Technical review of the Morrison Lake Water Quality Model contained in Pacific Booker Minerals’ (the proponent) Application for an Environmental Assessment Certificate for the proposed Morrison Copper/Gold project.

By: Dr Bernard Laval, PhD, PEng

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1 Introduction

1.1 Background

Due to uncertainties relating to the potential for significant adverse effects from the proposed project, BC-EAO undertook a third-party review of hydrogeology, geochemistry and water quality predictions for a major mine proposal in north-central BC. The project is located adjacent to a high-value sockeye salmon lake, and would leach tailings water (tailings storage facility, TSF and potentially acid generating material, PAG) and discharge treated mine effluent (water treatment plant, WTP) into the lake year-round.

The external review report by Robertson GeoConsultants (RGC, 2011) cautioned that there is some uncertainty regarding the lake-mixing model that needs to be addressed. The proponent has responded to this external review. This review assesses the proponent's response, with a focus on the concerns listed below, and ends with a written opinion and recommendations on the lake water quality model validity.

RGC (2011) Section 3.3.2:

"**Of particular concern is the large difference in salinity between mine water seepage (TDS ~2,500 mg/L) and lake water (TDS ~50 mg/L) which could potentially result in concentration of mine seepage at the bottom of Morrison Lake ("density-driven flow")**. We therefore recommend that an independent expert in physical limnology be consulted to assess the assumptions of physical mixing in the lake water quality predictions used by the Proponent (see Section 4)."

RGC (2011) Appendix D, Section 3.2:

"… For the purpose of predicting water quality in Morrison Lake, the discharge of treated effluent from the WTP was assumed by the Proponent to be constant and to enter the lake via a diffuser at the bottom end of the north basin. Flows of TSF porewater were assumed to enter the lake via streams MCS-7, MCS-8, and MCS-10 and direct groundwater discharge. PAG-contaminated groundwater from the open pit was assumed to discharge directly to Morrison Lake. After considering loads from each source, predicted concentrations are compared to the BCWQGs in order to identify potential exceedances."

"… **However, it is important to recognize that the final concentrations provided in the REV2 report assume that (i) Morrison Lake has reached a condition of steady-state (i.e. outflows from the lake are equivalent to inflows of treated effluent) and that (ii) the highly-idealized model of physical mixing in Morrison Lake is a realistic representation of actual conditions in the lake.** The main point of concern for the author is that water quality conditions in the lake could be significantly worse than predicted by the Proponent if assumptions regarding complete mixing and steady-state conditions are invalid and/or if higher flows to the lake occur after mine closure (see Appendix A).

"**For instance, it seems plausible that higher concentrations could occur at certain times of the year when complete mixing has not yet occurred or almost permanently in areas where mixing is restricted** (either due to lake bathymetry or due to changes in the physical and chemical condition of the lake that would prevent the lake from turning over). **Specifically, it seems likely that ‘hotspots’ of contamination could develop if contaminant loads from PAG-contaminated groundwater mixed with a volume of water that is less than the total lake volume and in deeper parts of the lake where dense effluent from the diffuser could accumulate.**

“In light of these uncertainties, the author recommends that the mixing assumptions used by the Proponent to predict lake water quality be reviewed by an independent expert in physical limnology. **This review should include an assessment of the potential development of contaminant ‘hotspots’ in different parts of the lake and the potential effect of effluent discharge on mixing and lake turn-over.**”

1.2 Review objectives

- Assess the relevant baseline data provided by the Proponent for the lake mixing model used to predict the effects on water quality in Morrison Lake
- Assess the validity of the model used for prediction of the effects to the lake water quality overall, in particular the potential for incomplete lake mixing and localized areas of contamination near shorelines, taking into account the full lifecycle of the mine
- Determine if the model supports the proponent’s conclusions that the lake water quality predictions represent a realistic outer bound scenario. If the data and assessment do not support the proponent’s determination of effects, the contractor will specifically define for the Environmental Assessment Office what data and assessment is required for the environmental assessment.

2 Review:

The proponent’s lake model (“the lake model”), described in Appendix V of KCB (2012a) and developed by Dr Lawrence, is a highly idealized, conceptual model designed to provide the outer bound for the time evolution of the lake-wide-average concentration. Note that the model is designed to provide an outer bound for the maximum lake-wide-average concentration, not the overall maximum within the lake. There has been no calibration or validation as there is insufficient data to do this. This lack of data supports the use of this simple model versus a more complex or realistic model.

The time evolution component of this model addresses RGC (2011)’s concern about the proponent’s earlier (KCB, 2010) assumption that the lake had reached steady state. However, it does not address RGC (2011)’s concern about incomplete mixing and spatial distributions of contaminant concentration. This review first considers the lake model assumptions about seasonal evolution of stratification and freshet. Consideration is then given to spatial distribution of water treatment plant (WTP) discharge and associated diffuser design constraints. Subsequently, spatial distributions of an unlined tailing storage facility (TSF) and potentially acid generating (PAG) material seepage into Morrison Lake will be considered. Potential impacts of local climate change over the full life cycle of the mine are discussed. Finally, the same considerations are given to the case of a fully geomembrane lined TSF.

2.1 Lake model

The lake model is designed to provide an outer bound for the lake-wide-average concentration of effluent from all sources. The effluent sources include discharge through a diffuser at the lake bottom from a water treatment plant (WTP), near-surface seepage of water from the tailings storage facility (TSF) and potentially acid generating (PAG) material, as well as creek inflow containing TSF seepage. Limitations of the assumption of rapid and complete mixing of mine effluent within the lake are addressed in later sections. This section focuses on the model assumptions about season stratification and freshet. Note that all simulations presented in this report use effluent concentrations given in Table 5.2 (Upper Bound Concentrations (mg/L) of Key Parameters in Morrison Lake) of KCB (2012b)

2.1.1 Stratification

The lake model assumes Morrison Lake is dimicitic, with complete mixing or overturn occurring in fall and spring. The lake is assumed to be weakly stratified during winter such that effluent can freely circulate throughout the lake. During spring and fall overturn and winter, effluent from all sources is assumed to mix rapidly and completely throughout the entire lake volume. During summer, the lake stratifies into an epilimnion overlying a hypolimnion, separated by a thermocline. The strong vertical variation in density associated with the thermocline effectively isolates the epi- and hypolimnion from each other. During summer TSF seepage and creek inflow, as well as PAG seepage are assumed to rapidly and completely mix throughout the epilimnion volume, while WTP discharge mixes rapidly and completely throughout the hypolimnion volume.

The main limitation of these assumptions is how quickly and completely mixing of effluent with lake water occurs. Mixing of WTP water in the lake is discussed in section 2.2. Mixing of TSF and PAG water in the lake is discussed in section 2.3. The assumption of spring freshet occurring during spring overturn and prior to onset of summer stratification is discussed next.

2.1.2 Freshet

Other than input of effluent mass, the lake model assumes there are no inflows or outflows except during spring freshet, which is assumed to occur during spring overturn and prior to onset of summer stratification. During freshet, Morrison Lake is assumed to behave as a continuously stirred reactor (CSR), in which the year's annual runoff enters the lake, mixes rapidly and completely with lake water, and there is a commensurate outflow of the resulting mixture. This CSR assumption is reasonable given that about 50% of the annual outflow from Morrison Lake occurs during freshet. Furthermore, this assumption is conservative in that it results in a larger maximum lake-wide-average concentration when compared to not making this assumption.

The lake model assumes that overturn and freshet occur at the same time. Penetration of sunlight through the ice will destabilize and mix the water column prior to ice off. Thus, overturn will likely occur within a few days or weeks to either side of ice-off in mid-April to mid-May. With the strong solar heating at this time of year, thermal stratification will establish rapidly. For example, the June 2011 survey (KCB, 2011) shows a roughly linear thermal stratification of the lake water with ~10ºC near the surface decreasing to

~4ºC at ~10 m depth. This shows that the lake is not isothermal during freshet and that the river inflow is therefore not mixing with the entire lake volume at this time.

Inflow propagation through the lake will depend on the relative density of the lake and river water. Assuming the solute and suspended solid concentrations for the inflows and lake are similar, the relative density will be primarily determined by relative temperature. A warmer inflow will be confined to the epilimnion. It will traverse the lake at the surface (i.e. an overflow) and exit at the outlet. A colder inflow will be confined to the hypolimnion. It will plunge along the lakebed as a dense underflow, mixing with overlying lake water, until it reaches a depth of neutral density (underflow density equals the density of surrounding water) or the lake bottom. The inflow will then traverse horizontally and fill the lake from the bottom up, while water from the epilimnion will exit the lake at the outflow.

Freshet inflow not mixing with the entire lake volume will have implications for the lake model predictions. After spring overturn, the lake will stratify into an epilimnion and hypolimnion, each having similar initial effluent concentrations. The epi- and hypolimnion will then evolve independently through freshet.

In the overflow scenario, the hypolimnion will be effectively isolated, and the epilimnion will behave as a continuously stirred reactor. After freshet, concentrations in the epilimnion and hypolimnion will evolve independently until fall overturn when the two layers mix. This differs from the lake model in that only the epilimnion volume participates in the CSR during freshet.

In the underflow scenario, only epilimnetic water will exit via the outflow. Thus, the concentration of effluent in the exiting water could be approximated as the overturn concentration. The lake will fill from the bottom up with a mixture of hypolimnetic and inflowing water. This differs from the lake model in that only the hypolimnion participates in the CSR, while only the epilimnion water exits the lake.

Consider the following four scenarios for the freshet period: a) continuously stirred reactor (the proponent’s model); b) overflow; c) underflow; d) alternating between the three other scenarios as the freshet progresses. The underflow scenario is the best case because the water exiting via the outflow has the highest concentration. The overflow scenario is the worst case because the water exiting via the outflow has the lowest concentration. The other two scenarios are intermediate.

The available data suggest the lake is stratified during freshet (June 2011, KCB 2011) and temperature of the main inflow (Tahlo Creek) could be sufficiently high (David Bustard June 2000. Coho Fry Sampling Results in the Morrison Watershed) for the overflow scenario to occur. Furthermore, Tahlo Creek is fed from upstream lakes, increasing the likelihood that it will be warm enough to form an overflow in Morrison Lake. However, there are insufficient data to determine the probability and duration of each scenario. An upper bound can be established by assuming the overflow scenario occurs over each freshet. Applying this assumption to the lake model results in an increase in maximum lake-wide-average concentration for all contaminants (Figure 1), with the annual maximum shifting from end of winter to end of summer in the hypolimnion. Cadmium, which was already predicted to be in excess of the BCWQG increases by 13%. Iron, whose baseline value exceeds BCWQG, remains relatively unchanged. Sulphate, magnesium and zinc approach, but still remain below, the BCWQG. All other contaminants are relatively unchanged from the proponent's prediction.

2.1.3 Other considerations

The lake model assumes that WTP water is mixing across the entire hypolimnion volume, including across the sill joining the north and south basins. The likelihood of complete mixing of WTP water in the hypolimnion of the south basin is low. A more conservative approach would be to consider complete mixing across the north basin hypolimnion only. This will only make a small difference since the south basin hypolimnion volume is only 4% of the total hypolimnion volume.

2.2 Water treatment plant discharges

The proponent's conceptual diffuser design is unconventional in that the equations used are for upward discharge of positively buoyant jets and, based on the proponent's estimate for the water properties of the effluent (TDS ~2500 mg/L and temperature 7-10ºC), the design discharge will be negatively buoyant. However, this is specifically addressed by designing the diffuser discharge to behave as a turbulence jet to overcome buoyancy effects. This added design constraint leads to the conclusion that the design dilution cannot be achieved with a single port diffuser as proposed in KCB (2010). KCB (2012a) address this by proposing a multi-diffuser, which provides an extra design parameter (diffuser length) allowing design dilution to be reached, while still satisfying the additional constraint that the discharge behave as a turbulent jet.

2.2.1 Overmixing

The conceptual diffuser design in KCB (2012a) is intended to provide conservative estimates for the dilution that can be attained with a well-designed diffuser, but neglects the impact of diffuser-induced mixing of the ambient stratification. The diffuser design overcomes buoyancy effects on the jet by using excessive jet momentum, but as a result injects more energy than necessary into the lake. This may alter ice-cover timing and thickness, as well as altering the natural progression of stratification by weakening seasonal stratification during winter and summer and/or altering timing and duration of overturn. The ecosystem of the lake has adapted to the current stratification regime, and so added mixing to the environment should be considered with care. Containing the negatively buoyant plume to the deep regions of the lake could minimize these impacts. As discussed below, this should be attainable through changes in diffuser design.

2.2.2 Fountain filling box model

The lake model assumes that diffuser effluent will mix rapidly and completely with either the lake or hypolimnion (depending on the stratification). This assumes the negatively buoyant jet associated with the diffuser will spread radially when it impacts a boundary (in this case either the thermocline or free surface) with considerable upward momentum. This assumption likely not appropriate. I am not aware of detailed experiments that investigate this particular geometry; however, Figure 9.13 (round negatively buoyant jet) in Fischer et al (1979) suggests that a negatively buoyant jet impacting a boundary will not spread radially; rather it will fall back on itself like a fountain. There are two important implications of this observation. 1) The uprising jet will interact with itself as it falls down, thereby changing the behavior and dilution associated with this jet from that assumed by the proponent. 2) The effluent will not mix with the entire volume of the lake (or hypolimnion) before falling to the lake bottom.

Regardless of the amount of dilution incurred through diffuser design, the effluent at the edge of the initial mixing zone will always be denser than the surrounding water and the effluent mixture will fall back towards the lakebed. As the negatively buoyant plume travels through the background stratification and mixes with it, the resulting effluent mixture will eventually fall back to the lake bottom and form a slightly denser layer at the lake bottom. The negatively buoyant plume will then travel through and entrain this denser layer along with ambient water, thereby have an even higher density when it too eventually falls back to the lake bottom. This will create an even denser layer at the lake bottom. Through this mechanism, known as a filling box model, the lake will fill from the bottom-up with progressively denser water.

Filling box models fed by a negatively buoyant jet (a.k.a fountain filling box models) have been studied before (c.f. Baines et al., 1990) and estimates can be made of the resulting density stratification. A fountain filling box model predicts higher concentrations at the bottom than the complete mixing model used by the proponent. As well, the fountain filling box model predicts a steady increase in stratification over time. Thus, it is important that the diffuser provide sufficient dilution such that the maximum concentration immediately prior to turnover meets water quality guidelines.

The optimal diffuser design must meet the following criteria: 1) avoid overmixing of the environment, 2) consider the fountain-like behavior of a negatively buoyant jet, and 3) achieve appropriate dilution. A diffuser design that meets these criteria is that based on negatively buoyant jet issuing at a small angle to the vertical that is allowed to reach its terminal height within the hypolimnion (i.e. within 40 m of the bottom) and fall away from the upward jet. This design will better characterize dilution within the initial mixing zone and prevent adverse effects of overmixing the environment. Preliminary calculations for a negatively buoyant jet from a single port oriented at a 7° angle to the vertical (i.e. allowing the used of Baines et al., 1990 for calculations) with a port diameter of 15 cm will provide a fountain with a terminal height of 40 m. Such fountain will provide a dilution that decreases with time as effluent concentration in the hypolimnion increases with time; however, even after 300 days the minimum dilution[†] exceeds 100:1. Thus, even with the increased duration of summer stratification that is expected to occur with climate warming (see section 2.4) a minimum dilution of 100:1 can be attained through appropriate diffuser design. Even better performance could be achieved with a multiport diffuser.

[†] Here dilution is defined as $S = \frac{C_{eff} - C_{amb}}{C_{bott} - C_{amb}}$ (Fischer et al., 1979) where C_{eff} is the concentration in the WTP effluent, C_{amb} is the baseline lake concentration, *and* C_{bott} is the effluent concentration at the lake bottom predicted by the fountain filling box model.

With a 100:1 dilution of effluent achieved through diffuser design the bottom water density is predicted increase by 0.03 kg/m^3 over current conditions. This slight increase in bottom density has a very low probability of resulting in meromixis or suppression of annual overturn.

2.3 Impacts of TSF seepage into creeks/groundwater (3rd party review response section 2.2 and 7)

2.3.1 Creek inflow to lake (TSF)

Creeks MC-7, MC-8, MC-10 containing TSF seepage enter into the lake and mix with lake water. The concentration of TSF seepage in the creeks as they enter the lake will vary seasonally as it is diluted by creek water. During winter, when creeks flows are minimal, the proponent conservatively assumes no dilution by creek water.

Spatially, there will be a mixing zone around each creek mouth in which contaminant concentrations will vary from creek to lake concentrations. The spatial extent of this mixing zone will depend on wind speed and direction, and the relative density of the creek and lake water. If the creek water is less dense than the lake water, the creek water will float above the lake water and drift downwind (overflow), while it is mixed vertically. If the creek water is denser than the lake water it will form a dense underflow and flow down along the lakebed. As this dense underflow propagates along the lakebed it will mix with overlying lake water, thereby reducing the density of the underflow, until reaching either the lake bottom or a level of neutral density; i.e. the depth at which the underflow has the same density as surrounding lake water. If the underflow reaches a level of neutral density, it will lift off the bottom and propagate horizontally.

In the creek overflow scenario, creek water will be mixed rapidly across the epilimnion first by its own momentum, then by wind. This is the condition assumed in the proponent's lake model.

In the underflow scenario, the creek water will be confined to a relatively thin layer at the lakebed. This thin layer would likely extend along the lakebed from the creek mouth to the thermocline, whereupon it may form a layer within the thermocline, or it could extend along the lakebed to the lake bottom and fill the lake from the bottom up. Thus the underflow scenario has two main implications for concentration distributions. 1) The filling of the lake either at the thermocline or lake bottom would interact with a similar filling due to fountain filling box phenomenon described in section 2.2.2. 2) From a spawning salmon perspective, the dense underflow scenario is of concern as there will be higher contaminant concentrations along the lakebed in the vicinity of the creek mouth as this thin layer flows along the lakebed.

The proponent's lake model assumes the rapid mixing of creek water throughout the lake, which would occur with an overflow. Using the upper bound concentration for TSF (Table 5.2, KCB 2012b) to calculate inflow density suggests that the creek inflows will always be denser than lake water (assumed to have TDS 50 mg/L and temperature 4ºC) for creek inflows cooler than ~18ºC. Therefore, at the upper bound concentration the creek inflows would almost always behave as underflows. This is primarily driven by the relatively high sulphate concentration of 1700 mg/L. For illustrative purposes only, assuming less conservative values for sulphate of 500 mg/L (250mg/L), while keeping the other solute concentrations the same, the creek inflows will behave as underflows for creek temperature less than ~13ºC (~11ºC). Thus, even at much lower concentrations, the creek inflows will behave as underflows for much of the year.

Without more data and analysis, it is difficult to predict contaminant concentration near the lakebed in the region of the seepage input; however, outer bounds range from the lake-wide-average as predicted by the lake model to undiluted seepage.

2.3.2 Groundwater seepage into lake (TSF and PAG)

Groundwater seepage of TSF and PAG water is predicted to enter Lake Morrison over a broad (~1 km) region of shoreline at shallow depths. As discussed in the previous section, this water will likely be denser than lake water and therefore behave as an underflow. As the spatial input of this water is much broader than the creek inputs, there is more potential for mixing with lake water, while the underflow is within the epilimnion. This mixing should be effective whenever the wind is acting on the water surface above the seepage input region. However, during periods of weak wind or in wind shelter regions, TSF and PAG seepage will form an underflow along the lakebed with the same consequences as described above for creek inflow. Note that the seepage will form an underflow during periods of ice-cover, which currently represents about 1/3 of the year for Morrison Lake.

2.4 Climate change

The proponent has not considered the influence of climate change on Morrison Lake over the 100-year prediction of the lake model. Air temperature is often used an indicator of climate change, though changes in other parameters such as cloud cover, precipitation, storm tracks and wind speed will also impact lake function. BCMOE (2007) predicts an increase in annual average temperature of 0.30 ºC/decade for Smithers, B.C., and an increase of 0.65 ºC/decade for winter average temperature. A warming climate will change the seasonal progression of mixing in the lake. As the local climate warms, fall overturn will occur later and spring overturn sooner. This will result in increased duration of the summer-stratified period, with a commensurate decrease in winter stratification and ice-cover.

Considering over 100 years a possible 6.5ºC increase in winter average temperature it is possible that Morrison Lake could reach point where ice-cover does not occur every year. In this case, winter wind storms could keep the lake well mixed throughout the winter, changing the lake's mixing status from dimictic to monomictic, whereby overturn only occurs once per year (i.e. throughout the winter). Furthermore, this warming will also impact timing and magnitude of freshet. With decreasing snow pack, the amplitude of freshet will diminish and inflows during winter will increase. With warmer air temperature the freshet will occur sooner and inflow temperature will generally increase. These changes will have implications for the lake model and its predictions of lake-wide-average concentration.

The potential impacts of these changes are both positive and negative. Increasing winter inflows will dilute TSF seepage into creeks, thereby reducing concentrations within the creeks and the lake in the vicinity of the creek mouths. Local climate change will alter the magnitude and timing of the freshet, as well as timing and evolution of the season lake stratification. This will change duration each season state, as well as interactions between freshet and onset of stratification.

Modifying the proponent's lake model can bound impacts of local climate warming on lake-wide-average concentration. Within the assumptions of the lake model, whether the lake is dimictic or monomictic is irrelevant since the model assumes complete mixing during winter. Therefore, the predominant effect of local climate warming on the model prediction will be an increasing duration of the summer stratified versus the winter unstratified period. As an outer bound for climate change effects on lake-wide-average maximum concentration, consider a linear in time reduction of the duration of full lake mixing (winter plus freshet) from the current 8 months to 2 months over 100 years. Next, to establish an outer bound for climate change combined uncertainty of inflow mixing during freshet (see section 2.1.2), consider the following two freshet scenarios: 1) freshet mixes rapidly and completely throughout the lake (proponent's current assumption); and, 2) freshet is confined to the epilimnion (overflow assumption). For purposes of comparison the proponent's lake model assumptions (i.e. no climate warming and freshet mixes completely) is taken as the baseline.

With increasing duration of summer stratification, under the freshet-mixes-completely assumption, there is very little change in maximum lake-wide-average concentration (**Figure 2**). This shows that if the lake is completely mixed over the 2 months of freshet, lake-wide-average concentration will not be significantly increased by climate-induced increases in summer stratification. Though the concentration remains well below the water quality guidelines, it is interesting to note the persistent increase in nitrate concentration over the entire 100-year period.

Assuming the freshet is confined to the epilimnion (i.e. overflow), maximum lake-wide-average concentration increase for all contaminants (Figure 3), with the annual maximum occurring in the hypolimnion at the end of summer. Cadmium, which was predicted to be in excess of the BCWQG in the baseline simulation, increases by 15% over the baseline case. Sulphate, magensium and zinc approach, but do not exceed, the BCWQG. All other contaminants are relatively unchanged from the proponent's prediction.

2.5 Geomembrane Liner

Lining the TSF with a geomembrane with reduce the flow rate of contaminated water reaching Morrison Lake though it is conservatively assumed that the contaminant concentrations remain unchanged. To estimate an outer bound for contaminant concentration in Morrison Lake, consider the upper bound flow rate of 10 m^3/hr for TSF flow reporting to Morrison Lake (KCB 2012b). Figures Figure 4Figure 6 show the same comparisons presented for the unlined case in the above sections. Reducing the TSF inflow to Morrison Lake reduces contaminant concentrations in Morrison Lake. Iron still exceeds BCWQG, because the baseline concentration already exceeds BCWQG. There is a significant reduction in cadmium concentration such that it no longer exceeds BCWQG for any case. While neither sulphate nor magnesium are predicted to exceed BCWQG within 100 years, both show a significant increasing trend for the freshet overflow case with consideration of climate change (Figure 6).

3 Conclusions and Recommendations

There is very little existing data on the physical characteristics of Morrison Lake. As a result the proponent's lake model is conceptual and intended to provide an outer bound for the lake-wide-average over the lifetime of the mine closure. In the model, the lake is idealized as one or two boxes depending on the thermal stratification. Any input to a box is assumed to mix instantaneously across the box, thereby providing box-wide-average concentrations. The lake model is based on several assumptions about how a typical lake in this climate would function. These assumptions were chosen to be conservative, thereby providing an outer bound. The lake model has four main weaknesses. 1) It does not consider that the freshet inflow will likely have a temperature different from that of lake water, or that the lake may be thermally stratified during freshet. 2) It assumes effluent from the WTP mixes completely throughout the hypolimnion. 3) It assumes seepage from TSF and PAG entering via creeks and as seepage through the lakebed mixes completely throughout the epilimnion. 4) It does not consider the effect of local climate warming on the seasonal evolution of lake thermal structure.

June 2011 temperature profiles in Morrison Lake indicate the lake is not fully mixed during spring freshet. This implies that, rather than mix with the entire lake as assumed by the proponent, freshet water will only mix with either the epi- or hypolimnion depending on the density difference between inflow and lake water. If possible, concurrent measurements of inflow temperature and lake thermal stratification should be made to establish the flow regime. In the absence of any measurements of inflow temperature, an upper bound can be established by assuming the freshet acts an overflow in the proponent’s model. Results suggest an increase in maximum lake-wide-average concentration for all contaminants (Figure 1), with the annual maximum shifting from end of winter to end of summer. Cadmium, which was predicted to be in excess of the BCWQG in the proponent’s simulation, increases by 13% over the proponent’s prediction. Sulphate, magnesium and zinc approach, but still remain below, the BCWQG. All other contaminants are relatively unchanged from the proponent’s prediction.

The proponent’s conceptual design of WTP discharge into Morrison Lake introduces excessive momentum to overcome the effluent’s negative buoyancy. This has the potential to unnecessarily overmix the lake. Furthermore, the proponent’s design does not consider that the negative buoyancy of the buoyant jet will cause it to act as a fountain filling-box. Diffuser design should directly include the effects of negative buoyancy of the discharge and attempt to keep the terminal height of the plume below the seasonal stratification. This will minimize the amount of energy added to the lake. Modelling evolution of the background stratification with a fountain filling-box type model to account for accumulation of the diluted (but still denser than lake water) discharge leads to the following conclusions: 1) the upward buoyant jet should be slightly off vertical, such that the falling plume does not interact with the upwards jet; 2) 100:1 dilution or better dilution can be obtained with a single port diffuser within a terminal height of 40 m even for a 300 day stratified period. Higher dilution could be obtained with a multiport diffuser, though there will be increased volume of the initial mixing zone.

In the lake model, TSF and PAG seepage is assumed to mix rapidly and completely with the lake epilimnion or across the entire lake. This assumption neglects the predicted negative buoyancy of these inflows, which will cause them to flow along the bottom in a relatively thin layer. The outer bounds for contaminant concentration near the lakebed in the region of the seepage input range from the lake-wide-average as predicted by the lake model to undiluted seepage.

The proponent does not consider changes to local climate over the entire mine lifecycle. Local climate warming will alter the seasonal thermal cycle of the lake, as well as ice-cover thickness and duration. The effect of a warming climate on lake-wide-average concentration can be estimated by steadily increasing the duration of the summer-stratified period. Simulations show that warming has little impact on the proponent's prediction if it is assumed that freshet occurs during overturn and mixes rapidly and completely throughout the lake. However, it is unlikely that the entire freshet will occur during overturn, and freshet overflow and underflow scenarios must be considered. An upper bound for lake-wide-average concentration can be estimated by assuming the freshet forms an overflow. Assuming freshet overflow with climate warming, predicted maximum lake-wide-average concentration increases for all contaminants (Figure 3), with the annual maximum occurring in the hypolimnion at the end of summer. Cadmium, which was predicted to be in excess of the BCWQG in the proponent's simulation, increases by 15% over the proponent's prediction. Sulphate, magnesium and zinc approach, but do not exceed, the BCWQG. All other contaminants are relatively unchanged from the proponent's prediction. Note that the iron exceeds BCWQG because the baseline concentration exceeds BCWQG.

The proponent predicts that lining the TSF with a geomembrane will reduce contaminant input to Morrison Lake. An upper bound for lake-wide-average contaminant concentration in Morrison Lake was established as for the unlined scenarios using the proponent's predicted upper bound inflow (Figures Figure 4Figure 6). Concentration is reduced for all contaminants relative to the unlined case. Iron, whose baseline concentration exceeds BCWQG, remains relatively unchanged. All other contaminants are below BCWQG. Cadmium and aluminum could exceed BCWQG if freshet behaves as an overflow. While neither sulphate nor magnesium are predicted to exceed BCWQG within 100 years, both show a significant increasing trend for the freshet overflow case with consideration of climate change (Figure 6).

There has been no calibration or validation of the lake model as there is insufficient data to do this. This lack of data supports the use of this simple model versus a more complex or realistic model. The lake model is in neither precise nor accurate, but is conservative and with the added consideration of freshet overflow and climate change it is unlikely that the predicted lake-wide-averages would be exceeded if the effluent concentrations used as input to this model are indeed an upper bound. In this sense the model is robust in terms of its stated objective of providing and outer bound for lake-wide-average contaminant concentration. However, there will be higher concentrations in the vicinity of the seepage and creek inflow, which will vary seasonally. This model could also be very useful as a validation of more complex models that may be developed at a later date.

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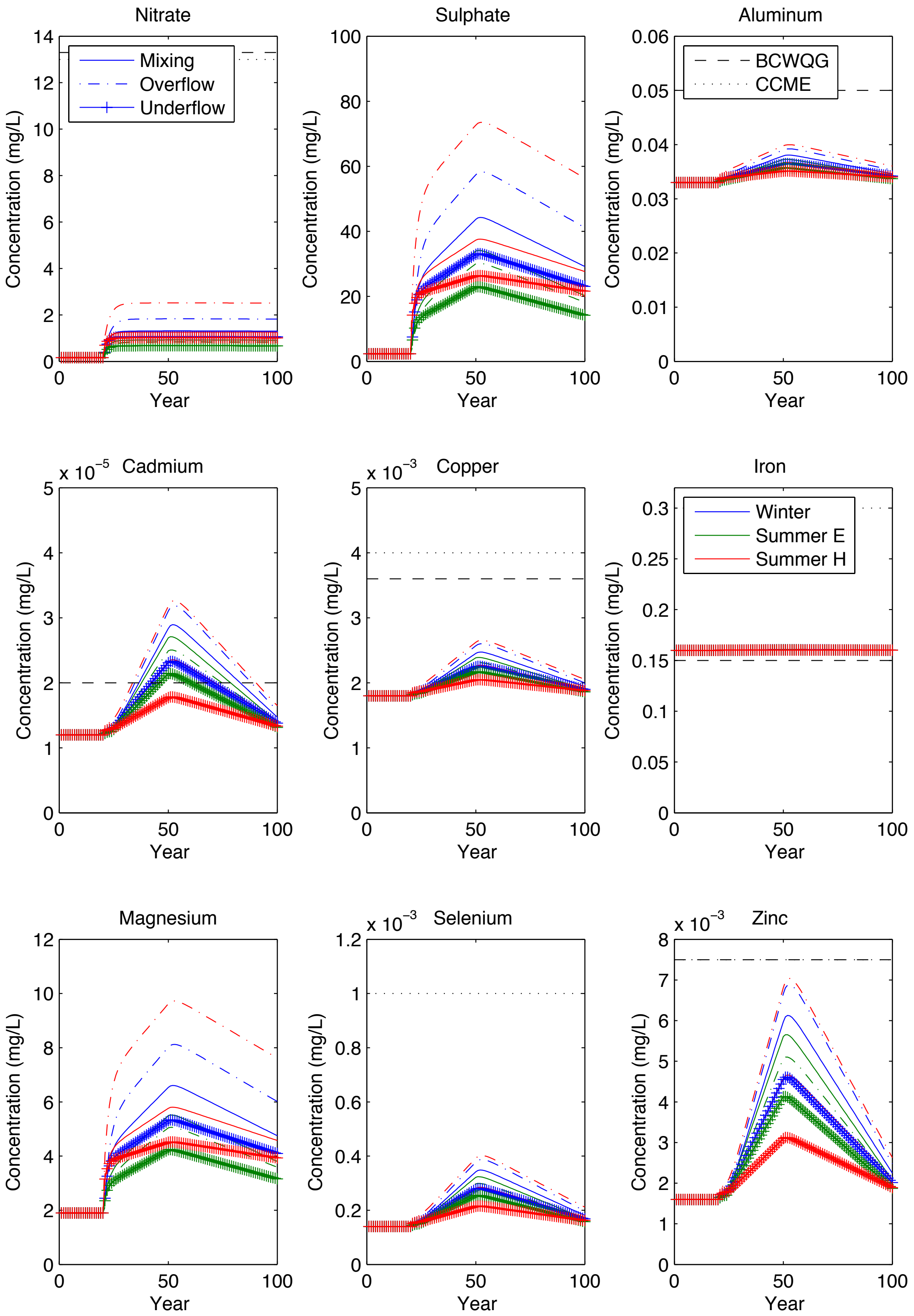

Figure 1. Lake model (upper bound flow rate and concentration, no liner) comparison of freshet scenarios with no climate change.

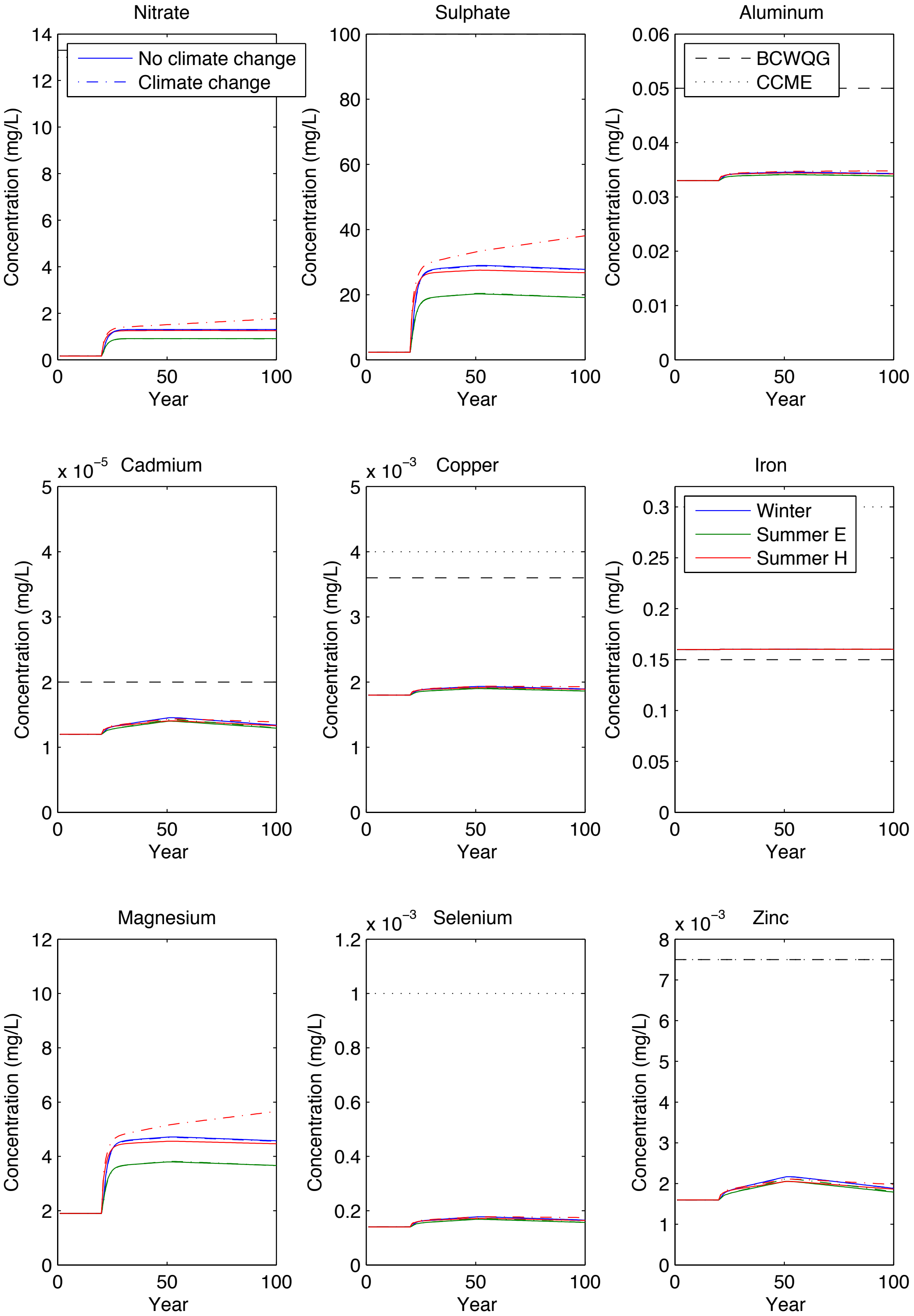

Figure 2. Lake model (upper bound flow rate and concentration, no liner) comparison of no climate change versus climate change.

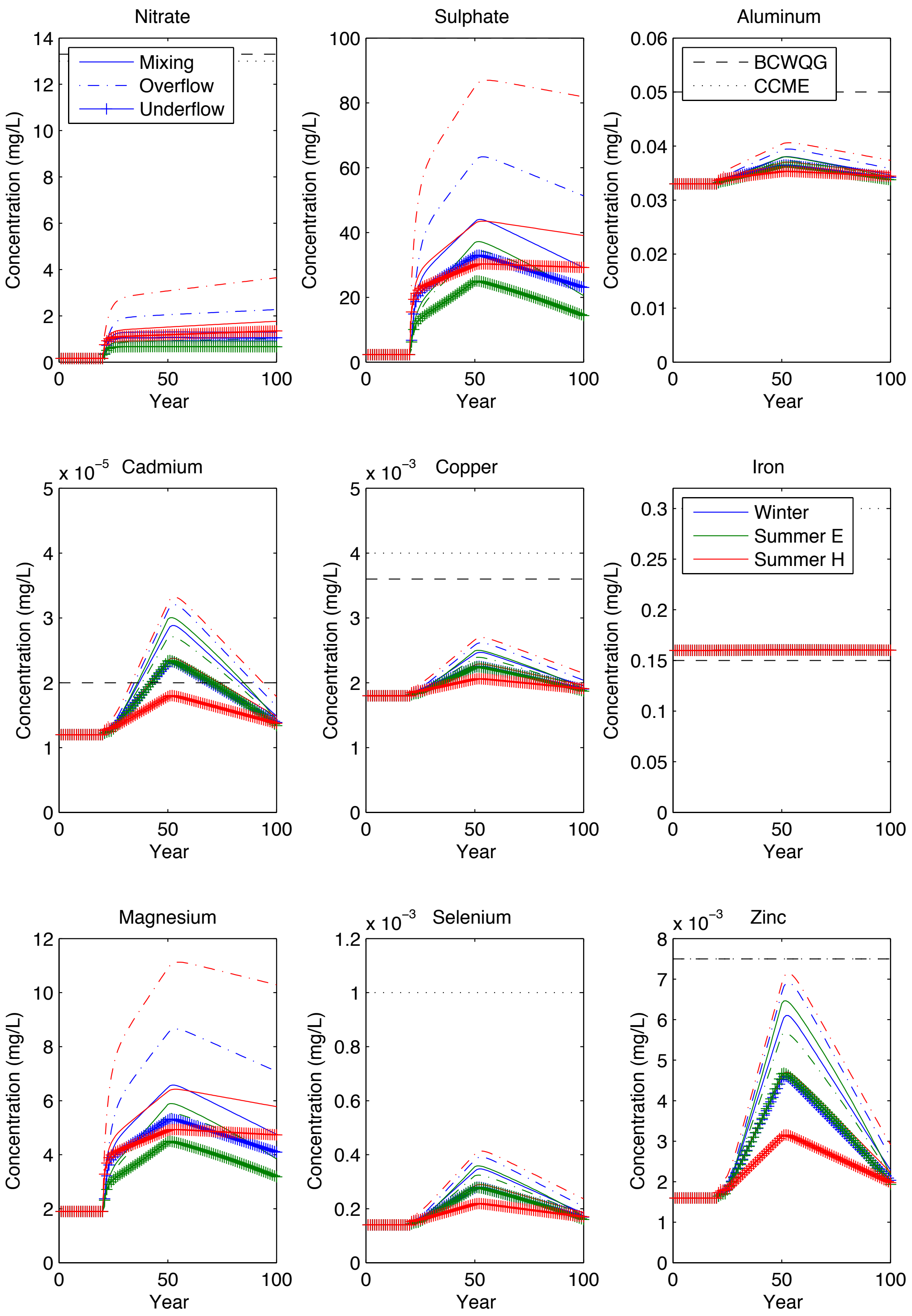

Figure 3 Lake model (upper bound flow rate and concentration, no liner) comparison of freshet scenarios with climate change.

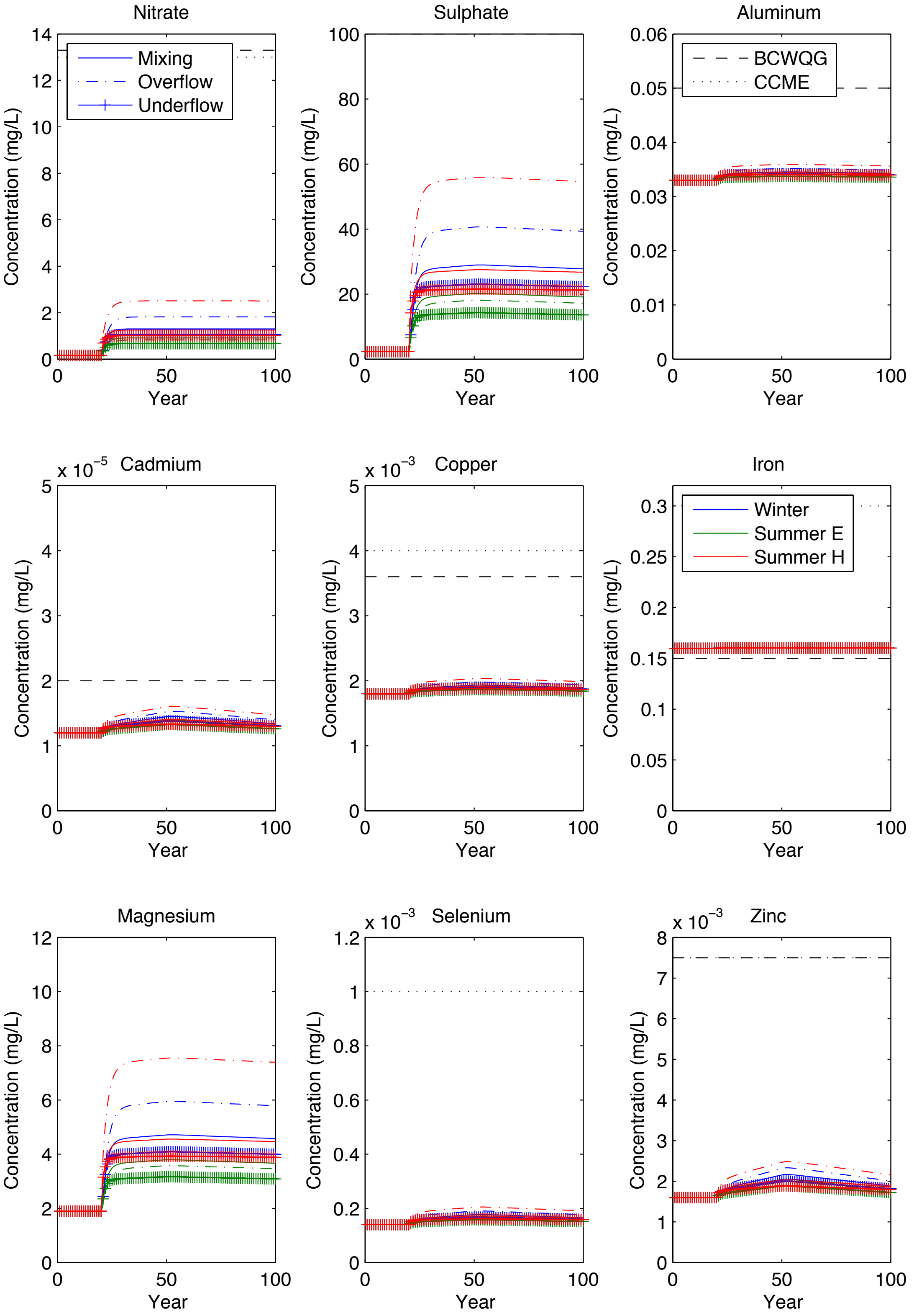

Figure 4. Lake model (upper bound flow rate and concentration, geomembrane liner) comparison of freshet scenarios with no climate change.

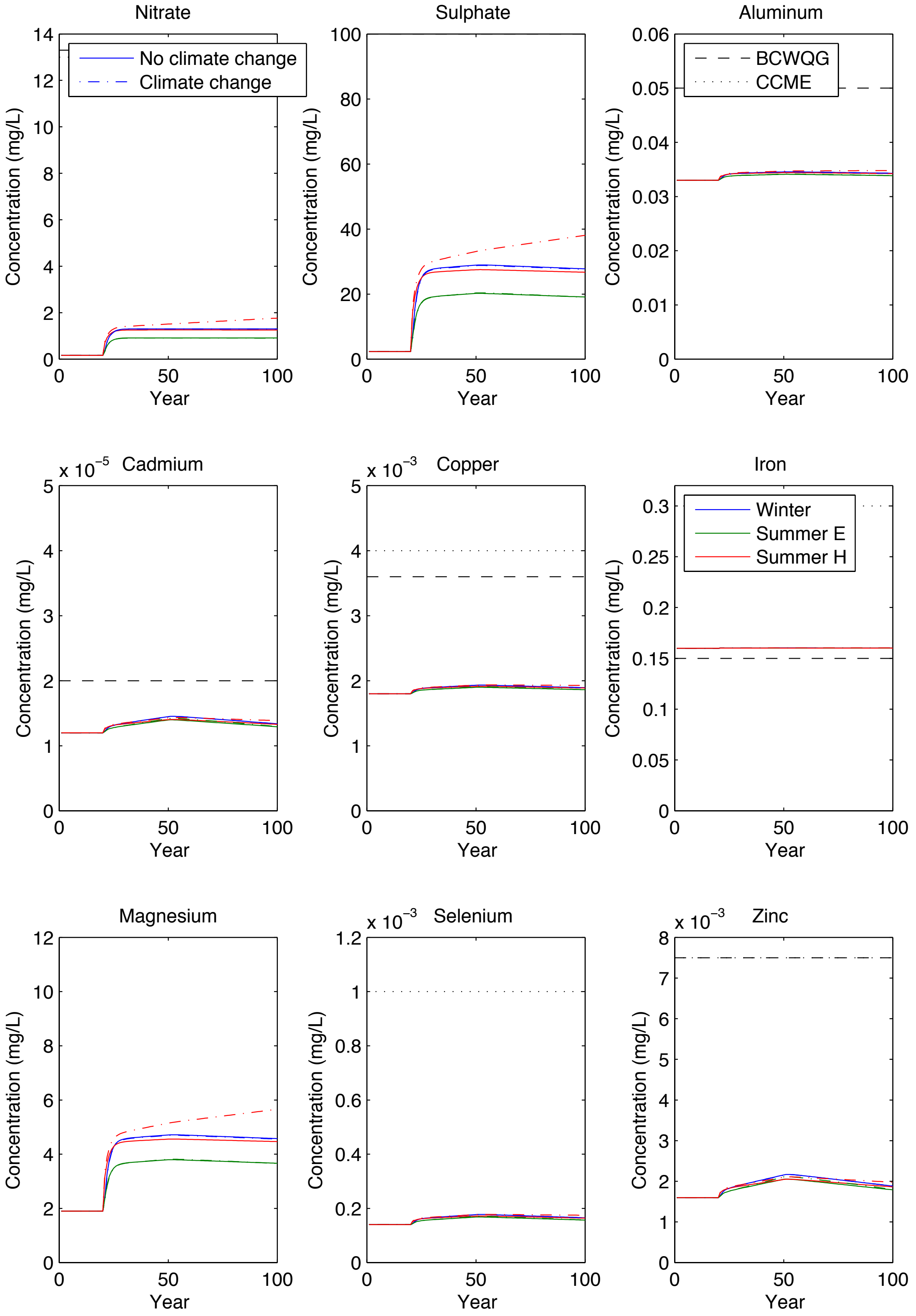

Figure 5. Lake model (upper bound flow rate and concentration, geomembrane liner) comparison of no climate change versus climate change.

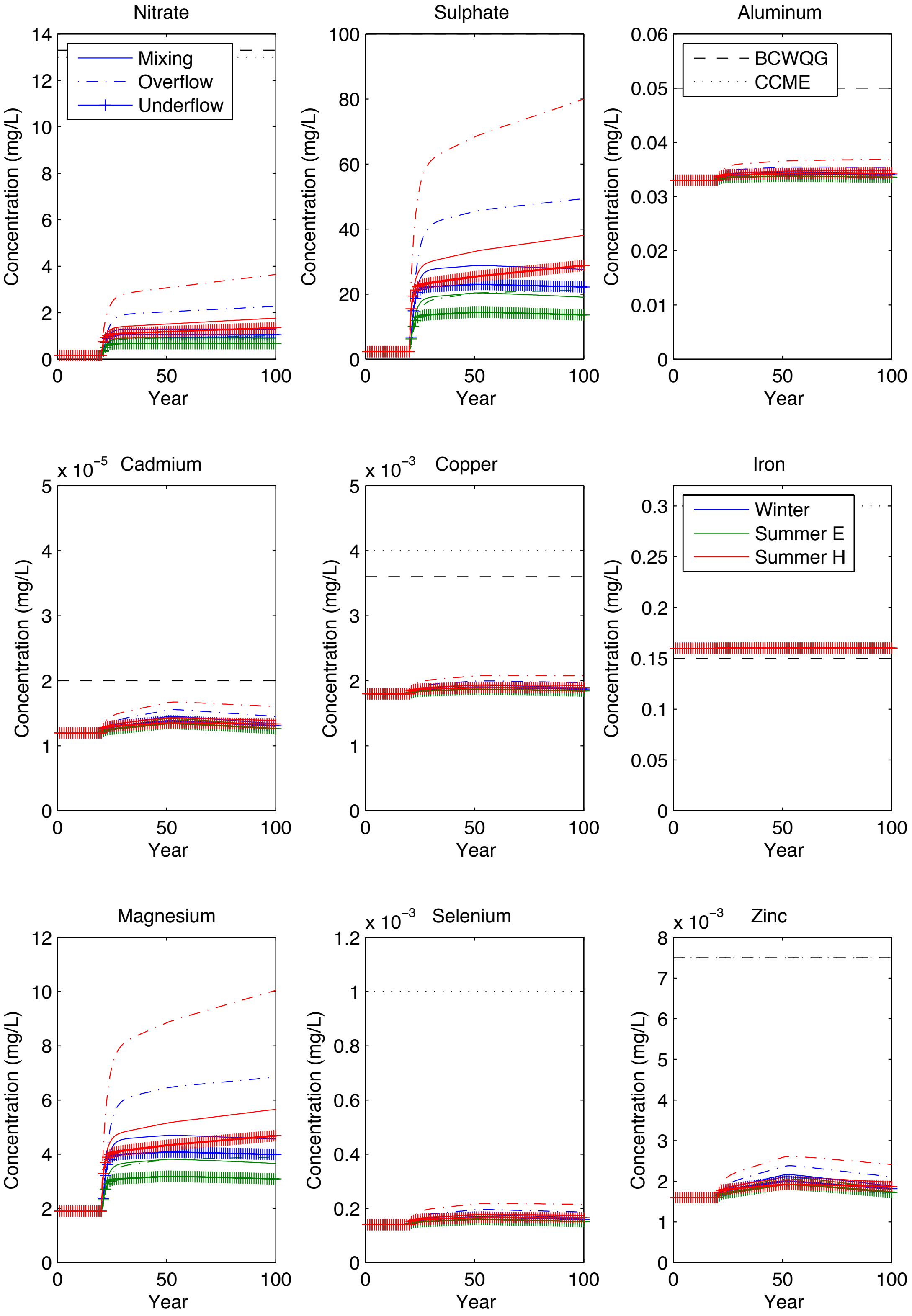

Figure 6 Lake model (upper bound flow rate and concentration, geomembrane liner) comparison of freshet scenarios with climate change.