AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063345

Key Points:

- Hypolimnetic increase in temperature and turbidity due to a mine tailings spill
- Stratification and seiching promote and distribute fine-grained sediment plume
- Physical, biological and chemical implications for a near-pristine lake

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Citation:
Petticrew, E. L., et al. (2015), The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: Quesnel Lake, British Columbia, Canada, *Geophys. Res. Lett.*, *42*, 3347–3355, doi:10.1002/2015GL063345.

Received 14 FEB 2015
Accepted 25 MAR 2015
Published online 5 MAY 2015
Corrected 19 JUN 2015

This article was corrected on 19 JUN 2015. See the end of the full text for details.

The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: Quesnel Lake, British Columbia, Canada

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Abstract On 4 August 2014, a catastrophic breach of the Mount Polley mine tailings impoundment released ~25 M m^3 of tailings and water and scoured an unknown quantity of overburden into the West Basin of Quesnel Lake. We document Quesnel Lake and Quesnel River observations for 2 months postspill. Breach inflows raised Quesnel Lake by 7.7 cm, equivalent to ~21 M m^3. The West Basin hypolimnion was modified immediately, exhibiting increased temperature (~5°C to 6–7.5°C), conductivity (110 to 160 μS/cm), and turbidity (<1 to 200–1000 nephelometric turbidity units (NTU)). Cooscillating seiches moved West Basin hypolimnetic water both westward and eastward contaminating the Main Basin. Postspill, high-turbidity water propagated eastward (~1 cm/s), introducing a persistent ~20 m thick layer below the thermocline and an ~30 m thick layer at the bottom. The contaminant introduction, mobilization, and bioaccumulation may pose risks to resident and anadromous fish stocks, which support recreational, commercial, and First Nations fisheries.

1. Introduction

Quesnel Lake is a large, deep, oligotrophic lake in British Columbia, Canada (Figure 1a). A tailings impoundment for the Mount Polley Mining Corporation (MPMC) copper and gold mine sits ~9.2 km upstream and ~200 m above the lake. On 4 August 2014, the impoundment wall failed, catastrophically releasing 10.6 M m^3 of supernatant water, 7.3 M m^3 of tailings solids, 6.5 M m^3 of interstitial water, and 0.6 M m^3 of construction materials [*Mount Polley Mining Corporation* (*MPMC*), 2014a]. The materials flowed into Polley Lake and subsequently along Hazeltine Creek channel into the West Basin of Quesnel Lake. This surge of material generated an extensive lake bottom deposit, consisting of tailings and eroded overburden, measuring ~600 m wide, 1–3 m deep, and ~1.2 km across the West Basin (MPMC data discussions, L. Nikl, personal communication, 2014). In the days following the breach event, MPMC received permission to pump contaminated water from the geotechnically unstable and elevated (1.7 m) Polley Lake into Hazeltine Creek; pumping continued into October [*MPMC*, 2014b].

Quesnel Lake and Quesnel River support important anadromous Pacific Salmon (*Oncorhynchus* spp.) and resident fish populations (*Salvelinus* spp. and *Oncorhynchus* spp.) that contribute to diverse and productive aquatic ecosystems and support commercial, recreational, and aboriginal fisheries. When the MPMC tailings impoundment breach event occurred, Quesnel Sockeye Salmon stocks were moving into and up the Fraser River on their annual return to their spawning grounds. Quesnel Lake stocks predominantly spawn in the Mitchell and Horsefly Rivers (Figure 1a), but a significant number also use littoral habitat. Preliminary escapement estimates to Quesnel Lake in 2014, the dominant cycle line in their 4 year population cycle, indicate that ~822,000 adult Sockeye Salmon returned to the system [*Fisheries and Oceans Canada*, 2014], but also, the progeny of the 2013 nondominant cycle line were rearing within Quesnel Lake during and following the breach event.

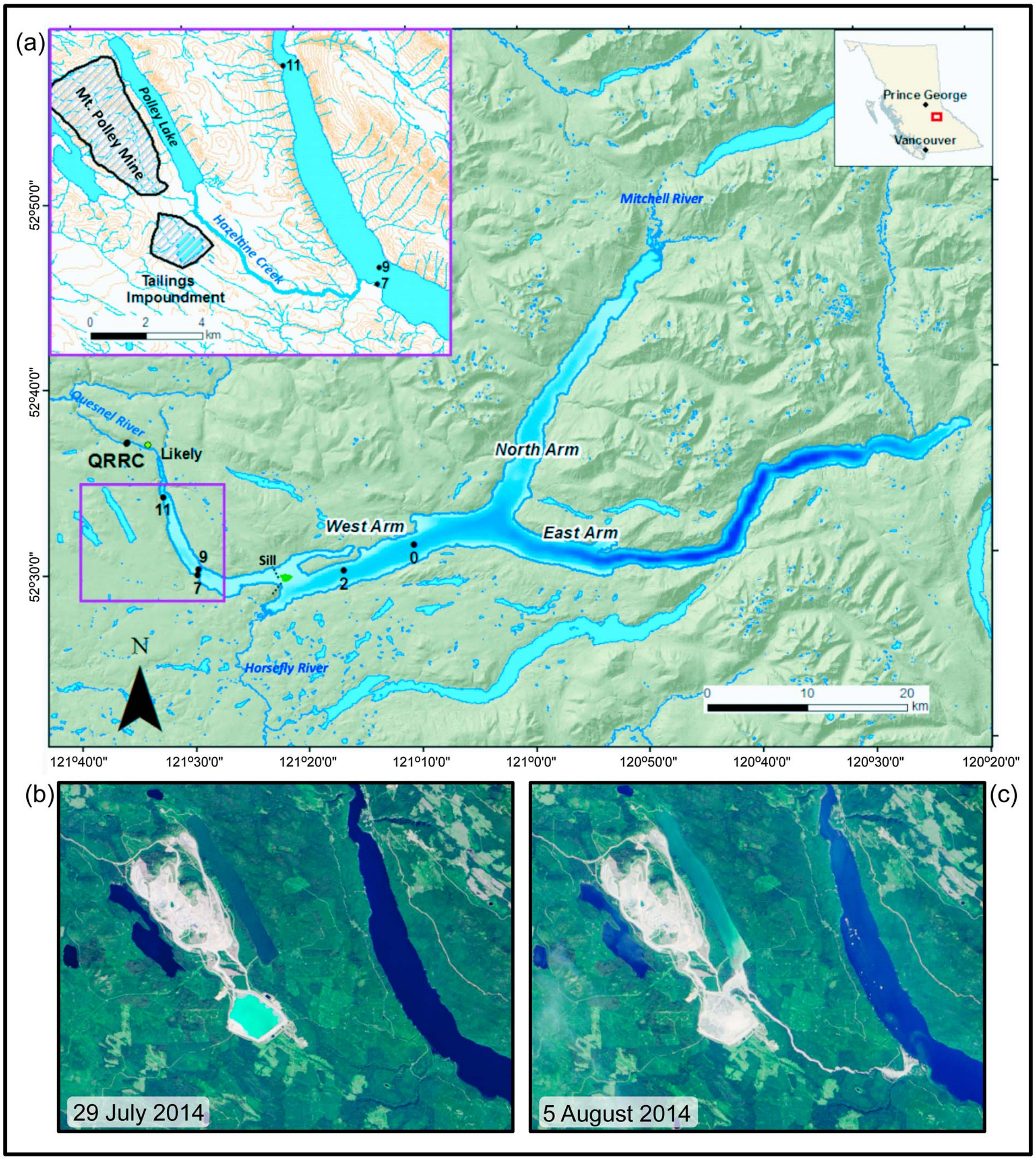

Figure 1. (a) Map of Quesnel Lake and Mount Polley mine site. Shading indicates water depth, and numbers are sampling stations. Satellite image of region (b) before and (c) after the spill [*NASA*, 2014].

We document observations of physical and chemical water column parameters from Quesnel Lake and Quesnel River in the first 2 months following the Mount Polley spill, focusing on the behavior and impact of a massive, sediment-laden surge entering a deep, near-pristine lake. We present an overview of this unique lake and relevant aspects of MPMC operations, followed by our preliminary results. Our objectives are to (1) document the initial response of the Quesnel system to this large disturbance and (2) identify potential medium- to long-term physical, chemical, and biological responses in this aquatic system.

1.1. Site Description

Quesnel Lake is a fjord-type lake with west, north, and east arms (Figure 1a). It is narrow (2.7 km mean width), long (east-west span ~100 km), and deep (maximum 511 m) with a surface area of 266 km^2, volume of 41.8 km^3, and mean depth of 157 m. The mean residence time of Quesnel Lake is 10.1 years [*Laval et al*., 2008].

The West Basin is the western portion of the West Arm that extends 20 km from the 35 m deep sill at Cariboo Island (Figure 1) to the Quesnel River outflow. It has a maximum depth of 113 m, volume of ~1 km^3, and hydraulic residence time, based on Quesnel River outflow, of ~12 weeks. During the summer-stratified period, however, episodic wind-driven seiching results in thermocline upwelling within the West Basin [*Laval et al*., 2008]. Such events last 3–6 days, and individual seiche-exchange events can exchange 25–30% of the hypolimnetic volume of the West Basin giving a seiche-based exchange residence time of 6–8 weeks. Thus, during summer, West Basin hypolimnetic water episodically exits via Quesnel River and then changes direction and exits over the sill toward the main body of Quesnel Lake [*Laval et al*., 2008]. Once in the lake's main body, wind- and river-generated currents transport West Basin hypolimnetic water throughout the lake.

The Mount Polley mine site is located between Polley and Bootjack Lakes, while its tailings impoundment (surface area ~2.4 km^2) is adjacent to Hazeltine Creek (Figure 1a inset). Ore from the open pit mine is processed on site via crushers, grinders, and floatation resulting in material with a mean particle size of 50 μm [*MPMC*, 2014c]. Tailings impoundment water quality concentrations for 2013 indicate that the supernatant water exceeded BC drinking water guidelines only for selenium, total dissolved solids, and sulfates [*MPMC*, 2014d]. However, average metal (here the term metals includes metalloids and nonmetals) concentrations reported for 2013 stored tailings had concentrations of arsenic, copper, iron, and manganese above BC freshwater sediment quality guidelines. [*MPMC*, 2014e; *BCMoE*, 2014a].

The discharged water and tailings from the breach event flowed down and scoured Hazeltine Creek and entered Quesnel Lake midway along the West Basin. Figures 1b and 1c indicate the amount of overburden transported to the lake from the creek's watershed, which was predominantly forested and underlain by Quaternary glaciolacustrine sediment [*Gilbert and Desloges*, 2012].

2. Methods

Conductivity-temperature-depth (CTD) profiles were collected using a Seabird Electronics SBE19plus profiler equipped with Seapoint turbidity and fluorometer sensors. The turbidity probe was calibrated to formazin turbidity units, which we consider equivalent to nephelometric turbidity units (NTUs). Historic data presented (2002, 2005, and 2007) were collected with this instrument.

Prespill temperature data were available from a mooring deployed near Station 9 between July 2001 and June 2005 which included a Vemco Minilog (resolution 0.1°C, calibrated accuracy 0.2°C), a Hobo Tidbit (resolution and calibrated accuracy 0.2°C), and an RBR-Global TR-1000 (resolution 0.001°C, calibrated accuracy 0.003°C).

Two river monitoring stations were deployed at Quesnel River Research Centre (QRRC) (Figure 1a). MPMC installed a YSI EX02 multisonde including a turbidity probe and University of Northern British Columbia (UNBC) installed an Analite thermistor in the channel.

Particle size distributions were analyzed using a Malvern Mastersizer 3000 (range 0.01–3500 μm) at UNBC's Northern Analytical Laboratory. Inorganic and organic proportions of suspended sediment were determined gravimetrically [*Rice et al*., 2012].

3. Results

3.1. Water Level

The time series of water level change in Quesnel Lake in the days surrounding the breach event is shown in Figure 2a. The surge of water, tailings, and Hazeltine Creek overburden into Quesnel Lake generated a series of surface seiches with an 84 min period and ~20 cm peak to peak amplitude that lasted ~12 h. Following this seiching, the lake level had risen 7.7 cm, representing a lake volume increase of ~21 M m^3 assuming a surface area of 266 km^2 [*Laval et al*., 2008].

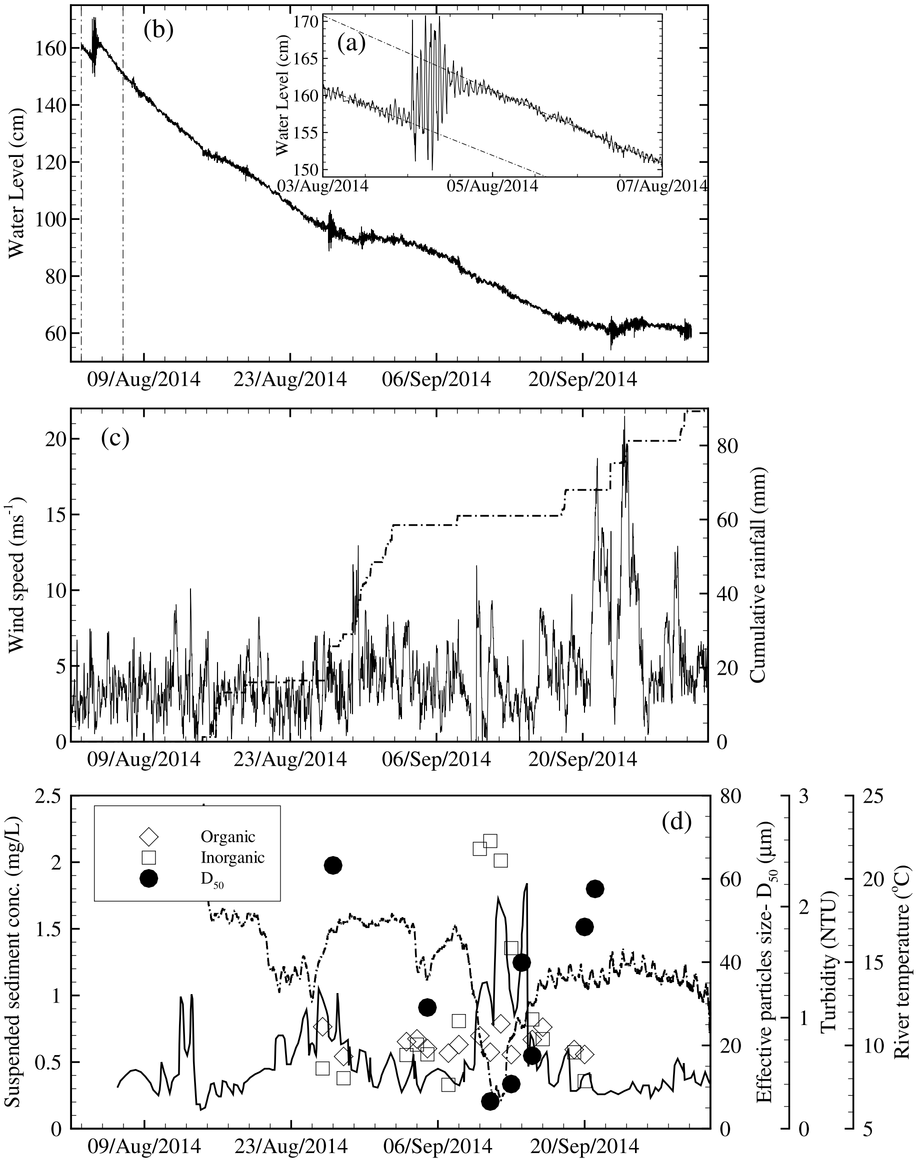

Figure 2. (a) Water level for period in broken lines in Figure 2b measured in Quesnel Lake near Station 11. (c) Wind speed (solid line) and cumulative rainfall (dash-dotted line) from Browntop Mountain (52°42′48″N, 121°20′02″W). (d) Turbidity (solid line), temperature (dashed line), median particle size (D_{50}), and suspended sediment concentrations in Quesnel River at QRRC.

Before and after this event, the lake level decreased steadily (Figure 2b) following normal seasonal patterns. Around 15–17 August, 27 August to 2 September, and mid-September onward, this decrease in lake level slowed due to rainfall (Figure 2c). During the latter two sampling events (27 August and 22 September) increased surface seiching was observed, associated with wind forcing (Figure 2c).

3.2. Postspill State of the West Basin

Spill materials entered Quesnel Lake, immediately modifying the water properties of the West Basin below 30 m depth (Figures 3a–3d). Historically, the seasonal cycle of temperature is dimictic (Figure 3e). Bottom temperatures at 108 m depth vary between 2.5°C and 5.5°C seasonally, being ~4.0°C–4.5°C in early August. Historic profiles indicate temperatures at 30 m ~0.5°C warmer than bottom waters (Figure 3f). However, postspill hypolimnetic temperatures increased to 6–7°C below 30 m (Figures 3a and 3f).

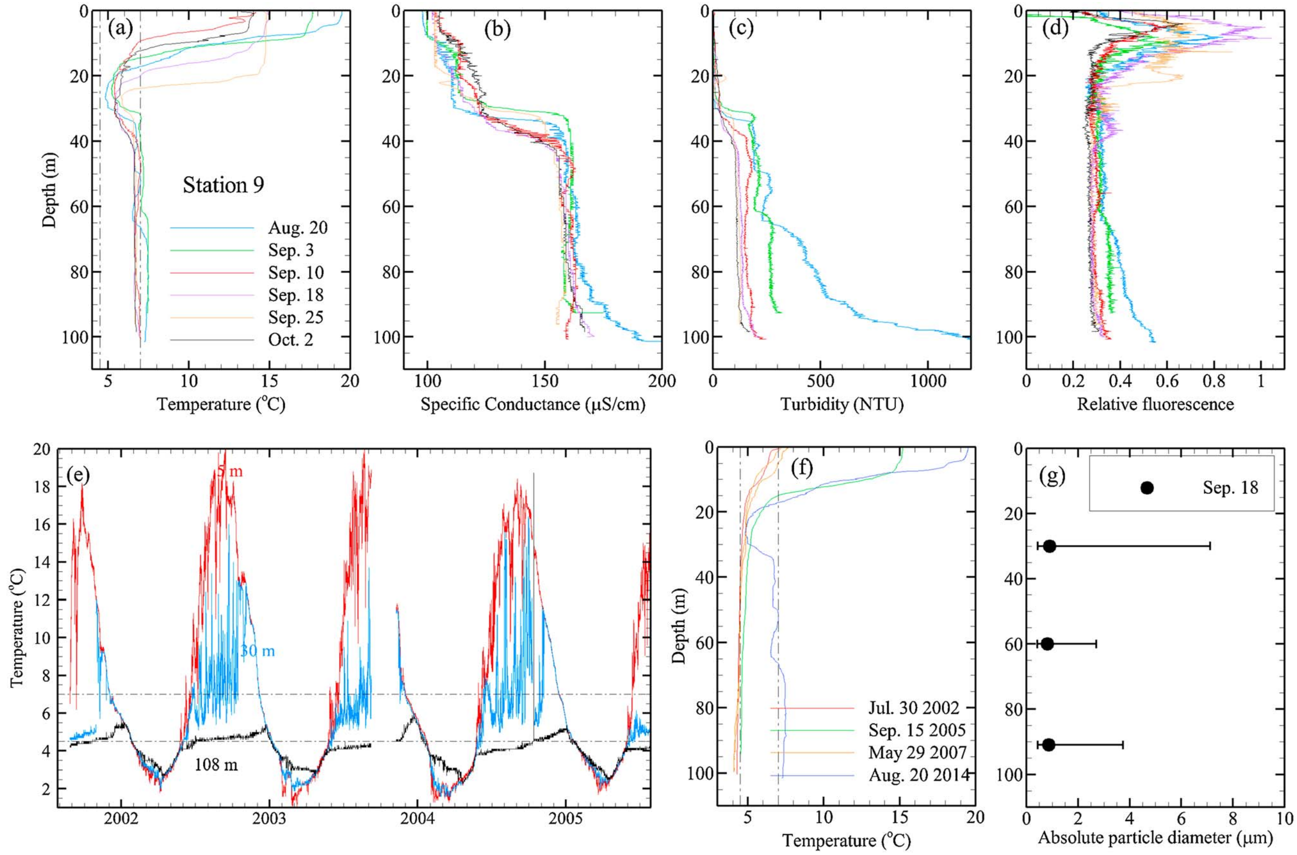

Figure 3. Temporal evolution of breach impact shown by Station 9 CTD profiles of (a) temperature, (b) specific conductance, (c) turbidity, and (d) relative fluorescence. Vertical lines in Figures 3a and 3f indicate prebreach (~4.5°C) and postbreach (7°C) deepwater temperatures. (e) Historic temperature time series at Station 9 (2001–2005), horizontal lines showing deep water temperatures from Figures 3a and 3f. (f) Compares historic profiles (2002, 2005, and 2007) with 2014 data. (g) Median particle size data, with D_{10} and D_{90} shown as bars, on 18 September.

Quesnel Lake specific conductance has historically been measured at 80–90 μS/cm [*Laval et al.*, 2012]. Postspill, it was observed to be 100–120 μS/cm above 30 m depth and 160–170 μS/cm below 40 m with a weak chemocline at ~35 m (Figure 3b).

Historically, Quesnel Lake turbidity was <1 NTU, but at Station 9 on 20 August turbidity exceeded 1000 NTU in bottom waters (Figure 3c), decreased up column, remained >100 NTU to ~35 m, then rapidly decreased above that. Hypolimnetic turbidity between 20 August and 10 September decreased to ~200 NTU below 35 m depth. Thereafter, turbidity below 35 m decreased slowly to ~100 NTU on 2 October. Chlorophyll *a* (Chl *a*) fluorescence profiles indicated relatively high Chl *a* above 30 m, suggesting that this deeper turbidity was not associated with phytoplankton (Figure 3d). Particle size results (Figure 3g) indicated median sizes in the turbidity plume of <1 μm, while surface waters were too dilute to measure.

CTD profiles near Hazeltine Creek (Station 7) (Figures 4d–4f) indicated elevated turbidity (>5 NTU) between 5 and 20 m depth starting 19 August suggesting persistent delivery of turbid water to Quesnel Lake via Hazeltine Creek after the initial surge. Formation of this secondary turbidity layer followed rainfall on 15–17 August and the initiation of MPMC Polley Lake pumping into Hazeltine Creek on ~10 August.

3.3. Westward Fluxes (Toward Quesnel River)

Weekly CTD profiles collected near the lake outlet (Station 11, Figures 4a–4c) exhibited considerable variability in all properties. The water column was initially vertically stratified and warmed until 12 August. By 26 August, vertical stratification had weakened and surface temperature had decreased. Then, by 10 September, the entire water column had cooled by 10–12°C and exhibited elevated specific conductance and turbidity. On 18 September, the water column had warmed by ~7°C (in contrast with seasonal air

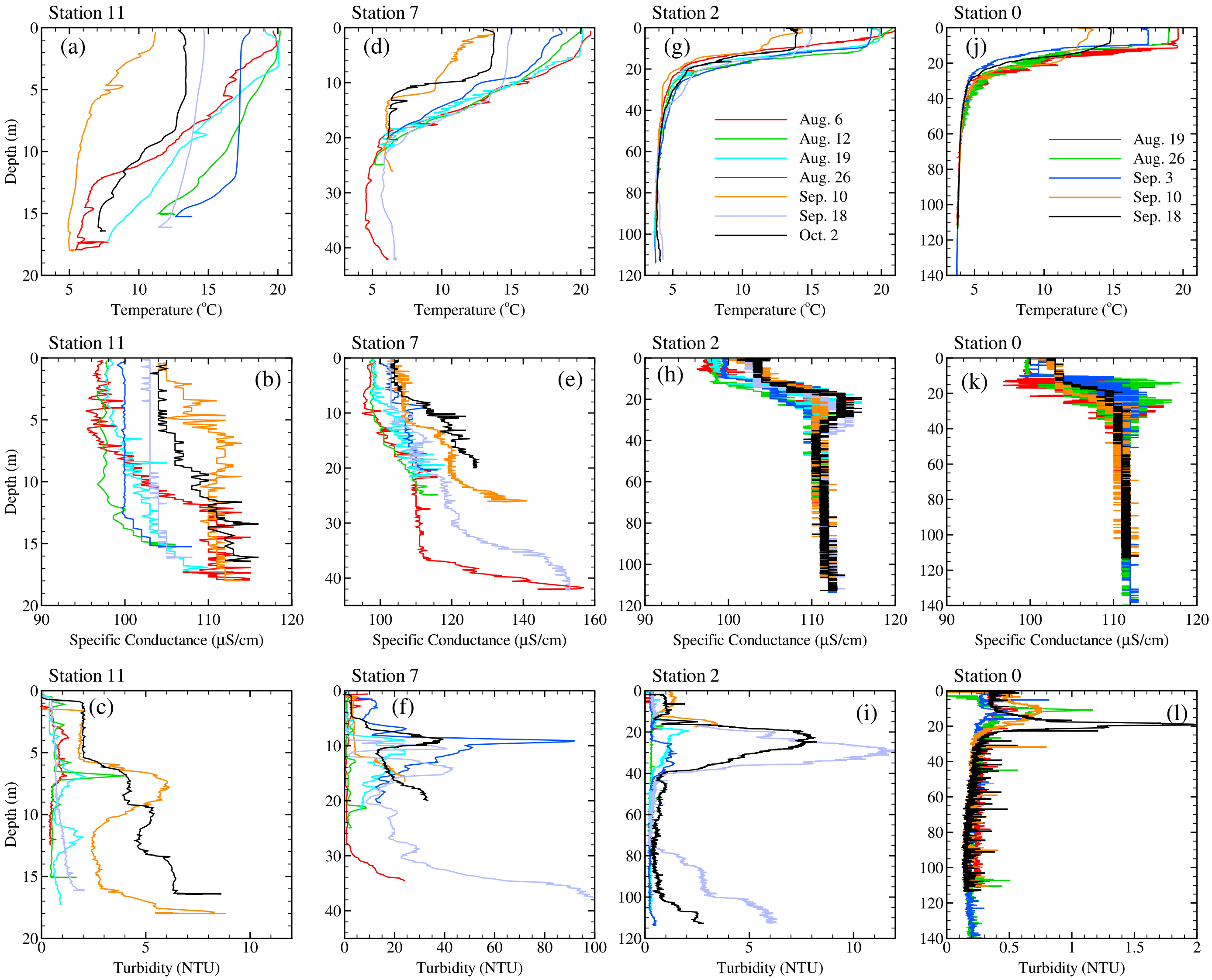

Figure 4. Stations 11, 7, 2, and 0 CTD profiles showing time evolution of breach impact on water (a, d, g, and j) column temperature, (b, e, h, and k) specific conductance, and (c, f, i, and l) turbidity. Figure 4g legend refers to Stations 11, 7, and 2, whereas Figure 4j represents Station 0.

temperature cooling), and specific conductance and turbidity had decreased. By 2 October, temperature had decreased, with a commensurate increase in both specific conductance and turbidity.

Data from instruments deployed in the Quesnel River, at QRRC (Figure 2d), indicated elevated turbidity from 8 to 15 September, which correlated significantly with lowered river temperatures (Spearman's rank correlation: $r_s = -0.67$, $p < .001$, and $n = 768$). During this period of elevated river turbidity the D_{50} of suspended inorganic particles ranged from ~50 to 5 µm and showed a significant negative correlation between concentration and median particle size (Spearman's $r_s = -1.0$, $p = 0.017$, and $n = 5$). These relationships imply that this turbidity was likely derived from Mount Polly tailings and overburden materials.

These extreme weekly water column changes, at the western end of the West Basin, are suggestive of the episodic seiche-exchange process previously observed by *Laval et al.* [2008], whereby cold hypolimnetic water is upwelled throughout the West Basin resulting in rapid Quesnel River temperature decreases. Postspill, the West Basin hypolimnetic water was warmer (but still colder than the epilimnetic water), more turbid, and had slightly elevated specific conductance, in contrast to the overlying epilimnetic water. The highly variable patterns of near-outlet water parameters thus suggest that episodic seiche-exchange

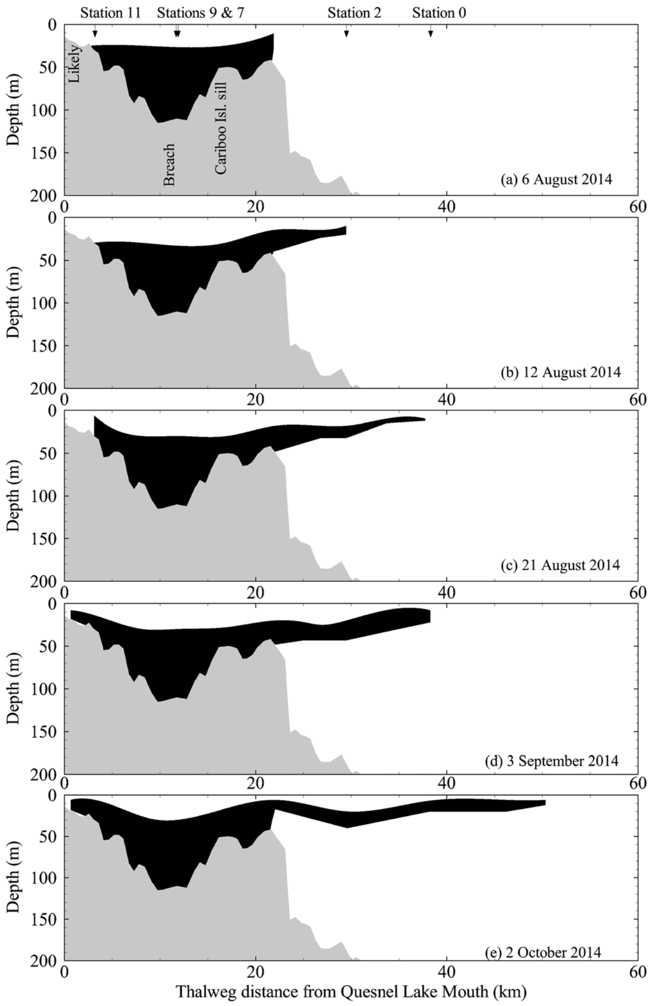

Figure 5. Plume evolution in Quesnel Lake based on water column data.

events resulted in periodic extrusions of event-impacted water from Quesnel Lake. This interpretation was supported by the rapid decreases in temperature, along with rapid increases in turbidity observed in the Quesnel River.

3.4. Eastward Fluxes (Into the Main Body of Quesnel Lake)

Weekly CTD profiles at Station 2, east of the Cariboo Island sill (35 m) that separates the West Basin from the rest of Quesnel Lake (Figure 1a), showed elevated turbidity between 20 m and 40 m depths starting on 19 August (Figure 4i) which increased until 18 September. Note that water at this depth was noticeably warmer on 18 September then decreased somewhat by 2 October (Figure 4g). At the same time, elevated temperature and turbidity at the lake bottom increased in magnitude and layer thickness until 18 September. Given that this turbid water had to pass over the 35 m deep Cariboo Island sill to reach Station 2, it is possible that a turbidity current composed of larger, heavier particles plunged to the lower depths of the West Arm while smaller particles remained in a layer below the thermocline. The slight increase in bottom temperature, commensurate with increased turbidity, (Figures 4g and 4i) suggests that suspended sediment concentrations were sufficient to stabilize this weak temperature inversion.

At Station 2 variations in specific conductance were small, with the hypolimnion nearly uniform at 110 μS/cm (Figure 4h) but with a conductivity maximum at the same depth (20–40 m) as the turbidity maximum. There was no evidence of suspended sediment from the Mount Polley spill between 40 m and 80 m depths.

Similarly, farther east at Station 0 (Figures 4j–4l) CTD profiles do not show elevated turbidity prior to 26 August when a small signal was observed between 10 and 20 m. A smaller signal was detected on 3 September but then increased again until 18 September. Over the complete monitoring period, the mixed layer temperature of the water column's top 10 m generally decreased, consistent with seasonal cooling, while hypolimnetic water stayed approximately the same. At this location variations in specific conductance were also small, with the hypolimnion nearly uniform at 110 μS/cm.

The observed "upstream" transport (i.e., against the hydraulic flow) of event-impacted West Basin hypolimnetic water into the Main Basin of Quesnel Lake (Figure 5) was likely due to the episodic seiche-exchange events observed by *Laval et al.* [2008], bringing West Basin hypolimnetic water over the sill, whereupon buoyancy differences drove this water to preferred depths and eastward toward the lake's East and North Arms. A 7 day interval occurred between the first observations of high-turbidity water at Stations 2 and 0. Given the station separation of 9 km, a propagation speed of ~1 cm/s was calculated which is in agreement with earlier current measurements obtained near Cariboo Island sill (archived data).

4. Discussion

Our observations indicate that the spill rapidly mixed and significantly modified the water properties of the West Basin, including a hypolimnetic (below 30–35 m) temperature increase of 2.5°C (Figure 3a). Naturally, this warm water would have been lighter than overlying water and quickly risen to the surface. However, the water column remained relatively stable up to 2 October therefore providing an opportunity to estimate the minimum amount of suspended sediment required to maintain a stable density gradient. The volume of the West Basin below 30 m depth is 410 M m^3. An ~2.5°C increase in hypolimnetic temperature is observed between historical and postbreach data (Figure 3f). The corresponding density difference is 0.07 kg/m^3, suggesting that ~30 M kg of fine sediment remained suspended in the West Basin water column below 30 m as of 2 October, the last sampling date of the data set.

Subsequent to the initial disturbance, West Basin event-impacted hypolimnetic water was transported (1) into the Main Basin of Quesnel Lake at a speed of ~1 cm/s as a plume held below the thermocline and (2) into the Quesnel River. This eastward and westward transport is captured in snapshots of along-thalweg turbidity from the CTD profiles (Figure 5).

Historically, autumnal turnover in the West Basin begins with deepening of the surface layer starting in late August, reaches 30 m by middle to late October, and the bottom of the West Basin by late December (Figure 3e). Visual observations of the lake surface in late November and early December verified that this pattern was repeated in 2014 as high-turbidity event-impacted hypolimnetic water was entrained into the surface layer and exited via the Quesnel River.

Using a density of 2535 kg/m^3, the average density of the two dominant tailings minerals plagioclase and orthoclase [*MPMC*, 2014f], the 30 M kg of event-related suspended particulate represents a particle volume of 11,000 m^3. Given a median diameter of 1 μm, this corresponds to a total particle surface area of ~10^{11} m^2. Retention of metals, nutrients, and bacteria on these very small and mobile particles provides a potential vector for event-associated contaminant mobilization [*Horowitz*, 1991] throughout the lake as well as into food webs as sediment-ingesting organisms, which are relied upon by anadromous and resident fish, constitute a route of metal bioaccumulation [*Luoma and Rainbow*, 2008]. Settling of these fine particles, while slow, suggests that future monitoring at the sediment-water interface, where biogeochemical conditions facilitating transformation (i.e., redox) occur [*Hamilton-Taylor and Davidson*, 1995], will aid in assessing impacts to the lake ecosystem. Postbreach sediments collected from near the tailings pond, along Hazeltine Creek, and from within the West Basin exceed provincial freshwater sediment quality guidelines for total arsenic, copper, iron and manganese [*BCMoE*, 2014a, 2014b; *MPMC*, 2014f]. While the bioavailability of the suite of metals now in the lake and river has not yet been evaluated by the authors, the literature from other ecosystems identifies several potential pathways for biotic incorporation of sediment-associated and dissolved metals including uptake by biofilm, plankton, and benthos, transference by benthic-pelagic coupling [*Farag et al.*, 1998, 1999], and direct exposure to organisms in the sediments and the water column [*Luoma and Rainbow*, 2008]. Potential ecological implications of metals such as dissolved copper include latent or delayed effects on fish growth, survival and homing, which may be a concern for both resident fish and anadromous salmonids (i.e., juvenile Sockeye and Chinook Salmon) [*Johnson et al.*, 2007; *Lürling and Scheffer*, 2007; *Pyle and Mirza*, 2007; *McIntyre et al.*, 2008]. Focused biotic monitoring to assess bioaccumulation in Quesnel Lake and Quesnel River benthos, zooplankton, and fish should be undertaken.

Food web transfers of metals (e.g., mercury and selenium) occur efficiently in oligotrophic lake ecosystems and are influenced by food web structure and functioning [*Gantner et al.*, 2009; *Lavoie et al.*, 2013]. Mercury and selenium were reported to be low in Quesnel Lake water on 12 August [*BCMoE*, 2014c] yet elevated in salmonid tissues collected 9 August 2014 in Quesnel Lake [*BCMoE*, 2014d]. This suggests that historically, food web transfers (biomagnification) to top predator species occur efficiently within Quesnel Lake. We thus expect that some spill-related metals in Quesnel Lake will be subject to bioaccumulation and/or biomagnification through aquatic food webs to planktivorous fish (i.e., Sockeye Salmon and Kokanee) and top predator fish species (i.e., Rainbow Trout and Lake Trout) over time. Late September 2014 hydroacoustic and trawl surveys conducted in Quesnel Lake indicated an abnormal spatial aggregation of juvenile Sockeye Salmon in the West Basin relative to data collected over the period 1982–2012. Spatial variation consistent with historical patterns of diurnal vertical migration was also observed in late September 2014, suggesting the juveniles likely entered the turbid bottom waters and were exposed to materials associated with the mine spill for substantial periods each day. This potential for pervasive abiotic and biotic contamination in Quesnel Lake and Quesnel River warrants studies to measure and evaluate contaminant mobility and entry into food webs, food web transfer and biomagnification, and subsequently, long-term trends in metals of concern in resident and migratory fish species.

5. Summary and Conclusions

This unfortunate Mount Polley mine tailings impoundment breach into Quesnel Lake provided an opportunity to observe the behavior of a massive turbidity current entering a deep water body. Natural lake processes, including seiching, contributed to the spread of the turbidity plume upstream into the main body of the lake and downstream into Quesnel River. While dilution effects and remediation efforts underway as part of the MPMC cleanup process may reduce the observable impact on the lake's ecosystem, tailings and scour materials are and will continue to be transported throughout the lake. Also, twice annually (spring and autumn) the West Basin will experience isothermal conditions and overturn, potentially reentraining settled tailings and scour material into the water column. The nature of waste materials now present in Quesnel Lake presents a potential hazard to the metal content of aquatic food webs and the growth, survival, and behavior of important fish species.

Acknowledgments
All hydrometric data were obtained from Environment Canada's HYDAT database, while lake surface elevations from a station at Cedar Point, near Station 11, were retrieved from Environment Canada's Real-time Hydrometric Data website http://wateroffice.ec.gc.ca/report/report_e.html?type=realTime&stn=08KH011. Quesnel River turbidity data were obtained at http://www.imperialmetals.com/i/mt-polley/2014-11-28_MOE.pdf. Historic Quesnel Lake physical data are archived at http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/index-eng.html. Earlier involvement of BC Provincial Ministry of Environment (Rob Dolighan and Dale Sebastian) and Fisheries and Oceans Canada personnel (Jeremy Hume, Ken Shortreed, Garrett Lidin, and Lucas Pon) in Quesnel Lake generated initial collaborative research on the physical and biological limnology, providing invaluable background data for this type of research. Funding was provided by NSERC, FRBC, and UNBC bridging funds to various researchers. Laszlo Enyedy, Jessica Gillis, Jacob Duros, Richelle Sussbauer, Will Procter, and Brody Granger provided assistance in the field. Kristy Rasmus assisted with field sampling and prepared the map, and Todd French assisted with edits. This paper comprises part of the Quesnel River Research Centre Publication Series.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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Erratum

In the originally published version of this article, there were errors in the estimations of the order of magnitude of sediment mass, volume, and surface area due to the use of the wrong water volume for the West Basin bottom water. The following have since been corrected, and this version may be considered the authoritative version of record (all corrections in section 4): The volume of the West Basin below 30 m depth was changed from ~14 Mm^3 to 410 Mm^3. The density difference was changed from 0.08 $\mathrm{kg/m}^3$ to 0.07 $\mathrm{kg/m}^3$. The amount of fine sediment that remained in the West Basin water column below 30 m was changed from ~1 M kg to ~30 M kg (stated in the 1st paragraph and 4th paragraph). The particle volume was changed from 394 m^3 to 11,000 m^3. The total particle surface area was changed from ~10^9 m^2 to ~10^{11} m^2.