Some Thoughts on Columbia River Tsunami Propagation

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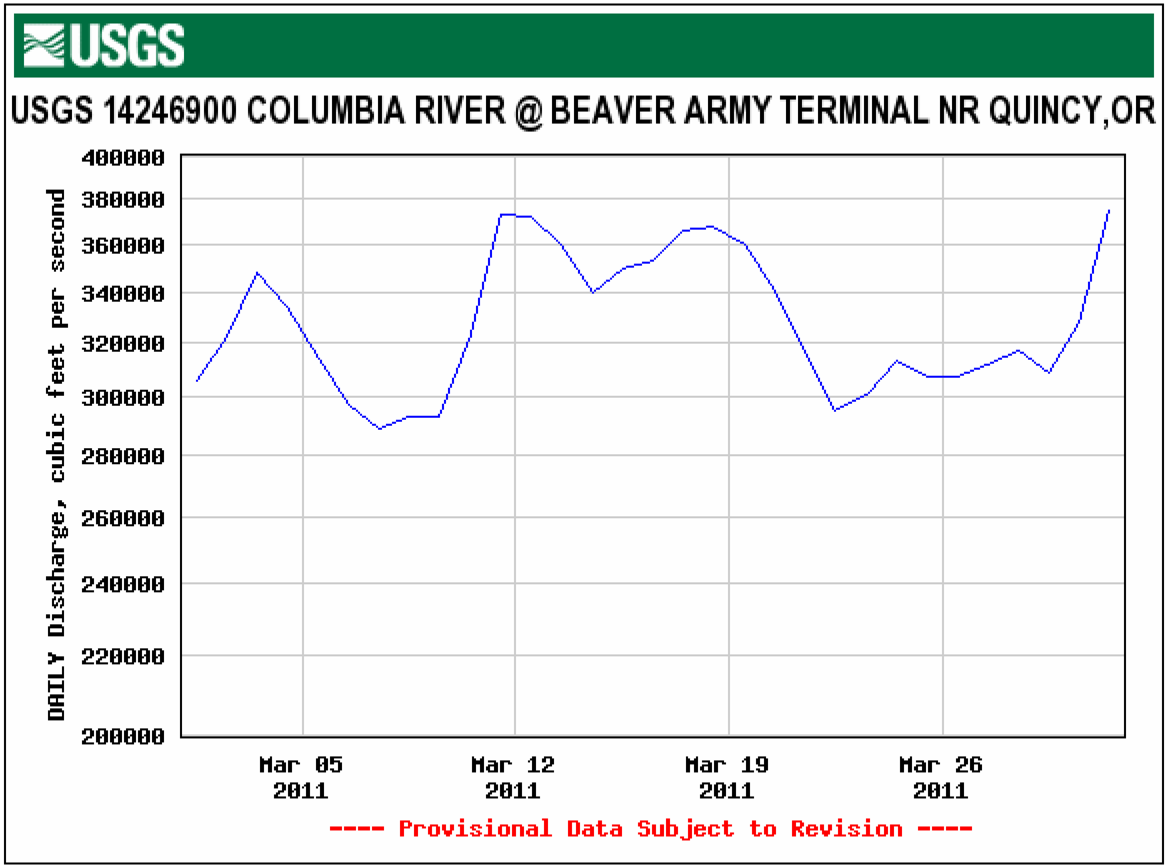
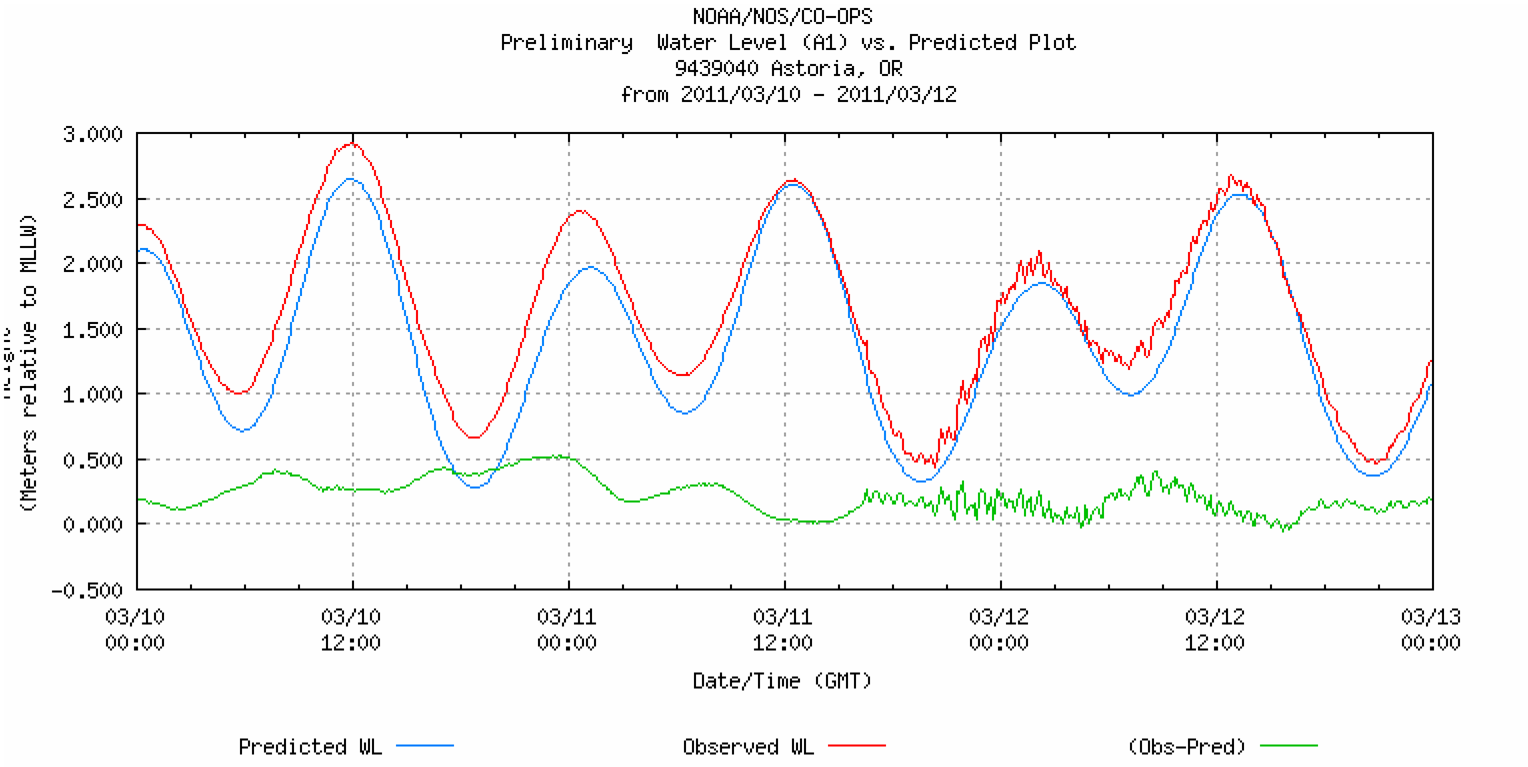
11 March 2011 Tsunami Propagation in the Columbia:

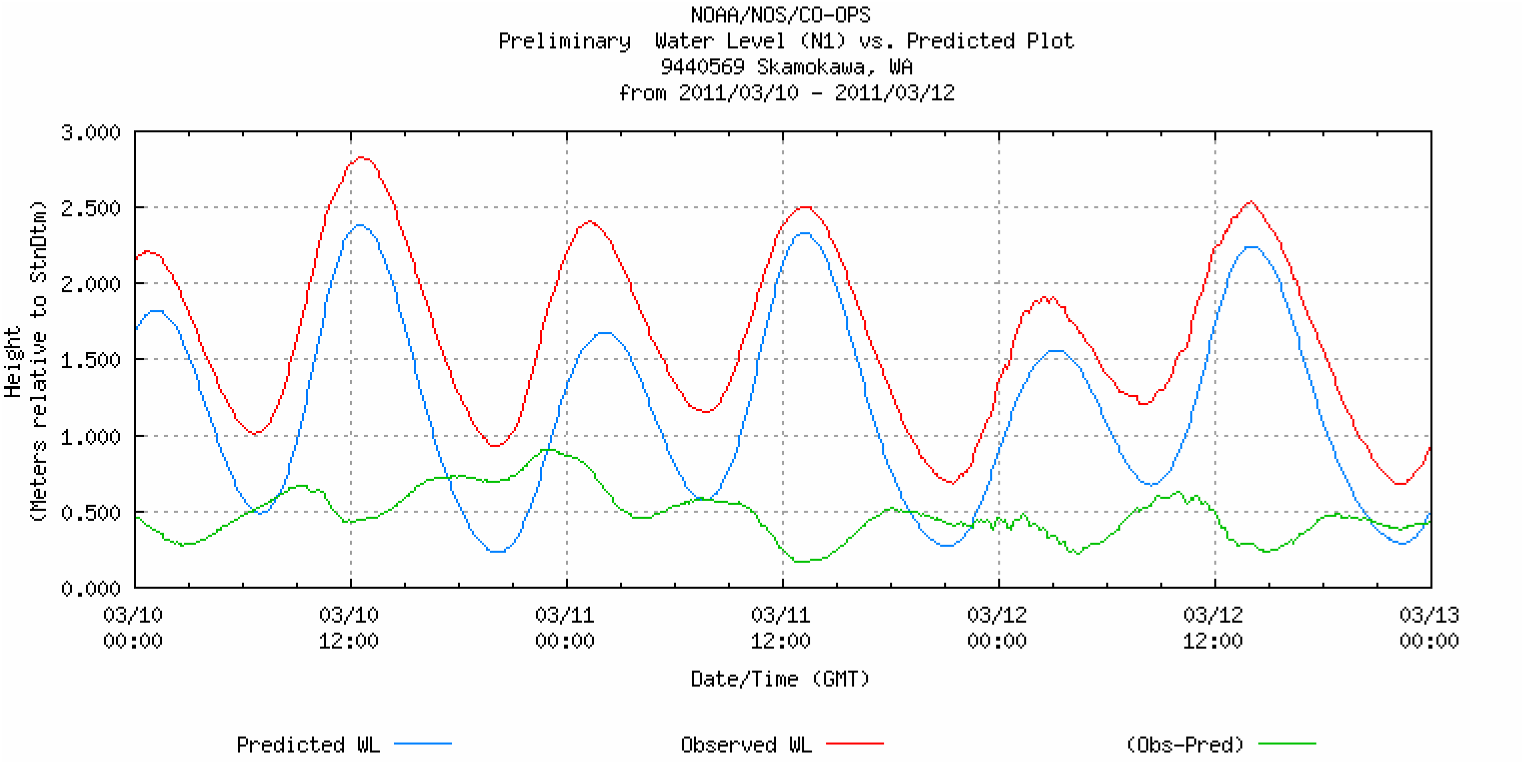
River flow at Beaver:



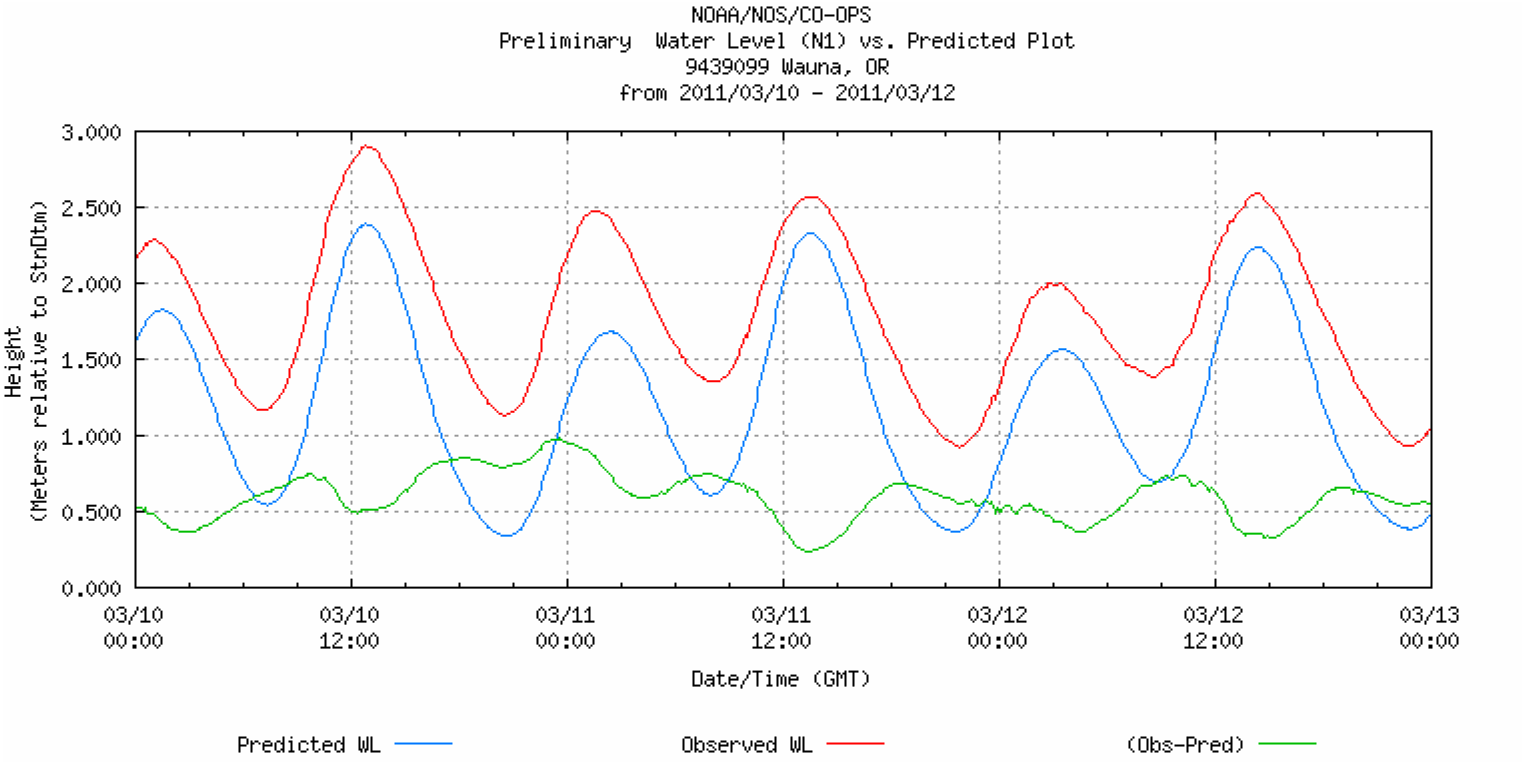
Astoria:


NOAA/NOS/CO-OPS
Preliminary Water Level (A1) vs. Predicted Plot
9439040 Astoria, OR
from 2011/03/10 - 2011/03/12
Height (Meters relative to MLLW)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
-0.500
03/10 00:00
03/10 12:00
03/11 00:00
03/11 12:00
03/12 00:00
03/12 12:00
03/13 00:00
Date/Time (GMT)
Predicted WL
Observed WL
(Obs-Pred)

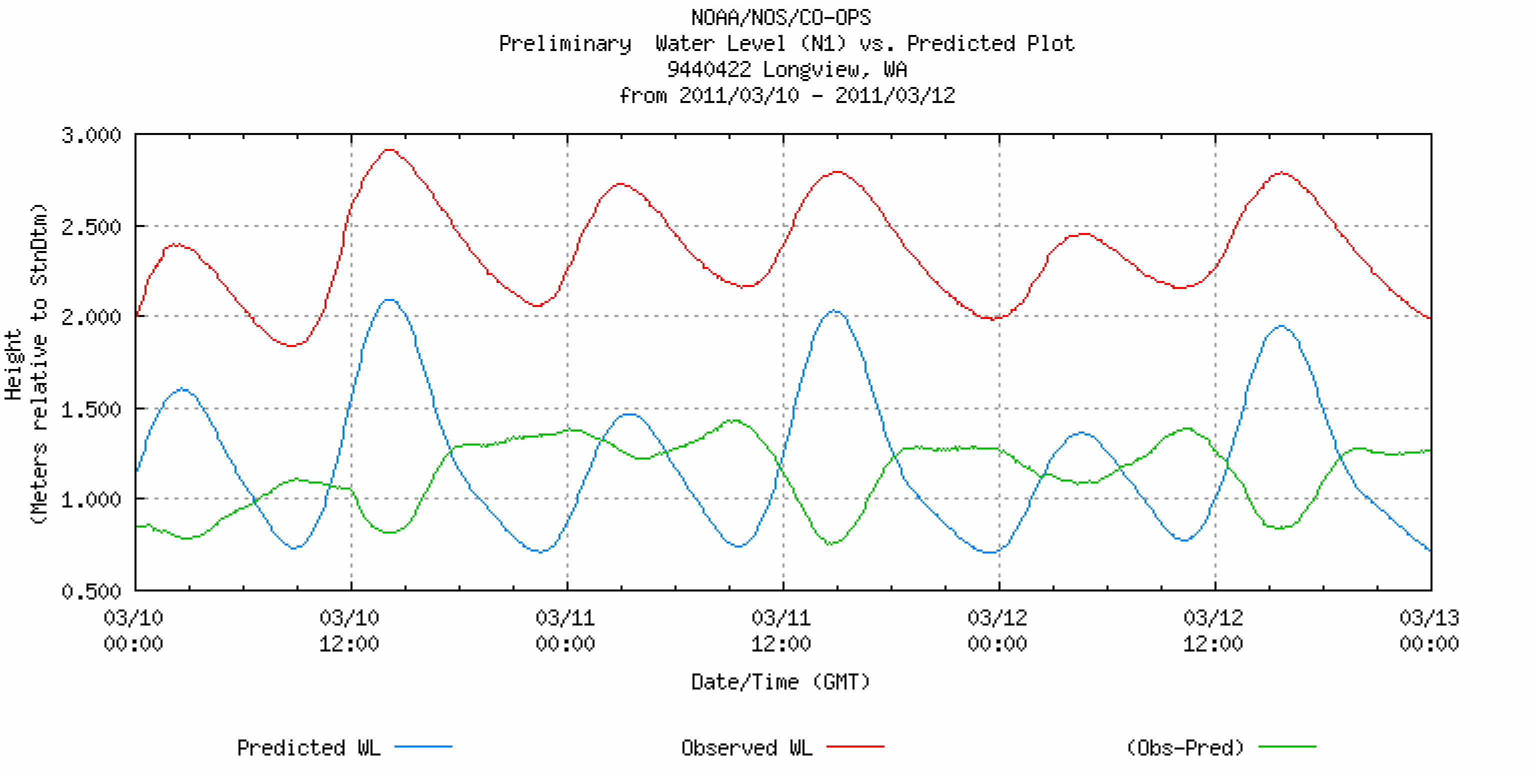
Skamokawa:


NOAA/NOS/CO-OPS
Preliminary Water Level (N1) vs. Predicted Plot
9440569 Skamokawa, WA
from 2011/03/10 - 2011/03/12
Height
(Meters relative to StnDtm)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
03/10 00:00
03/10 12:00
03/11 00:00
03/11 12:00
03/12 00:00
03/12 12:00
03/13 00:00
Date/Time (GMT)
Predicted WL
Observed WL
(Obs-Pred)

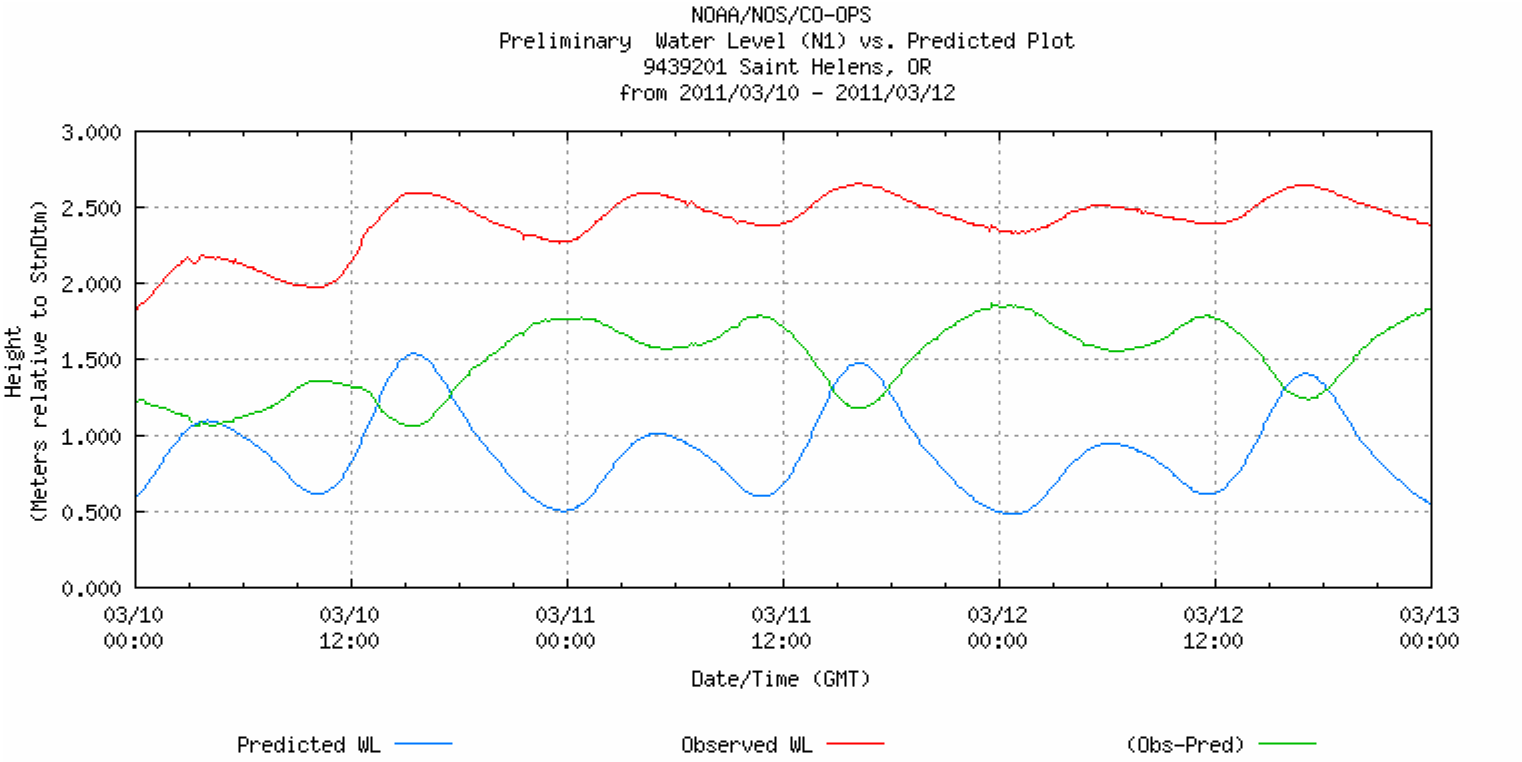
Wauna


NOAA/NOS/CO-OPS
Preliminary Water Level (N1) vs. Predicted Plot
9439099 Wauna, OR
from 2011/03/10 - 2011/03/12
Height
(Meters relative to StnDtm)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
03/10 00:00
03/10 12:00
03/11 00:00
03/11 12:00
03/12 00:00
03/12 12:00
03/13 00:00
Date/Time (GMT)
Predicted WL
Observed WL
(Obs-Pred)

Longview:


NOAA/NOS/CO-OPS
Preliminary Water Level (N1) vs. Predicted Plot
9440422 Longview, WA
from 2011/03/10 - 2011/03/12
3.000
2.500
2.000
1.500
1.000
0.500
Height
(Meters relative to StnDtm)
03/10 00:00
03/10 12:00
03/11 00:00
03/11 12:00
03/12 00:00
03/12 12:00
03/13 00:00
Date/Time (GMT)
Predicted WL
Observed WL
(Obs-Pred)

St Helens


NOAA/NOS/CO-OPS
Preliminary Water Level (N1) vs. Predicted Plot
9439201 Saint Helens, OR
from 2011/03/10 - 2011/03/12
3.000
2.500
2.000
1.500
1.000
0.500
0.000
Height
(Meters relative to StnDtm)
03/10 00:00
03/10 12:00
03/11 00:00
03/11 12:00
03/12 00:00
03/12 12:00
03/13 00:00
Date/Time (GMT)
Predicted WL
Observed WL
(Obs-Pred)

Conclusions from Above images:

1. Waves damp quickly in real river
2. Waves seen throughout tidal cycle at Astoria, Rkm-29, but stronger on flood/rising tide
3. At Skamokawa (Rkm-50) and Wauna (Rkm-64), tsunami waves seen mostly on flood/rising tide
4. Waves scarcely visible at Longview (Rkm-106) and St Helens, Rkm-139

What is Different about LCR?:

1. System geometry -- Columbia is long and has at least five different propagation regimes with different physics
2. A difference between tsunami in LCR and tsunami in a short system –
    a. In a short system, the tsunami mass transport >> tidal prism
    b. In the LCR, the tsunami mass transport << tidal prism
3. It is both very stratified and highly frictional
4. Channels are all sand-bedded
5. Vegetation – much of the shallow water habitat is forested, not marsh or mangrove
6. The numerous shoals and islands in lower estuary are important
7. The system is very different, in terms of depth and surface area during high and low-flow periods, at least upriver

Long Waves

As different as they are, tides and tsunamis in coastal waters are both part of the long-wave spectrum

1. Little seems to be known about the physics of tsunami propagation and interaction with topography in the presence of ambient river, tidal, and wind-wave currents
   - Yet all three are very strong in the Columbia
2. Tsunami waves are much more non-linear and dispersive than tides—

   But: are tsunami waves subject to some of the interactions that complicate tidal propagation???
3. A long wave in a channel is nearly 1D (only really true if width B < wavelength λ) and strongly constrained by changes in width and depth – use the well-developed theory for frictional long-wave is convergent channels

Thus following puts forward some speculations regarding tsunami waves in channels and tsunami-tide interactions, based on analogy, however faulty, to 1D tidal propagation in a convergent channel.

Several topics are covered (or at least mentioned):

A. Doppler shifting of tsunami waves by ambient flows
B. Frictional effects
C. Tsunami reflection/refraction
D. Long-wave mass conservation
E. The long-wave energy flux balance
F. Long-wave propagation speed and wavenumber

A. Doppler Shifting by Mean Currents –

Barotropic tidal waves are not Doppler shifted by mean flows
Surface waves and internal tides are Doppler shifted

Why??

The "natural" reference frame for a surface wave is the seabed, a fixed reference frame.

The natural frame for surface waves is the free surface, that for internal waves is the "interface." Both are mobile, allowing a Doppler shift in the reference frame of an observer on land.

Where does this leave tsunami waves, which are long-waves and very non-linear, but attached to the bottom (maybe)??

If they are Doppler-shifted, then:

- River flow/ebb currents should increase tsunami wave frequency (crests would be compressed, like wind waves on the bar)
- Flood currents (opposed by river flow) are weaker and would decrease frequency somewhat, but not so dramatically

The filtering of high-frequency waves seen in model results and (maybe) in the tide gauge data seems too strong to be caused simply by Doppler shifting.

B. Frictional interactions –

What happens to tidal long waves? They are affected by many non-linear interactions, but quadratic (and cubic) frictional interactions are the dominant effects:

- This shifts energy to both higher and lower frequencies
- How does this work?:

- The bed stress friction term on the tsunami wave is $\sim R_0\, C_D |U_{total}| U_{tsunami}$, where:
  - $U_{total} = \Sigma$(tidal+tsunami+mean flows)
  - The | | ensures that the stress term opposes the wave motion
- In the presence of a mean flow of the same order as the wave flows, the above can be expanded out as an odd-order polynomical (cf. Dronkers, 1964). The coefficients of the terms depend on the ratio of wave flow to mean flow. This is messy and involves a lot of frequencies

- While lower frequencies are created, most of the frequencies created are higher, not lower, than the basic wave
- If frictional interactions of this sort are vital, then high frequencies must damp very quickly, or they would be seen preferentially.
- Look at R_0:

- o $R_0 = C_d U_{scale}/(\omega_{tusnami} H)$.
- o If U_{scale} is set by the ambient tides and river flow (not the tsunami wave), then higher frequencies have less friction, in proportion to the tides with $\omega < \omega_{tusnami}$
- o This doesn't seem to explain the loss of high frequencies

C. What about Tsunami Reflection/Refraction?

The model results yesterday showed lots of reflection/refraction in the complex lower estuary.

So what governs tidal long-wave reflection?

- Waves reflect off of sharp topographic changes
- More generally, wave reflection occurs at changes in celerity; e.g., at a change in cross-section or bed friction

- Celerity $c=\omega/k$ changes when cross-section changes, because wave number k is affected by cross-sectional area convergence or divergence
- For tidal long waves with wavelength λ ~50-150km, reflection is minor in a river estuary with strong friction, and width B of O(a few km). (If the system were much wider, then friction wouldn't be strong…)
- It appears that reflection occurs much more readily for waves with wavelength $\lambda \leq$ width B (but 1-D theory can't explain this!)

So can reflection in the lower estuary account for lack of propagation of the shorter waves? Maybe!

Lets think about another mechanism – one related to dissipative effects

D. Long Wave Mass Conservation

The mass balance for a 1-D long wave is:

$$\frac{\partial Q}{\partial x} + B\frac{\partial \zeta}{\partial t} = 0$$

This says that the along-channel change in wave transport Q goes into raising or lowering surface elevation ζ. In the tidal context, the along-channel change in wave transport Q fills or empties the tidal prism.

Note that for a wave, all changes are wave-like (no zero-frequency component).

Implications for tidal modeling:

1. Tide has wave ~O(length of system). There are strong gradients in Q along channel due to change of phase of tide. If it is flooding at Astoria, it is ebbing at Longview

2. Changes in width B are very important (depth changes are smaller). Peak tidal transport at Beaver might be 7000m^3/s. Peak tidal transport at the mouth is ~7000m^3/s.

3. Propagation time for tsunami waves is O(tidal period) – tides will change as waves propagate

Conclusion—time and space gradients in tides are a vital part of the problem.

E. On the Long-Wave Energy Balance

The wave-cycle average, long wave energy flux in a channel is governed by:

$$b\,\frac{\partial E}{\partial t} + \tfrac{2}{3}\rho\bar{A}\,\frac{\partial}{\partial x}\,\overline{u^3} + \rho g\bar{A}\,\frac{\partial}{\partial x}\,\overline{uh} + \rho b C_D\overline{|u|u^2} = 0$$

where:

$E = 1/2\rho(d\overline{u^2}+g\overline{h^2})$ is the energy density, and
an overbar indicates a time average.

(from Jay et al., 1990)

For any finite section, and neglecting time changes in E:

$$\left(\tfrac{2}{3}\rho\bar{A}\overline{u^3}\right)\Big|_{x_1}^{x_2} + \left(\rho g\bar{A}\overline{uh}\right)\Big|_{x_1}^{x_2} + \int_{x_1}^{x_2} \rho b C_D \overline{|u|u^2}\,dx = 0$$

For tides, the last two terms are the largest. Thus:

Energy not transferred landward from x_1 to x_2

= dissipation between x_1 to x_2

Implications:

1. The wave horizontal P.E. flux = ~Stokes drift
2. If <A> decreases then <uh> has to increase (topographic funneling causes wave amplitudes to grow, despite friction)
3. The wave interacts with the mean flow mostly through the dissipation term

4. Because the horizontal P.E. flux term is quadratic, there is zero net change over a wave cycle associated with the mean slope – thus:
   - A tidal wave can propagate up a steep tidal river until it disappears due to frictional energy loss
   - We <u>don't expect</u> to see an ebb-flood difference in tsunami propagation due to the elevation difference
   - We <u>do expect</u> to see an ebb-flood difference in tsunami propagation due to the an ebb-flood difference in currents
   - A non-wave-like surge that changes mean elevation would interact with mean slope
5. Larger amplitude waves (like M_2) damp smaller waves (like S_2). If the tsunami waves (not the mean+tidal flows) have the strongest currents, then the most energetic tsunami components would damp the remaining components

- This could act as to filter shorter waves

Summary So Far –

Two mechanisms seem to offer some hope of explaining the loss of short wave tsunami components in the MCR and lower estuary:

- Preferential reflection/refraction of waves with wavelength $\lambda \leq$ width B (for which, however, 1D theory provides no real explanation)
- Preferential damping of shorter wavelengths by higher-energy, larger waves with longer wavelengths

F. Long-wave propagation speed

A 1D long wave in a channel behaves, due to energy conservation constraints, very differently from an unconstrained wave at sea

What are the wave number k, and propagation speed (celerity) c?:

1. $c=\omega/k$, as for any other wave (sort of)
2. But: frictional energy loss makes the actual wave number complex. Write incident wave elevation as (Jay, 1991, Green's Law Revisited):

$$\zeta[x,t] = Amp * B^{-\frac{1}{2}} H^{-\frac{1}{4}} e^{-i(qx-\omega t)}$$

   (x has been transformed so that, regardless of depth, a wave moves the same distance in a *given* time)

3. Call the wave number $q= k+i*r$ (q=complex wave number, k= real part, r =imaginary part or damping modulus), $r<0$ so that wave damps as it propagates

4. Analysis of the wave equation shows that the wave number q is given by:

$$q = \frac{\omega}{(gH)^{\frac{1}{2}}}\left(1 \quad - \quad \frac{\Delta^2}{2} \quad - \quad i\,R\,F_{\text{Dronkers}}\right)^{\frac{1}{2}}$$

accel. convergence friction

$$F_{\text{Dronkers}} = \text{Cubic polynomial related to wave flow/total flow}$$

$$\Delta^2 = \text{Geometric convergence factor (always} \geq 0)$$

$$R = \frac{C_D U_{scale}}{\omega\, H}$$

$$\text{Real part of } q^2 = 1 - \frac{\Delta^2}{2} \qquad \text{Imaginary part of } q^2 = \frac{C_D U_{scale}}{\omega\, H} F_{\text{Dronkers}}$$

5. Note that q has real and imaginary parts.

Let S be a vector in the complex plane; let S = $(q\ l)^2$, where l is a convenient length scale, so that q l is non-dimensional

6. The complex wave number has different behaviors, depending on the balance of friction, acceleration and convergence:

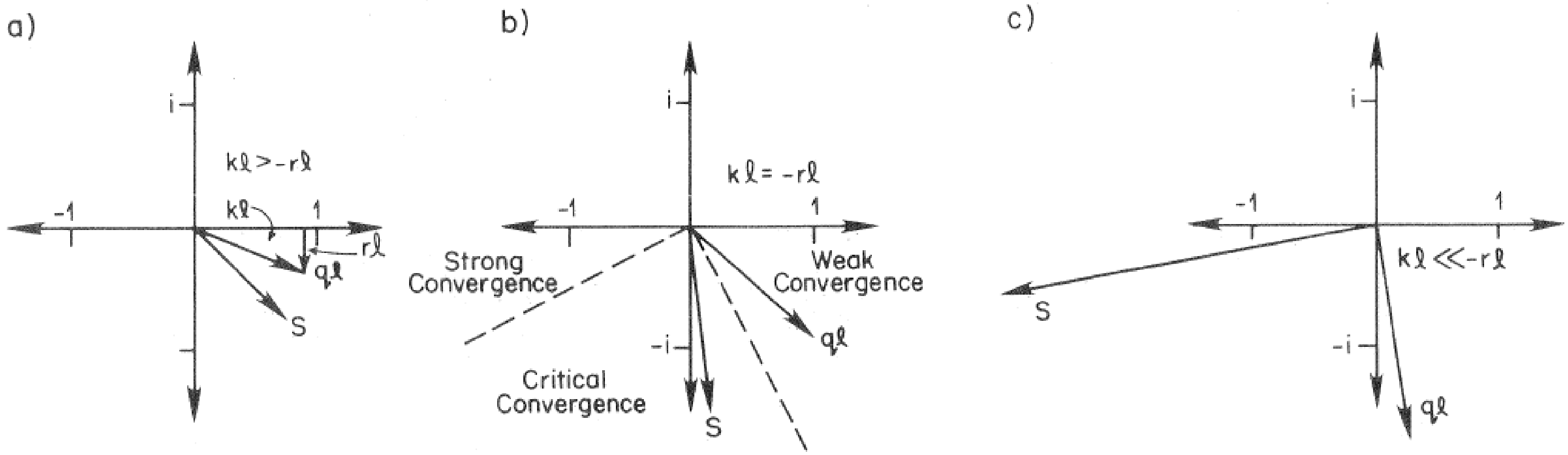


Fig. 6. *Sl* and *ql* in the complex plane for (*a*) weak convergence, (*b*) critical convergence/strong friction, and (*c*) strong convergence. Dotted lines in Figure 6*b* show boundaries between normal (for weak and strong convergence) and critical solutions as employed in the model.

7. Cases:

a. Weak convergence: for r< -k, fairly straight channel with weak friction (not too relevant)

b. Critical convergence: for r~-k, this is a very common case for tides in estuaries. Wave slightly slower than for no friction

c. <u>Strong convergence</u>: for $1-\Delta^2/2 \sim 0$, $r >> k$, $k \to 0$, and the incident wave acts like a standing wave; the phase is uniform (c very large), and Q and ζ are 90° out of phase.

8. So – do tsunami waves speed up in a constriction? (This does not imply an increased rate of energy transmission, because of the energy balance -- U and ζ are ~90° out of phase, so the wave crest translates w/o transferring much energy)

Summary

How many of these analogies to tidal propagation can we totally dismiss??? How many are useful???

Looking at 1D non-linear waves in a convergent channel looks like a useful idea