TETRA TECH

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From:	Daniel Potts, Tetra Tech	**File:**	704-WTR.WTRM03015-02
Subject:	Evaluation of the Potential for Sediment Resuspension in Quesnel Lake during Overturn: An Integration of Available Information		

1.0 INTRODUCTION

During the early hours of August 4, 2014, the failure of a glacial lacustrine layer beneath the Perimeter Embankment of the Tailings Storage Facility (TSF) at the Mount Polley Mine caused a breach of the embankment, resulting in a terrestrial debris flow down the course of Hazeltine Creek and into Quesnel Lake. The debris flow continued underwater and deposited materials in the lake, including tailings from the TSF, coarse construction materials from the TSF, and fine and coarse native material scoured from the bed of Hazeltine Creek. The materials that entered Quesnel Lake settled at a range of rates corresponding to their sizes and other properties: larger, heavier particles settled relatively quickly while finer particles remained in suspension for weeks to months.

Mount Polley Mining Corporation (MPMC) retained Tetra Tech (formerly Tetra Tech EBA) to carry out several field and modelling studies related to water quality resulting from the embankment breach and also to support the evaluation of a discharge permit in Quesnel Lake, including

- **Bathymetry Analysis and Volume Balance** (Tetra Tech EBA, 2015a): Tetra Tech EBA assessed the overall volume balance of the TSF breach event, giving consideration to all available sources of data, both on land and within Quesnel Lake. Based on changes in bathymetry and on sub-bottom profiles, this study concluded that coarser material settled predominantly at the foot of the underwater slope below Hazeltine Creek, while finer material settled over a wider area of about 1.8 km^2, generally filling in below the 100 m depth contour of Quesnel Lake's West Basin.

- **Quesnel Lake Water Column Observations and Modelling** (Tetra Tech EBA, 2015b): Tetra Tech EBA was retained to perform both field measurements and numerical analyses to develop a predictive model that evaluated the fate of the suspended particulate material in Quesnel Lake and the turbidity resulting from that material. The model was validated against ongoing monitoring and provided predictions that Quesnel Lake turbidity would return to low single digits by mid-2015. This was later confirmed by observations; for example, the limnological profile at site QUL-18 on 6 May 2015 reached a depth of about 100 m and found turbidity below 1.2 FNU (Formazin Nephelometric Units) throughout the water column.

- **Dilution Modelling at Potential Outfalls in Quesnel Lake** (Tetra Tech EBA, 2015c) and **Mt. Polley Long Term Far Field Diffuser Modelling** (Tetra Tech EBA, 2016): Tetra Tech EBA was retained to identify preferred diffuser depths and assess the far field performance of proposed, and subsequently installed, diffusers in Quesnel Lake. The potential for long-term buildup of discharge constituents in the West Basin was evaluated through numerical modelling of Quesnel Lake covering a ten-year period.

Tetra Tech's previous study of the fate of suspended material in Quesnel Lake predicted mixing, flushing and settling but did not predict resuspension (Tetra Tech EBA, 2015b). However, area residents and members of local First Nations have questioned whether resuspension could occur at lake overturn and some have suggested

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linkages between perceived differences in lake colour and potential resuspension. Since Tetra Tech's previous study, considerable additional data have been collected. MPMC requested Tetra Tech to evaluate these other information sources as well as previous work to provide an opinion on whether resuspension of sediments is likely at lake overturn. There are several significant lines of evidence available, each of which is examined below:

1. Turbidity measurements in Quesnel Lake and Quesnel River.
2. Observed rates of deposition at sediment traps.
3. Theoretical estimates of sediment mobility based on measured sediment properties and predicted deep-water velocities during the overturn process from Tetra Tech's validated hydrodynamic model.
4. Video footage obtained during surveys using a remotely operated underwater vehicle (ROV).

For the purposes of this analysis, the resuspension hypothesis is clarified and limited as follows:

- The concern is TSF-derived material resuspending and reappearing in the upper depths (top 10 m) of the lake. This material had deposited deep in the lake (Tetra Tech EBA, 2015a).
- There are other potential sources of turbidity in Quesnel Lake such as Hazeltine Creek, other creeks and rivers, forestry and placer mining activities, and shoreline erosion. These processes do not constitute resuspension of event material and are not considered in this memo.
- Lake overturn is the semi-annual natural process in which surface and deep water masses are mixed and exchanged; in Quesnel Lake it generally occurs in late spring and late fall.

2.0 TURBIDITY MEASUREMENTS

The field work and numerical modelling (Tetra Tech EBA, 2015b) provided a quantitative narrative of the fate of the suspended material in Quesnel Lake. This narrative was confirmed and refined by continued monitoring with no qualitative changes. A brief summary of this narrative is presented here, to provide context for the discussion of observations that follows.

2.1 Narrative: Fate of Suspended Material

As a result of the August 4, 2014, TSF breach event, approximately 14 million m^3 of solids and interstitial water entered Quesnel Lake (Tetra Tech EBA, 2015a). The solids were predominantly tailings from the TSF, but included dam construction material and a small proportion of native material scoured from Hazeltine Creek. The weight of the solids carried the debris flow below the thermocline and down to the bottom of the West Basin (greater than 100 m depth). Coarser solids settled rapidly, on a time scale of hours to days. Finer solids such as silts and clays mostly moved with the debris flow, but some were dispersed throughout the West Basin, generally between 35 and 100 m depth. The volume of solids remaining in suspension in the West Basin nine days after the event was an estimated 0.025 million m^3 (Tetra Tech EBA, 2015a).

While the West Basin remained stratified, the suspended material settled gradually. By September 1, 2014, the volume in suspension had dropped to 0.016 million m^3. At this point, a bathymetric survey was conducted which indicated a deposited volume of approximately 18 million m^3 over an area of 1.8 km^2 generally below the 100 m depth contour; this deposited volume was greater than the debris flow volume, likely due to entrainment of supernatant and ambient water. By October 24, 2014, the estimated volume in suspension was 0.005 million m^3. (Tetra Tech EBA, 2015a)

When the West Basin's temperature stratification broke down at the end of fall 2014, the natural wind-driven overturn process homogenized the water column, bringing suspended material to the surface. Some suspended material exited via the Quesnel River, while some crossed the sill at Cariboo Island and was dispersed into the main body of Quesnel Lake. (Tetra Tech EBA, 2015a and 2015b)

Suspended material continued to exit via the Quesnel River and also across the sill over the winter and through to May 2015, despite the weak winter stratification. By summer 2015, the predicted concentration of event-related suspended material in Quesnel Lake and Quesnel River dropped to effectively zero. Resuspension of event-related sediment was neither predicted nor expected, although the question was not studied in detail at the time.

2.2 Discussion: Turbidity in Quesnel Lake and Quesnel River

Turbidity measurements in Quesnel Lake are done using a profiling instrument lowered through the water column, at various times, but are not continuous; these measurement profiles are called "casts." Turbidity in the Quesnel River was measured continuously and logged for later download, as well as sampled periodically for laboratory analysis.

The first measurements of turbidity below the thermocline in Quesnel Lake were conducted by the BC Ministry of Environment (MoE) on August 12 and 13, 2014. They showed turbidity of around 2-3 NTU above the thermocline and turbidity ranging from 100 to over 1000 NTU below. These are consistent with the narrative presented above: they show the suspended material was trapped below the thermocline, and as a result of the settling process, concentrations of suspended sediment, indicated by turbidity, increased with depth. Measured turbidity in Quesnel River (QUR-1; see Figure 1) remained in the 0-2 NTU (Nephelometric Turbidity Units) or range until the onset of fall overturn in November 2014 (MPMC, 2016). Tetra Tech notes that the continuous turbidity monitoring data in Quesnel River included spikes and apparent instrument or baseline drift, possibly due to the effects of materials such as drifting leaves or due to biofouling affecting the instrument optics; therefore, only the laboratory turbidity data are considered in this discussion because those data are not subject to the same effects.

(NTU and FNU are generally considered numerically similar, although they follow different measurement standards. Following MPMC (2016), the two units are treated as interchangeable for the purposes of this discussion.)

The epilimnion (surface layer) of the lake cooled through the fall of 2014, while the sediment continued to settle below. By the beginning of November the epilimnetic turbidity was under 2 FNU while at the bottom it was around 40 FNU (cast at QUL-18 on 4 November 2014; see Figure 1). The thermocline began to deepen in late November, signalling the beginning of the overturn process. At the beginning of December the water column was homogeneous at 5.6°C and 10 FNU (cast at QUL-18 on 2 December 2014). This condition was reflected in the Quesnel River turbidity, which rose to over 8 NTU at that time.

Over the course of winter 2014-2015, the Quesnel River turbidity tapered off: by mid-January 2015 the turbidity was consistently below 2 NTU. By mid-March, the weak winter stratification had disappeared and the West Basin water column was essentially uniform at 2.8°C and 2.2 FNU (cast at QUL-18 on 12 March 2015). This spring overturn caused no observed rise in turbidity in the Quesnel River, which instead continued to taper, stabilizing at around 0.5 NTU by June 2015. These observations are consistent with the narrative presented above.

To examine the question of a possible resuspension of deposited fine sediments during lake overturn, this discussion now turns to turbidity measurements during fall 2015 overturn, and 2016 overturn events.

In fall 2015, the thermocline had deepened to 70 m by late November (cast at QUL-18 on 26 November) at which time the turbidity was about 0.6 NTU at the surface and 1.2 NTU at depth. By 7 December, the water column at

QUL-18 was homogeneous at 5.1°C and 0.8 NTU. A very slight rise in Quesnel River turbidity is present at this time, essentially matching the QUL-18 data.

In spring 2016, the water column was already homogeneous by 23 February at QUL-58 (maximum depth around 68 m) with a temperature of 2.7°C and turbidity of 0.6 NTU. By 27 April, the stratification had been re-established and surface turbidity fell to 0.3 NTU, leaving 0.6 NTU at depth (QUL-58; see Figure 1). Measured turbidity in Quesnel River shows a very slight rise in February and essentially matches the surface turbidity at QUL-58. One laboratory sample taken 1 June 2016 showed an elevated turbidity of 2.7 NTU, but does not correspond to the timing of overturn; the field measurement of turbidity on the same date was 0.6 NTU, suggesting possible contamination of the laboratory sample.

In fall 2016, surface turbidity in Quesnel Lake ranged from 0.1 to 0.4 NTU (casts at QUL-66a on 5 October and 16 November, respectively; see Figure 1). The thermocline had deepened to about 60 m by 30 November, at which time cold conditions forestalled further field work. Data from Quesnel River for fall 2016 were not available at the time of writing.

The observations described above are typical of the entire data set and are consistent with the narrative understanding presented before. Turbidity in Quesnel River and the West Basin have remained below 2 NTU since January 2015, and mostly below 1 NTU since May 2015. The one laboratory sample over 2 NTU occurred while the lake was stratified, not overturning. These observations provide no support to the theory of overturn causing a resuspension of event-related sediment, but rather point to the re-establishment of steady state conditions.

3.0 OBSERVED RATES OF DEPOSITION

Minnow Environmental Inc. (Minnow) deployed sediment traps in Quesnel Lake at three locations between August 2014 and May 2015 and between May and August 2015 (Minnow 2016; tan circles on Figure 1). Sediment traps are moored passive collectors that measure the amount of sediment that deposits (falls) onto them. At one of the deployment locations, an intended reference location in Horsefly Bay (QUL-ST-REF 1-6), the deposition data are strongly influenced by the Horsefly River and, therefore, this station is not a good representation of deposition rates across much of the lake. However, the “near-field” sediment traps offshore from Hazeltine Creek at a depth of about 110 m (QUL-ST-NF 1-6), and “far-far-field” traps downstream (north) of Cedar Point at a depth of about 35 m (QUL-ST-FFF 1-6), provide useful observations as described below.

During the August 2014 to May 2015 deployment, the near-field sediment traps were overfilled and, therefore, a deposition rate could not be computed. These traps were deployed less than four weeks after the event, and substantial event-related deposition was ongoing for the first part of the deployment period; therefore, the overfilling is no surprise. The sediment in the near-field traps during that initial deployment had a bulk dry density around 600 kg/m^3, a total carbon by combustion of 1.0%, and elemental composition reflective of a significant contribution of tailings. Dry density is the weight of sediment in a fixed volume. The far-far-field traps, which were deployed at a depth shallower than the general zone of deposition, measured a deposition rate of 1.9 mm/yr and a bulk dry density around 280 kg/m^3. The findings from this deployment period demonstrate that the event-related deposition was both substantial (the overfilling) and localized (not seen at the traps north of Cedar Point). This pattern of settling fits well with other data collected as part of the overall program and with the narrative outlined above.

During the May to August 2015 deployment (one year after the event), the near-field sediment traps measured a deposition rate of 1.2 mm/yr and a bulk dry density around 100 kg/m^3: a dramatic decrease from the previous deployment. There was not enough sample material to determine the carbon content, but the substantially lower metal concentrations are not consistent with the deposited sediments being tailings (first deployment [Cu]=1144 mg/kg; second deployment [Cu]=239 mg/kg; see Kennedy et al., 2016, for tailings composition). The far-

far-field traps measured a deposition rate of 2.2 mm/yr and a bulk density around 170 kg/m^3. Considering the degree of variability between individual trap measurements, this similarity with the previous period's findings shows no significant change. The findings from this deployment period indicate that event-related deposition was effectively over as it could not be detected.

If any event-related, deposited materials, which mostly deposited at a depth greater than 100 m, became resuspended during the spring overturn in 2015, one would expect to find additional mineral-enriched sediment in the far-far-field traps after that time. The far-far-field traps downstream of Cedar Point were retrieved and redeployed on the same day (21 May 2015), and therefore could not have missed a spring overturn deposition episode. However, the average copper concentrations in the first and second deployments of the far-far-field traps agree within one standard deviation, and the deposition rates stayed relatively constant. Therefore, neither their deposition rates nor their metals concentrations give any support to the theory of resuspension during overturn.

4.0 THEORETICAL SEDIMENT MOBILITY

The erosion of sediment from the bottom of a water body is a well-studied field. In order to initiate sediment motion an outside force is required – typically flowing water or waves. Up to a point, smaller sediment grains are easier to move than larger sediment grains; however, below approximately the silt-sand threshold (perhaps 60 to 120 µm) the finer-grained a material is, the harder it is to transport. Particularly if clay minerals are present (sub-4 µm sediments), cohesion tends to dramatically reduce sediment mobility. As compared to the movement of non-cohesive sediments, the transport of clays and silts is more difficult to estimate from process-based approaches (i.e., building up a theoretical model from first principles) and there is, consequently, a heavy reliance on measured data and analogous sites.

This section discusses the physics of sediment motion relative to known parameters on the Quesnel Lake bed and, based on comparisons to a wide variety of field measurements, provides an estimate of its resuspension potential.

4.1 Bed Sediment Observations

Grab samples of bottom sediment from approximately 100 m depth were collected by Minnow from Quesnel Lake near the Hazeltine Creek delta in September 2014 and October 2015 (Minnow 2016; blue circles on Figure 1). In the same area, Minnow deployed sediment traps from August 2014 to May 2015 and May 2015 to August 2015 as described above (tan circles on Figure 1).

Table 1 presents the sediment particle size distribution of the grab samples, with corresponding classification in the left-most column. The samples collected in September 2014 (left column under each sample location) show a primarily silty lake bottom with sufficient clay to indicate a cohesive sediment. By October 2015 (right column under each sample location), the clay content of the on bed sediment has increased at every sample location and nearly doubled at QUL-PNF-01 and -03. The increase in clay content of the lake-bed sediments is consistent with the fact that in September 2014, based on turbidity profiles, there was a measureable concentration of unsettled (very fine) sediment still in the water column following the TSF breach (Tetra Tech EBA, 2015a). Over the succeeding months (i.e., between September 2014 and October 2015), much of that fine sediment either settled on the lake bed or was advected out of the West Basin such that by October 2015 the amount of suspended sediment in the water column was significantly reduced (cast at QUL-18 on 28 October). In all cases, the dry density of the September 2014 samples is considerably greater than the October 2015 samples. Recently deposited cohesive sediments will have a lower value of dry density than solids that have been on the lake bed for longer periods of time.

Table 1: Bottom Grab Samples from Quesnel Lake near Hazeltine Creek from September 2014 and October 2015

Sample Location	QUL-PNF-01		QUL-PNF-02		QUL-PNF-03		QUL-PNF-04		QUL-PNF-05	
Collection Date	Sept 2014	Oct 2015	Sept 2014	Oct 2015	Sept 2014	Oct 2015	Sept 2014	Oct 2015	Sept 2014	Oct 2015
Gravel > 2000 µm	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Sand 63-2000 µm	4.1%	1.4%	0.3%	1.7%	0.2%	1.8%	4.0%	1.9%	30.0%	28.2%
Silt 4-63 µm	70.0%	44.1%	60.0%	48.5%	75.0%	54.7%	84.0%	81.7%	59.0%	58.7%
Clay < 4 µm	26.0%	54.5%	40.0%	49.9%	25.0%	43.5%	12.0%	16.4%	11.0%	13.1%
Organics	0.2%	0.4%	0.3%	0.5%	0.2%	0.3%	<0.1%	<0.1%	<0.1%	0.2%
Dry Density◊ kg/m³	1,529	945	1,341	914	1,610	1,165	1,755	1,711	1,855	1,837

◊ Dry Density = (1 – porosity) x density, with sediment density of 2588 kg/m^3 calculated based on samples retrieved from sediment traps deployed from September 2014 to August 2015.

Data table adapted from Minnow (2015).

The increase in clay content and decrease in dry density recorded by the grab samples (Table 1) is consistent with the sediment trap data presented in Table 2. The data presented in Table 2 show that sediment deposited between September 2014 (one month after the event) and August 2015 had a clay content of approximately 50%. This matched the observed change in on-bed clay content from approximately 25% in September 2014 to approximately 50% in October of 2015. This sedimentation pattern is similarly consistent with water samples taken by the Ministry of Environment in September 2014 which recorded a suspended sediment load in the lake consisting of primarily clay with a mean diameter (d_{50}) of 2.1 µm (unpublished data, received from MPMC). Similarly, the dry density of the deposited material recorded by the sediment traps (Table 2) is consistent with an unconsolidated to moderately consolidated mud, which accounts for the reduction in the on-bed dry density between September 2014 and October 2015 recorded by the grab samples (Table 1). Reported annualized sedimentation during the measurement period was on the order of a few millimeters.

The dry density of the on-bed sediment recorded in September 2014 was in the range of a moderate to well consolidated mud. Between September 2014 and October 2015, this dry density uniformly declined due to fresh sedimentation. The dry density of the deposited layer suggests that this recently deposited layer was largely undisturbed:

- The lowest dry densities were recorded at locations with the highest clay content. This observed correlation between clay content and dry density is consistent with the behaviour of consolidating lacustrine mud (van Rijn, 1993).
- For sediments with a high clay content, the dry density of the bed is strongly related to the age of the sediments (i.e., time since deposition). The recorded dry densities strongly suggest that these sediments have been undisturbed for a period of several months but not more than a year (van Rijn, 1993).

Table 2: Sediment trap samples from Quesnel Lake near Hazeltine Creek from September 2014 to May 2015 (May 2015) and May 2015 to August 2015 (Aug 2015)

	QUL-ST-NF-1		QUL-ST-NF-2		QUL-ST-NF-3		QUL-ST-NF-4		QUL-ST-NF-5		QUL-ST-NF-6	
	May 2015	Aug 2015	May 2015	Aug 2015	May 2015	Aug 2015	May 2015	Aug 2015	May 2015	Aug 2015	May 2015	Aug 2015
Gravel > 2000 µm	<0.1%		<0.1%		<0.1		<0.1		<0.1			
Sand 63-2000 µm	1.7%		0.3%		0.2		0.2		0.3			
Silt 4-63 µm	48.3%		48.8%		47.9		47.6		47.9			
Clay < 4 µm	50.0%		50.8%		51.9		52.2		51.8			
Organics	1%		1%		1		1		1			
Dry Density kg/m^3	646		638		630	89	592	143	710			73

Data table adapted from Minnow (2016).

4.2 Comparison to Observations at Other Sites

The mobilization potential of on-bed sediments is generally described in terms of their resistance to shear forces. For non-cohesive sediments, this shear resistance is highly predictable but this is not the case for cohesive sediments such as those at the Quesnel Lake bottom. Therefore, to infer the behaviour of the on-bed sediments, this section presents a comparison to other locations for which shear resistance data exist.

Table 3 provides a range of typical properties and dry density measurements for estuarine and lacustrine muds. Broadly speaking, muds with a similar sediment composition (proportions of sand, silt, clay and organics) and similar dry density (consolidation) will have approximately similar behaviour. This is an important consideration in Section 4.4, where the critical mobility (i.e., movement threshold) of Quesnel Lake sediments is estimated from existing measurements.

A comparison of Tables 1 and 3 indicates that the grab samples of Quesnel Lake bottom material are more consolidated than typical recently deposited natural fine sediment beds, and are more similar in level of consolidation to inter-annual deposits of fine sediment (van Rijn, 1993). This increase in consolidation may be attributable to the mass deposition event following the TSF breach. Based on the grab sample and sediment trap data, recent sedimentation on the lake bottom consists of a bed comprised of month-to-year-old cohesive sediment overlain by relatively thin layer (one to several millimeters) of soft clay or fluid mud consistent with the properties of recent (i.e., weeks old) naturally deposited fine sediments presented in Table 2 (Minnow, 2016):

- Between September 2014 and May 2015 Minnow does not present a depositional rate, but reported a potentially large deposition of material in the sediment traps (overflowing but potentially faulty sediment traps), which, in accordance with the 'Bottom Layer' data presented van Rijn (1993) and summarized in Table 3, would result in a deposited layer with a dry density in the range of 400 kg/m^3 to 600 kg/m^3. This is consistent with the dry density of mud reported from the sediment traps in May 2015.

- Between May 2015 and August 2015 Minnow reported a thin depositional layer in the sediment traps (order of a millimeter) with a dry density indicative of a fluid mud. This observation is consistent with world measurements of thin deposits of fine sediment layers, where dry densities in the range of 50 kg/m³ to 250 kg/m³ have been reported for layers less than a month old with a thickness in the range of 3 mm to 5 mm.

Therefore, the lake bed sediments at the bottom of Quesnel Lake in the vicinity of Hazeltine Creek likely consist of a moderately- to well-consolidated clayey silt overlain by a thin layer of gradually consolidating month-to-year-old silty-clay mud with deposits of fluid mud less than a month old at the surface.

Table 3: Typical Dry Densities of Consolidated Fine Sediment Layers Based on Measurements at 14 Lakes, Estuaries, and Coasts

Sand %	Organics %	Thickness Bed Layer (m)	Thickness Top Layer (mm)	Dry Sediment Density (kg/m³)			
				Top Sediment Layer		Bottom Sediment Layer	
				1 Day◊	≥ 7 Days	1 Day	≥ 7 Days
22	**6**	**0.1-0.2**	**3-6**	**96-156**	**103-177**	**589**	**558-604**

◊ Age of sediment in days (i.e. the number of days since deposition)

Table adapted from van Rijn (1993).

4.3 Critical Mobility of Bed Sediments

Sediments containing a clay fraction larger than approximately 10%, such as those on the bed of Quesnel Lake, will tend to be cohesive, greatly increasing their resistance to shear forces, erosion and resuspension. Additionally, fluid mud layers, such as those comprising the surficial sediment layer in Quesnel Lake, will have a specific resistance to erosion tied to their dry density (a proxy for the degree of consolidation), depositional history and mineralogy.

For beds comprised of fine sediments, two mechanisms of erosion are possible: surface erosion of individual particles, and/or mass erosion (bed failure) of large pieces of the bed. The surficial soft and fluid muds will be eroded by surface erosion at shear stresses in the range of 0.15 to 0.30 Newtons per square metre (N/m²; approximately equal to a sheet of paper dragged across a desk). Once these surficial layers are eroded, the remaining consolidated bed will begin to erode, typically at shear stresses ranging from 0.5 to as much as 1.2 N/m². Table 4 presents a range of shear stresses required to initiate erosion of natural fine sediment beds at various levels of consolidation.

Table 4: Critical Bed Shear Stress for Erosion of Consolidated Mud at Different Sediment Concentrations (Dry Densities) Based on Data Collected at 14 Lakes, Estuaries and Coasts

Sand %	Organics %	τ_e = critical bed shear stress for erosion (N/m²)				
		ρ◊ = 100 kg/m³	ρ = 150 kg/m³	ρ = 200 kg/m³	ρ = 250 kg/m³	ρ = 300 kg/m³
22	6	0.14-0.25	0.24-0.32	0.36-0.46	0.55-0.72	0.53-0.75

◊ Dry density of sediment

Table adapted from van Rijn (1993).

4.4 Near Bed Hydraulic Loading

From past work (Tetra Tech EBA 2016), Tetra Tech had archived hydrodynamic model output available at daily intervals over a ten-year period. To identify the maximum hydraulic loading (shear stress) expected at the lake bed, the archived data were first screened for velocity at the QUL-66a location in the bottom model layer (104-106 m depth). Yearly velocity maxima occurred invariably during fall overturn, in November or December. The maximum predicted bottom-layer velocity over ten years at QUL-66a was 0.09 m/s.

Following this initial screen, maps of bottom shear stress in the West Basin were generated for the dates of yearly peak velocities at QUL-66a, as well as the two days prior and two days following each peak. In these maps, the shear stress below a depth of 75 m in the West Basin typically peaked between 0.01 and 0.04 N/m^2, and the maximum in a single location on any date was 0.07 N/m^2.

This maximum shear stress is 53% lower than the lower bound estimate of shear stress required to mobilize the surficial fluid mud layer and 86% lower than the lower bound estimate of the shear stress required to mobilize the underlying consolidated clayey silt. The predicted hydraulic loading on the surface of the deposited sediments is therefore considerably lower than the expected threshold for resuspension, in even the most energetic of overturn events.

5.0 ROV VIDEO EVIDENCE

On 7 September 2016 Fraser Burrard Diving carried out engineering inspections of MPMC's diffusers in Quesnel Lake. The diffuser pipes lie along the lake bottom, reaching from shore on the Hazeltine Creek delta to a depth of about 50 m. The inspections were carried out with an ROV equipped with a camera; the video footage capture is available in three segments:

- Diffuser 1_Main Pipe and West outlet 101558.AVI – This recording documents the inspection of the westerly diffuser pipeline (discharge at approximately 45 m depth) and its west diffuser port, and will be referred to as *D1-W*.
- Diffuser 1_East outlet 112141.AVI – This recording documents the continuation of the westerly diffuser pipeline inspection, including its east diffuser port, and will be referred to as *D1-E*.
- Diffuser 2_East and West outlets 120609.AVI (D2) – This recording documents the inspection of the easterly diffuser pipeline (discharge at approximately 50 m depth), and will be referred to as *D2*.

The purpose of the inspections was to confirm the condition, stability, and functionality of the diffusers. Nevertheless, the video footage constitutes a valuable observation of the underwater environment and adjacent lake bed, and offers insight into the question of sediment mobility as described below.

With spring and fall overturn in Quesnel Lake typically occurring in April-May and November-December, the survey captured the condition approximately four months after spring overturn, and approximately three months prior to the expected fall overturn. Any deposited sediment seen in the footage could therefore be attributed to deposition since the spring overturn, or to accumulated deposition from a longer period, or to both. Any suspended sediment seen in the footage could be material that has remained in suspension since the spring overturn or since some earlier event, or could be material from a more recent or ongoing source. To narrow down these possibilities, further discussion is undertaken regarding both the nature of the sediments and the timing of their deposition.

5.1 Nature of the Observed Sediments

Throughout all three videos, suspended and deposited materials are ubiquitously evident.

The suspended material is visually reminiscent of snow, while the ROV's lights are on: that is, the suspended material consists of distinct dots rather than appearing cloudy. Just after the lights are turned on, the ROV operator remarks that there is a "bit of turbidity in the water here – very minor, but easily picked up by the lights" (D1-W 8:48; see Figure 2, panel 1). It can also sometimes be seen without the ROV lights, but is much less striking (e.g., D1-E 19:05). Different from snow, however, the suspended material does not have a visible downward-drifting tendency: on the rare occasions when the ROV is still, the suspended material swirls in a seemingly random fashion (e.g., D2 31:10).

The suspended particles give the impression of having individual shapes – as they swirl they appear to rotate, elongate or shorten – much as snowflakes can do under the right conditions. The apparent particle size is on the order of 0.1 to 3 mm, or approximately the size of sand grains. However, mineral particles of this size would exhibit a strong downward drift. The observations are therefore more consistent with organic material, or an agglomeration of primarily organic material and some possible mineral matter. "Lake snow," described by Grossart and Simon (1993), is similar to the more well-known marine snow in oceans; it is comprised of senescent aggregates of phytoplankton and other organisms, which are a normal part of a lacustrine ecosystem because of their role in the transformation of organic matter and nutrient distribution and cycling in lakes.

Deposited material can be seen on the diffuser pipes, the concrete ballast weights and the lake bottom. It is generally light-coloured in contrast to the black HDPE pipes, but makes only a weak contrast against the concrete weights (e.g., D1-W, 13:15). When stirred up by the ROV's propulsion, the deposited sediments are similar in appearance and behaviour to the suspended materials (e.g., bottom materials at D2 18:50; bumped off a rope at D2 11:15). At D2 25:00, the ROV disturbs bottom sediments near the diffuser port with its camera pointing downwards; a small dusting is swirled about, while a thick layer remains undisturbed (Figure 2, panel 2). These observations are consistent with a deposited layer of lake snow, overlying a different sediment that is more cohesive and less easily disturbed.

5.2 Timing of Deposition

There is a noticeable difference between the sediment deposited on the diffuser pipes and the sediment on the lake bottom. The sediment on the diffuser pipes appears to be only a few millimetres thick (e.g., D1-E 5:35), and is easily disturbed; for example, at D1-W 13:50 there are streaks in the sediment suggestive of fish passage; and at D2 33:00 there are streaks apparently made by the ROV's earlier passage, since they are not visible in that location on the outbound transit (D2 13:09).

The sediment on the lake bottom, however, appears to be several centimetres thick. At each diffuser port, there is a patch of exposed gravel and cobbles several metres in diameter, surrounded by a layer of uniform, light-coloured deposited material (e.g., D1-E 4:50 and D2 27:25; see Figure 2, panel 3); the edges of the deposited layer around these exposed patches appear to have heights of approximately 3-10 cm.

While a flange is being inspected by the ROV, about ten loose bolts with washers are visible on the bottom, about halfway buried or sunk into the bottom sediments (D1-W 19:44 and 21:10; see Figure 2, panel 4). The degree of sediment cover on the top surfaces of the bolts is quite slight – shiny metal is apparent in the ROV's lights – suggesting that the bolts sank into sediment existing at the time of construction, rather than having been buried since that time.

As previously mentioned, at D2 25:00 the ROV disturbs bottom sediments near the diffuser port with its camera pointing downwards. A thin swirl of disturbed material is visible, but the texture on the top of the thicker sediment layer remains constant, indicating relatively strong cohesion within that layer.

Evidence from water column profiling, sediment traps and numerical modelling all indicate that deposition of the event-related sediments was progressive and effectively irreversible. Observations from the ROV footage are consistent with this understanding. At the depth of the diffusers, approximately 50 m, the deposited layer appears to be a few centimetres thick. The shiny appearance of the half-sunk bolts supports the interpretation that the event-related sediments deposited prior to construction of the diffusers and have not been significantly redistributed since. The deposition since construction of the diffusers appears to be material of a different nature than the event-related sediments.

6.0 CONCLUSIONS

Following the embankment breach in August 2014, mixed sediments including tailings entered Quesnel Lake. Some of the material remained in suspension for a period of weeks to months following the event. The fate of this material has been studied through field observation and numerical models, and is well understood and described. Aside from the fraction advected out of the West Basin by currents, its deposition was progressive, localized, and irreversible. At least seven lines of evidence support this understanding:

- Water column profiling showed high turbidity below 35 m depth immediately following the event (August 2014). This turbidity declined continuously over the following months. Suspended material was redistributed and appeared at the surface during the 2014 fall overturn, and at a much lower concentration during the 2015 spring overturn. Turbidity profiles during and after the 2015 fall overturn and 2016 spring overturn show no evidence of resuspension of deposited materials.

- Turbidity monitoring in the outflowing Quesnel River matches the surface turbidity measured in the limnological profiles. As expected, it showed a turbidity elevation during the 2014 fall overturn. Thereafter the observed turbidity declined in laboratory samples and has remained below 2 NTU since January 2015 and below 1 NTU since May 2015 with only one exception. The exception did not coincide with an overturn event. No evidence is present to suggest resuspension of deposited sediments during overturn events.

- Sediment grab samples were taken by Minnow at approximately 100 m depth in the West Basin in September 2014 and October 2015. The October 2015 samples show finer, less-consolidated material than the September 2014 ones; this finding is consistent with the understanding of gradual deposition of the finest fraction of the suspended material.

- Sediment traps were deployed by Minnow at approximately 100 m depth off Hazeltine Point (“near-field”) and approximately 35 m depth north of Cedar Point (“far-far-field”). The near-field traps were filled to overflowing between August 2014 and May 2015, which was the period of substantial settling of suspended material. The near-field traps were re-deployed May to August 2015 and measured a deposition rate of just 1.2 mm/yr, indicating that deposition of event-related material was effectively over. The far-far-field traps showed no significant difference in deposition rates between the two deployment periods, indicating that the deposition of event-related material was localized south of Cedar Point and deeper than 35 m.

- The deposited material in the sediment traps in the first deployment (immediately post-breach) had copper concentrations that are consistent with concentrations in milled tailings from the mine. In the second deployment, the copper concentrations resembled background sediment concentrations, indicating that the material deposited during that deployment was not resuspended tailings but material of natural origin.

- Minnow’s field program indicated that the deposited event-related sediments are characterized by a thin layer of fluid mud or gradually consolidating mud with moderately- to well-consolidated clayey silt beneath. The estimated shear stresses required to remobilize these layers are 0.15-0.30 N/m^2 and 0.5-1.2 N/m^2, respectively. Numerical hydrodynamic models of the overturn process indicated typical peak shear stresses of 0.01-0.04 N/m^2, with an extreme of 0.07 N/m^2 predicted once over a ten-year period. Based on these estimates, resuspension of deposited sediments during overturn is very unlikely.

- Underwater video footage was available from inspection of MPMC's diffusers in September 2016 at approximately 50 m depth, near the upper edge of the event-related deposition. Two distinct sediments are present. One: suspended material (lake snow), is apparent as individual flakes with near-neutral buoyancy; this is judged to be primarily organic material of natural origin, unrelated to the TSF breach event, and is easily mobilized by the ROV's propulsion. Two: a light-colored layer of cakey mud coats the bottom and is cohesive enough to be undisturbed by the ROV's propulsion; this is interpreted as the event-related material and appears to have been undisturbed since construction of the diffusers, or before.

The above lines of evidence collectively indicate, through observational and computational evaluations, that resuspension is very unlikely. All observations of sediment in Quesnel Lake support the understanding of the progressive and irreversible deposition of event-related material.

7.0 LIMITATIONS OF REPORT

This report and its contents are intended for the sole use of Mount Polley Mining Corporation and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than Mount Polley Mining Corporation, or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech Canada Inc.'s Services Agreement. Tetra Tech's General Conditions are attached to this memo.

8.0 CLOSURE

We trust this technical memo meets your present requirements. If you have any questions or comments, please contact the undersigned.

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REFERENCES

Grossart, H.-P. and Simon, M. 1993. Limnetic macroscopic organic aggregates (lake snow): Occurrence, characteristics, and microbial dynamics in Lake Constance. Limnol. Oceanogr. 38(2): 532-546.

Kennedy, C.B., S.J. Day & C.D. Anglin. 2016. Geochemistry of tailings from the Mount Polley Mine, British Columbia. In: Proceedings of the Tailings and Mine Waste Association Conference 2016. Keystone, Colorado.

Minnow Environmental Inc., 2015. Sediment Quality Data Report – August 2015 Collections. Techincal memo to MPMC, October 29, 2015.

Minnow Environmental Inc., 2016. Assessment of Sediment Deposition Rate and the Chemistry of Depositing Sediment in the Vicinity of the Mount Polley Mine – 2014 and 2015 Sediment Trap Deployments. Technical memo to MPMC, June 30, 2016.

MPMC, 2016. Quesnel River Continuous Monitoring Data, Aug 12, 2014 – May 30, 2016. Prepared for BC MoE, December 5, 2016.

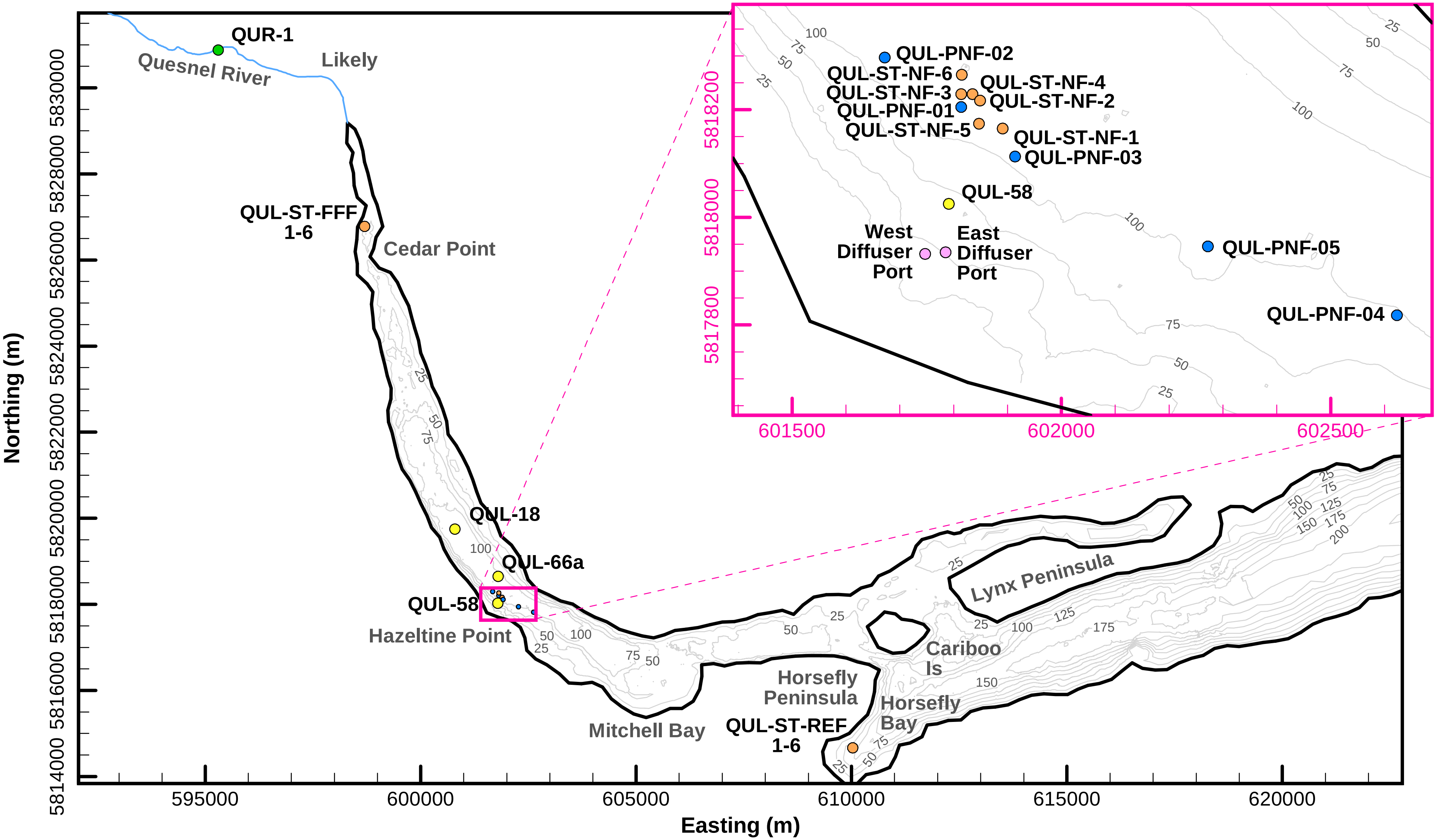
Tetra Tech EBA, 2015a. Bathymetry Analysis and Volume Balance. Prepared for MPMC, May 2015.

Tetra Tech EBA, 2015b. Quesnel Lake Water Column Observations and Modelling. Prepared for MPMC, May 2015.

Tetra Tech EBA, 2015c. Dilution Modelling at Potential Outfalls in Quesnel Lake. Technical memo to MPMC, May 2015.

Tetra Tech EBA, 2016. Mt. Polley Long Term Far Field Diffuser Modelling. Technical memo to MPMC, June 2016.

van Rijn, 1993. Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Aqua Publications, Amsterdam.



NOTES

- MPMC CTD Profile
- Minnow Sediment Grab
- Minnow Sediment Trap
- Turbidity Monitoring

Depth contours derived from survey data are shown at 25-m intervals. In locations not covered by the 2014 survey, contours are based on the 2001 survey data.

Vertical datum is the zero on the WSC lake level gauge at Likely.

STATUS
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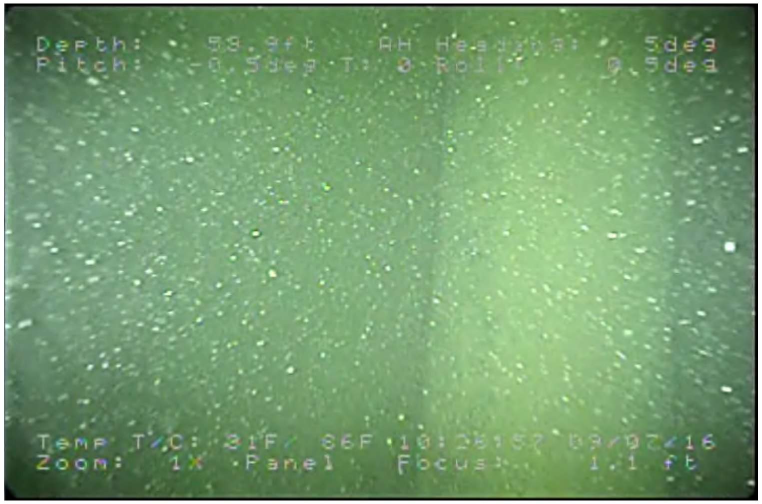
EVALUATION OF THE POTENTIAL FOR SEDIMENT RESUSPENSION

Locations of Sediment Observations in Quesnel Lake

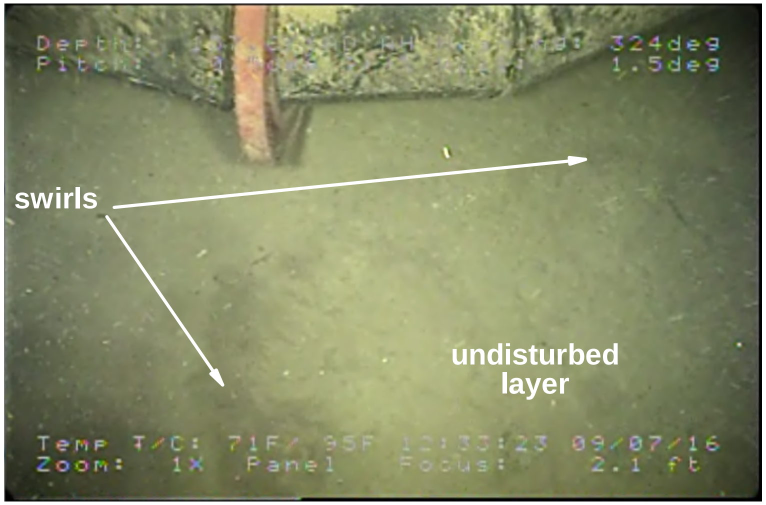
PROJECT NO.	DWN	CKD	APVD	REV
V13203212-02	DP	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	March 9, 2017

Figure 1



Panel 1. D1-W 8:48, lake snow



Panel 2. D2 25:04, disturbed by ROV propulsion

Panel 3. D2 27:25, edge of bare patch

Panel 4. D1-W 21:10, bolts on bed

NOTES

Panels are referenced and discussed in the text.

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EVALUATION OF THE POTENTIAL FOR SEDIMENT RESUSPENSION

Still Images from ROV Diffuser Inspections on 7 September 2016

PROJECT NO.	DWN	CKD	APVD	REV
V13203212-02	DP	JAS	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	March 30, 2017

Figure 2

GENERAL CONDITIONS

HYDROTECHNICAL

This report incorporates and is subject to these "General Conditions".

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This report pertains to a specific site, a specific development, and a specific scope of work. The report may include plans, drawings, profiles and other supporting documents that collectively constitute the report (the "Report").

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Both electronic file and hard copy versions of TETRA TECH's Instruments of Professional Service shall not, under any circumstances, be altered by any party except TETRA TECH. TETRA TECH's Instruments of Professional Service will be used only and exactly as submitted by TETRA TECH.

Electronic files submitted by TETRA TECH have been prepared and submitted using specific software and hardware systems. TETRA TECH makes no representation about the compatibility of these files with the Client's current or future software and hardware systems.

1.3 STANDARD OF CARE

Services performed by TETRA TECH for the Report have been conducted in accordance with the Services Agreement, in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this Report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of the Report.

If any error or omission is detected by the Client or an Authorized Party, the error or omission must be immediately brought to the attention of TETRA TECH.

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Unless expressly agreed to in the Services Agreement, TETRA TECH was not retained to investigate, address or consider, and has not investigated, addressed or considered any environmental or regulatory issues associated with the project.

1.5 DISCLOSURE OF INFORMATION BY CLIENT

The Client acknowledges that it has fully cooperated with TETRA TECH with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The Client further acknowledges that in order for TETRA TECH to properly provide the services contracted for in the Services Agreement, TETRA TECH has relied upon the Client with respect to both the full disclosure and accuracy of any such information.

1.6 INFORMATION PROVIDED TO TETRA TECH BY OTHERS

During the performance of the work and the preparation of this Report, TETRA TECH may have relied on information provided by persons other than the Client.

While TETRA TECH endeavours to verify the accuracy of such information, TETRA TECH accepts no responsibility for the accuracy or the reliability of such information even where inaccurate or unreliable information impacts any recommendations, design or other deliverables and causes the Client or an Authorized Party loss or damage.

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This Report is based solely on the conditions present and the data available to TETRA TECH at the time the Report was prepared.

The Client, and any Authorized Party, acknowledges that the Report is based on limited data and that the conclusions, opinions, and recommendations contained in the Report are the result of the application of professional judgment to such limited data.

The Report is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site conditions present at or the development proposed as of the date of the Report requires a supplementary investigation and assessment.

It is incumbent upon the Client and any Authorized Party, to be knowledgeable of the level of risk that has been incorporated into the project design, in consideration of the level of the hydrotechnical information that was reasonably acquired to facilitate completion of the design.

The Client acknowledges that TETRA TECH is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the Client.

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TETRA TECH is only responsible for the activities of its employees on the job site and was not and will not be responsible for the supervision of any other persons whatsoever. The presence of TETRA TECH personnel on site shall not be construed in any way to relieve the Client or any other persons on site from their responsibility for job site safety.