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Simulating the cumulative effects of potential open-pit mining and climate change on streamflow and water quality in a mountainous watershed

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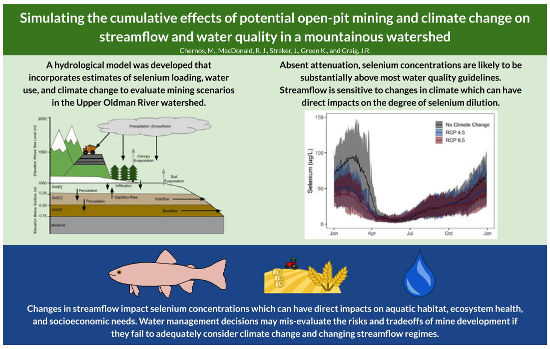
HIGHLIGHTS

- A hydrological model incorporates selenium loading, water use, and climate change.
- Streamflow is sensitive to changes in climate and impacts selenium dilution.
- Absent attenuation, selenium concentrations exceed most water quality guidelines.
- Water management decisions should consider changes in climate and streamflow regimes.

GRAPHICAL ABSTRACT



Simulating the cumulative effects of potential open-pit mining and climate change on streamflow and water quality in a mountainous watershed

Chernos, M., MacDonald, R. J., Straker, J., Green K., and Craig, J.R.

A hydrological model was developed that incorporates estimates of selenium loading, water use, and climate change to evaluate mining scenarios in the Upper Oldman River watershed.

Absent attenuation, selenium concentrations are likely to be substantially above most water quality guidelines. Streamflow is sensitive to changes in climate which can have direct impacts on the degree of selenium dilution.

Changes in streamflow impact selenium concentrations which can have direct impacts on aquatic habitat, ecosystem health, and socioeconomic needs. Water management decisions may mis-evaluate the risks and tradeoffs of mine development if they fail to adequately consider climate change and changing streamflow regimes.

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ABSTRACT

Land use and climate change effects on water quality and water quantity are well documented globally. Most studies evaluate individual factors and effects, without considering the interrelationships between land use, climate, water quality, and water quantity. This study provides an integrated assessment of the cumulative effects of climate change and potential open-pit coal mining on streamflow and water quality in the Oldman River Basin, Alberta, Canada. A hydrological model was developed that incorporates estimates of future selenium loading, water use, and projected changes in air temperature and precipitation to evaluate changes in water quantity and quality. Model results indicate that estimated selenium concentrations, absent any attenuation, are likely to be substantially above most water quality guidelines and strong reliance on mitigation technologies would be required to maintain adequate water quality in the watershed if mine development were to take place. Streamflow is sensitive to changes in climatic conditions, and modelling results suggest there are likely to be increases in winter flow, earlier peak flow, and reductions in flow during the summer and fall months under the climate change scenarios. These changes can have direct impacts on the degree of selenium dilution and more generally on aquatic habitat, ecosystem health, and socioeconomic needs. This study highlights that water management decisions may mis-evaluate the risks and tradeoffs of future mine development if they fail to adequately consider climate change and changing streamflow regimes and their indirect effects on water quality.

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1. Introduction

The timing and magnitude of streamflow has important socioeconomic, cultural, and environmental implications. Downstream communities rely upon rivers to provide water resources for irrigation, drinking water, and industrial applications. These factors are of heightened importance in water stressed regions where downstream communities can be particularly vulnerable (Anderson and Radić, 2020; Qin et al., 2020). Limits on water withdrawals or temporary suspension of water licenses can occur during low flow periods (Rood and Vandersteen, 2010; Marcotte et al., 2020), disrupting industrial processes and/or threatening agriculture. Aquatic and terrestrial ecosystems also rely on adequate environmental flows and low streamflow reduces and degrades aquatic habitat (e.g. Koning et al., 2016; Schmidt and Potyondy, 2004). In addition, low streamflow can degrade or further exacerbate stressors to water quality including the concentration of pollutants (via dilution) and altered thermal regimes (Tu, 2009; MacDonald et al., 2014).

The hydrologic regime of a watershed is affected by changes in climate and land cover. A shift in the timing of peak flows and decreasing late-summer flows has been observed across western Canada in response to warming air temperatures (Bonsal et al., 2019). Future projections broadly estimate a further shift in streamflow seasonality, particularly in watersheds reliant on snowmelt. The risk of drought and low flow periods is more difficult to ascertain and is highly variable and regionally specific (Nkemdirim and Purves, 1994; Mahat and Anderson, 2013; Newton et al., 2021). In addition, changes in land cover can impact streamflow timing and magnitude, notably, deglacierization (Bliss et al., 2014; Moore et al., 2020), forest disturbance (Green and Alila, 2012; Pomeroy et al., 2012), agricultural expansion (Schilling et al., 2008), and open-pit mining (Evans et al., 2015; Chiew et al., 2018). These land cover changes can impact water quality, directly through the discharge of dissolved chemicals or particulates, and indirectly through changes in streamflow.

One land cover change that can have important effects on water quantity and quality is open-pit coal mining. Mining coal for generating steel (metallurgical or coking coal) and to produce energy (thermal coal) requires removal of large quantities of rock, topsoil, and vegetation to expose coal ore bodies (Ross et al., 2016; Mossa and James, 2013). These changes in topography and vegetation, coupled with mine-scale water management and use, can dramatically alter streamflow in the downstream environment. Recent work in China has shown that runoff can be substantially reduced (Luan et al., 2020), while paired-watershed analysis in the Appalachian coal region of the United States of America suggests an increase in water yield due primarily to larger, more sustained baseflows, even with a decrease in stormflow (Nippgen et al., 2017). Other studies document a range of hydrologic responses, with increases and decreases in surface flow (Miller and Zégre, 2014). Ultimately, the structure and function of watersheds post-mining can be altered, leading to long-term and often irreversible changes in hydrologic processes (Palmer et al., 2010).

Surface coal mining produces a large quantity of non-coal-bearing rock, termed “waste rock”, which is placed in nearby valleys (valley fill) and in piles within and adjacent to mine pits. Over time, this waste rock undergoes geochemical weathering as it oxidizes, producing selenium (Se), along with other constituents, which are subsequently carried into waterways and affect water quality. Studies show that the degree of water quality degradation is directly correlated with the relative proportion of mined area, with effects on water quality persisting two decades following reclamation (Lindberg et al., 2011). Because selenium bioaccumulates, it can present risk to aquatic ecosystems, including fish (Miller et al., 2013), and in higher levels, risk to human health, consequently limiting the water's suitability for irrigation or consumption (Lemly, 2019).

In addition to attenuation from waterways at the mine site, the severity of water quality degradation from selenium leaching also depends on the amount of dilution in rivers and streams from unaffected tributaries. This dependency highlights that the concentration of selenium in a stream is likely to vary throughout the year in response to seasonal streamflow patterns and is elevated during periods of low flow. As such, an understanding not only of selenium loading, but also of streamflow magnitude and timing is integral to manage water supply and water quality effectively and sustainably.

In southern Alberta, water resources are already under strain due to human and natural factors (Alberta Environment, 2006). In the Oldman River Basin (ORB), extensive land use, major irrigation supply dams, large-scale diversions, and population and economic growth have increased demand on an already limited water supply (Byrne et al., 2006; Oldman Watershed Council, 2010). In addition, a modest decline in streamflow has already been observed over the past century in the ORB and reflects the effects of climate change (Rood et al., 2005), while paleohydrology evidence suggests that these records likely do not capture the full range of variability in the regional hydrologic regime (Sauchyn et al., 2015) and that more severe droughts have occurred in the past (Axelson et al., 2009).

Currently, the ORB has increased industrial interest in its headwaters. Several proponents are in various stages of planning and environmental review to develop open-pit coal mining operations in the coal-rich rocks of the upper Oldman River. In addition to increased water use, open-pit coal mining operations bring renewed concern related to water quality, particularly selenium transport. The cumulative effects of increased industrial development and changing climatic conditions have the potential to place additional stress on water resources and water quality. In turn, these changes could have cascading environmental, cultural, and socioeconomic effects.

The goal of this work is to provide an integrated assessment of the cumulative effects of climate change and open-pit coal mining on streamflow and water quality in the ORB, outlining the potential effects on water resources in the coming decades. A hydrological model of the upper ORB was developed to simulate streamflow for tributaries and the mainstem Oldman River during a historical period (1990-2019) and under two future climate change scenarios (RCP 4.5 and RCP 8.5; 2021-2080). Water use and selenium loading associated with two future mine development scenarios were integrated into the hydrological model to estimate potential changes to water quantity and quality in the basin. Concentrations of selenium at all sub-basin outlets were simulated within the hydrological model and compared to water quality guidelines. This study provides a template for assessing the cumulative effects of mine development and a quantitative estimate of potential environmental risks due to climate change and proposed open-pit coal mining in the Oldman River Basin.

2. Study area

The Oldman River Basin is in southwestern Alberta and is a major tributary of the South Saskatchewan River (Fig. 1). The headwaters lie within the Rocky Mountain Natural Region of Alberta, and include the Alpine, Subalpine, and Montane Natural Subregions, while the lowest reaches near the Oldman Reservoir are part of the Grassland Natural Region. The Rocky Mountain Natural Region is known for cool summers and high annual precipitation, particularly in the winter, and its vegetation consists primarily of coniferous forests, alpine meadows, and exposed rock at highest elevations (Natural Regions Committee, 2006). Grasslands make up approximately 80% of the land area of the ORB (Poirier and De Loe, 2011). The climate is semi-arid and the watershed receives the highest amount of precipitation in June. The eastern portion of the ORB is extensively used for agriculture. Agricultural activities have been enhanced by irrigation since the early 1900s. The expansion of irrigation in the 20th century was accompanied by a sequence of on-stream and off-stream dams and reservoirs and an extensive canal network. The St. Mary River Projects and Lethbridge Northern Irrigation District rely on streamflow from the Oldman River and its southern

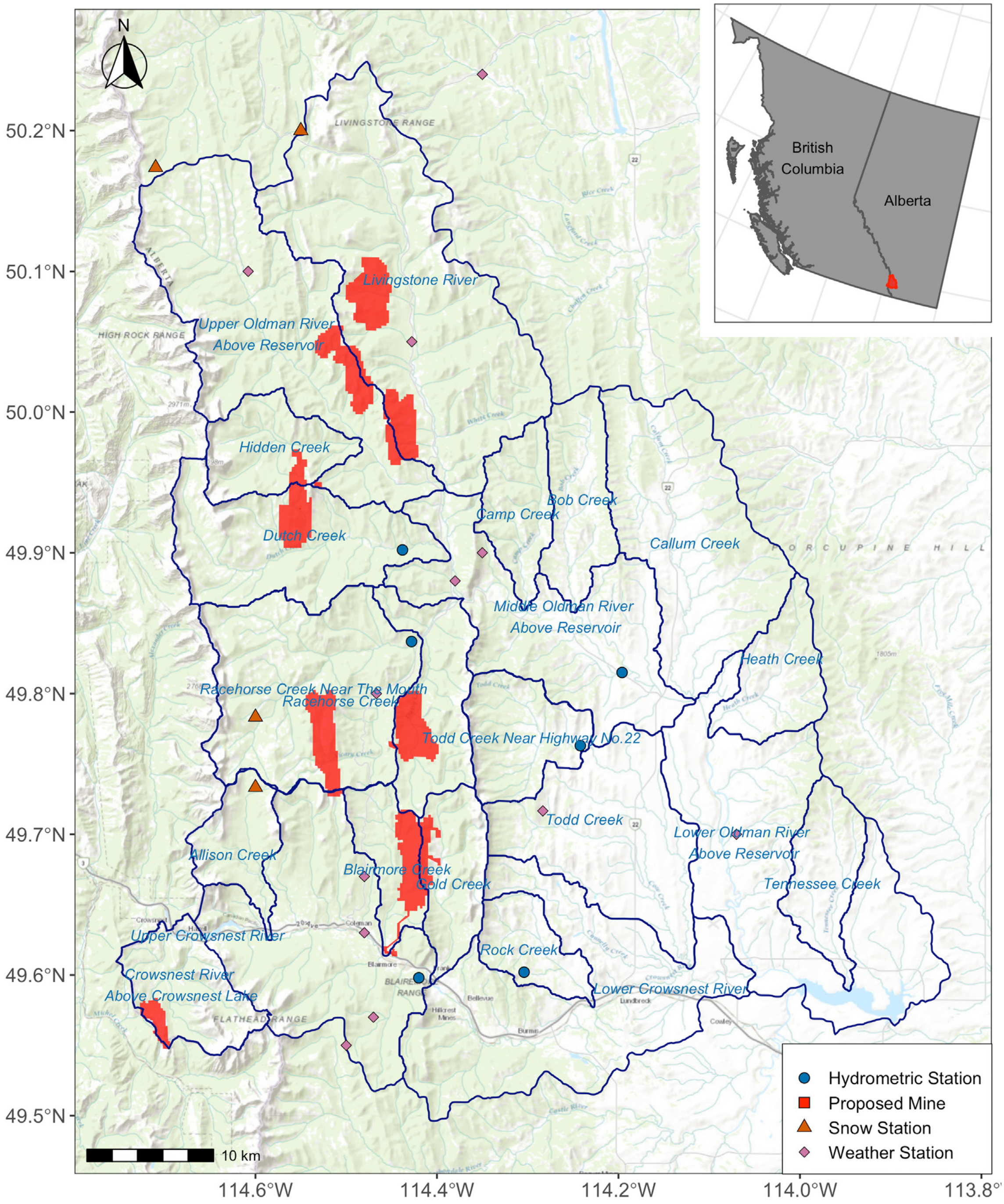

Fig. 1. Map of the Oldman River study area, approximate potential open-pit coal mine locations, hydrometric stations, snow stations, and weather stations.

tributaries to irrigate agricultural lands in southern Alberta (Sauchyn et al., 2016).

Natural disturbances including wildfire and mountain pine beetle infestation have affected the forests that cover the western portion of the basin, while forest harvesting activities continue presently. Urban development has expanded, primarily along the Crowsnest River in the Crowsnest Pass, including the towns of Coleman, Blairmore, Frank, Bellevue, and Lundbreck. The region has a history of coal mine development dating back to the late 1800s and currently there is renewed interest in developing new metallurgical open-pit coal mines in the Oldman River headwaters and Crowsnest Pass.

Our study area comprises the 3150 km^2 area upstream of the Oldman Reservoir (Fig. 1). This drainage area includes the Upper Oldman River and the Crowsnest River, a major tributary of the Oldman River that drains the Crowsnest Pass area. The study area is delineated by Hydrological Unit Classification 10 (HUC 10) watersheds as well as Water Survey of Canada hydrometric gauge outlets and major points of interest.

3. Methods

3.1. Oldman River hydrological model

Streamflow and other hydroclimatic variables in the upper Oldman River watershed are simulated using a process-based hydrological model. This model is an adapted version of the distributed HBV-EC hydrological model (Bergström, 1992), emulated within the Raven Hydrological Modelling Framework version 3.0 (Craig et al., 2020). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep. The model integrates weather data (daily minimum and maximum air temperature and precipitation) and landscape attributes (land cover, elevation, soil types) to simulate major hydrological processes including canopy interception, snow accumulation and melt, evaporation, soil infiltration, percolation, interflow, baseflow, as well as runoff. Major processes are described below, while a comprehensive discussion of model algorithms can be found in Bergström (1992), Jost et al. (2012), and Chernos et al. (2020).

Water input to the hydrological model occurs as precipitation, which is partitioned into rain or snow following the HBV linear transition based on air temperature (Craig et al., 2020). Precipitation interception by the forest canopy is estimated as a function of Leaf-Area Index (LAI; Craig et al., 2020; Hedstrom and Pomeroy, 1998). Snowmelt is calculated using a spatially corrected temperature index model, which accounts for aspect, slope, and day length (Jost et al., 2012, Craig and the Raven Development Team, 2020). Potential evapotranspiration is calculated using the Priestley-Taylor equation (Priestley and Taylor, 1972). Once water infiltrates the three-layer conceptual soil profile, it moves downwards through percolation and upwards through capillary rise. Soil water becomes runoff (i.e. streamflow) through (faster) interflow and (slower) baseflow pathways.

Contaminant loading and transport (i.e., selenium loading and concentration estimates) is simulated within Raven using built-in functionality to calculate sub-basin concentrations based on supplied mass loadings. Downstream transport of selenium is simulated using Raven's constituent transport algorithms which incorporate sub-basin routing and travel times based on sub-basin properties, including slope, Manning's roughness, and length (Craig et al., 2020).

3.1.1. Data sources

3.1.1.1. Landscape. The upper Oldman River was discretized into hydrological response units (HRUs) for input into the hydrological model. The area within each HRU is assumed to have uniform hydrologic behavior and is summarized with a land cover type, soil type, elevation, aspect, and slope. Land cover for the area was obtained from the ABMI wall-to-wall 2010 Land Cover Inventory (ABMI, 2013) and reclassified into 7 classes: Alpine, Coniferous, Deciduous, Developed (i.e. bare or urban cover), Grassland, Lake, and Shrubland. Soil type was tied to whether the land cover was vegetated. Elevation, slope, and aspect were obtained using the Canadian Digital Elevation Data digital elevation model (Natural Resources Canada, 2016).

3.1.1.2. Weather and climate. To run the hydrological model, daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required. These data were collected from DayMet (Thornton et al., 2020) using the Single Pixel Extraction Tool to obtain observations from 1980 to 2019 at a 0.15 degree resolution. Since DayMet data are based on a 1 × 1 km grid cell, reference elevations were obtained for each data point and are used within the hydrological model to adjust observations to HRU elevations using specified lapse rates. To calibrate model parameters and verify model performance at reproducing hydroclimatic variables such as snow water equivalent, precipitation, and air temperature, additional independent weather station data were obtained (see Fig. 1 for station locations). These data were obtained for the historical simulation period (1990-2019) from Environment Canada and Alberta Environment and Parks (LaZerte and Albers, 2018; Government of Alberta, 2020).

Future climate change scenarios were generated from statistically downscaled climate scenarios obtained from Environment and Climate Change Canada (ECCC, 2021) under two representative concentration pathways (RCPs). RCP 4.5 corresponds to a scenario where carbon emissions stabilize by 2040, while RCP 8.5 represents a scenario with minimal greenhouse gas emission mitigation. These scenarios applied the median projection from an equal-weighting ensemble forecast of 24 General Circulation Models (GCM) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) from 2021 to 2080. Projections among climate models can vary because of differences in their underlying representation of earth system processes. Thus, the use of a multi-model ensemble approach has been demonstrated in recent scientific literature to likely provide better projected climate change information (Zhang et al., 2019; ECCC, 2021).

Daily future weather was generated by first bias-correcting projected climate values by calculating the change between monthly simulated future air temperature and precipitation and historical (simulated). Each future month and year were then matched with a proxy month from the baseline (observed) period and scaling factors for each month and year were derived by finding fractional difference in precipitation and absolute difference in air temperature between the proxy and scenario. These scaling factors were then used these to correct the daily observed record from 1986 to 2005 for each climate scenario.

3.1.2. Model calibration

Model parameters were calibrated to hydroclimatic observations in the watershed following a stepwise approach outlined in Chernos et al. (2017) and Stahl et al. (2008). This approach was used as additional verification to ensure hydrologic processes were properly represented. Air temperature, precipitation, and snow simulations were verified against local weather stations and snow surveys. Streamflow was calibrated and verified against Water Survey of Canada (WSC) hydrometric stations on the Oldman River and Crowsnest River as well as major tributaries Racehorse Creek and Dutch Creek (WSC, 2021). Oldman River at Waldron's Corner (Middle Oldman River Above the Reservoir) WSC hydrometric station was used to calibrate the model for the 2000-2008 period. All other hydrometric stations (over their full 1990-2019 record) were used to verify model performance, as well as the Oldman River hydrometric station over the remainder of the record (1990-1999, 2009-2019).

3.2. Hydrologic regime and watershed indicators

Three hydrologic indicators were derived to capture the effect of a changing landscape and climate on water resources in the ORB. These indicators were then used to identify changes in streamflow during key periods of the year and are summarized in Table 1.

3.3. Mine development

The hydrological model was run under two future development scenarios to estimate the effect of potential coal mine development in the study area. The Moderate Scenario assumes the development of only the Grassy Mountain and Tent Mountain mines, both proposed mines located in the Crowsnest River watershed. The High Scenario assumes all eight proposed mines depicted in Fig. 1 are developed: Grassy

Table 1
Hydrologic indicators used to identify changes in hydrologic regime and function.

Variable	Description
Annual flow	The average annual streamflow, representative of the amount of water passing through this point in a calendar year.
Winter flow	The average January-March streamflow, representative of conditions prior to snowmelt, which has historically coincided with the lowest flows of the year.
Summer flow	The average August-September streamflow, representative of conditions following snowmelt, which has historically coincided with summer low flows and heightened risk of droughts, degraded water quality, and water scarcity.

Mountain and Tent Mountain (Crowsnest River watershed); and Isolation South, Elan South, Chinook Vicary, Cabin Ridge, Isola, and 4-Stack (upper ORB). This study integrates the effects of selenium loading on waterbodies and the increased consumptive water use due to mine development into the hydrological model but does not consider the effects of land cover changes, water management, or other mine infrastructure (such as settling ponds, water storage ponds, or in-stream diversions).

3.3.1. Water use estimates

Water use was incorporated into the hydrological model for all mines developed in each scenario. Water use for each mine was estimated using reported water use values from Grassy Mountain Mine, which consisted of 900,000 m^3/year in “Plant Make-up Water” and 60,000 m^3/year in dust suppression (Riversdale Resources Ltd, 2016). Of this volume, Grassy Mountain Mine estimates approximately a third of this water is consumptive and therefore is treated as a loss from the system and not returned. This consumptive water use was scaled by the maximum clean metric tonne (CMT) coal production estimated for Grassy Mountain. This value (0.204 m^3/CMT consumptive and non-consumptive, 0.067 m^3/CMT consumptive) was used to correct water use for each year for all mines based on their estimated coal production by year from 2021 to 2069 (Fig. 2). Water use for each mine is assumed to be removed from their immediate sub-basin (i.e., no water is piped in or diverted from another sub-basin) and to be constant throughout the year.

We note that since the ORB is closed to new water licenses, the volume of allocated water should not change; however, it is possible that the consumptive use of water could increase or decrease, and the point of withdrawal could also be located in a headwater tributary rather than on a larger river. In addition, there is uncertainty in the location and amount of available water that could be obtained by mining proponents, either through purchase of an existing water license or accessing an existing industrial allocation held by Alberta Environment and Parks from the Oldman Reservoir. To reflect this uncertainty, we refer to “potential allocation” as the amount of water potentially requested by each mine proponent for industrial operations, including consumptive water use and return flow.

3.3.2. Selenium loading

The mass of selenium released into waterways by leaching from waste rock (i.e. mass loading of selenium) was estimated for each year corresponding with the timing of mine development, based on coefficients relating annual selenium loads to the volume of coal waste rock (SRK, 2014; SRK, 2016). The rationale for this approach and corresponding coefficients is the observed relationship between selenium concentrations and the deposition of coal waste rock in the Elk River watershed in southeast British Columbia, which implies that selenium release can be predicted from waste-rock volumes generated by future mining operations (SRK, 2014).

Annual mass loading of selenium (L_{Se}, in mg/year) was estimated from each simulated mine as:

$$L_{Se} = V_{rock} R_{Se}$$

where V_{rock} is the cumulative volume of coal waste rock deposited (in bank cubic metres, or BCM), and R_{Se} is the generation rate of selenium from waste rock in mg/m^3/yr (SRK, 2014). The rate coefficients for selenium generation vary by mine based on lithology and available information. Selenium generation rates for Grassy Mountain (3.20 mg/m^3/year) were obtained from SRK (2016). The rate for Tent Mountain was estimated from the value for the nearby Coal Mountain mine (0.55 mg/m^3/year) since the two mines are assumed to have similar selenium generation rates, which are lower than those generally observed from the Mist Mountain formation in the Elk Valley (SRK, 2014). The selenium generation rates for all other mines were assumed equal to the rate given by SRK (2014) for all mines in the adjacent Elk Valley (1.60 mg/m^3/year) other than Coal Mountain.

Simulating selenium loads therefore required simulation of waste rock deposition by mine site over time. The basis of this simulation was published values for waste rock deposition and stripping ratios (i.e. volume of waste rock deposited per tonne of coal production) from Grassy Mountain (SRK, 2016) and Tent Mountain (SRK, 2020). These values were used directly to simulate these two operations in the Moderate Scenario and were scaled based on simulated production and stripping ratios, and/or shifted in time to simulate the remaining six operations for the High Scenario. Simulated annual waste rock deposition was then multiplied by selenium generation rates to yield estimates of selenium mass loadings (Fig. 3).

Mass loadings were injected into the immediate sub-basin and were assumed seasonally constant and to continue indefinitely following mine closure. Since the mass loading of selenium is derived from regional relationships relating mine development to environmental selenium concentrations, selenium immobilization (i.e. removal of dissolved selenium through biological uptake and/or chemical adsorption) is accounted for, assuming environmental conditions in the Oldman River are comparable to the adjacent Elk River. In addition,

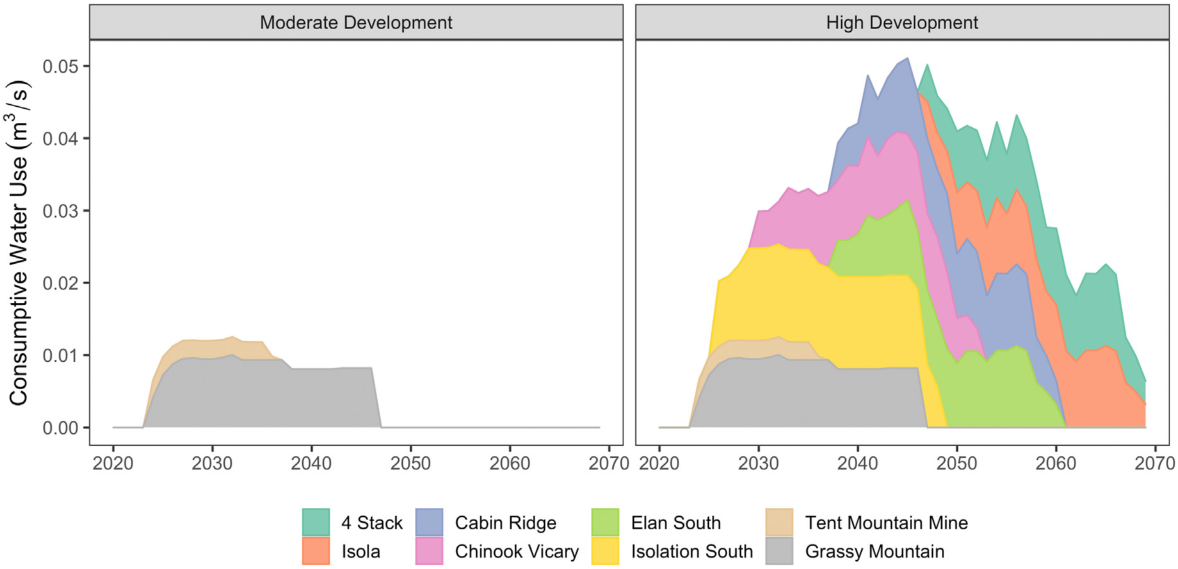

Fig. 2. Consumptive water use (m^3/s) at each mine under both the Moderate and High scenarios.

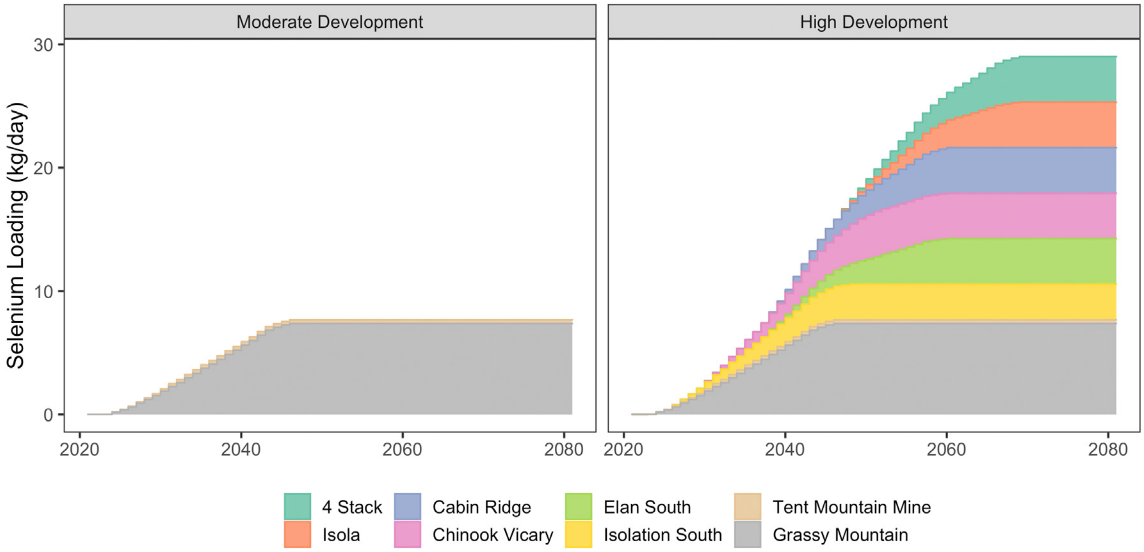

Fig. 3. Raw mass loading (i.e. no attenuation) by mine under both the Moderate and High scenarios.

the assumption of conservative transport of selenium in surface waters has been supported by several studies. For instance, Wellen et al. (2015) find insignificant in-stream attenuation of selenium in the Elk River, BC, “implying Se is subject to long range transport downstream”. Furthermore, studies simulating the effect of riparian areas on selenium immobilization in the Arkansas River in Colorado found these biogeochemical processes to be minimal; accounting for approximately 1% of the total selenium mass loading (Bailey et al., 2013).

In order to account for the sensitivity of selenium attenuation (i.e. on-mine water treatment) estimates (through mechanisms such as subaqueous waste disposal or contact-water capture and treatment), mass loadings were run under a variety of attenuation rates, from 0% (i.e. no attenuation), 80% (lower case capture efficiency in SRK Consulting (2016)) to 99% (i.e. almost all selenium is removed at source and not injected to the watershed). Using the hydrological model's contaminant transport algorithm, the mass loading estimates were used to calculate selenium concentrations at source and were tracked at all subbasin outlets. Background concentrations of selenium were not considered (treated as zero within the hydrological model) as they are substantially lower than the modelled loading from mine development.

Water quality guidelines for selenium are provided in (Table 2). These guidelines are based on long-term (chronic) exceedances. Following the Government of British Columbia *Ambient Water Quality Guidelines for Selenium* (Beatty and Russo, 2014), water quality guidelines were compared against 30-day average simulated selenium concentrations.

4. Results

4.1. Model calibration and performance

Overall, the model displays good performance at reproducing daily streamflow as well as accurately reproducing air temperature, precipitation, and the winter snowpack across the watershed. Air temperature was well represented at independent verification stations (r^2 values ranging from 0.93 to 0.99), as was monthly precipitation ($r^2 = 0.76 - 0.93$). Snow water equivalent was underestimated along the Continental Divide, with annual percent bias ranging from -20% to -60% and moderate correlation coefficients (daily $r^2 = 0.53$ to 0.76).

Table 2
Published water quality guidelines for long-term selenium concentrations.

Category	Source	Guideline (μg/L)
Aquatic life	Government of Alberta (2018)	2
Drinking water, human	British Columbia (2020)	10
Irrigation	British Columbia (2019)	10
Irrigation - continuous	Government of Alberta (2018)	20
Drinking water, human	Health Canada (2020)	50

Qualitatively, the timing and magnitude of spring runoff are well simulated, indicating that snowmelt timing and rate is generally well reproduced (Fig. 4, Table 3). In addition, winter streamflow, only available for verification at the Oldman River hydrometric site, is well reproduced. Streamflow during the late summer and fall period (August-November) is well represented, but is slightly over-estimated, particularly in Racehorse Creek. Overall, the inter-annual and daily variability in flow is well reproduced, following the character of the observed hydrographs.

4.2. Runoff generation

In the Oldman River, water originates disproportionately from its mountain headwaters (Fig. 5). Runoff, a measure of streamflow generated, scaled by watershed area, is highest in sub-basins situated along the Continental Divide. In these sub-basins, including the headwaters of the Crowsnest River and Oldman River, as well as major tributaries including Racehorse, Dutch, and Allison Creeks, average runoff ranges from 400 to 500 mm/year. By comparison, lower elevation sub-basins located further east and south produce less than half as much runoff; for example, the Lower Oldman River averages less than 200 mm/year. This dynamic is largely because precipitation is substantially greater at higher elevations and further west in this region. Conversely, evaporation tends to be much greater in the lower elevation prairie located in the southeastern portion of the basin. Proposed open-pit coal mines are located along the western margin and at higher elevations, which means development could potentially affect these high-runoff portions of the ORB that are the most hydrologically productive areas.

4.3. Streamflow timing and hydrologic regime

Streamflow in the Oldman River follows a strongly snowmelt-driven pattern (Fig. 6). Streamflow is exceptionally low during the winter months where most precipitation falls as snow and air temperatures are cold, leading to little snowmelt. During the spring, as air temperatures warm, snowmelt begins, which leads to a rise in streamflow. In addition to snowmelt, most of the annual rainfall falls during the spring,

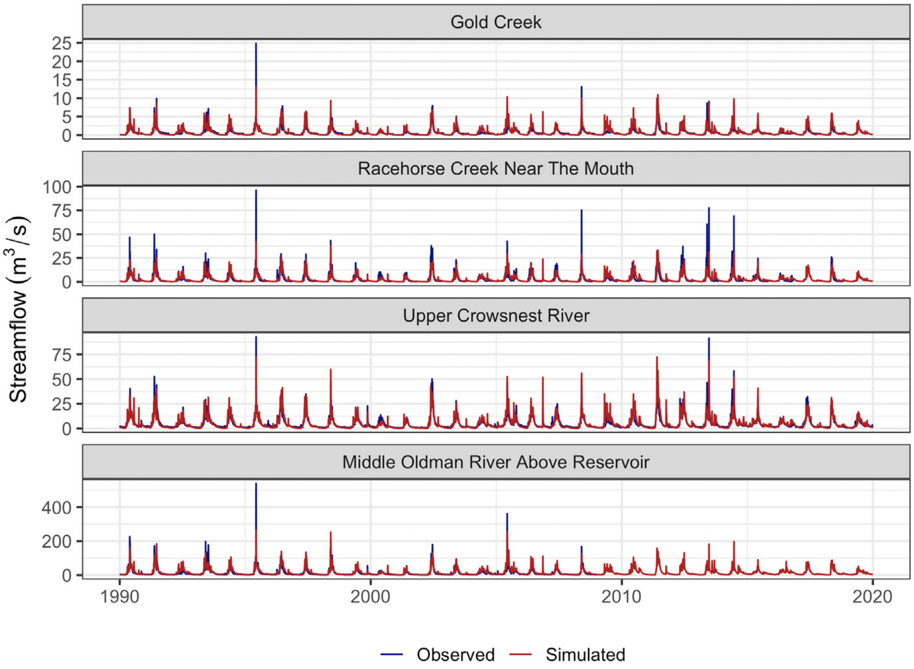

Fig. 4. Simulated and observed average daily streamflow for four hydrometric stations used to calibrate and verify the hydrological model.

which coincides with peak snowmelt and typically produces the maximum annual streamflow. Once the winter snowpack has been depleted, streamflow declines throughout the summer and coincides with the highest annual rates of evaporation.

Under the climate change scenarios, warmer air temperatures are predicted to result in less winter precipitation falling as snow and an earlier spring snowmelt. Winter rainfall and more frequent snowmelt events are projected to lead to higher winter streamflow. In addition, earlier snowmelt during March and April is likely to lead to higher spring streamflow. Conversely, an earlier snowmelt is likely to lead to earlier snowpack depletion and subsequently lower streamflow from June through August. In all cases, greater changes are simulated further into the future (2051-2080 vs. 2021-2050), with marginally greater changes under RCP 8.5.

4.4. Changes in hydrologic indicators

4.4.1. Annual flow

With changes in climate, the hydrologic regime in the ORB is likely to see substantial changes during key times of the year (Fig. 7). In most sub-basins, Annual Flow (i.e. the amount of streamflow produced in a year) is projected to increase. This increase is greatest along the prairie sub-basins, while some headwater sub-basins (Allison Creek and Crowsnest River Above Crowsnest Lake) are projected to see decreases in mean annual flow. At the outlet of the study area (Lower Oldman River Above Reservoir), increases in average Annual Flow range from 6% under RCP 8.5 (2021-2050) to 10% under RCP 8.5 (2051-2080).

Table 3
Daily streamflow performance statistics for the calibration (2000-2008 for Oldman River Near Waldron's Corner/Middle Oldman River Above Reservoir) and verification periods (entire record except on Oldman River). Note: NSE is the Nash-Sutcliffe Efficiency, KGE is the Kling-Gupta Efficiency; both ranging from negative infinity to 1 (perfect simulation), and PBIAS is the percent bias.

Site	Period	NSE	KGE	PBIAS (%)
Dutch Creek	Verification	0.70	0.67	6.2
Gold Creek	Verification	0.46	0.66	14.0
Middle Oldman River Above Reservoir	Calibration	0.85	0.82	16.3
Middle Oldman River Above Reservoir	Verification	0.78	0.81	10.5
Racehorse Creek Near the Mouth	Verification	0.72	0.71	0.9
Todd Creek Near Highway No.22	Verification	0.42	0.46	46.0
Upper Crowsnest River	Verification	0.81	0.89	0.4

4.4.2. Summer flow

Although Annual Flow is projected to increase in many tributaries and in the Oldman and Crowsnest rivers, Summer Flow is projected to decrease in most sub-basins in the coming 30 years (2021-2050), while almost all portions of the study area are projected to experience declines in Summer Flow by the second half of the century (Fig. 7). The average Summer Flow at Lower Oldman River Above Reservoir is projected to decline by 4% (RCP 8.5) to 6% (RCP 4.5) over the next 30 years, with a decline of 15-18% by 2051-2080 (greater decline under RCP 8.5). In addition, Summer Flow is projected to decline substantially in major tributaries in the watershed, including the Lower Crowsnest River (13-17% by 2051-2080) and Livingstone River (17-21% by 2051-2080).

4.4.3. Winter flow

While Summer Flow is likely to decline in the coming decades in large part due to warming air temperatures further shifting snowmelt to earlier in the spring, this dynamic is likely to also increase the average Winter Flow throughout the watershed (Fig. 7). Increases are more modest over the next thirty years (2021-2050), ranging from 13 to 95%, while increases over the 2051-2080 period are projected to be larger (86 to 284%). Increases are projected to be largest under the RCP 8.5 scenario, where warming is more severe and periodic winter snowmelt and rainfall events are more common.

4.5. Mine development scenarios

4.5.1. Water usage

As part of the South Saskatchewan River Basin (SSRB), the ORB is closed to new water license applications; therefore, any new proponent must obtain a water license through a transfer. While the volume of water allocated cannot increase, water use does not necessarily equal the water allocated. In many cases, license holders only use a fraction of

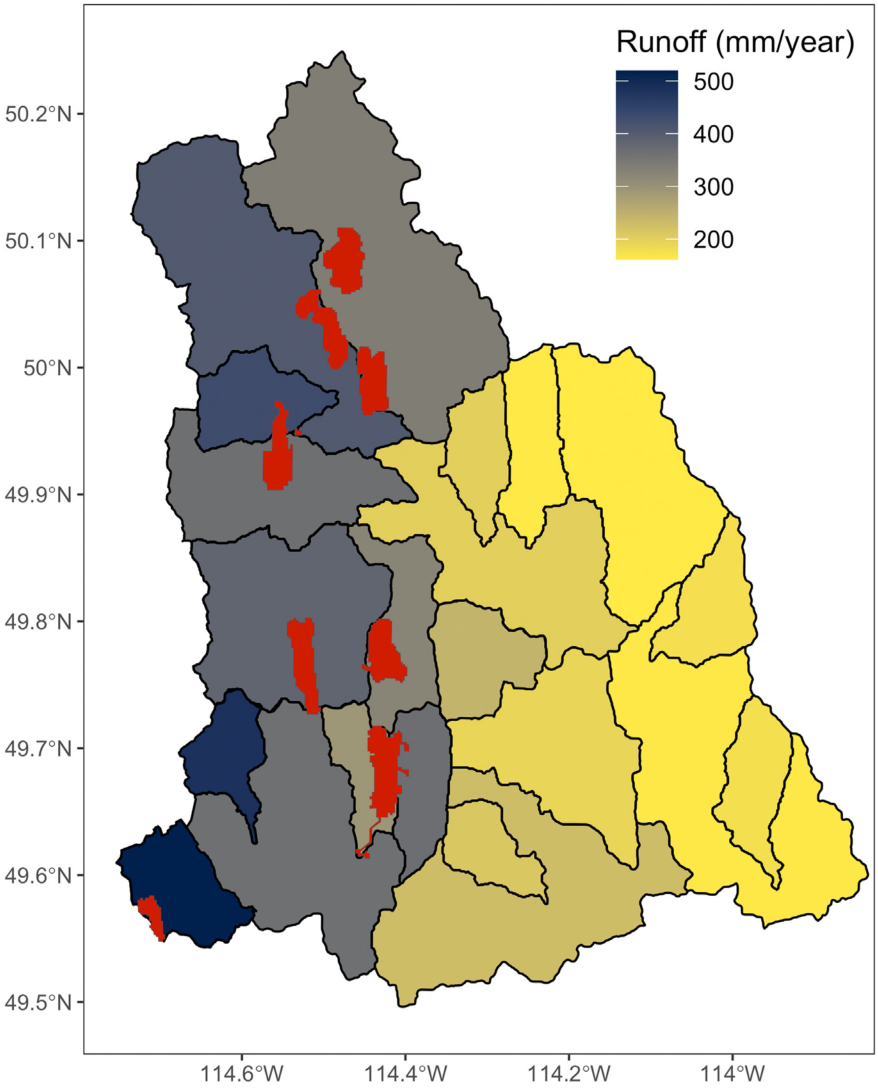

Fig. 5. Simulated runoff by sub-basin, averaged over the 1990-2019 period. The approximate footprint of mines simulated in this study are drawn in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the allocated water; however, this is highly variable between years, industries, and project stages, among other factors. As such, increased mining development has the potential to increase the fraction of allocated water that is used and not returned to the system (i.e., consumptive use).

Scenarios of potential mine development water use suggest consumptive use could affect seasonal streamflow in smaller tributaries (Fig. 8). Although potential water allocations are assumed to be seasonally constant, consumptive use would make up a larger proportion of streamflow during low-flow periods of the year, specifically late summer, fall, and winter. Under the Moderate Scenario, the largest relative water use would be in Blairmore Creek, where potential water allocation for the Grassy Mountain Mine exceeds 50% of February and March streamflow approximately once every ten years (consumptive use of approximately 20%), with lowest proportions during the spring and early summer (consumptive use in June exceeding 5% approximately once every ten years). Further downstream, approximately once every ten years consumptive water use could exceed 0.75% of February-March streamflow in the Crowsnest River, 0.3% of streamflow in the Lower Oldman River Above Reservoir, and 0.07% of the streamflow in the Oldman River at Lethbridge.

Under the High Scenario, several major tributaries in the upper ORB could experience substantial modifications in flow due to consumptive water use. In Dutch Creek, Racehorse Creek, and in the Livingstone River, winter consumptive losses could exceed 5% of streamflow in one out of ten years, while winter potential allocations could account for upwards of 8% in the Livingstone River in an average year. In the Oldman River, approximately once every ten years consumptive water use could exceed 1% of February-March streamflow above the Oldman Reservoir and 0.3% at Lethbridge. Likewise, under this High mine development scenario, potential allocations to coal mining could account for over 1.5% of winter streamflow in the Oldman River Above Reservoir in an average year over the 2025-2069 period.

4.5.2. Selenium concentrations

Simulated selenium concentrations in the watershed display a strongly seasonal pattern, with concentrations several times higher during the winter and late summer/fall than during spring freshet (Fig. 9). This pattern coincides with the natural seasonal pattern in streamflow in the watershed, where higher streamflow leads to lower selenium concentrations and spikes in selenium concentrations occur during low-flow periods. In addition, low flow periods tend to have higher variability in selenium concentrations, while variability is substantially lower during spring freshet (April-June).

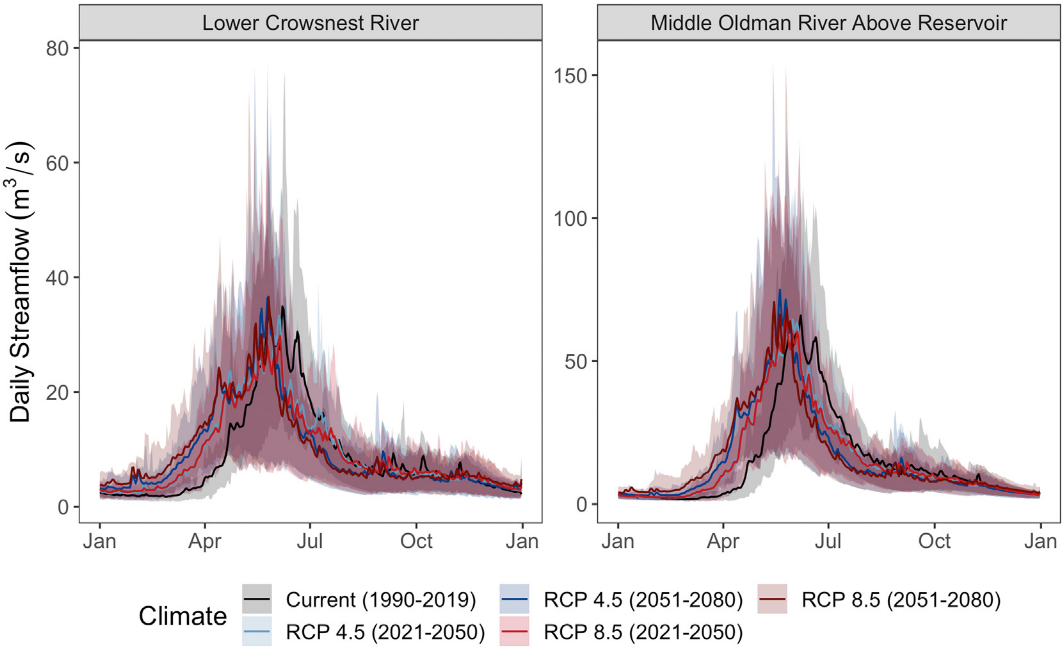

Fig. 6. Daily streamflow for two major tributaries in the Oldman River basin under current conditions and future climate change scenarios. Solid lines correspond to the average while shaded areas correspond to 10-90% quantiles.

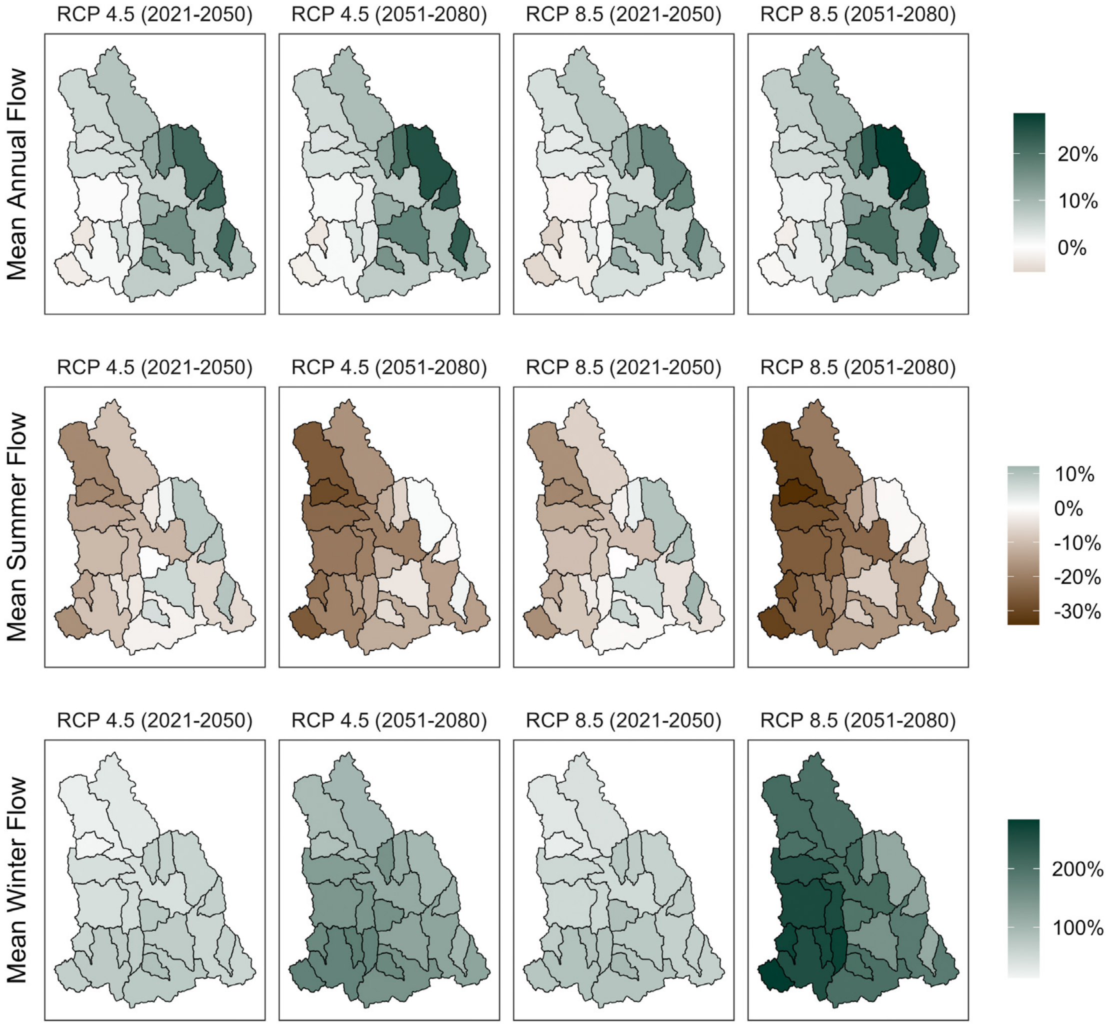

Fig. 7. Percent change in watershed indicator average for the specified period relative to 1990-2019 conditions.

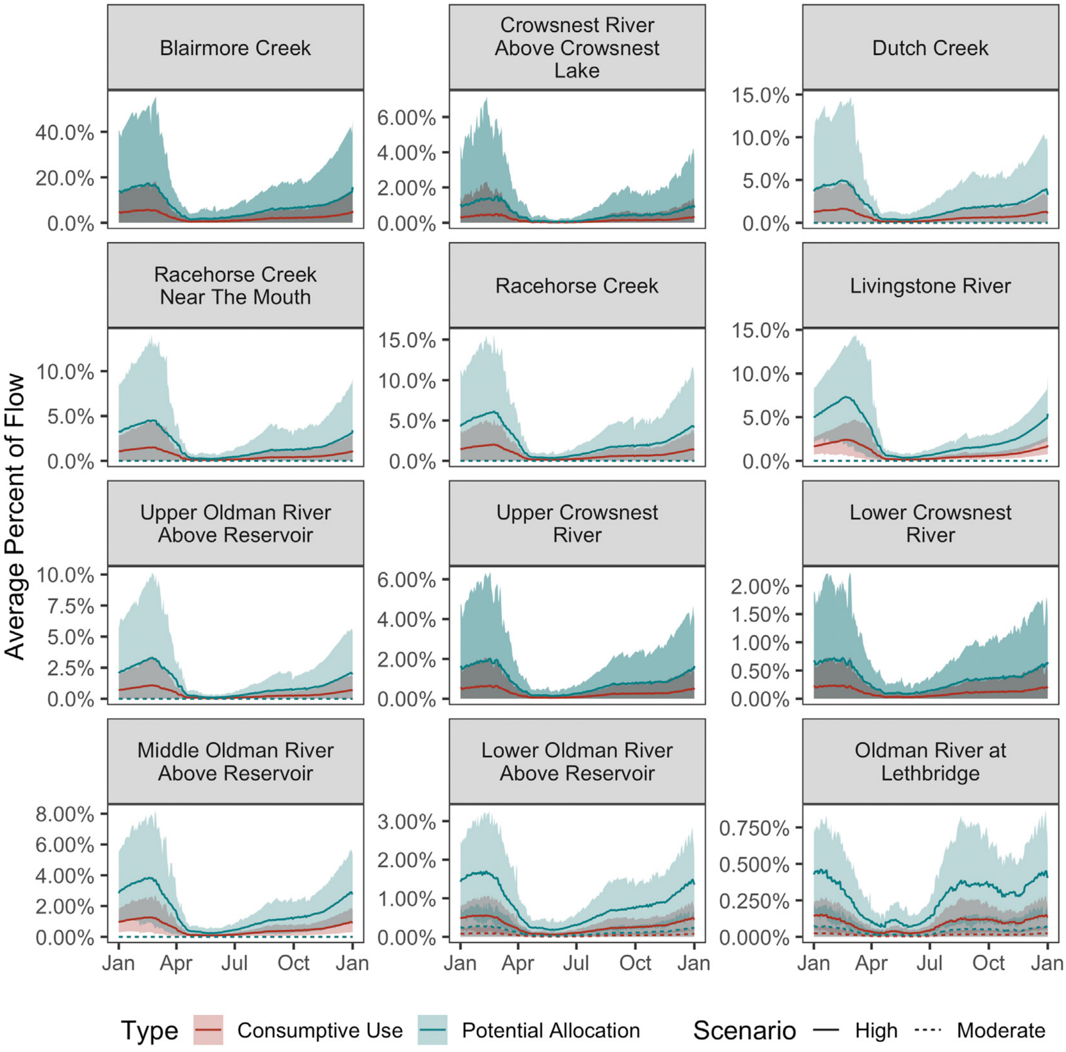

Fig. 8. Potential allocation and consumed water, as a percent of streamflow under each mining scenario under averaged future climate change projections. Solid lines represent the average over the 2025-2069 period while the shaded lines represent the 10-90% quantiles (i.e. in four out of five years values are within this shaded area).

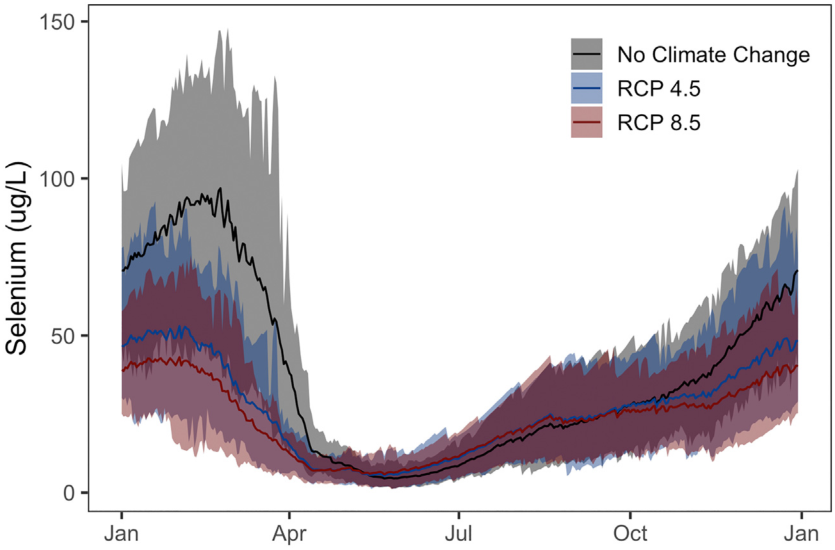

Fig. 9. Average daily selenium concentrations at the hydrological model outlet (Lower Oldman River Above Reservoir) for the 2051-2080 period under the High mine development scenario, assuming no attenuation. The solid line corresponds to the average daily value while the shaded area corresponds to the 10 and 90% quantiles (i.e. four out of five years fall within the shaded area).

Winter (January-March) selenium concentrations are estimated to be approximately half as high under the two climate change scenarios relative to the No Climate Change (i.e. historical climate) conditions. Conversely, selenium concentrations are estimated to be higher during the summer months (June-September) under both climate change scenarios relative to the No Climate Change Scenario. These substantial differences highlight the importance of seasonal shifts in streamflow on selenium concentrations.

Annual selenium concentrations are highly dependent on the rate of attenuation achieved (Fig. 10). Considering simulations averaged between the two future climate change scenarios, under the Moderate Scenario, average annual selenium concentrations are projected to range from 130 to 760 μg/L in Blairmore Creek by 2040 with no attenuation, which is approximately 2.5-7.5 times higher than the highest water quality guidelines. Even with moderate attenuation (80%), annual average concentrations would range from 87 to 152 μg/L in the 2040s. We note that these estimates assume that all selenium from the Grassy Mountain Mine reports to Blairmore Creek, while its Environmental Assessment (Riversdale Resources Ltd, 2016) assumes some portion of this selenium would instead report to adjacent Gold Creek. Further downstream, annual average concentrations in the Lower Crowsnest River peak above 40 μg/L with no attenuation, 8.2 μg/L with 80% attenuation, and 0.4 μg/L with 99% attenuation.

Considering future climate change scenarios, under the High Scenario, selenium concentrations in tributaries are projected to require high rates of attenuation to maintain levels below water quality guidelines. With no attenuation, average annual selenium concentrations are projected to exceed drinking water guidelines (50 μg/L; Health Canada, 2020) in Dutch Creek (150 μg/L), Racehorse Creek and the Livingstone River (130 μg/L), and the Lower Oldman River (50 μg/L), while others could exceed selenium concentration guidelines for aquatic health (2 μg/L; Government of Alberta, 2018) or continuous irrigation (20 μg/L; Government of Alberta, 2018) like the Crowsnest River (40 μg/L), and the Oldman River at Lethbridge (20 μg/L). With an attenuation of 80% (99%), average annual selenium concentrations are projected to reach 27 μg/L (1.3 μg/L) in the Livingstone River, while the Oldman River is projected to have annual average concentrations peak at 11 μg/L (0.6 μg/L) above the Reservoir and reach 4 μg/L (0.2 μg/L) at Lethbridge.

Estimated selenium concentrations in potentially affected tributaries and on larger rivers in the upper ORB, absent any attenuation, are substantially above most water quality guidelines (Table 4). As such, a range of effective mitigation approaches would be required to maintain adequate water quality in the watershed if mine development were to take place. For instance, in the Lower Crowsnest River, peak 30-day average selenium concentrations, without attenuation, reach 124 μg/L; an attenuation rate of at least 84% would be required

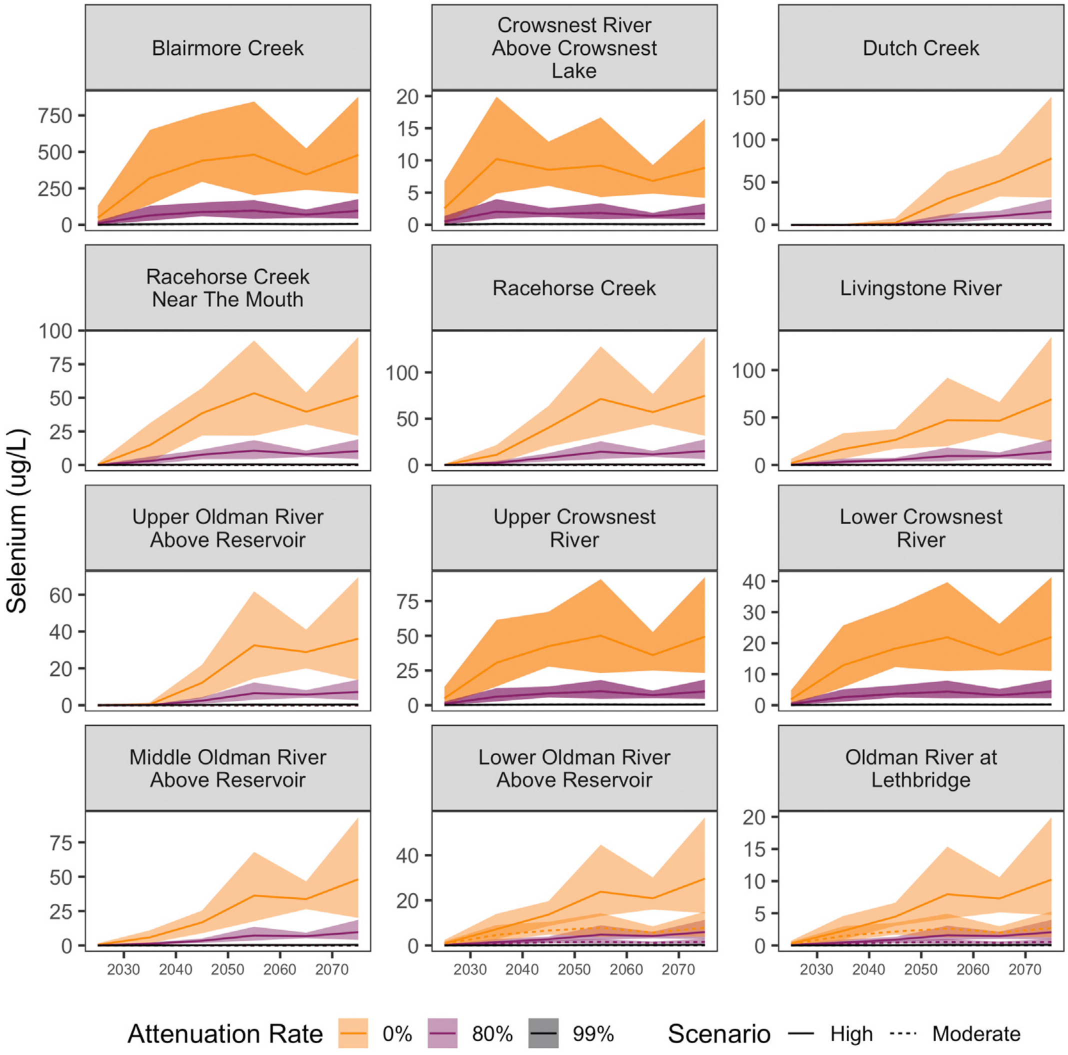

Fig. 10. Average annual selenium concentrations at all affected sub-basin outlets under both mine development scenarios and three attenuation rates. Solid line corresponds to the decadal average value while the shaded area corresponds to the maximum and minimum annual averages for the decade.

Table 4
Minimum selenium attenuation rate required to meet various water quality guidelines at selected affected waterways in the Oldman River watershed under the High mine development scenario. Peak 30-day average concentration is based on the average of the two future climate change scenarios (RCP 4.5 and RCP 8.5) over the full simulation period (2021-2080).

Site	Peak 30-day Average Concentration (μg/L)	BC - Drinking Water and Irrigation	Canada - Drinking Water	GoA - Aquatic Life	GoA - Irrigation (continuous)
Blairmore Creek	3073	99.7%	98.4%	99.9%	99.3%
Dutch Creek	614	98.4%	91.9%	99.7%	96.7%
Livingstone River	569	98.2%	91.2%	99.6%	96.5%
Racehorse Creek	563	98.2%	91.1%	99.6%	96.4%
Racehorse Creek Near The Mouth	396	97.5%	87.4%	99.5%	94.9%
Middle Oldman River Above Reservoir	372	97.3%	86.6%	99.5%	94.6%
Upper Crowsnest River	325	96.9%	84.6%	99.4%	93.9%
Upper Oldman River Above Reservoir	302	96.7%	83.4%	99.3%	93.4%
Lower Oldman River Above Reservoir	198	94.9%	74.7%	99.0%	89.9%
Lower Crowsnest River	124	91.9%	59.6%	98.4%	83.8%
Crowsnest River Above Crowsnest Lake	65	84.6%	22.9%	96.9%	69.2%

to maintain selenium concentrations below Government of Alberta irrigation thresholds, an attenuation rate of approximately 92% would be required to maintain the British Columbia human drinking water guideline, and an attenuation rate of over 98% would be required to achieve the Alberta aquatic life guideline.

Under the High Scenario, 30-day average selenium concentrations, without attenuation, peak at 198 μg/L on the Lower Oldman River above Reservoir; an attenuation rate of at least 89% would be required to maintain selenium concentrations below Government of Alberta irrigation thresholds, an attenuation rate of 95% would be required to reach the British Columbia human drinking water guideline, and an attenuation rate of 99% would be required to not exceed the Alberta aquatic life guideline. At smaller tributaries, such as Blairmore Creek, Dutch Creek, Racehorse Creek, and the Livingstone River, attenuation rates over 95% would be required in most cases to maintain 30-day average selenium concentrations below most water quality guidelines.

5. Discussion

5.1. Water supply

While this study considered the consumptive water use and selenium loading in two mine development scenarios, the model did not contemplate how the physical footprint of the mine would impact streamflow. Given that most of open-pit mines have a large physical footprint, their development will substantially alter the landscape. For instance, mine development will remove tree-cover, which can have important hydrological implications, such as less canopy interception, faster and earlier spring snowmelt, and possibly higher evaporation rates (e.g. Moore and Wondzell, 2005). In addition, most mines proposed are in higher elevations and in areas with greater precipitation; both factors that increase the impact of land cover change (Miller and Zégre, 2014). Overall, considerable uncertainty exists in understanding the hydrologic response to coal mining, with variable responses depending on a wide range of factors like topographic change, changes in soil depth and water residence times, water management, and geographic setting (Miller and Zégre, 2014; Nippgen et al., 2017; Wellen et al., 2018). This study does not contemplate how mines will manage their on-site water. Diversions, storing/settling ponds, and/or delayed releases of water will affect downstream hydrology. Further research into the physical effect of mine development on hydrological processes, including changing topography, vegetation, and soil characteristics, would provide valuable information and improve our understanding of changes in streamflow magnitude and timing due to mine development.

Water supply also depends in part on the amount of water consumed by coal mining operations. While water use is estimated to be relatively small at the scale of the Oldman River basin, it can account for a substantial portion of smaller tributaries, particularly during lower flow periods of the year. In addition, specific estimates of water consumption for open-pit mines are difficult to ascertain and are highly variable due to changing technology, operations, and climatic conditions (Côte et al., 2010; Dieter et al., 2018). For instance, some research suggests a baseline water withdrawal for an open pit mine should be approximately 0.76 m^3/t of ore processed, approximately three times greater than what is estimated in our study, while a substantial increase in sustainable technology and innovation could reduce that value to 0.20 m^3/t (Gunson et al., 2012).

5.2. Water quality

Simulations of mine development suggest that selenium concentrations are likely to exceed water quality guidelines without substantial mitigation measures. Headwater tributaries are particularly sensitive to water quality degradation since they are the receptors of selenium loading from montane coal mines but contain relatively little streamflow to aid in dilution. Likewise, water use from mining operations is likely to be largely concentrated in these same headwater sub-basins, where potential withdrawals make up a greater portion of streamflow and would exacerbate potential water quality concerns.

This study considered selenium concentration in exceedance of water quality guidelines on a 30-day average. This study choice was made given the relative uncertainty in mine development plans, potential seasonal patterns in selenium loading (Wellen et al., 2015), and uncertainty regarding the precise definition of “long-term” or “chronic” in relation to water quality guidelines. Simulations from the hydrological model at a daily timestep show that selenium concentrations vary substantially throughout the year, and concentrations during low flow periods can be several times greater than the annual average. As such, we emphasize that episodic low flow periods will lead to substantially higher selenium concentrations than captured in the 30-day average. Selenium concentrations during these periods may compromise the suitability of water in these rivers for aquatic life, irrigation, or human health, and present further short term socio-economic and environmental risks in the basin. For instance, given most water allocations in the ORB are for irrigation, selenium concentrations during the summer months are of primary concern. Conversely, aquatic habitat, particularly for threatened species such as westslope cutthroat trout (*Oncorhyncus Clarkii Lewisi*), is affected by selenium concentrations throughout the year, and high winter concentrations could have detrimental environmental impacts.

5.3. Cumulative effects

Climate change scenarios in the upper ORB suggest warmer air temperatures will likely lead to less winter precipitation falling as snow and earlier spring snowmelt, which subsequently could result in an increase in winter flows and decrease in summer streamflow (Luckman, 1998). The hydrological regime of the ORB will likely become increasingly sensitive to the timing and frequency of rainfall events and see increased water stress in downstream storage reservoirs in the late summer when water demand is highest and water quality concerns are heightened.

The climate change scenarios used in this study were median projections from a multi-model ensemble for two emissions pathways (RCP 4.5 and RCP 8.5). While RCP 8.5 represents a very high baseline emission scenario, and subsequently relatively large changes in climate, the use of median projections from an ensemble means that these scenarios represent the “middle-of-the-road” projections within each emissions pathway. As such, they may be our best guess at average future conditions under each emissions pathway, but likely underestimate the potential of extreme climate events, such as floods or prolonged droughts. This dynamic is important given the effects of both water use and selenium concentrations are sensitive to the hydroclimatic conditions. Prolonged drought conditions, for instance, could lead to significant degradation of water quality beyond what is estimated here. Further work could use this framework to provide a more robust risk analysis using a wider range of climate change scenarios.

These simulations highlight the importance of considering climate change in water quality modelling and watershed management. Changes in air temperature and precipitation can lead to substantial changes to the magnitude and timing of streamflow and these changes are likely to occur over the lifespan of any proposed mine. Changes to the hydrological regime of the watershed will have direct impacts on the degree of dilution and therefore are integral to effectively manage mine operations, including attenuation potential, and accurately evaluate the risks associated with potential future development.

6. Conclusions

This study provides an integrated assessment of the cumulative effects of climate change and potential open-pit coal mining on streamflow and water quality in the ORB, outlining the potential increase in risks to sustainable water management in the coming decades. A hydrological model of the upper ORB was developed to simulate streamflow for tributaries and the mainstream Oldman River under a recent historical period (1990-2019) and two future climate change scenarios (RCP 4.5 and RCP 8.5; 2021-2080). The model integrates water use and selenium mass loading associated with two future mine development scenarios to estimate changes to water supply and selenium concentrations in the watershed.

Consumptive water use projected from mine development scenarios is relatively small at the scale of the ORB but is seasonally significant and represents a substantial proportion of winter streamflow in major tributaries, where many mines are likely to be located. There is additional risk of greater reductions in streamflow if a low-flow year coincides with peak mine development or if consumptive water use is higher than currently estimated, since potential allocations are approximately three times greater. Estimated selenium concentrations in affected tributaries and on larger rivers in the upper ORB, absent any attenuation, are substantially above most water quality guidelines. A strong reliance on mitigation technologies (i.e. selenium attenuation) would be required to maintain adequate water quality in the watershed if mine development were to take place.

Streamflow in the Oldman River basin originates disproportionately from its mountain headwaters, while by comparison, lower elevation sub-basins located further east and south produce less than half as much runoff. Proposed mine development is primarily located in these hydrologically productive headwater areas. Under the future climate change scenarios, warmer air temperatures are likely to lead to less winter precipitation falling as snow and earlier spring snowmelt. These factors will influence the timing and magnitude of streamflow in the basin, which has important implications for water management and water quality in the coming decades. These simulations emphasize that water management decisions may mis-evaluate the impact of mine development if they fail to adequately consider climate change.

CRediT authorship contribution statement

M Chernos: Conceptualization, Methodology, Modelling, Writing. **RJ MacDonald**: Conceptualization, Methodology, Supervision, Writing. **J Straker**: Methodology, Writing. **K Green**: Methodology, Editing. **J Craig**: Software, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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