TIDAL ESTUARY MORPHODYNAMICS OF THE KNIK ARM – ALASKA

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TIDAL ESTUARY MORPHODYNAMICS OF THE KNIK ARM - ALASKA

A

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Abstract

A three-dimensional unsteady flow numerical model was developed to study sediment transport due to tidal circulation within Knik Arm, a dynamic well mixed macro-tidal sub-estuary of Cook Inlet in Alaska. The model was developed to gain a better understanding of the mechanisms that are creating the Point MacKenzie Shoal, located approximately 4 kilometers south of Port MacKenzie. Hydrodynamic conditions within the estuary are very complex in that ebb-and-flood tides, freshwater mixing, and wetting/drying of tidal mud flats significantly effects sediment transport within the estuary.

A Mike 3 numerical model was applied to simulate the sediment transport within the estuary under the action of tidal currents in the vicinity of the shoal. The computational domain of this simulation includes four sediment laden freshwater sources; Matanuska, Knik, Susitna, and Twenty-Mile Rivers as well as an open ocean boundary. The spatial resolution of the triangulated flexible mesh model is 0.00045 degrees^2 with a coupled fine resolution model of 0.000045 degrees^2.

The results of the numerical model are in agreement with previously collected field data. Simulation results indicate the shoal formation is the result of turbid tidal flows and deposition is occurring naturally.

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Chapter 1   Background

1.1 Introduction

Cook Inlet is a macro-tidal estuary located in south central Alaska with an open-ocean connection to the Gulf of Alaska at its southern terminus. Two sub-estuaries are present at the northern end of Cook Inlet, Knik Arm and Turnagain Arm.

Sediment laden freshwater flowing into northern Cook Inlet is dominated by four glacial rivers the Knik, Matanuska, Susitna, and Twenty-Mile Rivers. The Knik and Matanuska Rivers discharge directly into northern Knik Arm. The Susitna River, located west of Knik Arm, is the largest river discharging into Cook Inlet. Twenty-Mile River is located at the distal end of Turnagain Arm to the east of Knik Arm. These sediment laden rivers contribute approximately 44 million metric tons of suspended sediment per year resulting in tidal mud flats and shoal formations.

It was noted by Bluemink (2010) that a shoal, on the western bank of Knik Arm, posed a significant hazard to navigation. This shoal is known as the Point MacKenzie Shoal and is located approximately 4 kilometers south of Port MacKenzie, see Figure 1.

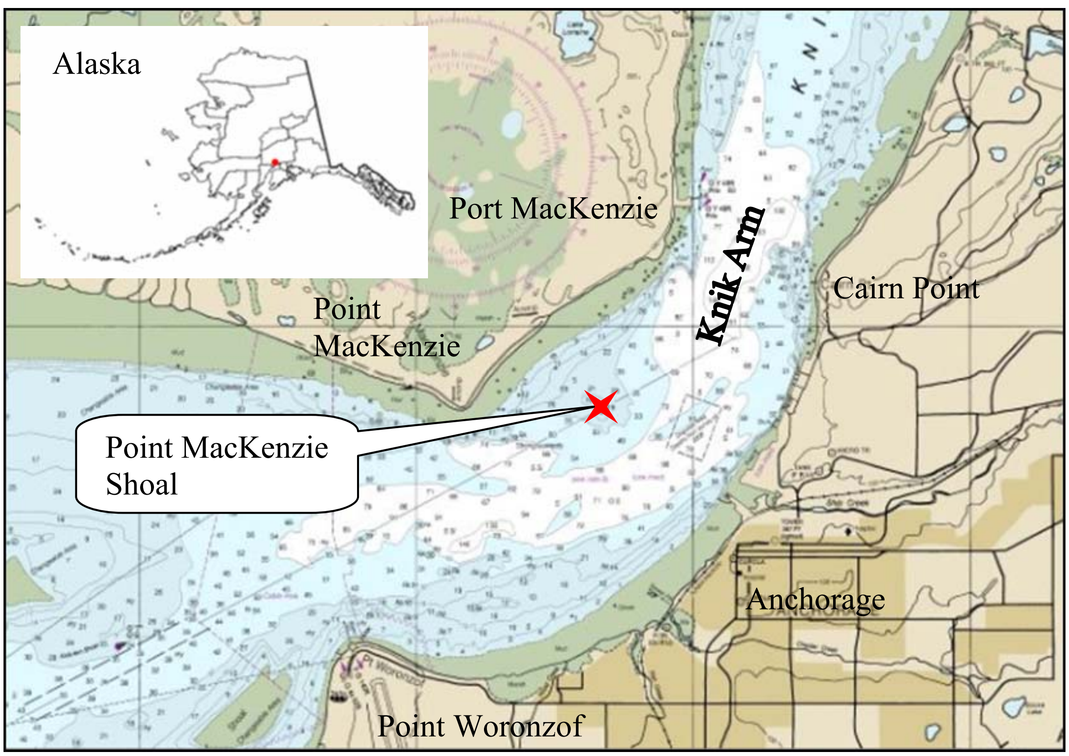

Figure 1: Knik Arm vicinity map. NOAA Chart 16664.

The purpose of this study is to develop a numerical model to examine changes in bed morphology in the vicinity of the Point MacKenzie Shoal resulting from bed load and suspended sediment transport of sand and mud. A three-dimensional hydrodynamic numerical model was established using a flexible mesh triangular grid with flooding/drying parameters utilizing MIKE 3 by DHI to evaluate sediment transport patterns due to tidally driven currents in the vicinity of the shoal.

1.2 Physical Setting

Knik Arm, a large macro-tidal mixed-semidiurnal tidal estuary approximately 50 kilometers long, ranging in width from 2 to 10 kilometers, is located in south central Alaska. It is orientated roughly southwest to northeast, on the northern extent of Cook Inlet. Knik Arm averages 15 meters in depth with the majority of the northern and southern end of the estuary comprised of tidal mud flats. There are two constrictions within Knik Arm and they are located between Cairn Point and Port MacKenzie, and Point MacKenzie and Point Woronzof. Predicted maximum tidal currents are ebb 1.9 meters per second and flood 2.1 meters per second near the Port of Anchorage (Smith et al. 2005).

The northern waters of Knik Arm are relatively fresh and turbid with sediment-laden discharges from the Matanuska and Knik Rivers, composed largely of glacial flour. Extensive mud flats exist at low tides in the upper reaches of Knik Arm.

1.3 Sediment

The Knik Arm is bordered by the Chugach Mountains to the east, Alaska Range to the west, and the Talkeetna Mountains to the north. The predominant source of rock and sediment in the Knik Arm area ranges in age from Pre-Cambrian to Quaternary. Pre-Cambrian rocks of the Talkeetna Mountains consist of mica, quartz-chlorite schists, and phyllite. Cretaceous rocks of the Chugach Mountains are composed of slate, greywacke, sandstone and argillite. The lowlands that constitute the major part of the Knik Arm area are glacial ruminants from Pleistocene and Holocene ages mantled by thick unconsolidated sediments of glacial and glaciofluvial origin, as well as terrace, beach, estuarine, lacustrine, and alluvial deposits (Moxham).

Measurements of the sediments were collected during the summers of 1971, 1972, 2004 and 2005 (Everts, 1976 and Smith et al. 2005). Everts and Moore placed a sedimentation tank in the tidal flats near Anchorage to observe shoaling rates the predominant suspended sediment size ranged from 0.004 to 0.4 millimeters with one percent finer than 2 micrometers. Bed load sediment materials sampled outside the tank had a mean particle size of 0.0514 millimeters in 1971 and 0.0233 millimeters in 1972. The mean bed sediment particle sizes collected in the tank were 0.0058 millimeters in 1971 and 0.0068 millimeters in 1972. Bed load sediment samples collected during the summer of 2004 and 2005 were predominantly silty sand with an average grain size of approximately 0.12 millimeters (Smith et al. 2005).

1.4 Freshwater Sources

Freshwater enters upper Cook Inlet waters from four major drainages. The sediment laden, glacial-fed Matanuska, Knik, Susitna, and Twenty-Mile Rivers contribute approximately seventy percent of the total fresh water entering upper Cook Inlet. The balance of freshwater is from minor drainages. The Matanuska and Knik Rivers combined discharge approximately 22 million metric tons of sediment annually while

Susitna contributes nearly the same volume alone, 25 million metric tons. The average recorded discharges and suspended sediment concentrations for Matanuska, Knik, Susitna, and Twenty-Mile Rivers are provide in Table 1.

Table 1: Average recorded data for the Matanuska, Knik, Susitna and Twenty-Mile Rivers

River	Average Discharge (m^3/sec)	Average Suspeneded Sediment Concentration (mg/l)
Matanuska	110.74	1276.43
Knik	198.33	906.68
Susitna	1426.1	577.5
Twenty-Mile	47.28	906.68

Note. Summary of average recorded data for Matanuska, Knik, Susitna and Twenty-Mile Rivers. No suspended sediment concentrations were recorded for the discharge of Twenty-Mile River. Based on visual observations, it was assumed the concentration for Twenty-Mile was equivalent to Knik and therefore it was assumed the same value for this study. Data was obtained from the USGS.

1.5 Water Properties

South of the Port of Anchorage along the eastern tidal flats a sedimentation tank was placed and a total of 287 water samples were collected during the ice free season of 1971 and 1972 (Everts, 1976). Water samples collected during this time were observed to have a mean suspended sediment concentrations of 1,280 parts per million, salinity measurements between 2.5 and 5.0 parts per thousand with an average of 4.0 parts per thousand, and water temperatures measured 14.0°C in mid-July to 15.5°C in mid-August.

During the summer of 2004 and 2005, 60 water samples were collected within Knik Arm north of the Port of Anchorage (Smith 2004 and Smith et al. 2005). From the water samples measured water properties were; temperatures between 7°C to 8°C, salinities between 4 and 8 PSU (Practical Salinity Units), and densities ranging from 1,002 to 1,005 kg/m^3. Typical open ocean water properties in the same temperature range as Knik Arm are 32 PSU and 1,025 kg/m^3. Low observed PSU is an indicator that Knik Arm is dominated by freshwater.

Temperature, salinity, and density were observed to be nearly uniform from the surface to the bottom by Everts and Smith et al. These observations are indicative of well mixed water properties.

1.6 Tidal Datum

There are four tidal observation stations located in Upper Cook Inlet with an overlapping period of observation; Point Possession, North Foreland, Anchorage, and Fire Island (see Figure 2).

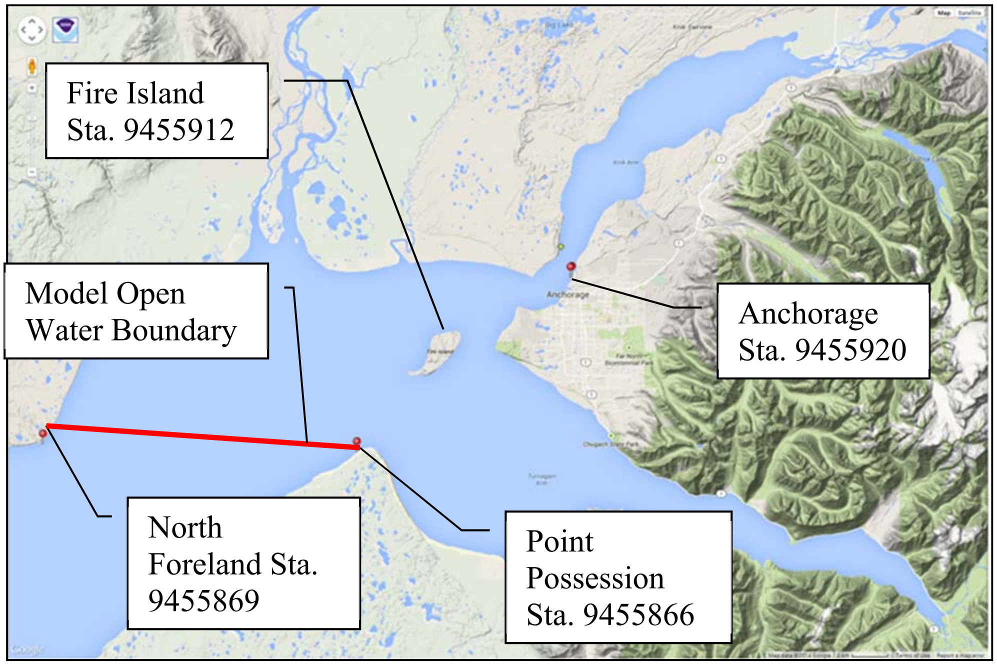

Figure 2: NOAA Tidal stations and model open water boundary
Figure depicts NOAA tidal station locations and the location of the open water boundary used in the model. Image source and data, NOAA.

From these four stations the period of common water elevation observation is beginning May 10, 1999 16:00 and ending July 13, 1999 12:42 (NOAA). Tidal datum information for these four stations is summarized in Table 2.

Table 2: Tidal observation stations Upper Cook Inlet (NOAA)

	Tidal Observation Station			
Tidal Datum	Point Possession (Sta. 9455866) meters	North Foreland (Sta. 9455869) meters	Anchorage (Sta. 9455920) meters	Fire Island (Sta. 9455912) meters
MHHW	7.935	6.399	8.889	8.203
MHW	7.730	6.192	8.667	7.986
MLW	0.673	0.661	0.685	0.672
MLLW	0.000	0.000	0.000	0.000

Note. This is a summary of tidal datums with an overlapping period of observation. Information from these stations was used to drive the water surface elevations within the model. Data was obtained from NOAA.

Point Possession and North Foreland are located at the eastern and western terminal ends of the proposed model open ocean boundary respectively. Tidal water elevation observations from the stations Point Possession and North Foreland are provided in

Figure 3. From the recorded observations the tidal periods are approximately equal with only a difference elevation.

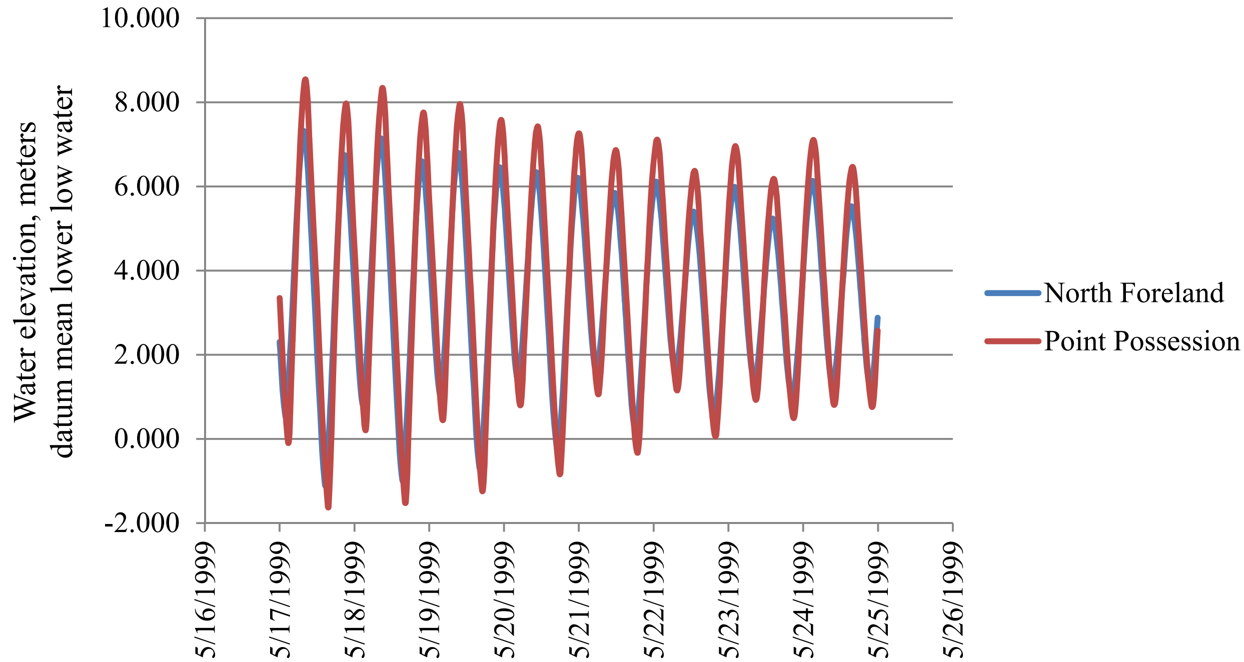

Figure 3: NOAA 6 minute verified water level data plot
Stations depicted are 9455866 Point Possession and 9455869 North Foreland, Cook Inlet, AK from 05/16/1999 – 05/26/1999. Data Source NOAA.

Chapter 2 Numerical Model

2.1 Model Selection

Smith (2004) and Smith et al. (2005) collected vertical salinity and temperature profiles in Knik Arm that were indicative of a well-mixed system based on near vertical distributions of salinity and temperature within the water column. These observations were confirmed by studies performed by Smith et al. (2010). Since the hydrodynamics are dominated by barotropic processes a depth-averaged hydrodynamic model of the study area would be appropriate, 2D numerical model, but to better understand the influence of high sediment concentrations within the water column and velocity changes between steep bathymetric gradients, a 3D numerical model was selected.

MIKE 3, software developed by DHI, was applied to simulate sediment transport due to tidal currents. The modules utilized within MIKE 3 are Hydrodynamic (HD) and Mud Transport (MT). The HD module was selected to simulate the three dimensional unsteady flows due to tidal circulation. Coupled with the HD the MT module was selected to simulate erosion, transportation, settling and deposition of cohesive sediments.

2.2 Methodology

The governing equations in HD module are the conservation of mass equation, the Reynolds-averaged Navier-Stokes equations in three dimensions, including the effects of turbulence and variable density, and the conservation equations for salinity and temperature. As part of this study the effects of salinity or temperature are not included therefore the resulting governing equations are as follows:

$$\frac{1}{\rho c_s^2}\frac{\partial P}{\partial t}+\frac{\partial u_j}{\partial x_j}=SS$$

$$\frac{\partial u_i}{\partial t}+\frac{\partial\left(u_i u_j\right)}{\partial x_j}+2\Omega_{ij}u_j=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+g_i+\frac{\partial}{\partial x_j}\left[\nu_T\left\{\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial x_j}\right\}-\frac{2}{3}\delta_{ij}k\right]+u_i SS$$

Where:

ρ	density of fluid (kg/m^3)
c_s	speed of sound in seawater (m/s)
u_i	velocity in x_i direction (m/s)
Ω_{ij}	Coriolis tensor
P	fluid pressure
Gi	gravitational vector
ν_T	turbulent eddy viscosity
δ	Kronecker's delta
k	turbulent kinetic energy
t	time (sec)
SS	source/sink terms

The MT module of the numerical model was applied to evaluate sediment transport rates within the estuary. The MT module simulates erosion, transportation and deposition of fine grained sediment as particles less than 63 micrometers (silt and clay) under the influence of currents and waves. The module can be used to simulate mud only or mud/sand mixture. Tidal currents calculated by the HD module are coupled with the MT module and provide the primary driving force for sediment transport. The governing equation for the MT module is the advection-dispersion equation:

$$\frac{\partial\bar{c}}{\partial t}+u\frac{\partial\bar{c}}{\partial x}+v\frac{\partial\bar{c}}{\partial y}=\frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial\bar{c}}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial\bar{c}}{\partial y}\right)+Q_L C_L\frac{1}{h}-S$$

Where:

c	depth averaged concentration (g/m^3)
u, v	depth averaged flow velocities (m/s)
D_x, D_y	dispersion coefficients (m^2/s)
h	water depth (m)
S	deposition/erosion term (g/m^3/s)
Q_L	source discharge per unit horizontal area (m^3/s/m^2)
C_L	concentration of the source discharge (g/m^3)

In the case of pure motion due to currents the flow resistance is caused by the bed roughness and it is calculated using standard logarithmic resistance law:

$$\tau_c = \frac{1}{2}\rho f_c V^2$$

Where:

t_c bed shear stress (N/m^2)

ρ density of fluid (kg/m^3)

V mean current velocity (m/s)

f_c current friction factor

$$f_c = 2\left(2.5\left(\ln\left(\frac{30h}{k}\right) - 1\right)\right)^{-2}$$

Where:

h water depth (m)

k bed roughness (m)

2.3 Model Domain

The model domain for this study is Upper Cook Inlet with an open water boundary located at a line between Point Possession and North Foreland, see Figure 4. The remainder of the model domain is bounded by the land boundary. Four turbid freshwater sources the Matanuska, Knik, Susitna and Twenty-Mile Rivers are located within the model domain.

A model grid was created using bathymetric data from NOAA. Horizontal and vertical datums utilized for the model are referenced to NAD83 and Mean Lower Low Water (MLLW) respectively. NOAA metadata for the model domain ranged in year of survey from 1910 to 2008. The bathymetric data sets were merged utilizing MIKE Zero by prioritization based on the year the survey was performed. From the merged prioritized data set, the bathymetry was reduced to 0.005 meter resolution to smooth the bathymetry. The prioritized data was converted to latitude and longitude for use in the model.

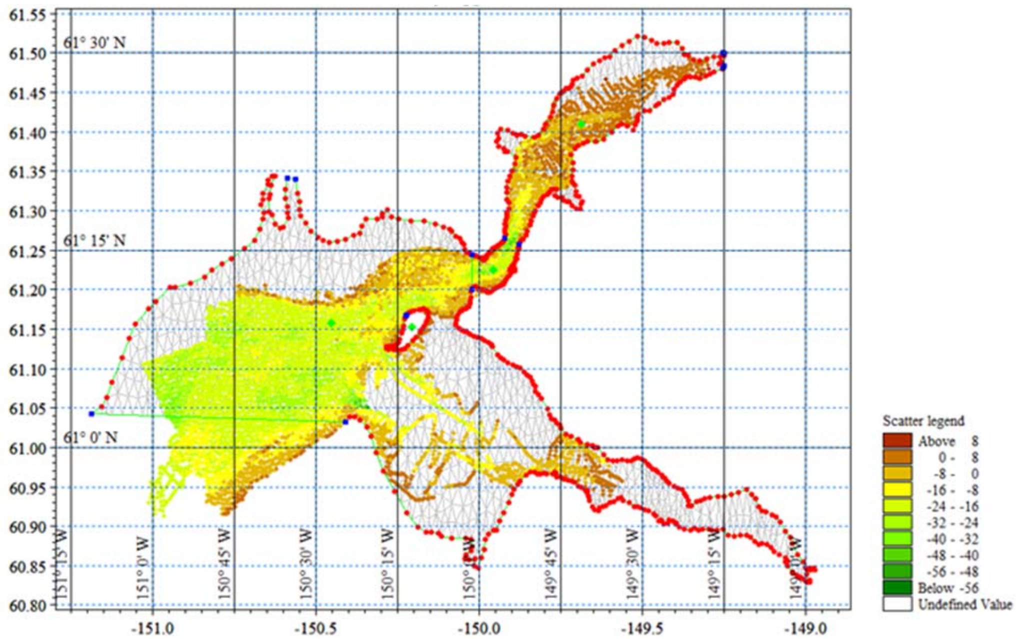

Figure 4: Prioritized bathymetric data and land boundary

The land boundary, developed by tracing aerial imagery using Google Earth™, and prioritized bathymetric data, downloaded from NOAA were compiled in MIKE Zero.

The land boundary was defined at points along the coastline above the expected maximum water surface elevation, 12.6 meters. This maximum land boundary elevation allows for flooding and drying of inter-tidal zones without compromising the stability of the model. Metadata from NOAA does not cover inter-tidal zones therefore linear interpolation was used between known bathymetric data and the land boundary.

The composite prioritized bathymetry and land boundary were combined and a flexible mesh was generated, see Figure 5 and Figure 7. Triangulated flexible mesh was chosen over a Cartesian mesh because of the nonlinear complex flows. A nested fine resolution mesh was applied in the vicinity of the shoal, see Figure 6. The spatial resolution of the model consisted of coarse and fine mesh resolution of 0.00045 degress^2 and 0.000045 degress^2 respectively. The transitional scaling of 10 is within the recommended range of 4 to 10. The resulting mesh consists of 3,595 elements and 2,279 nodes.

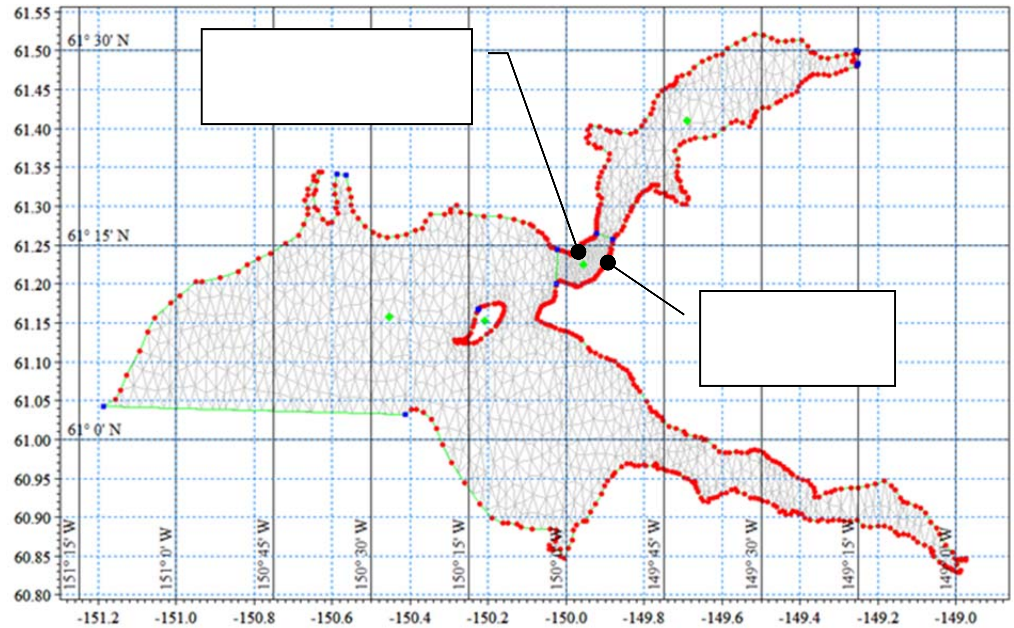

Figure 5: Model domain and grid
This is the model domain and triangulated mesh utilized in this hydrodynamic model.

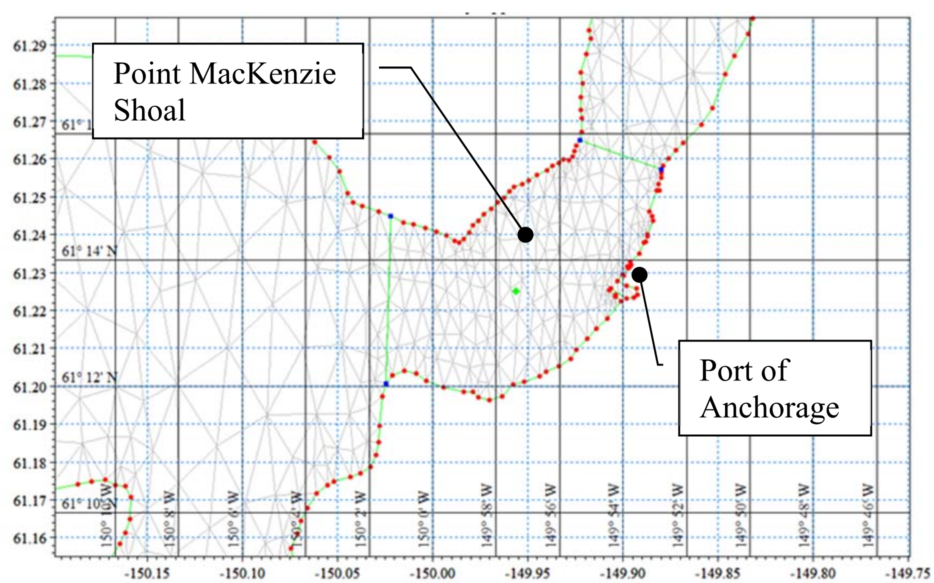

Figure 6: Nested fine resolution mesh
Nested fine resolution mesh was used to increase of model resolution in the vicinity of the shoal.

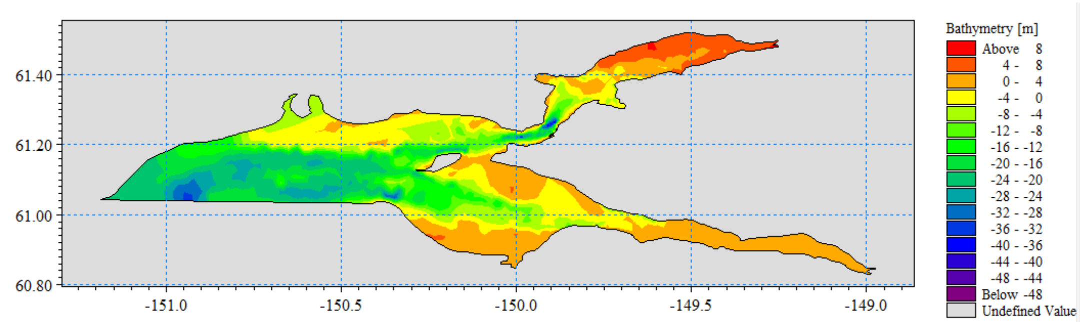

Figure 7: Model domain with composite bathymetry
Composite bathymetry with linear interpolated bathymetry between known bathymetry and the model land boundary.

2.4 Hydrodynamics

The model was forced at the open water boundary utilizing verified tidal data referenced to MLLW and local time from the common period of observation for Point Possession and North Foreland; May 5, 1999 16:00:00 through July 7, 1999 12:42:00 (122 days). Tidal datum information is referenced to NAVD88 therefore no vertical adjustments were applied. Using these values, the remaining grid points along the open water boundary were derived by linear interpolation.

Freshwater source information was applied using average measured river discharges and suspended sediment concentrations for the Matanuska, Knik, Susitna, and Twenty-Mile Rivers.

2.5 Sediment Transport

The Smith (2004) and Smith et al. (2005) investigations of mobile sediments noted a stratified bed of mobile sandy bed surface and a finer silt and clay layer in suspension above. Based on these observations a two layer bed was applied to the model domain utilizing calibrated sediment properties from URS Corporation (URS), see Table 3. Manning's n value of 0.025 and Smagorinsky coefficient of 0.25 were applied based upon previous models (URS). Boundary condition suspended sediment concentration of 5.0 g/L provided a best-fit based on measured data (URS).

Table 3: Calibration of sediment

Layer	Erosion Coefficient ($kg/m^2/s$)	Critical Shear Stress (N/m^2)	Dry Density (kg/m^3)
Upper	0.003	0.5	400
Lower	0.0002	1.5	800

Note. A two layer bed was applied to the model domain using calibrated sediment properties, URS.

The MT module of the numerical model can be used to simulate mud only or mud/sand mixture, and since both mud and sand are present the mud/sand mixture option was selected for this analysis.

2.6 Summary of Model Input

A summary of the model input information for both modules is tabulated in Table 4 and Table 5.

Table 4: Hydrodynamic module summary of set-up

Parameter	Value
Mesh and Bathymetry	From file
Simulation Period	
(Warm up)	1999-05-10 16:00:00 - 1999-05-11 16:00:00 (1 day)
(Period 1)	1999-05-11 16:00:00 - 1999-07-12 12:42:00 (62 days)
Time Step Interval	
(Warm up)	45 sec
(Period 1)	45 sec
Number of Time Steps	
(Warm up)	1,920
(Period 1)	119,304
Solution Technique	
(Warm up)	Critical CFL number 0.8
(Period 1)	Critical CFL number 0.8
Enable Flood and Dry	Drying depth 0.01 m
	Flooding depth 0.05 m
	Wetting depth 0.1 m
Initial Surface Elevation	8.1m
Sources	
	Matanuska River
	Knik River
	Susitna River
	Twenty-Mile River
South Boundary	Water Level: Tidal stations Point Possession and North Foreland
Density	Barotropic
Eddy Viscosity	
Horizontal	Smagoninsky formulation constant 0.25
Vertical	k-epsilon: 1.8e-006 m^2/s minimum and 0.4 maximum
Bed Resistance	Roughness height constant 0.025
Coriolis Forcing	Varying in domain
Wind Forcing	None
Ice Coverage	None
Tidal Potential	None
Precipitation-Evaporation	None
Wave Radiation	None
Structures	None

Table 5: Mud Transport module summary of model set-up

Parameter	Value
Number of Layers	2
Sand Fraction	Mean settling velocity 0.001
Critical Shear Stress	Constant 0.07 N/m^2
Bed Parameters	
Layer 1	Soft Mud; Power of erosion 8.3; Erosion coefficient constant 0.003 kg/m^2/s, Critical shear stress constant 0.5 N/m^2
Layer 2	Hard Mud; Power of erosion 1; Erosion coefficient constant 0.0002 kg/m^2/s, Critical shear stress constant 1.5 N/m^2
Density of Bed	
Layer 1	400 kg/m^3
Layer 2	800 kg/m^3
Bed Roughness	Constant 0.001 m
Transition Between Layers	Constant 0.001 kg/m^2/s
Wave Forcing	None
Dredging	None
Dispersion	
Horizontal	Scaled eddy viscosity formulation 1
Vertical	Scaled eddy viscosity formulation 1
Initial Surface Elevation	8.1 m
Sources	
	Matanuska River 1,276.43 mg/l
	Knik River 906.68 mg/l
	Susitna River 577.5 mg/l
	Twenty-Mile River 906.68 mg/l
Initial Conditions	
Concentration	1,003.5 mg/l
Layer Thickness	
Layer 1	0.5 m
Layer 2	0.5 m

Chapter 3 Results and Discussion

Contour and vector plots of the results from the simulation are provided in Figure 8 and Figure 9. Figure 8 shows the resulting current field from the simulation. In the vicinity of the Point MacKenzie Shoal the current velocity is approximately 1.20 meters per second (m/s). When currents are passing shoreline perturbations there are increases in current velocities which are noted by the areas in red (above 1.80 m/s) on Figure 8. Reasonable circulation patterns have been simulated in the model.

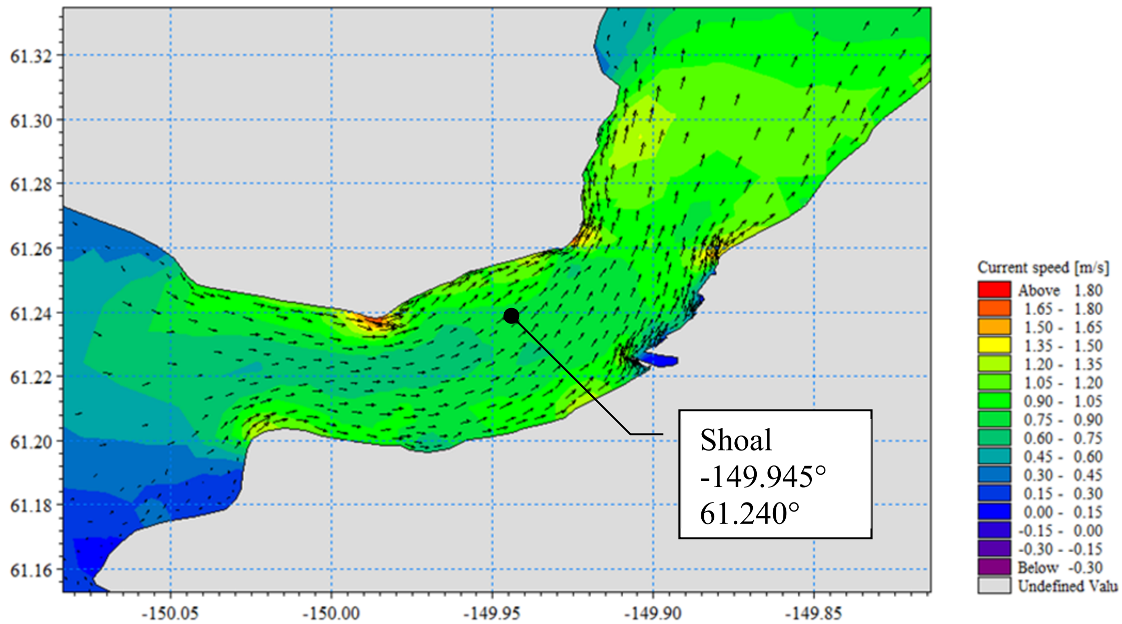

Figure 8: Average current speed (m/s) in the vicinity of the nested fine resolution model and Point MacKenzie Shoal

Figure 9 shows the resulting simulated sedimentation in the vicinity of the shoal. The simulation indicates there is possible deposition occurring in the vicinity of the shoal. A review of the simulated bed thicknesses showed no change in layer 2 (bottom layer).

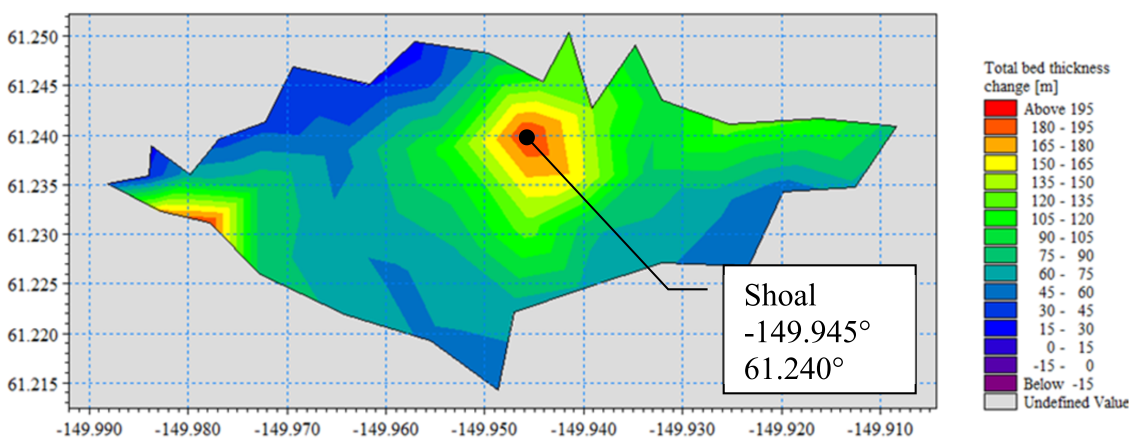

Figure 9: Total bed thickness (m) change in the vicinity of the Point MacKenzie Shoal

For model validation water surface elevations and current velocities were collected from the model for comparison with receded data from NOAA tidal station 9455920 Port of Anchorage, see Figure 10 and Figure 11. The computed tidal amplitudes are in reasonable agreement with the available observations from tidal station 945590. Computed tidal currents are approximately one-half the value predicted by Smith et al. (2005), ebb 1.9 and flood 2.1 meters per second.

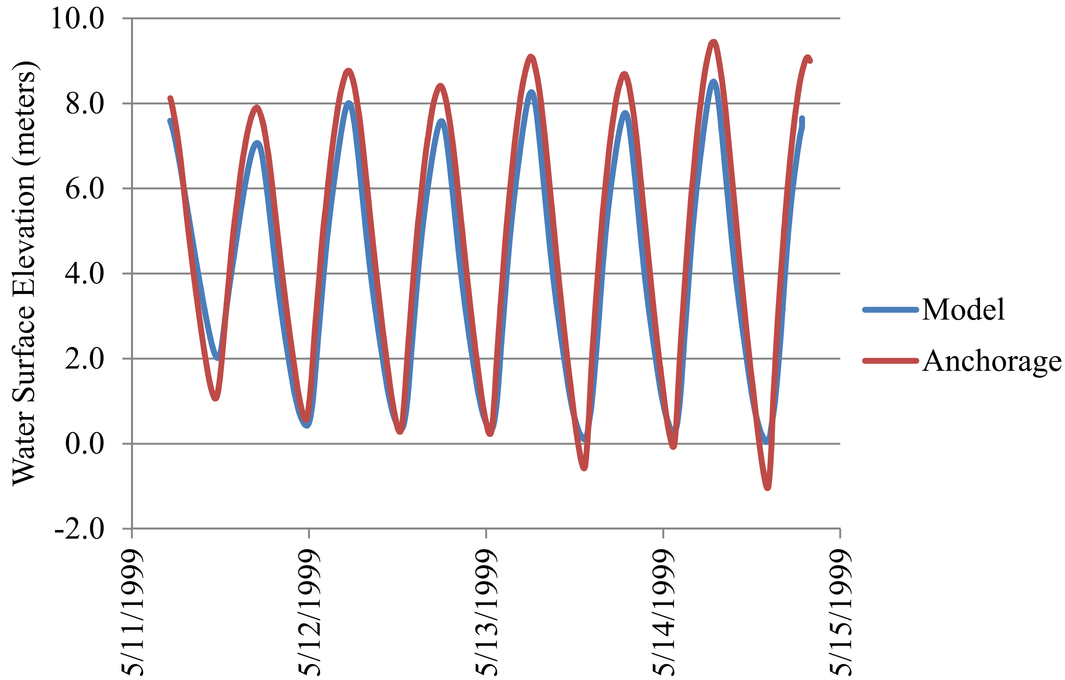

Figure 10: Model output of water surface elevation near Port of Anchorage compared with measure elevation at NOAA Tidal station 9455920 Anchorage

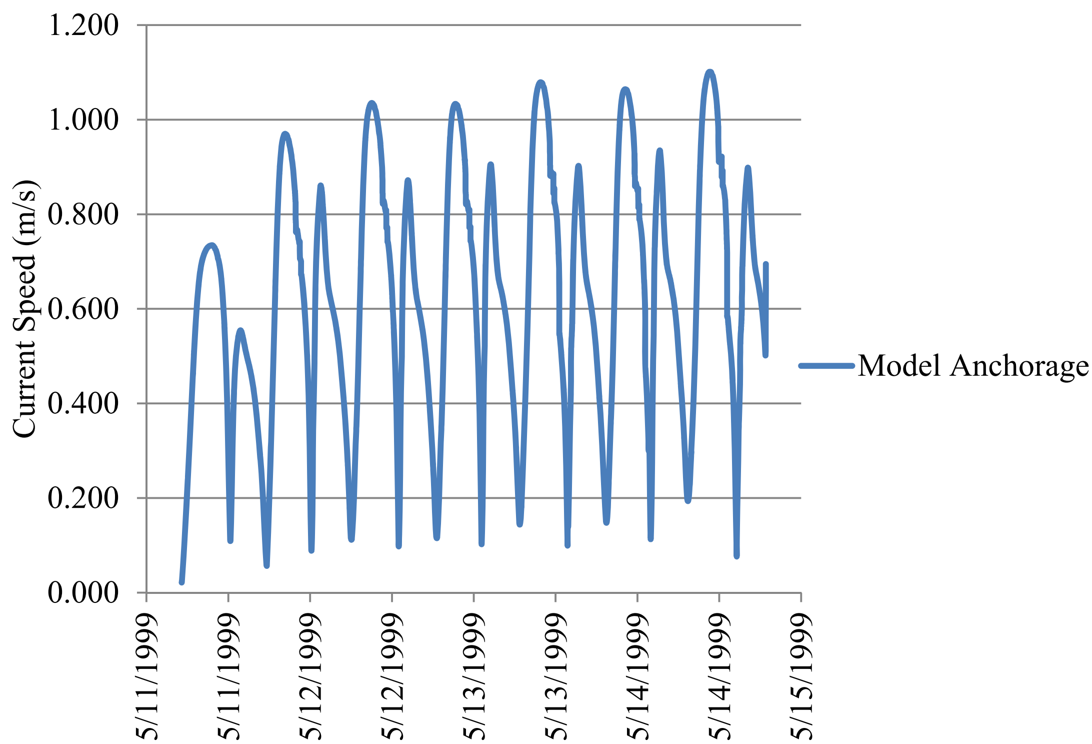

Figure 11: Model simulated water current speed near Port of Anchorage Tidal station (m/s)

Chapter 4 Conclusion

A numerical model was developed to evaluate tidal circulation and sediment transport in Northern Cook Inlet, for the year 1999, with focus on the Point MacKenzie Shoal. For this project a Mike3 by DHI model utilizing a triangulated flexible mesh model with a 0.00045 degree^2 resolution coupled with a fine resolution model of 0.000045 degress^2 for the Point MacKenzie Shoal. Boundary conditions included imposed tides and freshwater discharges from four rivers, namely, Knik, Matanuska, Susitna, and Twenty-Mile Rivers.

The computed tidal amplitudes at NOAA tidal station 9455920 Anchorage were found to be in reasonable agreement with the available observations. Computed tidal currents were found to be approximately one-half the value of the available observations. Reasonable circulation patterns have been simulated in the model. However, better representation of the suspended sediment concentrations and variable bed roughness would be more appropriate.

Comparison between simulation results and the observed data indicates that this model reasonably simulated the hydrodynamics and sediment transport present in the Upper Cook Inlet. Based on this comparison, the morphology in the vicinity of the Point MacKenzie Shoal appears to be in a state of deposition. The deposition at the Point MacKenzie Shoal has the potential to be a navigational hazard as was noted by Bluemink.

Chapter 5 Acknowledgements

I would like to express my sincere appreciation to my advisor Dr. Thomas Ravens and graduate committee member Dr. Helen Liu for their personal and professional guidance throughout my undergraduate and graduate careers. I would also like to thank Dr. Robert J. Lang for serving on my graduate committee. Special thanks to DHI for allowing me the opportunity to use MIKE 3 by DHI for this graduate research project. Finally, I would like to thank my family for their continual support throughout my graduate studies.

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