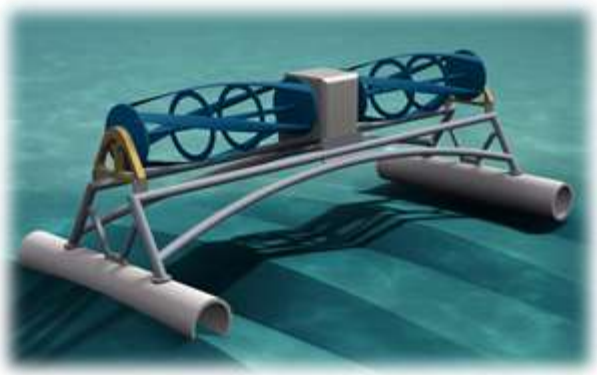

Assessment of Hydrokinetic Energy Resources and Potential Impacts

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Assessment of Hydrokinetic Energy Resources and Potential Impacts

I. Assessment of hydrokinetic resources in Alaska rivers.
II. Assessment of hydrokinetic resources in Cook Inlet.
III. Modeling impact of hydrokinetic devices on velocity, water level, and sediment transport.
IV. Abrasion testing of critical components of hydrokinetic devices.

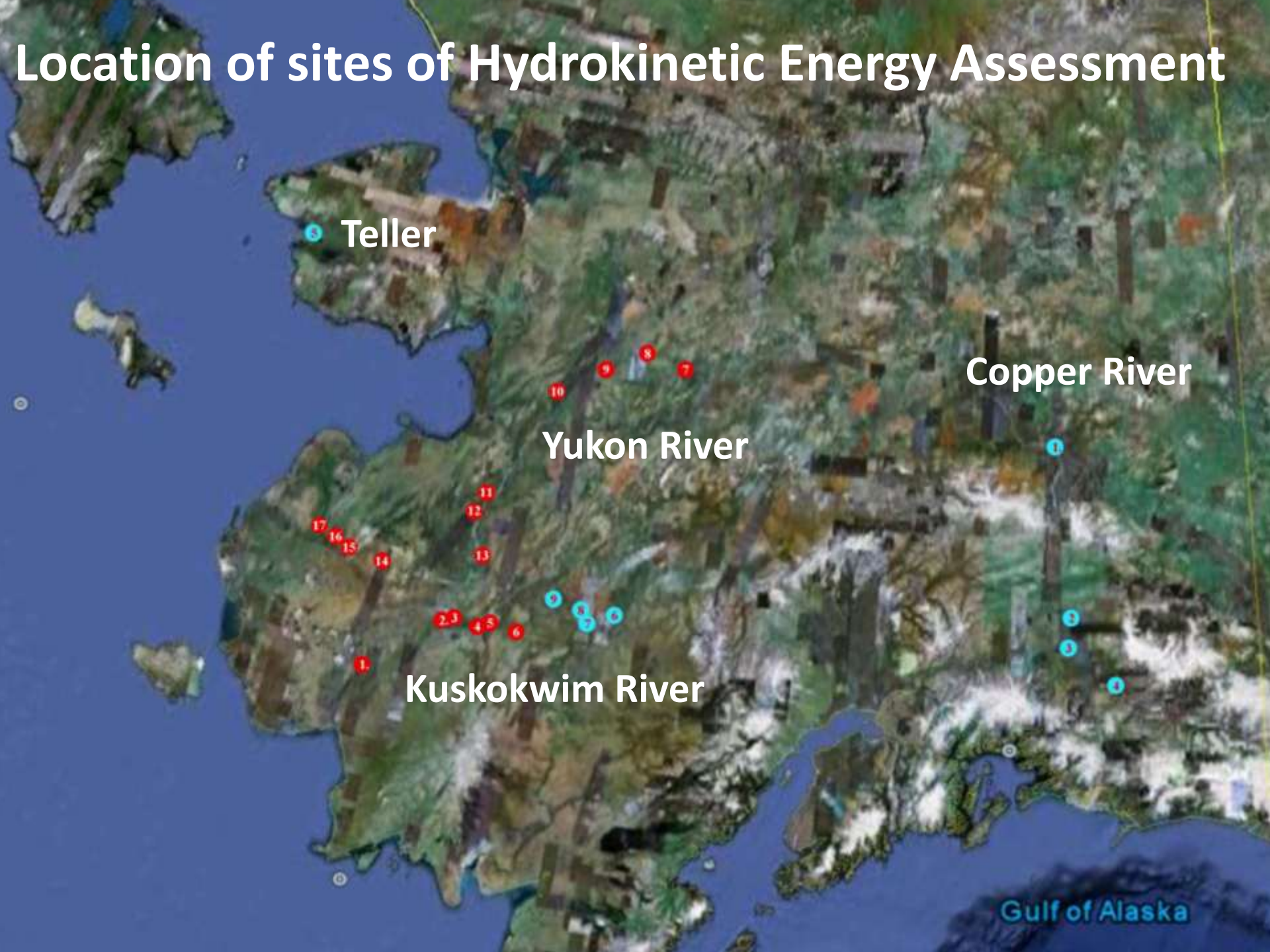
Assessment of the hydrokinetic resource in Alaska rivers

Overall goal: ***Assess hydrokinetic energy potential at 24 Alaska sites - (power density ~ .5 ρ ε V^3)***

Step 1: measure velocity, topography, bathymetry, river slope

Step 2: Develop hydraulic/hydrologic models

Step 3: Assess hydrokinetic energy potential


Location of sites of Hydrokinetic Energy Assessment
Teller
Yukon River
Copper River
Kuskokwim River
Gulf of Alaska

Alaska River HK Assessment Approach:

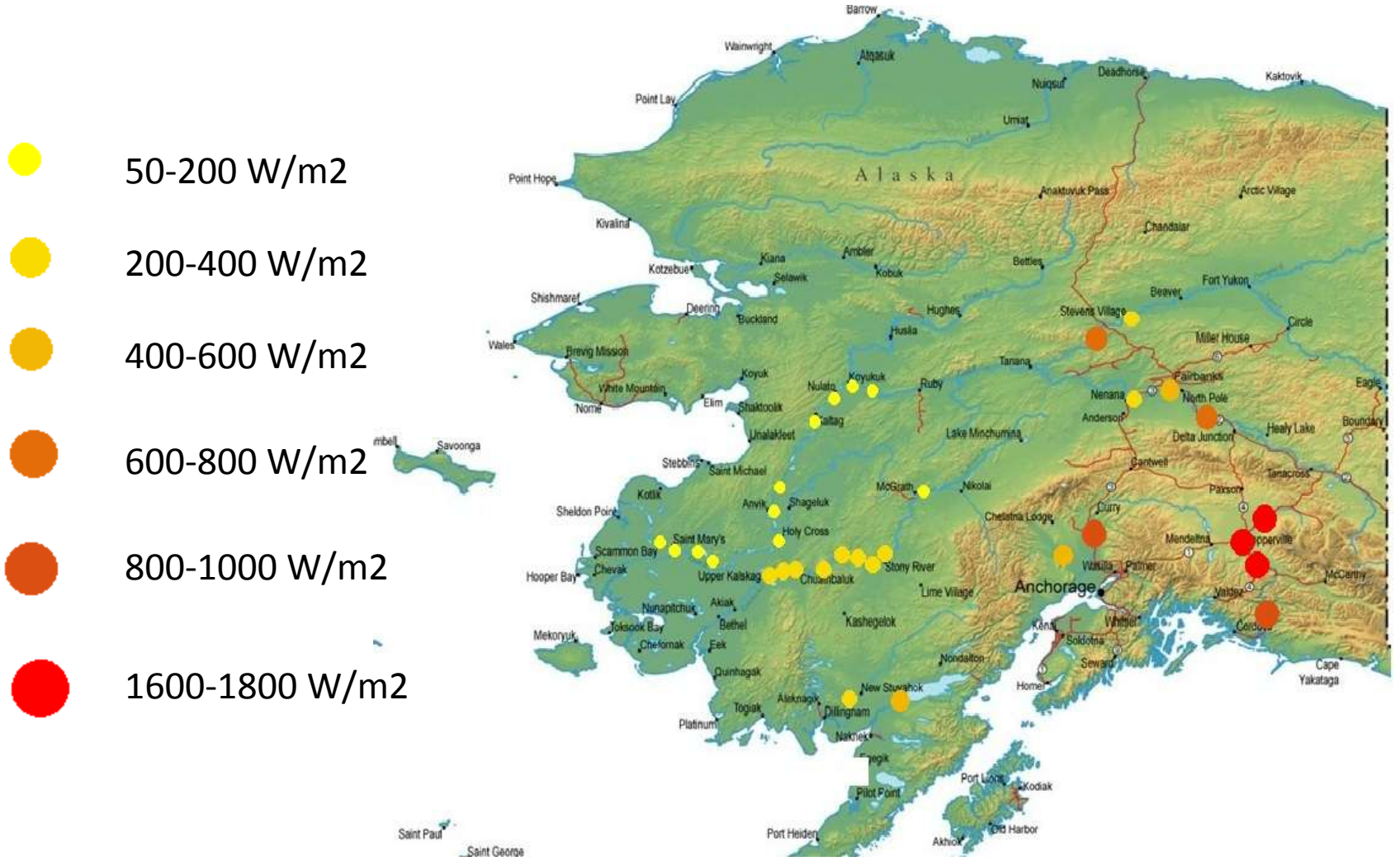
1. At a particular time, measure flow rate, velocity, bathymetry, and bank topography along approximately five cross-river transects in the vicinity of 24 village sites on major Alaskan rivers

Pilot Station survey transects

Alaska HK Assessment Approach (continued):

2. Determine the relationship between flow rate at the villages and flow rate at a nearby USGS gauge site, accounting for the time of travel of river flow.
3. Assume that the relationship between flow rate at the village and flow rate at the gauge holds throughout time.
4. Determine Q_{ave} Q_{25} Q_{50} and Q_{75} at each site based on (2) and (3).
5. Determine the cross-section average velocity V_{ave} assuming a flow of Q_{ave} and making use of Manning Equation.
6. Estimate average power density at each site for a preliminary estimate of the statewide distribution of HK power

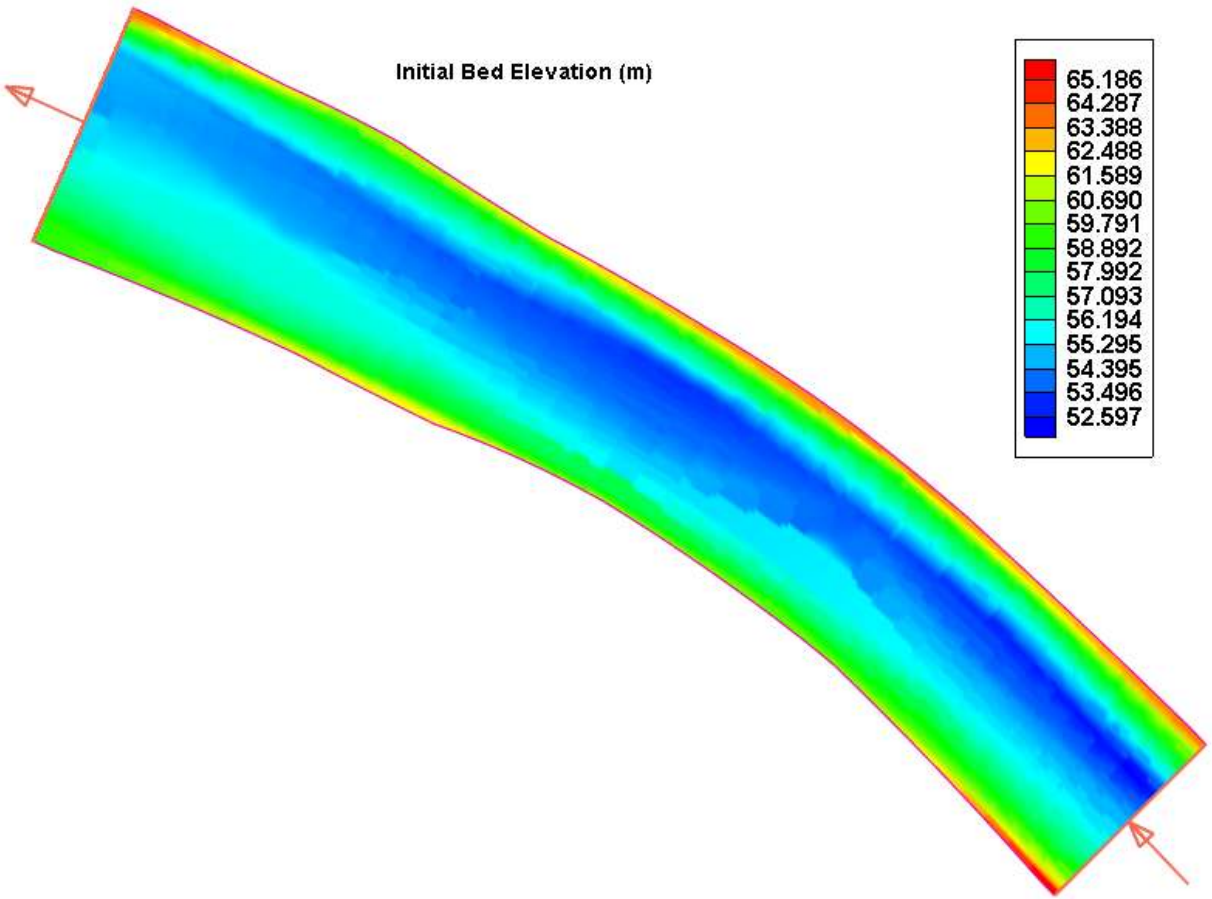
Power Density in Alaska (with additional data including USGS gauge



High resolution spatial distribution of power density at each site for Q_{25}, Q_{50}, and Q_{75}

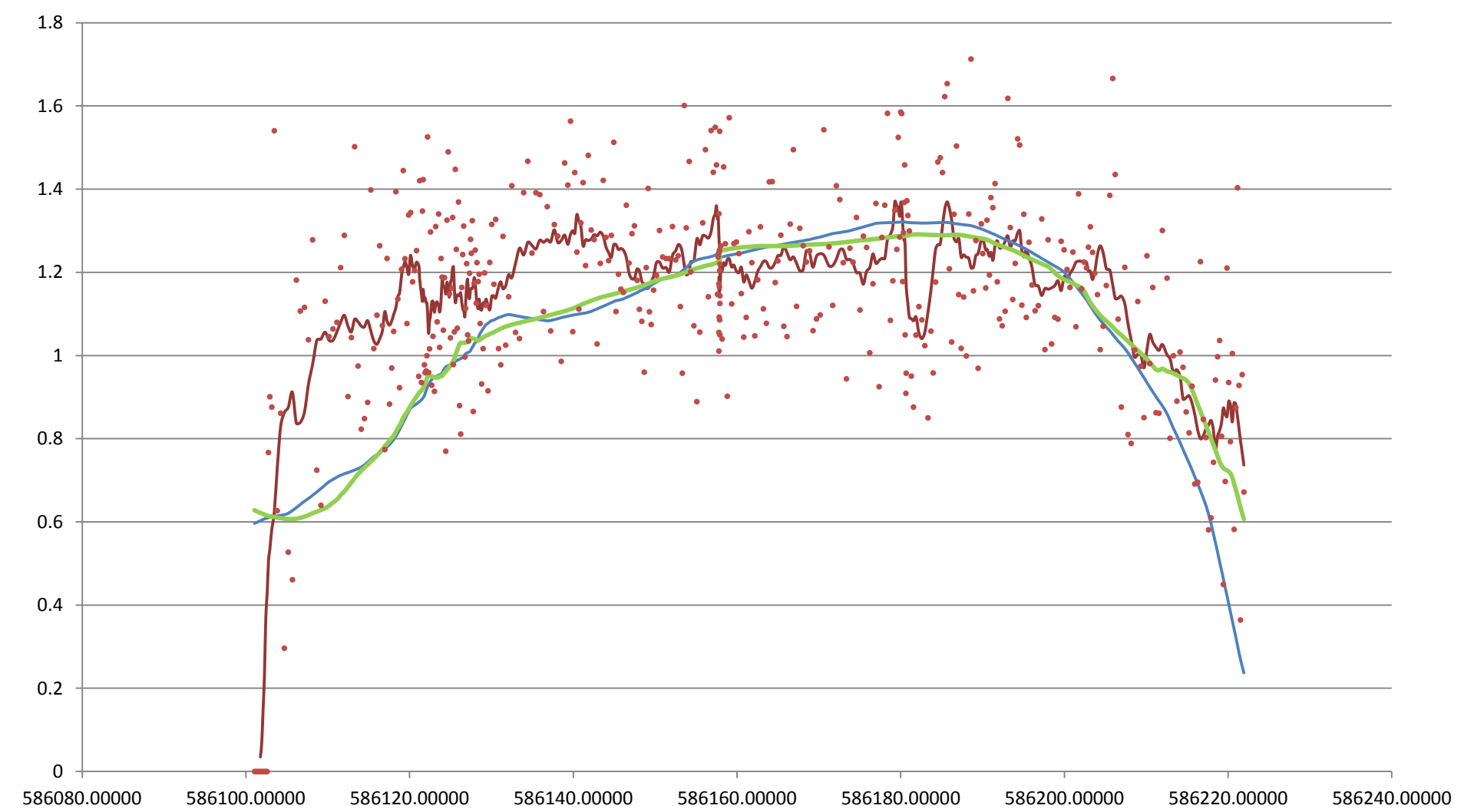
7. Develop 2D numerical model (CCHE) of flow for the flow conditions that prevailed at time of measurement (using bathymetry, topographic, and water level data)
8. Validate model's calculation of velocity using measurements
9. Calculate velocity distribution for Q_{25}, Q_{50}, and Q_{75}
10. Calculate distribution of power density for Q_{25}, Q_{50}, and Q_{75}

Bathymetry data –Red Devil

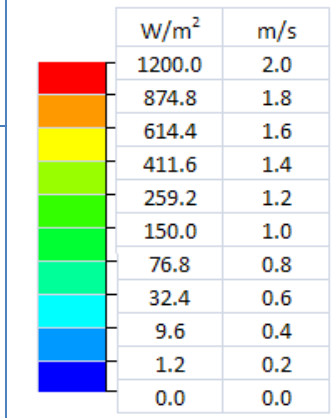


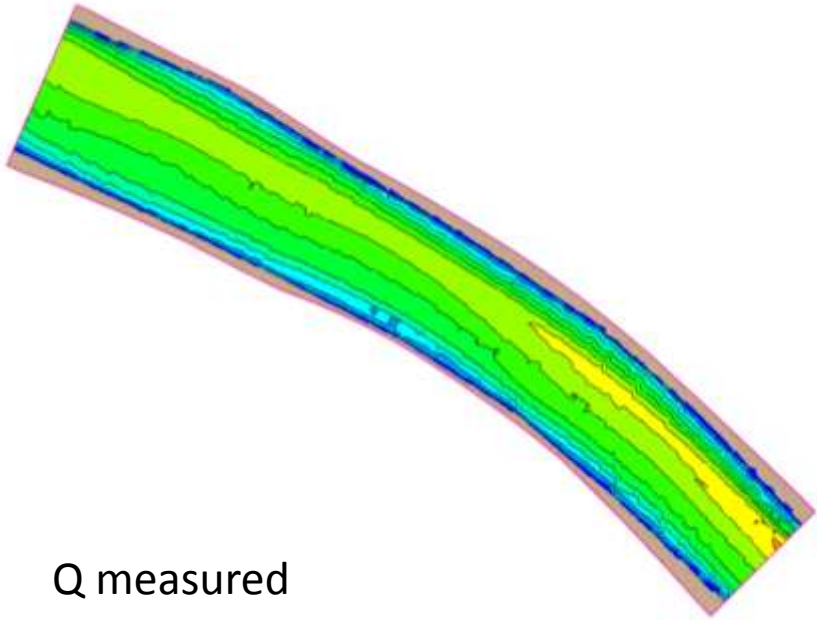
Discharge data for Red Devil, AK

	Q (m^3/s)	WL T1 (m)	WL T7 (m)
Q (measured)	1256.3	59.21	59.42
Q_{25}	1850	60.35	60.62
Q_{50}	1950	60.49	60.79
Q_{75}	2220	60.82	61.2

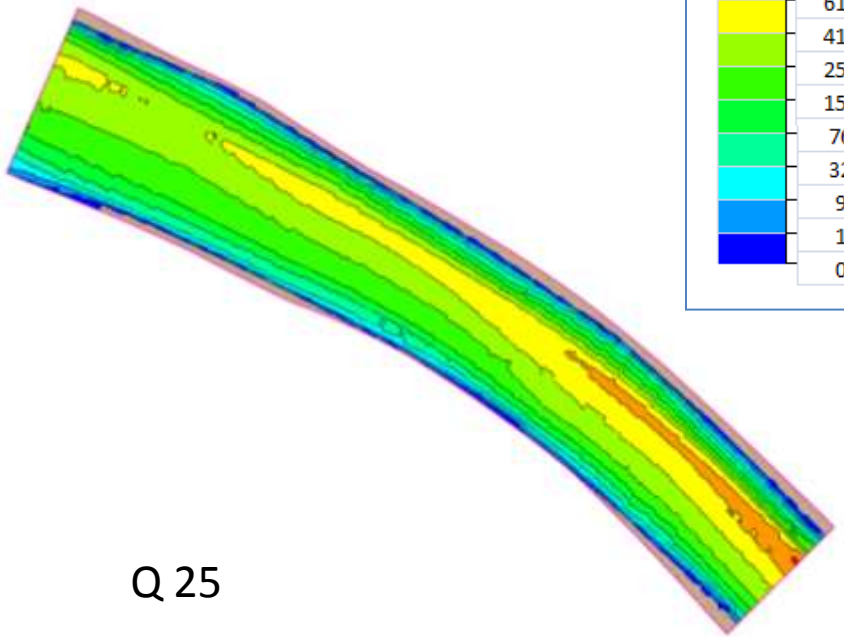

1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
586080.00000
586100.00000
586120.00000
586140.00000
586160.00000
586180.00000
586200.00000
586220.00000
586240.00000
Measured velocity
Savitzky-Golay Smoothing Filter
mcs-mesh results
xyz-mesh results

Power Density (W/m^2) and Velocity (m/s)

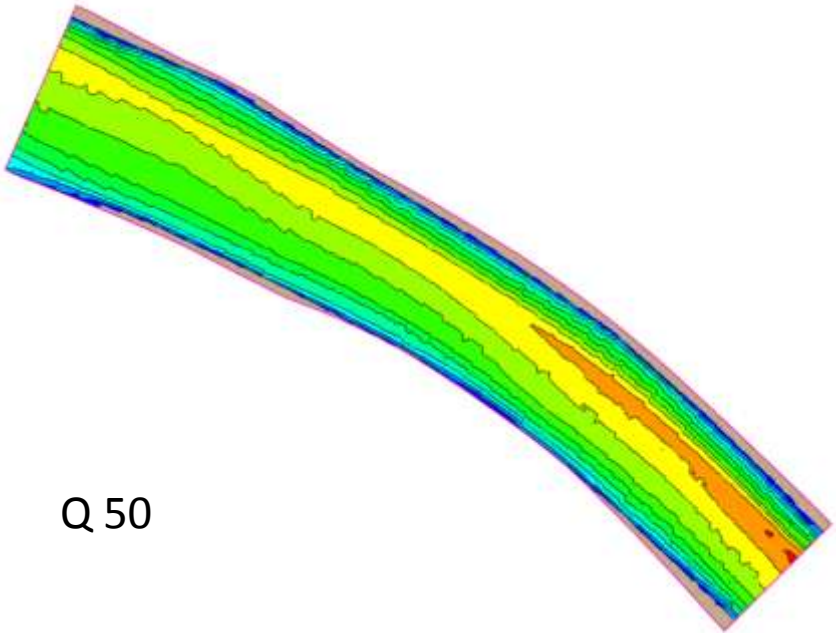




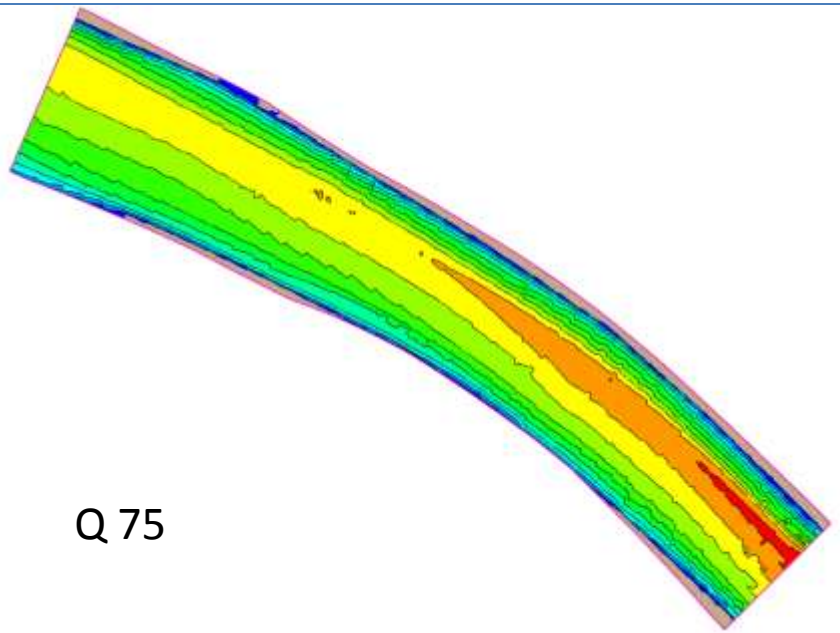
Q measured



Q 25



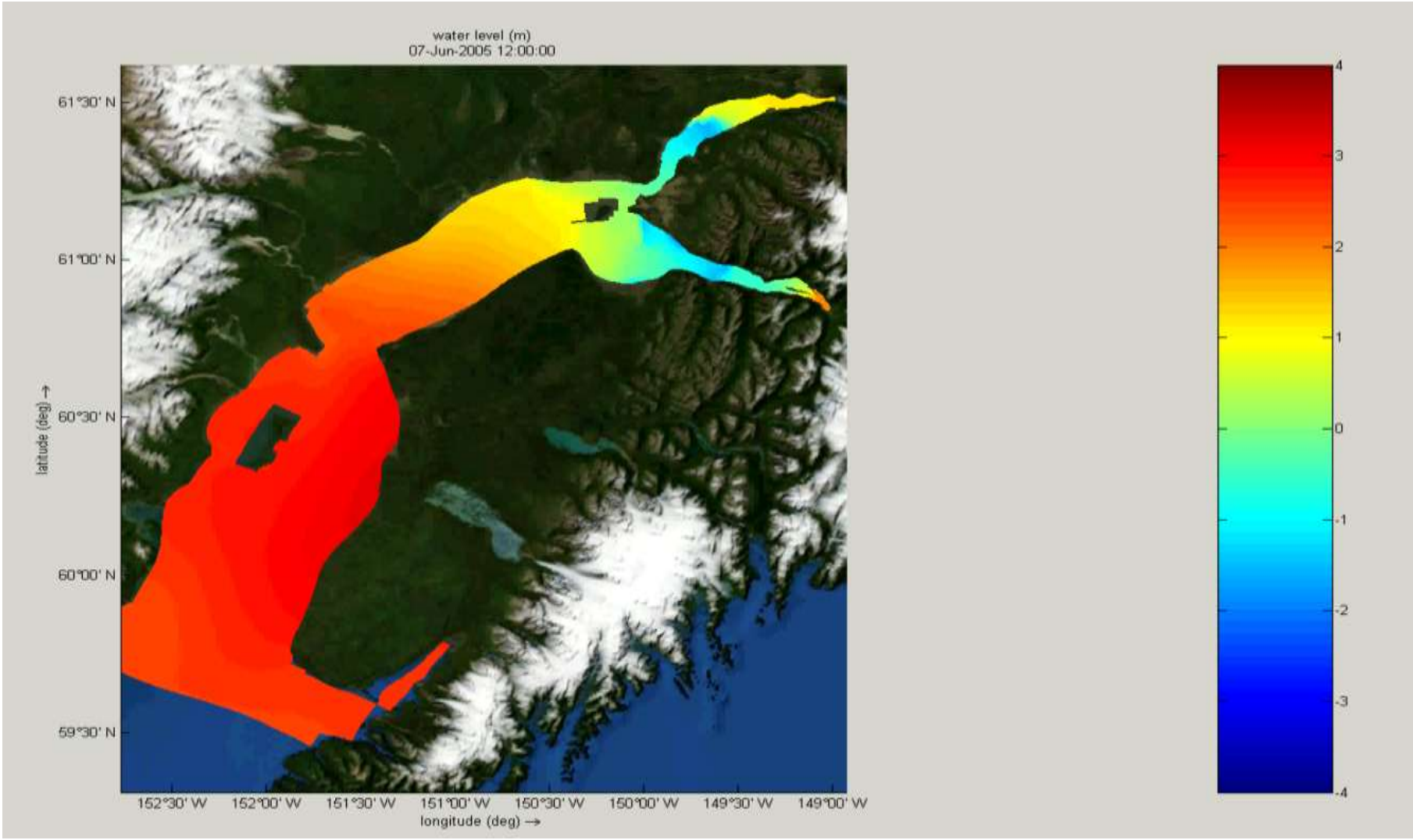
Q 50



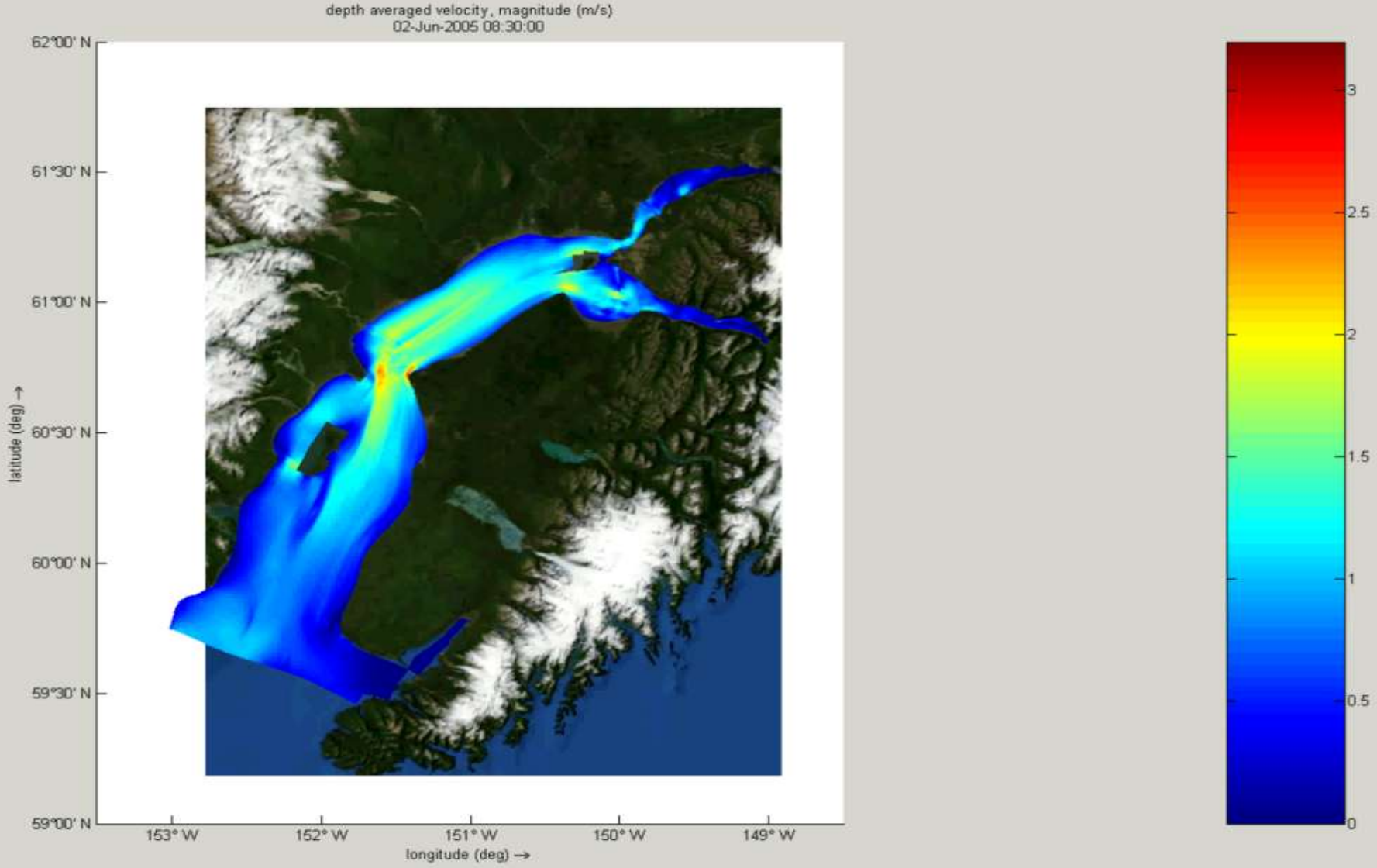
Q 75

Q m	1256.3
Q25	1850.0
Q50	1950.0
Q75	2220.0

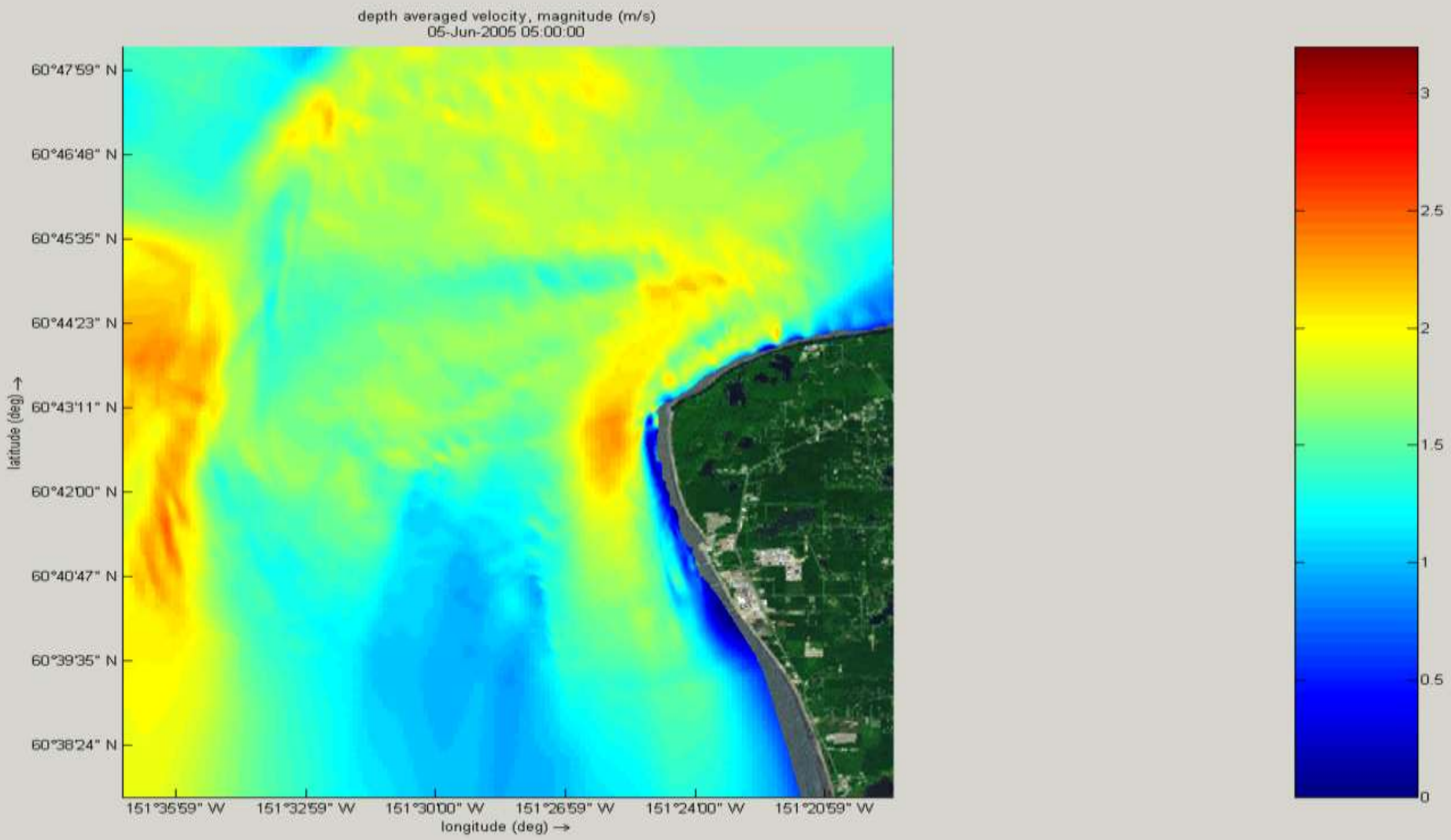
Application of HK impacts work to Cook Inlet (snapshot of Cook Inlet water level, no devices)



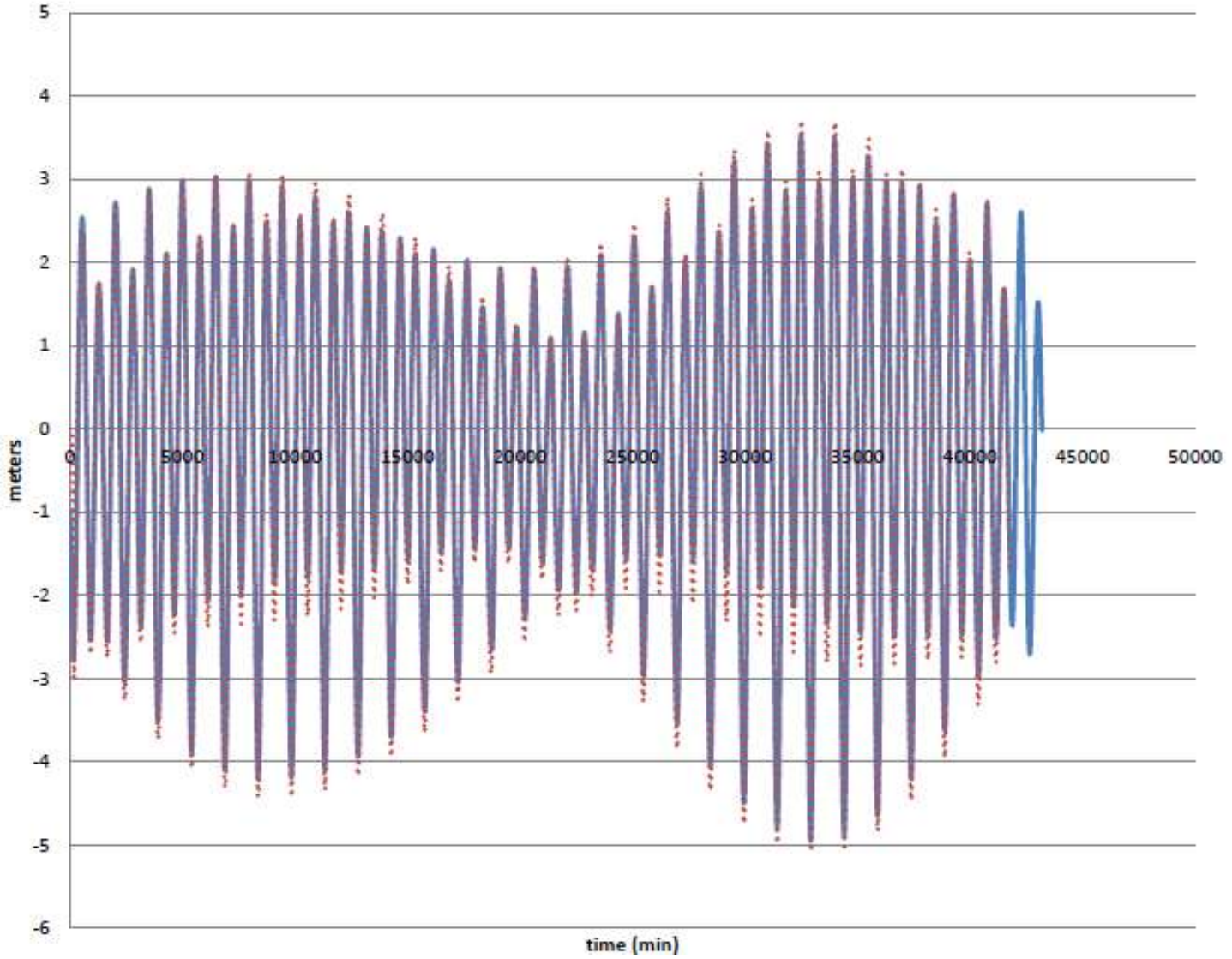
Snapshot of velocity of Cook Inlet velocity (no devices)



Snapshot of velocity by East Forelands (no devices)

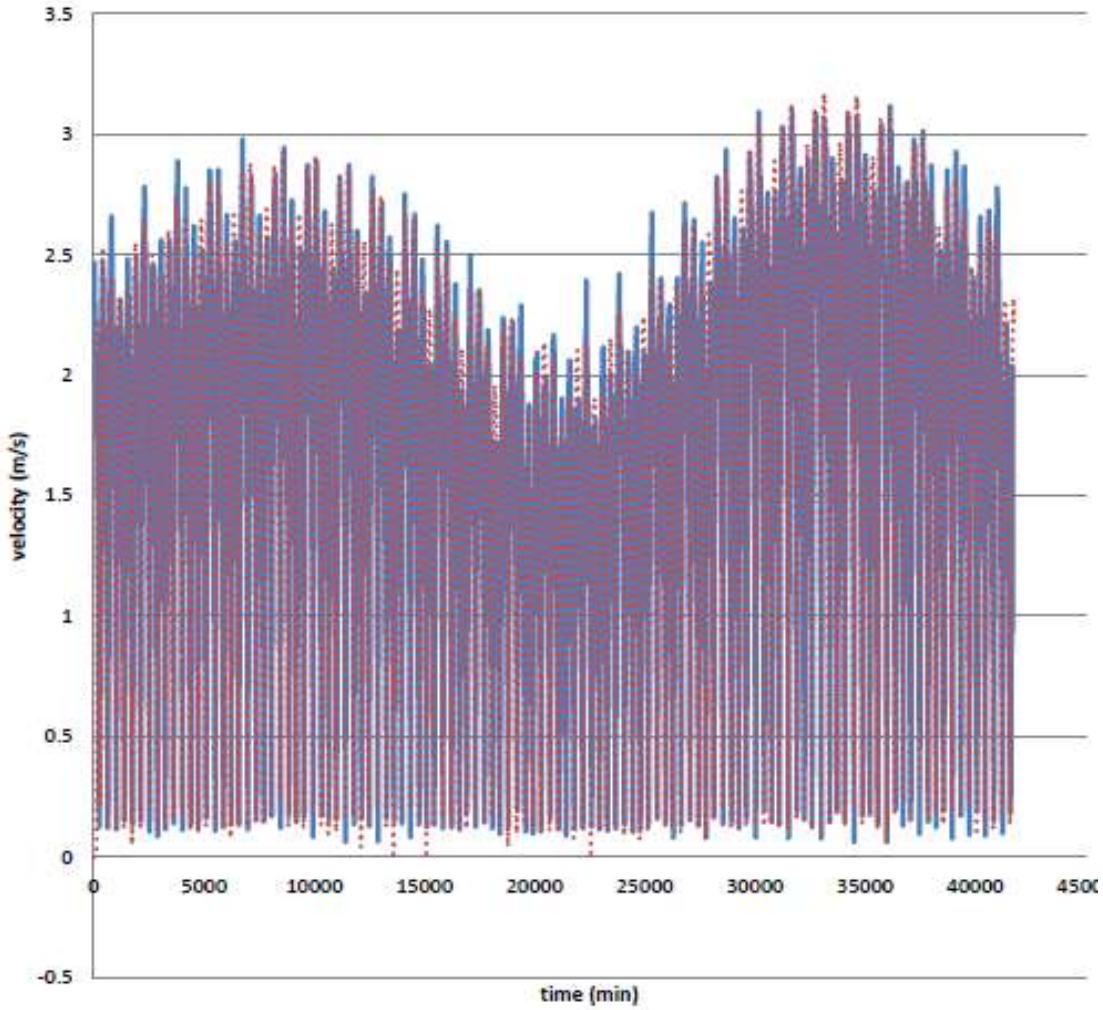


Comparison of modeled and measured water level at Nikiski (measured, —— , modeled ------)



Comparison of modeled and measured depth-averaged velocity at Nikiski

(measured, —— , modeled - - - - -)



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.

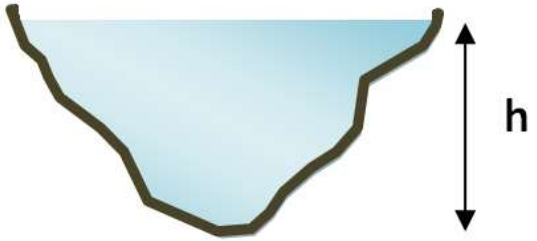
Background – the Manning Equation

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

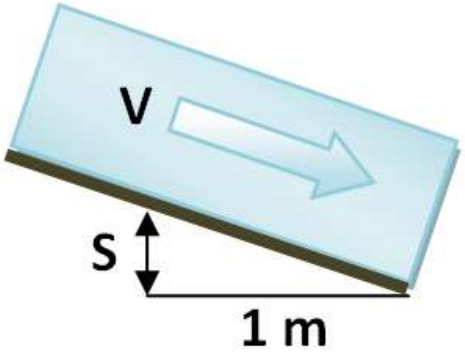
V	cross-sectional average velocity
n	Manning's roughness coefficient
R_h	hydraulic radius = A/P (in wide channels, approximated by water depth: $R_h \approx h$)
S	bottom slope

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:



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

- $$\frac{P_{1t}}{\gamma}+\frac{V_{1t}^2}{2g}+z_1=\frac{P_{2t}}{\gamma}+\frac{V_{2t}^2}{2g}+z_2+h_{Lt}+h_p$$
- 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:

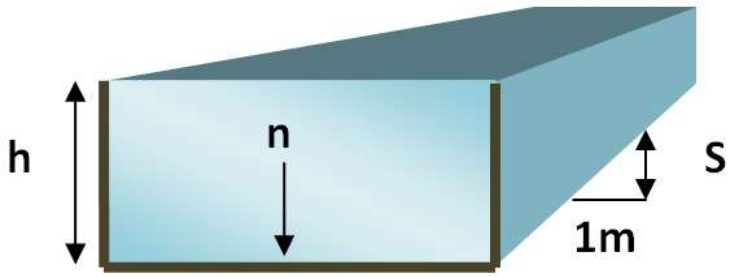
$$V_t = \frac{h}{h_t} V$$

$$h_p < \Delta z$$

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

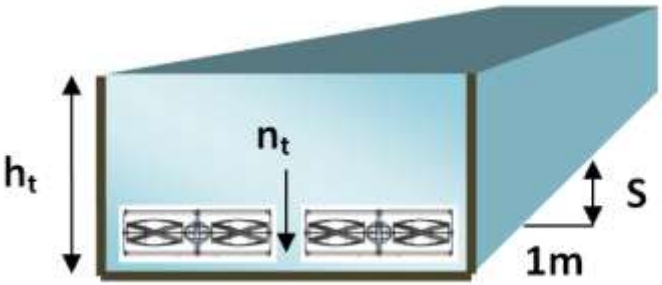
Δz – elevation change over the channel length

No turbines:



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

Turbines are uniformly distributed:



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

More findings:

$$n_t = n\left(b^{1/3} - 0.28263\, b^{-1/3} + 0.139296\right)^{3/5}$$

where:

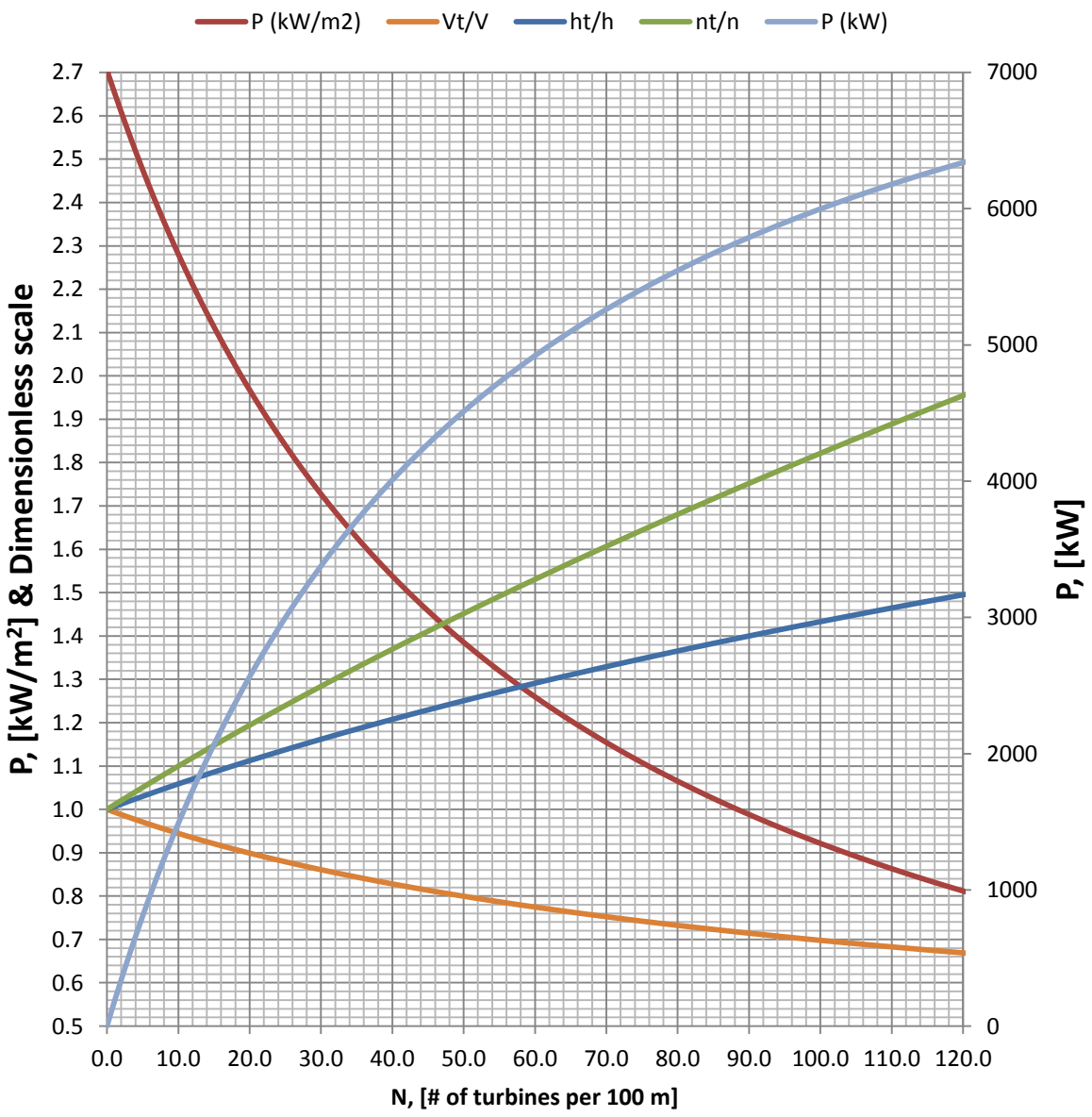
$$b = 0.46088 \cdot a + \left((0.46088 \cdot a + 0.68368)^2 + 0.022578\right)^{1/2} + 0.68368$$

$$a = \left(\frac{3}{4}\,(1+\epsilon)\,\frac{\varepsilon}{n^2 g}\,\frac{NA_r}{wL}\right)h^{1/3}$$

Summary of results – for uniform distribution of devices

Input:

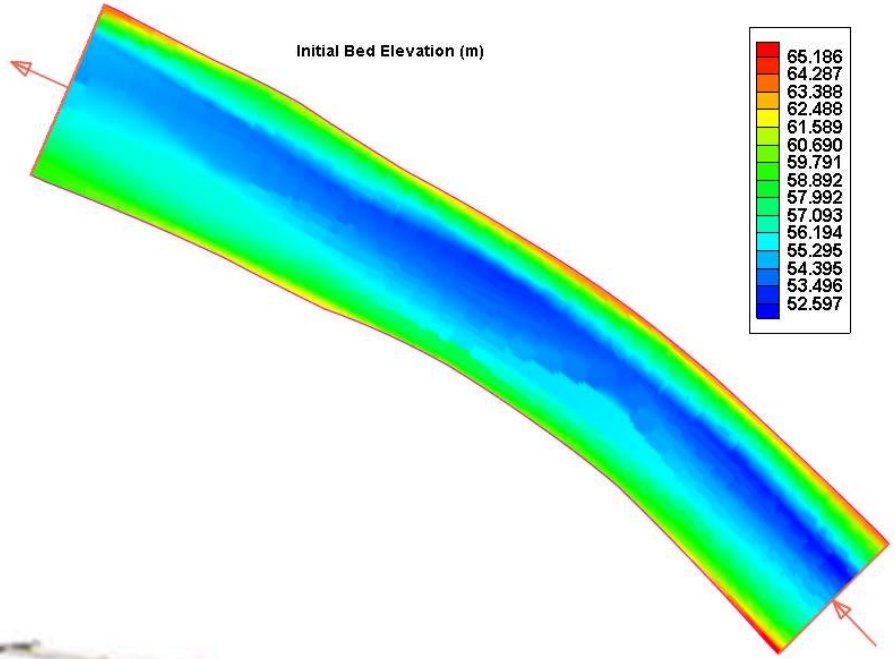
Channel geometry			
Water depth	**h=**	10	m
Width of the channel	**w=**	500	m
Turbines Characteristics			
Efficiency	**ξ=**	30%	
Rotor area	**Ar=**	13	m^2
Flow Characteristics			
Manning's roughness coefficient	**n=**	0.0250	
Slope	**S=**	0.0002	m/m



Application: Red Devil on Kuskokwim River

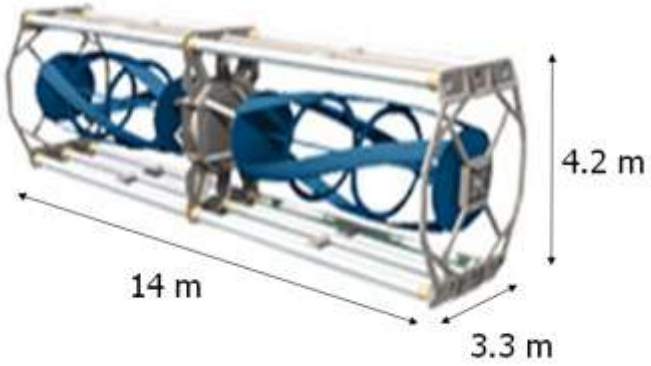
Data:

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



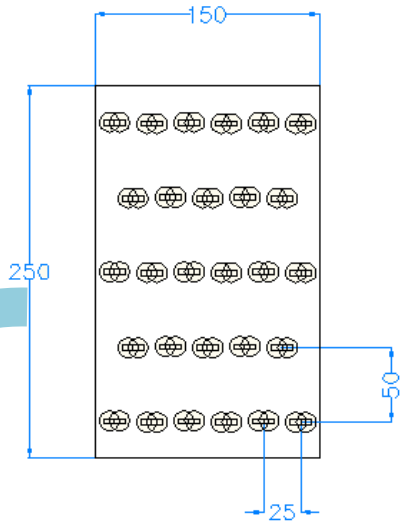
- Uniform turbine distribution

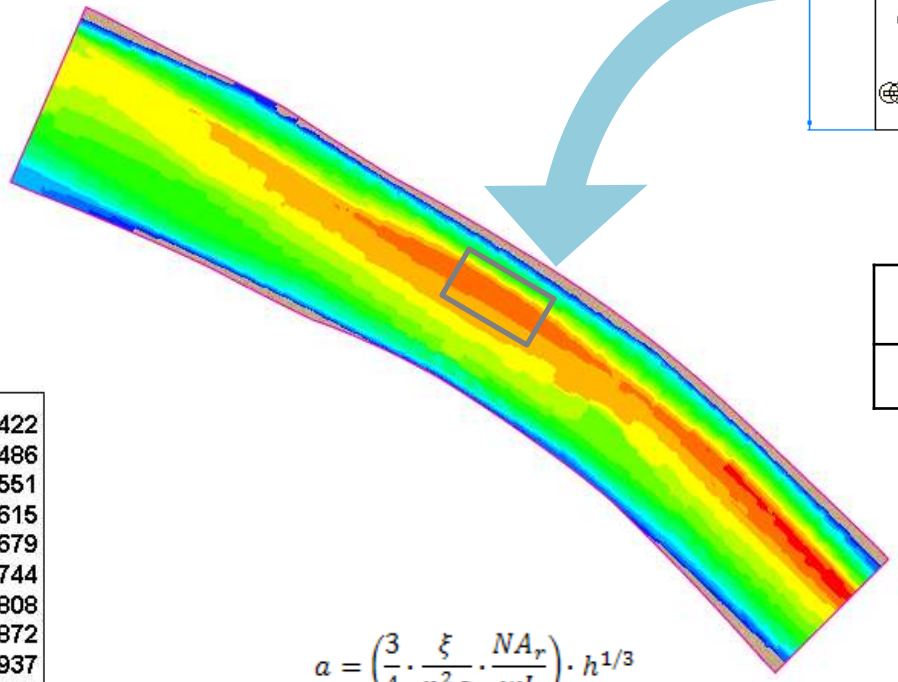
Turbines dimensions:



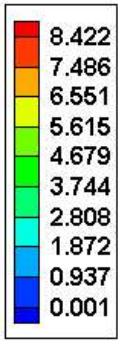
Turbines Location

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





Water depth (m):



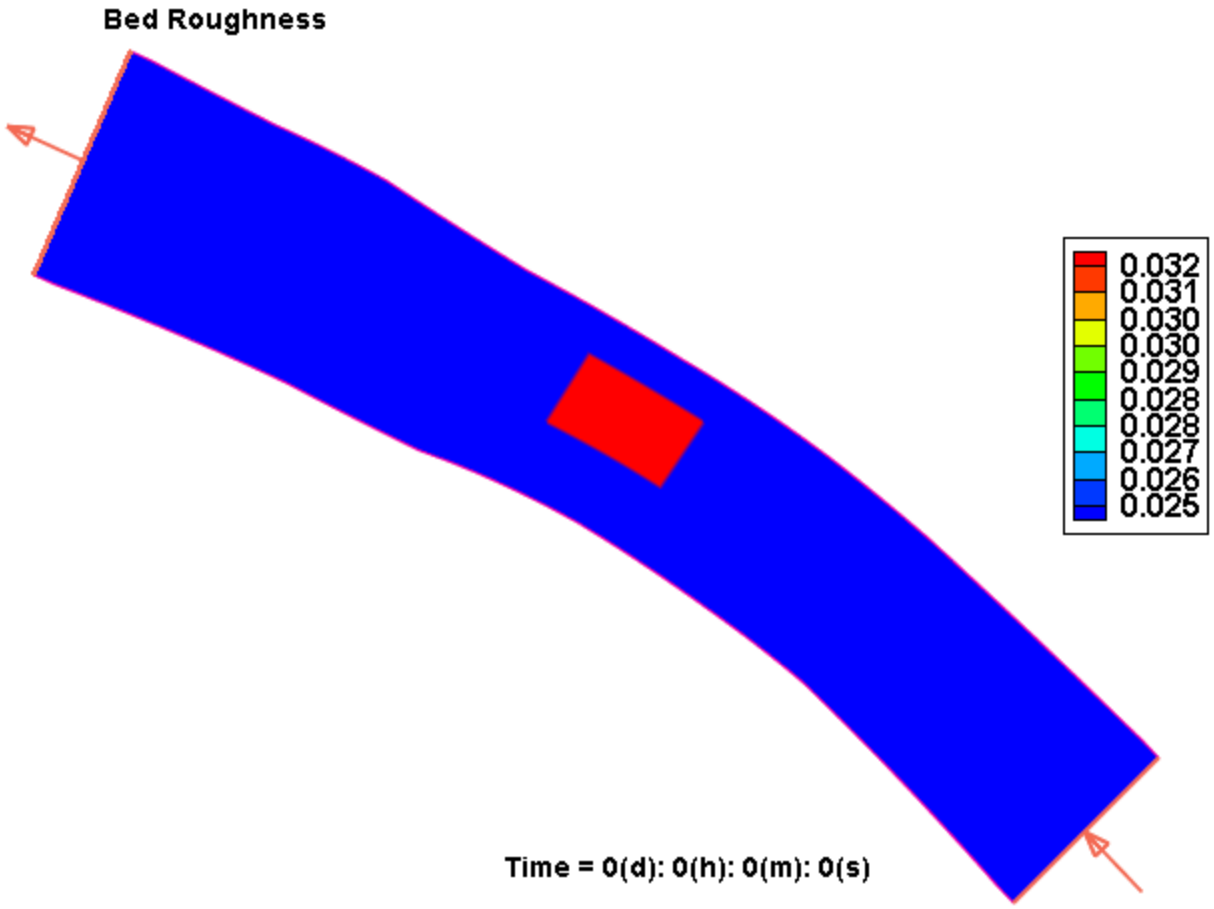
$$a = \left(\frac{3}{4} \cdot \frac{\xi}{n^2 g} \cdot \frac{NA_r}{wL}\right) \cdot h^{1/3}$$

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

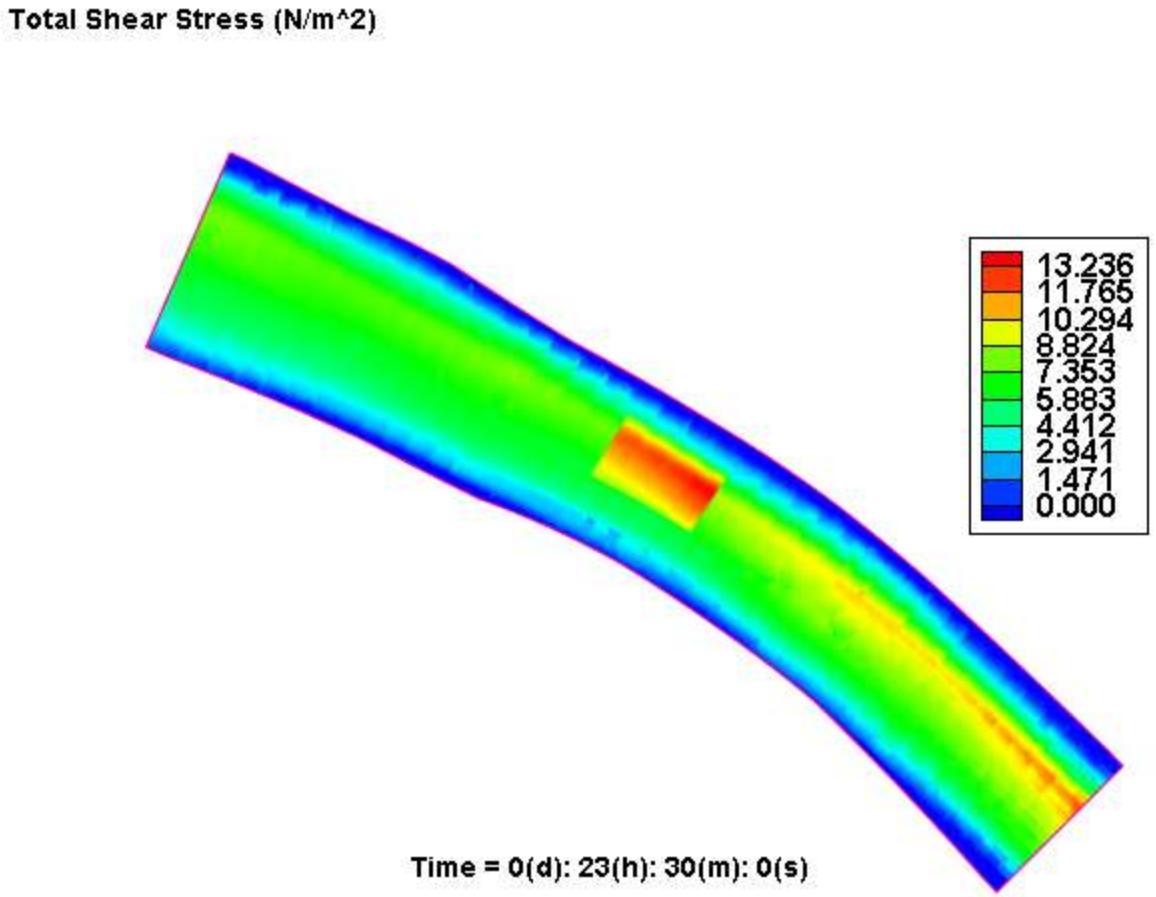
Number of turbines	n_t *
28	**0.0320**

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

Initial Conditions



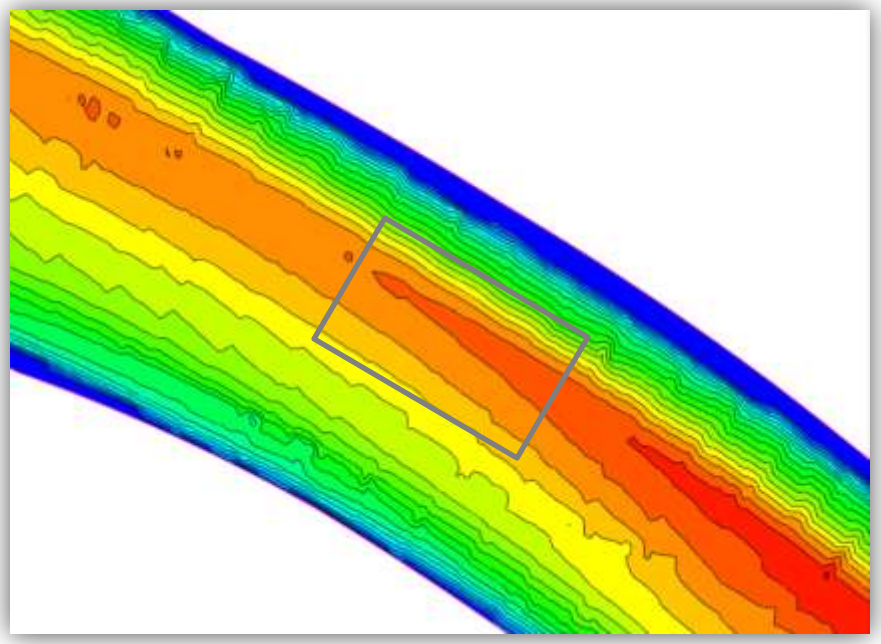
Total Shear Stress (N/m^2)

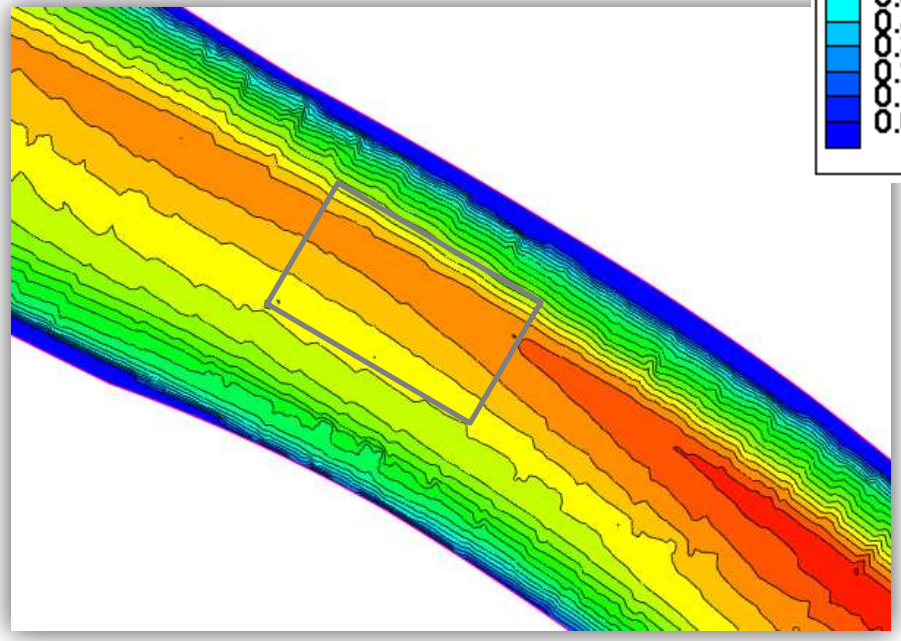


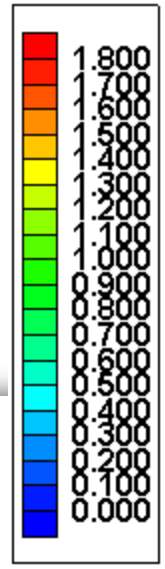
Results: Velocity Magnitude (m/s)

Original Conditions

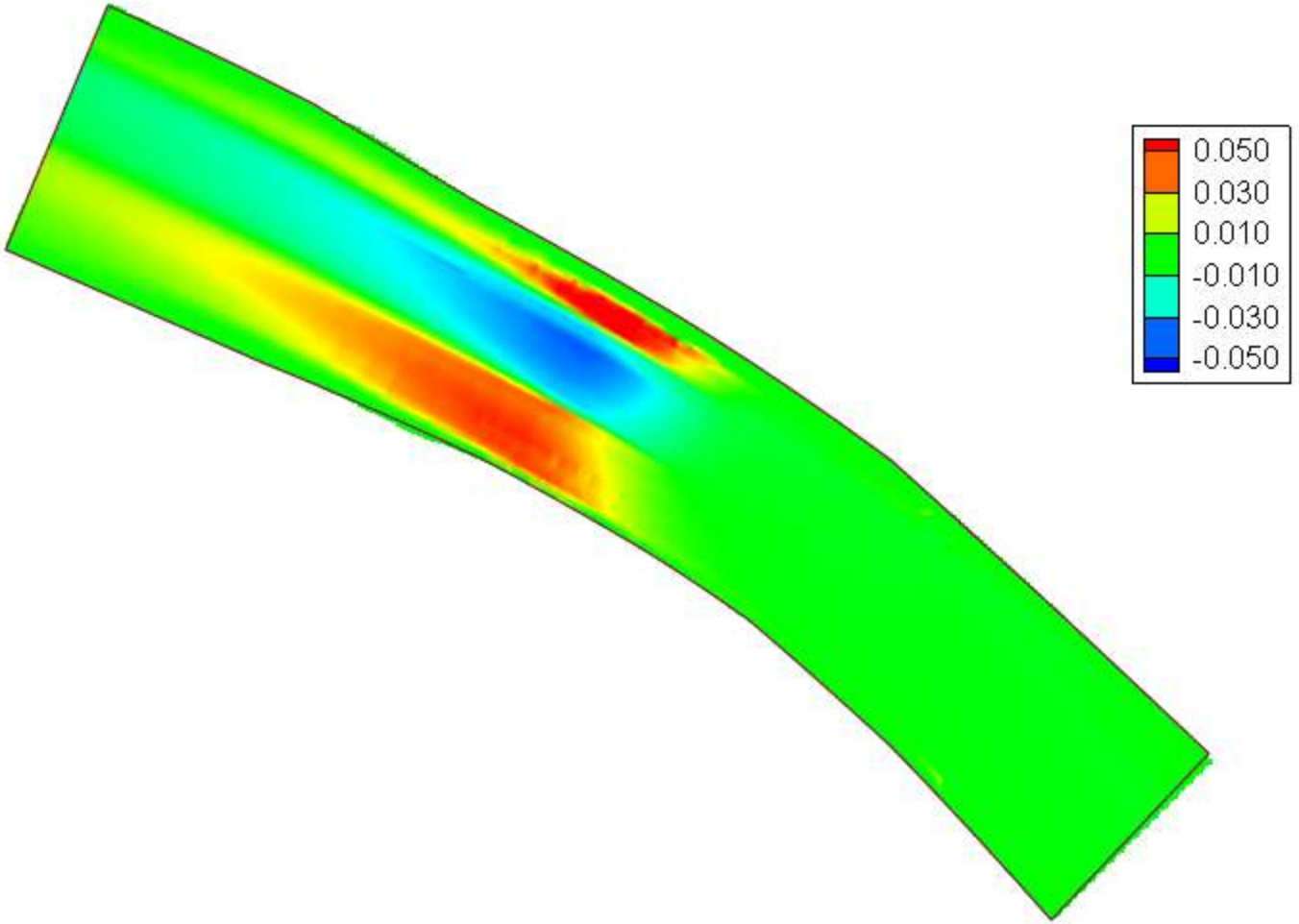
Case with Turbines



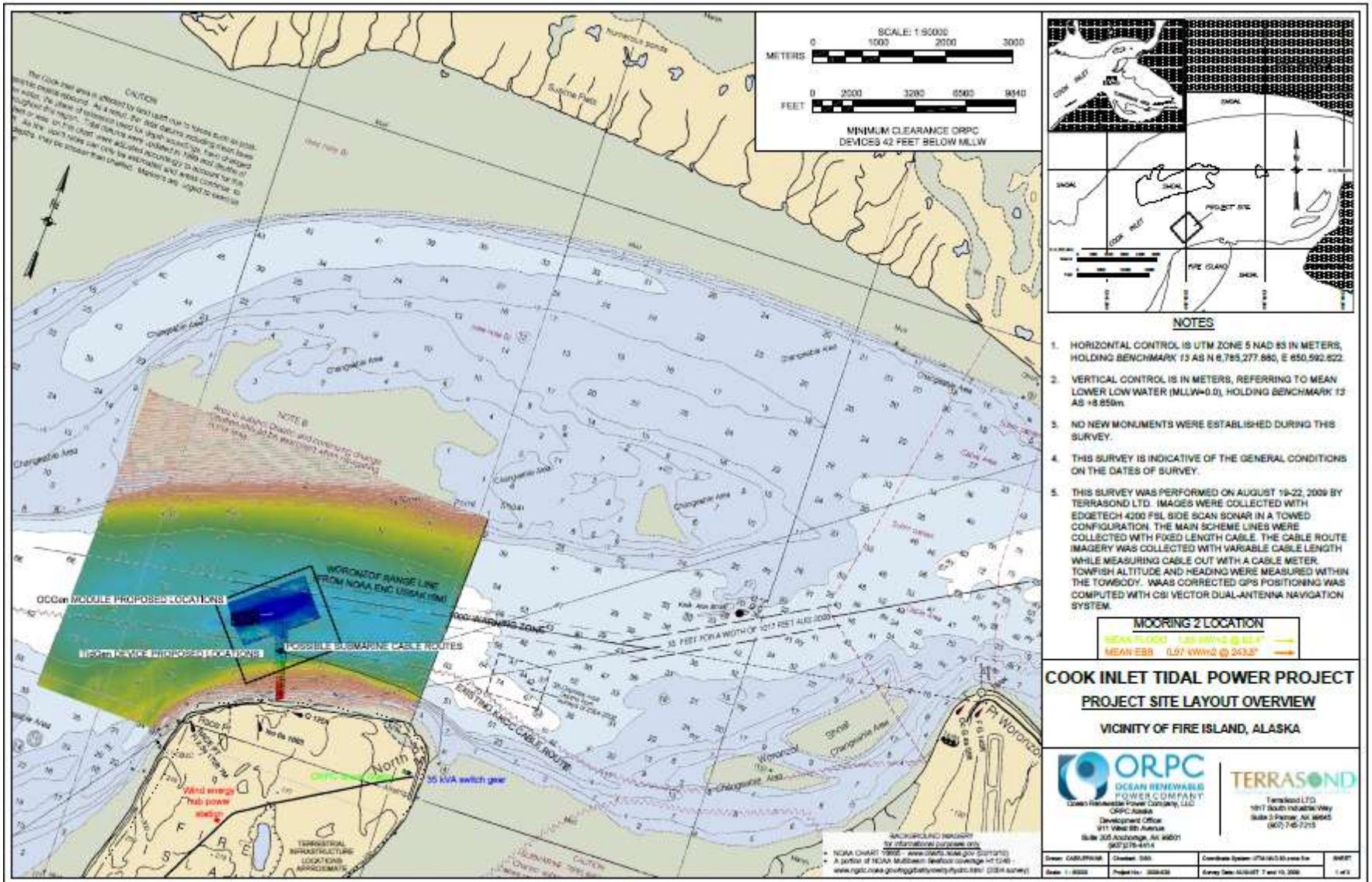




Change in Velocity (m/s)



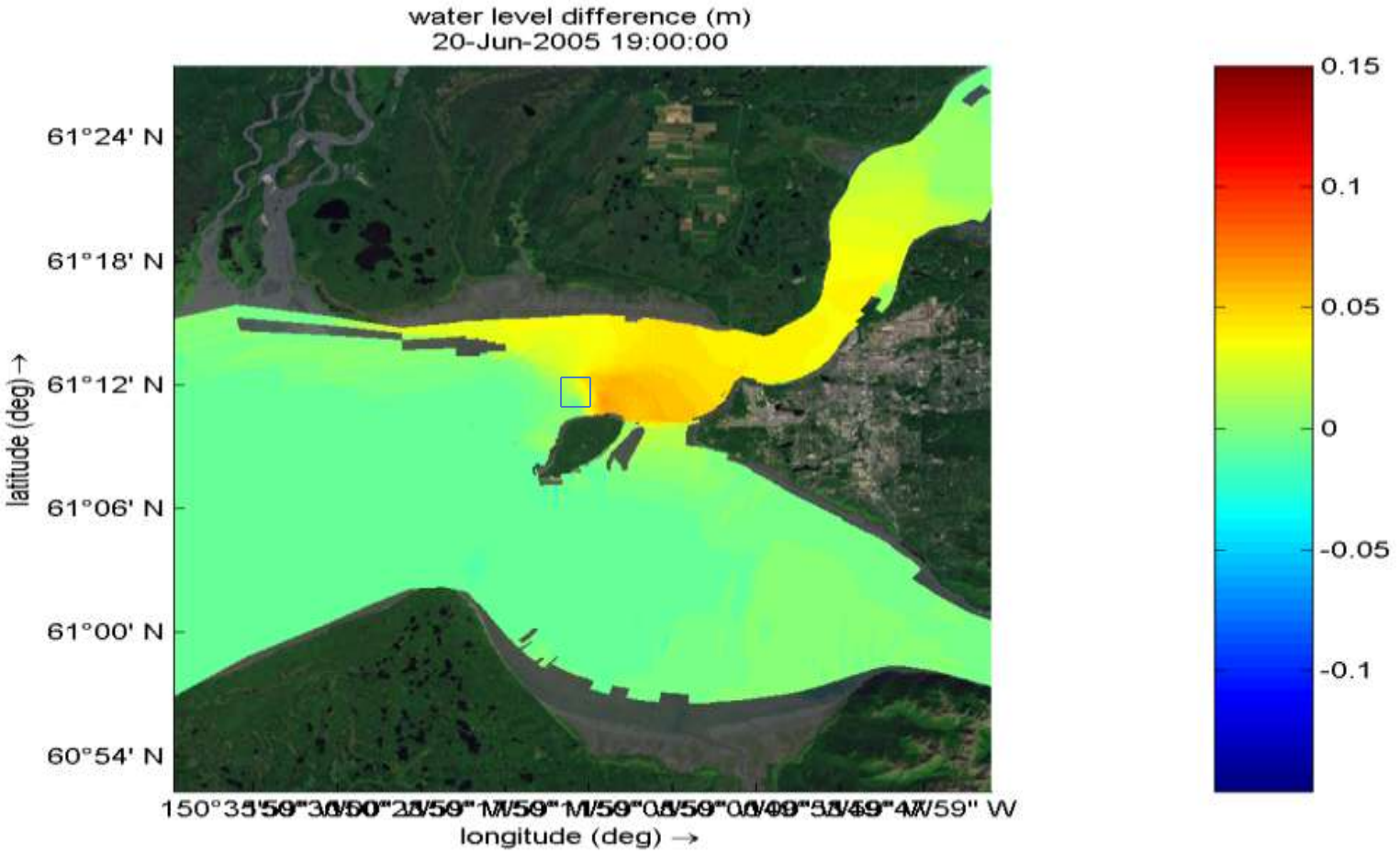
Application : assessment of ORPC HK deployment plan at Fire Island



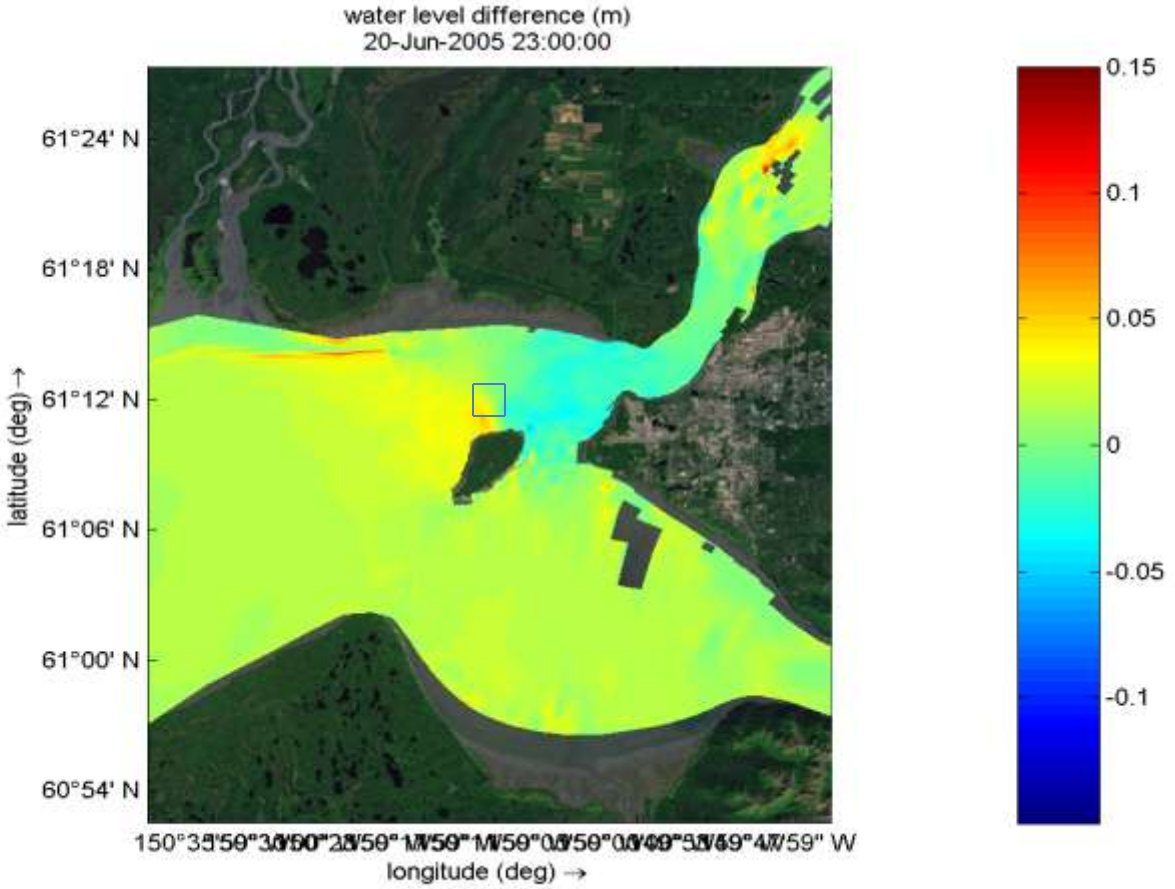
Estimation of potential HK impacts associated with virtual deployment by Fire Island

- 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

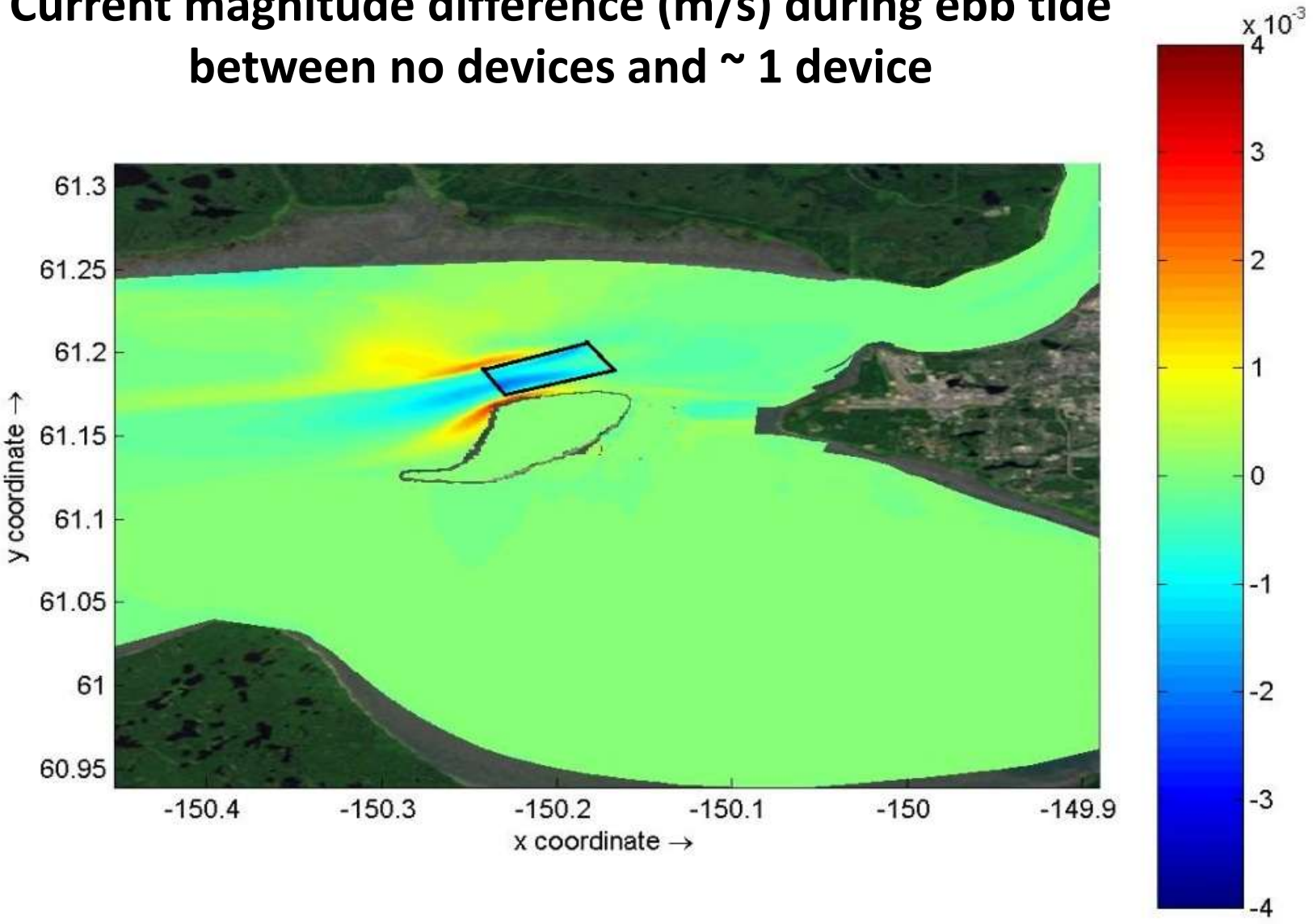
Snapshot of water level difference (assuming 134 devices, ebb tide



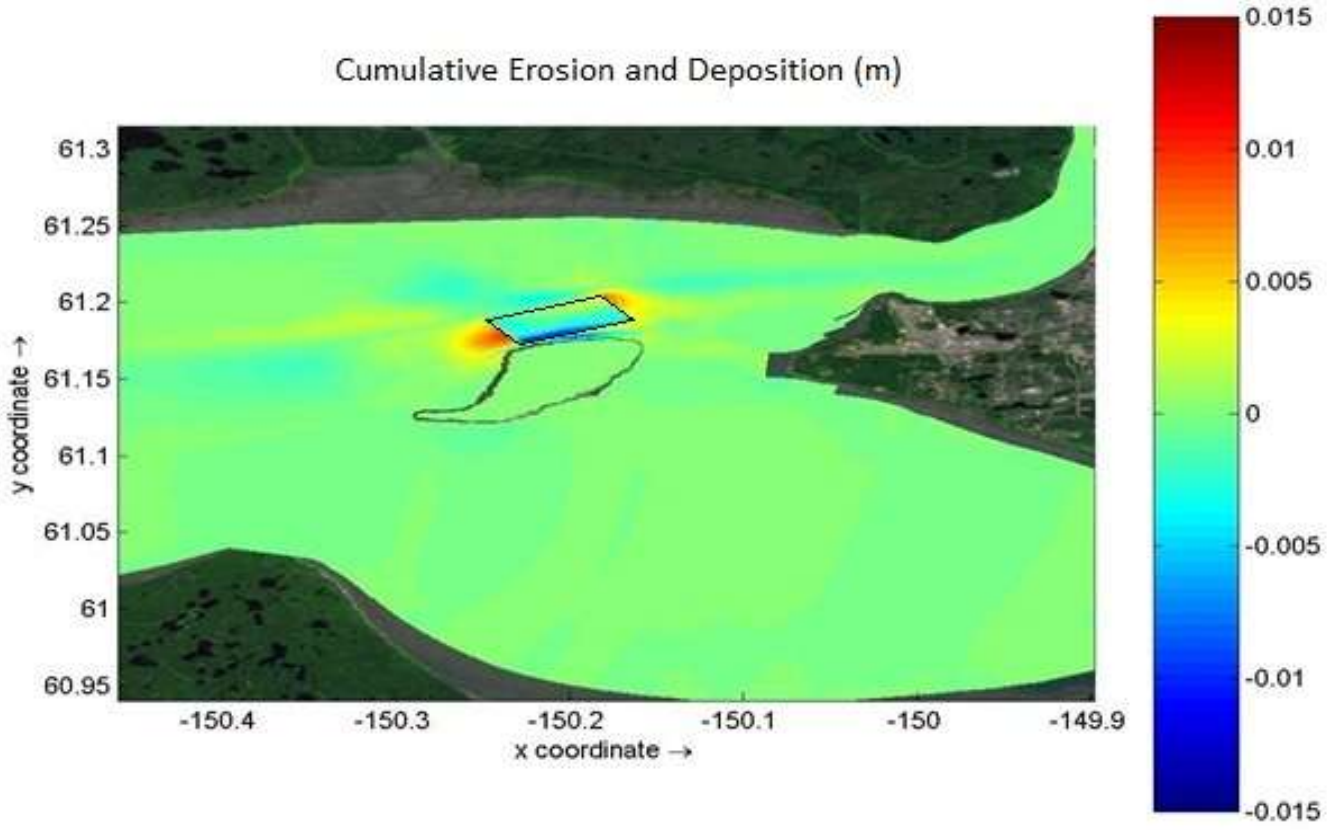
Snapshot of water level difference (assuming 134 devices, flood tide



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

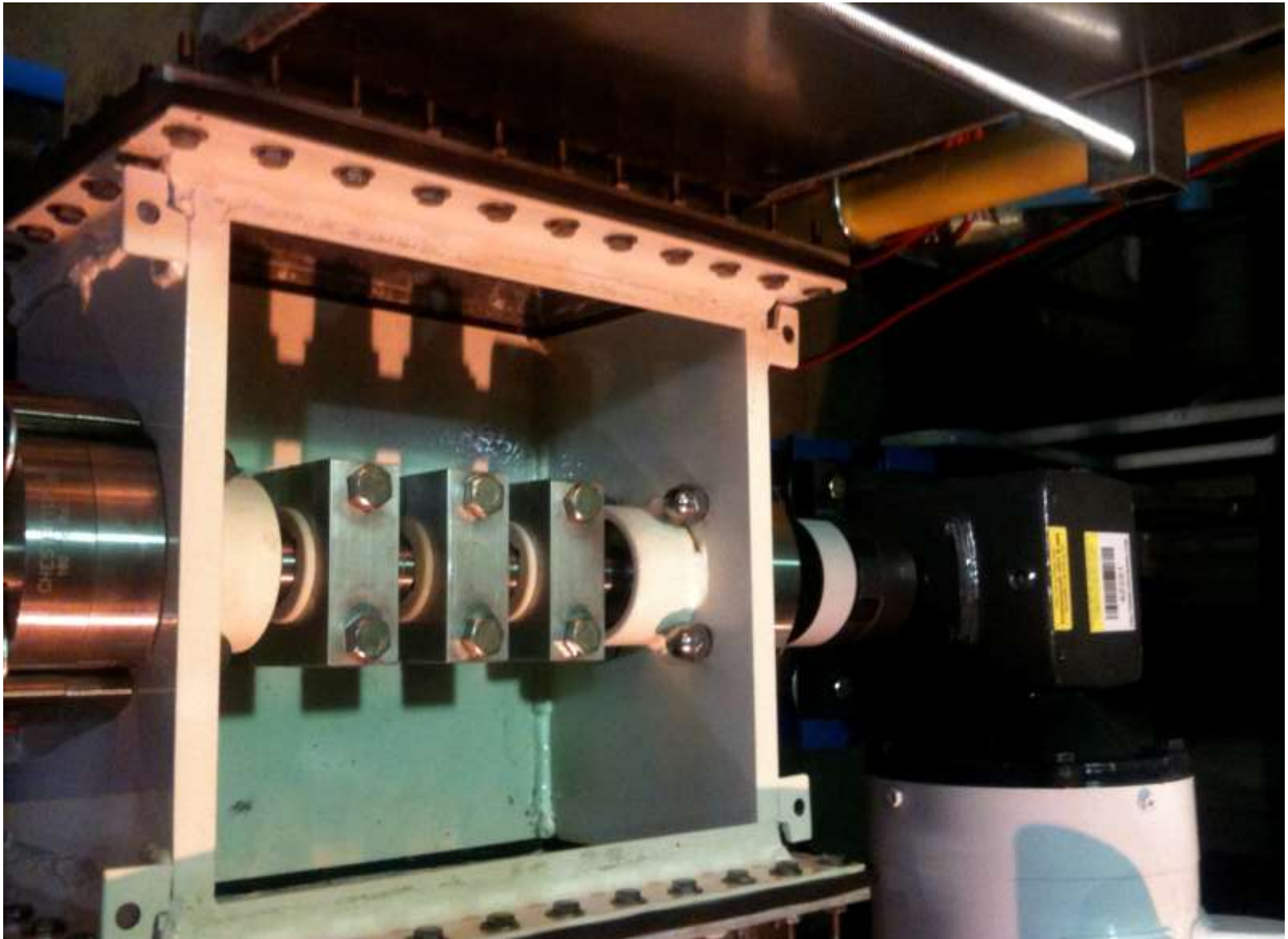


Calculated cumulative erosion and deposition difference (no devices vs. ~ 1 devices) over 30 day period assuming 0.2 mm sand.



UAA Flume for Abrasion Testing of Critical Device Components

Close up of test section including bearings and seals



Future work – HK device impacts

- 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

Future work – Abrasion Testing

- Effect of different particle sizes
- Effect of different particle concentrations
- Effect of water temperature
- Abrasion resistance of turbine vane materials

Thank you!

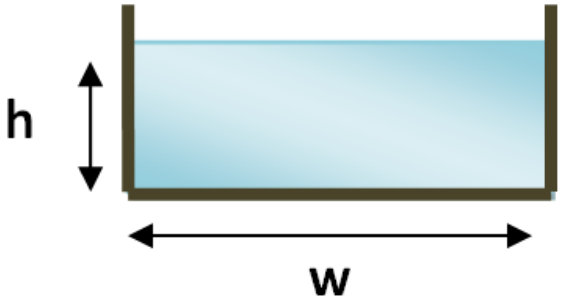
- Alaska Energy Authority
- Department of Energy
- Electrical Power Research Institute.
- Ocean Renewable Power Corporation
- University of Alaska Chancellor's Fund
- Kenai Borough

Approach to determining effective roughness accounting for presence of HK devices

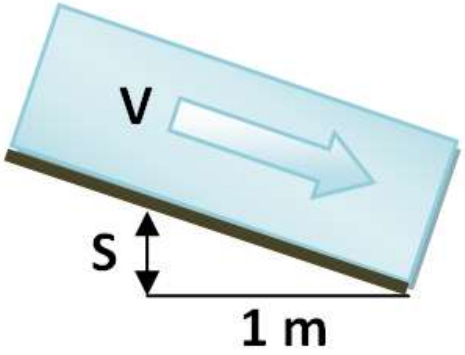
1. Assume:
   - simplified geometry:

     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:



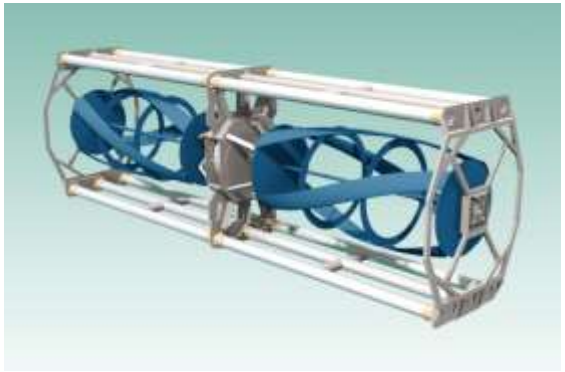
Side View:



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

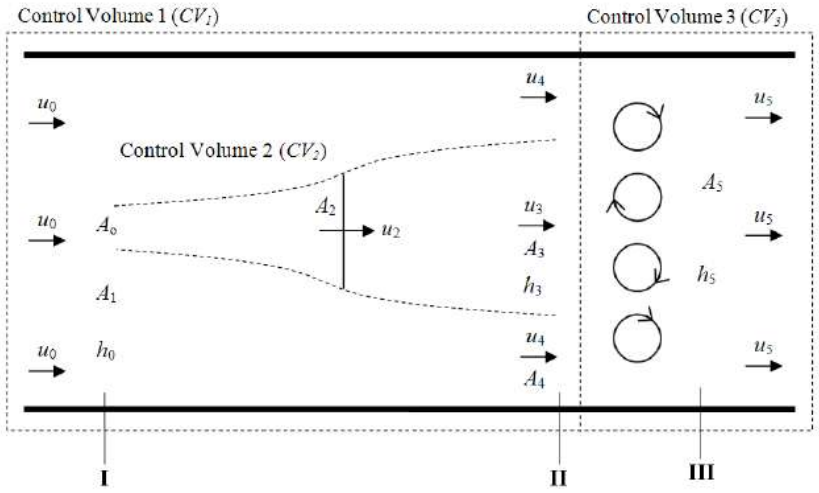
V average fluid flow velocity in the channel

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

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

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

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

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):

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

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

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

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

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 %):

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

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

$where:$

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

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

Numerical Models

Case 1: Original conditions of the channel.

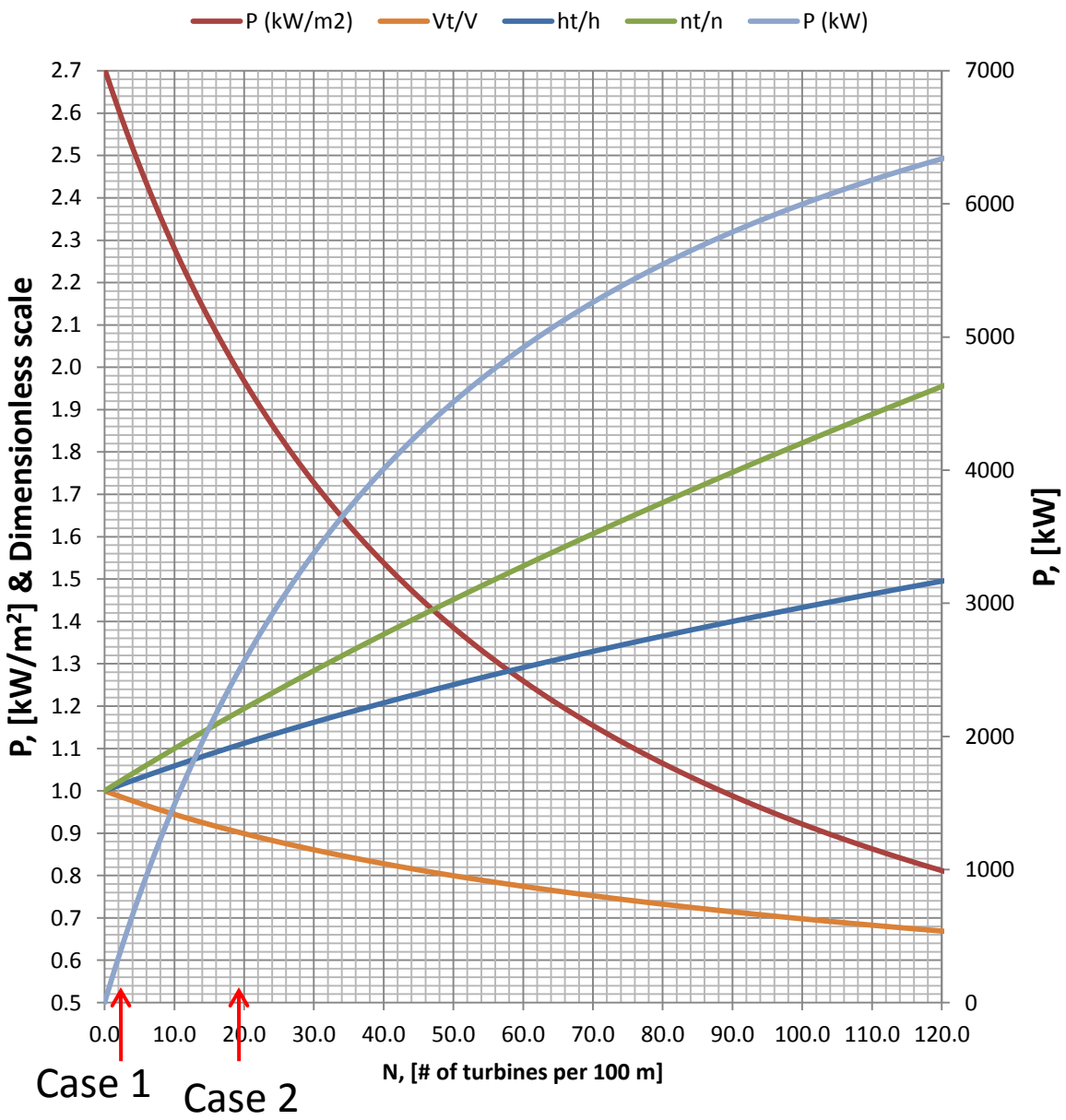
Case 2: Turbines are uniformly distributed on the bottom of the channel.

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	m^2
Flow Characteristics			
Manning's roughness coefficient	**n=**	0.0250	
Slope	**S=**	0.0002	m/m



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

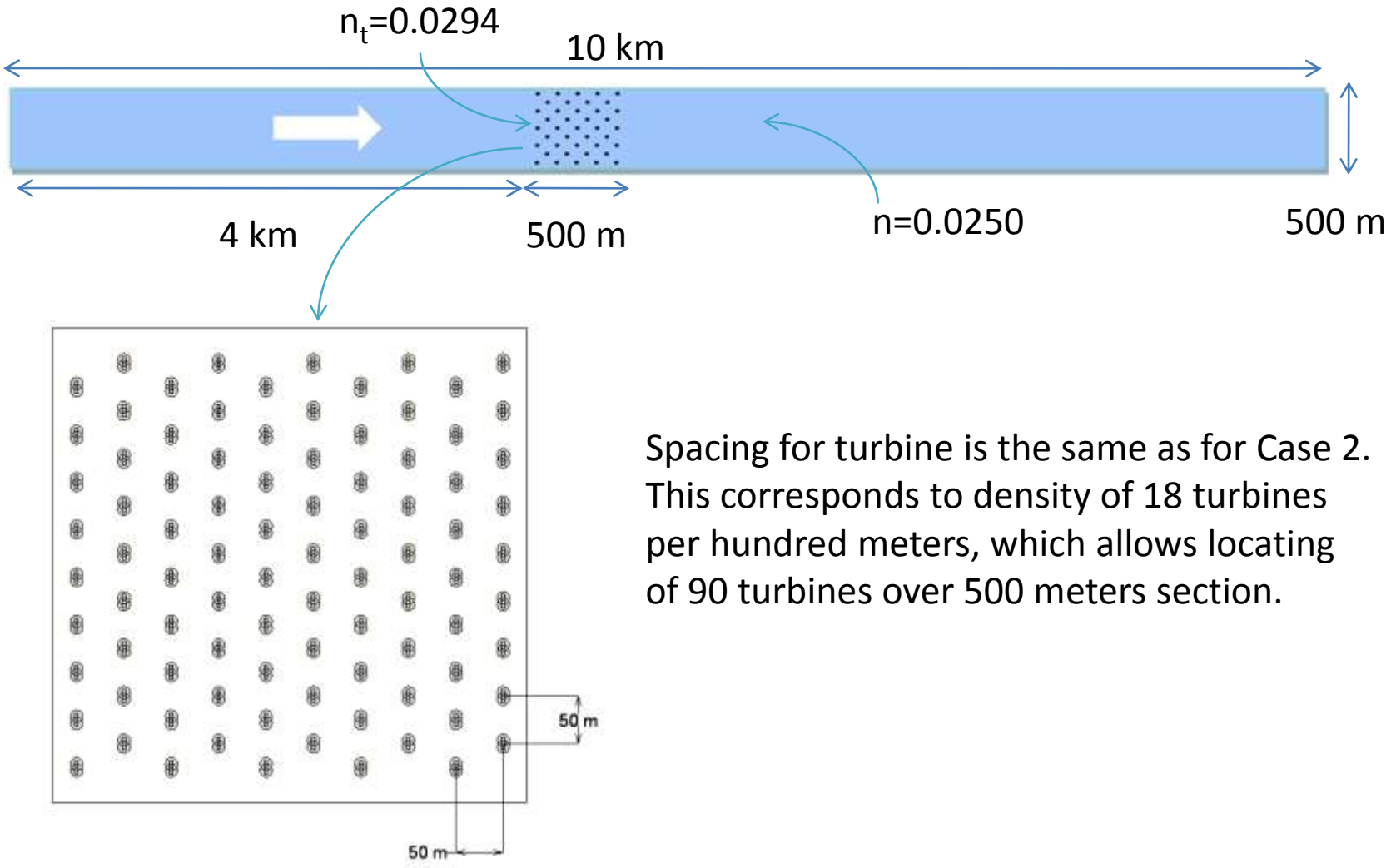
ε=.02

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

Discrepancy of the Estimated Results and ISIS Outputs:

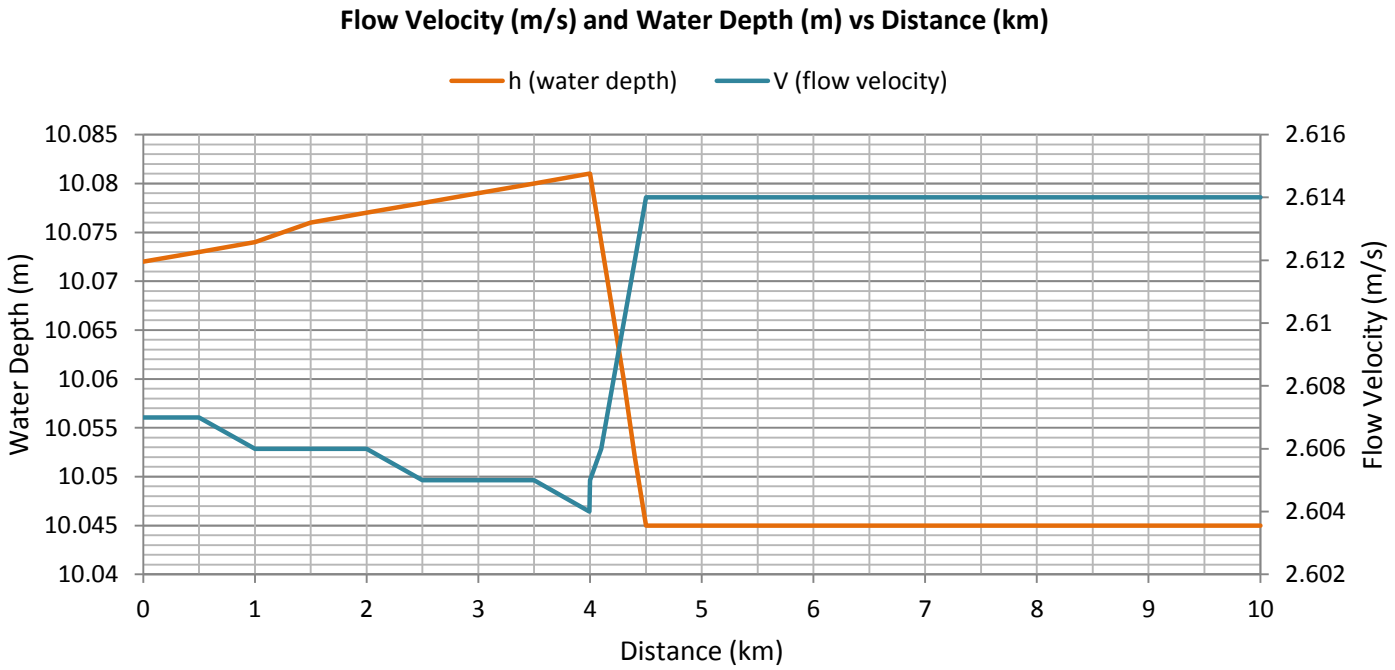
	Parameter	**Case 1**	**Case 2**
h (m)	ISIS Outputs	10.045	10.984
	Estimated results	10.000	11.020
	Discrepancy	**0.45%**	**0.33%**
V (m/s)	ISIS Outputs	2.614	2.390
	Estimated results	2.626	2.383
	Discrepancy	**0.46%**	**0.29%**

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



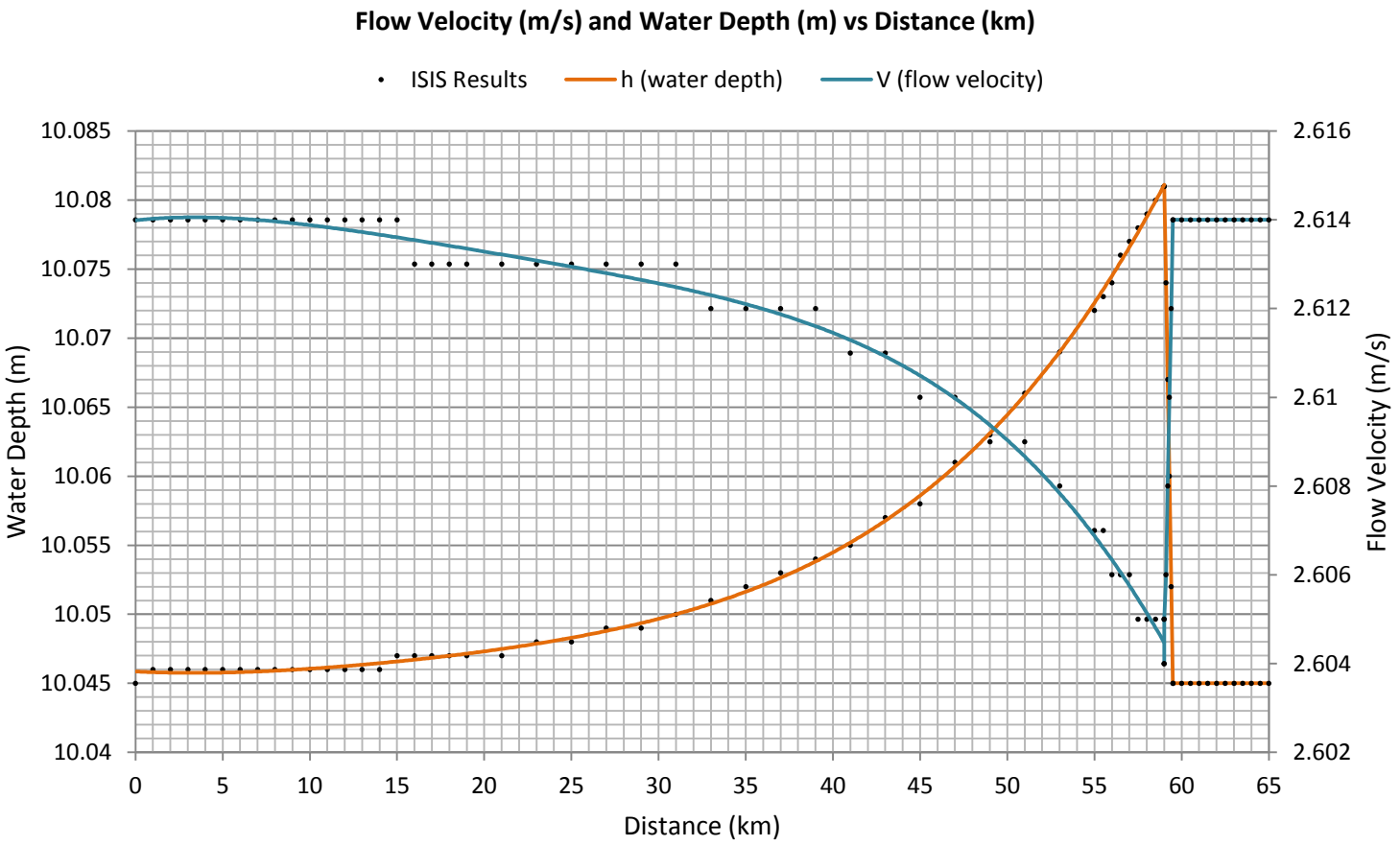
Spacing for turbine is the same as for Case 2. This corresponds to density of 18 turbines per hundred meters, which allows locating of 90 turbines over 500 meters section.

Case 3: Model Results



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

Further Investigation

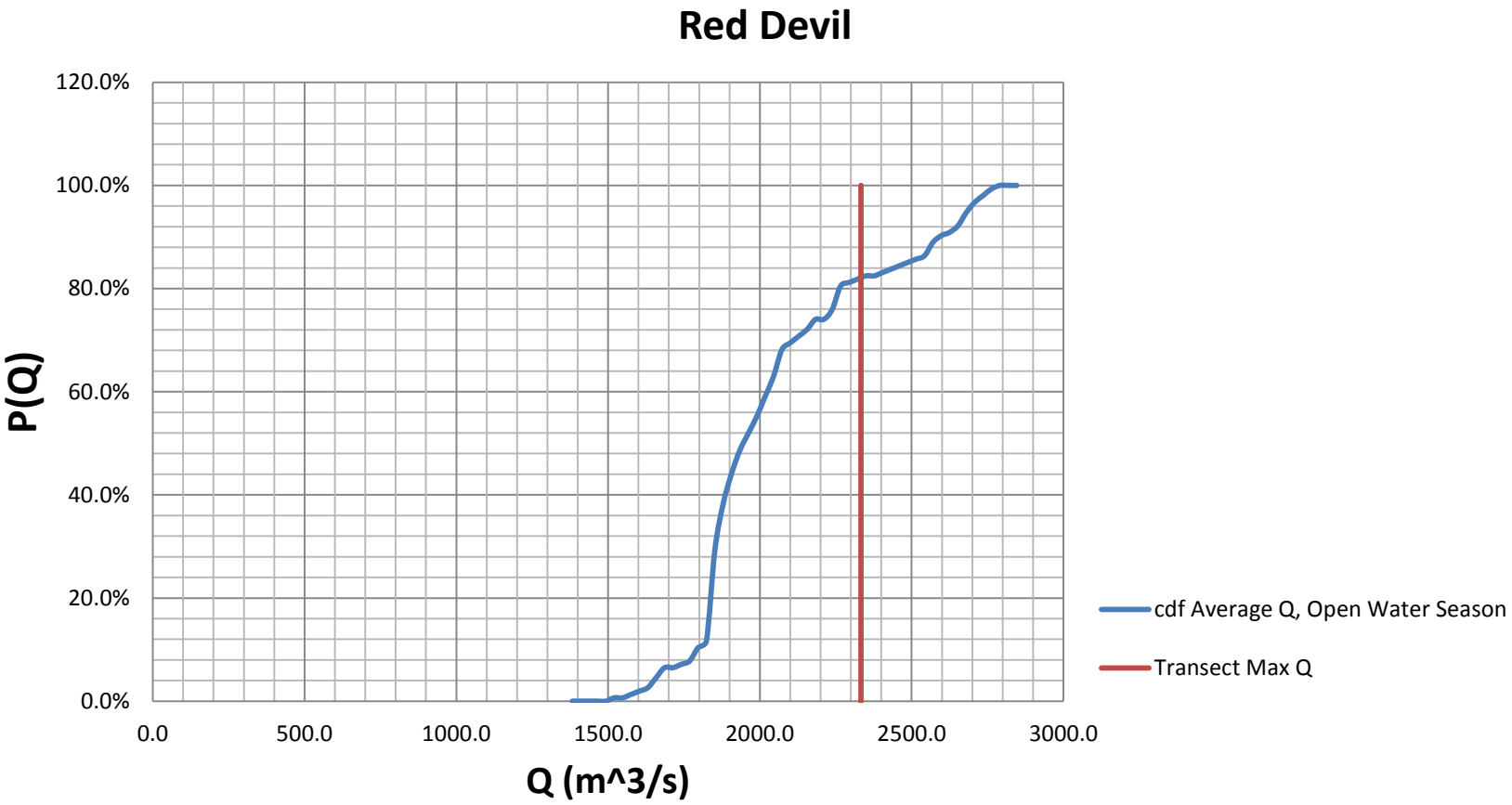


Summary: HK impacts

- 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)

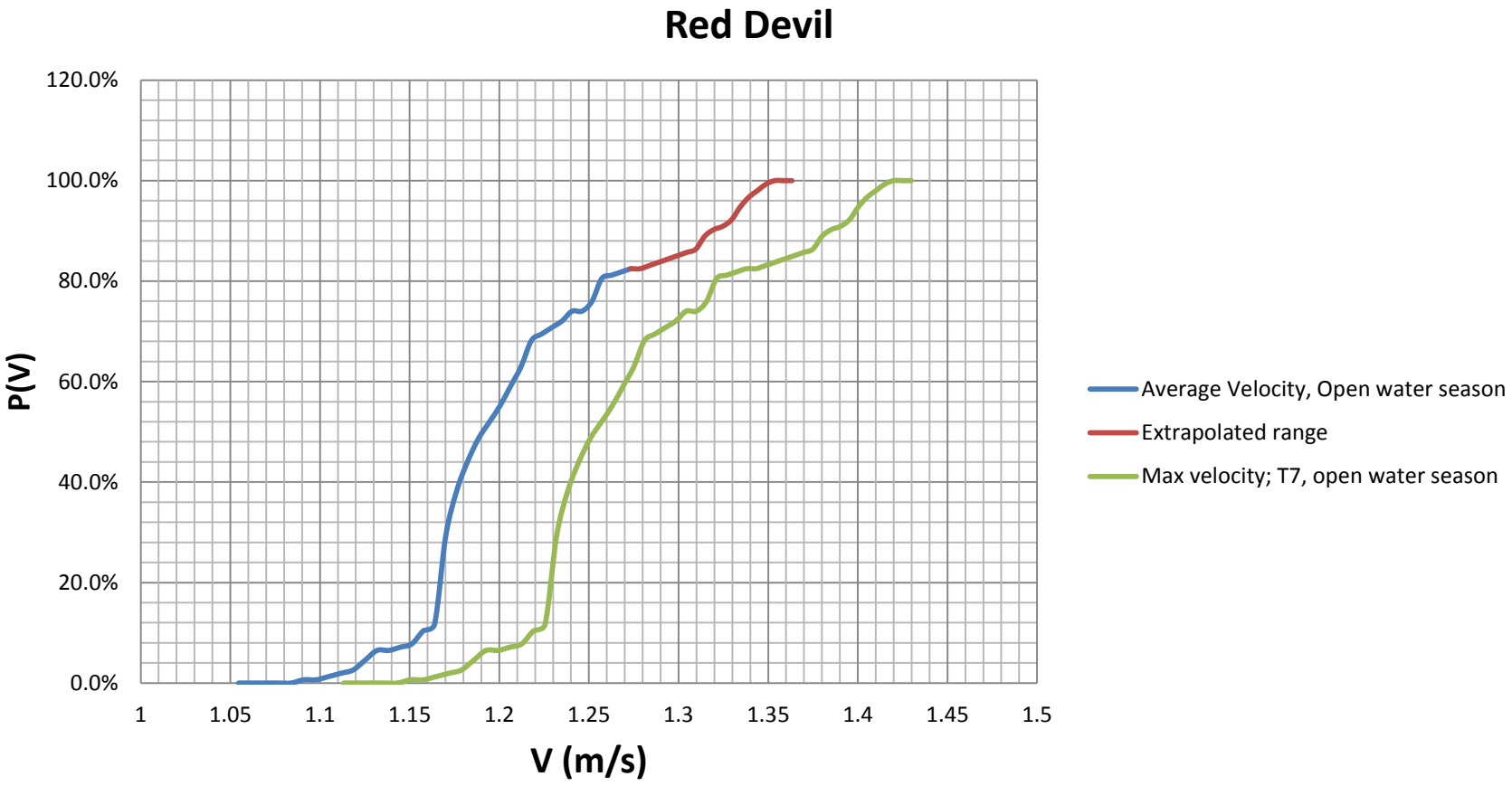
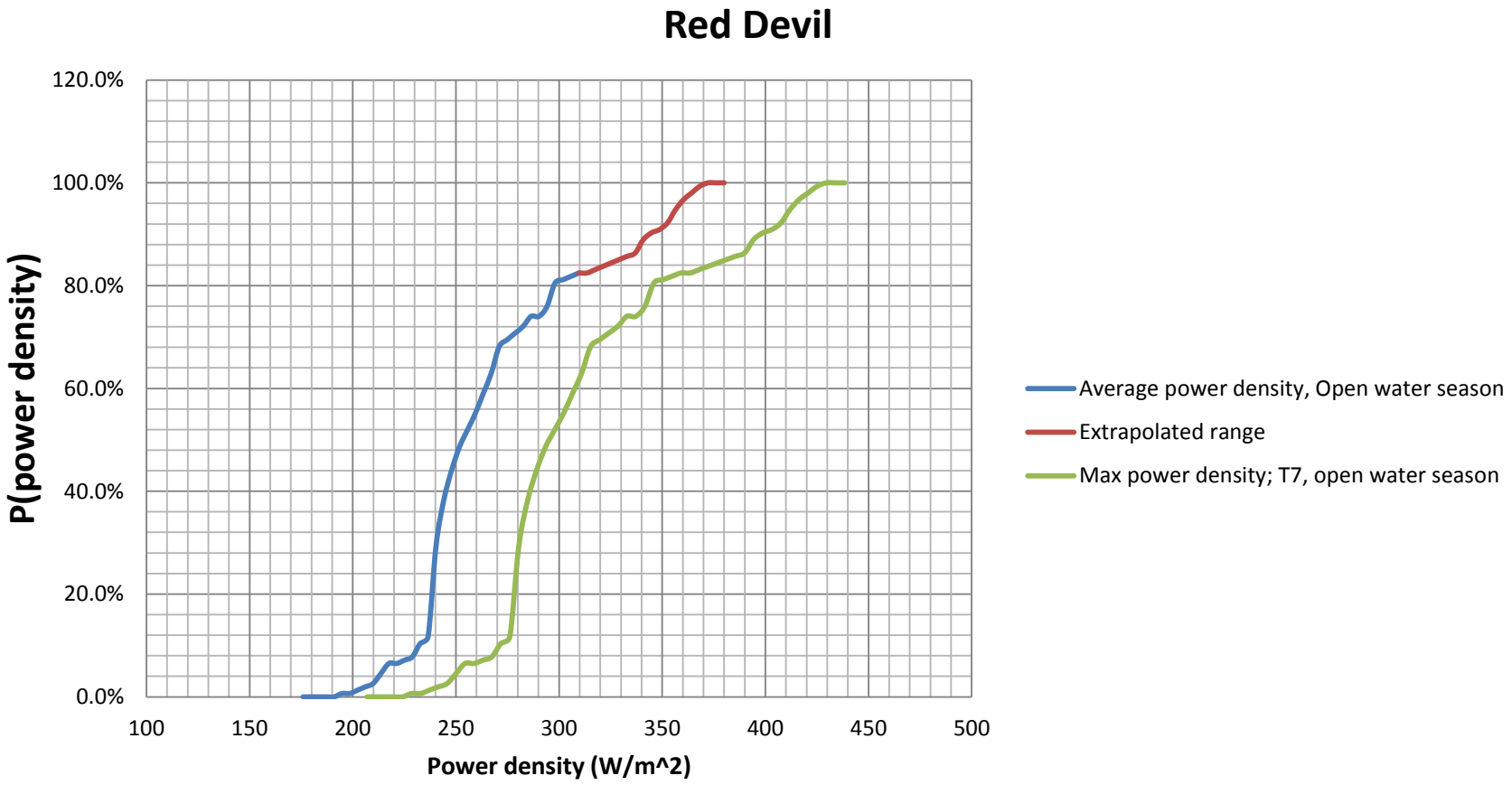
Determination of CDF of flow rate

- at a given site based on long term USGS data and using gage factor method



Determination of CDF of velocity

- at a given site based on long term USGS data and Manning Eq.



Determination of CDF of power density from velocity