
Criterion 1	Habitat of significant importance to Critically Endangered and/or Endangered species (Tier 1)	The discrete management unit supports Critically Endangered and/or Endangered species at the threshold specified	Habitat required to sustain ≥10% of the global population of a Critically Endangered or Endangered species/subspecies where there are known, regular occurrence of the species Habitat with known, regular occurrence of Critically Endangered or Endangered species where that habitat is one of ten or fewer management sites globally for the species
	Habitat of significant importance to Critically Endangered and/or Endangered species (Tier 2)	The discrete management unit supports Critically Endangered and/or Endangered species at the threshold specified	Habitat that supports the regular occurrence of a single individual of a Critically Endangered species and/or habitat containing regionally important concentrations of an Endangered species/subspecies Habitat of significant importance to Critically Endangered or Endangered species that are wide-ranging and/or whose population distribution is not well understood and where the loss of such a habitat could potentially impact the long-term survivability of the species
Criterion 2	Habitat of significant importance to endemic and/or restricted-range species (Tier 1)	The discrete management unit supports endemic and/or restricted-range species at the threshold specified	Habitat known to support ≥95% of the global population of an endemic or restricted-range species
	Habitat of significant importance to endemic and/or restricted-range species (Tier 2)	The discrete management unit supports endemic and/or restricted-range species at the threshold specified	Habitat known to sustain ≥1% but <95% of the global population of an endemic or restricted-range species
Criterion 3	Habitat supporting globally significant concentrations of migratory species and/or congregatory species (Tier 1)	The discrete management unit supports migratory or congregatory species at the threshold specified	Habitat known to sustain, on a cyclical or otherwise regular basis, ≥95% of the global population of a migratory or congregatory species at any point of the species' lifecycle
	Habitat supporting globally significant concentrations of migratory species and/or congregatory species (Tier 2)	The discrete management unit supports migratory or congregatory species at the threshold specified	Habitat known to sustain, on a cyclical basis or otherwise regular basis ≥1% but <95% of the global population of a migratory or congregatory species at any point of the species' lifecycle For species with large but clumped distributions, a provisional threshold is set at ≥5% of the global population Source sites that contribute ≥1% of the global population of recruits
Criterion 4	Highly threatened and/or unique ecosystems	The discrete management unit represents: an ecosystem that is currently listed or meets criteria for listing as Vulnerable, Endangered or Critically Endangered on the IUCN Red List of Ecosystems, or is unique on the island of New Guinea	
Criterion 5	Areas associated with key evolutionary processes	The discrete management unit contains: physical features of a landscape that might be associated with particular evolutionary processes, taking into account presence of isolated areas, areas of high endemism, spatial heterogeneity, environmental gradients, edaphic interfaces, connectivity and important areas for climate change adaptation subpopulations of species that are phylogenetically or morphogenetically distinct	

9.2. Drainage and Hydrology

The Mine Area is on the eastern side of the Lower Watut River. The Infrastructure Corridor, including the Northern Access Road, will cross the Watut River and the Markham River, adjacent to and upstream of its junction with the Watut River as shown in Figure 9.1. The Infrastructure Corridor between Yalu and the Coastal Area is located on the floodplain adjacent to the Lower Markham River, which discharges into the Huon Gulf.

Selected watercourses surveyed within each of these areas are described below.

9.2.1. Lower Watut River Catchment

The Markham River, a large, fast flowing and turbid river, is the fourth largest river in PNG, with a total catchment area of approximately 13,000 square kilometres (km^2) (including the Watut River catchment). The river originates in the Finisterre Range and flows approximately 170 kilometres (km) before discharging into the Huon Gulf at Lae. The combination of steep mountainous catchments in the upstream areas of the river and high rainfall contribute to relatively large flows with high concentrations of suspended sediment where the Markham River will be traversed by Project facilities (Renagi et al., 2010).

The Watut River catchment has a total area of approximately 4,860km^2 and contains five main river systems, namely Bulolo, Snake, Langimar and Banir rivers and the main arm of the Watut River. Other tributaries draining into the Watut River include the Waime, Isimp/Langimar, Mumena, Wafi and Laloona rivers. The total estimated length of the Watut River is between 157km and 224km (Osbourne, 1987; Pal et al., 2012) and the river drains the catchment in a generally northern direction to its confluence with the Markham River.

The upper Watut River highlands have a maximum elevation of 2,800 metres above sea level (mASL) and form steeply incised valleys with valley wall slope angles of 40 degrees (º) or more (Figure 9.3). The middle Watut River flows through a broad floodplain valley, as shown in Figure 9.4, and has several tributaries before flowing through a steep, confined gorge. The Lower Watut River lowlands have a typical elevation of 100mASL and are characterised as floodplains with highly meandering channels, oxbow lakes and backwater swamps (Figure 9.5).

The vegetation types within the Watut River catchment are forest and grassland, comprising approximately 76% and 20% of the catchment area, respectively. Mining land uses, including small-scale alluvial mining and the Hidden Valley Mine, comprise less than 0.5% of the catchment. On a whole of catchment scale, sediment generated as a result of alluvial mining occurring within Lower Watut River (e.g., Wau and Bulolo rivers) would likely represent a small fraction of the overall natural sediment loads based on the large catchments size and its high sediment transport capacity. On a more local scale, alluvial mining-related sediment loads would likely represent more significant proportions compared to the natural loads within these catchments.

The Mine Area extends across several sub-catchments and features of the Lower Watut River, which include (Figure 9.6):

- Lower Watut River (main channel) catchment
- Wafi River catchment
- Eastern floodplain catchments and floodplain streams

An overview of these catchments is given in Table 9.8.

Source: Alluvium

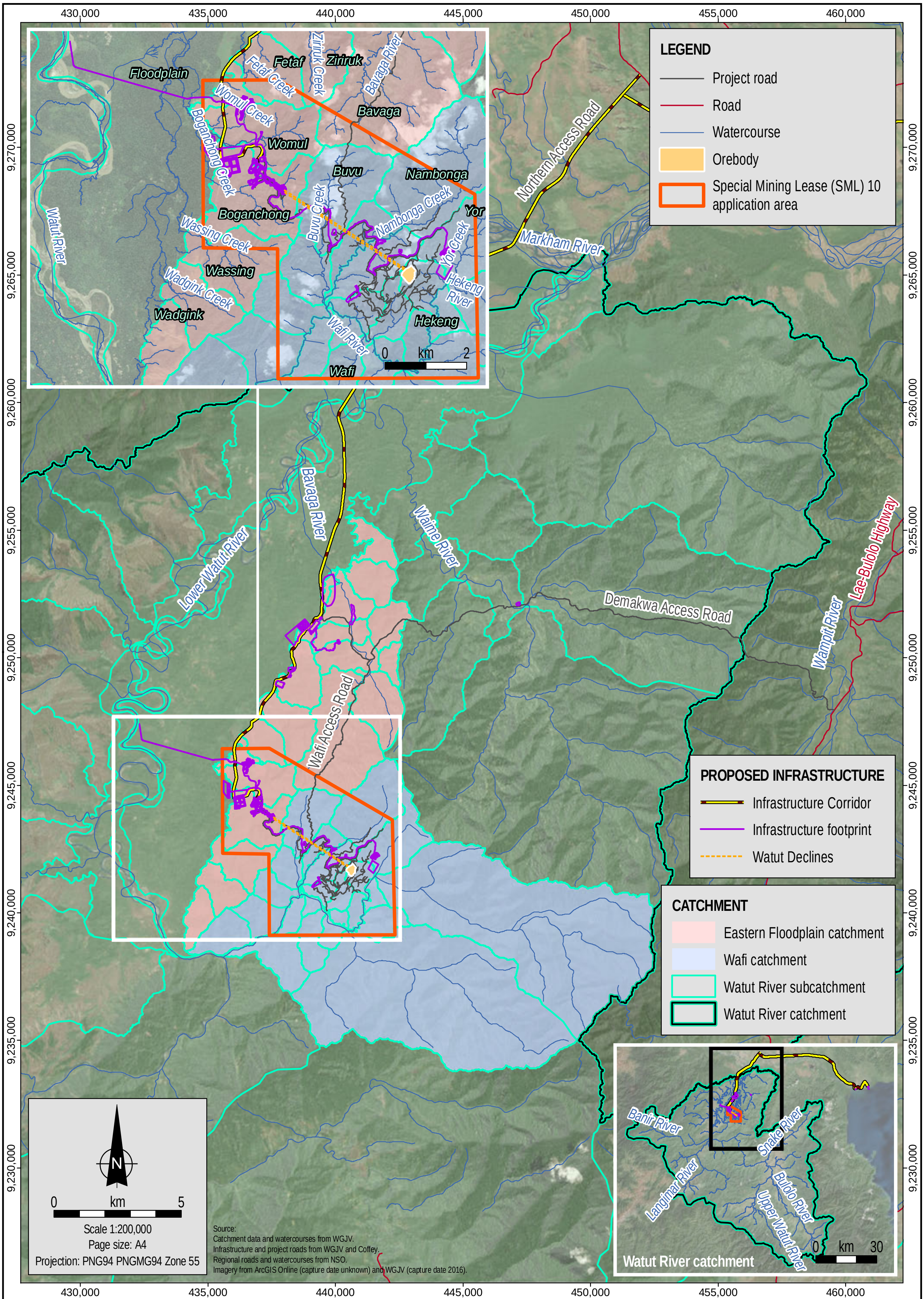
Figure 9.3
Upper Watut River

Source: Alluvium

Figure 9.4
Middle Watut River

Source: Alluvium

Figure 9.5
Lower Watut River



coffey A TETRA TECH COMPANY

Date: 13.06.2018
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.06_GIS

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Sub-catchments in the Lower Watut River catchment

Figure No: 9.6

Table 9.8: Lower Watut River catchments overview

Catchment	Sub-catchment	Catchment area (km^2)	Comments
Watut upstream of the Wafi River (total area: 4,161km^2)	Upper Watut	~670	Approximate area only
	Bulolo	~830	Approximate area only
	Snake	~400	Approximate area only
	Langimar	~900	Approximate area only
	Banir	~420	Approximate area only
Wafi River (approximate area: 120km^2)	Upper Wafi / Hekeng	41.5	-
	Heking Creek	4.5	-
	Zamen	40.7	-
	Nambonga/ Buvu	9.4/5.3	-
Eastern floodplain, catchments and floodplain creeks, including Bavaga River	Bavaga	27.5	-
	Bobul	6.2*	Catchment area includes Ziriruk Creek and upper Bobul (Finchif and Kufikasep Creeks)
	Mari	5.4*	Catchment area include Wassing and Wadgink Creeks
	Boganchong	3.7	-
	Womul	3.7	-
	Chaunong	19.0*	Catchment area includes Bobul, Mari, Boganchong and Womul Creeks.

* Catchment areas provided for the Bobul, Mari and Chaunong catchments only include steep regions within the 'eastern floodplain catchments'.

9.2.1.1. Lower Watut River (Main Channel)

The Lower Watut River is a large, turbid river that bisects a broad floodplain. It drains an area of approximately 4,161km^2 upstream of the confluence with the Wafi River. Within the low-lying floodplain area, a number of catchments drain into the river, including the small, steep catchments to the eastern side of the floodplain which are 1 to 5km^2 in area and prone to flash flooding.

The morphology of the Lower Watut River is highly dynamic and has changed considerably over time (refer to Section 9.3).

9.2.1.2. Wafi River Catchment

The Wafi River catchment is located in the middle section of the Watut River basin and has a catchment area of 120km^2. The catchment has a mountainous terrain with an elevation of 760 metres (m) at Mt Golpu, with deeply incised valleys and steep valley walls of up to 45 degrees (^{o}) that are largely forested.

Scattered vegetation clearing for villages and gardens occurs across the catchment while exploration activity is evident on Mt Golpu and other sites (camps, laydown areas and tracks). Artisanal timber harvesting by local communities is common along established tracks and roads.

Streams in the Wafi River catchment are fast-flowing with rocky substrates and largely intact riparian vegetation. The main tributaries of the Wafi River are Yor Creek, Hekeng River (upper Wafi River), Zamen River, Buvu Creek and Nambonga Creek.

These watercourses have highly-confined valleys with a steep gradient, as shown in Figure 9.7, resulting in hydrology characterised by water levels rising and falling rapidly. Streams are shallow and narrow, but widen and deepen in the middle and lower parts of the Wafi River valley. The tributaries of the Wafi River are predominantly fed by overland flows originating in their steep catchment areas; however, there is also an unquantifiable contribution to both major and minor tributaries from groundwater.

9.2.1.3. Eastern Watut River Floodplain Catchments and Floodplain Streams

The Lower Watut River floodplain area has numerous small streams draining the steep catchments to the west and east. Some sub-catchments to the east of the floodplain fall within the Mine Area and Infrastructure Corridor, and these include the Bavaga River and Bobul, Kufikasep, Finchif, Ziriruk, Fetaf, Womul, Boganchong, Wassing and Wadgink creeks. The eastern Watut River floodplain catchments are small in area and individually contribute a small proportion to the total Watut River flow.

The Bavaga River (Figure 9.8) is the one of the largest sub-catchments in the eastern Watut River floodplain, with a total area of 28km^2. The Bavaga River flows into wetlands within the Watut River floodplain, which then flows into the main Watut River channel.

A number of low-gradient streams occur within the Lower Watut River floodplain to the east of the main channel, and these eventually drain to the Lower Watut River. These streams include the Ngomang, Mari and Chaunong creeks (Figure 9.9). The floodplain streams receive inflows from the catchment areas to the east of the floodplain and are also likely to receive flows originating from groundwater within the floodplain, palustrine wetland areas (i.e., vegetated, non-riverine or non-channel systems) within the floodplain, and the Lower Watut River during times of flood. The flows from the Lower Watut River include overbank flow and flow through inlet streams which feed both the floodplain streams directly, and palustrine wetlands throughout the floodplain more generally during high flows.

Current information indicates that in low-gradient environments where the eastern catchments meet the Watut River floodplain, the streams infiltrate into the floodplain, resulting in ‘drying’ of creek beds at various locations, depending on the water table elevation and catchment inputs. Elsewhere, groundwater also has surface expression throughout the floodplain, and some of the floodplain creeks appear to have a groundwater source (e.g., Ngomang Creek). As such, many of the creeks and wetland environments on the eastern Watut River floodplain are likely to be at least partially dependent on groundwater.

9.2.1.4. Hydrology

9.2.1.4.1. Streamflow

Hydrologic and hydraulic analysis for the Watut River was undertaken by BMT WBM (see Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River and Appendix I, Catchment and Receiving Water Quality Modelling), building on previous analysis developed by SKM (2012a; 2012b). This analysis used streamflow data from the Sunshine gauge, which is located on the Watut River, 60km upstream of the Wafi River confluence, and has a catchment area of approximately 2,310km^2. While data available for this analysis was limited, a flow-duration relationship for the Watut River at Sunshine gauge was developed (Figure 9.10). This relationship indicates a significant, persistent baseflow in the Watut River at this point. Data to enable characterisation of the baseflow for the smaller catchments in the Lower Watut River catchment is still being accumulated. The WGJV will continue to collect additional data to improve capture over a range of flows and provide an update of the models.

Photo credit: WGJV

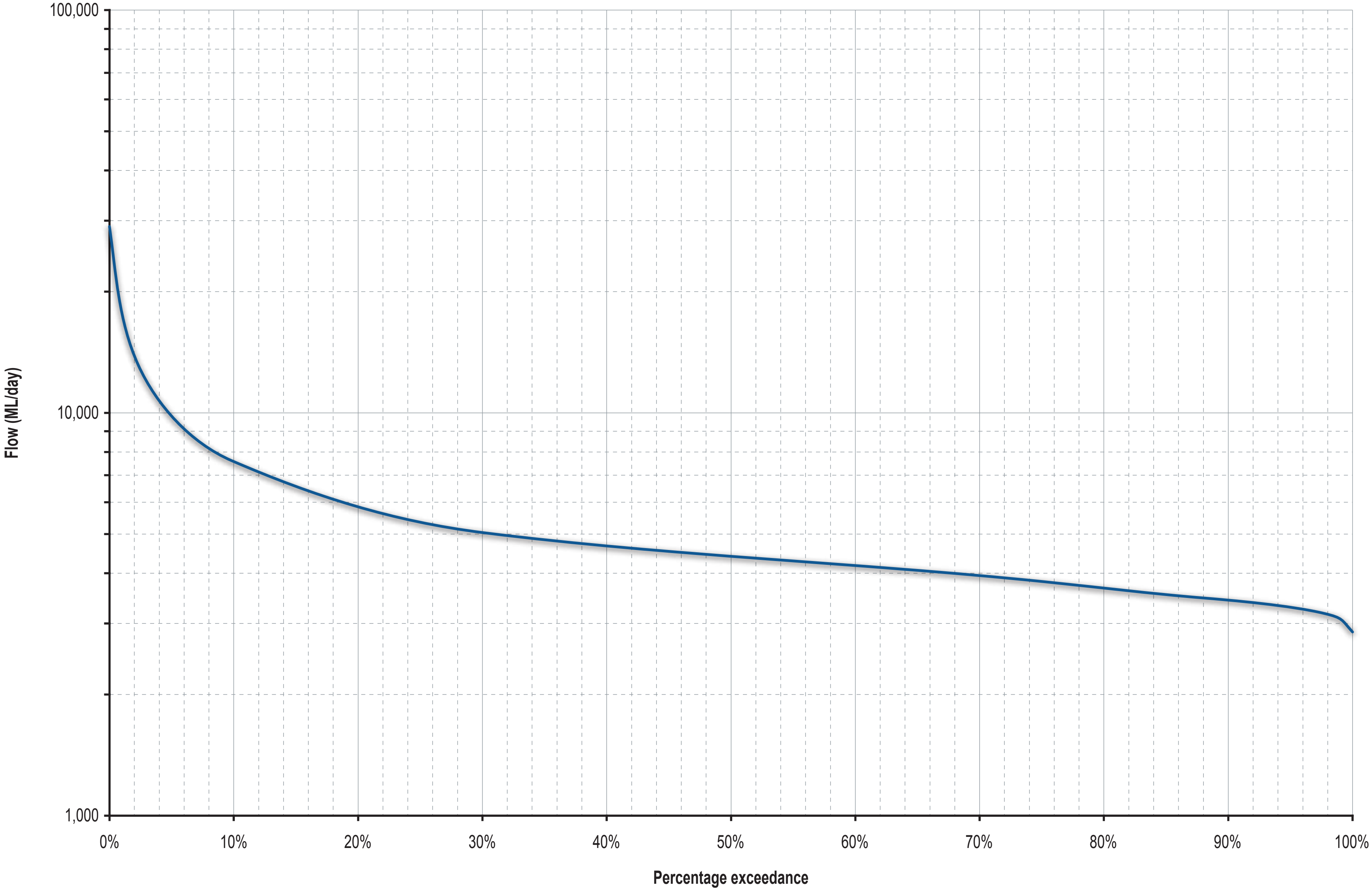
Figure 9.7
High energy tributary watercourses, Zamen River

Photo credit: WGJV

Figure 9.8
High energy tributary watercourses, Bavaga River Upstream

Photo credit: WGJV

Figure 9.9
Low gradient floodplain watercourses, Chaunong Creek Upstream



Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure9.3

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.10_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Sunshine gauge: flow-duration relationship

Figure No: 9.10

9.2.1.4.2. Flood Frequency Analysis

The flood frequency analysis undertaken by BMT WBM (Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River) used a number of methods to determine design discharges for the Watut River at Sunshine Gauge, with the adopted design discharges provided in Table 9.9. There is particular uncertainty in the estimated design discharges at longer recurrence intervals due to the short length of the data record used to generate the design discharge and the hazardous nature of gathering data for high flow events.

Table 9.9: Sunshine gauge: adopted design discharge

AEP	1:2 Year	1:5 Year	1:10 Year	1:20 Year	1:50 Year	1:100 Year
Discharge (m^3/s)	450	750	1,000	1,400	2,000	2,600

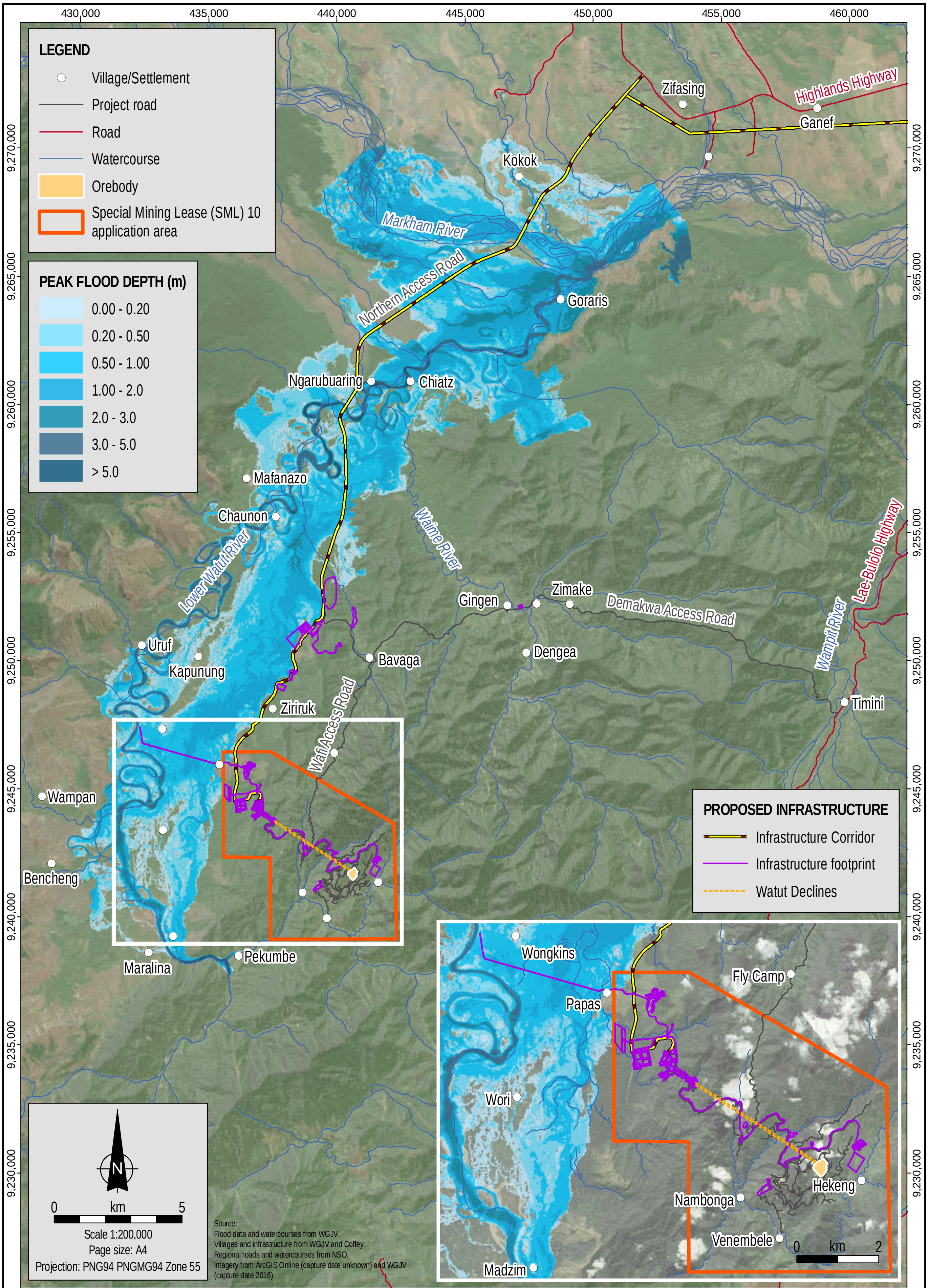
9.2.1.4.3. Flooding Analysis

Analysis of flood conditions in the Lower Watut River indicates that floodwaters regularly overflow the eastern bank of the Lower Watut River at two locations: immediately downstream of the confluence with the Wafi River and near Wongkins Village. Modelling indicates that flood waters break the bank and enter the Watut River floodplain at these locations in events less than the 1:2 year AEP flood event and flow north through the forests of the Watut River floodplain (refer to Figure 9.11 and Figure 9.12).

These breakouts appear to form a substantial overbank flow path on the eastern side of the Watut River and are expected to inundate a large area characterised by a complex network of braided streams. In the 1:2 year AEP flood event, the model predicts flow velocities of up to 0.5 metres per second (m/s) across much of the floodplain (Figure 9.12). In events greater than the 1:50 year AEP flood event, much of the Lower Watut River floodplain is predicted to be inundated.

An independent peer review of these modelling results (Appendix I of Appendix I, Catchment and Receiving Water Quality Modelling) concluded that:

- The flow breakouts between the Wafi River and Wongkins Village are expected to occur less frequently than the extent depicted on the flood maps in Figure 9.11 and Figure 9.12 (i.e., less than 2-year ARI frequency).
- Predictions of velocity of wet season flows across the eastern floodplain are most likely too high and unlikely to occur on a 2-year ARI frequency. Although flow in the defined channels (e.g., Chaunong Creek, Bobul Creek) may be of the order of up to 0.5m/s in certain circumstances, floodplain flow rates are likely to be significantly slower; the density of vegetation throughout the floodplain appears too high to allow flow velocities of the predicted magnitude to occur. A review of available recent satellite imagery shows little evidence of significant overspill from the Lower Watut River that would result in floodplain flows of between 0.15 and 0.5m/s over a flow width of approximately 1km.
- During the wet season, inundation of the Lower Watut River eastern floodplain due to high river levels are expected to be more gradual and the contribution of local runoff to be more significant. Filling of the floodplain basins are expected to occur from both upstream and downstream connection points, and from local runoff (i.e., rather than from overflow from the Watut River).



MXD Reference: 0520DD_10_GIS017_v0_8

coffey
A TETRA TECH COMPANY

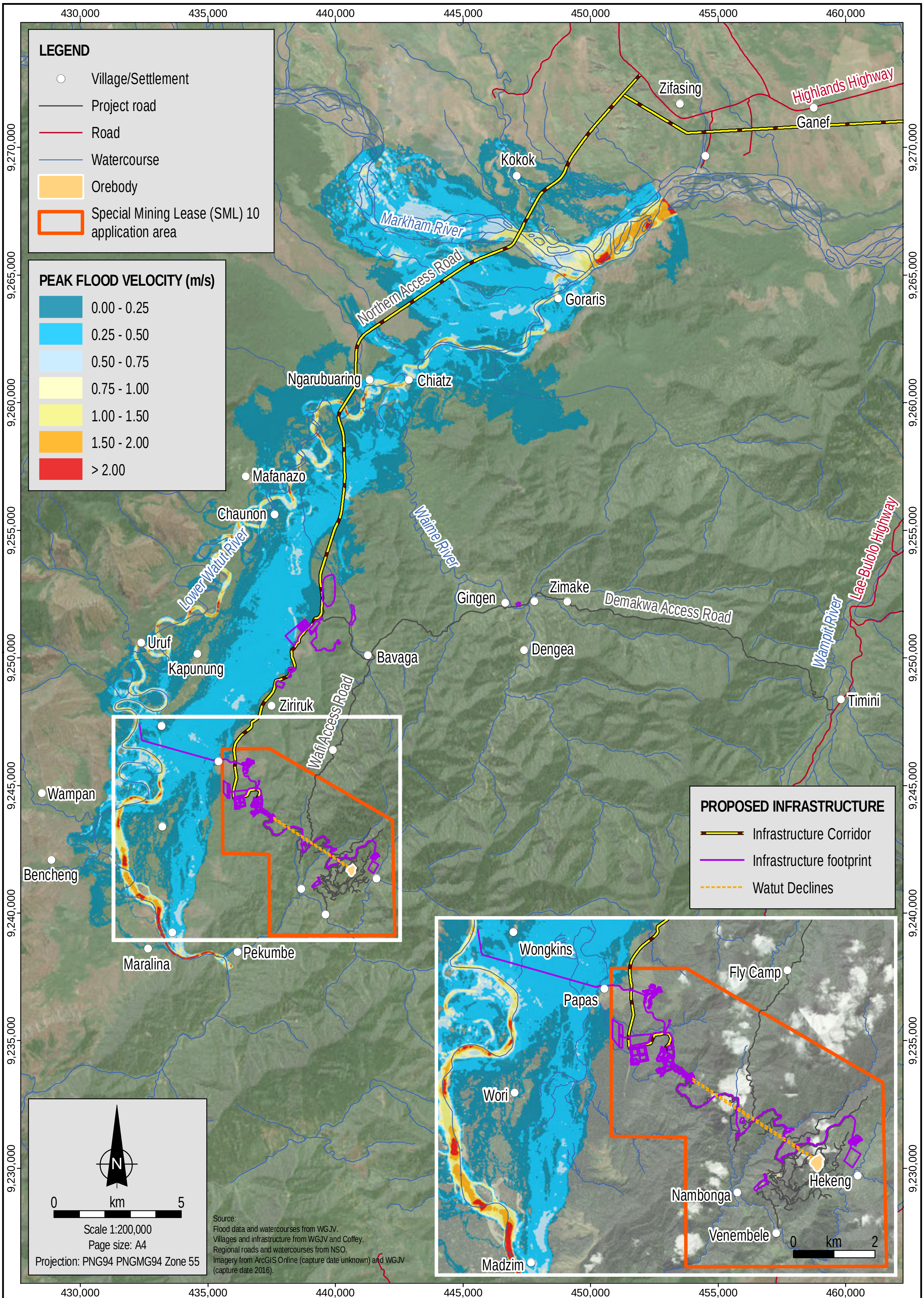
Date:	13.06.2018
Project:	754-ENAUABTF100520DD
File Name:	0520DD_10_F09.11_GIS

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Existing case 1:2 year AEP peak flood depth for the Watut River

Figure No: **9.11**



coffey
A TETRA TECH COMPANY

Date: 13.06.2018
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.12_GIS

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Existing case 1:2 year AEP peak flood velocity for the Watut River

Figure No: 9.12

MXD Reference: 0520DD_10_GIS018_v0_8

9.2.2. Lower Markham River Floodplain

Watercourses studied in the Lower Markham River floodplain south of the Atzera Mountain Range included the Markham River and Busanem, Amburinu, Buambub, Pumpkin and Maiwara creeks (see Figure 9.2).

As shown in Figure 9.2, the Atzera Mountain Range runs in a northwest–southeast direction and is bounded by the Markham River to the west and south and the Bumbu River to the north and east. The headwaters of the Yalu River originate in the Finisterre Range and flow south past the village of Yalu and western toe of the Atzera Mountain Range to meet the Markham River floodplain approximately 40km downstream of the Watut-Markham confluence. The Markham River discharges into the Huon Gulf a further 10km downstream.

The Markham River meanders within its floodplain, ranging from 3 to 8km wide in the lower catchment (Samanta et al., 2016), cutting new channels and reopening former channels following significant flood events. The floodplain is characterised by a lower terrace within which the current channels are located and an upper terrace occupied by swamp forest and sago palm.

Watercourses in the Lower Markham River floodplain were classified as small (<10m bank to bank), medium (10 to 25m bank to bank) or large (>25m bank to bank) and all had similar substrate compositions and gradients. Figure 9.13, Figure 9.14 and Figure 9.15 show several sites at which river banks and riparian zones have been influenced by access tracks, settlements, gardens and roads.

9.3. Sediment Transport and Fluvial Geomorphology

This section describes sediment transport and fluvial geomorphology characteristics for the Lower Watut River catchment. A sediment transport and fluvial geomorphology characterisation has not been conducted for the Lower Markham River floodplain, where Project activities are largely restricted to highly localised temporary construction activities.

9.3.1. Sediment Load and Sources

The Watut River catchment is a dynamic environment. High rainfall combined with steep, unstable slopes and associated high weathering rates results in significant sediment loads entering the watercourses that result in frequent and rapid changes in the stream bed of the majority of rivers and creeks.

Pal et al. (2012) predicted the catchment had high rates of soil loss (6.6 million tonnes per year (Mtpa) and 12 tonnes per hectare per year (t/ha/year)) because of the long steep slopes, with the highest rates occurring in steep mountainous areas. These rates do not include the impact of landslips, which are a significant contributor of sediment load to the Watut River.

Mass movements (landslips), ongoing soil erosion (via sheetwash, i.e., dislodgement of soil by rainfall and transport via sheet-like flow of water) and riverbank erosion represent sediment sources to the watercourses. Eroded sediments are initially transported towards the river by sheetwash.

Landscape denudation (i.e., processes that lead to loss of vegetation and subsequent erosion) due to mass movements (particularly landslips) contributes sediment to watercourses across the region and can lead to alterations in channel morphology and/or channel migration rates. Such events can occur to sloped areas and have variable magnitude and location.

Photo credit: WGJV

Figure 9.13
Buambub Creek, S/Site 3

Photo credit: WGJV

Figure 9.14
Pumpkin Creek, S/Site 4

Photo credit: WGJV

Figure 9.15
Markham River, S/Site 8

Mass movement potential was evaluated (Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River) using the SINMAP[4] program (Pack et al., 2005). Most of the Mine Area lies in a moderate risk area with a few higher risk zones (as defined by the slope stability index derived from SINMAP). This indicates that some landslips could occur in higher risk zones if vegetation is cleared, and also in flow convergence zones.

The sediment load in the Watut River catchment watercourses represents the combined inputs of highly localised point sources, which can continue to influence sediment loads in the system over many decades, to more diffuse or catchment-wide processes which contribute a more regular and ongoing base load of sediment to the rivers.

In the past, there have been several recognised sediment point sources in the catchment of the Watut River (ESAP, 2012) including:

- Bulolo River
- Alluvial and other mining
- Kumalu landslip

Land clearance across the catchment associated with population growth is considered as a more diffuse source of sediment.

Alluvial mining has occurred in the Bulolo River catchment since the 1930s. The current alluvial mining operations are considerably more sophisticated than those in the past, with high pressure sluicing now used to process the sediments and allow the gold to be recovered. These operations continue to contribute a considerable sediment load downstream.

Sediment loads to the Watut River have also been contributed to by overburden removal at Hidden Valley and Edie Creek mines, although the contribution from the Hidden Valley mine has substantially diminished.

A major landslip occurred in the Kumalu River catchment (a tributary of the Snake River) around the year 2000. This landslip contributes an unknown, but significant, load of sediment to the Watut River via the Snake River. Based on monitoring data gathered between 2010 and 2012, it was estimated that the Snake River contributed to the Watut River between four and five times the annual sediment loads from each of the upper Watut and Bulolo rivers (ESAP, 2012).

The annual suspended sediment load in the Watut River at Goraris (i.e., Lower Watut River near the Markham River confluence) was estimated to be between 6 to 9Mtpa[5]; however, there is a lack of data correlating NTU with TSS at the station, particularly at higher flows, so the actual suspended sediment load is likely to be higher.

9.3.2. Fluvial Geomorphology

9.3.2.1. Wafi River

In terms of sediment dynamics, the Wafi River catchment is predominantly an undisturbed system. Stream sediment originates from the weathering of valley slopes and from landslips triggered by a combination of heavy rainfall, seismic activity and river scour of the valley toe. The high drainage density (i.e., length of stream channels per unit area of the drainage

[4] SINMAP applies to shallow translational landsliding controlled by shallow groundwater convergence

[5] Based on referenced third party material

basin) of the catchment indicates a potential for sediment to report to streams in short timeframes.

Some coarser sediment fractions (cobbles, gravels and coarse sand) may deposit and be temporarily stored on the land surface or on the beds of tributaries, and there can be a longer lag response between delivery of the deposited sediment to the tributary and its transport to the major streams. The finer fraction (including silt, clay and fine sand) largely enters the streams and is transported downstream to the lower Wafi River and then to the Watut River.

The upper Wafi/Hekeng, Zamen rivers and Yor, Buvu and Nambonga creeks are headwater streams within highly confined valleys. These streams have a hydrology characterised by water levels rising and falling rapidly, which, due to their steep gradient rapidly move sediments downstream. Consequently, the substrates of these streams are typically comprised of boulders, bedrock, gravel and occasional areas of sand. These streams tend to be highly stable and resistant to erosion.

The middle reaches of the Wafi River are classified as a single confined channel. The steep gradient transports sediment downstream efficiently, although sand sheets occur in some areas. These reaches contain pool-riffle sequences, and cascades occur in the upper reaches; they are inherently stable, and not prone to erosion or accretion, and, therefore, do not contain well-developed floodplains.

The lower reaches of the Wafi River are classified as a partly confined meandering channel and have a lower gradient than those discussed above. Sediment accumulation within the channel is primarily restricted to the insides of bends, whereas the outsides of bends are prone to erosion. Substrates contain a mix of bedrock and sand, and meso-habitat[6] diversity is high with riffles, runs, sand and rock pools. A gravel-sand delta is present near the confluence of the Wafi and Watut rivers near Pekumbe village.

9.3.2.2. Lower Watut River

The Lower Watut River has an unconfined, meandering channel and contains an extensive floodplain and in-channel sediment deposits. The floodplain is approximately 35km long and 2 to 3km wide. The Lower Watut River is highly mobile, with the location of the channel migrating over time. Detailed mapping of landform ages shows that much of the inner floodplain has been reworked over 60 years (Figure 9.16).

Investigations of the meandering rates of the Lower Watut River identified strong evidence of past meandering across most of the floodplain, including the presence of oxbows and meander traces, chute cut-offs, and connecting channels across meander necks[7]. A comparative assessment of past flow paths highlighted the extent of these previous meanders, with migration rates in the more active meanders found to often exceed 50% of the channel width per year.

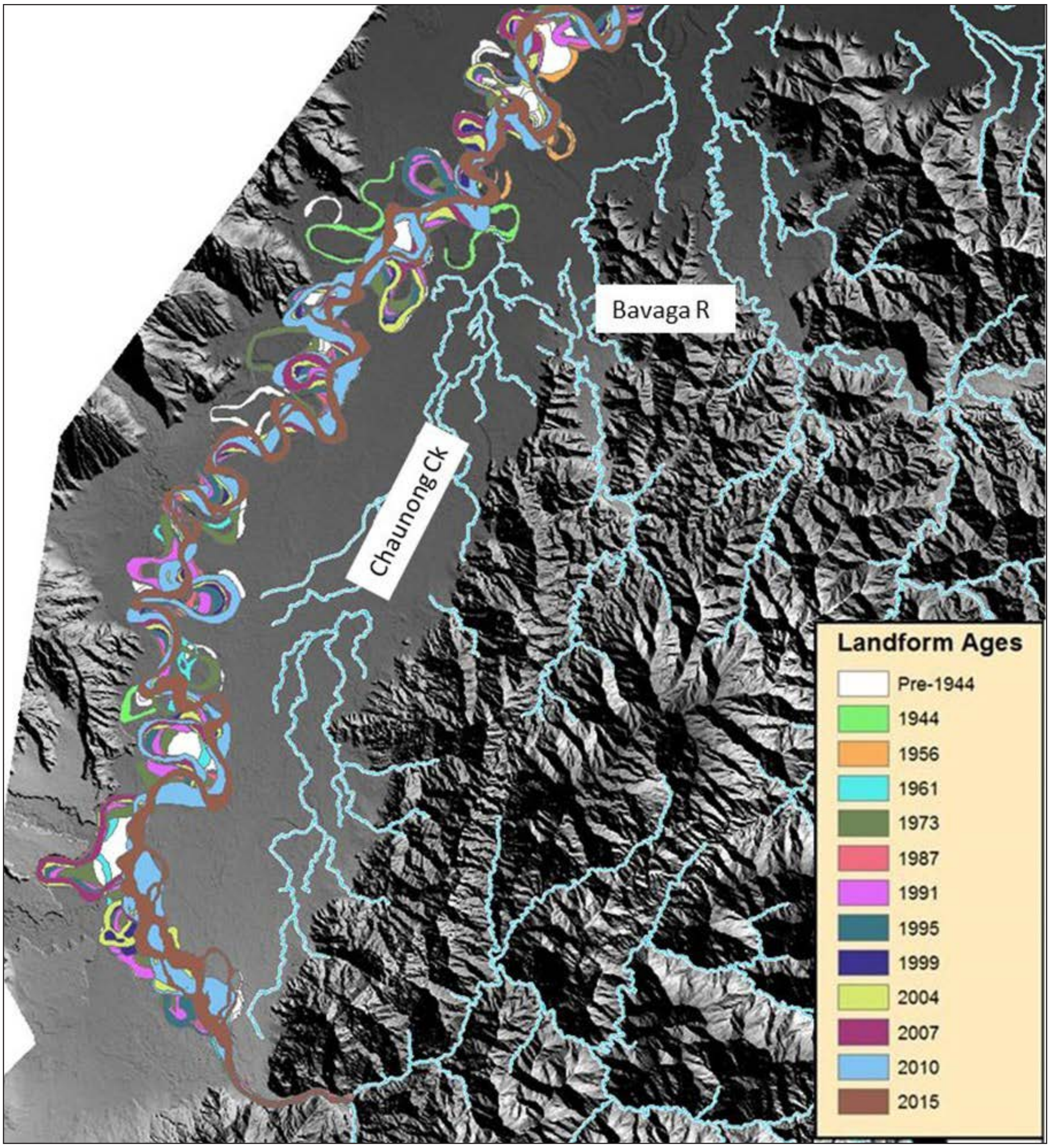
The Lower Watut River floodplain reach is a major sediment storage unit with pronounced meander and meander cut-off features. The complex history of the Lower Watut River floodplain is illustrated by the changes in channel sinuosity[8] shown in Figure 9.17 (further described in Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River). The recent increase in sediment supply (described in Section 9.3.1) has led to channel adjustment resulting in a sharp decrease in both channel length and sinuosity.

---

[6] Broad scale habitat types that are roughly the same scale as the channel width and delineated by localised slope, channel shape and structure

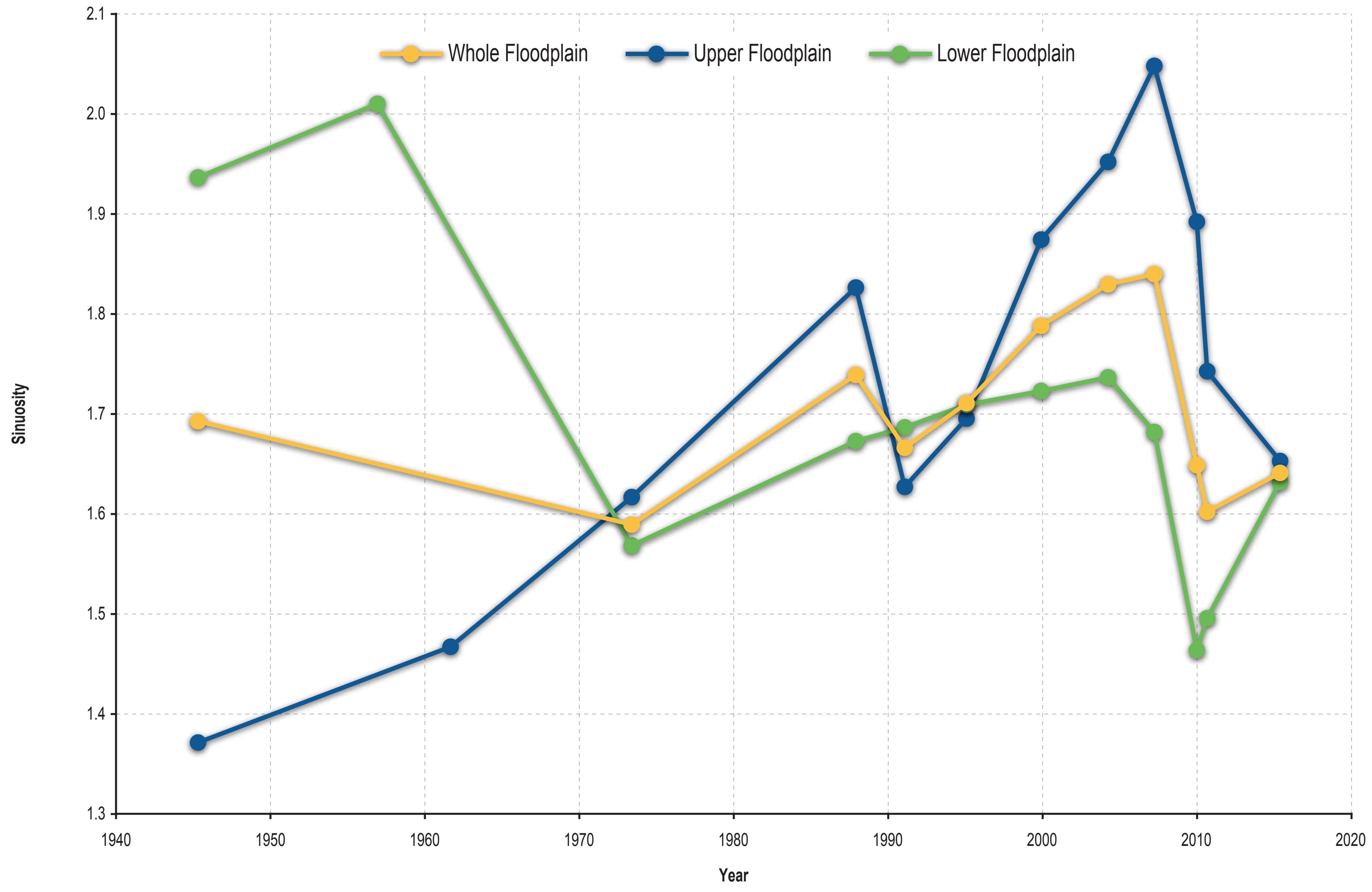
[7] Based on referenced third party material

[8] Channel length divided by valley length



Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.6

coffey A TETRA TECH COMPANY	Date: 30.11.2017 Project: 754-ENAUABTF100520DD File Name: 0520DD_10_F09.16_GRA	WAFI-GOLPU JOINT VENTURE Wafi-Golpu Project	Landform ages in the Lower Watut River floodplain meander belt	Figure No: 9.16



Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure9.7

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.17_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Changes in river sinuosity with time on the Lower Watut River floodplain

Figure No: 9.17

It is likely that the Watut River will continue to respond to changes in sediment supply as they arise, with the level of response dependent on the scale and duration of the changes in catchment processes.

Sediment transport processes (including overbank deposition) within the floodplain of the Lower Watut River are complex, dynamic and not yet well understood.

9.3.2.3. Eastern Watut River Floodplain Catchments and Streams

Given the similarities of the catchment on the east of the Watut River with the Wafi River catchment (including the undisturbed and hilly nature of catchments), the following sediment dynamics are likely:

- Supply of sediments to the streams will arise from the weathering of valley slopes and triggered by a combination of heavy rainfall, seismic activity and riverbed scouring.
- The high drainage density of the catchment is expected to yield sediment reporting to streams within short timeframes.
- The high-gradient upstream reaches will generally be free of fine sediment deposition due to sediment scour following rain.
- The lower-gradient downstream reaches of creeks will be sediment deposition zones.

Changes to river morphology in the floodplain, including Ngomang, Mari and Chaunong creeks, are complex and highly dynamic and, as such, these catchments are difficult to characterise. Runoff from the small, steep catchments flanking the eastern side of the floodplain is not confined to channels once it reaches the floodplain. In many instances, this runoff forms shallow sheet flow across the floodplain and has been observed to infiltrate the ground during the dry season, thereby contributing to groundwater.

BMT WBM (see Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River) and Hydrobiology (see Appendix I of Appendix I, Catchment and Receiving Water Quality Modelling) observed that coarse sediments do not reach Chaunong Creek main channel (nor the receiving Bavaga River and Lower Watut River) but settle on the outer backplain of the Lower Watut River's eastern floodplain between Chaunong Creek and the escarpment. The flow of sediment-laden high or flood flows across backplain vegetation results in a dropping out (sedimentation) of coarse-grained sediment particles by reduced water velocities and the trapping efficiency of vegetation.

9.4. Water Quality

9.4.1. Lower Watut River catchment

The water quality in watercourses in the Lower Watut River catchments is highly variable with variability of orders of magnitude both within and between streams over time. As identified in Section 9.1, WGJV water quality samples were typically collected when river flows were low, leading to a 'low-flow' sampling bias, which does not capture the higher-flow periods when a large proportion of the sediment and geochemical load typically occurs. Accurate estimation of geochemical load requires samples to be collected over the full range of flows for each site of interest, including both the rising and falling stages of the flood hydrograph. As a result, the water quality of any watercourse can only be discussed in general terms. As discussed above, WGJV will continue to collect additional data to improve capture over a range of flows and provide an update of the models.

Median values of the WGJV data are used to compare with relevant guidelines as these are typically used to assess the potential for long-term, chronic impacts

(ANZECC/ARMCANZ, 2000). Both dissolved and total metal/metalloid concentrations are presented below. For selected dissolved parameters, box and whisker plots are used to represent a summary of the numerical data through the lowest observation (sample minimum (Min)), lower quartile (25th percentile), median (50th percentile (Median)), upper quartile (75th percentile) and highest observation (sample maximum (Max)). The scales used for representation of the various parameters in the description below are typically logarithmic due to the range, i.e., where the increments in concentration are a multiple of ten.

The water and sediment quality data collected by BMT WBM in 2015 and 2016 is presented and discussed separately to the routine WGJV monitoring data to allow direct association of water quality with aquatic ecology sampling undertaken during the BMT WBM surveys.

For the purposes of describing the WGJV water (and sediment) quality data across the Lower Watut River catchment, the data have been summarised using the following sub-catchment classifications:

- Wafi River
- Eastern Watut River floodplain
- Bavaga River
- Wampit and Waime rivers
- Watut River
- Markham River

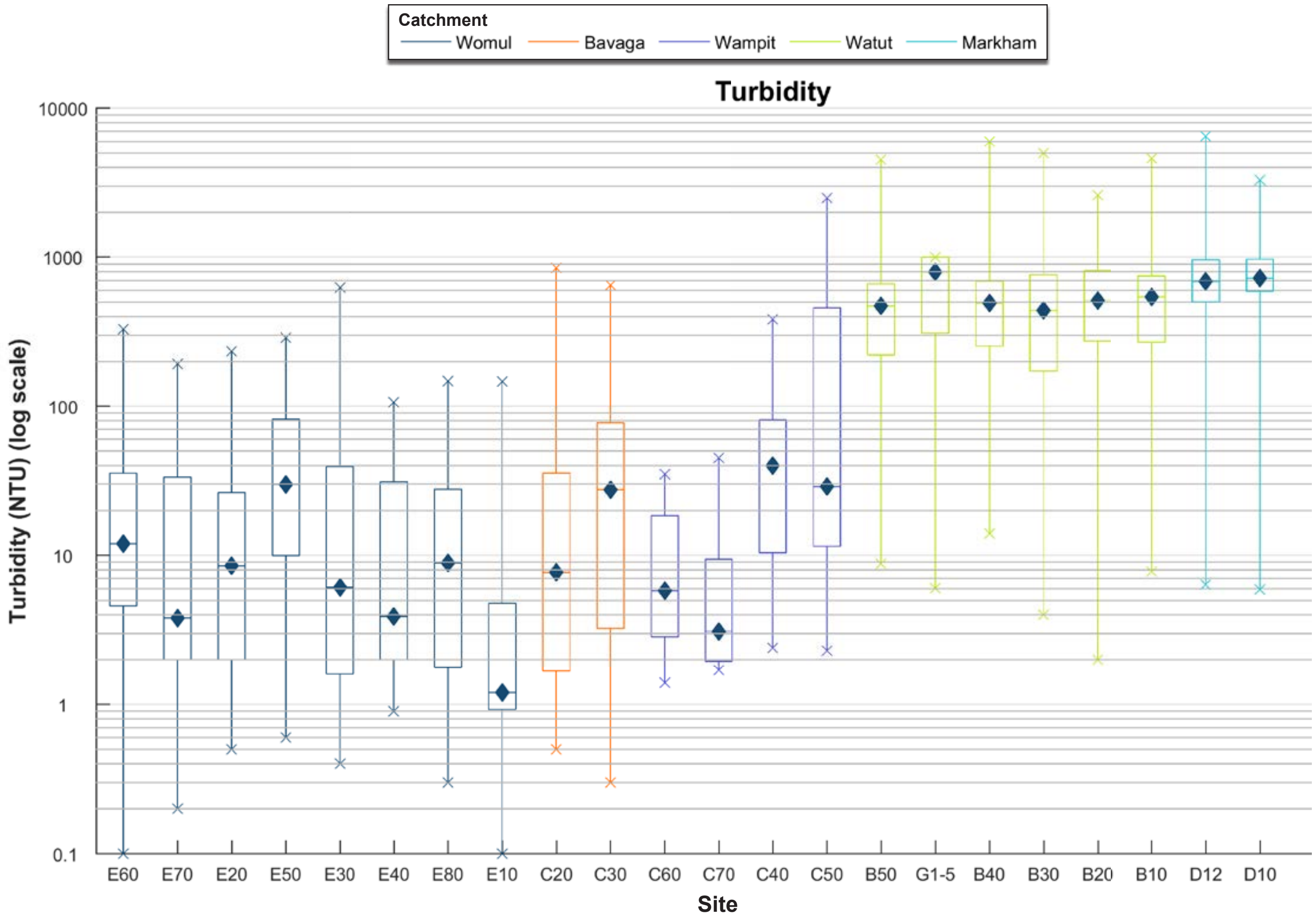
A more detailed summary of water quality results is provided in Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River and Appendix H, Surface Water and Freshwater Aquatic Ecology Characterisation - Yalu to Wagang.

9.4.1.1. Physico-chemical Parameters

Analysis of WGJV data shows that median turbidity in the Watut River and Markham River catchments is typically higher (greater than 400NTU) than within the Wafi River and eastern Watut River floodplain catchments (less than 100NTU). Figure 9.18 shows a comparison of WGJV turbidity data for the Eastern Watut River floodplain and Markham, Watut, Wampit and Bavaga river catchments.

Sampling undertaken by BMT WBM and described in Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River, is consistent with the longer term WGJV data trends showing that turbidity was generally higher at sites in the Watut River (>150NTU) compared to other monitoring sites (turbidity values <50NTU).

Median pH values across all WGJV water quality monitoring sites were mostly within the range for all guidelines (pH of 6 to 9). Exceptions to this are noted at some sites draining Mt Golpu in the Wafi River catchment where slightly acidic waters (pH below 6) were recorded at monitoring sites A20 (Hotel Creek) and A26 (Hekeng Road) and acidic waters (pH of around 4) at sites A60 and A70 in Nambonga Creek. These acidic conditions, along with elevated electrical conductivity and some elevated dissolved metals concentrations (see sections below) suggest the natural occurrence of acid and metalliferous drainage (AMD) at these monitoring sites due to their proximity to the mineralised zone.



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1-5	B40	B30	B20	B10	D12	D10
Samples	61	30	74	30	37	35	61	9	69	52	16	9	17	11	114	19	75	53	67	58	51	54
Min	0.1	0.2	0.5	0.6	0.4	0.9	0.3	0.1	0.5	0.3	1.4	1.7	2.4	2.3	8.8	6	14	4	2	7.8	6.4	5.9
25th Percentile	4.6	2	2	10	1.6	2	1.8	0.9	1.7	3.3	2.9	2	10.4	11.5	222	309.3	254	172	274.5	270	502.8	593
Median	12	3.8	8.5	29.9	6.1	3.9	8.9	1.2	7.7	27.5	5.8	3.1	40	29	472.5	797	493	441.2	514	542.5	689	726.5
75th Percentile	35.5	33.5	26.4	82	39.4	31.1	27.7	4.8	35.6	77.5	18.5	9.4	80.9	458	663	999	694.8	762.8	818.3	750	964.3	972
Mean	40.7	23.7	27.1	65.7	43.2	17.9	22.7	18.4	65.2	76.1	10.8	9.9	70.8	386.8	584.2	671.3	551.6	563.4	607.5	813.9	895.5	905.4
Max	329	193	235	288	627	107	148	147	850	652	35	45	384	2500	4500	999	6000	5000	2600	4600	6500	3300

INDD Reference: 0520DD_10_GRA031.indd_5

Source:
BMT WBM: R.B22395.001.02.Baseline, Figure A-2

coffey
A TETRA TECH COMPANY

Date:
30.11.2017
Project:
754-ENAUABTF100520DD
File Name:
0520DD_10_F09.18_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV turbidity data for Markham, Watut, Wampit, Bavaga and Womul catchments

Figure No:
9.18

For sampling undertaken by BMT WBM in March 2015, the pH was similar across most monitoring sites and was within the range for all guidelines (pH of 6 to 9) for most sites. An exception was in Nambonga Creek, which had a slightly acidic pH of 5.27. In the June 2015 BMT WBM sampling, the pH was similar across most monitoring sites and was within the range for all guidelines (pH 6 to 9). In the December 2016 BMT WBM sampling, pH was higher in the upper reaches of the Bavaga River catchment (high-moderate gradient tributary streams) than the lower reaches (low gradient streams) of the catchment; however, was within the pH range for all guidelines (pH 6 to 9).

Analysis of WGJV data indicates that median temperature was relatively consistent across all sites, with recorded temperatures generally ranging between 22ºC and 29°C. Median electrical conductivity was also relatively similar across most monitoring sites, with median values less than 600 micro-siemens per centimetre (µs/cm). An exception to this was at site A60 (Nambonga Creek) with a median electrical conductivity value of approximately 1,000µs/cm, consistent with AMD occurring at this site.

For sampling undertaken by BMT WBM in March 2015, electrical conductivity was also relatively consistent between monitoring sites, with values ranging from 100 to 415µs/cm. For sampling undertaken in June 2015, electrical conductivity ranged from 219 to 747µs/cm at monitoring locations Chaunong Creek downstream and Sago Swamp at Bambufo Creek, respectively. For sampling undertaken in December 2016, electrical conductivity was between 77µs/cm and 134µs/cm.

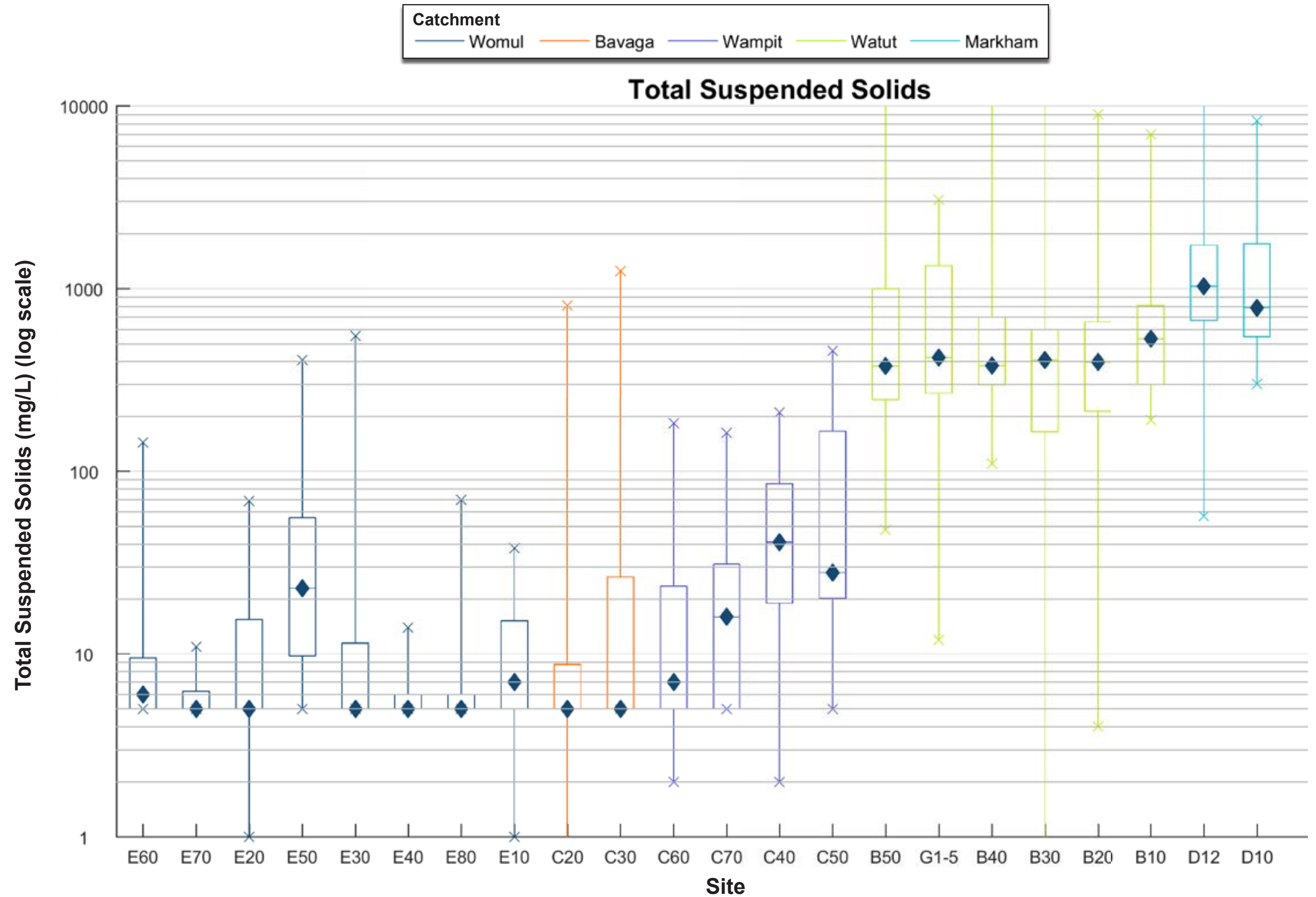
For the sampling undertaken by BMT WBM in March 2015, dissolved oxygen values were generally similar across all monitoring sites (approximately 90 to 100% saturation) and most sites had dissolved oxygen levels within the ANZECC guideline range of 85 to 120% saturation. Low dissolved oxygen values of less than 30%, however, were recorded at the two oxbow lake sites (Bali Oxbow and Uruf Oxbow). For the June 2015 sampling, dissolved oxygen values were slightly below the ANZECC guideline range at Sago Swamp at Unknown Creek (70.3%), while dissolved oxygen was significantly lower than the ANZECC guideline range at Sago Swamp at Bambufo Creek (17.6%). These sites are located within swamp areas with significant amounts of standing water, reduced flow rates and high levels of organic matter (i.e., leaf litter and decomposing vegetation). Low dissolved oxygen levels are typical of this type of environment.

In December 2016, dissolved oxygen values for the high-moderate gradient (i.e., high energy) tributary streams were within the ANZECC guideline range of 85% to 120%; however, the dissolved oxygen values for the low gradient stream at Bavaga River sites 6 and 7 (see Figure 9.32) were below the ANZECC guideline range, with values of 47.7% and 70.9%, respectively. Both of these sites are located within swamp areas with significant amounts of standing water and high levels of leaf litter and decomposing vegetation.

9.4.1.2. TSS, Major Ions and Hardness

Figure 9.19 shows a comparison of WGJV TSS data for the Womul Creek and Markham, Watut, Wampit and Bavaga river catchments. Similar to patterns in turbidity data, median TSS concentrations measured at sites in the Watut and Markham river catchments were considerably higher (at least an order of magnitude higher) than TSS concentrations measured in other catchments, including Womul, Wampit and Bavaga River catchments.

Median TSS concentrations ranged from 5 to 23mg/L in the Womul Creek catchment, 5mg/L in the Bavaga River and 5 to 28mg/L in the Wampit River catchment. In the Watut and Markham rivers, median TSS concentrations range from 28 to 420mg/L and 788 to 1,032mg/L, respectively, while maximum recorded concentrations in these rivers reach up to almost 14,000mg/L.



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1_5	B40	B30	B20	B10	D12	D10
Samples	60	17	75	17	23	22	59	11	63	40	24	14	16	9	86	19	62	40	46	24	28	29
Min	5	5	1	5	5	5	5	1	1	5	2	5	2	5	48	12	110	1	4	191	57	301
25th Percentile	5	5	5	10	5	5	5	5	5	5	5	5	19	20	247	269	298	165	213	300	673	547
Median	6	5	5	23	5	5	5	7	5	5	7	16	41	28	379	420	380	408	399	533	1,032	788
75th Percentile	10	6	16	56	12	6	6	15	9	27	24	31	86	166	1,000	1,339	702	600	661	810	1,730	1,765
Mean	11	6	14	51	37	6	7	12	45	63	20	28	59	119	1,164	848	1,097	702	915	959	1,577	1,322
Max	144	11	69	408	553	14	70	38	810	1,250	183	162	210	458	11,000	3,070	13,900	10,300	9,020	7,010	13,700	8,340

Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.9

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.19_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV TSS data for Markham, Watut, Wampit, Bavaga and Womul catchments

Figure No: 9.19

BMT WBM data collected in 2015 and 2016 indicated that most sites had a similar major ions composition. Calcium was the dominant cation at all sites and bicarbonate (HCO_3^-) was the dominant anion, referred to as calcium-bicarbonate type waters.

From limited data, hardness was variable, ranging from soft (categorised as 0mg/L to 59mg/L as $CaCO_3$) at sites in the Wafi River to very hard (categorised as 180mg/L to 240mg/L as $CaCO_3$) at sites in the Watut River floodplain creeks (with reference to ANZECC). This is broadly similar to hardness values derived from data collected by BMT WBM in March and June 2015 which also showed greater hardness values at floodplain creeks (typically hard and very hard waters) and softer waters in turbid major rivers including the Wafi River and Watut River (typically soft waters and moderately hard waters, respectively).

9.4.1.3. Dissolved Metals and Metalloids

9.4.1.3.1. WGJV Data

While median concentrations of arsenic were higher in the Watut River compared to other catchments, median concentrations at all monitoring sites were below the PNG ER criteria (0.05mg/L) and ANZECC (0.13mg/L (As V)) guideline values for ecosystem health.

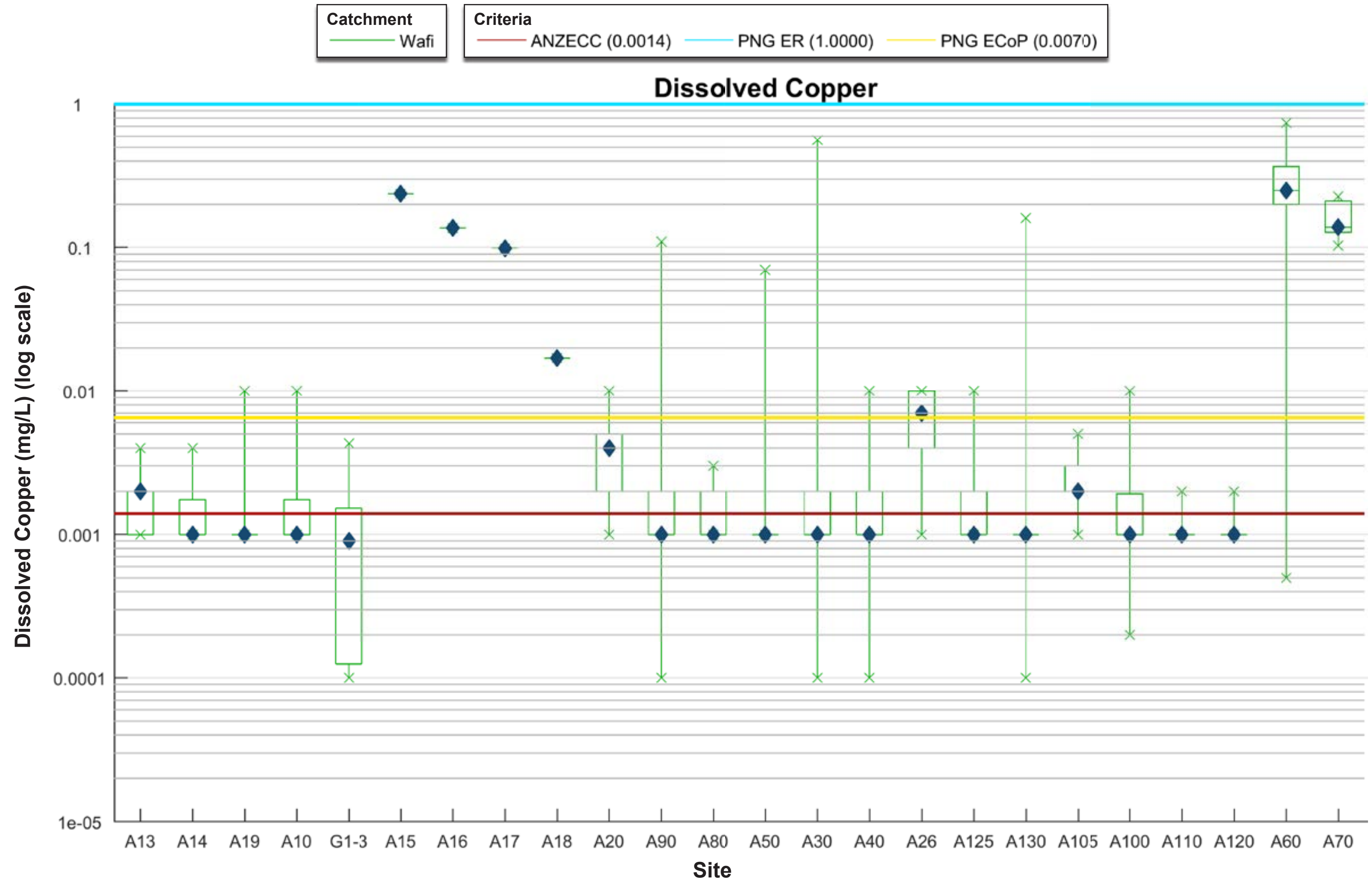
All monitoring sites had median cadmium concentrations below the PNG ER (0.01mg/L). Most sites had median cadmium concentrations below the PNG ECoP (0.0066mg/L), except for sites A15, A16, A17 and A18 (South Golpu sites[9] in the Wafi River catchment), and A60 and A70 in the Nambonga Creek catchment.

All monitoring sites had median copper concentrations (refer to Figure 9.20 and Figure 9.21) below the PNG ER criterion (1mg/L). When compared to the PNG ECoP and ANZECC guideline values of 0.00065mg/L and 0.0014mg/L respectively, median copper concentrations at six sites in the Wafi River catchment (including all four South Golpu and Nambonga Creek sites) exceeded both guideline values. As shown in Figure 9.20, median copper concentrations at these sites ranged from 0.017 to 0.25mg/L, while maximum dissolved copper concentrations reached 0.561mg/L in Hekeng Creek (A30) and 0.74mg/L in Nambonga Creek (A60). These background dissolved copper concentrations in the Wafi River catchment are likely indicative of naturally elevated copper levels in surficial soils and mineralised areas as well as exploration activities within its catchment, which may be expected given that the orebody to be developed for the Project is within the upper Wafi River catchment.

Several sites (including E60, E20, E50, E10) in the Eastern Watut River floodplain catchment recorded median dissolved copper concentrations of 0.002mg/L, which exceeded the ANZECC trigger value (Figure 9.21). Median copper concentrations at sites in the Watut (B50, B20 and B10) and Markham (D12 and D10) River catchments, ranging from 0.0015mg/L to 0.002mg/L, also exceeded the ANZECC guideline. Most maximum dissolved copper concentrations in the Markham, Watut, Wampit, Bavaga and Womul Creek (including the Lower Watut River floodplain) catchments exceeded the ANZECC guideline, and some also exceeding the PNG ECoP guideline, with the highest concentrations recorded in the Bobul Creek catchment (E60) and the Markham River (D12 and D10), where concentrations ranged from 0.09mg/L to 0.25mg/L.

---

[9] South Golpu sites (sites A15 to A18) are ephemeral streams draining the Golpu deposit near Venembele and were sampled for a short duration only while exploration drilling was occurring in the vicinity.



Sites	A13	A14	A19	A10	G1-3	A15	A16	A17	A18	A20	A90	A80	A50	A30	A40	A26	A125	A130	A105	A100	A110	A120	A60	A70
Samples	37	39	52	43	23	2	2	2	2	51	44	32	41	62	54	62	38	68	45	81	24	24	89	7
Min	0.001	0.001	0.001	0.001	0.0001	0.237	0.137	0.099	0.017	0.001	0.0001	0.001	0.001	0.0001	0.0001	0.001	0.001	0.0001	0.001	0.0002	0.001	0.001	0.0005	0.103
25th Percentile	0.001	0.001	0.001	0.001	0.0001	0.237	0.137	0.099	0.017	0.002	0.001	0.001	0.001	0.001	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.001	0.2	0.1278
Median	0.002	0.001	0.001	0.001	0.0009	0.237	0.137	0.099	0.017	0.004	0.001	0.001	0.001	0.001	0.001	0.007	0.001	0.001	0.002	0.001	0.001	0.001	0.25	0.139
75th Percentile	0.002	0.0018	0.001	0.0018	0.0015	0.237	0.137	0.099	0.017	0.005	0.002	0.002	0.001	0.002	0.002	0.01	0.002	0.001	0.003	0.0019	0.001	0.001	0.3662	0.2108
Mean	0.0016	0.0013	0.0013	0.0014	0.001	0.237	0.137	0.099	0.017	0.0042	0.0062	0.0013	0.0027	0.0407	0.0018	0.0069	0.0017	0.0036	0.0025	0.0016	0.0012	0.0011	0.2921	0.1599
Max	0.004	0.004	0.01	0.01	0.0043	0.237	0.137	0.099	0.017	0.01	0.11	0.003	0.07	0.561	0.01	0.01	0.01	0.16	0.005	0.01	0.002	0.002	0.74	0.227

Source:
BMT WBM: R.B22395.001.02.Baseline, Figure A-15

coffey A TETRA TECH COMPANY

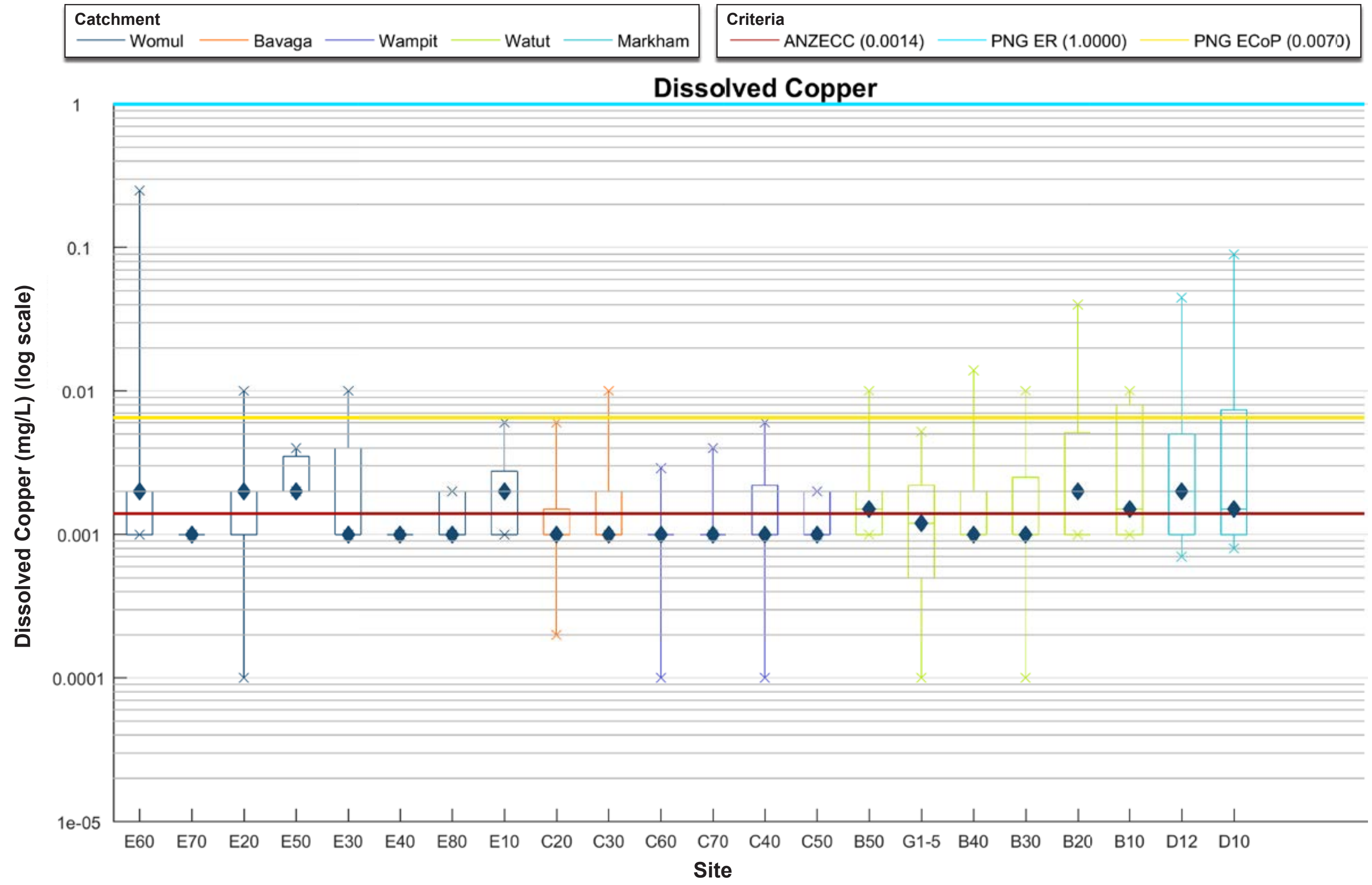
Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.20_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV dissolved copper data for the Wafi River catchment

Figure No: 9.20



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1-5	B40	B30	B20	B10	D12	D10
Samples	22	3	34	3	5	4	20	11	24	18	19	11	15	9	58	20	34	25	29	14	22	24
Min	0.001	0.001	0.0001	0.002	0.001	0.001	0.001	0.001	0.0002	0.001	0.0001	0.001	0.0001	0.001	0.001	0.0001	0.001	0.0001	0.001	0.001	0.0007	0.0008
25th Percentile	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.0005	0.001	0.001	0.001	0.001	0.001	0.001
Median	0.002	0.001	0.002	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.0015	0.0012	0.001	0.001	0.002	0.0015	0.002	0.0015
75th Percentile	0.002	0.001	0.002	0.0035	0.004	0.001	0.002	0.0028	0.0015	0.002	0.001	0.001	0.0022	0.002	0.002	0.0022	0.002	0.0025	0.0051	0.008	0.005	0.0073
Mean	0.0128	0.001	0.002	0.0027	0.003	0.001	0.0014	0.0023	0.0015	0.0019	0.0011	0.0014	0.002	0.0013	0.0021	0.0016	0.0024	0.0026	0.0044	0.0044	0.005	0.0092
Max	0.25	0.001	0.01	0.004	0.01	0.001	0.002	0.006	0.006	0.01	0.0029	0.004	0.006	0.002	0.01	0.0052	0.014	0.01	0.04	0.01	0.045	0.09

Source:
BMT WBM: R.B22395.001.02.Baseline, Figure A-16

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.21_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV dissolved copper data for Markham, Watut, Wampit, Bavaga and Womul catchments

Figure No: 9.21

INDD Reference: 0520DD_10_GRA034.indd_4

Most sites had median concentrations of lead below the PNG ER (0.005mg/L), PNG ECoP (0.0013mg/L) and ANZECC (0.0034mg/L) guideline values. Sites with elevated median concentrations of lead (i.e., exceeded all three guideline values significantly) included all four of the South Golpu sites in the Wafi River catchment (A15 to A18), A20 (Hotel Creek), A60 and A70 in Nambonga Creek in the Wafi River catchment, and E40 (Fetaf Creek) in the Eastern Watut River floodplain catchment.

Mercury data showed significant variability (refer to Figure 9.22 and Figure 9.23). Median mercury concentrations at most sites, with concentrations generally above 0.003mg/L, were elevated relative to the PNG ER (0.0002mg/L), PNG ECoP (0.0001mg/L) and ANZECC (0.00006mg/L) guideline values. Of these sites, the highest maximum dissolved mercury concentrations in the Wafi River catchment ranged from 0.044mg/L in Nambonga Creek (A70) to 0.11mg/L in Buvu Creek near Nambonga village (A125) (Figure 9.22).

As shown in Figure 9.23, median mercury concentrations in the Eastern Watut River floodplain sites ranged from 0.0001mg/L to 0.0146mg/L, with maximum concentrations ranging from 0.0071mg/L to 0.13mg/L. Concentrations of dissolved mercury in the Markham and Watut rivers were similar, with medians ranging from 0.0026mg/L to 0.01mg/L and maximums ranging from 0.04mg/L to 0.07mg/L at site B50 in the Watut River upstream of Pekumbe village, with most median concentrations elevated above the PNG ER criterion (0.002mg/L).

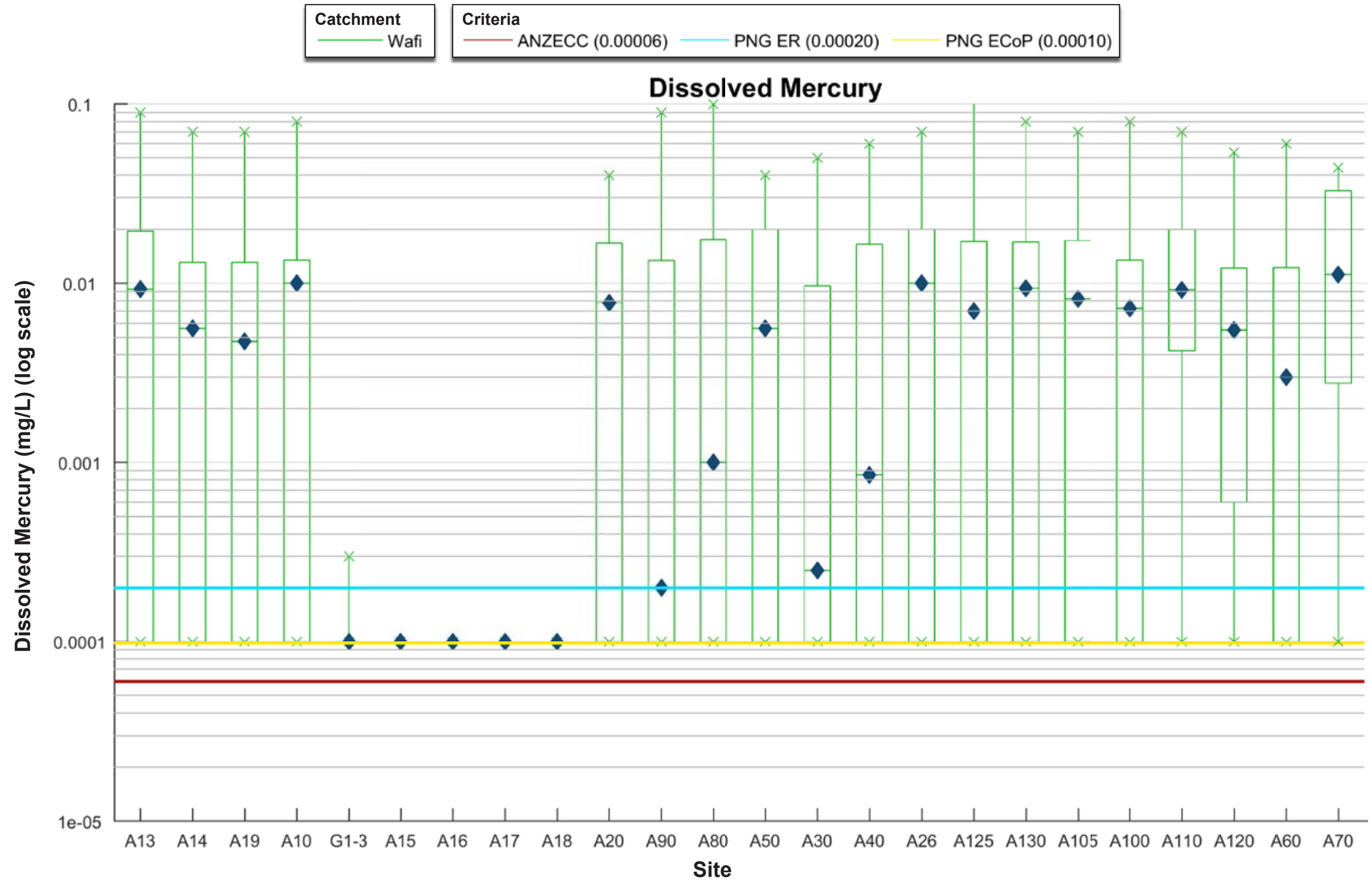
Median silver concentrations at all sites were below the PNG ER criterion (0.05mg/L). However, when compared to the PNG ECoP and ANZECC guideline values of 0.0001mg/L and 0.00005mg/L, respectively, median concentrations at all sites appear to exceed these guideline values. This is, however, an artefact of the laboratory limit of detection for silver (0.001mg/L). For samples analysed that are below the limit of detection, a value equal to the detection limit is reported for that sample.

Median zinc concentrations at all sites were below the PNG ER criterion (5mg/L, refer to Figure 9.24 and Figure 9.25). Approximately half of the sites had median values that exceeded the ANZECC guideline value of 0.008mg/L. Of these sites, A15 to A18 in watercourses near Mt Golpu and A60 and A70 in Nambonga Creek also exceeded the PNG ECoP guideline value of 0.18mg/L. Maximum zinc concentrations at these sites ranged from 0.477mg/L to 0.522mg/L. All sites in the Womul Creek catchment (including the Lower Watut River floodplain sites) and the Watut River catchment had median dissolved zinc concentrations that exceeded the ANZECC guideline but were below the PNG ECoP (and the PNG ER).

Median selenium concentrations at all sites were at or below the PNG ER criterion (0.01mg/L). Of these sites, most had median values that exceeded the ANZECC and PNG ECoP guideline values of 0.005mg/L. The difference in median values between sites is due to most of the data being recorded at or below the limit of detection (0.01mg/L).

Most sites had median manganese concentrations below the PNG criterion (0.5mg/L) and ANZECC (1.9mg/L) guideline values, with the exception of sites A15 to A18, A60 and A70 near Mt Golpu and in Nambonga Creek.

All sites had median nickel concentrations below the PNG ER criterion (1mg/L). Most sites also had median values below the ANZECC guideline value (0.011mg/L), except for the South Golpu sites in the Wafi River catchment (A15 to A18), A20 (Hotel Creek), and A60 and A70 in Nambonga Creek in the Wafi River catchment.



Sites	A13	A14	A19	A10	G1-3	A15	A16	A17	A18	A20	A90	A80	A50	A30	A40	A26	A125	A130	A105	A100	A110	A120	A60	A70
Samples	59	60	74	78	23	2	2	2	2	61	59	43	63	76	70	63	55	103	59	118	33	24	77	7
Min	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
25th Percentile	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0042	0.0006	0.0001	0.0028
Median	0.0093	0.0056	0.0048	0.0100	0.0001	0.0001	0.0001	0.0001	0.0001	0.0078	0.0002	0.0010	0.0056	0.0003	0.0009	0.0100	0.0070	0.0094	0.0082	0.0073	0.0092	0.0055	0.0030	0.0112
75th Percentile	0.0195	0.0131	0.0131	0.0135	0.0001	0.0001	0.0001	0.0001	0.0001	0.0168	0.0134	0.0175	0.0200	0.0097	0.0165	0.0200	0.0171	0.0170	0.0173	0.0135	0.0200	0.0122	0.0123	0.0328
Mean	0.0137	0.0112	0.0101	0.0112	0.0001	0.0001	0.0001	0.0001	0.0001	0.0108	0.0092	0.0113	0.0101	0.0068	0.0102	0.0155	0.0126	0.0118	0.0120	0.0121	0.0168	0.0096	0.0089	0.0176
Max	0.0900	0.0700	0.0700	0.0800	0.0003	0.0001	0.0001	0.0001	0.0001	0.0400	0.0900	0.1000	0.0400	0.0501	0.0600	0.0700	0.1100	0.0800	0.0700	0.0800	0.0700	0.0538	0.0600	0.0440

Source:
BMT WBM: R.B22395.001.02.Baseline, Figure A-19

coffey
A TETRA TECH COMPANY

Date:
30.11.2017
Project:
754-ENAUABTF100520DD
File Name:
0520DD_10_F09.22_GRA

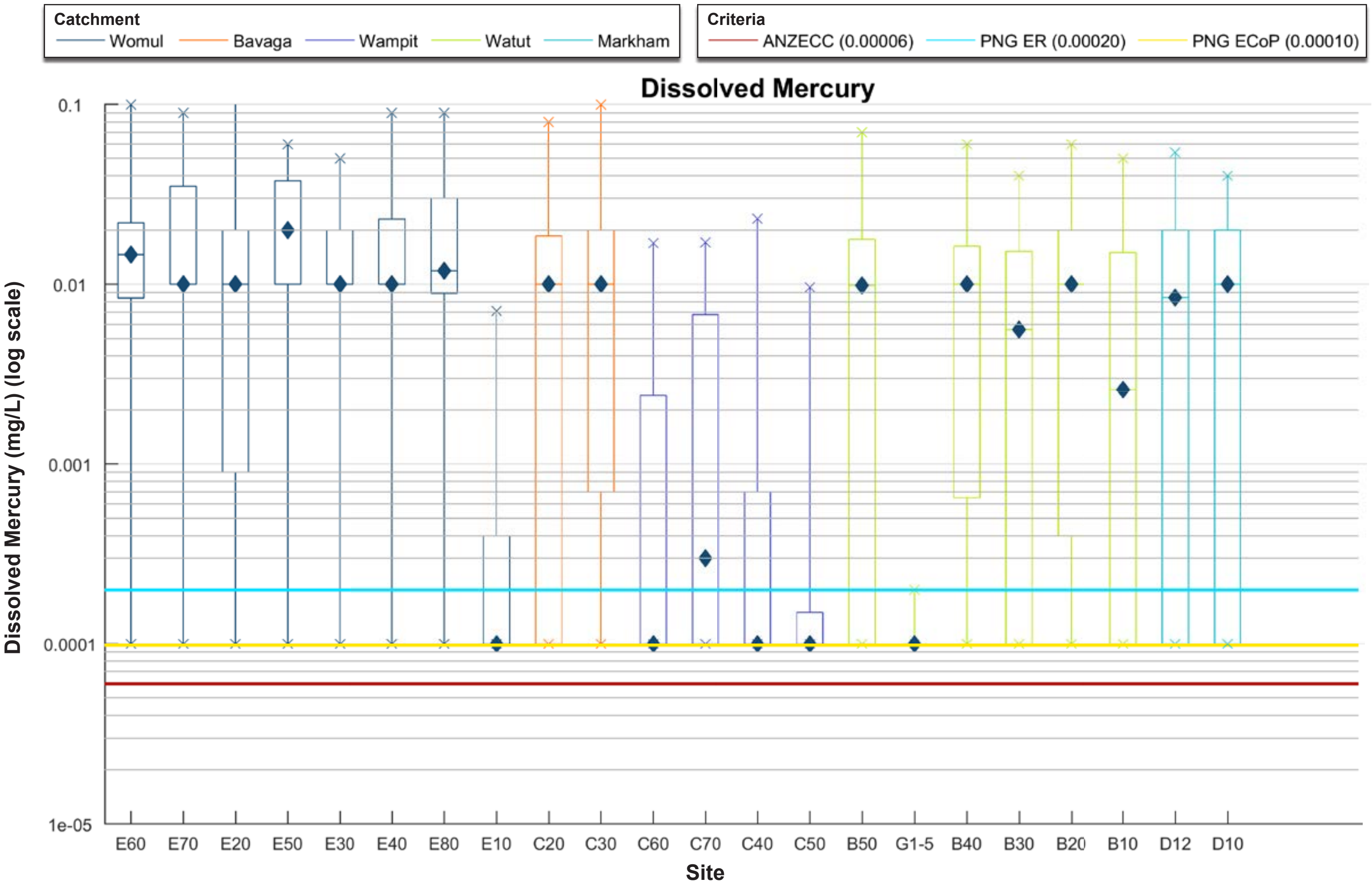
WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV dissolved mercury data for the Wafi River catchment

Figure No:
9.22

INDD Reference: 0520DD_10_GRA035.indd_3



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1-5	B40	B30	B20	B10	D12	D10
Samples	50	16	64	15	14	20	47	11	41	30	21	13	15	9	86	21	60	39	42	21	32	35
Min	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
25th Percentile	0.0084	0.0100	0.0009	0.0100	0.0100	0.0100	0.0089	0.0001	0.0001	0.0007	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0007	0.0001	0.0004	0.0001	0.0001	0.0001
Median	0.0146	0.0100	0.0100	0.0200	0.0100	0.0100	0.0119	0.0001	0.0100	0.0100	0.0001	0.0003	0.0001	0.0001	0.0099	0.0001	0.0100	0.0056	0.0100	0.0026	0.0085	0.0100
75th Percentile	0.0220	0.0350	0.0200	0.0375	0.0200	0.0231	0.0300	0.0004	0.0185	0.0200	0.0024	0.0068	0.0007	0.0002	0.0178	0.0001	0.0163	0.0152	0.0200	0.0150	0.0200	0.0200
Mean	0.0198	0.0235	0.0187	0.0233	0.0157	0.0212	0.0217	0.0009	0.0152	0.0170	0.0021	0.0036	0.0025	0.0012	0.0118	0.0001	0.0115	0.0088	0.0135	0.0112	0.0134	0.0118
Max	0.1000	0.0900	0.1300	0.0600	0.0500	0.0900	0.0900	0.0071	0.0800	0.1000	0.0169	0.0171	0.0231	0.0096	0.0700	0.0002	0.0600	0.0400	0.0600	0.0500	0.0540	0.0400

Source:
BMT WBM: R.B22395.001.02.Baseline, Figure A-20

coffey
A TETRA TECH COMPANY

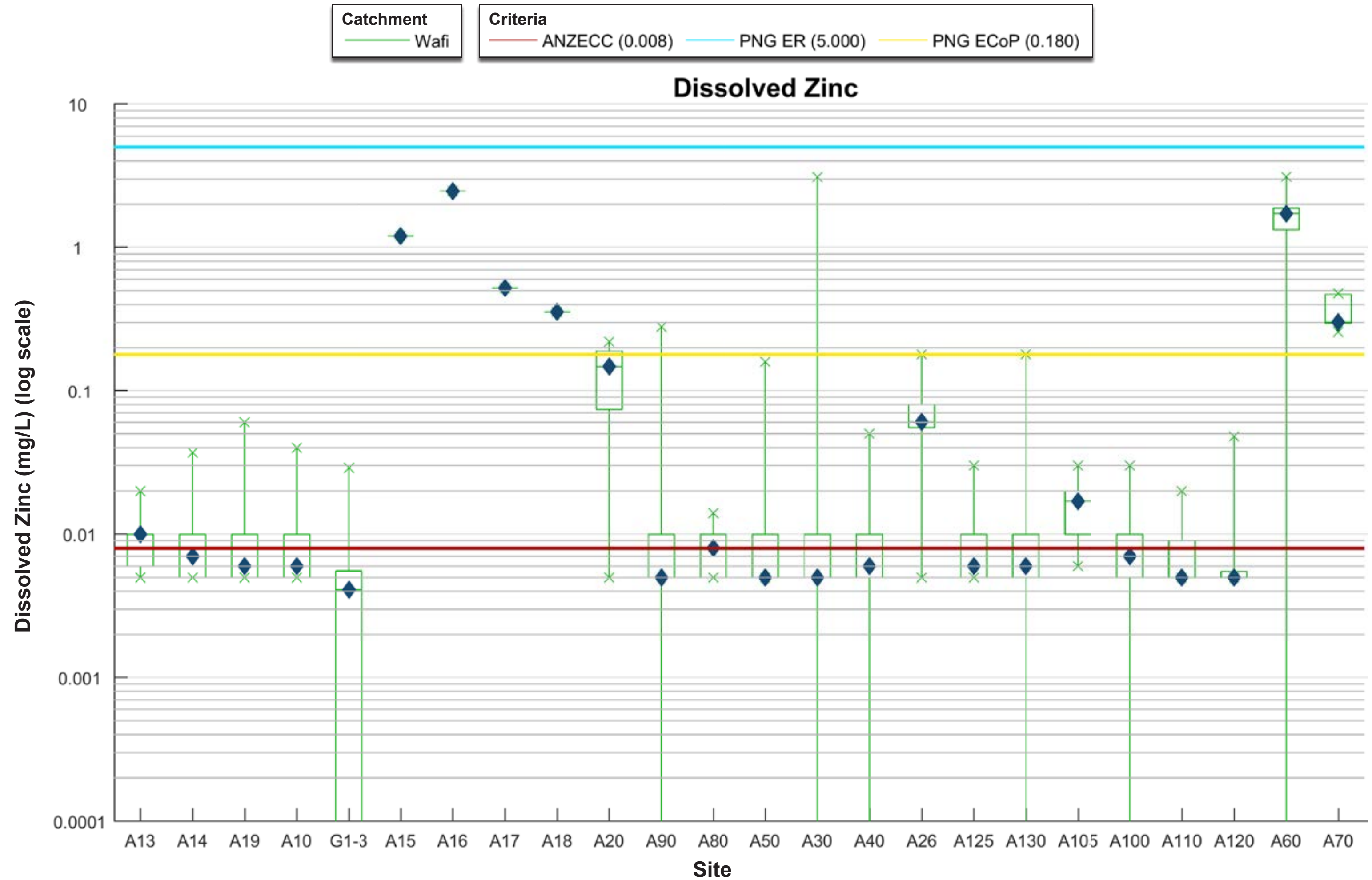
Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.23_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV dissolved mercury data for Markham, Watut, Wampit, Bavaga and Womul catchments

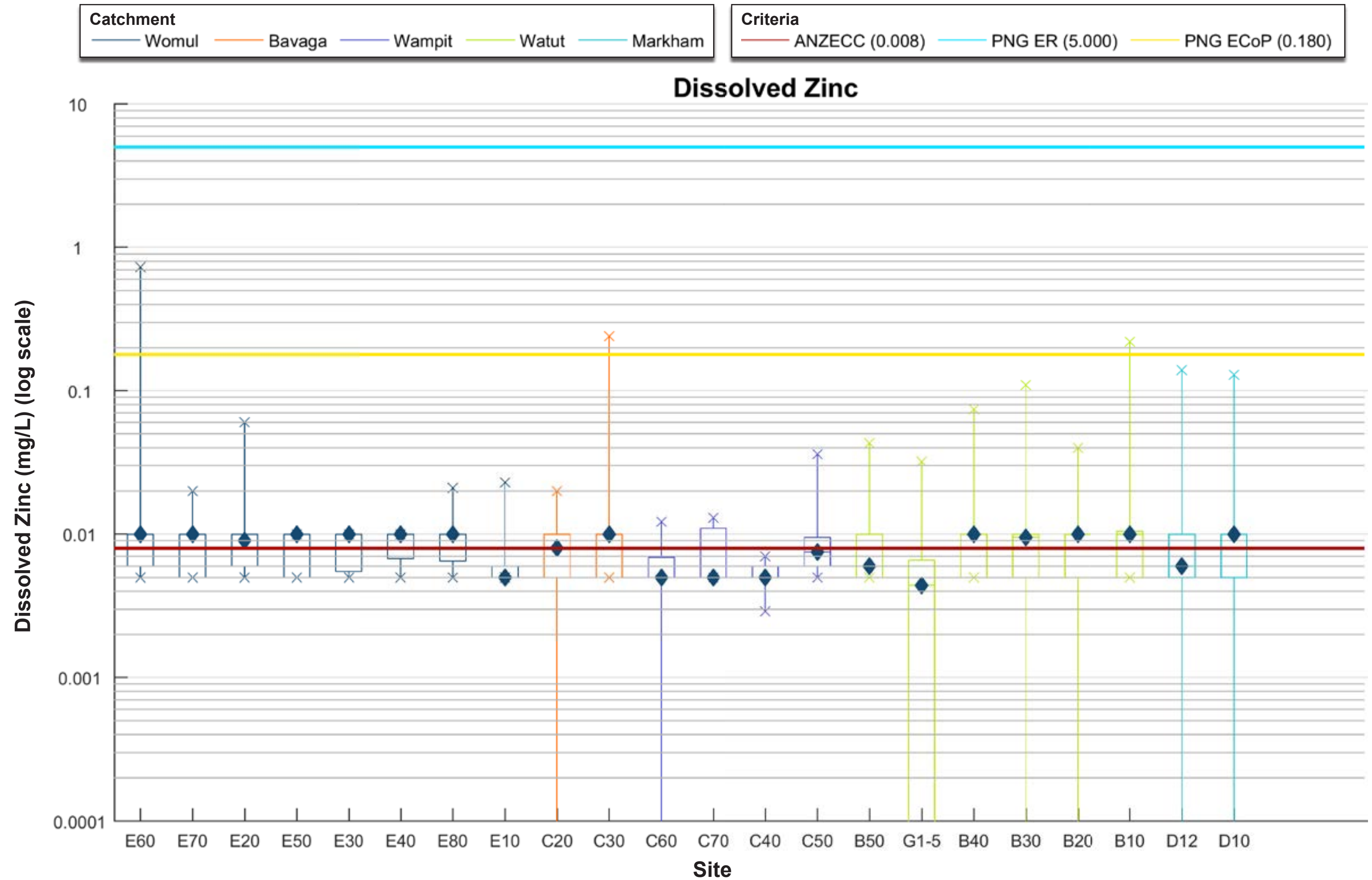
Figure No: 9.23



Sites	A13	A14	A19	A10	G1-3	A15	A16	A17	A18	A20	A90	A80	A50	A30	A40	A26	A125	A130	A105	A100	A110	A120	A60	A70
Samples	55	49	67	57	23	2	2	2	2	70	53	40	57	71	66	78	39	82	67	108	30	24	87	7
Min	0.005	0.005	0.005	0.005	0.0001	1.2	2.47	0.522	0.356	0.005	0.0001	0.005	0.005	0.0001	0.0001	0.005	0.005	0.0001	0.006	0.0001	0.005	0.005	0.0001	0.258
25th Percentile	0.006	0.005	0.005	0.005	0.0001	1.2	2.47	0.522	0.356	0.074	0.005	0.005	0.005	0.005	0.005	0.055	0.005	0.005	0.01	0.005	0.005	0.005	1.33	0.295
Median	0.01	0.007	0.006	0.006	0.0041	1.2	2.47	0.522	0.356	0.148	0.005	0.008	0.005	0.005	0.006	0.0605	0.006	0.006	0.017	0.007	0.005	0.005	1.72	0.302
75th Percentile	0.01	0.01	0.01	0.01	0.0056	1.2	2.47	0.522	0.356	0.19	0.01	0.01	0.01	0.01	0.01	0.08	0.01	0.01	0.02	0.01	0.009	0.0055	1.88	0.471
Mean	0.009	0.008	0.008	0.010	0.0045	1.2	2.47	0.522	0.356	0.135	0.017	0.008	0.010	0.230	0.009	0.067	0.010	0.009	0.016	0.008	0.008	0.008	1.554	0.365
Max	0.02	0.037	0.06	0.04	0.029	1.2	2.47	0.522	0.356	0.22	0.28	0.014	0.16	3.09	0.05	0.18	0.03	0.18	0.03	0.03	0.02	0.048	3.11	0.477

Summary of WGJV dissolved zinc data for the Wafi River catchment

Figure No:
9.24



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1-5	B40	B30	B20	B10	D12	D10
Samples	31	9	50	10	11	13	35	10	33	26	19	10	14	8	66	21	40	34	28	21	28	30
Min	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.0001	0.005	0.0001	0.005	0.0029	0.005	0.005	0.0001	0.005	0.0001	0.0001	0.005	0.0001	0.0001
25th Percentile	0.006	0.005	0.006	0.005	0.0055	0.0068	0.0065	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.005	0.0001	0.005	0.005	0.005	0.005	0.005	0.005
Median	0.01	0.01	0.009	0.01	0.01	0.01	0.01	0.005	0.008	0.01	0.005	0.005	0.005	0.0075	0.006	0.0044	0.01	0.0095	0.01	0.01	0.006	0.01
75th Percentile	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.006	0.01	0.01	0.0069	0.011	0.006	0.0095	0.01	0.0066	0.01	0.01	0.01	0.0105	0.01	0.01
Mean	0.033	0.009	0.011	0.009	0.008	0.009	0.009	0.007	0.008	0.027	0.006	0.007	0.005	0.011	0.010	0.006	0.013	0.014	0.010	0.030	0.017	0.017
Max	0.73	0.02	0.06	0.01	0.01	0.01	0.021	0.023	0.02	0.24	0.0122	0.013	0.007	0.036	0.043	0.032	0.074	0.11	0.04	0.22	0.14	0.13

Source:
BMT WBM: R.B22395.001.02.Baseline, Figure A-24

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.25_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV dissolved zinc data for Markham, Watut, Wampit, Bavaga and Womul catchments

Figure No: 9.25

INDD Reference: 0520DD_10_GRA038.indd_4

9.4.1.3.2. BMT WBM 2015 and 2016 Data

Concentrations of dissolved metals/metalloids at all sites were below the most stringent of guideline values for all metals/metalloids except for silver, copper, nickel, manganese and zinc. Dissolved silver levels exceeded the ANZECC trigger value at one site in March 2015 (Ziriruk Creek). All other monitoring sites had dissolved silver concentrations below the laboratory limit of detection (0.0001mg/L).

Dissolved copper, nickel and zinc levels slightly exceeded the ANZECC guidelines values of 0.0014mg/L, 0.011mg/L and 0.008mg/L respectively at one site in March 2015 (Nambonga Creek). Most other monitoring sites had dissolved copper, nickel and zinc concentrations below the laboratory limit of detection.

Dissolved manganese, with a concentration of 1.06mg/L, was elevated at the Swamp at Bambufo site in June 2015, where concentrations exceeded the PNG ER criterion.

The BMT WBM metals/metalloids data generally supports the WGJV data, with notable differences recorded for mercury and zinc, which were recorded in low levels in the BMT WBM data but occasional elevated levels in the WGJV data. This is likely due to timing of sampling events, as mercury levels are highly temporally variable in the WGJV data. Additionally, the BMT WBM data had a lower number of exceedances of guideline values. This may be attributable to BMT WBM not sampling at the WGJV sites located adjacent to the ore deposit (e.g., South Golpu sites A15 to A18) which regularly and expectedly recorded elevated concentrations of metals/metalloids above guideline values.

9.4.1.4. Metal Bioavailability Assessments

9.4.1.4.1. Chelex-labile Metals

Labile concentrations (i.e., portion of the dissolved concentration that is ‘free’ and potentially bioavailable) of copper, nickel and zinc were measured in the Watut River and Chaunong Creek floodplain using the Chelex method. These metals were selected based on their potential toxicity to aquatic biota. None of the measured labile concentrations of copper, nickel and zinc exceeded the ANZECC guideline values.

The concentrations of Chelex-labile copper, nickel and zinc represented between 9% to 17%, 10% to 45% and 30% to 89% of the dissolved copper, nickel and zinc, respectively (Table 9.10). The relatively low percentages of Chelex-labile copper are typical of freshwaters that contain significant concentrations of dissolved organic carbon. The organic ligands associated with dissolved organic carbon strongly bind the dissolved copper and lowers its availability to be taken up by organisms. The lowest Chelex-labile copper and nickel concentrations and percentages relative to dissolved concentrations were measured in the Watut River floodplain (Chaunong Creek). This is likely to be due to this site having almost double the concentration of dissolved organic carbon (2.9mg/L) available for complexation of the metals, than that measured in the Watut River (1.6 to 1.7mg/L). The percentages of Chelex-labile zinc relative to the dissolved concentrations were all 88% or greater except for one of the sites in the Watut River (upstream of Wongkins) and reflect the weak affinity of zinc for dissolved organic carbon and/or tendency to associate with colloids.

Dissolved organic carbon and metals can show great spatial and temporal variability, which can lead to changes in Chelex-labile metal concentrations. Dissolved organic carbon concentrations were generally similar to those measured by WGJV in February to December 2016, with a notable exception being higher dissolved organic carbon recorded in the Watut River (at Uruf) in February 2016, which indicates a short-term pulse of dissolved organic carbon occurred at this site, possibly due to catchment runoff.

Table 9.10: Summary of labile metals, complexation capacity and DOC data

Site	Sample	Watercourse	Copper				Nickel				Zinc				DOC (mg/L)
			Dissolved Cu (µg/L)	Labile Cu (µg/L)	% labile Cu	Cu complex capacity (µg/L)*	Dissolved Ni (µg/L)	Labile Ni (µg/L)	% labile Ni	Ni complex capacity (µg/L)	Dissolved Zn (µg/L)	Labile Zn (µg/L)	% labile Zn	Zn complex capacity (µg/L)	
Site 1	A1	Watut River	0.92	0.11	12	3.6	0.87	0.38	44	2.6	6.30	5.6	89	0.2	1.7
Site 1	A2	Watut River	1.18	0.20	17	4.7	0.98	0.44	45	2.7	1.0	0.3	30	0.7	1.7
Site 2	B1	Watut River	0.93	0.11	12	7.6	0.53	0.20	38	2.7	3.30	2.9	88	0.1	1.6
Site 2	B2	Watut River	0.95	0.10	11	7.9	0.58	0.22	38	2.8	2.50	2.2	88	0.2	1.7
Site 3	C1	Chaunong Creek	1.01	0.09	9	10.5	0.63	0.06	10	4.2	0.36	0.3	83	0.1	2.9

* Sample spiked with copper only.
Source: CSIRO, Appendix G of Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River

9.4.1.4.2. Complexation Capacity

The complexation capacity concentration indicates the concentration of dissolved metal above which any further added dissolved metal will lead to an increase in the Chelex-labile metal equal to the amount by which the complexation capacity is exceeded.

As shown in Table 9.10, analysis undertaken by CSIRO (Appendix G of Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River) indicated that copper had the highest measured complexation capacity (3.6µgCu/L to 10.5µgCu/L) of the metals tested, followed by nickel (2.6µgNi/L to 4.2µgNi/L) and zinc (0.1µgZn/L to 0.7µgZn/L). For copper and nickel the highest complexation capacity concentrations were measured in the Watut River floodplain (Chaunong Creek), which is consistent with the higher dissolved organic carbon concentrations measured at this location, as the higher dissolved organic carbon levels offer a greater number of complexation sites for binding.

Overall, the complexation capacity of copper (3.6 to 7.9µg/L in the Watut River and 10.5µg/L in Chaunong Creek) and nickel (up to 2.8µg/L in the Watut River and 4.2µg/L in Chaunong Creek) was substantially higher than the dissolved concentrations, resulting in the Chelex-labile concentrations of these metals (copper in the Watut River being 0.01 to 0.2µg/L and 0.09µg/L in Chaunong Creek and nickel being 0.2 to 0.44µg/L in the Watut River and 0.06µg/L in Chaunong Creek) being substantially lower than the dissolved concentration. This indicates that copper and nickel would likely have low bioavailability to aquatic organisms inhabiting these waters. The bioavailability of copper and nickel is unlikely to increase significantly until the dissolved concentration exceeds the complexation capacity at each site. For zinc, the complexation capacity was relatively low and most of the dissolved zinc was present as Chelex-labile species that are likely to be bioavailable.

9.4.1.4.3. Adsorption of Metals onto Suspended Particulate Matter

Analysis undertaken by CSIRO indicated that the percentages of copper, nickel and zinc removed from the dissolved phase through adsorption (onto particles or other matter) from the Watut River were in the range 75% to 96%, 53% to 73% and 90% to 99%, respectively. For the Watut River floodplain sample the percentages of copper, nickel and zinc removed from the dissolved phase through adsorption were in the range 19% to 32%, 7% to 14% and 17% to 46%, respectively.

Higher percentages of metal removed through adsorption were measured in the Watut River than the floodplain due to higher levels of suspended particulate matter in the Watut River than the floodplain. Further analysis undertaken by CSIRO of the partitioning coefficients[10] (K_d) for the samples indicated a general trend that zinc adsorption onto suspended particulate matter is higher than copper, which is higher than nickel.

Analysis of the concentrations of non-spiked dissolved metals indicate that, under the conditions predicted from the modelling assessment, particulate metals associated with suspended particulate matter in the Watut River would not be displaced by dissolved metals associated with mine waste water discharges.

9.4.1.5. Total Metals and Metalloids

Selected minimum, median and maximum total metals concentrations for the Lower Watut River catchment are presented in Table 9.11. The data indicate that total metals

[10] Particulate metal concentration divided by the dissolved metal concentration

concentrations were highly variable, which is typical of watercourses with TSS concentrations that are also highly variable.

While there are no State of PNG water quality criteria or ANZECC guidelines for total metals in the water column, drinking water guidelines have been used for comparative purposes. Most median total metal and metalloid concentrations in all catchments in the Lower Watut River catchment were below PNG and WHO 2011 drinking water guidelines. The exceptions to this were median iron concentrations in the Watut and Markham river catchments (6.84mg/L and 11.65mg/L, respectively).

Maximum concentrations of most measured total metals and metalloids in all catchments, however, exceeded either State of PNG and/or WHO 2011 drinking water guidelines (where a guideline value was available for comparison). Concentrations of arsenic, chromium, copper, iron, manganese, lead and zinc were significantly elevated in the Watut, Wafi and Bavaga river catchments. This is not unexpected based on the high concentrations of TSS that can persist within these catchments. Note: the analytical limit of detection for cadmium was higher than the guideline values hence conformance to guideline values could not be confirmed from the available dataset. One total cadmium concentration measurement in the Wafi River catchment was recorded of 3mg/L which was above the guideline values.

9.4.1.6. Nutrients

Water samples collected by BMT WBM in March and June 2015 and December 2016 were analysed for nutrients, including total nitrogen, ammonia, nitrate and nitrite (NO_x), total Kjeldahl nitrogen and total phosphorus. All sites had relatively low concentrations of nutrients. Ammonia and nitrate concentrations at all sites were below the relevant ANZECC guideline value.

9.4.2. Lower Markham River Floodplain

Field and laboratory analytical results for nine water samples collected in June 2017 are summarised below and presented in detail in Appendix H, Surface Water and Freshwater Aquatic Ecology Characterisation - Yalu to Wagang.

9.4.2.1. Physico-chemical Parameters

Watercourses ranged from circumneutral to slightly alkaline with pH ranging from 7.3 to 7.9. Water temperature ranged from 24.5°C (S/Site 2, Amburinu Creek) to 27.6°C (S/Site 9, Maiwara Creek) with most sites having a temperature of approximately 25°C.

Electrical conductivity across all sites ranged from 309µS/cm in the Markham River (S/Site 8) to 745µS/cm (S/Site 1S/Site 1, Busanem Creek).

Dissolved oxygen concentrations ranged from 3.8 to 7.9mg/L across all Lower Markham River sites. Dissolved oxygen concentrations in Pumpkin Creek (i.e., S/Site 4, S/Site 5 and S/Site 6) were below the PNG ER criterion of 6mg/L for ambient water quality. Low dissolved oxygen concentrations can be typical in swampy areas such as Pumpkin Creek.

9.4.2.2. TSS, Major Ions and Hardness

Turbidity and TSS concentrations were generally lower in smaller, slow-flowing watercourses than in larger, faster-flowing rivers; however, wide ranges in background turbidity are typical of many rivers in PNG subject to natural flooding-related sediment load.

Table 9.11: Total metals concentrations for the Lower Watut River catchment

	Ag	Al	As	Cd*	Co	Cr	Cu	Fe	Hg	Mo	Mn	Ni	Pb	Sb	Se	Zn
Wafi River catchment sites																
Minimum	0.001	0.01	0.001	0.0001	0.001	0.001	0.001	0.05	0.0001	0.001	0.001	0.001	0.001	0.001	0.01	0.005
Median	0.001	0.27	0.001	0.0001	0.001	0.001	0.002	0.275	0.0001	0.001	0.029	0.002	0.001	0.001	0.01	0.01
Maximum	**2.5**	24,300	**200**	**3**	38	**190**	0.017	**47,300**	**0.0056**	0.014	**2,720**	**0.78**	**172**	**0.15**	**0.1**	**476**
Bavaga River catchment sites																
Minimum	0.001	0.01	0.001	0.0001	0.001	0.001	0.001	0.05	0.0001	0.001	0.001	0.001	0.001	0.001	0.01	0.005
Median	0.001	0.06	0.001	0.0001	0.001	0.0025	0.002	0.2125	0.0001	0.001	0.0095	0.0015	0.001	0.001	0.01	0.01
Maximum	**1.9**	40	0.0097	**1**	19	**98**	**133**	**52.2**	**0.0018**	0.001	**754**	**0.11**	**9**	**0.009**	**0.0131**	**221**
Wampit River catchment sites																
Minimum	0.001	0.08	0.001	0.0001	0.001	0.001	0.001	0.037	0.0001	No data	0.001	0.001	0.001	0.001	0.01	0.005
Median	0.001	0.52	0.001	0.0001	0.001	0.001	0.001	0.105	0.0001	No data	0.0075	0.001	0.001	0.001	0.01	0.005
Maximum	0.0041	7.23	**2.6**	**0.8**	0.005	0.0343	0.024	**11.3**	**0.0027**	No data	**0.273**	**0.0147**	**0.0715**	**5.3**	**0.0212**	0.048
Watut River catchment sites																
Minimum	0.001	0.14	0.0013	0.0001	0.001	0.001	0.001	0.16	0.0001	0.001	0.027	0.001	0.001	0.001	0.01	0.005
Median	0.001	5.85	0.01	0.0001	0.0083	0.01	0.013	**6.84**	0.0001	0.001	**0.275**	0.01	0.01	0.001	0.01	0.022
Maximum	0.0293	11,100	**30**	**1**	15	**49**	**125**	**37,900**	**0.0088**	0.001	**856**	**0.201**	**24**	**0.028**	**0.0523**	**126**
Womul River (including the Lower Watut River floodplain) catchment sites																
Minimum	0.001	0.01	0.001	0.0001	0.001	0.001	0.001	0.05	0.0001	0.001	0.001	0.001	0.001	0.001	0.01	0.005
Median	0.001	0.04	0.001	0.0001	0.001	0.001	0.002	0.13	0.0001	0.001	0.0335	0.001	0.001	0.001	0.01	0.01
Maximum	0.0204	78	**0.02**	**1**	21	**116**	**89**	**13.4**	**0.0021**	0.001	**801**	**0.64**	**8**	**0.035**	**0.0179**	**103**
Markham River catchment sites																
Minimum	0.001	1.8	0.001	0.0001	0.001	0.001	0.001	0.05	0.0001	0.001	0.028	0.001	0.001	0.001	0.01	0.005
Median	0.001	17.58	0.004	0.0001	0.01	0.0125	0.025	**11.65**	0.0001	0.001	**0.295**	**0.0155**	0.0035	0.001	0.01	0.03

	Ag	Al	As	Cd*	Co	Cr	Cu	Fe	Hg	Mo	Mn	Ni	Pb	Sb	Se	Zn
Maximum	**0.61**	170	**0.02**	**1**	18	**30**	**117**	**212**	**0.0021**	0.001	**987**	**0.24**	**11**	**0.069**	0.01	**68**
Guidelines																
PNG raw drinking water[a]	0.1	-	0.007	0.002	-	0.05	1	0.3	0.001	-	0.1	0.01	0.02	0.003	0.01	3
PNG Schedule 2[b]	0.05	-	0.05	0.01	-	-	1.5[c]	1[c]	0.001	-	0.5[c]	0.1	-	-	0.01	15[c]
WHO (2011)[d]	-	-	0.01[e]	0.003	-	0.05[e]	2	-	0.006	-	-	0.01[e]	0.07	-	0.04[e]	-

Exceedances of the most stringent drinking water criteria are indicated by bold text.
For statistical purposes, where recorded concentrations are below the limit of detection, a value equal to the detection limit has been assumed.
[a] Raw drinking water quality criteria described in OEC (2000). Metal concentrations are for dissolved metals.
[b] State of PNG Public Health (Drinking Water) Regulation, Schedule 2, 1984.
[c] Aesthetically-based value.
[d] World Health Organisation (WHO) drinking water guidelines (2011).
[e] Provisional guideline value.
* The detection limit for cadmium ranged from <0.001mg/L to <1mg/L.

Turbidity ranged from 1.8NTU in Busanem Creek (S/Site 1) to 671NTU in the Markham River (S/Site 8), with corresponding TSS concentrations of less than 5mg/L and 1,050mg/L, respectively. Pumpkin Creek had turbidities ranging from 39.2 to 654NTU and TSS concentrations ranging from 44 to 833mg/L.

Water quality in the Markham River floodplain watercourses was dominated by calcium and carbonate, typical of streams influenced by the presence of limestone in the surrounding rocks. This is consistent with the stratigraphy of the Lower Markham River reaches, which comprise a number of rock types (including sandstone, greywacke, shale, phylite, slate, quartzite, and alusite schist and quartz-sericite schist) with interbedded recrystallised limestone (Mackay, 1955). Busanem Creek (S/Site 1) and Amburinu Creek (S/Site 2) showed the greatest karstic influence with the highest calcium (80mg/L and 63mg/L) and total alkalinity (310 and 330 mg/L $CaCO_3$) concentrations.

Water was hard (i.e., between 120 to 179mg/L $CaCO_3$) or very hard (i.e., between 180 to 240mg/L $CaCO_3$) at most sites. The very hard water is likely attributed to the presence of limestone in the stratigraphy of the Lower Markham River (Mackay, 1955).

9.4.2.3. Dissolved Metals

Table 9.12 shows that at sites in the Lower Markham River floodplain, most dissolved metals concentrations were below the limit of detection, as well as PNG ER criteria and ANZECC guideline values. An exception to this was dissolved manganese concentrations which were generally above the limit of detection, including one exceedance of the PNG ER criterion of 0.5mg/L in Maiwara Creek (S/Site9).

9.4.2.4. Total Metals

As shown in Table 9.13, total metals at sites in the Lower Markham River floodplain were generally low with the exception of aluminium and iron, mostly correlating with higher suspended sediment concentrations. The highest total aluminium and total iron concentrations were measured in the Markham River, with concentrations of 36.4mg/L and 38.9mg/L, respectively. Most concentrations of iron exceeded the State of PNG drinking water guidelines, while some concentrations of manganese (in Pumpkin and Maiwara Creeks), arsenic (Pumpkin Creek and Markham River) and nickel (Pumpkin Creek and Markham Rivers) exceeded State of PNG drinking water guidelines.

Total cadmium, mercury, selenium and silver concentrations were at or below the limit of detection at all sites.

9.4.2.5. Nutrients

Nutrients were generally low and below State of PNG and ANZECC criteria. An exception to this was identified in Maiwara Creek (S/Site 9) where the ammonia concentration (0.51mg/L) exceeded the State of PNG criterion of 0.3mg/L but were below the ANZECC guideline of 0.9 mg/L. Nitrite concentrations were below the limit of detection at all sites except in Maiwara Creek (S/Site 9) where 0.04 mg/L was recorded. Nitrate concentrations at all sites were well below the State of PNG and the ANZECC guideline value.

Total Kjeldahl nitrogen (TKN), representing organic nitrogen (i.e., total nitrogen minus nitrite and nitrate) was also relatively low, reflective of the low concentrations of nitrate and nitrite in the watercourses.

Total phosphorus ranged from 0.06mg/L in Busanem Creek (S/Site 1) to 0.087mg/L in Pumpkin Creek (S/Site 6) and the Markham River (S/Site 8). Reactive phosphorus concentrations were low at all sites, ranging from 0.05mg/L in the Markham River (S/Site 8) to 0.25mg/L in Buambub Creek (S/Site 3).

9.4.3. Summary of Background Water Quality

Turbidity and TSS concentrations in watercourses in the Wafi River and eastern Watut River floodplain catchments were typically lower than levels in the Watut and Markham rivers. The TSS concentrations in the Watut and Markham rivers were sometimes very high, with some concentrations in excess of 10,000mg/L recorded in WGJV data (refer to Figure 9.19).

Some sites in the Nambonga Creek (sites A60 and A70) had acidic waters (pH of around 4). Site A60 also had elevated electrical conductivity levels (approximately 1,000µs/cm) compared to all other sites, which had electrical conductivity levels less than 600µs/cm.

Sites in South Golpu (A15 to A18) in the Wafi River catchment had elevated dissolved concentrations of cadmium, copper and lead.

Mercury data showed significant variability. The data indicates that mercury levels were likely to be more elevated during periods of rainfall compared to base flow conditions.

Water quality in the Lower Watut River catchment is generally consistent with that found in other regions in PNG with similar catchment hydrology, geology, metalliferous ore deposits and artisanal mining activities. The exception to this is mercury, which is not typically found in such elevated concentrations in other regions of PNG and is significantly elevated in parts of the Lower Watut River catchment. This could be a function of historic alluvial mining activities in the region.

Most median total metal and metalloid concentrations in all catchments in the Lower Watut River catchment were below State of PNG and WHO 2011 drinking water guidelines, with the exception of median iron concentrations in the Watut and Markham River catchments.

In the Lower Markham River floodplain, turbidity and TSS concentrations were generally higher in the larger, faster-flowing rivers. In the main channel of the Markham River upstream of the Watut River confluence (site D12), median turbidity was around 700NTU and the median TSS concentration was just over 1,000mg/L, with maximum recorded measurements of 6,500NTU and 13,700mg/L.

These watercourses were dominated by calcium and carbonate, typical of streams influenced by the presence of limestone in the surrounding rocks.

Most dissolved metals concentrations were below the limit of detection, as well as PNG ER criteria and ANZECC guideline values, except for one dissolved manganese concentration which exceeded PNG ER criterion of 0.5mg/L. Total metals concentrations were generally low with the exception of aluminium and iron in the Markham River.

Table 9.12: Dissolved metal and metalloid concentrations in watercourses on the Lower Markham River floodplain (mg/L)

Site	Watercourse	Aluminium	Arsenic	Cadmium	Chromium	Copper	Iron	Lead	Manganese	Mercury	Nickel	Selenium	Silver	Zinc
Limit of detection		<0.01	<0.001	<0.0001	<0.001	<0.001	<0.05	<0.001	<0.001	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 1	Busanem Creek	<0.01	<0.001	<0.0001	<0.001	<0.001	<0.05	<0.001	0.065	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 2	Amburinu Creek	<0.01	<0.001	<0.0001	<0.001	0.001	<0.05	<0.001	0.059	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 3	Buambub Creek	0.03	<0.001	<0.0001	<0.001	0.002	<0.05	<0.001	0.02	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 4	Pumpkin Creek	0.02	<0.001	<0.0001	<0.001	0.002	<0.05	<0.001	0.025	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 5	Pumpkin Creek	<0.01	0.001	<0.0001	<0.001	0.001	<0.05	<0.001	0.09	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 6	Pumpkin Creek	0.03	0.001	<0.0001	<0.001	0.001	<0.05	<0.001	0.066	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 7	Pumpkin Creek	0.05	0.002	<0.0001	<0.001	0.002	<0.05	<0.001	0.028	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 8	Markham River	0.05	0.002	<0.0001	<0.001	0.002	<0.05	<0.001	0.009	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 9	Maiwara Creek	0.02	0.002	<0.0001	<0.001	<0.001	0.12	<0.001	**0.53**	<0.0001	<0.001	<0.01	<0.001	<0.005
PNG ECoP[b]		<0.1 (if pH >6.5)	0.05	0.00066-0.0011[c] 0.0011-0.002[d]	0.01	0.0065-0.012[c] 0.012-0.021[d]	1	0.0013-0.0032[c] 0.0032-0.0077[d]	-	0.0001	0.056-0.096[c] 0.096-0.160[d]	0.005	0.0001	0.180-0.320[c] 0.320-0.570[d]
ANZECC[e]		0.055	0.013	0.00054[f]	0.0025[f]	0.0035[f]	-	0.0136[f]	1.9	0.0006	0.0275[f]	0.011	0.0005	0.02[f]

- denotes no applicable guideline.
Exceedance of State of PNG criteria is shown in bold.
[a] Source: State of PNG Environment (Water Quality Criteria) Regulation 2002 – Schedule 1 Water Quality Criteria for Aquatic Life Protection (PNG, 2002).
[b] Source: State of PNG Environmental Code of Practice for the Mining Industry. Criteria for protection of freshwater aquatic life.
[c] Guideline is applicable to a hardness of 50 to 100 mg/L $CaCO_3$.
[d] Guideline is applicable to a hardness of 100 to 200 mg/L $CaCO_3$.
[e] Source: Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ, 2000).
[f] Guideline is a 'hardness modified trigger value' as per section 3.4.3.2 of ANZECC. This guideline takes into account the 'hard' hardness of the water.

Table 9.13: Total metals and metalloids in watercourses on the Lower Markham River floodplain (mg/L)

Site	Watercourse	Aluminium	Arsenic	Cadmium	Chromium	Cobalt	Copper	Iron	Lead	Manganese	Mercury	Nickel	Selenium	Silver	Zinc
Limit of detection		<0.01	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05	<0.001	<0.001	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 1	Busanem Creek	0.12	<0.001	<0.0001	<0.001	<0.001	<0.001	0.17	<0.001	0.094	<0.0001	<0.001	<0.01	<0.001	<0.005
S/Site 2	Amburinu Creek	1.41	<0.001	<0.0001	0.001	<0.001	0.004	***1.52***	<0.001	*0.146*	<0.0001	0.002	<0.01	<0.001	0.007
S/Site 3	Buambub Creek	1.76	<0.001	<0.0001	0.002	<0.001	0.006	***1.87***	<0.001	0.064	<0.0001	0.004	<0.01	<0.001	0.012
S/Site 4	Pumpkin Creek	2.9	0.001	<0.0001	0.003	0.002	0.008	***3.2***	<0.001	*0.179*	<0.0001	0.004	<0.01	<0.001	<0.005
S/Site 5	Pumpkin Creek	1.97	0.001	<0.0001	0.004	0.001	0.006	***2.33***	<0.001	*0.179*	<0.0001	0.004	<0.01	<0.001	0.006
S/Site 6	Pumpkin Creek	18.5	0.004	<0.0001	0.018	0.011	0.039	***20.5***	0.004	0.61	<0.0001	**0.027**	<0.01	<0.001	0.035
S/Site 7	Pumpkin Creek	26.8	**0.008**	0.0001	0.025	0.017	0.06	***29.5***	0.006	***0.894***	<0.0001	**0.036**	<0.01	<0.001	0.055
S/Site 8	Markham River	38.9	**0.009**	0.0001	0.04	0.025	0.087	***46.4***	0.01	***1.21***	<0.0001	**0.058**	<0.01	<0.001	0.084
S/Site 9	Maiwara Creek	0.19	0.002	<0.0001	<0.001	<0.001	0.002	*0.58*	<0.001	***0.534***	<0.0001	0.001	<0.01	<0.001	<0.005
PNG raw drinking water[a]			0.007	0.002	0.05	-	1	0.3	0.01	0.1	0.001	0.02	0.01	0.1	3
PNG Schedule 2[b]			0.05	0.01	-	_	1.5[c]	1[c]	0.1	0.5[c]	0.001	-	0.01	0.05	15[c]
WHO (2011)[d]			0.01[e]	0.003	0.05[e]	_	2	-	0.01[e]	-	0.006	0.07	0.04[e]	-	-

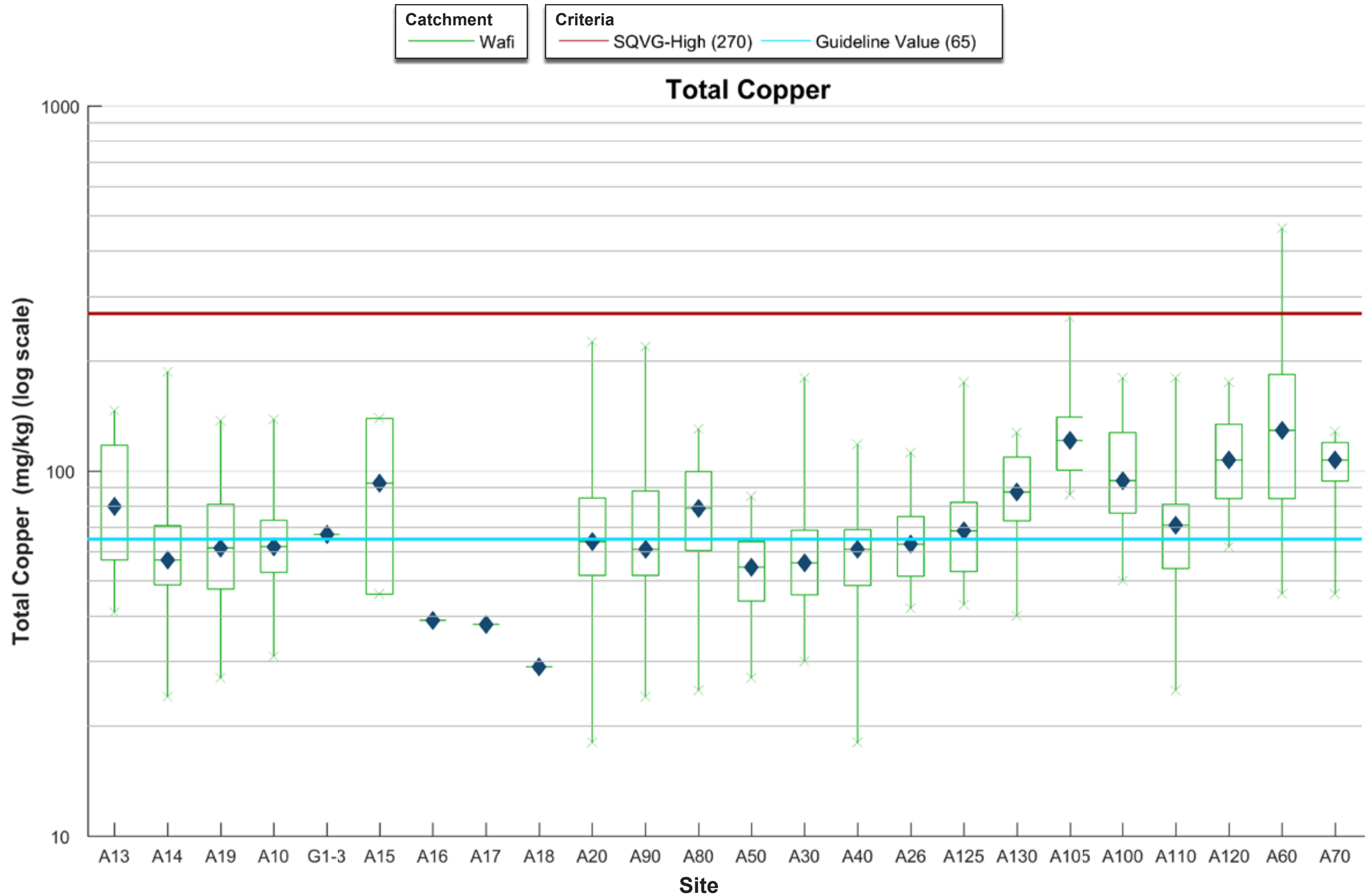
Bold text indicates exceedance of State of PNG raw drinking water guidelines and italic text indicates exceedance of State of PNG Schedule 2 criteria.
[a] Raw drinking water quality criteria described in OEC (2000).
[b] State of PNG Public Health (Drinking Water) Regulation, Schedule 2, 1984.
[c] Aesthetically-based value.
[d] World Health Organisation (WHO) drinking water guidelines (2011).
[e] Provisional guideline value.

9.5. Sediment Quality

Sediment quality results for the Lower Watut River are described below. No sediment quality data were collected for the Lower Markham River floodplain area based on the reduced survey effort, aligned with the duration and level of Project activities in this area. Furthermore watercourses in this area are highly modified by anthropogenic effects such as settlements, gardens and industrial activity.

The WGJV sediment metals data collected between 2006 and 2016 included total metal/metalloid concentrations in sediment fractions less than 63 microns (µm) and less than 2,000µm. As fine particles (<63µm) have higher adsorption capacity for dissolved metals and metalloids (see Section 9.4.1.7), these are considered most relevant to environmental impacts. The key findings of a comparison between WGJV data median metal concentrations in sediment (<63µm) and Sediment Quality Guideline Values (i.e., the SQGV and the SQGV-High values) are as follows:

- Median concentrations of arsenic at half the sites in the Wafi River exceeded the SQGV. Other sites in the Wafi River catchment, including sites in the Zamen and Hekeng rivers, and Yor Creek, had median concentrations below the SQGV. Three South Golpu sites (A15 to A17) and three sites in Nambonga Creek (A60, A70 and A105), had median concentrations of arsenic that exceeded the SQGV-high value.
- Median concentrations of cadmium were generally below the SQGV at all monitoring sites except for one site in Nambonga Creek (A60).
- At approximately half of the sites, median concentrations of copper exceeded the SQGV, though they did not exceed the SQGV-High value (refer to Figure 9.26 and Figure 9.27). South Golpu sites (A16 to A18) and all sites in the Watut River had median concentrations below the Guideline Value. The maximum concentrations of copper (462mg/kg) in Nambonga Creek (A60), the Bavaga River (C30) and Timini River (C60), however, exceeded the SQGV-High value.
- Median concentrations of lead were below the SQGV at all sites in the Womul Creek and Bavaga, Wampit/Waime, Watut and Markham river catchments. Most sites in the Wafi River catchment were also below the SQGV, except for the South Golpu sites (A15 to A18), and sites in Nambonga Creek (A60, A70, A100 and A105).
- Median concentrations of mercury were below the SQGV at most monitoring sites (refer to Figure 9.28 and Figure 9.29). However, three South Golpu sites (A15, A16 and A18), Hotel Creek (A20) and four Nambonga Creek sites (A60, A70, A105 and A125) had elevated concentrations above the SQGV but below the SQGV-High value (1.1mg/kg). One of the South Golpu sites (A17) had a median mercury concentration of 1.4mg/kg, exceeding the SQGV-High value. Several maximum concentrations of mercury in sediments exceeded the SQGV-High guideline including Wafi River (A19), Hekeng Creek (A26), Buvu Creek (A125), an unnamed tributary of Nambonga Creek (A120), Nambonga Creek (A60), Ziriruk River (E80), Uruf Stream (E10), Bavaga River (C20) and Watut River (B30).
- Median concentrations of silver were above the SQGV of 1mg/kg at all monitoring sites; however, this is associated with the laboratory limit of reporting for WGJV silver data, which is 2mg/kg. Median concentrations at all sites were below the SQGV-High value.



Sites	A13	A14	A19	A10	G1_3	A15	A16	A17	A18	A20	A90	A80	A50	A30	A40	A26	A125	A130	A105	A100	A110	A120	A60	A70
Samples	17	19	36	25	1	2	1	1	1	29	21	20	30	29	31	29	18	32	19	35	18	14	26	7
Min	41	24	27	31	67	46	39	38	29	18	24	25	27	30	18	42	43	40	86	50	25	62	46	46
25th Percentile	57	48.8	47.5	52.8	67	46	39	38	29	51.8	51.8	60.5	44	45.8	48.5	51.5	53	73	100.5	76.5	54	84	84	93.8
Median	80	57	61.5	62	67	92.5	39	38	29	64	61	79	54.5	56	61	63	68.5	87.5	121	94	71	107	129	107
75th Percentile	117.5	70.8	81	73.3	67	139	39	38	29	84.3	88	99.5	64	68.8	69	75	82	109	140.3	127.3	81	134	184	119.5
Mean	88.2	66.1	66.9	67.8	67	92.5	39	38	29	77.2	82.5	78.7	54.5	62.8	61.7	64.3	80.1	89.2	130.8	101.9	73.9	111.5	155.2	101.7
Max	146	187	137	138	67	139	39	38	29	226	219	130	85	180	118	112	175	127	263	180	180	175	462	128

Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.16

coffey
A TETRA TECH COMPANY

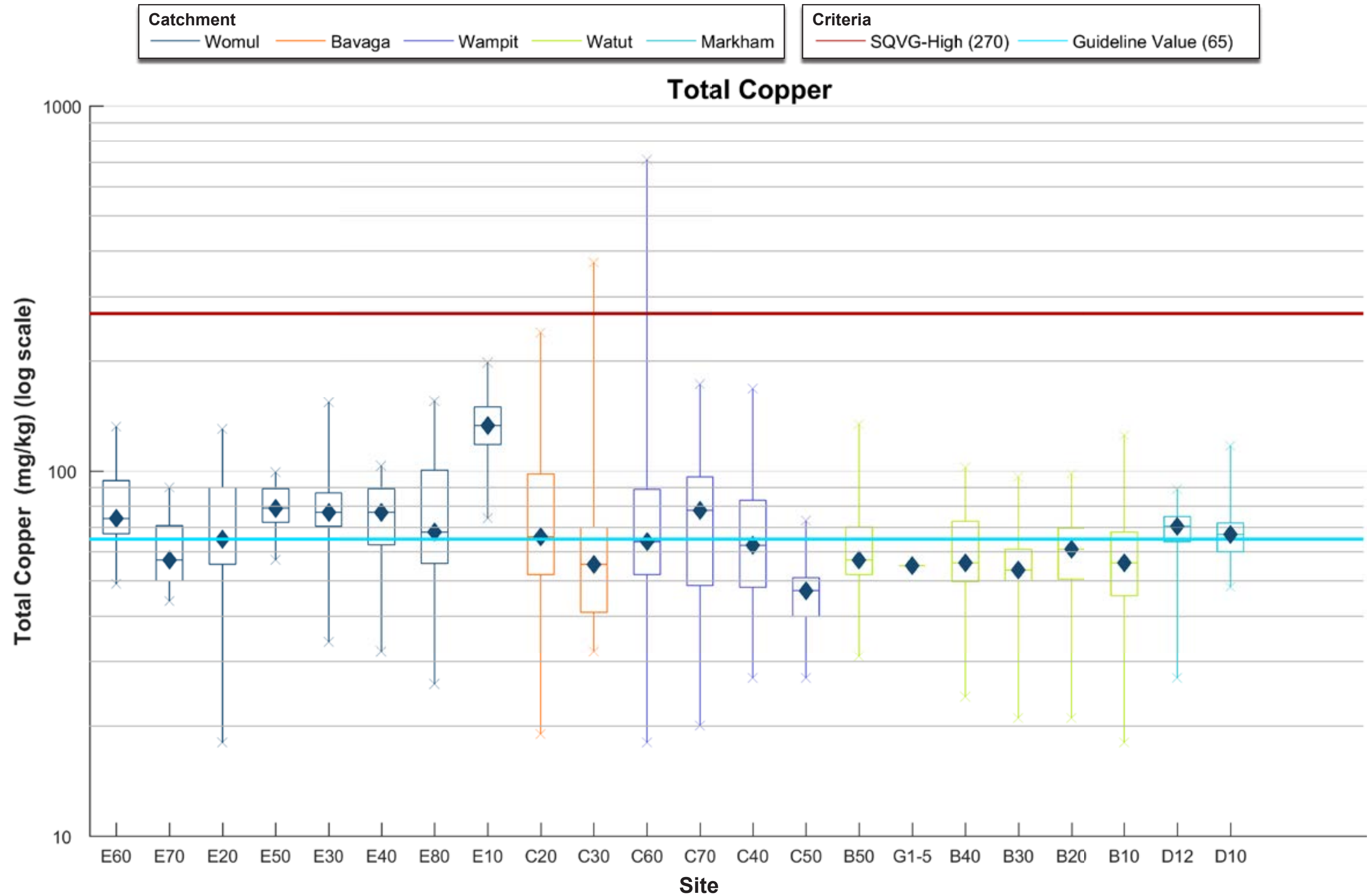
Date:
30.11.2017
Project:
754-ENAUABTF100520DD
File Name:
0520DD_10_F09.26_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV copper data for the Wafi River catchment: sediment

Figure No:
9.26



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1_5	B40	B30	B20	B10	D12	D10
Samples	17	17	28	17	13	13	17	20	30	26	26	25	26	16	29	1	27	22	27	20	22	30
Min	49	44	18	57	34	32	26	74	19	32	18	20	27	27	31	55	24	21	21	18	27	48
25th Percentile	67.3	50	55.5	72.3	70.5	62.8	55.8	118	52	41	52	48.5	48	40	52	55	49.8	50	50.5	45.5	64	60
Median	74	57	65	79	77	77	68	133	66	55.5	64	78	62.5	47	57	55	56	53.5	61	56	70.5	67
75th Percentile	94	70.8	90	89.3	87	89.3	100.5	149.5	98	70	89	96.3	83	51	70.3	55	72.8	61	69.8	68	75	72
Mean	79.8	61.3	69.7	79.5	81.8	74.9	83.4	132.4	81.8	76	102.2	76	70.8	46.6	63.7	55	59.9	56.7	61.6	58.6	68.3	67.3
Max	132	90	130	99	154	103	155	198	239	372	711	173	168	73	134	55	102	96	98	125	89	117

Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.17

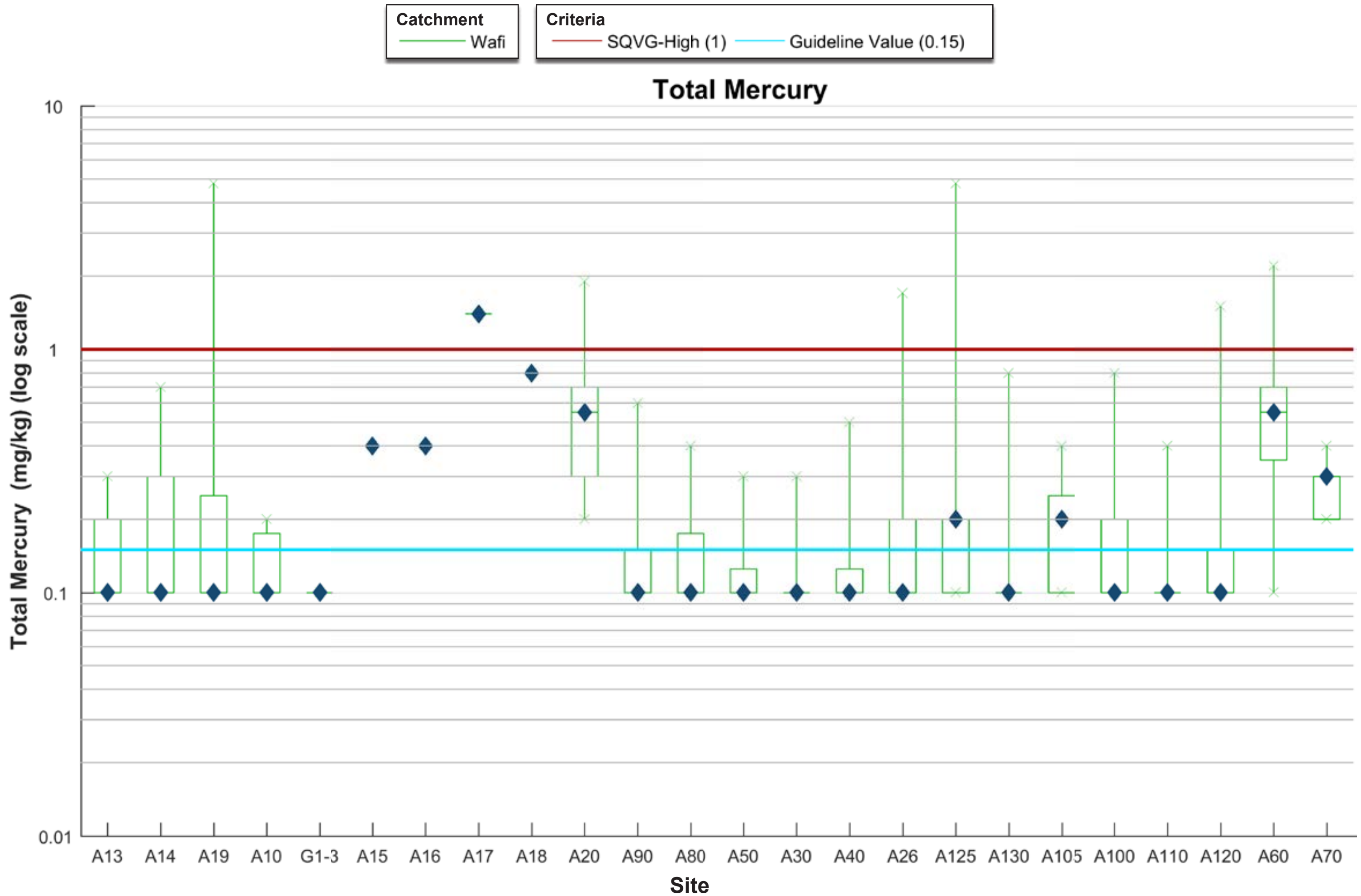
coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.27_GRA

WAFI-GOLPU JOINT VENTURE
Wafi-Golpu Project

Summary of WGJV copper data for Markham, Watut, Wampit, Bavaga and Womul catchments: sediment

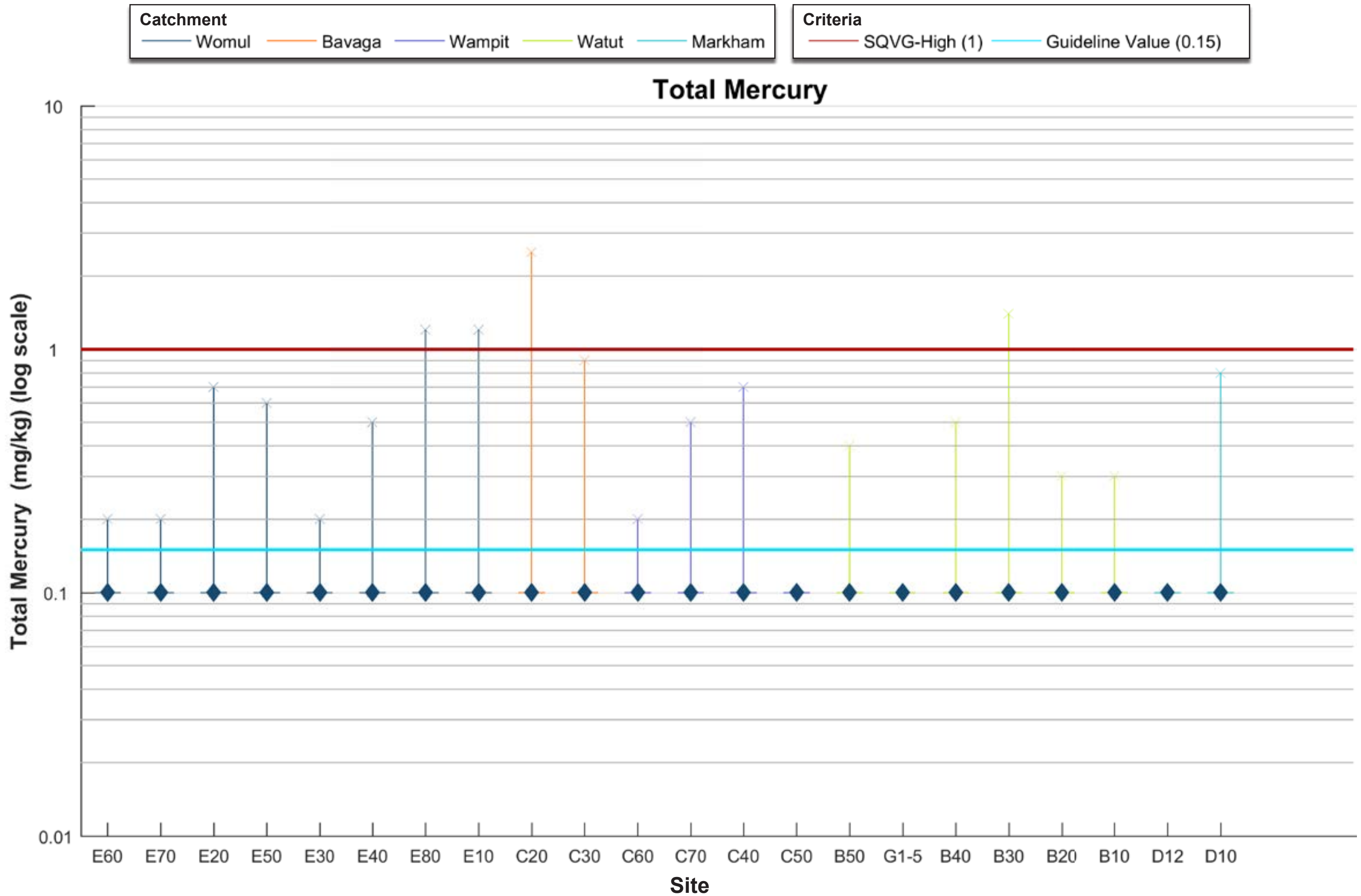
Figure No: 9.27



Sites	A13	A14	A19	A10	G1_3	A15	A16	A17	A18	A20	A90	A80	A50	A30	A40	A26	A125	A130	A105	A100	A110	A120	A60	A70
Samples	11	12	28	19	1	1	1	1	1	22	16	15	21	20	21	22	12	25	12	28	14	12	20	7
Min	0.1	0.1	0.1	0.1	0.1	0.4	0.4	1.4	0.8	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
25th Percentile	0.1	0.1	0.1	0.1	0.1	0.4	0.4	1.4	0.8	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.2
Median	0.1	0.1	0.1	0.1	0.1	0.4	0.4	1.4	0.8	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.6	0.3
75th Percentile	0.2	0.3	0.3	0.2	0.1	0.4	0.4	1.4	0.8	0.7	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.3	0.2	0.1	0.2	0.7	0.3
Mean	0.1	0.2	0.4	0.1	0.1	0.4	0.4	1.4	0.8	0.6	0.2	0.2	0.1	0.1	0.1	0.2	0.6	0.1	0.2	0.2	0.1	0.2	0.6	0.3
Max	0.3	0.7	4.8	0.2	0.1	0.4	0.4	1.4	0.8	1.9	0.6	0.4	0.3	0.3	0.5	1.7	4.8	0.8	0.4	0.8	0.4	1.5	2.2	0.4

Summary of WGJV mercury data for the Wafi River catchment: sediment

Figure No: 9.28



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1_5	B40	B30	B20	B10	D12	D10
Samples	15	15	21	15	11	11	15	15	23	20	21	20	20	11	21	1	20	17	20	16	18	26
Min	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
25th Percentile	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Median	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
75th Percentile	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mean	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Max	0.2	0.2	0.7	0.6	0.2	0.5	1.2	1.2	2.5	0.9	0.2	0.5	0.7	0.1	0.4	0.1	0.5	1.4	0.3	0.3	0.1	0.8

Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.19

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.29_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV mercury data for Markham, Watut, Wampit, Bavaga and Womul catchments: sediment

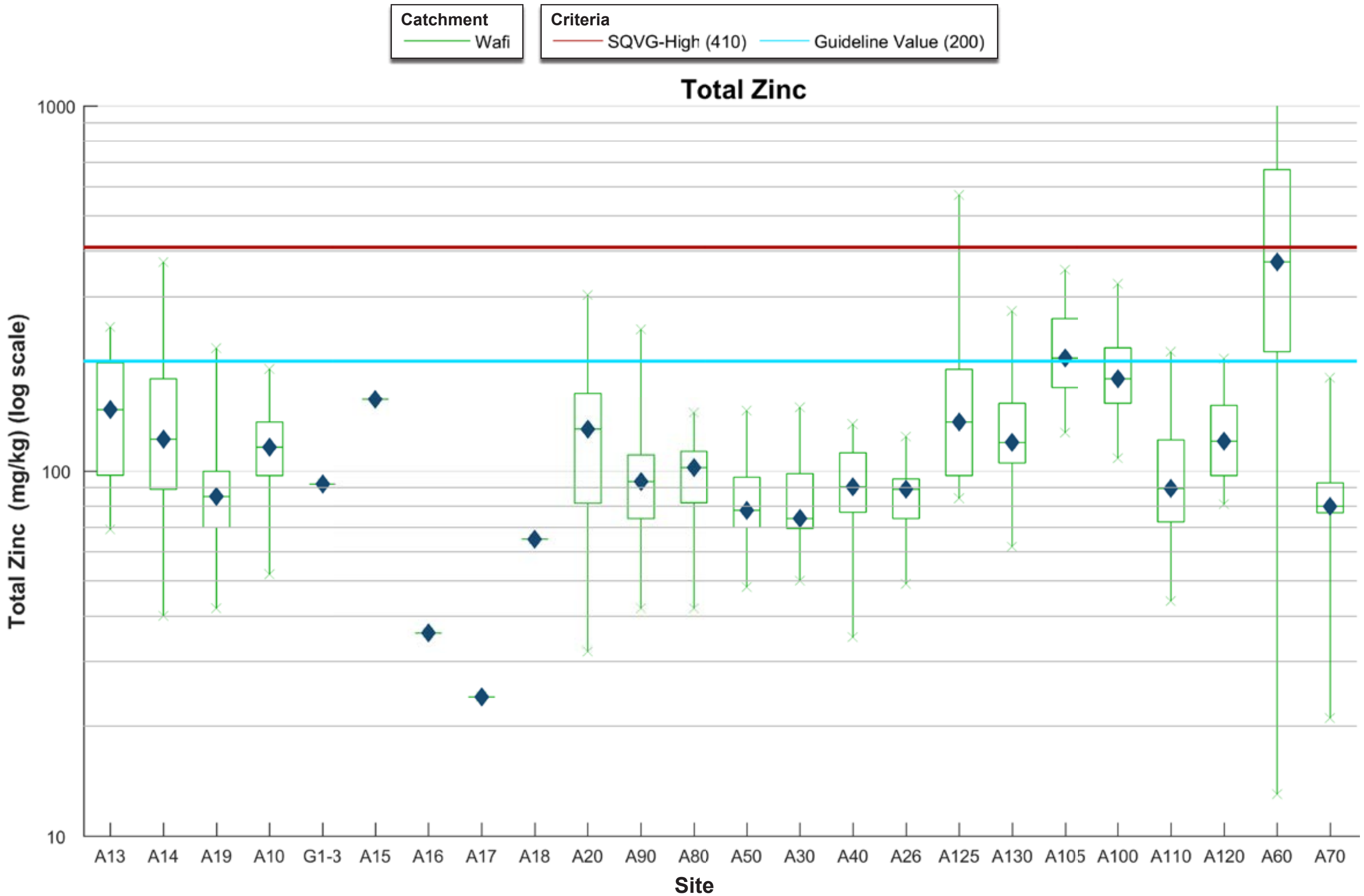
Figure No: 9.29

INDD Reference: 0520DD_10_GRA042.indd_4

- Median concentrations of zinc were below the SQGV at all sites, except for sites A60 and A105 in Nambonga Creek catchment, which exceeded the SQGV. None of the sites had median concentrations that exceeded the SQGV-high value (refer to Figure 9.30 and Figure 9.31). Several maximum zinc concentrations were higher than the SQGV-High, including in the Wafi River catchment (A125 and A60), Womul Creek (including the Lower Watut River floodplain catchment) (E20 and E10), Wampit River catchment (C30 and C50) and the Bavaga River (C20 and C30).
- There are no SQGVs for selenium. Most sites had median concentrations of selenium of 5mg/kg, which is the laboratory limit of reporting.
- There are no SQGVs for manganese. Most sites had median concentrations of manganese around 500mg/kg to 1,500mg/kg.
- Most sites had median nickel concentrations that exceeded the SQGV. Sixteen sites in the Wafi River catchment and four sites across all other catchments also exceeded the SQGV-High value.

Key sediment quality results of the BMT WBM (2015/2016) sampling are summarised as follows:

- The data show significant variability between sites and between sampling campaigns indicating the dynamic nature of sediment delivery, transport and deposition processes throughout the study catchment.
- Oxbow lake sites and sites located in low gradient floodplain streams typically had a substrate with a high (greater than 30%) proportion of clays and silts. Sites located in the Watut River channel and high to moderate gradient tributary streams typically had substrates comprised mostly of coarser sediments (gravel, sands).
- Arsenic concentrations exceeded the SQGV at two sites in the Watut River (Maralina and Uruf) in March 2015. Similar arsenic concentrations were previously recorded in the Watut River by WGJV. The monitoring site at Nambonga had arsenic concentrations that also exceeded the SQGV-High value. No sites exceeded the SQGV in June 2015 or December 2016.
- Chromium concentrations exceeded the SQGV at five monitoring sites across various catchments in March 2015, two sites (Wassing and Wadgink) in June 2015, and all Bavaga River sites in December 2016.
- Copper levels were below the SQGV at all sites in March 2015, except for Nambonga, Banir and Bobul Xing, which slightly exceeded the SQGV. Copper levels exceeded the SQGV at the Swamp at 'Unknown Creek' location in June 2015. Copper levels were below the SQGV at all sites in December 2016.
- Mercury concentrations exceeded the SQGV at two sites (Nambonga and Bobul Xing) in March 2015. Similar exceedances of mercury have been previously recorded by WGJV at Nambonga. Mercury was not analysed in June 2015 or December 2016.
- Nickel concentrations exceeded the SQGV at most sites in March 2015, and also exceeded the SQGV-high value at eight sites across various catchments. In June 2015, all sites exceeded the SQGV, and two sites (Wassing and Wadgink) also exceeded the SQGV-High value. In December 2016, all sites exceeded the SQGV-High value.



Sites	A13	A14	A19	A10	G1_3	A15	A16	A17	A18	A20	A90	A80	A50	A30	A40	A26	A125	A130	A105	A100	A110	A120	A60	A70
Samples	15	17	33	22	1	1	1	1	1	27	20	19	26	25	26	26	16	30	17	33	16	14	25	7
Min	69	40	42	52	92	157	36	24	65	32	42	42	48	50	35	49	84	62	127	108	44	81	13	21
25th Percentile	97.3	80	70	97	92	157	36	24	65	81.5	74	81.8	70	69.5	77	74	97	105	169.5	153	72.5	97	212.3	76.8
Median	147	122	85	116	92	157	36	24	65	130	93.5	102	78	74	90.5	89	136	119.5	204	179	89.5	120.5	374	80
75th Percentile	198	179	99.8	136	92	157	36	24	65	163.3	110.5	113	96	98.3	112	95	190	153	261.5	217.5	121.5	151	668.5	92.8
Mean	147.2	148.6	97.2	114.9	92	157	36	24	65	131.3	99.6	99.7	85.8	85.3	91.3	87.4	167.9	128.3	215.8	192	101.8	128.1	451.8	88.4
Max	248	373	217	190	92	157	36	24	65	303	244	144	146	149	134	124	570	274	355	325	212	203	1500	180

Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.20

coffey
A TETRA TECH COMPANY

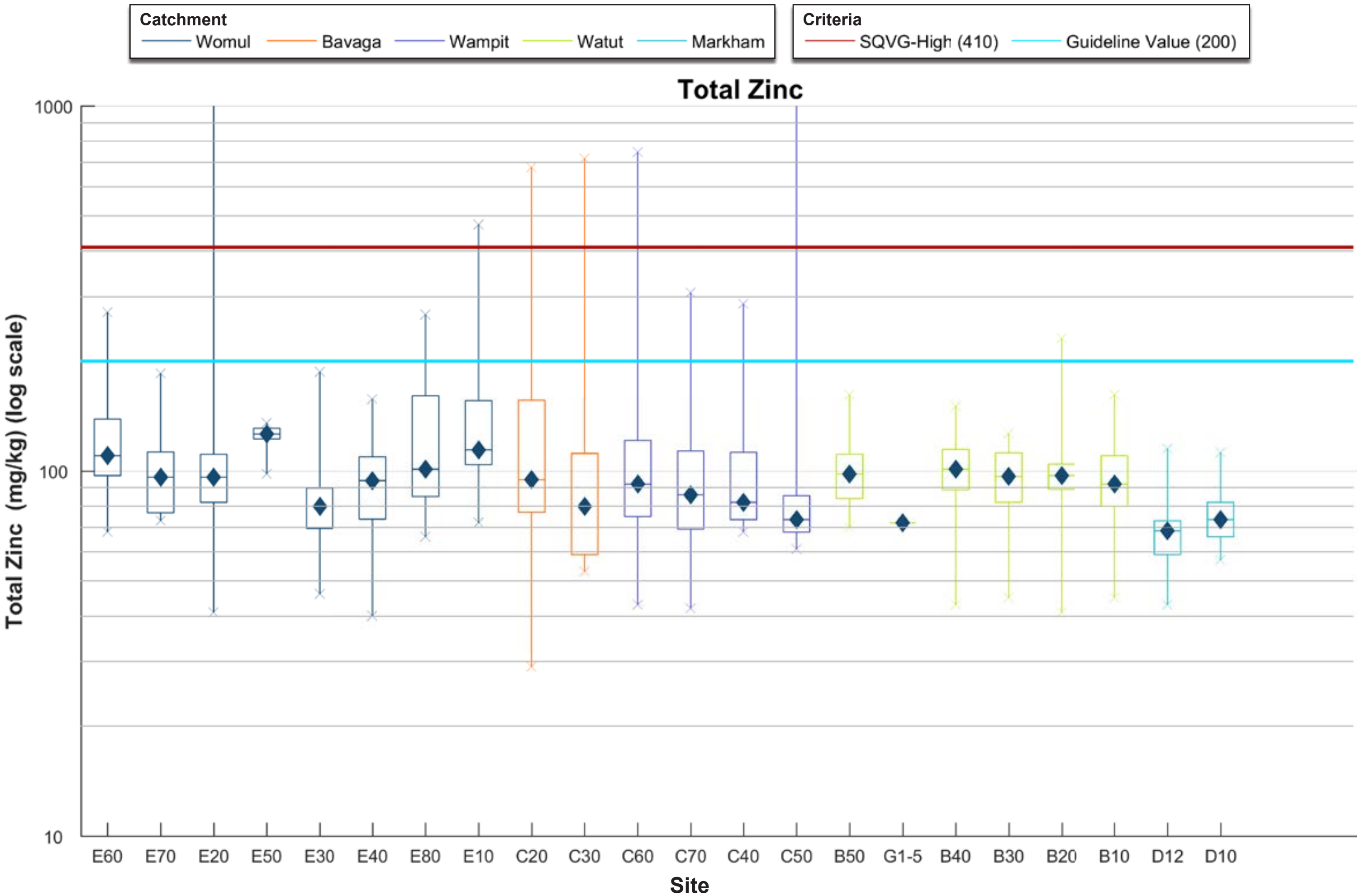
Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.30_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV zinc data for the Wafi River catchment: sediment

Figure No: 9.30



Sites	E60	E70	E20	E50	E30	E40	E80	E10	C20	C30	C60	C70	C40	C50	B50	G1_5	B40	B30	B20	B10	D12	D10
Samples	15	15	26	15	13	13	15	20	28	24	26	25	25	16	26	1	25	22	25	20	22	30
Min	68	73	41	98	46	40	66	72	29	53	43	42	68	61	70	72	43	45	41	45	43	57
25th Percentile	97	76.8	82	122.3	69.5	73.8	85	104	77	59	75	69.3	73.5	68	84	72	88.8	82	89	80	59	66
Median	110	96	96	126	80	94	101	114	94.5	80	92	86	82	73.5	98	72	101	96.5	97	92	68.5	73.5
75th Percentile	138.5	112.5	111	130.8	89.8	109.2	160.7	155.5	156	111.5	121	113.3	112.3	85.5	111	72	114.5	112	104.3	110	73	82
Mean	124.9	101.1	137.9	124.3	89	92.6	121.3	145.3	151.8	127.1	144.7	101.4	101.6	178.7	102	72	99.3	95.7	98.2	94.5	67.1	75.5
Max	272	185	1140	135	187	157	268	473	677	716	746	308	287	1600	162	72	150	126	231	162	115	112

Source:
WGJV: 532-1005-EN-REP-0004-1.9, Figure 9.21

coffey
A TETRA TECH COMPANY

Date: 30.11.2017
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.31_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Summary of WGJV zinc data for Markham, Watut, Wampit, Bavaga and Womul catchments: sediment

Figure No: 9.31

- Zinc concentrations were below the SQGV at all sites in March 2015, June 2015 and December 2016, except Nambonga in March 2015.
- All other metals/metalloids concentrations were below the relevant SQGV.
- Samples collected at Nambonga exceeded SQGVs for six out of the 13 metals/metalloids analysed.

In general, the BMT WBM metals/metalloids sediment data is similar to the WGJV data.

9.5.1. Organic Carbon in Sediment

Data for the Watut River catchment area (SolvFit Ltd, 2010) shows that total organic carbon and dissolved organic carbon (indicators of total organic matter content) vary among aquatic ecosystem types. Total organic carbon concentrations in sediments from floodplain wetlands (2.21% to 9.46%) and off-river waterbodies (0.84% to 1.41%) were generally higher than concentrations in low gradient watercourses (0.09% to 2.58%), Watut River channel (0.1% to 0.2%), and high to moderate gradient tributary stream (0.07% to 0.3%). Previous results from the main channel and tributary streams of the Watut, Bulolo and Markham rivers also reported low dissolved organic carbon concentrations (<1mg/L to 2mg/L) (SolvFit Ltd, 2010).

9.5.2. Summary of Background Sediment Quality

In comparison with the relevant guidelines (Simpson et al., 2013) elevated levels of arsenic, lead and mercury have regularly been recorded in fine sediments (<63µm) at South Golpu sites in the Wafi River catchment and some sites in the Nambonga Creek catchment.

Elevated concentrations of copper and nickel have regularly been recorded in fine sediments at various sites across all catchments.

It is notable that while dissolved mercury has been found in elevated concentrations in water in the Mine Area, concentrations in bed sediment samples are relatively low. Conversely, while copper and nickel are elevated in sediments, dissolved concentrations of these metals in water were recorded in relatively low concentrations. This may be due to limited flux of copper and nickel between bed sediments and the water column.

Sediment quality in the Lower Watut River catchment is generally consistent with that found in other regions in PNG with similar hydrology, geology, metalliferous ore deposits and artisanal mining activities (e.g., Frieda River).

9.6. Aquatic Ecology

Aquatic ecology results for the Lower Watut River are described below. The aquatic ecology survey effort for the Lower Markham River floodplain was more targeted and less comprehensive compared to the Lower Watut River catchment, corresponding to the likely duration and level of Project activities in each of the areas.

9.6.1. Aquatic Ecosystems and Habitats

Aquatic ecosystems and habitats in the Lower Watut River and Lower Markham River catchment are described below.

9.6.1.1. Lower Watut River Catchment

An overview of the characteristics of freshwater aquatic ecosystem types within the Lower Watut River catchment is provided in Table 9.14 with reference to aquatic ecosystem types of Polhemus and Allen (2006) and habitat classifications identified in IUCN (2015b).

Figure 9.32 shows the distribution of these aquatic ecosystem types within the Lower Watut River catchment.

Table 9.14: Aquatic ecosystem types based on different classification schemes

Area	Aquatic Ecosystem Type (Polhemus and Allen, 2006)	Habitat Classification (IUCN, 2015b)
High to moderate gradient tributary watercourses	Lotic: Perennial stream (headwater and mid reaches)	5.1 Permanent Rivers, Streams, Creeks [includes waterfalls]
Low gradient floodplain tributary watercourses and wetlands	Lotic: Perennial stream (mid and terminal reaches) Lotic: Intermittent stream Lotic: Flowing spring Palustrine: Lowland marsh (non-forested) Palustrine: Lowland swamp (forested)	5.1 Permanent Rivers, Streams, Creeks [includes waterfalls] 5.2 Seasonal/Intermittent/Irregular Rivers, Streams, Creeks 5.3 Shrub Dominated Wetlands 5.4 Bogs, Marshes, Swamps, Fens, Peatlands [>8ha] 5.7 Permanent Freshwater Marshes/Pools [<8ha] 5.8 Seasonal/Intermittent Freshwater Marshes/Pools [<8ha] 5.9 Freshwater Springs and Oases
Unconfined, turbid major river systems (Watut River and Markham River)	Lotic: Perennial stream (terminal reach)	5.1 Permanent Rivers, Streams, Creeks [includes waterfalls]
Oxbow lakes	Lentic: Oxbow lake Palustrine: Lowland marsh (non-forested)	5.6 Seasonal/Intermittent Freshwater Lakes [>8ha] 5.7 Permanent Freshwater Marshes/Pools [<8ha]

9.6.1.1.1. High to Moderate Gradient Tributary Watercourses

High to moderate gradient tributary watercourses occur within steep valleys, and have confined (high gradient headwaters (headwater reaches)) and partially confined (moderate gradient downstream reaches (mid-reaches)) channels, with examples of these shown in Figure 9.8. Watercourse flows vary substantially over time in response to rainfall and surface water runoff. The groundwater contribution to the flow regimes[11] of these watercourses is not well understood.

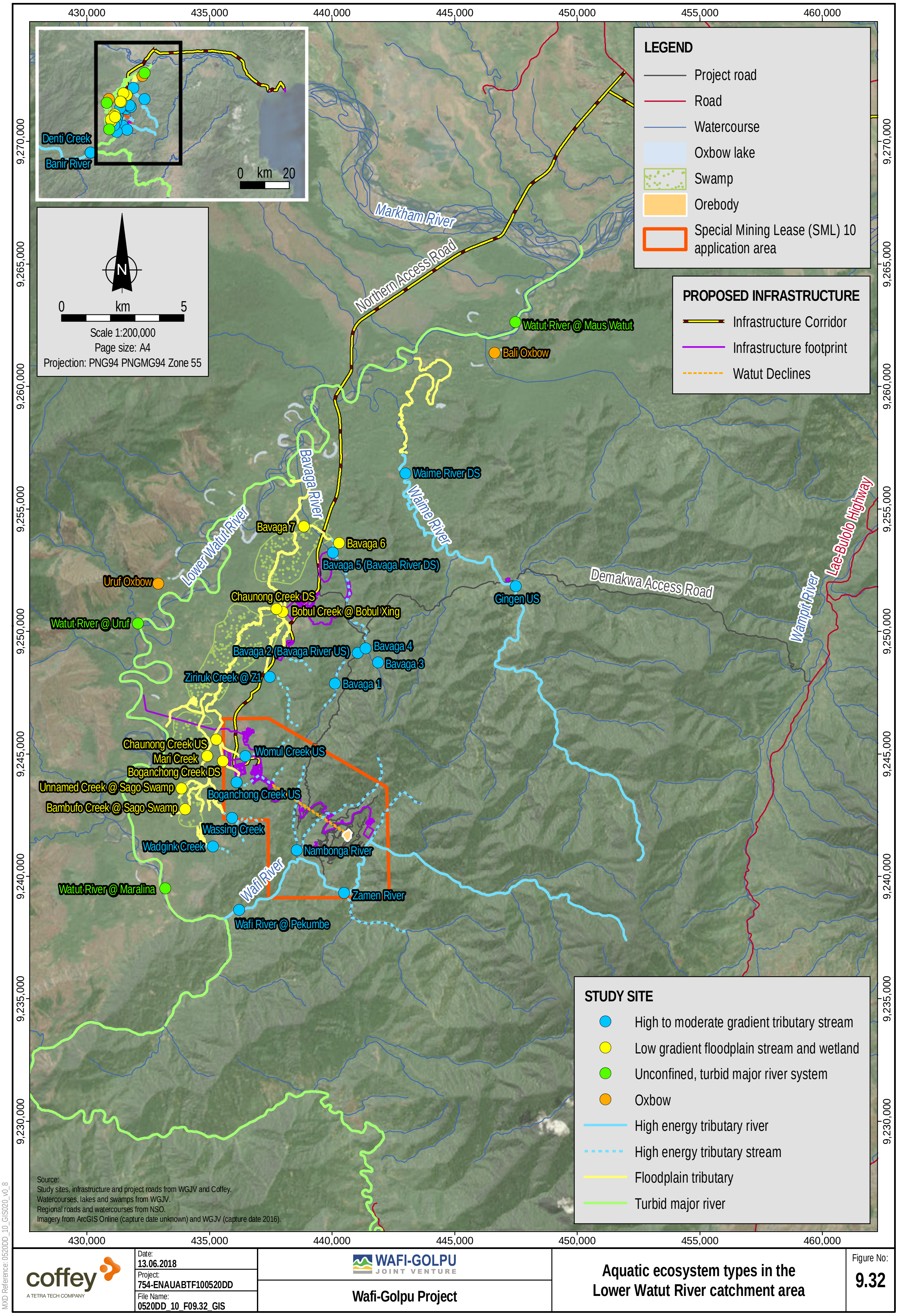
Headwater reaches typically have a substrate of bedrock, boulders, cobble and gravel, and due to their high energy typically do not accumulate sand and silty sediments. Meso-habitats[12] represented in these environments include rapids, riffles, runs and occasional backwaters.

Mid-reaches have channels that can be either confined or partially confined with small floodplains and some sediment deposition. As water velocities are quite high, runs, riffles and glides are present. Substrate consists of bedrock, boulders, cobble, gravel and sand. Water depth is typically shallow (0.1 to 0.8m), but would be greater during intense rainfall events. Watercourse width is typically less than 10m at sites classified as 'tributaries' and wider (10 to 40m) at sites classified as 'main channel'.

Due to the narrow width of high-energy tributary watercourses, the riparian canopy can completely shade the watercourse (see Figure 9.7). Riparian vegetation was continuous lowland and/or alluvial forests at sites where the local land use was predominately native forest and gardens. Semi-continuous to patchy riparian vegetation occurred where sites coincided with villages and gardens.

[11] Spatial and temporal patterns in flows

[12] Broad scale habitat types that are roughly the same scale as the channel width and delineated by localised slope, channel shape and structure



coffey
A TETRA TECH COMPANY

Date: 13.06.2018
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F09.32_GIS

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Aquatic ecosystem types in the Lower Watut River catchment area

Figure No: 9.32

Micro-habitat complexity was high at all sites. Rock crevices, woody debris and/or trailing vegetation were common physical instream habitat characteristics at all sites, often occurring with various combinations of root mats, undercut banks and/or overhanging vegetation. These features are critical in providing shelter for aquatic fauna, particularly when sites experience high flows. Instream vegetation, in the form of aquatic macrophytes[13], was absent at all sites.

Watercourses located in larger catchments typically comprised high to moderate gradient tributary watercourse habitat for their entire length to the confluence with the Watut River (e.g., Wafi River). Watercourses with smaller catchments (e.g., Bavaga River and Womul, Ziriruk and Bobul creeks) were high-energy watercourses in their headwaters and formed low gradient floodplain tributary watercourses and wetlands in their lower reaches (see Figure 9.32).

9.6.1.1.2. Low Gradient Floodplain Tributary Watercourses and Wetlands

A number of watercourses with small catchments eventually drain onto the Watut River floodplain to form floodplain watercourses and flood-out swamps, with examples of this shown in Figure 9.9 and Figure 9.33. Parts of the Lower Watut River floodplain have a water table that is at or near the surface, forming a water source (surface expressions of groundwater (springs)) and sink for floodplain tributary watercourses. The hydrological regime of floodplain wetlands and watercourses in the Lower Watut River catchment is complex; however, it is considered that they are at least partially dependent on groundwater.

Floodplain watercourses and wetlands represent a depositional environment, and substrates are typically comprised of clay, silt and sand. Structural and hydrological habitat conditions vary across a range of spatial scales. Physical and hydrological characteristics of these ecosystems are described below based on site surveys carried out by BMT WBM in March 2015, June 2015 and December 2016 (Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River):

- Upstream reaches – The upstream reaches of low gradient watercourses (i.e., immediately downstream of high and moderate gradient reaches) had low mud banks that typically reduce in height with increasing distance downstream. During dry periods, these watercourse reaches can completely dry, terminating in shallow pools. During wet periods, the upstream reaches of watercourses typically drained into freshwater wetlands, as described below.
- Freshwater wetlands – Sago palm (*Metroxylon sagu*) and a range of other wetland dependent vegetation species (as described in Chapter 8, Physical and Biological Environment Characterisation) numerically dominated in freshwater wetlands. Watercourse channels were typically absent or poorly defined within these wetlands. Water depths were shallow (approximately 0.2m) and the substrate comprised of mud, with a high proportion of organic matter. During wet weather periods, the water table can be at or near the surface, forming sheet flow across the wetland.
- Lower reaches of floodplain watercourses – Several watercourses (typically with a defined channel) intersected and drained the floodplain. These watercourses appear to be fed by both groundwater and surface water, although their hydrology is not well understood. These watercourses had low mud banks, and water depths were typically shallow (1m or less).

[13] Aquatic plants that grows in or near water

Photo credit: WGJV

Figure 9.33
Low gradient floodplain watercourses, Bobul Creek at Bobul Xing

Photo credit: WGJV

Figure 9.34
Unconfined, turbid major river systems, Watut River at Maralina

Photo credit: WGJV

Figure 9.35
Unconfined, turbid major river systems, Watut River at Uruf

This ecosystem type consists predominantly of pools or slow moving waters/glide habitat; however, some run and riffle habitat is present in the upper reaches of the Ngomang, Mari and Boganchong creeks. Snags, other woody debris, leaf litter, trailing vegetation and trailing roots are abundant at most sites, providing important micro-habitats for aquatic macroinvertebrates and fish. With the exception of Bavaga River site 6b[14], (see Figure 9.32) aquatic macrophytes were not abundant during survey, most likely due to high flows (which occur during flood events), high canopy cover and (in places) high turbidity.

9.6.1.1.3. Unconfined, Turbid Major River Systems

The Lower Watut River is located in a broad floodplain and has unconfined channels. In places, the river consists of multiple braided channels that are highly unstable, and subject to shifts in position of the thalweg[15]. The river also forms a continuous meandering channel that is highly unstable, migrating across the width of the floodplain over time.

The Watut River has an extensive floodplain and in-channel sediment deposits, is highly turbid, deep in areas (up to 4.5m), and consists mostly of pools and runs (refer to Figure 9.34 and Figure 9.35). Riffle-pool sequences can occur in shallow areas, but are not dominant meso-habitat features.

Aquatic macrophytes are not well represented in the Lower Watut River, most likely due to a combination of high turbidity, unstable substrates and high water depth. Shoals are well developed, and small riffles can occur in association with these sediment deposits. Substrates vary depending on channel form, and include gravel, sands and muds.

9.6.1.1.4. Oxbow Lakes

Oxbow lakes form where meander bends have been cut-off from the main channel. Several large oxbow lakes occur on the Watut River floodplain with examples shown in Figure 9.32, Figure 9.36 and Figure 9.37. While the ecological character can vary markedly among oxbow lakes, the common characteristics include:

- Substrates comprised of silt, clay and sand deposits, often with a high proportion of organic matter.
- High proportion of aquatic macrophytes.
- No to low flows in the lagoon proper but streams (tie-channels) can link the lagoons to the main channel and the floodplain, and form an important corridor for fauna movement.
- High groundcover along the fringes of the lagoon.

Aquatic macrophytes were present at the oxbow lake sites surveyed, with assemblages comprising submerged, emergent and floating growth forms. Aquatic macrophyte cover was extensive, particularly submerged macrophytes, which had up to 100% cover over large sections of both Uruf and Bali oxbows. Trailing vegetation cover was also high at the oxbow lake sites.

[14] Site 6b is a groundwater-fed wetland site which discharges into Bavaga River at the Bavaga River 6 sample location
[15] This is the deepest part of the channel where the main current flows.

Figure 9.36
Oxbow lakes at sites Bali Oxbow

Figure 9.37
Oxbow lakes at Uruf Oxbow

9.6.1.1.5. Ecosystem Representativeness and Distribution

The largest rivers in PNG are the Fly and Sepik (both longer than 1,000km), Purari (longer than 470km), Markham (180km) and Watut (157km) rivers (Osborne, 1987)[16]. All of these rivers have an extensive network of tributaries not included in these river lengths.

Riverine systems within PNG have not been mapped in their entirety, so it is not possible to determine their extent relative to IUCN criterion.

PNG has high rainfall (and river discharges) and due to its mountainous topography, rivers tend to have high velocities in their upper reaches (Osborne, 1987). The types and combination of riverine ecosystem types found in the Watut River catchment are characteristic and representative of those found elsewhere in PNG and the tropics worldwide.

The Lower Watut River has a broad floodplain containing a range of wetland types. The most extensive of these are lowland freshwater swamps (forested wetlands) and to a lesser extent marshes and lakes. The floodplain wetland types occurring along the Lower Watut River are well represented throughout PNG. In 1972 and 2002, it was estimated that the extent of swamp forest in PNG was approximately 3.4 million hectares (ha), remaining stable over time (Shearman et al., 2008). Lowland freshwater wooded and herbaceous swamps (e.g., marshes) represented 11% of PNG land area in 1976 (refer to Table 9.15) and occur throughout the country, with the largest occurring in the Sepik and Fly river basins and the numerous river systems discharging into the Papuan Gulf (Kikori, Turama, Purari, Vailala rivers) (Paijmans, 1976). Osborne (1987) identified the top 20 major freshwater wetlands in PNG, which included the Markham River but not the Watut River (refer to Figure 9.38).

Table 9.15: Percentage of PNG land area by ecosystem type

Ecosystem Type	PNG Land Area (%)
Coastal beach ridges and flats	0.5
Coastal saline and brackish swamps	1.5
Lowland freshwater swamps	11.0
Lowland alluvial plains and fans	15.0
Foothills and mountains below 1,000m above sea level	43.0
Lower montane zone, 1,000 to 3,000m above sea level	25.0
Upper montane zone, 3,000 to 4,000m above sea level	4.0

Source: Paijmans (1976)

Chambers (1987) mapped freshwater lakes with a surface area greater than 0.1ha within PNG and a total of 5,383 lakes were recorded. These lakes occurred at a range of altitudes from sea level to over 4,000m but most were situated below 40m in the floodplains of the Fly, Sepik and Aramia rivers. The combined area of lakes in PNG was estimated as 229,600ha, or 0.5% of the land area of PNG (Chambers, 1987)[17].

Four hundred and forty-three lakes were mapped in the northern PNG[18] region, which included 93 lakes in the Morobe Province. On this basis, floodplain lakes are considered to be a well-represented ecosystem type at a national and provincial scale.

---

[16] As noted in Section 9.2.1, Pal et al. (2012) used a different calculation method for watercourse length and determined a length of approximately 224km for the Watut River
[17] This figure underestimates the total area as some photo imagery was collected during the dry season when lakes were dry
[18] Consisted of Sandaun (West Sepik), East Sepik, Madang, Morobe and Northern provinces

Source:
WGJV: 532-1005-EN-REP-0004-1.10, Figure 10.7 (Osborn, 1987)

coffey
A TETRA TECH COMPANY

Date:	30.11.2017
Project:	754-ENAUABTF100520DD
File Name:	0520DD_10_F09.02_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Major wetland systems in PNG

Figure No: **9.38**

INDD Reference: 0520DD_10_GRA030.indd_2

The broad aquatic ecosystem types found in the Lower Watut River catchment are well represented throughout PNG. Lowland freshwater wetlands and lakes would not satisfy the Critically Endangered or Endangered classification in accordance with IUCN Criteria. Lotic ecosystem types are also well represented throughout PNG, and would not satisfy a Critically Endangered or Endangered classification on the basis of rarity.

9.6.1.1.6. Ecosystem Condition and Loss

There is little quantitative data describing the loss of aquatic habitat types in PNG. Shearman et al. (2008) found that the swamp forest extent remained stable over the period 1972 to 2002, which was attributed to the forest's inaccessibility to mechanised logging and absence of floodplain drainage for agriculture. Nonetheless, Shearman et al. (2008) note that this forest type may be sensitive to broad-scale mining impacts, such as occurred along the Fly River downstream of the Ok Tedi Mine as a result of the overbank deposition of mine tailings and waste rock and subsequent changed flooding patterns on the floodplains.

Due to the low number of village settlements, and therefore low level of associated disturbance such as clearing of vegetation and establishment of gardens, in the Lower Watut River area, aquatic ecosystems in PNG are relatively intact. Key threatening processes include:

- Sedimentation – Polhemus et al. (2004) and Nicholls (2004) note that large scale logging, development of oil palm plantations and mining can lead to sedimentation and aquatic habitat loss, and represent key threats to aquatic ecosystems in PNG. The effects of sedimentation due to mining and landslips in the Watut River catchment are well documented and include changes to downstream hydrology through the alteration of bed morphology, river alignment and water levels (Nicholls, 2004).
- Water quality impacts due to alluvial mining – Polhemus et al. (2004) note that artisanal mining leads to the accumulation of heavy metals (particularly mercury) in aquatic ecosystems, resulting in toxic effects to biota. This type of mining is widespread throughout PNG, including in the Watut River catchment.
- Introduced fish species – The Lower Watut River catchment has a large number of introduced fish species, which is a widespread issue throughout PNG (Polhemus et al., 2004). Introduced species can directly alter habitats (e.g., carp), or negatively affect native flora and fauna thereby leading to aquatic ecosystem degradation. This is considered a key threatening process in the Watut River catchment, particularly in oxbow lakes where introduced species are highly abundant.
- River flow regulation – The Watut River is not flow-regulated, with only small-scale extraction occurring in the catchment for drinking water and mining purposes.

With the exception of swamp forest, insufficient quantitative data is available to directly assess whether PNG aquatic ecosystems are threatened in accordance with the IUCN criteria described in Section 9.1.2.3. There is no evidence to suggest significant declines in the distribution and extent of aquatic ecosystems have occurred in PNG, although aquatic ecosystem condition is clearly threatened by a range of activities. For example, land clearing, construction of roads, logging, mining activities and natural landslides contribute increased sediment loads and/or contaminants to the environment.

9.6.1.2. Lower Markham River Floodplain

As mentioned above, the survey effort for the Lower Markham River floodplain was more targeted toward specific aspects compared to the Lower Watut River catchment. High level riparian vegetation condition, stream bed composition and instream habitat assessments were completed for the Lower Markham River floodplain.

9.6.1.2.1. Riparian Vegetation Condition

Riparian habitat observations were made in the vicinity of the Infrastructure Corridor on the Lower Markham River floodplain. At all sites, riparian habitat had a medium to high level of modification.

Due to the large population in and around Lae, the riparian habitat was largely modified at most of the sites visited in the form of gardens, settlements and roads. Vegetation had been cleared in some areas to accommodate other infrastructure, such as overhead power lines. The riparian zone along the lower reach of the Markham River was cleared due to the presence of a road.

Erosion was naturally high across the survey area and most streams had areas with exposed banks and actively eroding edges, most evident at sites in Pumpkin Creek and the Markham River.

9.6.1.2.2. Stream Bed Composition and Instream Habitat

Watercourses surveyed within the Lower Markham River floodplain were lower-gradient and slower-flowing. These streams were typically swampy, with beds and banks dominated by muddy clays and silts.

The lower-energy streams allow finer particles such as silts and clays to settle on the beds and banks. The domination of fine sediments combined with the lack of pebbles, cobbles and boulders, results in a lack of interstitial spaces for benthic macroinvertebrates to inhabit. The only exception was S/Site 8 on the Markham River, where cobbles and boulders were noted along the bed and banks, and as such this river provides benthic habitat suitable for macroinvertebrates.

The lack of coarser substrate, coupled with the lower gradient in these streams, meant there were few riffles.

The lower-energy streams provide conditions more conducive to aquatic plant growth, as the beds are not highly mobile and this allows plant roots to establish themselves in the stream bed. Aquatic plants were abundant, typically along the stream edges, at S/Site 1, S/Site 3, S/Site 4 and S/Site 9.

Woody debris were present at S/Site 1, S/Site 2, S/Site 4, S/Site 5, S/Site 7 and S/Site 9, as the streams lack the typical high energies required to transport decaying logs, sticks and branches.

9.6.2. Aquatic Flora

Aquatic flora results for the Lower Watut River and the Lower Markham River floodplain are presented below.

9.6.2.1. Lower Watut River Catchment

9.6.2.1.1. Aquatic Macrophyte Assemblages

Field survey in the Lower Watut River catchment identified 12 native and one introduced aquatic macrophyte species at the Watut River oxbow lake sites (Uruf Oxbow and Bali Oxbow) and within pool habitat at Bavaga River site 6b (Table 9.16). A range of riparian species were also present in moist littoral areas, with sago palm and various pandanus species being particularly abundant. These riparian forested wetlands were common throughout the Watut River floodplain and typically formed in the lower reaches of the Mari, Chaunong and Boganchong creeks and the southern end of the floodplain near Wori village.

Table 9.16: Aquatic macrophyte species recorded within the Lower Watut River catchment

Species Name	Common Name	Growth Form	Origin
Typhaceae			
Typha orientalis	Broad-leaved Cumbungi	Emergent	Native
Cyperaceae			
c.f Scirpus grossus	Giant bulrush	Emergent	Native
Ceratophyllaceae			
Ceratophyllum sp.	Hornwort	Submerged (rooted)	Native
Araceae			
Pistia stratiotes	Water lettuce	Floating or rooted	Exotic (highly invasive)
c.f Lemna perpusilla	Minute duckweed	Floating	Native
Spirodella polyrhiza	Common duckweed	Floating	Native
Hydrocharitaceae			
c.f Hydrocharis dubia	Frogbit	Floating or rooted	Native
Ottelia alismoides	Duck-lettuce	Rooted (submerged or emergent)	Native
Lentibulariaceae			
Utricularia sp.	Bladderwort	Floating or rooted (submerged)	Native
Nymphaeaceae			
Nymphaea sp.	Water lily	Floating or rooted	Native
Aponogetonaceae			
c.f. Aponogeton sp.	Aponogeton	Submerged (rooted)	Native
Lemnaceae			
Spirodela polyrhiza	Greater duckweed	Floating	Native
c.f. Lemna minor	Common duckweed	Floating	Native

Bali Oxbow had a high cover of aquatic macrophytes, with hornwort (*Ceratophyllum* sp.) the dominant submergent macrophyte, and giant bulrush (*c.f Scirpus grossus*) and various grass species dominating the littoral zone. The submerged macrophyte, hornwort, was also highly abundant at Uruf Oxbow and Bavaga River 6, forming dense meadows across the lagoon. Floating macrophytes were also common and included water lettuce (*Pistia stratiotes*), minute duckweed (*c.f Lemna perpusilla*), water lily (*Nymphaea* sp.) and frogbit (*c.f Hydrocharis dubia*).

The invasive water hyacinth (*Eichhornia crassipes*) was not observed in the field survey or by BMT WBM in Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River. The closely related water lettuce, which is also an introduced invasive species, was recorded at Uruf Oxbow. Field survey identified that local villagers collect plants for consumption either in slower-flowing watercourses or in off-river waterbodies adjacent to the Watut River.

Aquatic macrophyte communities were poorly developed within watercourses, which is consistent with the findings of previous investigations (see Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River). It was suggested by BMT WBM that the absence of aquatic macrophytes was a response to the following factors:

- Shading of watercourses – The dense canopy cover of riparian vegetation and narrow width of many watercourses results in a high degree of shading. The low light provides sub-optimal habitat conditions for most instream vegetation species.
- Substrate stability and flows – Most of the Lower Watut River catchment watercourses are flashy[19], and experience pulsed flows in response to rainfall events. High flow velocities can limit the development of aquatic macrophyte communities through substrate scour and direct physiological damage to plants.
- High turbidity – The Lower Watut River has high turbidity and low light conditions preventing the establishment of submerged aquatic macrophyte communities.

No aquatic macrophyte species of conservation significance were identified during field survey. Four species of aquatic macrophytes of conservation significance are known to occur in northern PNG (*Isoetes habbemensis, I. neoguineensis*, *I. stevensii* and *I. frigida*). These species are endemic to northern PNG but none have been evaluated under the IUCN Red List. Three of these species (*I. habbemensis, I. neoguineensis and I.stevensii*) appear to be confined to mountainous areas (greater than 3,200m) and are, therefore, unlikely to occur within the Lower Watut River catchment. A single specimen of *I. frigida* was recorded from a small lake near Mt Saruwaged (approximately 50km north of Lae). Further survey may find this species has a greater distribution throughout the Morobe Province than current data suggests.

9.6.2.1.2. Diatom Flora

Field survey investigations in the Lower Watut River catchment indicate that diatom samples from the Lower Watut River catchment are largely dominated by generalist taxa, more typically associated with low salinity and neutral to alkaline pH, and which are tolerant of elevated nutrient concentrations. Water quality monitoring data (summarised in Section 9.4) does not indicate that watercourses in this area have high nutrient concentrations.

Absence of diatom valve deformities suggests that watercourses in the Lower Watut River catchment do not currently experience high levels of metal contamination, which is consistent with metal bioavailability investigations (described in Section 9.4).

There is little differentiation in assemblages based on ecosystem type and considerable similarity in assemblage structure among sites.

[19] Water levels rise and fall rapidly

9.6.2.1.3. Primary Productivity

Primary producers (autotrophs[20]) form the base of every food web. Carbon is produced by autotrophs, which is then cycled through food webs by consumers and ultimately decomposed by bacteria. Primary producers present Lower Watut River catchment include:

- Aquatic macrophytes
- Algae including benthic microalgae and phytoplankton
- Riparian vegetation as described in Chapter 8, Physical and Biological Environment Characterisation

Stable isotope analysis undertaken in the Fly River found that algae (phytoplankton/periphyton) were an important carbon source to aquatic ecosystems, despite high turbidity levels (Bunn et al., 1999). Bunn et al. (1999) estimated that algae-derived carbon supported approximately 40% (riverine site) to 70% (floodplain lagoon site) of fish standing stock in the Fly River. Bunn et al. (1999) also found that terrestrial sources were an important source of carbon to aquatic ecosystems of the Fly River, and were particularly important to freshwater prawns, *Macrobrachium* spp..

The ecology of phytoplankton and benthic microalgae has not been examined in detail within the Lower Watut River catchment to date. Semi-quantitative investigations undertaken found the relative abundance (and richness) of littoral zone benthic microalgae was similar between streams, oxbow lakes and the Lower Watut River, despite differences in turbidity and riparian shading among aquatic ecosystem types. Algae productivity and biomass is likely to be significantly light-limited in deeper waters of turbid water environs (i.e., Lower Watut River and some tributary watercourses), but in shallow waters it is likely that benthic microalgae represents an important source of carbon to aquatic food webs.

Terrestrial vegetation within the Lower Watut River area is largely undisturbed. An intact riparian zone forms a dense canopy over many of the smaller watercourses. Floodplain and upland vegetation is also abundant. Riparian and floodplain vegetation is expected to represent an important carbon source to aquatic ecosystems in the Lower Watut River catchment, but like other primary producers, its relative importance to aquatic ecosystem functioning has not been quantified to date.

Investigations found that high and moderate gradient tributary watercourses were devoid of aquatic macrophytes, whereas floodplain lagoons and low gradient watercourses in the Bavaga River catchment had an abundant aquatic macrophyte flora. It is likely that aquatic macrophytes represent a locally important source of carbon in floodplain lagoons, which may be exported to the Watut River during flood events.

For the purposes of this assessment, it has been conservatively assumed that littoral zone algae in turbid water environments and both littoral and sub-littoral algae in clear water environments (lagoons, several tributary watercourses) represent an important source of carbon to aquatic ecosystems. Many algae species are known to be particularly sensitive to elevated metals (particularly copper) and low light (i.e., high TSS concentrations).

9.6.2.2. Lower Markham River floodplain

The lower-energy streams in the Lower Markham River floodplain provide conditions conducive to aquatic plant growth, as the streambeds are not highly mobile, thereby allowing plant roots to establish themselves in the stream bed. Aquatic plants and woody debris were abundant (typically along the stream edges) at sites in Busanem Creek,

[20] An organism that can produce its own food using light, water, carbon dioxide, or other chemicals

S/Site 1; Buambub Creek, S/Site 3; Pumpkin Creek, S/Site 4 and at Maiwara Creek, S/Site 9.

9.6.3. Aquatic Fauna

Aquatic fauna data including aquatic macroinvertebrate assemblages, chironomid deformities, fish assemblages, species of conservation and fisheries significance, semi-aquatic reptiles and fish tissue sample analyses for the Lower Watut River catchment are described in the sections below. No aquatic fauna data was collected for the Lower Markham River floodplain.

9.6.3.1. Aquatic Macroinvertebrate Assemblages

Analysis of sampling results indicated that aquatic macroinvertebrate assemblages in the Watut River and tributary watercourses were not consistently different from each other, but there was great variability in assemblage among sites. Most taxa recorded were habitat generalists, however several taxa appear to be restricted to one ecosystem type or meso-habitat (e.g., riffle versus edge) type.

Three PNG aquatic invertebrate species have been classified as either threatened or Near Threatened on the IUCN Red List. Given their known areas of occupancy, they are considered unlikely to occur in the Lower Watut River catchment. No aquatic invertebrates listed under other conservation schemes or legislation are known, or are likely to occur, in the Lower Watut River catchment. No endemic aquatic macroinvertebrate species are known or are likely to be restricted to the Watut River catchment; however, it is possible that the aquatic habitats in this area do support endemic aquatic insect species.

There is currently a lack of information on the distribution, ecology and systematics of PNG's macroinvertebrate fauna. With additional investigation it is possible that other endemic species would be found, and that some range-restricted species could occur over a much wider area than presently thought.

9.6.3.2. Chironomid Deformities

Chironomid deformities were analysed at 18 sites, of which 13 did not contain any deformed specimens and only 11 of a total of 703 specimens were deformed. Of the five sites where deformities occurred (refer to Figure 9.1):

- Two were in reference catchments (Waime (Gingen) River upstream and Denti Creek).
- One was in a moderate gradient tributary watercourse flowing into the Watut River floodplain (Ziriruk Creek).
- Two were in oxbow lakes (Bali and Uruf oxbows) where it is expected that the build-up of depositional sediments would be greatest.

The overall percentage of deformities was 1.6%. This value is similar to the frequency reported in uncontaminated field sites or sediments prior to widespread pollution of aquatic habitats (Warwick, 1980; Wiederholm, 1984; Burt et al., 2003).

9.6.3.3. Fish Assemblages

During sampling undertaken in March 2015, 1,156 individual fish from 28 species were captured. The catch comprised 22 native and six introduced (non-native) fish species. The most abundant fish species (by proportion of catch) overall were:

- Mosquitofish (*Gambusia holbrooki*) (non-native) (36% of catch, four sites)
- New Guinea rainbowfish (*Melanotaenia affinis*) (25% of catch, 12 sites)

- Golden mahseer (*Tor putitora*) (non-native) (24% of catch, ten sites)
- Swordtail (*Xiphophorus helleri*) (non-native) (24% of catch, eight sites)
- Sepik rainbowfish (*Glossolepis kabia*) (19% of catch, three sites)
- Tilapia (*Oreochromis mossambicus*) (non-native) (13% of catch, four sites)
- Yellowbelly gudgeon (*Mogurnda nesolepis*) (11% of catch, seven sites)

Additional sampling was conducted in June 2015 on the Lower Watut River floodplain within moderate gradient tributary watercourses and low gradient floodplain ecosystem types. Nine native species and two introduced species were recorded in this survey. All species recorded during this survey were also found within the March 2015 survey. The most abundant species recorded were New Guinea rainbowfish (approximately 70% of the catch), swordtail (non-native) (7% of the catch) and yellowbelly gudgeon (approximately 6% of the catch).

Fish sampling conducted in December 2016 focused on the Bavaga River catchment within high to moderate gradient tributary and low gradient floodplain ecosystem types. Fourteen native species and three introduced species were recorded, with these species being consistent with those captured in previous surveys. The most abundant species recorded were New Guinea rainbowfish (approximately 41% of the catch), yellowbelly gudgeon (17% of the catch), white water goby (*Glossogobius torrentis*) (15% of the catch) and barred rainbowfish (*Chilatherina fasciata*) (12% of the catch).

Analysis of sampling results indicated no consistent differences in the number of taxa present (species richness) among ecosystem types; however, the proportion of introduced fish species was generally lower in tributary and floodplain watercourses compared to oxbow lakes and Watut River sites (i.e., turbid major river). There appears to have been a fundamental change in fish community structure in the Lower Watut River catchment over time, with introduced fish now the dominant taxa in many watercourses and off-river waterbodies (Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River). Further, it is possible that the changes in abundance of some native species, including tapiroid grunter (*Mesopristes cancellatus*) and Idenburg's tandan (*Neosilurus idenburgi*) may be related to the dominance of introduced species.

9.6.3.4. Threatened and Endemic Species

Previous surveys in the Watut River catchment have recorded only one threatened species listed on the IUCN Red List, i.e., the Critically Endangered freshwater sawfish (*Pristis pristis*, formerly *Pristis microdon*). Adult sawfish breed in estuarine or marine ecosystem types but use freshwater reaches as nursery grounds (Thorburn et al., 2007). The recorded sample was collected in the Lower Watut River below the Wafi River junction (Gwyther, 1988) but has not been recorded in subsequent surveys between 2007 and 2015. Anecdotal evidence collected by BMT WBM field staff suggests that locals have historically seen this species in the Markham River (in 2005, Dave Bola, WGJV pers comm. May 2015) and the Lower Watut River in the vicinity of Maus Watut (dates unknown); however, it is unknown whether this species still occurs in the Watut River. It is unlikely that the freshwater sawfish would venture into fast flowing tributary watercourses due to unfavourable habitat conditions, i.e., because it has a preference for large deep rivers.

The bulolo rainbowfish (*Chilatherina bulolo*), which is classified by the IUCN as Data Deficient (i.e., further information is required to determine its population status), was collected in field survey of the Lower Watut River near Marilina (just below the Wafi River junction) and the Bavaga River catchment and has previously been collected in the Bulolo River and upper Watut River (Powell and Powell, 2000). While this species has been collected throughout the upper Watut River and associated tributaries, it has only recently been found in the Lower Watut River area. At a regional scale, this species occurs in both the Markham and Ramu river basins (i.e., over a wide geographic range), but appears to have a fragmented distribution within these basins.

Fish species that are endemic to northern PNG catchments with confirmed occurrence in the Lower Watut River catchment and tributaries (in the Lower Watut River catchment) are as follows:

- Bulolo rainbowfish as described above.
- Highlands rainbowfish (*Chilatherina campsi*), which has a wide geographic distribution, and has been recorded in the Markham, Ramu and Sepik river systems. This species favours small tributary watercourses, as found in the Mine Area, and was recorded at Bali Oxbow in field survey.
- Sepik rainbowfish, which has a wide geographic distribution, and has been recorded in the Markham, Ramu and Sepik, river systems. The species is known to occur within still-to-slow-flowing water in floodplain lakes and watercourses. This species was collected in the Waime River, Uruf Oxbow and in high abundance at Bali Oxbow during field survey.
- White water goby, which has a wide geographical distribution, and has been recorded in the Sepik, Ramu, Watut and Markham river systems. This species was commonly found through field survey and was recorded in the Waime River, extensively throughout the Bavaga River catchment and throughout the Lower Watut River floodplain and local watercourses flowing into the floodplain, including Boganchong and Wassing creeks.
- Sepik grunter (*Hephaestus transmontanus*), which has a wide geographical distribution, and has been recorded in the Sepik, Ramu, Watut and Markham river systems. This species was recorded through field survey of the Bavaga and Waime rivers.

In the broader Watut River catchment, the wau gudgeon (*Allomogurnda flavimarginata*), has been collected in small numbers from small creeks near Wau in the upper Watut River catchment on the Bulolo River (Allen, 1991, BMT WBM personal observations 2015). Given this very small distribution, it is considered to be endemic to the Watut River catchment. This species has not been recorded downstream of Wau, and its occurrence within the Lower Watut River catchment is considered possible, but unlikely. The spotted rainbowfish (*Glossolepis maculosus*) is restricted to the Markham and Ramu river systems (Allen, 1991) and while it has not been recorded in the Watut River to date, it is considered possible that this species occurs in watercourses in the Lower Watut River catchment.

The Lower Watut River catchment is not considered likely to support a significant proportion of the population of any endemic fish species.

Three aquatic invertebrate species have been included on the IUCN Red List as either Vulnerable or Near Threatened in PNG: freshwater crayfish (*Cherax papuanus)*; and two dragonflies, *Diplacina arsinoe* and *Idiocnemis adelbertensis* (IUCN, 2015a). None of these species are known to occur in the Lower Watut River catchment. The aquatic macroinvertebrate assemblage recorded through previous surveys contained a wide variety of taxa, though none that may be considered of conservation significance.

9.6.3.5. Species of Fisheries Significance

Most fish species, including small-bodied species, are important food species for local villagers. Many of the non-native fish species recorded in the Lower Watut River catchment (e.g., golden mahseer, tilapia and carp) were introduced into the Watut River as a food source. No significant commercial fisheries operate in the Watut River catchment.

9.6.3.6. Semi-Aquatic Reptiles

The freshwater turtle fauna of PNG are poorly understood (Georges et al., 2006) and there is little information on the geographic distribution of most species. The northern PNG turtle fauna is depauperate, and comprises two species: Schultze's snapping turtle (*Elseya schultzei*) which was captured in the Mine Area during field survey at Uruf Oxbow (refer to Figure 9.39 and Figure 9.40) and Northern New Guinea giant softshell turtle (*Pelochelys signifera*) which may occur in the Lower Watut River based on habitat conditions identified in the area (Woxvold, 2012).

Six freshwater turtles found in PNG are listed as threatened under the IUCN Red List. None have been recorded in the Markham River basin, but one, the Northern New Guinea giant softshell turtle, may occur. This species was recently (in March 2018) assessed as Vulnerable under the IUCN Red List Criteria, but at the time of writing this assessment was not published. Eight of the freshwater turtle species known to occur in New Guinea are endemic to the island. All of these species have a widespread geographic distribution, and none are restricted to a small number of catchments.

Two crocodile species occur in PNG: the saltwater crocodile (*Crocodylus porosus*) and New Guinea crocodile (*C. novaeguineae*). Crocodiles were recorded as incidental sightings during the 2015 field survey transit of the Lower Watut River, and they are considered likely to also occur in the Lower Watut River floodplain area; however, they are unlikely to occur in any high velocity (high gradient) tributary watercourses in the Lower Watut River catchment. The two crocodile species are listed by the IUCN as least concern (i.e., not threatened or Near Threatened). The New Guinea crocodile is endemic to PNG, but is widespread throughout its range.

The Lower Watut River catchment is not known to support outstanding biodiversity values from an aquatic reptile perspective. This area is not known to support a significant proportion of the population of any species, or provide critical functions required for the long-term survival of threatened or otherwise conservation-dependent species.

9.6.3.7. Trace Metal/Metalloids in Tissue Samples

Consistent with previous studies (Appendix G, Surface Water and Freshwater Aquatic Ecology Characterisation - Mine Area to Markham River), zinc (prawns and fish) and copper (prawn) metal burdens exceeded the ANZFA General Expected Levels (GEL)[21]. All other metals and metalloids had concentrations below relevant guidelines/standards.

[21] NB the GEL does not represent a guideline for assessing health risk

Photo credit: WGJV

Figure 9.39
Schultze's snapping turtle captured at Uruf Oxbow

Photo credit: WGJV

Figure 9.40
Underbelly of Schultze's snapping turtle captured at Uruf Oxbow

For zinc, the ANZFA 90th percentile GEL (fish (15 milligrams per kilograms (mg/kg)) and shellfish (40mg/kg)) was exceeded as follows:

- Most New Guinea rainbowfish samples (five of the six sites where it was sampled)
- Tilapia (two of five samples at Bali Oxbow)
- Golden mahseer (one sample at Nambonga Creek, one sample at Pekumbe, five samples at Maralina on the Watut River)
- Gjellerup's mouth almighty (*Glossamia gjellerupi*) (one sample at Bavaga River 5 (Downstream))
- Snakehead gudgeon (*Ophidieleotris aporos*) (two samples at Chaunong Creek Upstream, five samples at Uruf Oxbow)
- Walking catfish (*Clarias batrachus*) (one sample at Womul Creek)
- Prawn cephalothorax (two of five samples at Uruf on the Watut River)

Copper concentrations in all prawn cephalothorax samples collected at Uruf on the Watut River exceeded the ANZFA 90th percentile GEL (shellfish (20mg/kg)); however, for the hind body samples there were no exceedances. Copper, like several other metals, has a key role in maintaining physiological processes in freshwater prawns (in trace quantities), and can be readily uptaken from the ambient environment (Shuhaimi-Othman et al., 2006).

The analysis demonstrated clear differences in the concentrations of certain metals among different taxa. In particular, all rainbowfish had elevated concentrations of zinc (and to a lesser extent copper), while the *Macrobrachium* prawns had elevated concentrations of zinc and copper. Other taxa such as tilapia tended to have lower metal concentrations. These differences may partly reflect differences in the metal regulation, diet, habitat usage and mobility among species (and individuals within species) (Rainbow, 2002).

9.6.3.8. Areas of High Biodiversity Significance (Lower Watut River catchment)

As described in Section 9.1.2.3.2, all habitat types were assumed to be natural habitat except where it has been subject to substantial modifications that prevent the functioning of ecosystem processes and/or the support of viable populations of native species. While much of the Lower Watut River catchment has been disturbed through the introduction of non-native fish species (e.g., tilapia, mosquitofish) resulting in changes to population assemblages, this has not removed the natural values of these systems. For this reason, all four habitat types in the Lower Watut River catchment (refer to Section 9.6.1.1) are considered to be 'natural habitat' for the purposes of IFC PS 6. Of these habitat types, none are considered to be 'critical habitat' in accordance with PS 6 criteria, as discussed below.

9.6.3.8.1. Criterion 1: Critically Endangered and Endangered Species

The only Critically Endangered and Endangered aquatic species that could occur within the habitats of the Lower Watut River catchment is the freshwater sawfish. No habitat within this area can be considered as supporting regular occurrences of this species, as freshwater sawfish is known only from a single historical record (from the 1980s, see Section 9.6.3.3).

9.6.3.8.2. Criterion 2: Endemic and Restricted-Range Species

A number of species that occur or may occur in the Lower Watut River catchment are considered endemic to the island of New Guinea (i.e., Papua and PNG), namely the bulolo rainbowfish, wau gudgeon, highlands rainbowfish, sepik rainbowfish, spotted rainbowfish, papuan black bass (*Lutjanus goldei*), white water goby, sepik grunter, Schultze's snapping turtle, Northern New Guinea giant softshell turtle and New Guinea crocodile.

Of these species, none is expected to have a population greater than 1% within a discrete management unit that overlaps with the Mine Area or Infrastructure Corridor to Zifasing for the following reasons:

- Northern New Guinea giant softshell turtle, spotted rainbowfish and papuan black bass have not been recorded in the Watut River catchment.
- While the upper Watut River may support greater than 1% of the global population of bulolo rainbowfish and wau gudgeon, this is considered to be a separate discrete management unit (and population) from the habitats in the Lower Watut River catchment. These habitats do not support regular occurrences of either of these species.
- There is insufficient evidence to suggest populations of New Guinea crocodile and Schultze's snapping turtle recorded in the Watut River catchment represent more than 1% of the global population.
- While the global populations of sepik rainbowfish, highlands rainbowfish, white water goby and sepik grunter are not known, these species are known from multiple, large catchments in PNG. The Lower Watut River floodplain is expected to be a discrete management unit for these species (based on habitat preferences) thereby representing an area that is less than 1% of the known area of distribution for these species. Given the widespread distribution of these species within the catchments they have been found in, it is unlikely that the Lower Watut River catchment contains habitat supporting greater than 1% of a global population.

Therefore, there is no critical habitat in the Lower Watut River catchment on the basis of Criterion 2.

9.6.3.8.3. Criterion 3: Migratory and Congregatory Species

The only migratory species known from the Lower Watut River catchment is the saltwater crocodile. No habitat in the Lower Watut River is known or expected to sustain greater than 1% of the population of this species at any one time. No congregatory species are known to occur in the area. Therefore, there is no critical habitat in the Lower Watut River catchment on the basis of Criterion 3.

9.6.3.8.4. Criterion 4: Highly Threatened and/or Unique Ecosystems

No assessments have been conducted to date for wetland/aquatic ecosystems on the island of New Guinea (i.e., Papua and PNG) against the criteria of the IUCN Red List of Ecosystems. At present, there is no quantitative or qualitative evidence to suggest any particular aquatic ecosystem type in the Lower Watut River catchment presently qualifies as highly threatened and/or unique. Therefore, there is no critical habitat in the Lower Watut River catchment on the basis of Criterion 4.

9.6.3.8.5. Criterion 5: Key Evolutionary Processes

No previous studies have been conducted of the Lower Watut River catchment in relation to the identification of unique evolutionary processes. As a result, there is little evidence available to suggest any of the habitats of the area represent critical habitat on the grounds of key evolutionary processes. Reproductive isolation is a key mechanism driving speciation, a key evolutionary process (Rosenzweig, 1995). As discussed in Section 9.2.1, the Lower Watut River floodplain regularly experiences overland flows and flooding, which promotes inter-connectivity among aquatic ecosystem types in the floodplain (i.e., floodplain watercourses, oxbow lakes, Watut River channel), and leads to rapid ongoing geomorphological changes. Therefore, there is no critical habitat in the Lower Watut River catchment on the basis of Criterion 5.

9.7. References

Allen, GR. 1991. *Field Guide to the Freshwater Fishes of New Guinea*. Publication No. 9, Christensen Research Institute, Calendar Print Pty. Ltd., Singapore, p. 268.

ANZECC/ARMCANZ. 2000. Guidelines for fresh and marine water quality, Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand.

ANZFA. 2000. *Australia New Zealand Food Standards Code,* FSANZ, Canberra.

BAAM. 2017. *Terrestrial Flora and Fauna Baseline Assessment - Mine Area to Markham River, Wafi-Golpu Project*. Report prepared by BAAM Ecological Consultants.

Bird, GA. 1994. *Use of chironomid deformities to assess environmental degradation in the Yamaska River*, Quebec, *Environmental Monitoring and Assessment, no.* 30, pp.163-175.

Bunn, SE., Storey, AW., Tenakenai, C. 1999. *Energy sources supporting Fly River fish communities.* Unpublished report to Ok Tedi Mining Ltd. http://www.oktedi.com/reports/

Burt, J., Ciborowski, JJH., & Reynoldson, TB. 2003. *Baseline incidence of mouthpart deformities in Chironomidae (Diptera) from the Laurentian Great Lakes, Canada*, *Journal of Great Lakes Research*, no. 29, pp. 172-180.

Chambers, MR. 1987. *The freshwater lakes of Papua New Guinea: an inventory and limnological review*, *Journal of Tropical Ecology* no. 3, pp. 1-23.

Chessman, B., Gell, P., & Newall P. 2015. *Standard methods for sampling diatoms for the monitoring and assessment of streams,* University of Adelaide, Adelaide.

Coffey. 2012. *Environmental Inception Report Wafi-Golpu Advanced Exploration Project,* November 2012. Report prepared by Coffey Environments Australia Pty Ltd.

Office of Environment and Conservation. 2000. *Environmental Code of Practice Environmental Code of Practice for the Mining Industry,* Boroko, PNG.

DNRM. 2001. *Queensland Australian River Assessment System (AusRivAS): Sampling and processing manual*. Queensland Government Department of Natural Resources and Mines.

Dudgeon, D. 1994. The Influence of Riparian Vegetation on Macroinvertebrate Community Structure and Functional-Organization in 6 New-Guinea Streams. *Hydrobiologia* 294, 65-85.

EMPS. 1993. *Aquatic Resources Studies. Baseline Water Quality and Aquatic Resource Surveys of Wafi River,* Morobe District, PNG, Report prepared by Environmental Management Planning Services Pty Ltd for Minenco Pty Ltd.

ESAP. 2012. *Annual Report on the Hidden Valley Joint Venture, July 2011 - June 2012 (Report No. 1)*. Hidden Valley External Stakeholder Advisory Panel.

Georges, A., Guarino, F., & Bito, B. 2006. *Freshwater turtles of the TransFly region of Papua New Guinea – notes on diversity, distribution, reproduction, harvest and trade*. *Wildlife Research*, no. 33, pp. 373–384.

Gwyther, D. 1988. *Water use and Subsistence Fishery Investigation, Appendix 6, Hidden Valley Gold Project Draft Environmental Plan, Volume C Appendices, prepared for Hidden Valley Gold Pty Ltd*. 28 Clarendon Street, South Melbourne 3205, Australia, September 1988.

IFC. 2012. '*IFC Performance Standards on Environmental and Social Sustainability'*, Published by International Finance Corporation World Bank Group, January 2012.

IUCN. 2015a. *'IUCN Red List of Threatened Species'* (Version 2015.4), viewed 05 May 2015 <www.iucnredlist.org>. International Union for Conservation of Nature.

IUCN. 2015b. '*Habitats Classification Scheme'* (Version 3.1), viewed July 2015 <http://www.iucnredlist.org/technical-documents/classification-schemes/habitats-classification-scheme-ver3>. International Union for Conservation of Nature.

Mackay, N. J., 1955. Geological report on a reconnaissance of the Markham and Upper Ramu drainage systems, New Guinea. Records No. 1955/25. Bureau of Mineral Resources, Canberra, ACT.

Madden, C., Austin, A., & Suter, P. 1995. *Pollution monitoring using chironomid larvae: What is a deformity? In: 'Chironomids: From Genes to Ecosystems'*, (Ed. P Cranston), pp. 89-94. (CSIRO Publications: East Melbourne).

Nicholls, S. 2004. *The priority environmental concerns of Papua New Guinea, IWP-Pacific Technical Report (International Waters Project) no. 1*, South Pacific Regional Environment Programme, Apia.

Osbourne, PL. 1987. *A draft inventory of wetlands in Papua New Guinea, Department of Environment and Conservation*, Waigani, Papua New Guinea pp. 163.

Pack, RT., Tarborton, DG., Goodwin, CN., and Prasad, A. 2005. *SINMAP2 – Stability Approach to Terrain Stability Hazard Mapping*, Utah State University, Terratech Consulting Ltd, Canadian Forest Products & C. N. Goodwin Fluvial System Consulting.

Paijmans, K. 1976. New Guinea vegetation. Australian National University Press and Commonwealth Scientific and Industrial Research Organization. Canberra, ACT.

Pal, B., Samanta, S., & Pal, DK. 2012. *Morphometric and hydrological analysis and mapping for Watut watershed using remote sensing and GIS techniques*, International Journal of Advances in Engineering and Technology, vol. 2, no. 1, pp. 357-368.

Polhemus, D., & Allen, G. 2006. *Inland water ecosystems in Papua: classification, biota and threats. In: 'The Ecology of Papua'.* (Eds A Marshall and B Beehler) pp. 858-901, Tuttle Publishing: Singapore.

Polhemus, D., Englund, RA., & Allen, GR. 2004. *Freshwater biotas of New Guinea and nearby islands: Analysis of endemism, richness, and threats*, report for Conservation International.

Powell, JH., & Powell, RE. 2000. *Downstream ecological effects of mining development in the Watut River catchment, Markham Basin, Morobe District, Papua New Guinea*: a review, *Science in New Guinea* vol. 25, no. 1-3, pp. 74-115.

Rainbow, P.S. 2002. *Trace metal concentrations in aquatic invertebrates: why and so what*? Environmental Pollution, 120: 497–507.

Renagi, O., Ridd, P., and Stieglitz, T. 2010. *Quantifying the suspended sediment discharge to the ocean from the Markham River, Papua New Guinea.* Continental Shelf Research, 30 (9). pp. 1030-1041

Rosenzweig, M.L. 1995. *Species Diversity in Space and Time*. Cambridge University Press, Cambridge, UK.

Samanata, S., Koloa, C., Kumar Pal., D., and Palsamanta, B. 2016. Flood risk analysis in the lower part of the Markham River based on multi-criteria decision approach (MCDA). *Hydrology*, 2016, 3, 29.

Shearman, PL., Bryan, JE., Ash, J., Hunnam, P., Mackey, B., & Lokes, B. 2008. *The State of the Forests of Papua New Guinea, Mapping the extent and condition of forest cover and* *measuring the drivers of forest change in the period 1972-2002*, University of Papua New Guinea, 2008.

Shuhaimi-Othman, M., Ahmad Abas, S., Yap, SS., Maziati, M. 2006. *Bioaccumulation and Elimination of Copper and Lead by Freshwater Prawn Macrobrachium lanchesteri*. Journal of Biological Sciences, 6: 717-722.

Simpson, SL., Batley, GE., and Chariton, AA. 2013. *Revision of the ANZECC/ARMCANZ Sediment Quality Guidelines*, CSIRO Land and Water Science Report 08/07, prepared for Department of Sustainability, Environment, Water, Population and Communities

SKM. 2012a. *Wafi Golpu Prefeasibility Study Hydrology Report* (QN10190-0000-ESW-RP-E4-0003). Report prepared by Sinclair Knight Merz.

SKM. 2012b, *Wafi Golpu Prefeasibility Study Flooding Report* (QN10190-0000-ESW-RP-E4-0010). Report prepared by Sinclair Knight Merz.

SolvFit Ltd. 2010. *Water Quality Assessment Bulolo, Lower Watut and Markham Rivers*.

Ter Braak, CJF., & Prentice, IC. 1988. *A Theory of gradient analysis*, *Advances in Ecological Research*, vol. 18, pp. 271-317.

Thorburn, DC., Morgan, DL., Rowland, AJ., & Gill, HS. 2007. *Freshwater sawfish Pristis microdon* Latham, 1794 (Chondrichthyes: Pristidae) in the Kimberley region of Western Australia, *Zootaxa*, vol. 1471, pp. 27-47.

Tiller, D., Metzeling, L. 1995. The Rapid Bioassessment of streams: The approach and methods of the Victorian Environment Protection Authority. DRAFT. In.

Tiller, D., Metzeling, L. 2002. 'Australia-Wide Assessment of River Health: Victorian AusRivAS Sampling and Processing Manual - Monitoring River Heath Initiative Technical Report no 15.' Commonwealth of Australia and VIC Environment Protection Authority, Canberra and Melbourne.

USFDA. 2001. *Centre for Food Safety and Applied Nutrition, Fish and Fisheries Products, Hazards and Control Guidance.*

Warwick, WF. 1980. *Palaeolimnology of the Bay of Quinte, Lake Ontario: 2800 years of cultural influences, Canadian Bulletin of Fisheries and Aquatic Sciences*, no. 206, pp. 1-117.

Warwick, WF. 1985. *Morphological abnormalities in Chironomidae (Diptera) larvae as biological indicators of toxic stress in freshwater ecosystems: indexing antennal deformities in Chironomus Meigen, Canadian Journal of Fisheries and Aquatic Sciences*, no. 42, pp. 1881-914.

WHO. 2011. *Guidelines for Drinking-water Quality*, World Health Organisation, no. 4, pp. 1-564.

Wiederholm, T. 1984. *Incidence of deformed chironomid larvae (Diptera: Chironomidae) in Swedish lakes, Hydrobiologia,* no. 109, pp. 243–249.

Woxvold, IA. 2012. *Terrestrial Fauna Study of the northern Wafi-Golpu Project Area and Markham Gap Basin: Faunal Communities, Tailings Storage Facility Impacts and Recommendations*. Draft report prepared for Coffey Environments, March 2012.