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NUMERICAL MODELING OF FLOW AND SEDIMENT TRANSPORT WITHIN THE LOWER REACHES OF THE ATHABASCA RIVER: A CASE STUDY

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This study investigates flow and sediment transport patterns within the lower reaches of the Athabasca River (~200 km) in Alberta, Canada. These reaches are characterized by complex bathymetry, regions of high tortuosity, and variable discharges and bed slopes. Sediment within this reach is primarily sand and gravel, but there is also a high percentage (>10%) of cohesive sediment with unique settling properties. A regional Environmental Fluids Dynamics Code (EFDC) 2D numerical model was setup to predict hydrodynamics of the flow and suspended sediment transport. Bathymetry measurements were obtained from a combination of high resolution 3D Geoswath and ADCP surveys, and detailed 2D cross-section measurements. A local high resolution 2D numerical simulation was also completed for a reach near Steepbank River (<20 km) to better understand the effects of a coarser grid resolution on the regional model predictions. Model results were validated using field measurements including water surface elevations collected with Global Positioning System (GPS), water velocities collected using a Gurley current meter, and suspended sediment measurements obtained from the Regional Aquatics Monitoring Program. The results showed that the regional model was capable of making reasonable predictions of water surface elevations, flow velocities, and suspended sediment concentrations. Simulation results with a rigid bed, estimated sediment inputs and assumed parameters, have also shown that a large proportion of incoming sediments get deposited along the lower reaches of the Athabasca River, and the model was able to identify those major depositional areas.

INTRODUCTION

The lower Athabasca River in Alberta, Canada is located in a constantly changing and dynamic landscape that has seen significant rates and magnitudes of change in cumulative land use and industrial development in recent years. The reach below Fort McMurray has bed elevations ranging between 245 m and 205 m above sea level and includes several smaller tributaries such as the Steepbank, Muskeg, and Firebag rivers flowing from the east, and the MacKay and Ells rivers from the west, which provide additional sources of flow and sediments for the main stem. The main stem sediment bed is comprised primarily of a mixture of gravel, sand and cohesive sediment between Crooked Rapids and Shott Island (Doyle [2]; Shaw and Kellerhals [4]; WSC [1]), and fine sand and cohesive sediment downstream of Shott Island (Shaw and Kellerhals [4]; WSC [1]). The transport of cohesive sediment within the lower reaches is of particular interest, as it has the capability to transport toxins such as polycyclic aromatic hydrocarbons (PAHs) (Garcia-Aragon et al. 2011) and metals which may negatively impact aquatic life. Also, the transport of naturally occurring bitumen is of interest due to its close proximity to the earth surface (Conly et al. 2002) and likelihood to be affected by sediment erosional and depositional processes. The use of numerical modeling can provide insight into the transport of sediment and possibly contaminants which may be of interest to the numerous operations that the river supports, including forestry and pulp, mining, and agriculture. Also, knowledge of possible depositional locations and the origins of sediment may aide in determining optimum sampling locations for benthic organisms in the river.

Numerical modeling of the lower reaches of the Athabasca River however, is challenging due to its complex geometry and hydraulics. There are numerous rapids upstream of Fort McMurray, where the channel is described as 'meandering'. Downstream of Fort McMurray, the bed slope decreases substantially and the river contains vegetated islands, alternating sand bars and an unpredictable thalweg. From Fort McMurray to Old Fort, the river has been characterized as being somewhere between a meandering and a 'braided' river (Conly et al. [3]). The river also experiences variable flow regimes throughout the year, and Total Suspended Sediment (TSS) concentrations do not always correlate well with discharge. Water Survey of Canada records show maximum summer flows just below Fort McMurray to range from 1190 to 4500 m^3/s, while winter flows have ranged from 75 to 211 m^3/s WSC [1].

In this study, numerical simulation models have been developed for the lower reaches of the Athabasca River (from Fort McMurray to Old Fort) to help identify major locations of deposition, and the sources (the main stem or tributaries) from which these sediments originate. Previously, physical and numerical studies examining sediment transport through long reaches of the lower Athabasca River have been limited due to difficulties in obtaining adequate spatial resolution of sediment samples, and limited bathymetric data available for modeling. This is the first time that such a high resolution 2D model has been setup for the whole lower reach of the Athabasca River, and it is also the first time that high resolution Geoswath data has been available, which has been incorporated into this model.

Therefore, the specific objectives of this paper are:

1. To setup regional and local two-dimensional hydrodynamic and sediment transport numerical models of the Athabasca River between Fort McMurray to Old Fort and to validate simulation results using field measurements; and
2. To use the validated models to make estimates of sediment flux and depositional patterns in this lower reach of the Athabasca River

METHODOLOGY

Description of the reach and sediment data

The reach being considered in this study extends ~200km from Fort McMurray to Old Fort (see Figure 1). Lateral inflows, from a total of up to eight tributaries, were considered in the simulations including, Clearwater, Ells, Firebag, MacKay, Muskeg, Steepbank, and Tars Rivers, as well as Poplar Creek. For the purpose of this simulation study, it was assumed sediment loads from Tars River and Poplar Creek were relatively small and hence insignificant. Bathymetric data was obtained from a total of five sources. 127 rectangular sections (1 km intervals) located between Steepbank River and Embarass Airport were obtained from the Mackenzie River Basin Hydraulic Model (Pietroniro *et al.* [5]). 54 detailed surveyed sections between Crooked Rapids and Steepbank River were obtained from Dr. Faye Hicks [6] from the University of Alberta. Six high resolution surveyed reaches (collected with a Raytheon Fathometer echo sounder) were obtained from CEMA [7]. Environment Canada also collected ~40km of high resolution Geoswath bathymetry between Fort McMurray and Old Fort that were incorporated into the 2D model. DEM data (Geobase [8]) was also used for the topography of the flood plain and islands. Post processing techniques were used to transform the 127 rectangular flatbed sections into parabolic-type cross-sections in order to prevent sudden changes in water surface elevation due to contraction and expansion of the flow. In addition, HEC-RAS was used to create interpolated sections, such that minimum spacing between sections was between 100-200m for the 2D model.

For the validation model with an erodible bed, the distribution of sediment along the reach was determined from cores obtained from Water Survey of Canada [1] and Shaw and Kellerhals [4]. Upstream of Shott island the sediment was considered to be a trimodal mixture of gravel, sand and cohesive sediment, while downstream of Shott Island it was considered a bimodal sand and cohesive sediment mixture. For the 2D model, the sand was considered uniform with a D_{50} of 0.16 mm. The gravel was also considered uniform with a D_{50} of 1.5 cm. The properties (settling velocity, bulk density, and critical shear stresses for erosion and deposition) of the cohesive sediment were estimated from a combination of measurements in laboratory experiments by Droppo [9] and Garcia-Aragon *et al*. [10], and calibration runs. The effective sediment bed roughness height (k_s) and the cohesive reference surface erosion rate were also first estimated from measured data, and finalized through calibration.

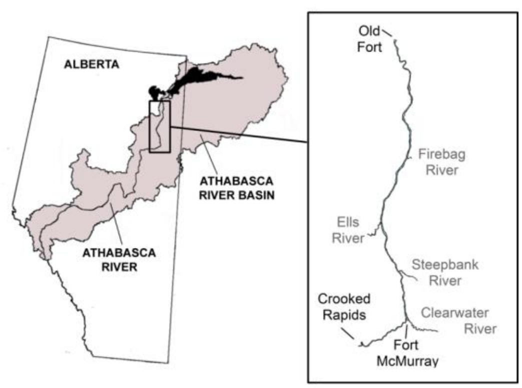

Figure 1. Location of the lower Athabasca reach (within the Athabasca Watershed) consider in this study. The reach extends from Fort McMurray to Old Fort.

Description of the 2D numerical simulation

The Environment Fluid Dynamics Code (EFDC Explorer 7.1), available from DSI Consulting Group, was the 2D numerical software used to simulate flow and suspended sediment transport (Craig [11]), and is decribed in detail in Hamrick [12]. The 2D Cartesian mesh was created from a shape file containing both the main channel and flood plain. The shape file was created by cutting the bathymetric and topographic data by a plain representing the high flow water surface plus 1m of freeboard. The regional model grid (Figures 2e, d) consisted of 81 700 square elements of 65m width, while that for the local model (Figures 2b, c) contained 32 600 cells of 25m width. The inflow and tributary discharges were obtained from WSC [1] and RAMP [13] gauging stations. The outflow water surface elevation was obtained from a validated MIKE-11 one-dimensional numerical model. As sediment data was not always available for all dates, TSS loads at the inflow and tributary boundaries were determined through discharge rating curves developed from the WSC and RAMP data. Validation data for the depth-averaged velocities and water surface elevations were obtained from CEMA[7], and measurements used to validate TSS loads were obtained from RAMP [13]. The TSS were considered to consist of 90% cohesive sediment, and 10% noncohesives, while the bed material (used for the validation model) was considered to be 90% noncohesive and 10% cohesive. Wetting and drying conditions were used in the model.

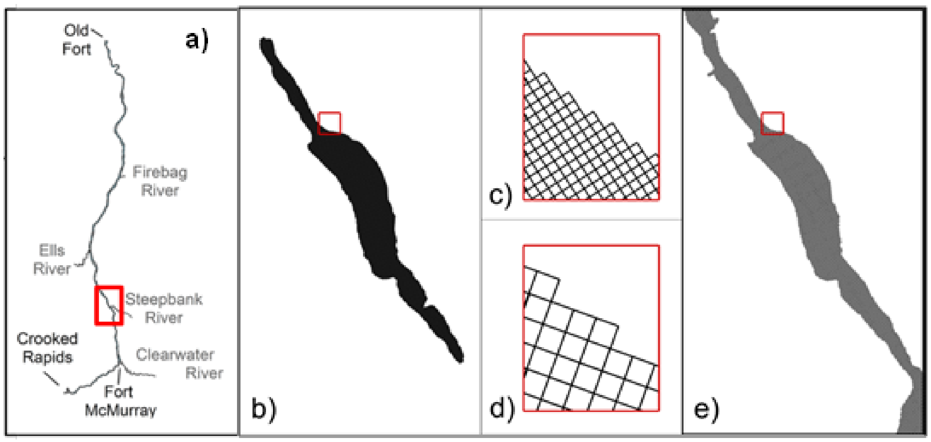

Figure 2. a) Plan view showing location of ~20km reach downstream of Steepbank River. Grids for a) local and e) regional models for area within red box in a). Close-ups of grids for c) local and d) regional models for areas within red boxes shown in b) and e), respectively.

Table 2. Peak boundary input flows and [cohesive suspended sediment] for Cases I and II.

Source	Max Flow from Hydrograph (m^3/s)	Max. Cohesive Suspended Sediment Released (mg/L)	Peak Flow (m^3/s)	Cohesive Suspended Sediment Released (mg/L)
	CASE I (hydrographs)		CASE II (peak flows)	
Main Inflow	4410.00	2081.59	4410.00	2081.59
Steepbank River	3.02	14.60	80.00	835.99
Ells River	30.04	232.24	237.00	6533.00
Firebag River	24.50	8.68	238.00	399.53
MacKay River	30.05	62.25		
Muskeg River	1.63	4.95		

Two numerical experiments were conducted by simulating 23 days of flow with cohesive and noncohesive suspended sediment transport. While the original setup and validation of the regional model considered an erodible bed, the river bed for these numerical experiments was considered to be nonerodible (rigid) so that the depositional pattern of incoming sediments could be identified. In both cases the settling velocity of cohesive sediments was 1mm/s, the critical shear stress for deposition was 0.35N/m^2, and the critical shear stress for erosion was 0.4 N/m^2 It should be noted that these values (particularly the critical shear stress for deposition) are slightly greater than those found through the experiments (Droppo [9] and Garcia-Aragon *et al*. [10]), as EFDC defines the depositional critical shear stress to be the upper limit, above which no deposition occurs, and the erosional critical shear stress to be when substantial erosion occurs. The reference surface erosion rate was determined from calibration to be 1.5g/m^{2}s. For both cases the flow at the inflow boundary was from the hydrograph obtained between July 9 and July 31, 2011, which contained the peak flow near Fort McMurray (from all available gauging station data). For Case I, the tributaries also used observed hydrographs at the corresponding gauging stations during the same time period. For Case II, however, a constant peak flow (the maximum obtained from available gauging station data, see Table 2) was used at all locations (except Muskeg and MacKay Rivers, which were not considered in Case II),. Corresponding sediment loads at the upstream boundary and each tributary inflow were calculated using the corresponding sediment discharge rating curves.

RESULTS AND DISCUSSION

Validation of hydrodynamics and suspended sediments

Validation of the hydrodynamics for the regional model was completed along a ~6 km long bend reach near Embarass Airport (Figure 3) containing detailed ADCP bathymetry (CEMA [7]). The flow conditions corresponded to measurements obtained from WSC [1] on August 9, 2004 (~ flow at station 07DA001 was 672 m^3/s). Agreement between simulated and measured depth average velocity across the river appeared very good (see Figure 3). Errors in computed water surface elevations (WSE) were between 0.5 to 1 m, and were attributable to error associated with interpolating high resolution bathymetry onto a courser grid.

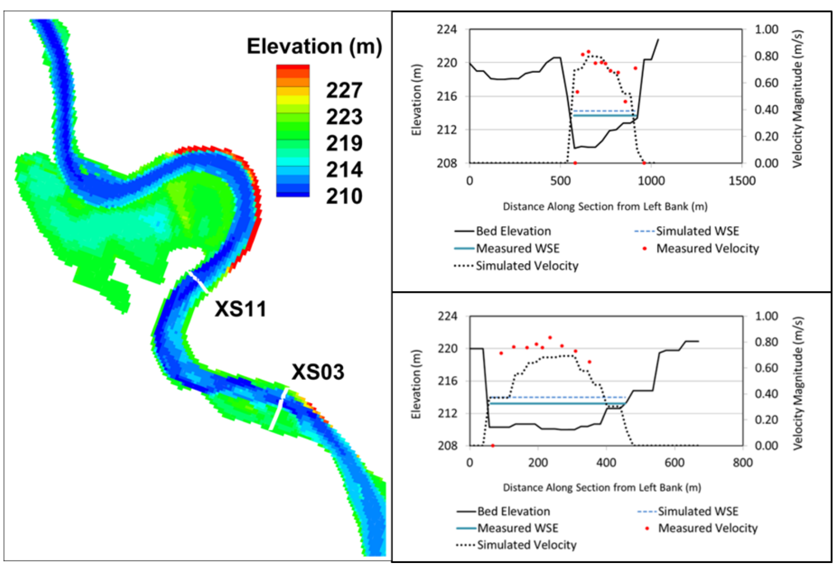

Figure 3. (Left) Plan view showing cross section locations near Embarass Airport. (Top Right) Validation for XS03. (Bottom Right) Validation for XS11.

Figure 4 shows simulated TSS and Noncohesive SS consentrations for the erodable bed case. Simulated results agreed fairly well with measurements (RAMP [13]) taken locally along certain cross sections. The small discrepancies are mainly due to local variations in actual bed material. High levels of noncohesive suspended sediments were predicted upstream of Steepbank River, and are likely due to higher velocities and bed shear stresses due to an abrupt change in bed slope near Fort McMurray. Downstream of Steepbank River average levels of noncohesisve sediments do not show either an increasing or decreasing trend. However, at about 150 km downstream of the upstream boundary, TSS begin to increase, likely due to greater availability of cohesive sediment in the downstream part of the reach.

Comparison of results from the regional 2D rigid bed model with the high resolution 2D local model (~20km reach near Steepbank River) revealed that, the proportion of cohesive sediment coming from Steepbank River being deposited in the main channel, were simulated within 1% difference between the two models. A visual comparison in Figure 5 showed good agreement between the two models in terms of location of areas and magnitudes of cohesive and total bed mass deposited (Figures 5b, c, d, e).

Cohesive sediment fluxes and depositional patterns

Based on model predictions, the majority of deposition downstream of Steepbank River occurred within the floodplain, and on or around the channel islands. Deposition on the floodplain is likely due to the low flow velocities and vegetation, allowing sediments to be trapped and settled easier (Figures 5b and c). The majority of sediment in area A1 is cohesive sediment which originated from the main stem upstream inflow boundary. Here sediment settled in the pool as water levels dropped and the surrounding elevated land areas dried up. Areas A3 and A4 (Figures 5b and c) also show cohesive sediment to settle within the narrow side channels.

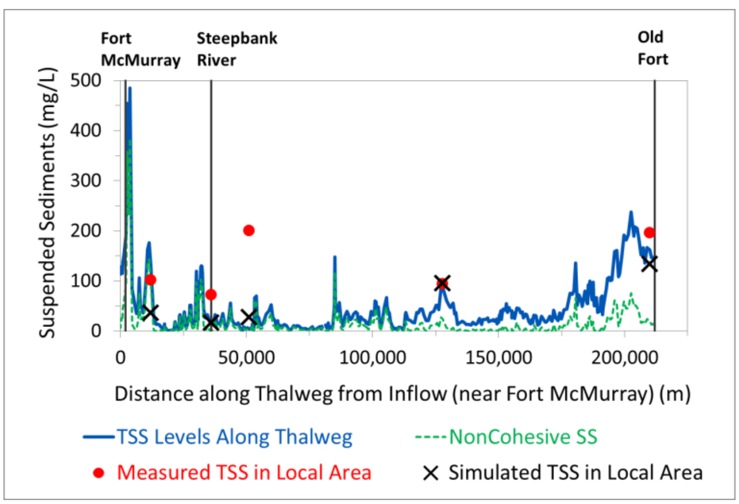

Figure 4. Distributions of simulated TSS and noncohesive suspended sediments along the thalweg. A comparision between measured and simulated TSS are given at particular locations at a given cross-section.

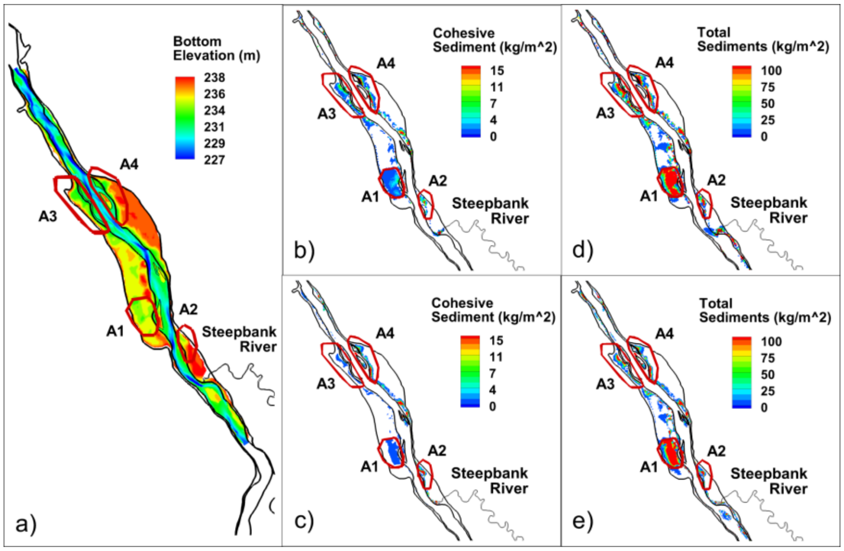

Figure 5. a) Geoswath bathymetry combined with DEM topography. Depositional areas for cohesive sediment downstream of Steepbank River for b) regional and c) high resolution local model. Depositional areas for total sediments (including main inflow and steepbank) for d) regional and e) local model. The main depositional areas are within the red circles and are referred to in the discussion as A1 to A4.

The estimate of sediment flux based on our model assumptions showed that more than half of the total cohesive sediment entering at the upstream boundary and being released from the tributaries may be deposited with the lower reaches of the river under high flow conditions (see Table 2). The majority of this sediment originates from the main stem, but the tributaries (particularly Ells River) also contribute substantial amounts under peak flow conditions. It should be noted, however, that a conservative cohesive settling velocity of 1mm/s was assumed in the simulation, while existing measurements of cohesive sediment in Ells River suggests it may be anywhere between 0.1 to 1 mm/s (Droppo [9]). Therefore, while the results are consistent with our modeling assumptions (using a conservative estimate of cohesive settling velocity, and a rigid bed), it may be possible that more sediment could move through the system and discharge into Lake Athabasca.

CONCLUSIONS

A 2D hydrodynamic and sediment transport model for the lower Athabasca River has been setup and successfully validated with observed data. The relatively lower resolution regional numerical model was shown to be capable of making comparable estimates of sediment deposition and helped identify areas of significant deposition compared to a high resolution local model. Simulation experiments with the regional model showed that sediment entering through the models upstream boundary, and those released from tributaries, deposit mainly within the floodplain. Moreover, based on some modeling assumptions, it was predicted that more than half of the sediment originating from the main stem and tributaries in the lower Athabasca River would deposit within the main stem before leaving the downstream boundary at Old Fort. Care must be taken, however, in understanding these results, as they are based on estimated model inputs, and calibrated model parameters.

Table 2. Simulated results with respect to cohesive suspended sediment budget in the lower reaches of the Athabasca River corresponding to the two case studies.

Source	Sediment Released from each source (ton)	Sediment Deposited from each source (ton)	% Sediment Deposited from each source (%)	Sediment Deposited as % of Total Released (%)	Sediment contribution as % of Total Deposited (%)
CASE I					
Main Inflow	4,221,571	2,993,280	70.904	70.799	99.875
Steepbank River	509	232	45.580	0.005	0.008
Ells River	2,806	1,729	61.618	0.041	0.058
Firebag River	743	420	56.528	0.010	0.014
MacKay River	1,795	1,171	65.237	0.028	0.039
Muskeg River	459	191	41.612	0.005	0.006
TOTALS	4,222,883	2,997,023		70.888	100.000
CASE II					
Main Inflow	4,221,571	3,158,970	74.829	41.448	61.604
Steepbank River	133,351	92,313	69.225	1.211	1.800
Ells River	3,077,272	1,756,533	57.081	23.047	34.254
Firebag River	189,408	120,081	63.398	1.58	2.342
TOTALS	7,621,602	5,127,897		67.286	100.000

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