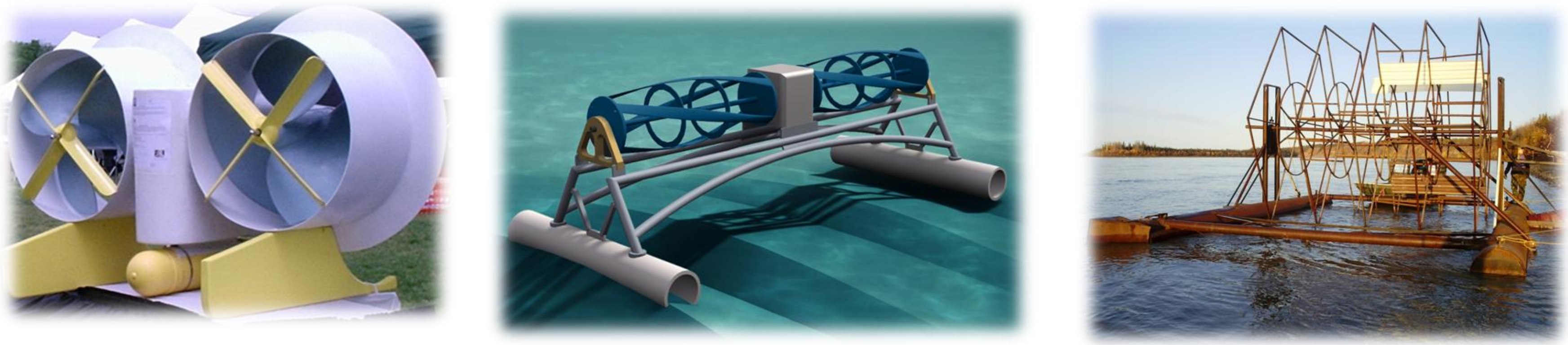

Modeling Impact of Hydrokinetic Devices

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Modeling Impact of Hydrokinetic Devices

- Focus on impacts to:
  - velocity
  - water level
  - sediment transport (sedimentation/scour)
- Application to deployments in:
  - rivers
  - tidal inlets

Goals and Objectives

- Develop technique to represent presence of hydrokinetic devices using an enhanced bottom roughness.
- Use the enhanced roughness, in conjunction with standard circulation/sediment transport models, to estimate the impact of the HK devices on water level, water velocity, and sediment transport processes – in both riverine and coastal settings.

Background – the Manning Equation

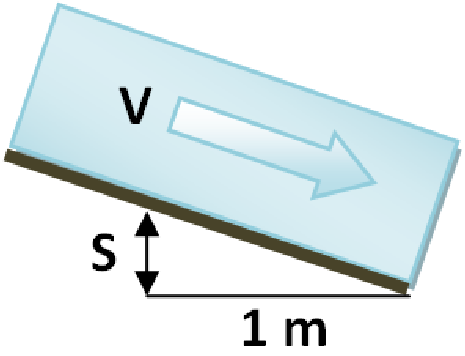
Manning Formula: $$V = \frac{1}{n} R_h^{\frac{2}{3}} S^{\frac{1}{2}}$$

V	cross-sectional average velocity
n	Manning's roughness coefficient
R_h	hydraulic radius = A/P (in wide channels, approximated by water depth: $R_h \approx h$)
S	bottom slope

Manning's equation is the most commonly used flow resistance equation, linking mean velocity (V) and flow resistance (n) in open channel.

Typical Cross Section:

Side View:

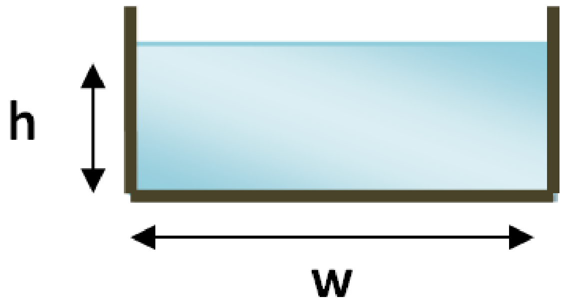


Approach to determining effective roughness accounting for presence of HK devices

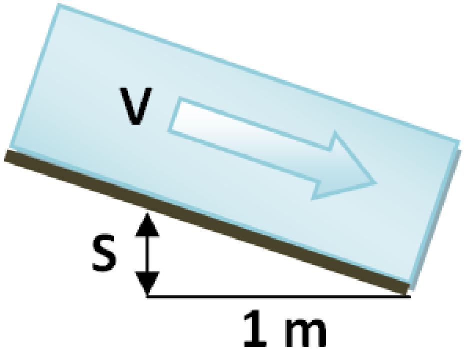
1. Assume:
    - simplified geometry:

      wide rectangular channel ($R_h \approx h$)
    - steady, uniform flow
    - uniform distribution of devices
2. Analyze flow energetics with and without devices.
3. Determine effective Manning roughness when devices present.
4. Determine velocity and water level impacts – assuming uniform distribution of devices.
5. Determine impacts of non-uniform distributions of devices – in realistic flow situations - using an enhanced roughness to represent devices.

Cross section:



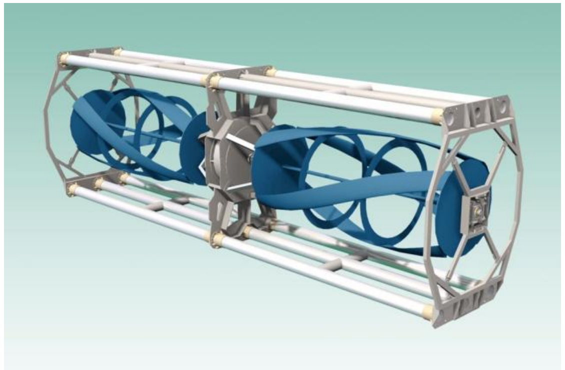
Side View:



Background – Hydrokinetic Power Generation

$$P_e = \frac{1}{2}\xi\rho V^3 A$$

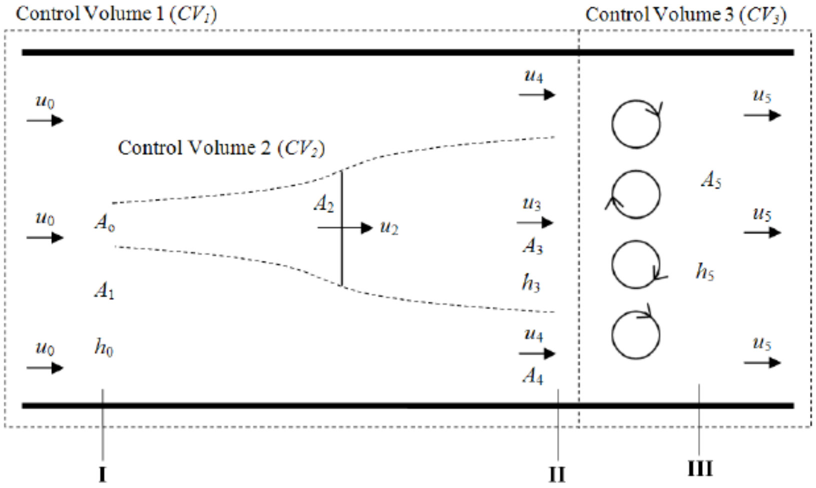
$$P_e < P_d$$



A	cross sectional area of the rotor for turbine unit
P_e	power extracted by the turbines
ρ	fluid density
V	average fluid flow velocity in the channel
ξ	turbine efficiency
P_d	total power dissipated including mixing losses and extraction

Determination of total dissipation of energy associated with the presence of the HK devices

Garrett & Cummins (2007):



$$\epsilon = \frac{A_2}{A_0 + A_1},$$

Blockage ratio, the non-dimensional ratio of the turbines swept area to the channel cross sectional area

Power extracted by the turbines

$$\boxed{\frac{P_{\text{extracted}}}{P_{\text{dissipated}}} = \frac{2}{3(1+\epsilon)} = \frac{u_2}{u_0}.}$$

Total power dissipated due to the turbine operation, it includes the power extracted, power lost due to turbulence when the turbine wake merges with the free stream

$$h_p = \frac{P_{dissipation}}{\gamma Q}$$

System of Equations Defining Turbines Impacts

Case 1:

Energy Equation - No turbines

- $$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$$
- Head losses are associated only with bottom friction (h_L).

Case 2:

Energy Equation - Turbines are uniformly distributed

- $$\frac{P_{1\mathrm{t}}}{\gamma} + \frac{V_{1\mathrm{t}}^2}{2g} + z_1 = \frac{P_{2\mathrm{t}}}{\gamma} + \frac{V_{2\mathrm{t}}^2}{2g} + z_2 + h_{Lt} + h_p$$
- Head losses are associated not only with bottom friction (h_{Lt}), but also with turbines operation (h_p).

Continuity:

Discharge is unaffected by turbines presence

- $$Q_{case\ 1} = Q_{\ case\ 2}$$
- Both cases are considered over the same portion of the channel.

Findings

Manning's Roughness Coefficient:

$$n_t = \frac{n}{\left(1 - \frac{h_p}{\Delta z}\right)^{1/2}}$$

Water Depth:

$$h_t = \frac{h}{\left(1 - \frac{h_p}{\Delta z}\right)^{3/10}}$$

Velocity:

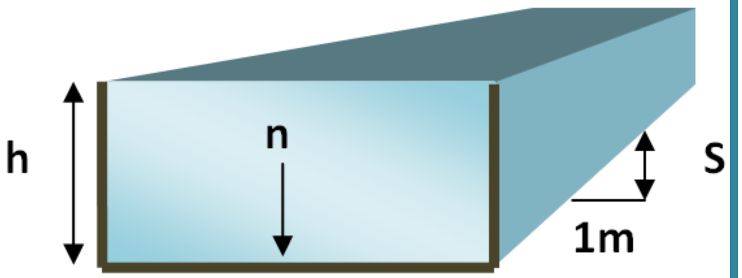
$$V_t = \frac{h}{h_t} V$$

$$h_p < \Delta z$$

$h_p = h_p(h_t)$ – head loss due to turbines operation, caused by power production and mixing losses

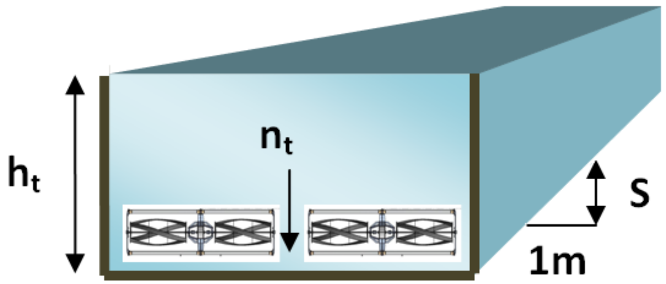
Δz – elevation change over the channel length

No turbines:



$$V = \frac{1}{n} h^{\frac{2}{3}} S^{\frac{1}{2}}$$

Turbines are uniformly distributed:



$$V_t = \frac{1}{n_t} h_t^{\frac{2}{3}} S^{\frac{1}{2}}$$

Equations – determining h_p

$$\frac{P_e}{P_d} = \frac{2}{3(1+\epsilon)} \approx \frac{2}{3}$$

Head loss due to turbine operation (assuming a single turbine):

$$h_p = \frac{P_d}{\dot{m}g} = \frac{3}{2\dot{m}g} \cdot P_e = \frac{3}{2\dot{m}g} \cdot \left(\frac{1}{2}\xi\rho A_r V_t^3\right)$$

$$h_p = \frac{3}{4}\frac{(\xi A_r V_t^2)}{gA}$$

$$h_p = \frac{3}{4}\frac{\xi A_r}{gwh_t} \cdot \left(\frac{Q}{wh_t}\right)^2 = \left(\frac{3}{4} \cdot \frac{\xi A_r Q^2}{gw^3}\right) \cdot \frac{1}{h_t^3}$$

$$\boxed{h_p = \underset{\uparrow}{N} \cdot \left(\frac{3}{4} \cdot \frac{\xi A_r Q^2}{gw^3}\right) \cdot \frac{1}{h_t^3}}$$

allowing for multiple devices

Notation

A_r – cross sectional area of the rotor for one turbine unit (m^2)

g – acceleration due to gravity (9.81 m/s)

h – water depth (m)

h_t – water depth for the case when turbines are uniformly distributed over the bottom (m)

ρ – fluid density (1000 kg/m^3)

Q – volume flow rate (m^3/s)

V – average fluid flow velocity in the channel (m/s)

w – channel width (m)

ξ – turbine efficiency

N – number of turbines

Equations – determining h_t/h

Substituting for $\boldsymbol{h_p}$ into Energy Equation gives:

$$h^{-10/3} - h_t{}^{-10/3} - \left(\frac{3}{4} \cdot \frac{\xi}{n^2 g} \cdot \frac{NA_r}{wL}\right) \cdot h_t{}^{-3} = 0$$

Approximated solution for $h_t \leq 1.5h$ (with average error of only 0.0006 %):

$$h_t = h \cdot \left(b^{1/3} - 0.28263 \cdot b^{-1/3} + 0.139296\right)$$

$$\frac{n_t}{n} = \left(\frac{h_t}{h}\right)^{3/5}$$

$where:$

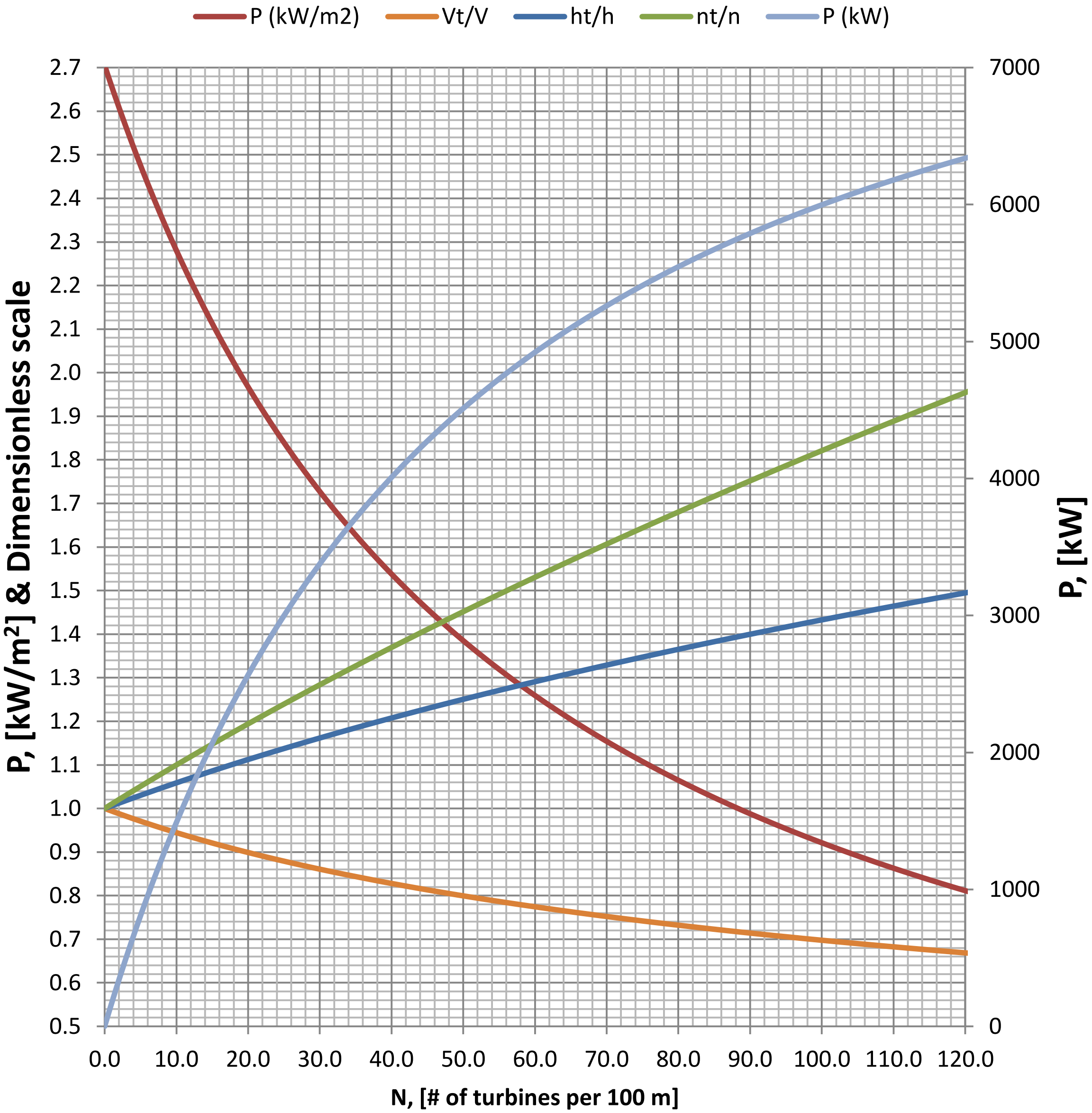
$$b = 0.46088 \cdot a + \left((0.46088 \cdot a + 0.68368)^2 + 0.022578\right)^{1/2} + 0.68368$$

$$a = \left(\frac{3}{4} \cdot \frac{\xi}{n^2 g} \cdot \frac{NA_r}{wL}\right) \cdot h^{1/3}$$

Summary of results – for uniform distribution of devices

Input:

Channel geometry			
Water depth	**h=**	10	m
Width of the channel	**w=**	500	m
Turbines Characteristics			
Efficiency	**ξ=**	30%	
Rotor area	**Ar=**	13	m^2
Flow Characteristics			
Manning's roughness coefficient	**n=**	0.0250	
Slope	**S=**	0.0002	m/m



Numerical Models

Case 1: Original conditions of the channel.

Case 2: Turbines are uniformly distributed on the bottom of the channel.

Case 1 and 2 models were used to determine discrepancy between model and estimated results

Summary of results – for uniform distribution of devices

Input:

Channel geometry			
Water depth	**h=**	10	m
Width of the channel	**w=**	500	m
Turbines Characteristics			
Efficiency	**ξ=**	30%	
Rotor area	**Ar=**	13	m²
Flow Characteristics			
Manning's roughness coefficient	**n=**	0.0250	
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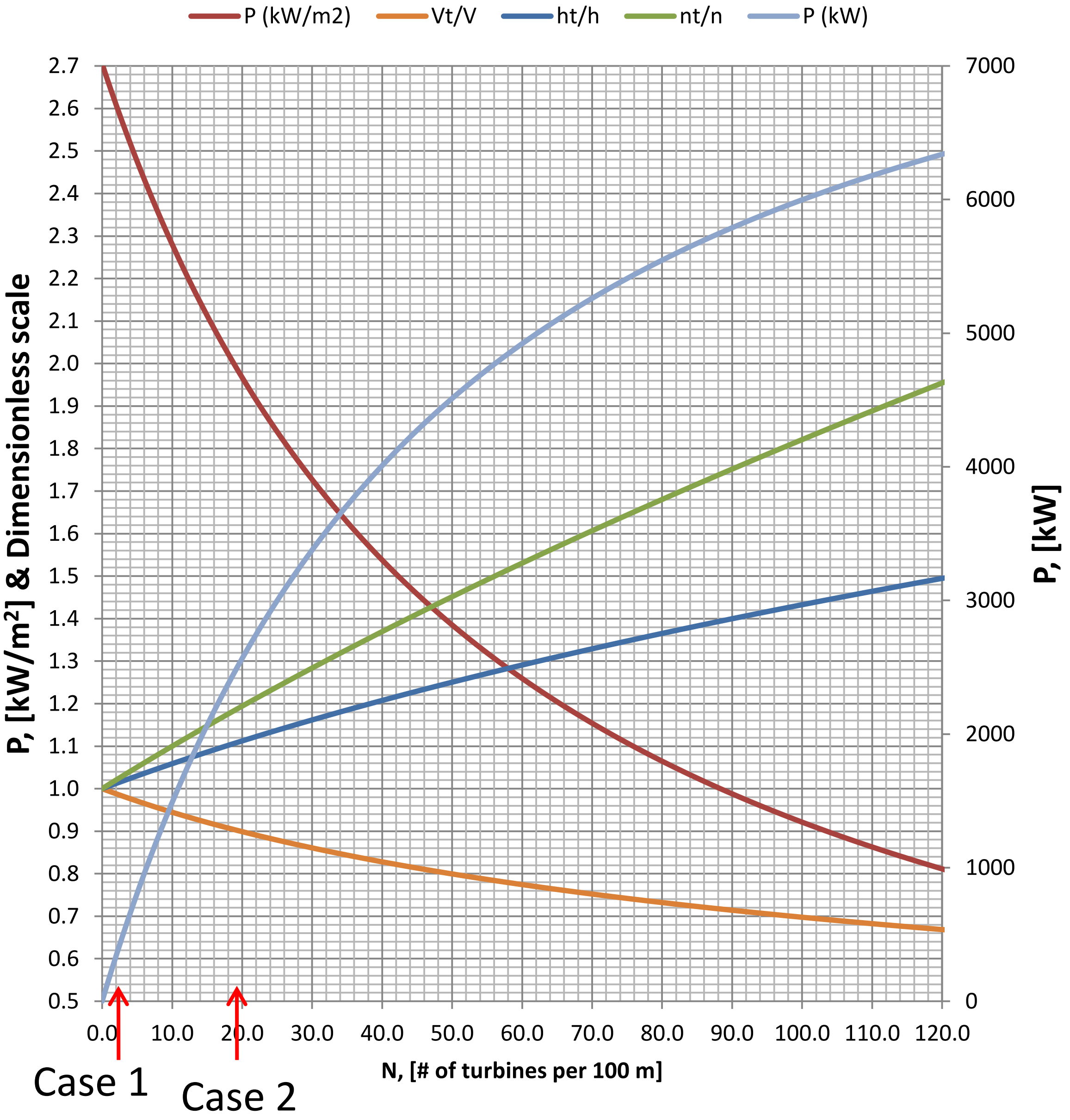


Validation of analytical calculations with numerical models

Parameter	Notation	Case 1	Case2 (with devices)	Units
Input Data:				
Width	w =	500	500	m
Slope	S =	0.0002	0.0002	m/m
Manning's roughness	n=	**0.0250** **(original conditions)**	**0.0294** **(18 turbines/100 m)**	-
ISIS Output Data:				
Water Depth	h=	**10.045**	**10.984**	m
Flow Velocity	V=	**2.614**	**2.390**	m/s

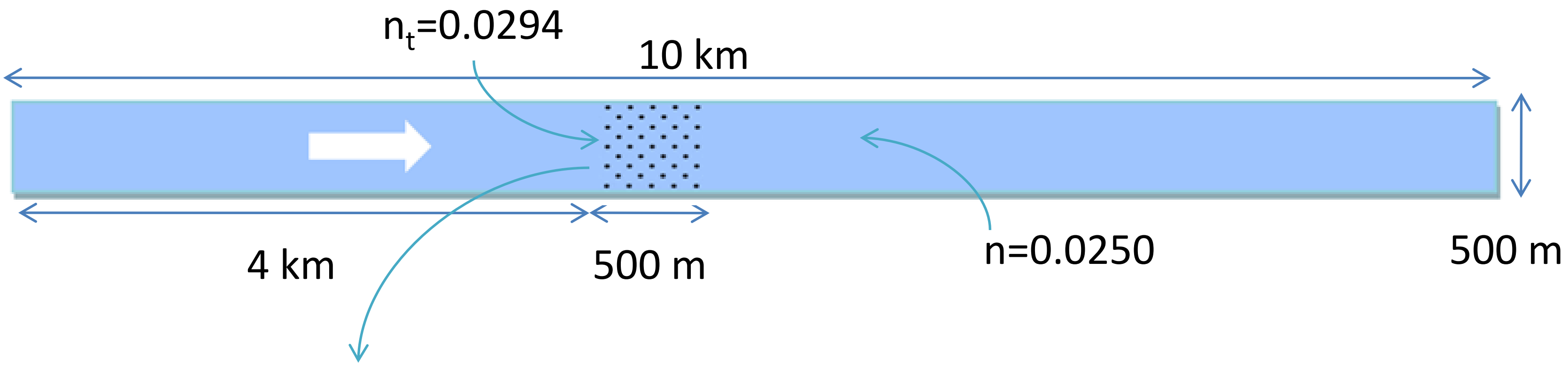
ε=.02

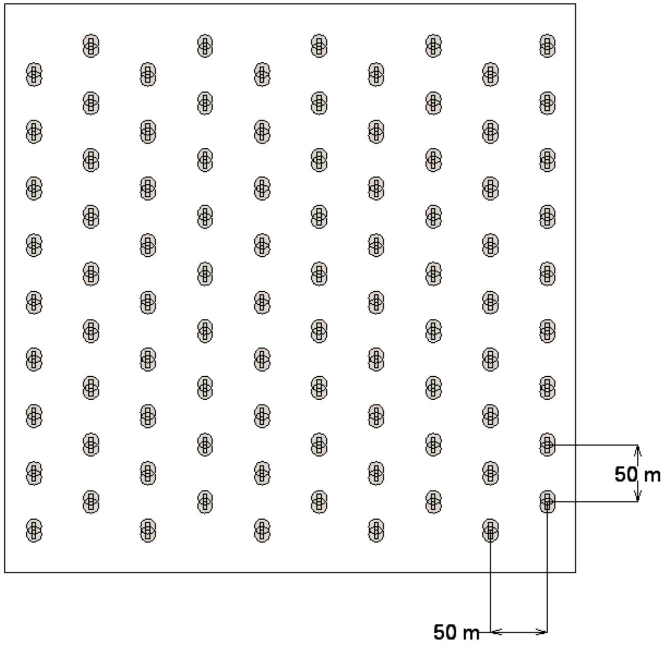
10% rise in water level, 10% reduction in velocity

Discrepancy of the Estimated Results and ISIS Outputs:

	Parameter	**Case 1**	**Case 2**
h (m)	ISIS Outputs	10.045	10.984
	Estimated results	10.000	11.020
	Discrepancy	**0.45%**	**0.33%**
V (m/s)	ISIS Outputs	2.614	2.390
	Estimated results	2.626	2.383
	Discrepancy	**0.46%**	**0.29%**

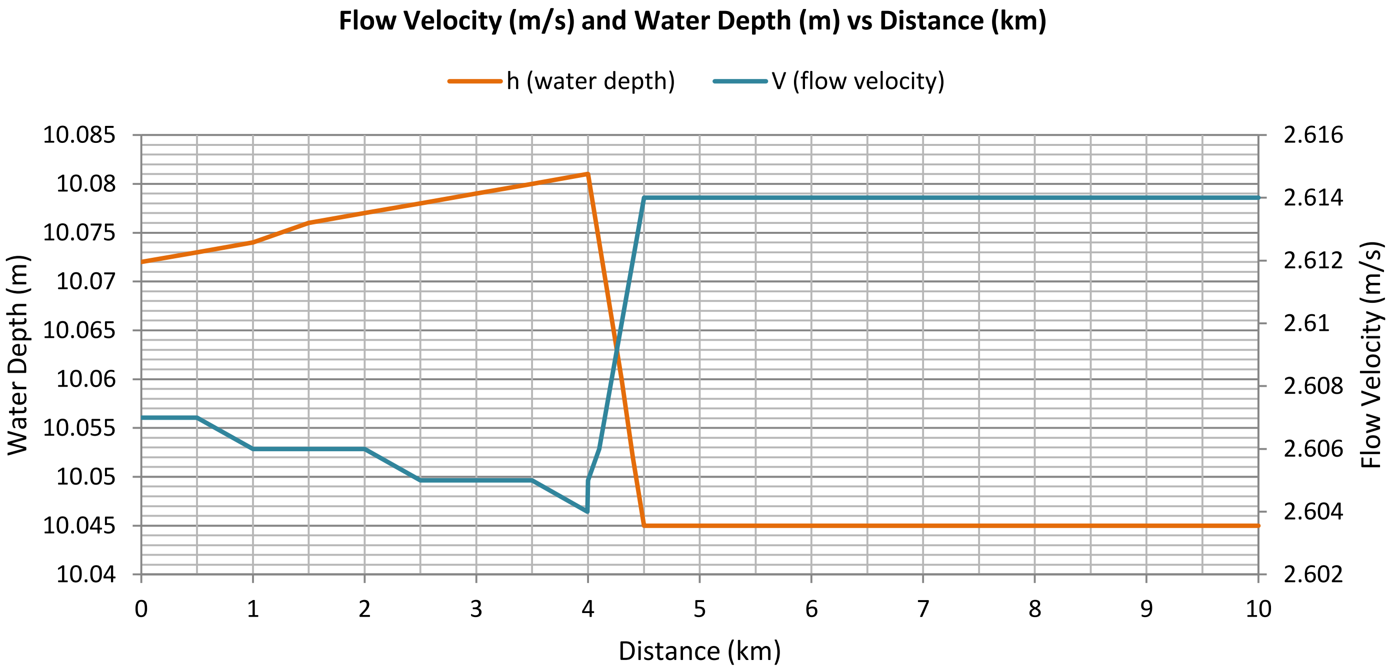
Case 3: Turbines are uniformly distributed only on short section of the channel.

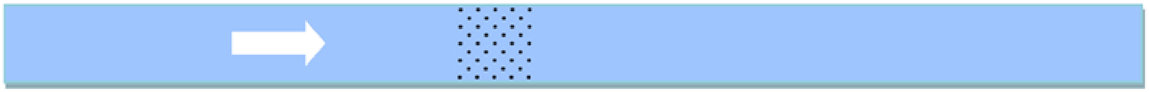




Spacing for turbine is the same as for Case 2. This corresponds to density of 18 turbines per hundred meters, which allows locating of 90 turbines over 500 meters section.

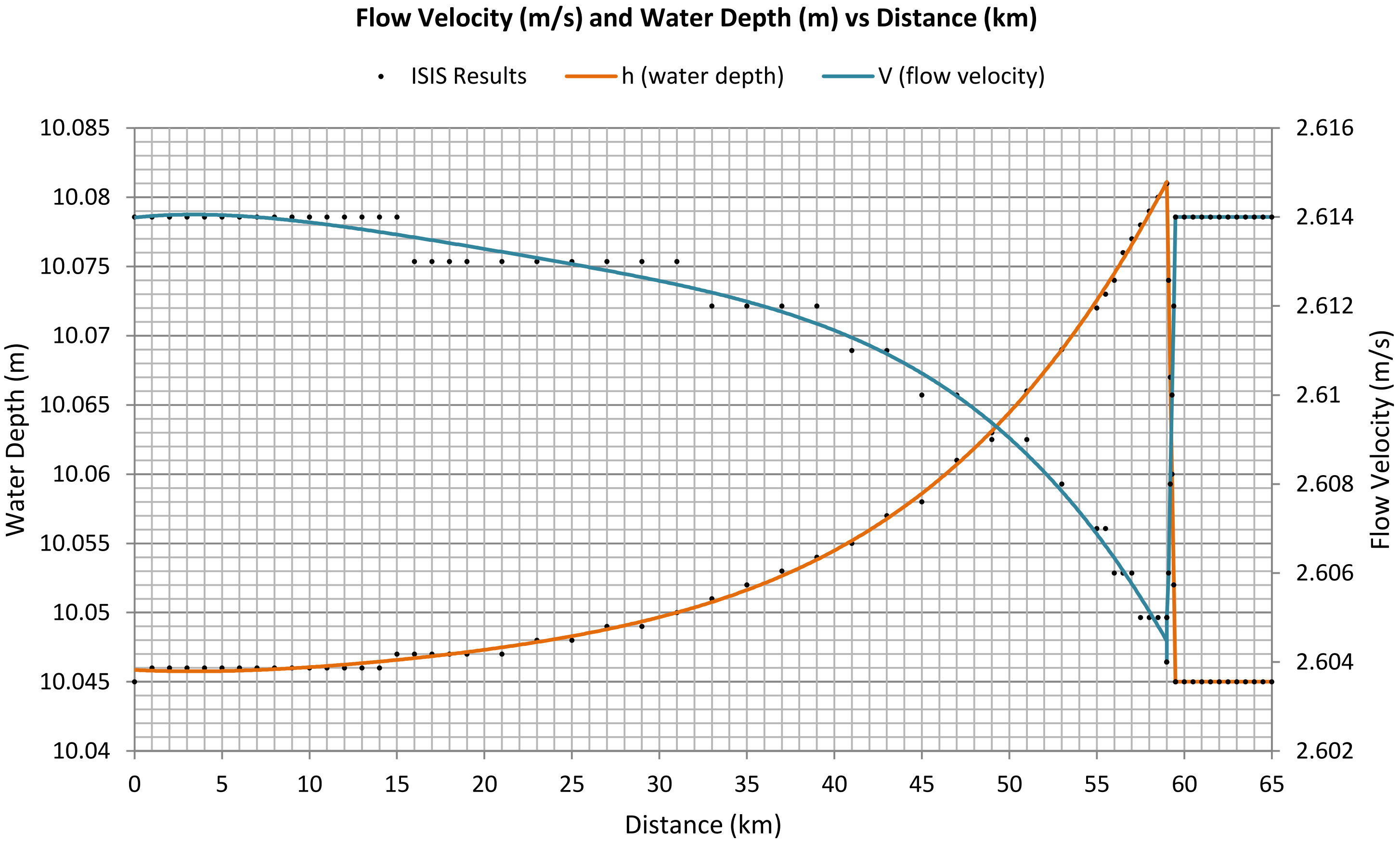
Case 3: Model Results





Significantly reduced impact (~.3%, if devices are localized)

Further Investigation



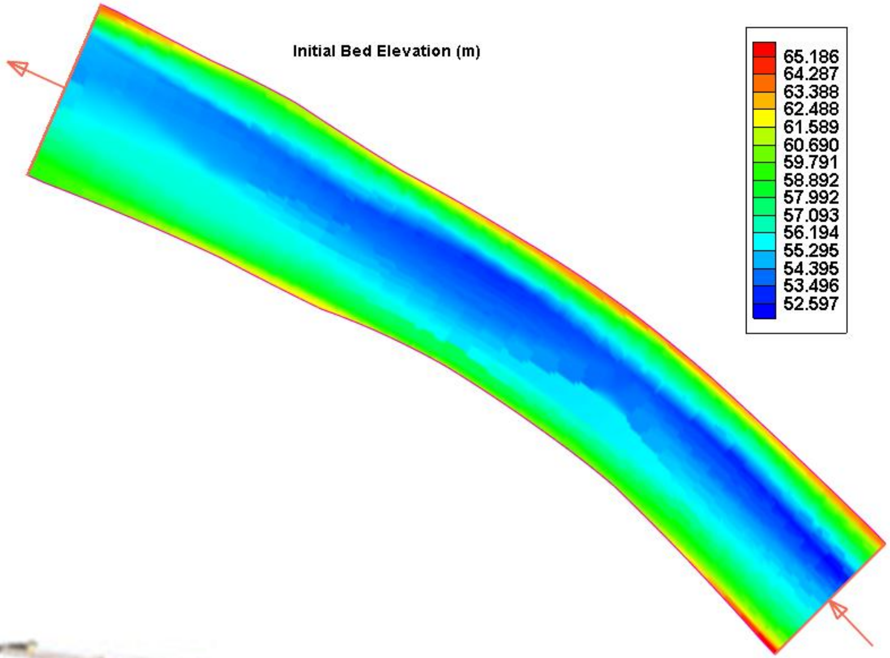
Summary: HK impacts

- Relatively significant impact of HK devices when devices are uniformly distributed and when the density is sufficiently high
- Deployment of devices over a limited portion of the river leads to a significantly reduced impact
- Approach described can be used to estimate the far-field impacts of complex deployments of devices in water bodies with realistic geometry
- Approach can be extended to examine sediment transport impacts (e.g., sedimentation caused by reduced velocities)

Application: Red Devil on Kuskokwim River

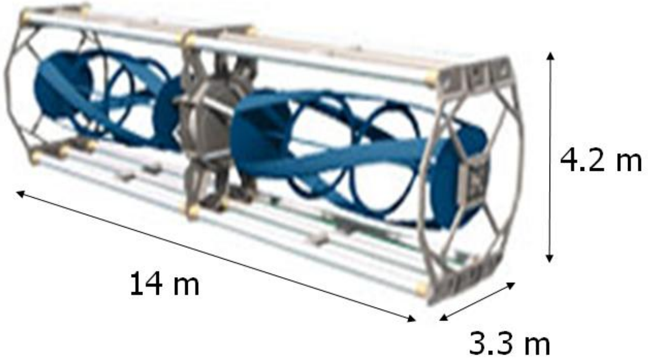
Data:

Q_{75} (m^3/s)	2220
River Slope (m/m)	0.000115
Average Width (m)	350
Manning's roughness coefficient	0.0257
Average depth (m)	4.90



- Uniform turbine distribution

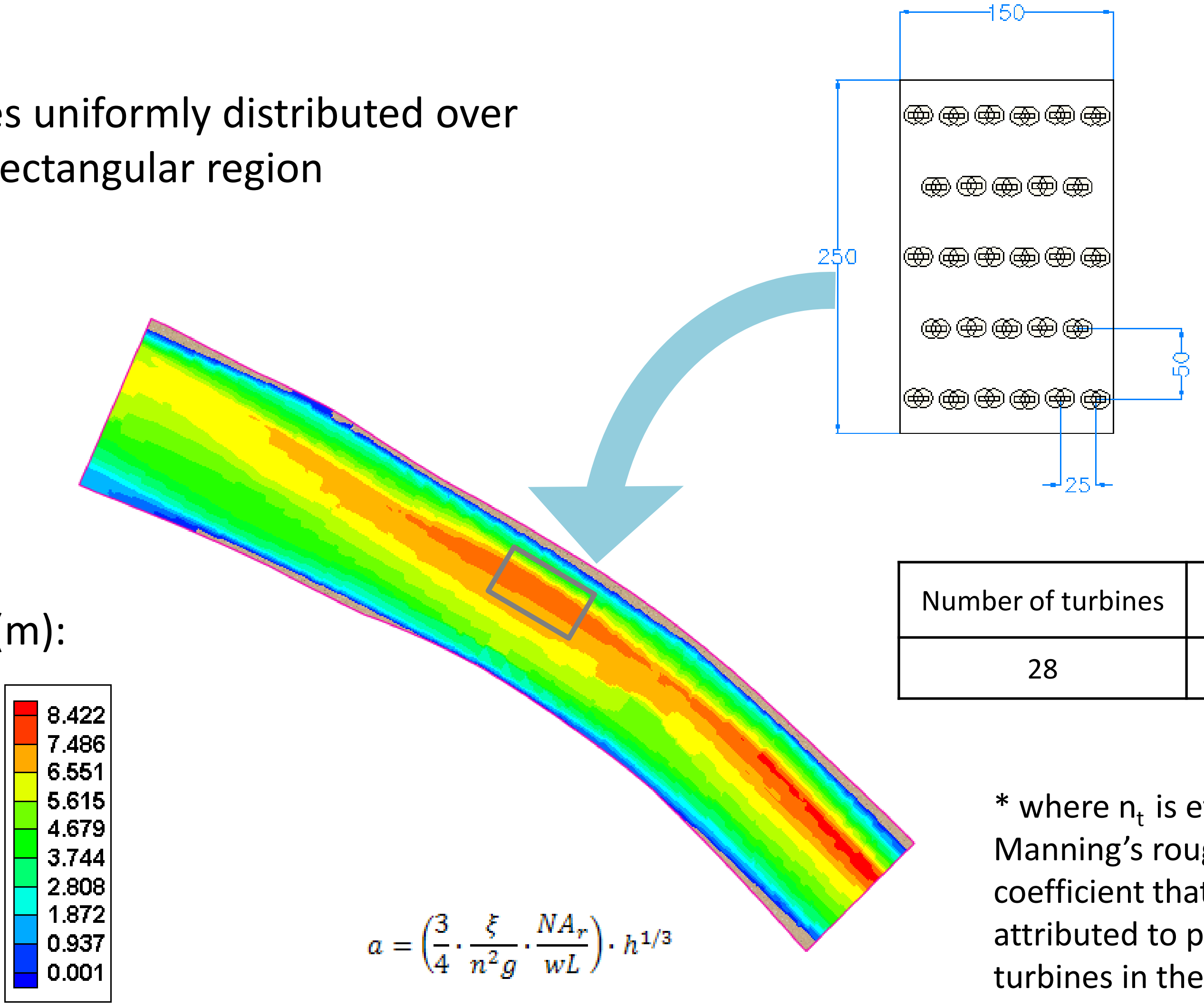
Turbines dimensions:



Turbines Location

Assume: turbines uniformly distributed over 150 m x 250 m rectangular region

Water depth (m):



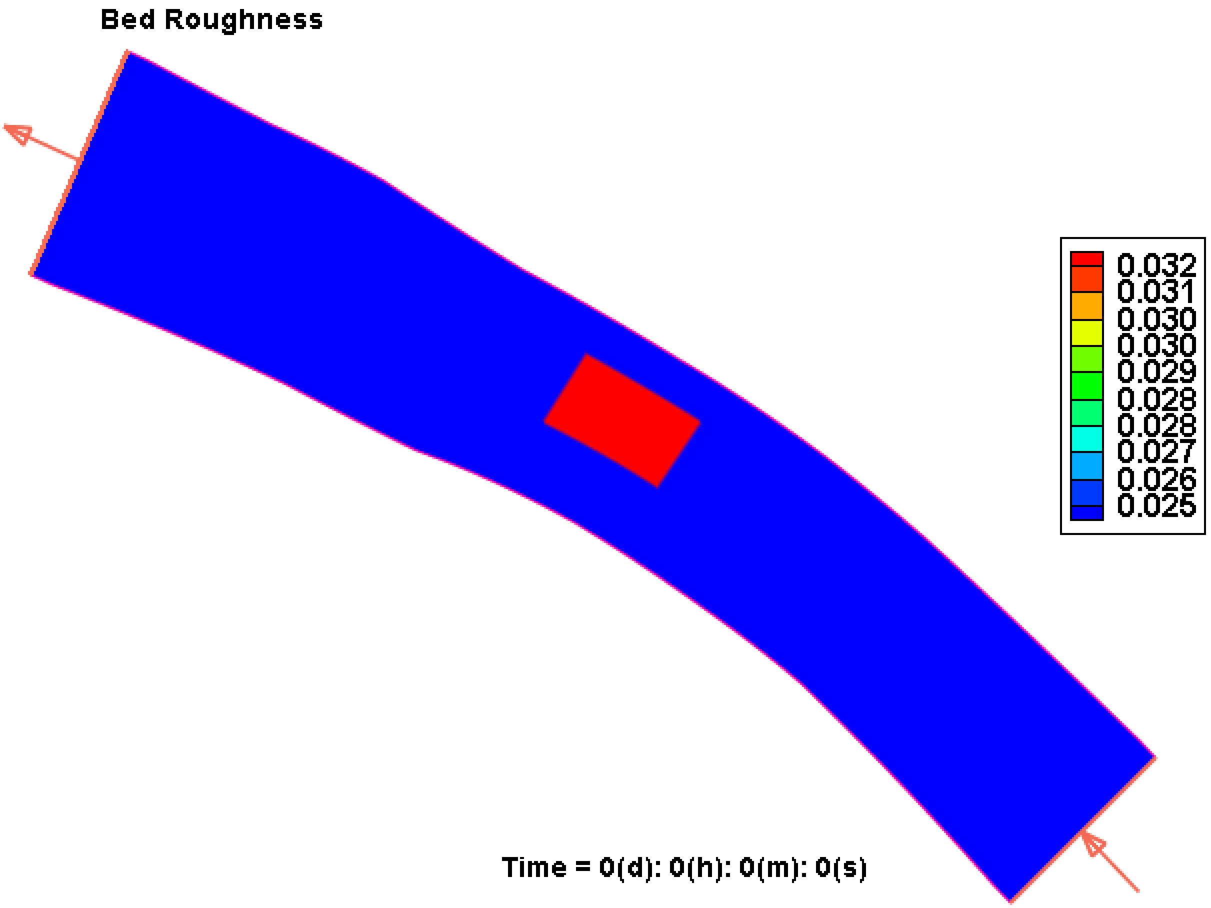
Number of turbines	n_t *
28	**0.0320**

$$a = \left(\frac{3}{4} \cdot \frac{\xi}{n^2 g} \cdot \frac{NA_r}{wL}\right) \cdot h^{1/3}$$

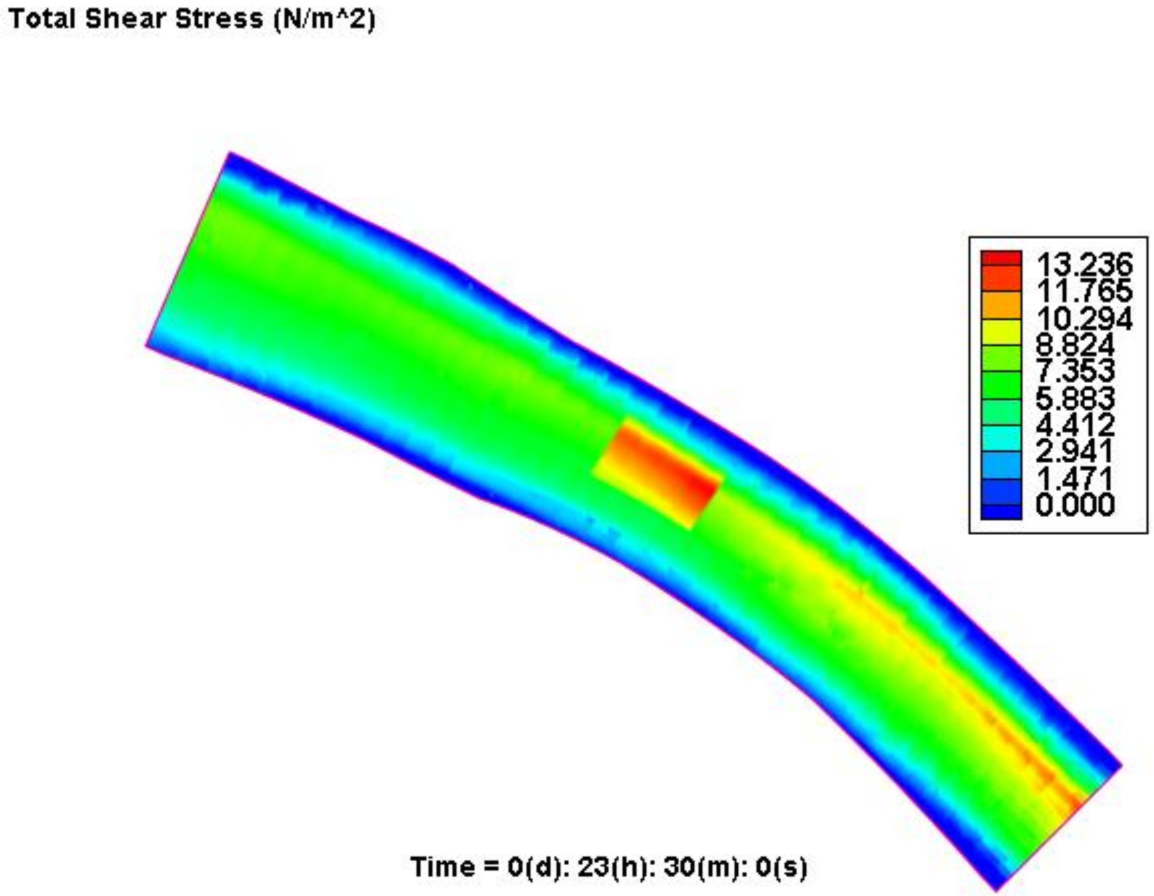
$$\frac{n_t}{n} = f(a)$$

* where n_t is effective Manning's roughness coefficient that is attributed to placing turbines in the path of the natural flow

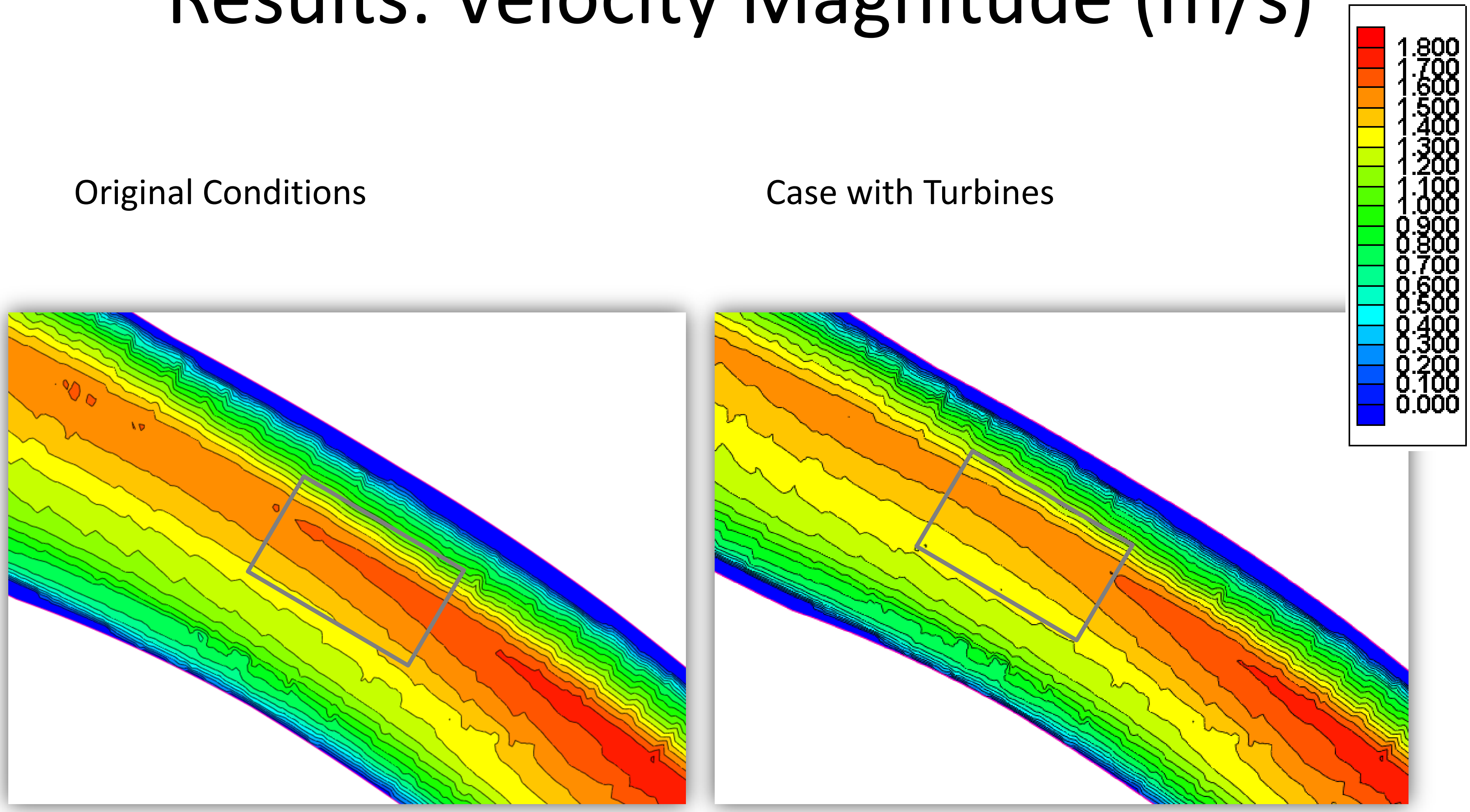
Initial Conditions



Total Shear Stress (N/m^2)



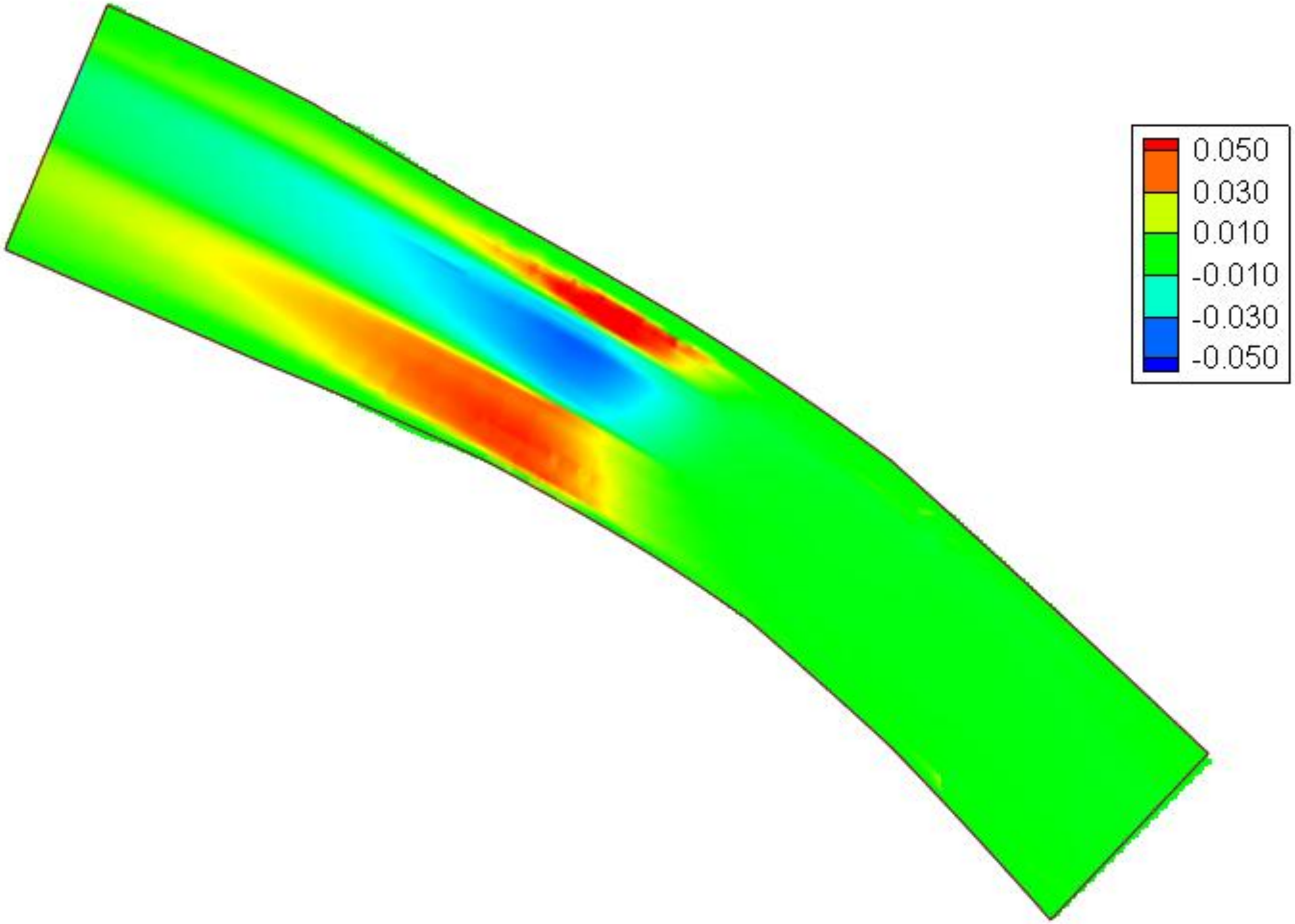
Results: Velocity Magnitude (m/s)



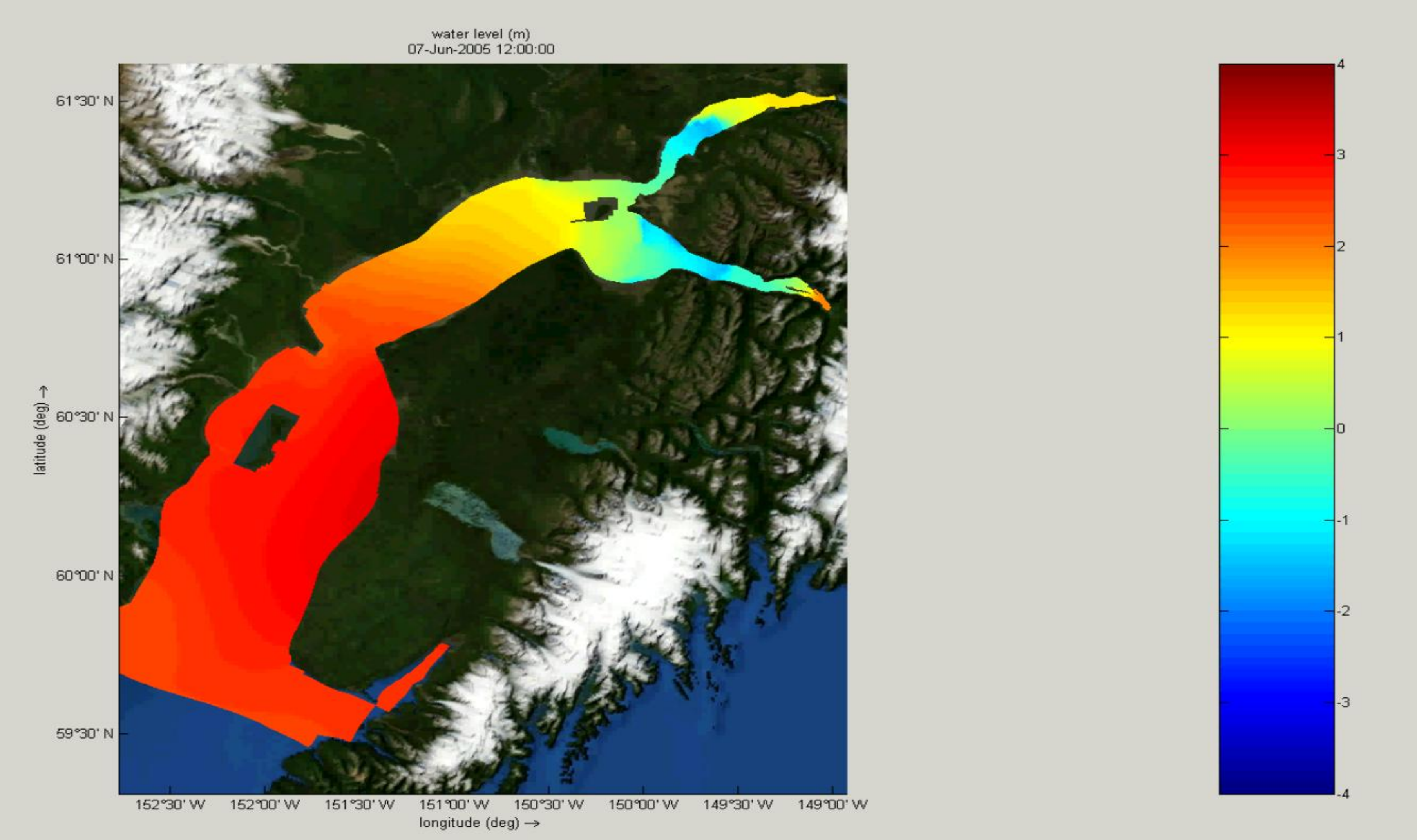
Original Conditions

Case with Turbines

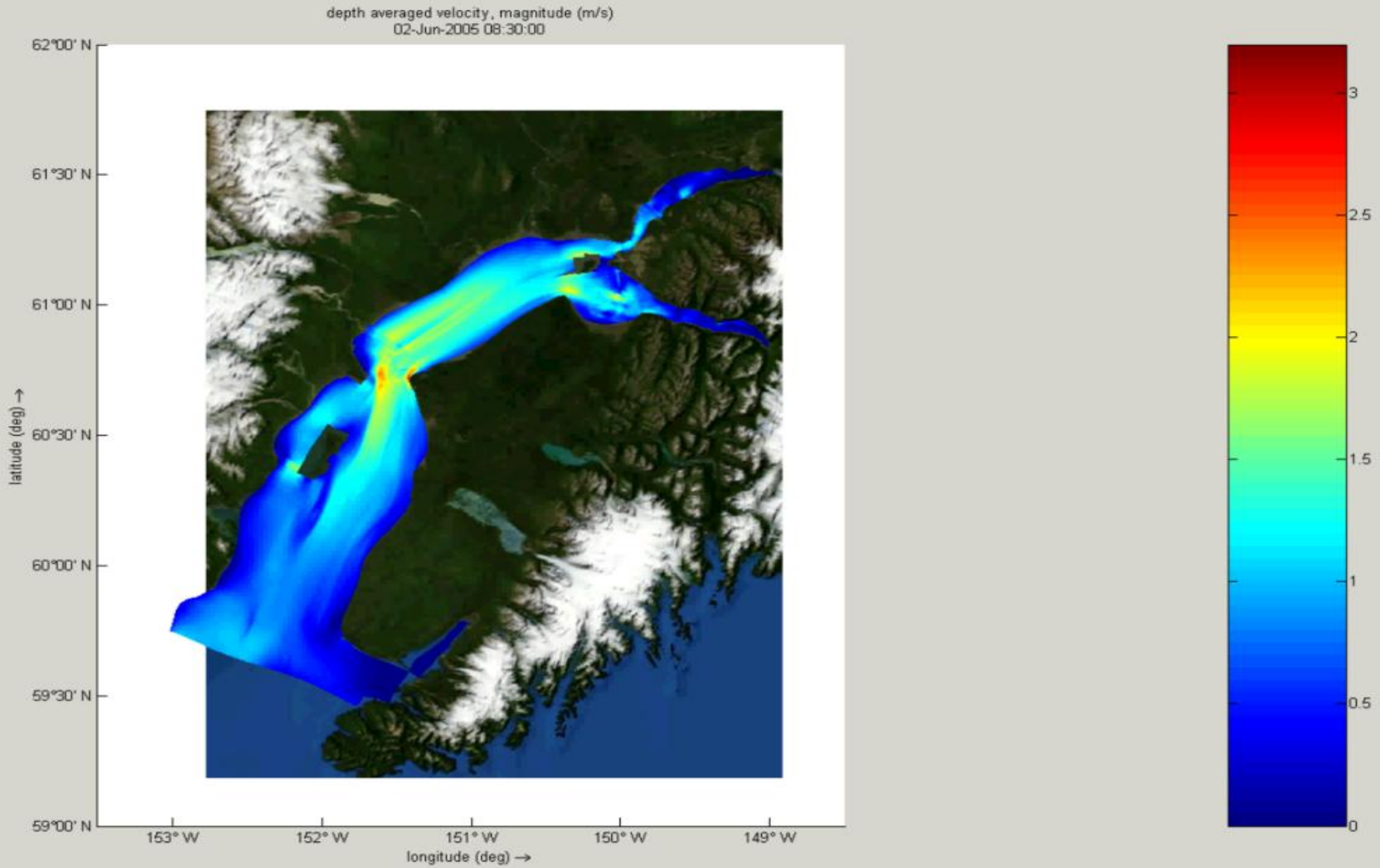
Change in Velocity (m/s)



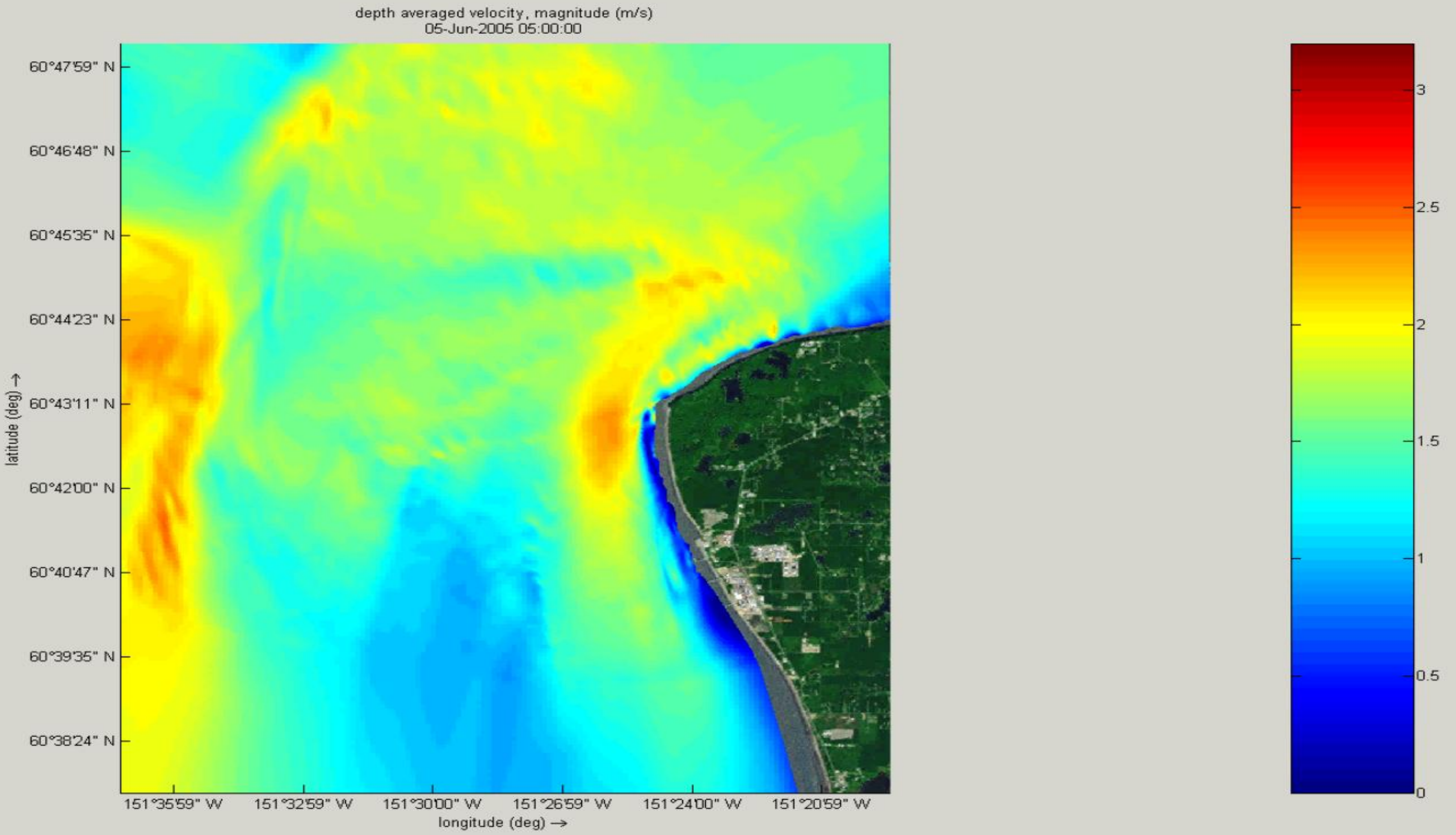
Application of HK impacts work to Cook Inlet (snapshot of Cook Inlet water level, no devices)



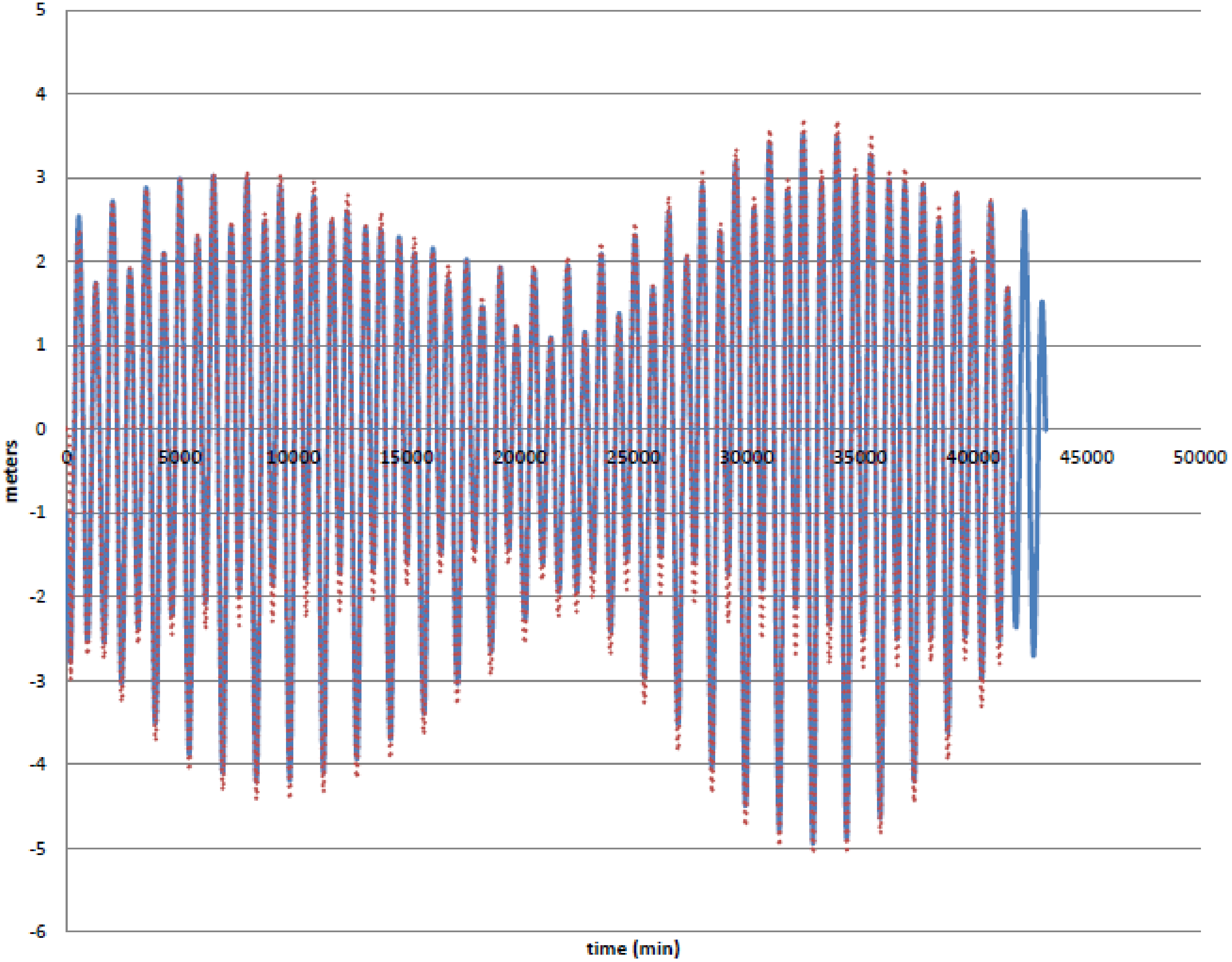
Snapshot of velocity of Cook Inlet velocity (no devices)



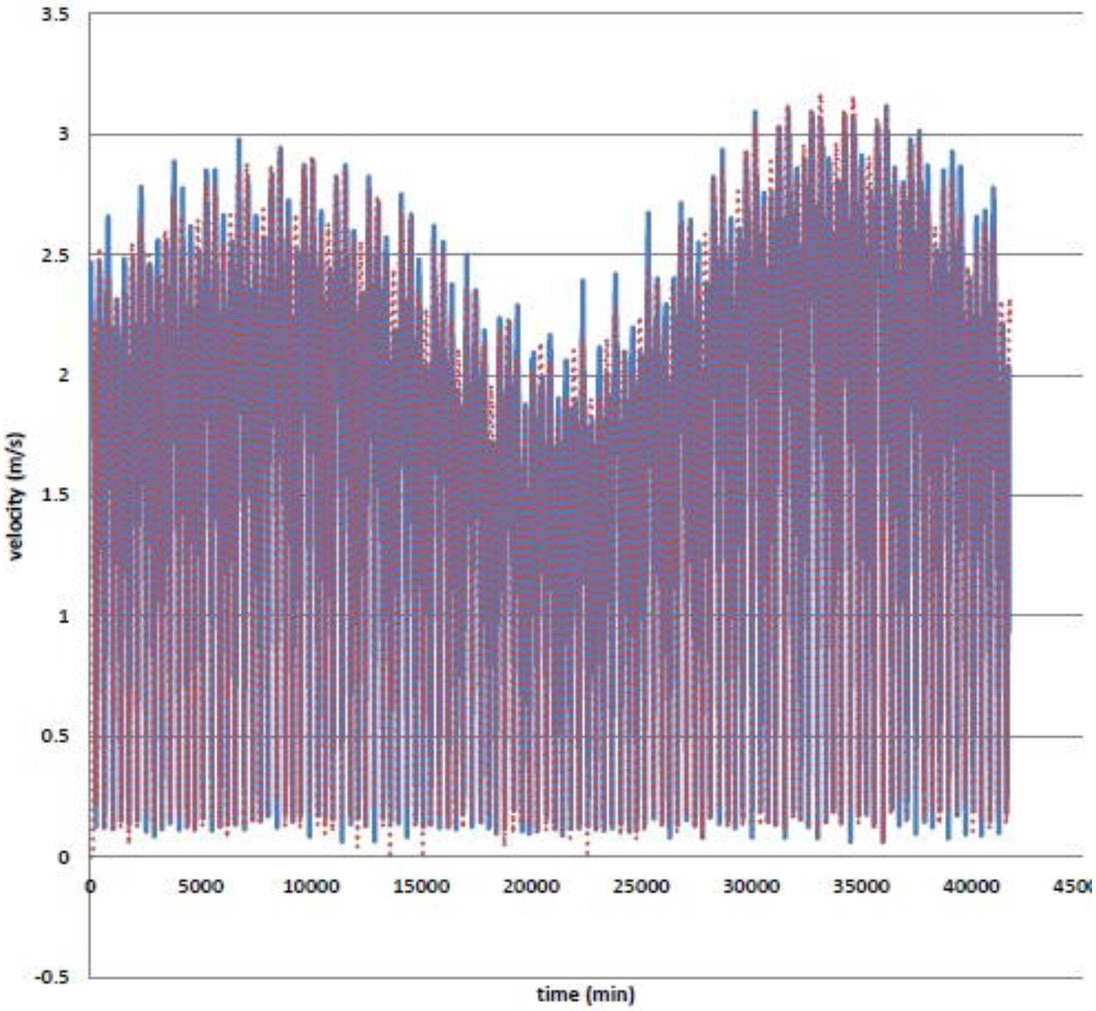
Snapshot of velocity by East Forelands (no devices)



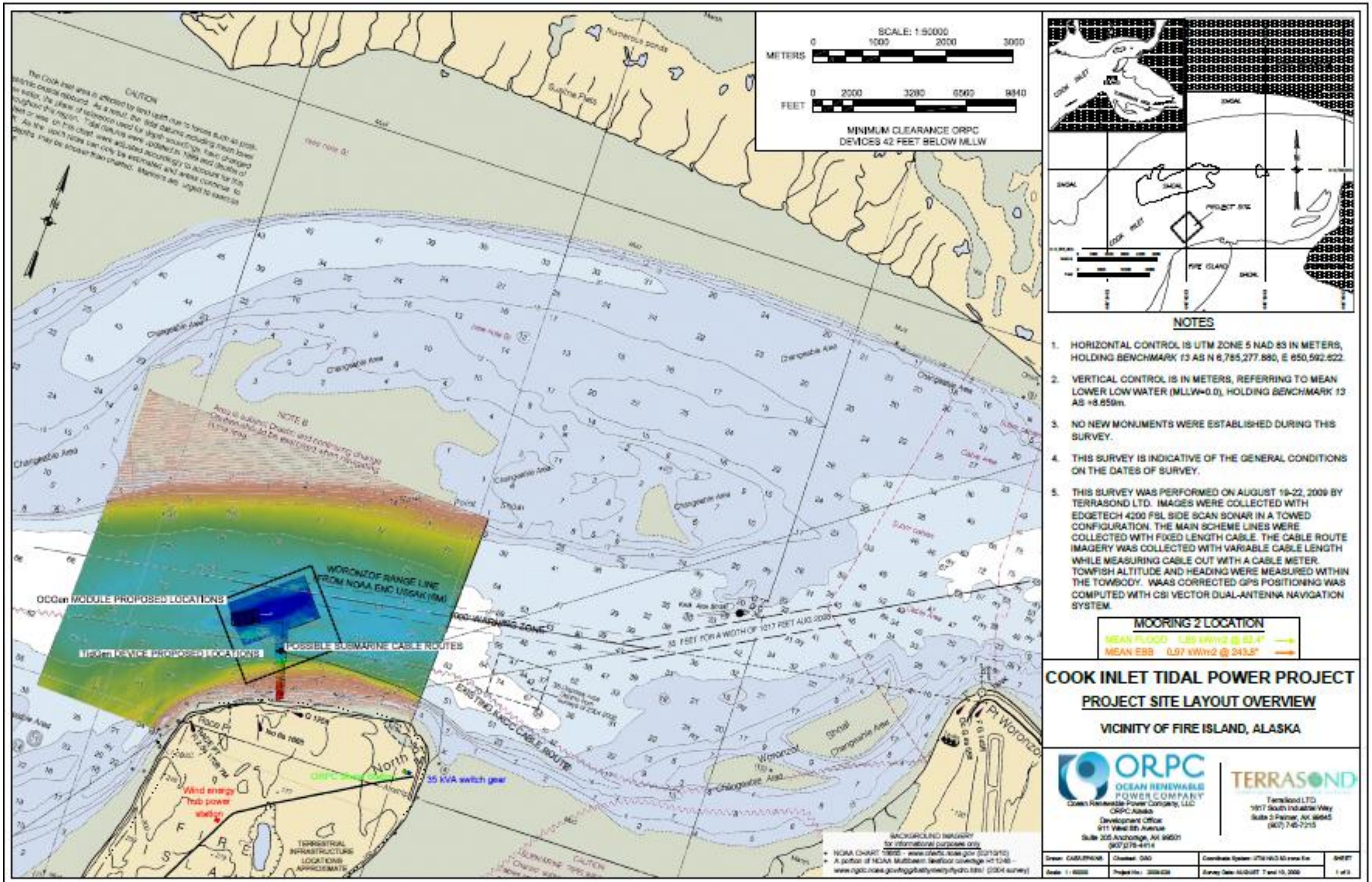
Comparison of modeled and measured water level at Nikiski (measured, ━━━ , modeled ------)



Comparison of modeled and measured depth-averaged velocity at Nikiski (measured, ── , modeled ------)



Layout of ORPC Fire Island HK deployment plan



NOTES

1. HORIZONTAL CONTROL IS UTM ZONE 5 NAD 83 IN METERS, HOLDING BENCHMARK 13 AS N 6,785,277.880, E 650,592.622.
2. VERTICAL CONTROL IS IN METERS, REFERRING TO MEAN LOWER LOW WATER (MLLW=0.0), HOLDING BENCHMARK 13 AS +8.659m.
3. NO NEW MONUMENTS WERE ESTABLISHED DURING THIS SURVEY.
4. THIS SURVEY IS INDICATIVE OF THE GENERAL CONDITIONS ON THE DATES OF SURVEY.
5. THIS SURVEY WAS PERFORMED ON AUGUST 19-22, 2009 BY TERRASOND LTD. IMAGES WERE COLLECTED WITH EDGETECH 4200 FSL SIDE SCAN SONAR IN A TOWED CONFIGURATION. THE MAIN SCHEME LINES WERE COLLECTED WITH FIXED LENGTH CABLE. THE CABLE ROUTE IMAGERY WAS COLLECTED WITH VARIABLE CABLE LENGTH WHILE MEASURING CABLE OUT WITH A CABLE METER. TOWFISH ALTITUDE AND HEADING WERE MEASURED WITHIN THE TOWBODY. WAAS CORRECTED GPS POSITIONING WAS COMPUTED WITH CSI VECTOR DUAL-ANTENNA NAVIGATION SYSTEM.

MOORING 2 LOCATION

MEAN FLOOD 1.89 kW/m2 @ 62.4° →

MEAN EBB 0.97 kW/m2 @ 243.8° →

MINIMUM CLEARANCE ORPC DEVICES 42 FEET BELOW MLLW

COOK INLET TIDAL POWER PROJECT

PROJECT SITE LAYOUT OVERVIEW

VICINITY OF FIRE ISLAND, ALASKA

Ocean Renewable Power Company, LLC
ORPC Alaska
Development Office
911 West 8th Avenue
Suite 305 Anchorage, AK 99501
(907) 278-4414

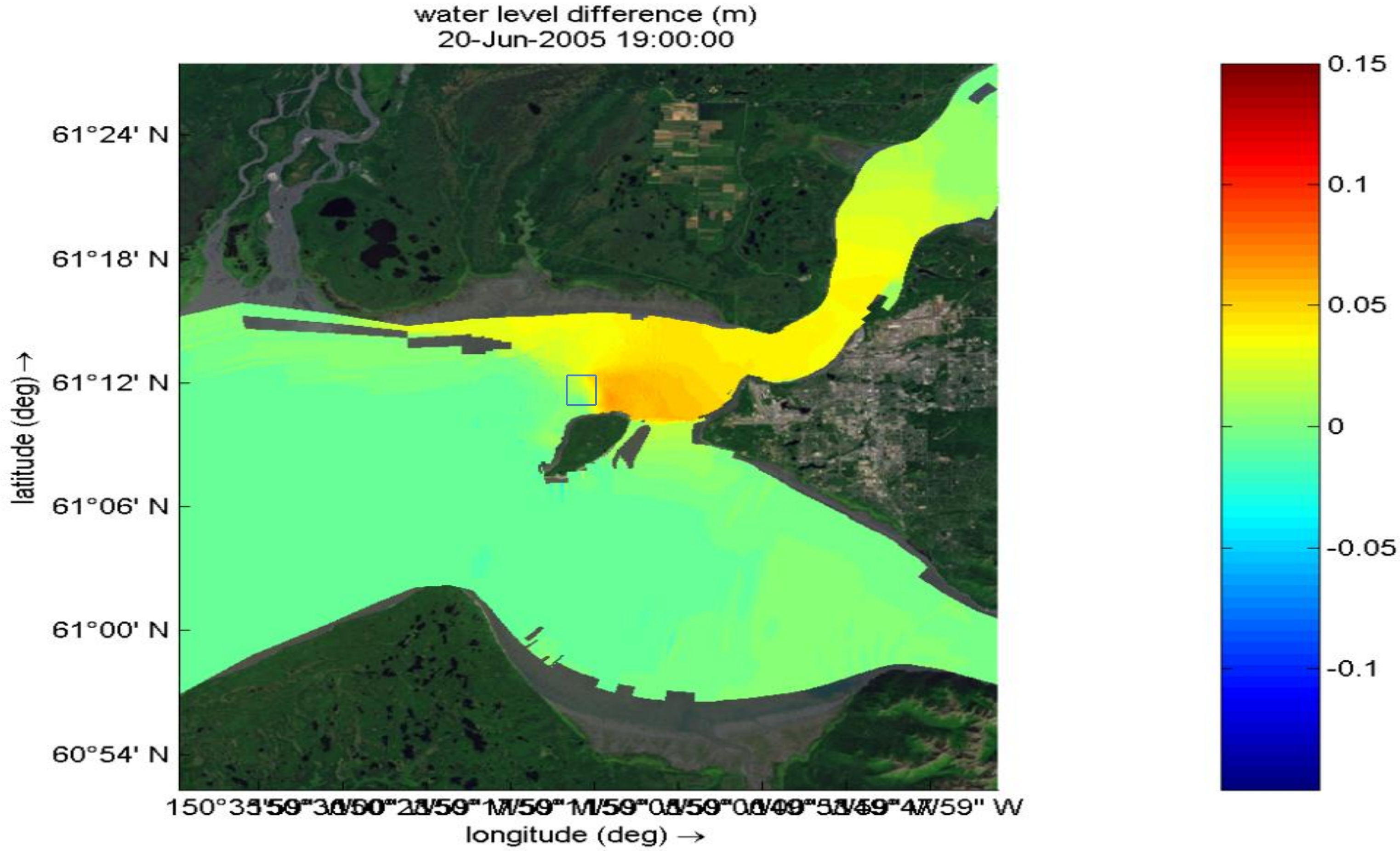
TerraSond LTD
1617 South Industrial Way
Suite 3 Palmer, AK 99645
(907) 745-7215

BACKGROUND IMAGERY
for informational purposes only
- NOAA CHART 16665 - www.charts.noaa.gov (02/13/10)
- A portion of NOAA Multibeam Seafloor coverage H11246 - www.ngdc.noaa.gov/mgg/bathymetry/hydro.html (2004 survey)

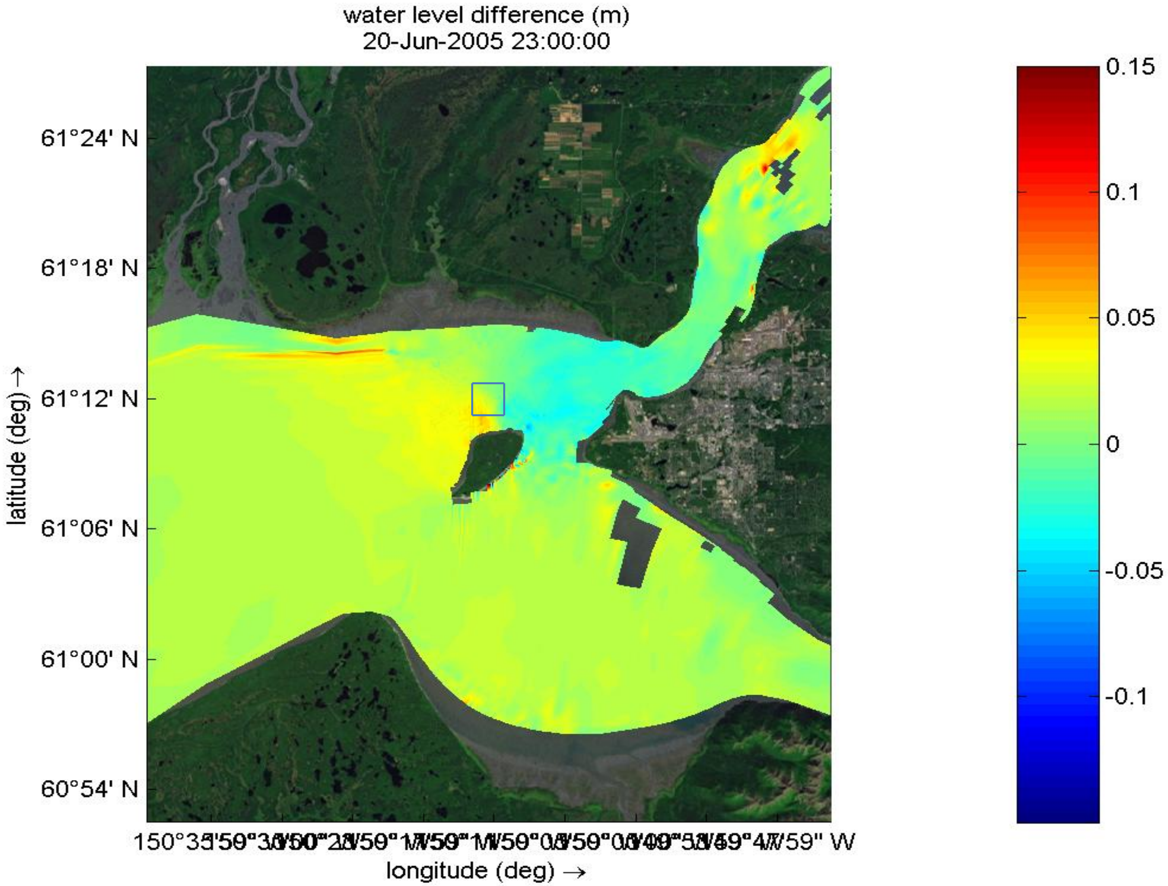
Estimation of potential HK impacts associated with virtual deployment by Fire Island

- Determination of effective Manning roughness associated with likely HK device deployment
- Assumptions:
  - Device area: 80 m^2
  - Device efficiency: 30%
  - Number of devices: 134
  - Planform area of deployment: 750 m x 960 m
  - Blockage ratio: 0.03 (neglected)
  - Effective Manning roughness: .042

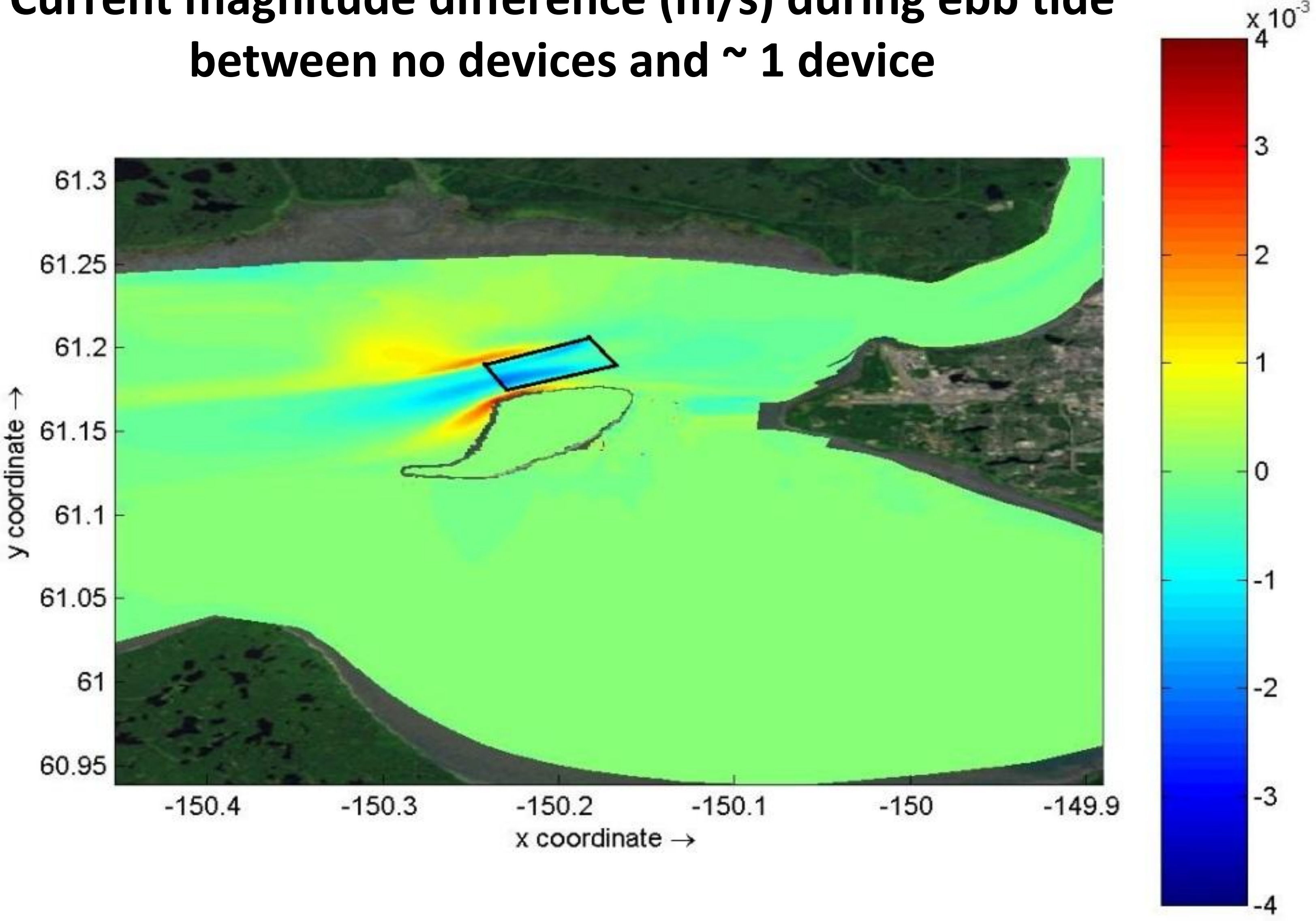
Snapshot of water level difference (assuming 134 devices, ebb tide



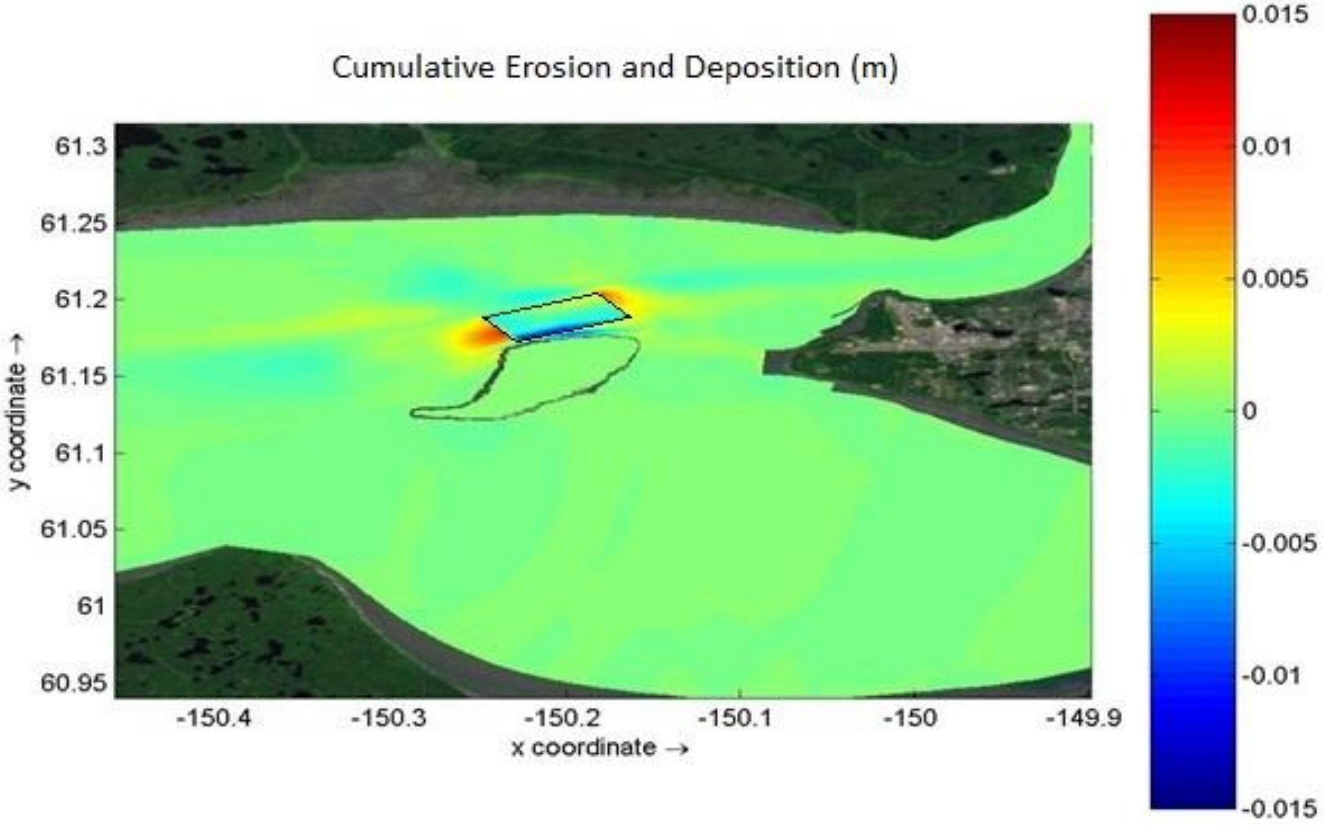
Snapshot of water level difference (assuming 134 devices, flood tide



Current magnitude difference (m/s) during ebb tide between no devices and ~ 1 device



Calculated cumulative erosion and deposition difference (no devices vs. ~ 1 devices) over 30 day period assuming 0.2 mm sand.



Future work

- Develop 3D circulation model and capacity to model the presence of HK devices at various locations with water column.
- Make detailed measurements of impact of HK devices (e.g., ORPC device) on flow velocity, turbulence and sediment transport
- Collect bottom, bedload, and suspended sediment samples in area of focus in Cook Inlet
- Develop sediment transport model for area of focus in Cook Inlet
- Project sediment transport impacts of HK devices in area of focus

Thank you!

- Department of Energy
- Electrical Power Research Institute.
- Alaska Energy Authority
- Ocean Renewable Power Corporation
- University of Alaska Chancellor's Fund
- Kenai Borough