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Modelling transverse mixing of sediment and vanadium in a river impacted by oil sands mining operations

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ABSTRACT

Study region: The lower Athabasca River was used as a test case using total suspended sediment, chloride and vanadium as the model variables. Upstream model boundary conditions included water from the tributary Clearwater River (right stream tube) and the upper Athabasca River extending upstream of the tributary mouth (left stream tube). This model will be extended to include the Peace-Athabasca Delta (PAD), to determine the implications of mining outfall discharges on a large region of the Athabasca – PAD region.
Study focus: A novel, quasi-two-dimensional surface water-quality modelling approach is presented in which the model domain can be discretised in two dimensions, but a one-dimension solver can still be applied to capture water flow between the discretisation units (segments). The approach requires a river reach to be divided into two stream tubes, along the left and right river sides, with flows exchanging through the segments longitudinally and also laterally between adjacent segments along the two streams.
New hydrological insights for the region: The new method allows the transverse mixing of tributary and outfall water of different constituent concentrations to be simulated along the course of the river. Additional diffuse loading of dissolved vanadium could be determined from the model's substance balance. A scenario was then simulated in which the transport and fate of vanadium in a floodplain lake and a secondary channel was determined.

1. Introduction

Release of treated oil sands process water is an option that is currently being evaluated to reduce inventories on oil sands sites. Vanadium was modelled in this exercise since it is present in bitumen mined in the Athabasca Oil Sands region and in oil sand process water (Schlesinger et al., 2017). The metal can have toxic effects on aquatic life, for example, phytoplankton and zooplankton (Schiffer and Liber, 2017a) and selected macroinvertebrates and fish (Schiffer and Liber, 2017b). Other studies have been carried out to further understand the toxicity, transport, fate, and environmental behaviour of vanadium (e.g. Jardine et al., 2019; Kay et al., 2020; Klemt et al., 2020; Tendler et al., 2020). Our modelling study work can contribute to this understanding.

Gupta et al. (2021) provides a historical overview of modelling in the Athabasca River basin. Only the instream water-quality modelling of the lower Athabasca River will be highlighted here. Since the 1970s, it has been understood that near-field mixing is a key factor influencing the fate and transport of releases to the lower Athabasca River (Beltaos, 1979; Lipsett and Beltaos, 1978). A

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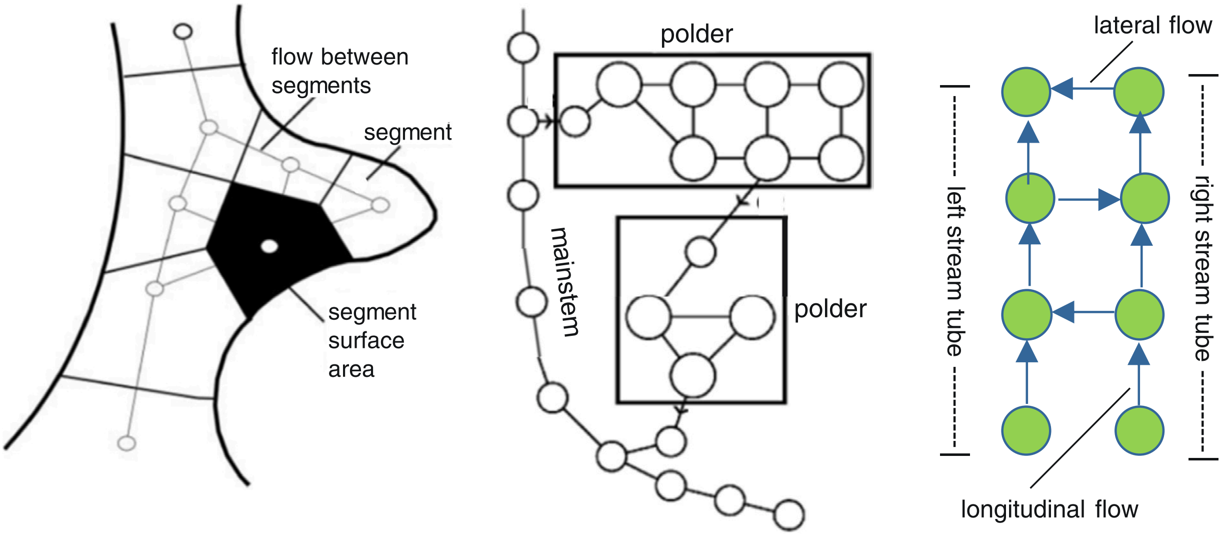

Fig. 1. *left panel*: two-dimensional discretization in WASP (adapted from Ambrose et al., 1993); *middle panel*: discretization of off-channel storage basins (adapted from Sehnert and Lindenschmidt, 2009); *right panel*: discretization of a river to capture both lateral and longitudinal mixing.

model of the lower Athabasca River developed at the National Water Research Institute in the 1970s had initially been developed as a one-dimensional model; however, the need for two-dimensional analysis was identified based on observed mixing patterns downstream of Fort McMurray to the delta at Lake Athabasca (Booty, 1994; Bourbonniere, 1992). A two-dimensional model was calibrated using mixing in the Athabasca and Clearwater rivers (Booty, 1994) and later using the wastewater from the oil company Suncor (Booty et al., 1996). At the time, the Suncor wastewater had measurable concentrations of several organic constituents, including 2,4 – dimethylbenzothiophene, which were used to validate the two-dimensional mixing model (Booty et al., 1996). A model for transport and fate of substances was developed for the Athabasca and Wapiti/Smoky Rivers using the WASP model as part of the Northern Rivers Basin Study (Golder, 1997a). The purpose of the model was to predict the fate and transport of sediment-associated substances that were accumulating in the bed sediment downstream of pulp mill outfalls. The WASP model for the Athabasca River was successfully configured to capture the process and longitudinal pattern of sediment flocculation and deposition downstream of the pulp mill releases (Krishnappan, 1996; Golder, 1997b).

Vanadium has been modelled for the lower Athabasca River using the two-dimensional model EFDC (Kashyap et al., 2017), set within a surface water modelling framework for water quality assessment and substance load allocation along the lower Athabasca River (EC, 2011). Although it has been asserted that conditions in the lower Athabasca River require a fully dynamic two- or three-dimensional model of the river, the implementation of these types of models for the lower Athabasca River has encountered computational issues resulting in costly and protracted model development. One-dimensional models have also been applied to the lower Athabasca River, such as Mike 11 model (Dibike et al., 2018). One drawback with Mike 11 is that the model does not account for transverse mixing, which has been identified as a key feature for modelling operational releases to the lower Athabasca River, as stated above. Based on analyses completed as part of a regional substance allocation study (RSLA, 2021), substance load allocations calculated without accounting for transverse mixing would be approximately ten times higher than those accounting for delayed transverse mixing.

In order to accommodate for the aforementioned model shortcomings, the following criteria were considered paramount for a new development of a model of the lower Athabasca River:

- Leanness in computational resources, including short simulation times – this is important for planned future work in (i) scaling up the model spatially when extending the lower Athabasca River model to include the Athabasca Delta, (ii) coupling the model to a hydrological and sediment transport model MESH-SED for climate-change scenario modelling (Rokaya et al., 2019; Das et al., 2020, 2021) and (iii) incorporating the river ice model RIVICE of the Athabasca River (Lindenschmidt, 2017; Lindenschmidt et al., 2019) into the MESH-SED → WASP modelling system to investigate the impact of ice-cover breakup and ice jams on the transport of sediments and contaminants within the river;
- Simulation of transverse mixing, which must be accounted for to accurately predict concentrations in the mid-field downstream of outfalls.

Hence, we introduce a novel, quasi-two-dimensional modelling approach, in which a one-dimensional modelling solution can be used to reduce computation resources which allows discretization in a manner to mimic a two-dimensional configuration. The WASP platform is an ideal avenue to fulfil such a setup. The model takes advantage of short computational times offered by its one-dimensional solver but allows for transverse mixing with a discretization that accounts for, not only longitudinally, but also

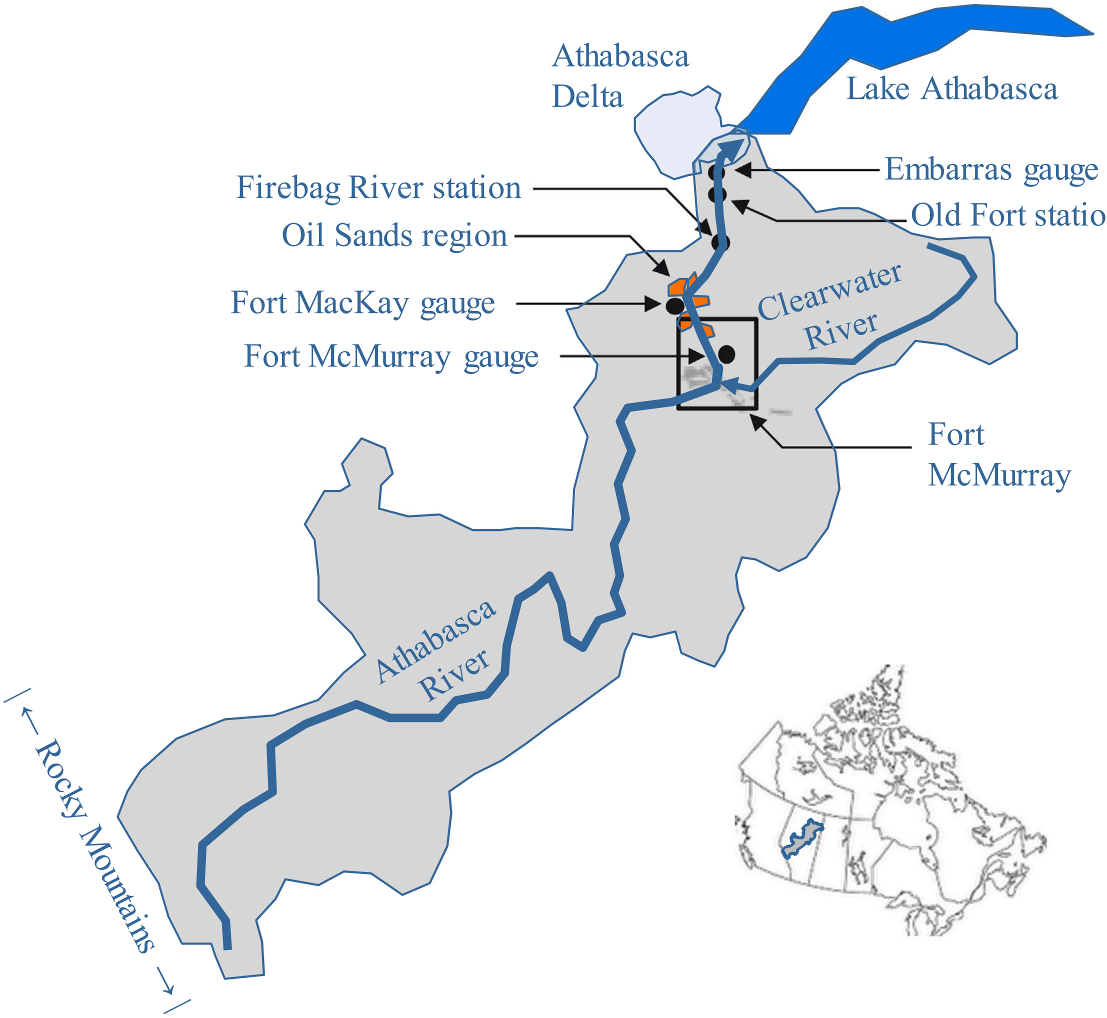

Fig. 2. The Athabasca River basin in Alberta, Canada. The square is the extent shown in Fig. 3.

laterally exchanges along the river, as shown in Fig. 1 (left panel). For comparison, a two-dimensional model of the Lower Athabasca River developed by Kashyap et al. (2017), with a domain extending 160 km downstream from Fort McMurray, required computational times greater than 3 h. Our quasi two-dimension model requires only 2 min to reach steady state conditions. Taking into account that our model domain is only about one-third of the domain modelled by Kashyap et al. (2017), the quasi-two-dimensional approach is still at least 20 times faster than a full two-dimensional setup.

Such an approach is yet to be documented in the literature for heavy-metal transport. The closest study to such an approach is the modelling of the deposition of zinc in off-channel storage basins (polders) along the Elbe River (Lindenschmidt et al., 2008; Sehnert and Lindenschmidt, 2009), but only longitudinal, not transverse, mixing within the river was considered. The two-dimensional discretization only came into play when coupling the polder to the river's mainstem (Fig. 1; middle panel). In this study, however, the two-dimensional discretization is to be carried out within the river's mainstem as two stream tubes to allow flow and hence mixing between lateral segmentations (Fig. 1; right panel).

Key objectives of this paper are:

- Mimic transverse mixing in a river using a quasi-two-dimension approach in which a river model domain is discretised in two dimensions but the flows between discretisation units are in one direction allowing a one-dimensional solver to be used in the simulations;
- Verify the accuracy of the quasi-two dimensional approach by simulating chloride, total suspended sediments and vanadium.

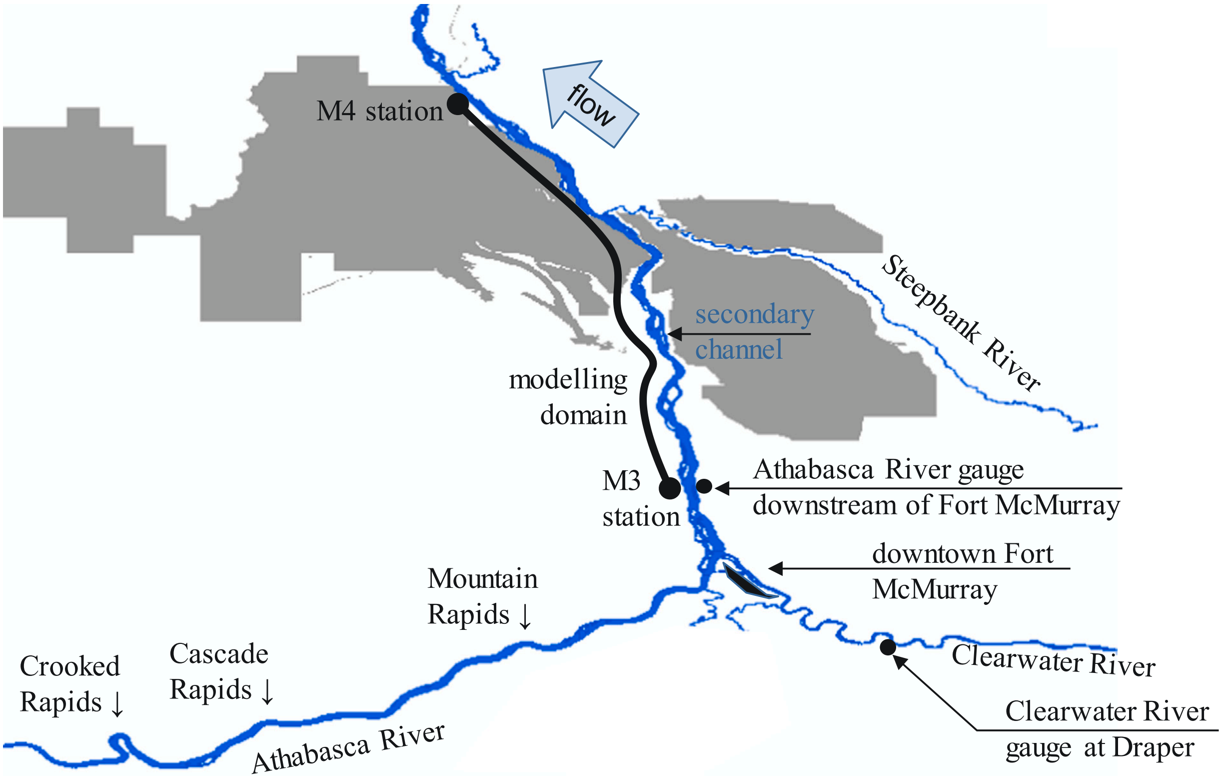

Fig. 3. Lower Athabasca River.

1.1. *Site description*

The Athabasca River originates on the eastern slopes of the Rocky Mountains and flows unregulated approximately 1500 km through Alberta in a north-easterly direction to the Athabasca Delta and Lake Athabasca (see Fig. 2). Water quality in the Athabasca River and tributaries is rated as good or excellent (Charette and Trites, 2011; Fiera, 2012), with relatively low contributions from non-point sources associated with urban and agricultural development (Fiera, 2013).

This study focuses on a stretch along the lower Athabasca River, downstream of Fort McMurray (see Fig. 3), between water-quality sampling stations M3 and M4. The lower Athabasca River, within the oil sands region, extends from just upstream of Fort McMurray to the Athabasca Delta. At Fort McMurray, there is a convergence of the Athabasca River with the Clearwater River, which has unique water quality and flow characteristics compared to the Athabasca River upstream of the Athabasca/Clearwater river confluence. Mixing of the Clearwater River water is delayed and results in gradients in concentrations of chloride and other ions for many kilometres downstream of the confluence. Major tributaries along the lower Athabasca River are the Steepbank, Muskeg, McKay, Ells, and Firebag rivers. However, only the Steepbank River, whose average flow constitutes less than 1% of the Athabasca River, is found within our modelling domain.

The lower reaches of the Clearwater River and many areas of the lower Athabasca River are incised into the Devonian and Cretaceous geological formations. As a result, there are numerous fens, springs, and riverbed seeps that contribute high salinity groundwater to the river (Roy et al., 2016; Gue et al., 2018; Birks et al., 2018). Additionally, erosion of the bank and bed of tributaries contributes bituminous material to the Athabasca River. Along the upper Athabasca River are sources of natural bitumen erosion, including prominent McMurray Formation outcrops at Crooked Rapids, Mountain Rapids, and between Mountain Rapids and Fort McMurray (Hein et al., 2001). There is also substantial bituminous material in the Clearwater River and other smaller tributaries.

The lower Athabasca River contains many islands, secondary channels, wetlands, and floodplain lakes. Many of these secondary channels freeze to the bottom or have low oxygen levels during winter. Sediment deposition areas occur below tributaries (confluence bars), in mid-channel bars, and in secondary channels throughout the river. During flooding events in tributaries, substantial amounts of oil sands material can be transported downstream and deposited on the surface of confluence bars. Over time, these areas of high oil sands material are mixed with sediment coming from upstream and are diluted (Conly et al., 2002).

Most sediments conveyed through the lower Athabasca River stem from upstream sources in the Athabasca and Clearwater rivers, with minor contributions from tributaries and from within the lower Athabasca River. There is an abrupt change in the river slope at Fort McMurray at the confluence of the Clearwater River where the gradient of about 0.00014 (Carson and Hudson, 1997). Downstream of Fort McMurray, there is less gravel than the upstream reaches, and the substrate is dominated by sand. Between Fort Mackay and Embarras Airport, the river slope decreases further to about 0.0001, and the character of the channel becomes more sinuous with

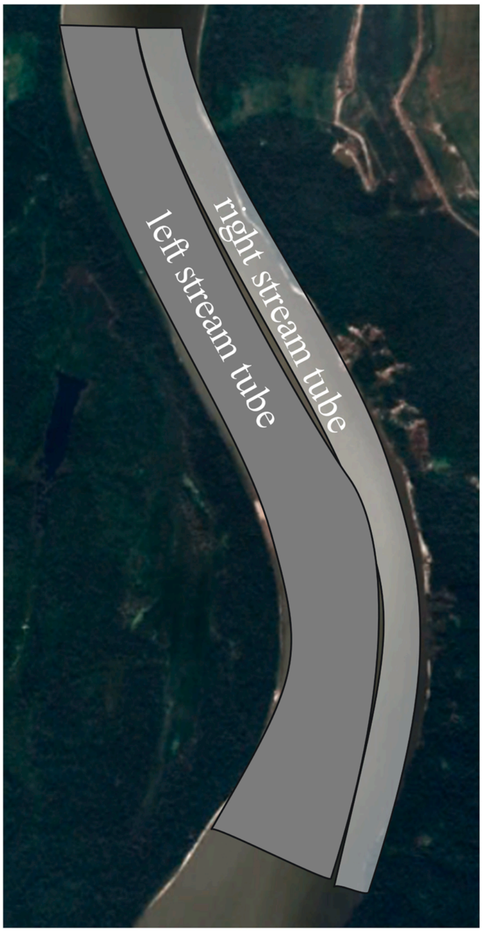

Fig. 4. Left and right stream tubes along the model domain.

occasional well-developed meanders, and a well-defined floodplain of silt and sand has been built-up in most places. The bed is sandy throughout, with finer sediment in the secondary channels. Downstream of the Embarras Airport, the river gradient again decreases as the river enters the Peace-Athabasca Delta. Bed sediment in this area is much finer as silt and clay settle out in the more slowly flowing water.

The Athabasca River receives continuous releases from five pulp mills and four municipal wastewater treatment plants upstream of Fort McMurray. In 2011, the total release from these uses was estimated to be about 5 m^3/s (AG, 2015). Wastewater loadings to the lower Athabasca River are limited to treated municipal wastewater from the city of Fort McMurray, Suncor’s industrial release, and Syncrude’s clean water release. In addition, approximately 3300 tonnes of road salt are applied as road de-icing agents in Fort McMurray in the winter (Jasechko et al., 2012).

2. Materials and methods

2.1. Hydraulic modelling with HEC-RAS

The hydraulic model HEC-RAS, developed by the U.S Army Corps of Engineers, was used to simulate the hydrodynamics of the model domain. Flow rates of 600 m^3/s (approximate average flow at the Athabasca River gauge below Fort McMurray) and 1600 m^3/s (a high flow corresponding to approximately the maximum 3rd quartile of monthly flow) were chosen to run the model for steady-state conditions. Water-quality data were also available for these flows. The flow widths, average depths and water volumes between cross-sections were used as a basis for the dimensioning of the segmentation of the WASP model, described below. Bathymetry data provided by Alberta Environment and Parks was used to generate the 100 cross-sections at approximately 500 m intervals along the model domain. Due to the lack of gauges along this stretch, the model’s accuracy for predicting water-level elevations was verified through the hydraulic model ONE-D in a previous study (Sabokruhie et al., 2021). The one-dimensional HEC-RAS model could not be coupled to the quasi-two-dimensional WASP model since HEC-RAS incorporates the entire cross-section of the channel as a single entity. The cross-sections cannot be further discretized into two entities transversely as we have done in our quasi-two-dimensional WASP setup as

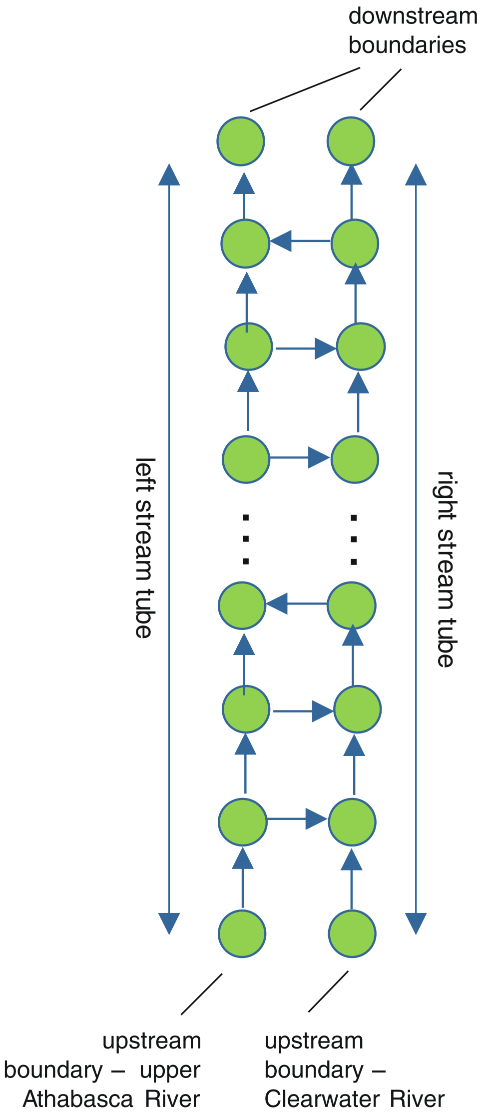

Fig. 5. Discretisation of model domain with longitudinal and lateral flows between segments.

left and right stream tubes along the channel.

2.2. *Water-quality analysis simulation package, WASP*

The Water Quality Analysis Simulation Program (WASP 8.3.2) was used to model the water quality of the study, a stretch of the lower Athabasca River. WASP is a finite difference model for analysing the transport and fate of sediments and toxicants in aquatic environments and to simulate key processes to describe eutrophication. This latest version of WASP has undergone many significant changes, which are briefly discussed in Wool et al. (2020). The model was developed based on the conservation of mass, momentum, and energy. The model domain is discretised by water volumes called segments allowing the simulation of water depths, flow velocities and water volumes based on the segment geometries and roughness coefficients. These in turn control the passage of sediments and chemicals by advection, deposition, resuspension, partitioning, oxidation, photolysis and many other processes and transformations.

Additional inputs to the model include a flow routing map, boundary conditions, environmental functions, constants, loads, and initial conditions for segments. The WASP segment geometries were generated from the HEC-RAS model. The uneven shape of the channel was described using a depth exponent of 0.3. The segment length considered for modelling was 500 m. This length grants an acceptable mixing and an approximate uniform volume for segments and deems computational times acceptable.

Although the water-quality simulations were carried out one-dimensionally, the discretization of the surface-water segments into two stream tubes longitudinally along the studied reach allowed for a two-dimensional representation of the model domain, as shown in Fig. 4, a novel approach we have coined quasi-two-dimensional modelling. Benthic segments were also inserted under each surface-

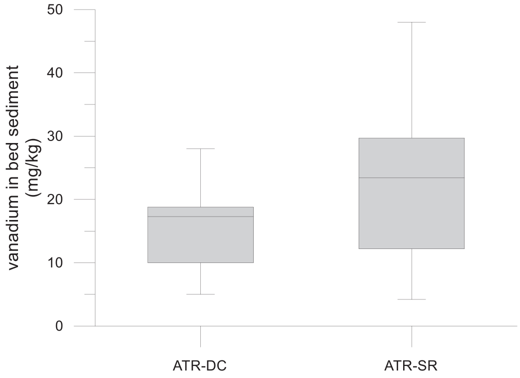

Fig. 6. Vanadium concentrations in riverbed sediments; ATR-DC is closest to the upstream station M3 and ATR-SR is closest to the downstream station at M4 (data from Regional Aquatics Monitoring Program, http://www.ramp-alberta.org/RAMP.aspx).

water segment to characterise erosion and deposition processes. For the upstream model boundary, the flow from the Clearwater River was supplied to the right stream tube segment, while the upper Athabasca River flow (flow along the Athabasca River upstream of the Athabasca/Clearwater river confluence) was inserted into the left stream tube segment. The width of each stream tube was proportional to the discharge allocation. The flow mapping was carried out in such a way that a 50:50 ratio of the flow in each tube was achieved by the time the flow reached the downstream boundary, from the 80:20 ratio of the left:right stream tubes for the upper Athabasca:Clearwater flows at the upstream boundary.

The Draper gauge provided daily flows along the Clearwater River whereas the upper Athabasca River flow was obtained by simple subtraction of the Clearwater River flow from the flow recorded at the Athabasca River gauge downstream of Fort McMurray. This estimation was deemed suitable since transit times between gauges are much shorter than one day. For total flows at the Athabasca River gauge of 600 and 1600 m^3/s, the Clearwater River supplies respectively approximately 14% and 16% of the flow to the lower Athabasca River. Flow mapping was carried out to characterise a complete mixing in the 50 km stretch of the modelling domain. Transverse transport between segments was configured so that a 1:1 flow ratio was obtained after 50 kilometres of flow at the downstream boundary of the model domain. This was done by progressively inserting flows between laterally adjacent segments, with more flows from left stream tube segments to right stream tube segments as shown in Fig. 5.

The hydrodynamics of the system was modelled using the kinematic wave flow option throughout the network. The algorithm used to solve the equations involves finite-difference formulations of flow and continuity in one-dimensional conditions. This method is based on solutions of one-dimensional continuity equations and the momentum equation that addresses gravity and friction.

The flow between the left and right side segments was transferred by diverting 1% of the longitudinal flow between adjacent upstream and downstream segments to laterally adjacent segments, alternating from right to left and left to right, with the right side progressively receiving more water volume and the left side less water volume. At the upstream boundary 80% of the flow was emitted in the left stream tube whereas 20% in the right stream tube, based on the 80:20 ratio of the flows from the upper Athabasca and Clearwater rivers, respectively. The 1% flow exchange was configured in such as way that the downstream boundary flows in the left and right stream tubes became balanced 50:50. At this location, the concentrations of sediment and chloride across the river were relatively uniform indicating full mixing. The kinematic wave equation was used to model the flow from one segment to another. The kinematic wave estimates wave propagation and variation in flow velocity through a stream network. Kinematic wave formulation controls flow by river bottom and slope roughness and can be described using Manning's equation:

$$Q = \frac{1}{n}\frac{A^{5/3}}{B^{2/3}}{S_0}^{1/2}$$

and the continuity equation differentiated with respect to distance in the flow direction and time:

$$\frac{\partial Q}{\partial x} + \alpha\beta Q^{\beta-1}\frac{\partial Q}{\partial t} = 0$$

where Q is flow, x is distance in the flow direction (one-dimensional flow), t is time, α and β are functions of hydraulic coefficients which are related to channel geometry, S_0 is the bottom slope, n is Manning's roughness coefficient, A is cross-sectional area and B is channel width. A depth exponent is used along with segment geometries to estimate hydraulic coefficients, which are later used to calculate segment flow depths under specific flow rates. A more detailed description of stream transport in WASP is provided in Wool et al. (2020). Further descriptions of the flow mapping and transverse mixing can be obtained from Sabokruhie et al. (2021).

Boundary and initial conditions for the segments were determined using existing water quality and flow data at the existing stations. WASP uses flow and dispersion paths to specify boundary paths. For the upstream boundary condition, these data were obtained from the M3 station. Initial concentrations for all segments along the model domain were derived by linear interpolation of values between the M3 and M4 stations. Settling of silt and clay was estimated using Stokes Law, and the settling velocity of sand was estimated based on Ferguson and Church (2004). Resuspension was based on van Rijn (2007). To model vanadium, the partitioning

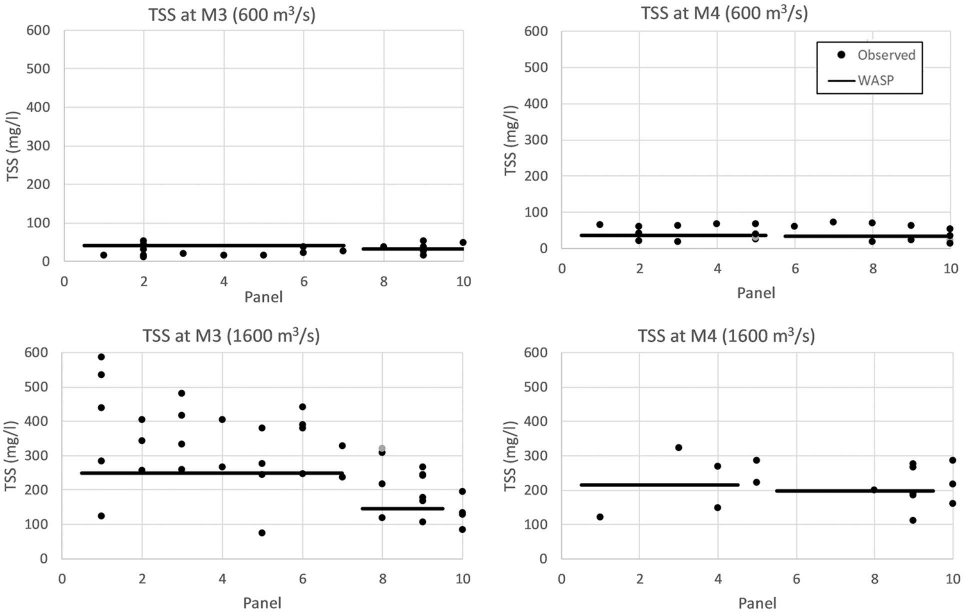

Fig. 7. Transect of total suspended sediment concentrations at the upstream (left panels) and downstream (right panels) boundaries of the model domain for flows of 600 m^3/s (top panels) and 1600 m^3/s (bottom panels). Points are sampled values collated from many sampling compaigns and the horizontal line is the averaged value used for the left and right WASP streams.

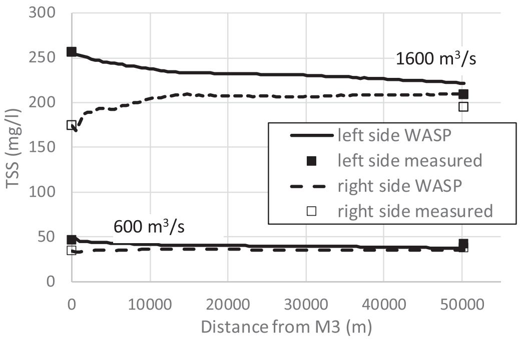

Fig. 8. Longitudinal profiles of total suspended sediment concentrations along the left and right stream tubes of the model domain for flows of 600 and 1600 m^3/s.

coefficient was obtained from Allison and Allison (2005). The deposition rate of vanadium was calibrated using the sampled concentration at the upstream and downstream model boundaries. The concentration of vanadium in the riverbed was taken to be 18 mg/kg, which is an average of all the values available from field sampling (see Fig. 6). The model was run in a steady state until equilibrium conditions of constituent concentrations in all segments was reached.

3. Results

3.1. Total suspended sediment

Constitutent sampling was carried out for many days between 2011 and 2018. However, the sampling at stations M3 and M4 were carried out on different days. Constitutents for flows of approximately 600 m^3/s and 1600 m^3/s, ± 25% for each were sought and collated in Fig. 6. As indicated in the top panels of Fig. 6 for the lower flow scenario of 600 m^3/s, the total suspended sediment concentrations are only slightly greater stemming from the upper Athabasca River (left stream tube) than those from the Clearwater River (right stream tube). The concentrations quickly become uniform across the two streams as flow moves downstream, as indicated by the 600 m^3/s longitudinal profiles in Fig. 7. For the higher flow scenario, there is a larger difference in total suspended sediment concentrations between the upper Athabasca and Clearwater rivers (see bottom left panel of Fig. 6), about one-third less for the Clearwater River. The concentrations are almost uniform between the two stream tubes by the time the flow reaches the downstream

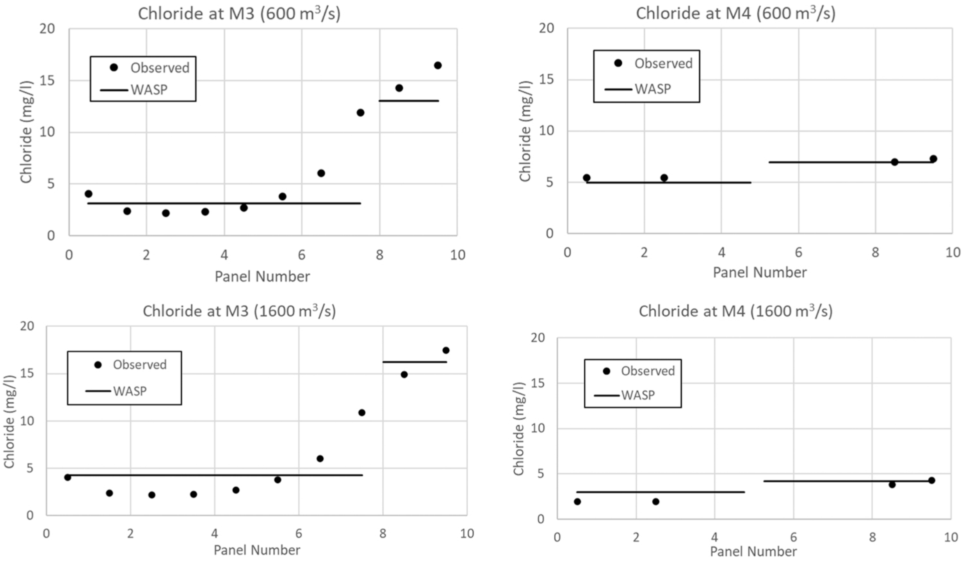

Fig. 9. Transect of chloride concentrations at the upstream (left panels) and downstream (right panels) boundaries of the model domain for flows of 600 m^3/s (top panels) and 1600 m^3/s (bottom panels).

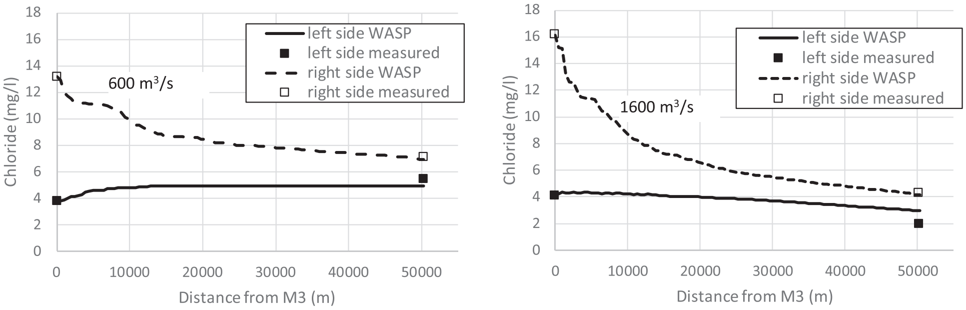

Fig. 10. Longitudinal profiles of chloride concentrations along the left and right stream tubes of the model domain for flows of 600 m^3/s (left panel) and 1600 m^3/s (right panel).

model domain boundary at station M4 (see bottom right panel of Fig. 6). The total suspended sediment concentrations between the two streams become uniform quicker at the higher flow scenario, as indicated by the 1600 m^3/s longitudinal profiles in Fig. 7. This is due to both the larger transverse flows between laterally adjacent segments and the high concentration gradients between the two stream tubes (Fig. 8).

3.2. Chloride

Chloride was modelled for the same flow dates as for total suspended sediments above in order to show that our quasi-two-dimensional model setup can capture the lateral mixing along the lower Athabasca River. Chloride is considered to be a conservative substance, making it suitable for tracking its mixing along a river. For the upstream boundary of our modelling domain, at station M3 (referring to the left panels of Fig. 9), chloride concentrations in the right stream tube, hence from the Clearwater River, are higher than the concentrations in the left stream tube, hence the upper Athabasca River, for both flow scenarios of 600 and 1600 m^3/s. The concentrations of chloride in the two streams remain relatively the same. There is a slight increase in chloride concentrations at 1600 m^3/s compared to 600 m^3/s. By the time the flow has reached the downstream boundary of our modelling domain, at station M4 (referring to the right panels of Fig. 9), chloride concentrations across the transect are almost uniform, indicating the complete mixing of chloride has occurred across both stream tubes. Chloride concentrations are slightly greater at the 600 m^3/s flow scenario compared to the higher 1600 m^3/s flow. This is substantiated with the longitudinal profiles of simulated chloride concentrations along the model domain between station M3 (upstream boundary) and station M4 (downstream boundary), shown in Fig. 10. The chloride concentrations along the right stream tube tend to drop off faster for the higher flow scenario due to the higher mixing between segments at higher flows. Lateral flows between segments are input as a percentage of the longitudinal flow through the segments. Hence, for higher flows, a larger flow is simulated between two laterally adjacent segments. The chloride concentrations in the left stream tube

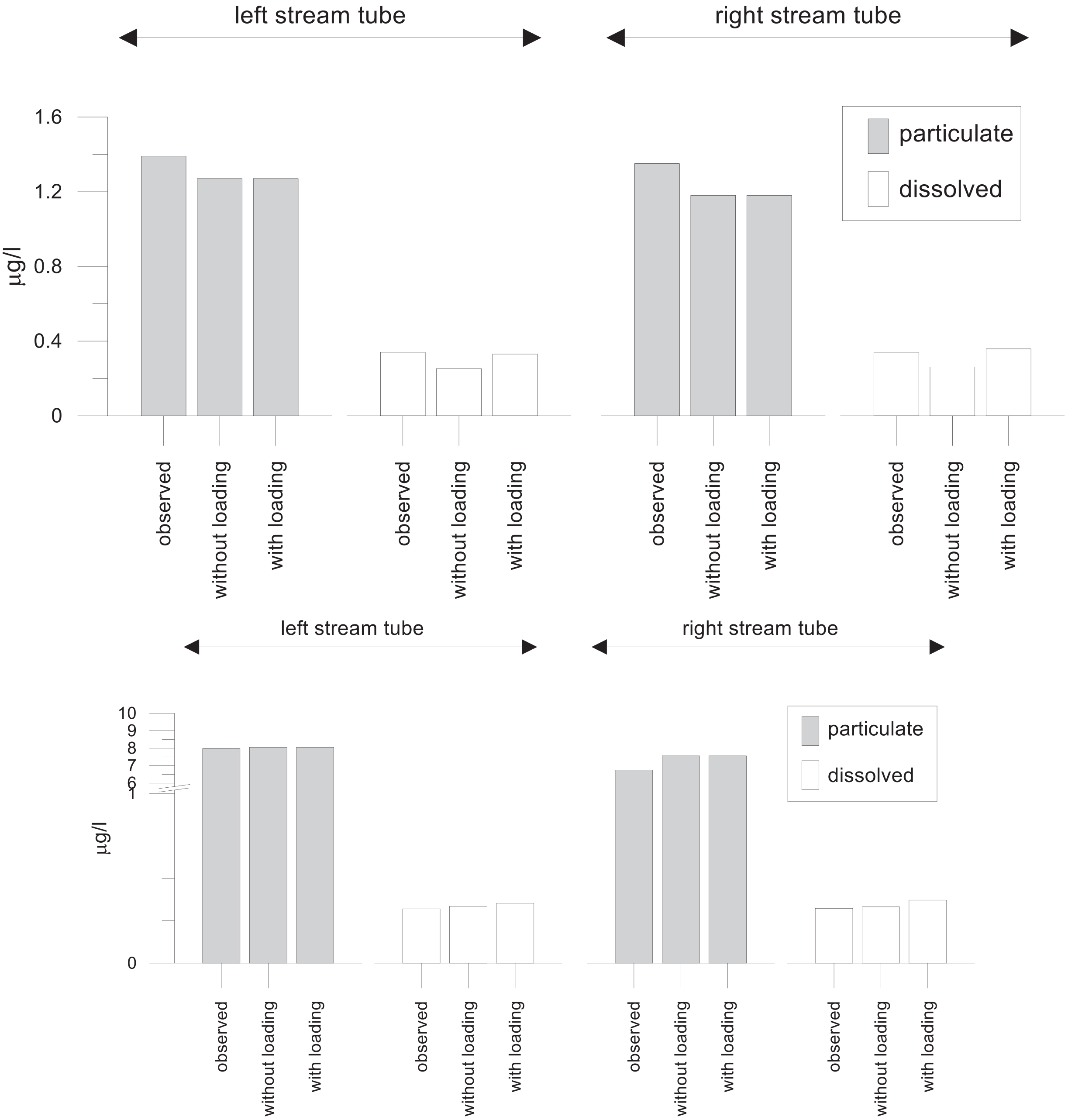

Fig. 11. Vanadium concentrations of particulate and dissolved fractions at the downstream model boundary, observed and simulated with and without additional loading, for flows of 600 m^3/s (top panel) and 1600 m^3/s (bottom panel).

increase slightly for the lower flow scenario but dilute more for the higher flow simulation.

3.3. Vanadium

Referring to Fig. 11 and Fig. 12, vanadium was present mainly in particulate form for both left and right stream tubes and for both flow scenarios of 600 and 1600 m^3/s. Eighty percent of the metal was in particulate form at 600 m^3/s whereas 97% of it was particulate at 1600 m^3/s. Particulate vanadium concentrations were almost 10 times higher at the higher flow compared to the lower flow scenario. This follows a trend in which more of the vanadium is transported in particulate form at higher flows, which aligns with more sediment being transported in the river at higher flows, particularly for the upper Athabasca River. Modelling both particulate and dissolved fractions of vanadium concentrations required setting both a partitioning coefficient and deposition rate for the particulate fraction. As shown in Fig. 11, initial simulations (without additional non-point source loading) were not obtained between simulated

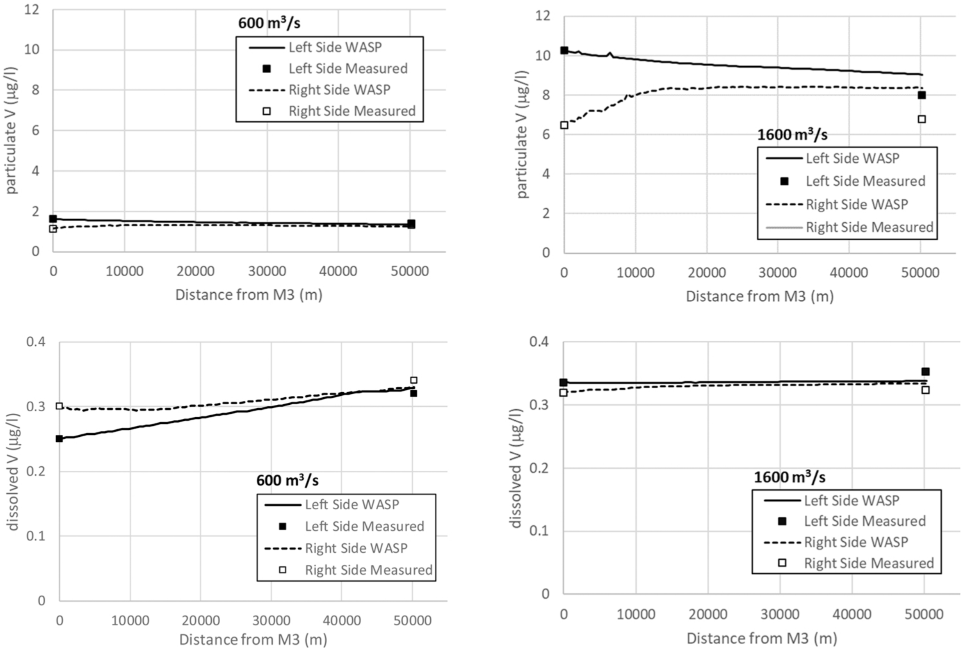

Fig. 12. Longitudinal profiles of particulate (top panels) and dissolved (bottom panels) components of vanadium concentrations along the left and right stream tubes of the model domain for flows of 600 m^3/s (left panels) and 1600 m^3/s (right panels).

and observed vanadium concentrations at station M4, particularly the dissolved fraction of vanadium. The left stream tube for a flow of 600 m^3/s was also underestimated, especially at the lower flow scenario (top right panel of Fig. 11), although the discrepancy for the particulate fraction was not as large. Hence, an additional source of dissolved vanadium (with loading) was included in the simulations, as shown in the longitudinal profiles in Fig. 12. This markedly improved the accuracy of the simulations with modelled values matching observations better, especially for dissolved vanadium. Some of the additional dissolved vanadium load partitioned to its particulate form; this partitioning was stronger at the lower flow scenario of 600 m^3/s. An additional 3 kg/day and 1 kg/day of dissolved vanadium needed to be added as a diffuse loading to, respectively, the left and right stream tubes of the modelling domain. The additional loading of dissolved vanadium was distributed along the course of the river as a diffuse load of approximately 0.06 and 0.02 kg/day/km, respectively, for the left and right sides of the river at the 600 m^3/s flow rate. These values were decreased 10-fold for the high flow of 1600 m^3/s. These amounts were determined through the calibration process. As was the case for chloride and total suspended sediment, the left and right stream concentrations of both particulate and dissolved vanadium were nearly uniform at the downstream boundary of the model domain at M4.

4. Discussion

4.1. Total suspended sediment

The higher sediment concentrations in the upper Athabasca River compared to the Clearwater River at higher flows can be attributed to the larger catchment size of the former river providing higher ratios of flow to the lower Athabasca River and more eroded and transported sources of sediment. It is evident that the Athabasca River carries more sediment concentration compared to the Clearwater River. Total suspended sediment concentrations increase exponentially with flow for both the upper Athabasca and Clearwater rivers, as was similarly found by Sabokruhie et al. (2021).

4.2. Chloride

The chloride simulations indicate that our quasi-two-dimension approach is suitable to mimic transverse mixing along a river. Chloride concentrations along both stream tubes converge to become closer to being uniform as flow moves further downstream. In this case, flow lengths of up to 50 km are required for full mixing to have occurred. Mixing is faster leading to shorter mixing lengths for higher flows. Mixing is induced by not only longitudinal flows along the stream tubes but transverse flow between laterally adjacent segments. These flows are higher for higher flow scenarios. Mixing is also quicker between the two stream tubes when concentration gradients of substances between the two streams is greater.

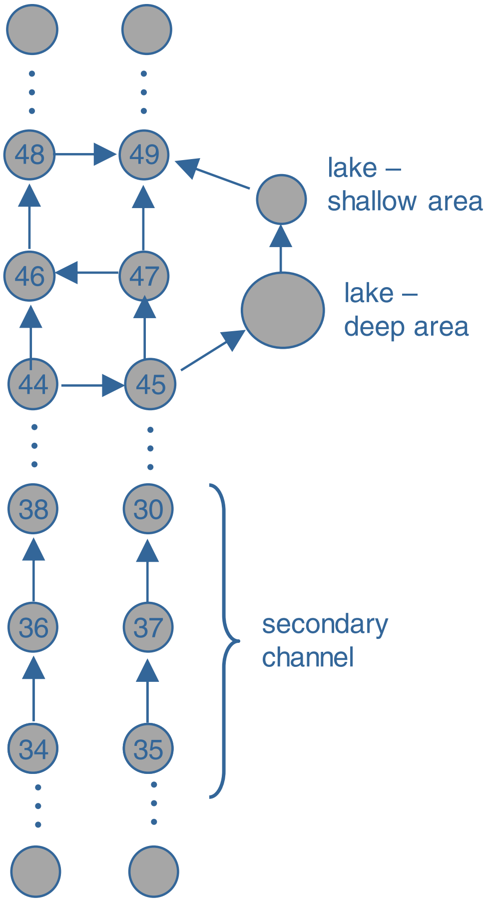

Fig. 13. Modified segmentation of the WASP model to include a side lake and a secondary channel.

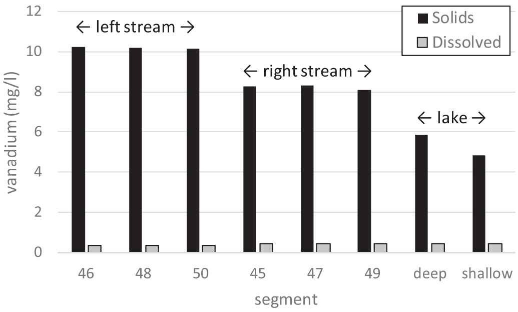

Fig. 14. Vanadium concentration within the deep and shallow areas of the side lake and the left and right stream tubes immediately adjacent to the lake.

4.3. Vanadium

Shotyk et al. (2017) also investigated the transport of dissolved vanadium and noted a statistically significant increase in concentration along the lower Athabasca River. However, they did not attribute the increase to any specific source. Their data, which was collected on the same day, and shows an increase in concentrations between their sites corresponding to stations M3 to M4, with the increase occurring primarily between just upstream of the Steepbank River inflow to just downstream of Saline Lake, approximately a 9 km stretch. Vanadium is elevated in local tributaries, including the Mildred Lake reservoir which is used for the Syncrude potable water supply (Tondu, 2017). Hence, it can be assumed that vanadium is present in surficial aquifer and muskeg dewatering water from the mine sites. Additional sources may be surficial aquifer water that is exfiltrating into the river, deposition of dust and bank erosion. Other possible sources such as contaminated sediment or tailings water seepage do not seem as likely based on the available evidence.

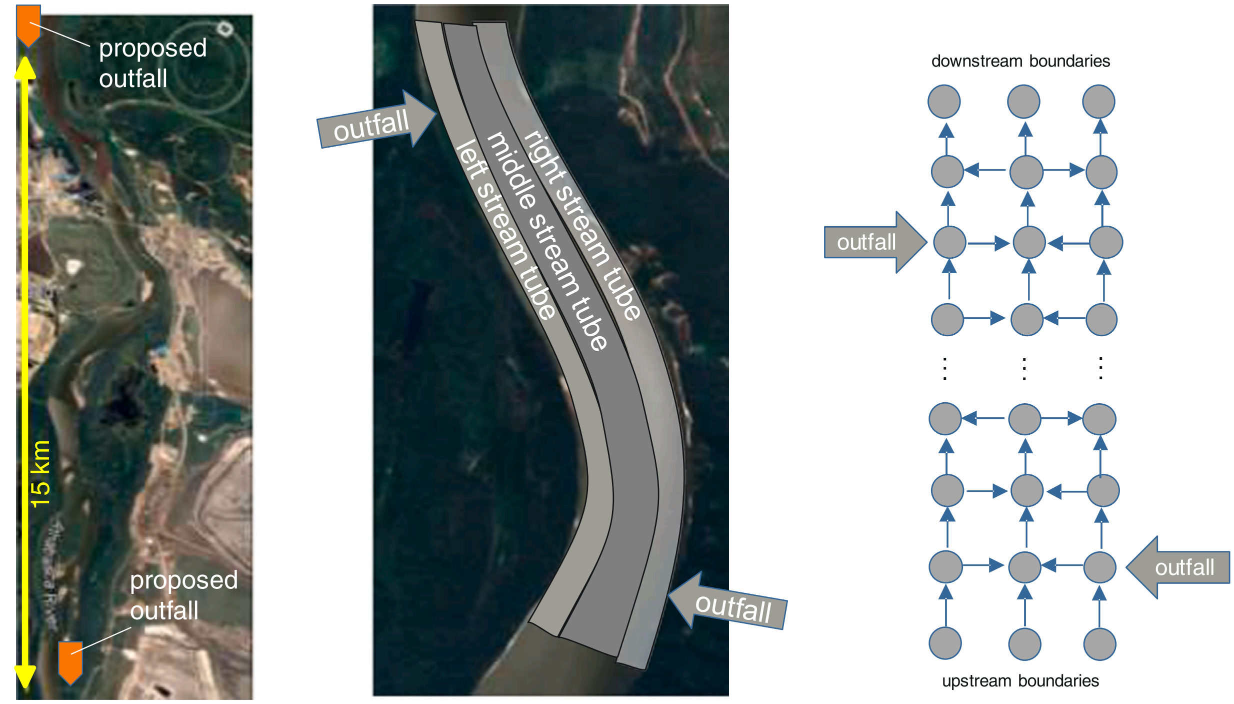

Fig. 15. Discretizing the river stretch with outfalls at both banks (left panel), requiring left, middle and right stream tubes (middle panel) for the quasi-two-dimensional segmentation (right panel) of WASP.

These transport processes have been described as critically important to understanding potential environmental effects of oil sands development. Our modelling has the aim to determine those processes that are critical to understanding impacts to the Peace-Athabasca-Delta, but on a much smaller scale. The sediment processes and the representation of a floodplain lake and a secondary channel are important parts of the design. These types of features were addressed in the Mike 11 (Dibike et al., 2018) and EFDC (Kashyap et al., 2017) modelling, with the relevance of the work described in detail by Culp et al. (2021). Hence, a scenario was run with our model which included a side lake in the floodplain (with additional segments representing the deep and shallow areas of Shipyard Lake) and a secondary channel (removal of lateral flow exchange between the left [mainstem] and right [secondary channel] stream tubes), to determine the transport behaviour of vanadium in these features. The modified segmentation is shown in Fig. 13. As expected vanadium concentrations in the lake are less than in the adjacent stream of the mainstem. Increased residence times and lower flow velocities contribute to the high sedimentation rates within the lake areas. Fig. 14.

5. Conclusions

The quasi-two-dimensional approach was successful in capturing the mixing character of tributary water (Clearwater River) with the mainstem water (upper Athabasca River), substantiated by the simulation of chloride, a conservative constituent, and total suspended sediment. A length of 50 km suffices to mix constituents uniformly for a range of flows (between 2nd, i.e. the mean, and 3rd quartiles of recorded flows). Mixing is quicker at higher flows. An additional loading of dissolved vanadium was required to simulated values to match observed concentrations.

Including outfalls in the modelling is a topic of future work which may require an additional stream tube to be included in the discretisation, especially if the outfalls are at both the left and right banks and less than 50 flow kilometres apart (see Fig. 15). This is the case for the proposed outfalls of Syncrude and Suncor, one being on the left bank and the other on the right bank of the lower Athabasca River. The flow distance between the two outfall locations is approximately 15 km from each other.

Using the quasi-two-dimensional modelling approach has applicability beyond riverine systems impacted by mining sites. Floodplains can be included in the discretisation as a separate cluster of segments connected to the mainstem of the river segmentation.

CRediT authorship contribution statement

KEL: Conceptualization. **PS, TR:** Data curation. **KEL, TR:** Formal analysis. **TR:** Funding acquisition. **KEL, TR:** Investigation. **KEL, PS:** Methodology. **KEL, TR:** Project administration. **PS, TR:** Resources. **PS:** Software. **KEL, TR:** Supervision. **PS:** Validation. **PS:** Visualization. **KEL:** Writing – original draft. **TR, PS:** Writing – review & 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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101043. These data include Google maps of the most important areas described in this article.

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