Improving Estuarine Transport Models using Satellite Measurements

Stefan A. Talke
Civil and Environmental Engineering Department, Portland State University
PO Box 751-CEE
Portland, OR 97207-0751
phone: (503) 725-2870    fax: (530) 725-4282    email: s.a.talke@pdx.edu

Award Number: N00014-13-1-0084

LONG-TERM GOALS

Satellite measurements of coastal and estuarine water level, water temperature, salinity, and turbidity continue to improve and now provide an opportunity to interpret coastal processes over an unprecedented range of spatial scales. Because these measurements are surface manifestations of tidal processes, river flow, and bathymetry, they can be used to obtain information about underlying physical characteristics. Improved understanding of the underlying physical processes that produce remotely-sensed surface patterns provides a means for testing and improving numerical models, particularly in areas in which limited or no measurements are available.

OBJECTIVES

The overall objective of the project “Improving Estuarine Transport Models using Satellite Measurements” is to gain a better understanding of the spatial variability of surface sediment concentrations, salinity, and water temperature in estuaries, using models, in-situ data, and satellite measurements. The specific objective is to address the following questions:

- What insights into sediment distribution, salinity, and water temperature in estuaries can be gained by collating and mining satellite images from 14+ years of MODIS satellite measurements and higher resolution LANDSAT images?
- Can canonical relationships for the longitudinal distribution of scalars such as salinity and turbidity be observed in satellite data under different physical conditions?
- Can satellite measurements of water level and scalars be used to determine system response and calibrate numerical models as a function of river flow and tidal forcing?

APPROACH

A three-fold approach has been used since the project started in Dec. 2012. First, we are developing and refining our processing of satellite measurements, using the Columbia River estuary (CRE; Fig. 1) as a test case due to the availability of in-situ measurements and local knowledge. Second, we are actively developing analytical and numerical modeling capabilities for stratified conditions which we are using to interpret results from satellite measurements and improve process knowledge. Finally, we have invested time and funds into a novel method for estimating tides using airborne Lidar data.
Following standard methods (Siegel, 2005; Palacios et al., 2009; Doxaran et al. 2009; Hu et al. 2004), we estimate turbidity and water temperature by regressing in-situ measurements against appropriate bands of surface reflectance measured by the MODerate Imaging Spectrometer (MODIS) installed on the Terra and Aqua satellites. Level 2 satellite data with atmospheric corrections are obtained from http://ladsweb.nascom.nasa.gov/, while in-situ data are obtained from the Center for Coastal Margin Observation and Prediction (CMOP): http://www.stccmop.org/datamart/observation_network. A total of 6 in-situ stations were used, although good quality measurements were generally available only from two locations. All satellite data are filtered for clouds, aerosols, and poor quality, and data are further binned into low, medium, and high aerosol conditions. A total of nearly 1300 good images have been observed since 1999. Turbidity is correlated most strongly with surface reflectance and is the focus of this report. Measurements were averaged over about 1 hour at each MODIS pass; this was necessary to filter smaller scale variability in the in-situ data.

Figure 1: Transects flown during the June 2013 LIDAR experiment on the Columbia River Estuary

Turbidity patterns in the CRE are investigated using both statistical and semi-analytical approaches. Regression analysis is used to determine how wind, river flow, and tides affect turbidity distributions.

River flow data are obtained from the United States Geological Survey (USGS), tidal data and wind are obtained from the National Oceanographic and Atmospheric Administration (NOAA), and ocean swell data are obtained from the National Buoy Data Center (Buoy 46029). We have also adapted semi-analytical channel models to stratified environments to understand the physical mechanisms behind the surface turbidity signal, and its relationship to in-situ patterns. The semi-analytical approach combines 3 semi-analytical models (for the first time) to obtain tidally-averaged circulation
and turbidity patterns in a stratified estuary (MacCready, 2007; Jay, 2010; Talke et al., 2009). First, the MacCready (2007) salinity intrusion model is modified to include the circulation due to internal asymmetry (Jay & Musiak, 1994; Jay, 2010): this circulation, which occurs because one tidal phase (usually flood) produces more mixing than the other (usually ebb), is thought to be more important than traditional gravitational circulation (flow induced by density gradients) in many estuaries. This circulation model forms the basis for a tidally averaged turbidity model, following the ‘morphodynamic equilibrium’ approach outlined by Talke et al., 2009 (see also annual report, 2013). Morphodynamic equilibrium occurs when erosion equals deposition, and the outflow of sediment equals the inflow of sediment everywhere within the system. Applying these conditions in mathematical form has yielded a model in which we can investigate the mechanisms of turbidity trapping, for example bathymetric trapping, in a ‘Columbia-like’ estuary (see Results). A fully numerical Delft3D model has also been improved this year and will be compared in the future against the semi-analytical model.

In June 2013, surface temperature imagery and Lidar elevation data were collected upstream of the mouth of Columbia River inlet using the APL (Applied Physics Laboratory) airborne remote sensing system. Multiple transects (8 total) were run over a 60km transect between Hammond and Wauna, allowing up to 16 repeat measurements of the same location over a 16 hour period (Fig. 1). Corrections for plane elevation, pitch, and roll have been made by APL. These corrected data have then been fit to a sinusoidal tide curve with a K1 and M2 tidal frequency, and compared against tide data at 4 locations.

WORK COMPLETED

Over the past year we have improved our calibration of satellite data with in-situ turbidity and water temperature data in the CRE, and have refined our understanding of which factors determine turbidity. A climatology of annual turbidity patterns based on nearly 1200 images has been defined. A similar effort is underway in other estuaries, focusing on the Ems estuary, Germany. A semi-analytical model of turbidity has been developed, and is being used to understand the dynamic mechanisms producing topographically trapped turbidity maxima (see Results). The results of the CRE effort have been incorporated into a Masters thesis draft (expected completion: Dec. 2014), and will be incorporated into 1-2 papers over the coming year. A Master’s project report (June, 2014) looked into methods of improving estimates of chlorophyll in coastal waters using LANDSAT data. LIDAR data has been successfully analyzed, and will be incorporated into a paper in the coming year (see Results). Three conference presentations have been made over the past year.

RESULTS

Regressions of MODIS data to in-situ turbidity and water temperature exhibit excellent correlation values when high-quality, low-aerosol data are used (R^2~0.9; see 2013 report). Averaged by month, the resulting climatology shows that turbidity in the CRE is largest during winter months (Fig. 2). A second, smaller maximum occurs in May, and the lowest concentrations occur in late summer. A coastal plume is clearly evident, particularly during periods of high turbidity. Interestingly, the plume hooks slightly southwards during July, possibly due to down-coast summer wind patterns.
Figure 2: Monthly averaged turbidity distributions. Elevated concentrations begin during the winter months and persist throughout the spring while high river flows are maintained. Minimum concentrations occur in late summer at periods of low flow.

A number of insights and inferences are made possible from the database of surface turbidity in the CRE. Since turbidity theoretically depends on river flow rate, the observed annual turbidity pattern (Fig. 2) contradicts the annual Columbia River flow hydrograph, in which peak flows are observed from April-June. This apparent anomaly is solved by considering smaller, rain-fed coastal rivers. As shown in Fig. 3, the coastal Willamette River flow record is much more correlated with estuary and coastal turbidity than the relatively sediment poor Columbia River, which drains the interior basin. Hence, the majority of sediments (and nutrients) supplied to the coastal ocean are sourced from coastal mountains during winter storms. Results also show that tidal range is predictive of turbidity levels (Fig. 4), with a larger tide producing more surface turbidity. Wind, however, is only weakly correlated with turbidity patterns (Fig. 5). The distribution of sediment shifts as forcing changes: low river flow and/or low tidal range (neap tides) tend to produce an upstream maximum, while larger flows and larger tidal range move the turbidity maximum downstream (Fig. 6). Over many different flow and tidal conditions, turbidity is elevated between km 15-25, and decreases steeply in the seaward direction. Since several topographic holes are known to exist within this stretch of the estuary, we posit that these features are contributing to the trapping and distribution of surface sediment.
Figure 3. Correlation map between MODIS derived turbidity and river flow measured for the Columbia River and the Willamette River.

Figure 4: Left: Correlation map between MODIS derived turbidity and tidal range. Tidal range is positively correlated with surface turbidity.
Figure 5: Correlation map between surface turbidity and wind–related forcing. Wind speed has a minimal effect on turbidity and is confined to shallow regions in the system. Wind direction is of greater importance when measured at either location.

Figure 6 Longitudinal transects of turbidity in the North (left) and South (right) Channels. Transects are averaged in bins according to greater diurnal tidal ranges (0.5m window) and river flow (1000 m$^3$s$^{-1}$ window, spring tides only).
Figure 7: Estimates of tidally averaged velocity, salinity intrusion, and sediment distribution from an idealized semi-analytical model of the Columbia River. Grey line is surface turbidity (bottom).

We investigate the processes leading to the turbidity distribution with our idealized model (Fig. 7). Preliminary results show that tidally averaged circulation (top panel) is highly depth dependent, since both gravitational circulation (GC) and internal asymmetry (IA) are nonlinearly dependent on depth. For the conditions observed in the CRE, the circulation from IA typically dominates over GC (Fig. 8). The tidally-averaged IA circulation produces salinity intrusion (middle panel, Fig 7) and moves bottom sediment landward. Downstream movement of sediment by river flow produces a convergence of sediment and an ETM (Bottom panel, Fig. 7), consistent with previous studies in unstratified environments (e.g., Talke et al., 2009). As shown, the turbidity profile is affected by bottom bathymetry, and sediment is trapped at or near the holes. Model results suggest that the surface turbidity observed by the MODIS satellite is also affected by the vertical distribution of sediment; because sediment concentration decays exponentially, the modeled surface concentrations are less over a hole than over a topographic high point (Fig. 7). These two factors combine to produce (in this case) a surface turbidity distribution with two maxima and an asymmetric, ‘skewed right’ profile (i.e., a steep seaward gradient). A similar profile is observed in MODIS profiles (Fig. 5). Interestingly, the
bottom sediment concentration maxima are in a different location than the surface maxima; this occurs because of stratification, which reduces mixing downstream of km 20 (Fig. 7). The morphodynamic equilibrium condition of no net transport into or out of the estuary also requires that surface sediment concentrations decrease when seaward circulation increases (otherwise, sediment would be exported, which requires net erosion at the bed). These insights show that the surface turbidity and bottom turbidity are not directly correlated; nonetheless, modeling can begin to explain and infer the processes that are occurring subsurface.

![Graph](image)

**Figure 8** Ratio of gravitational circulation (GC) to internal asymmetry (IA) scaling as a function of depth (x-axis) and top to bottom salinity difference (y-axis). IA dominates over GC for most conditions.

Model sensitivity studies demonstrate how idealized bathymetric features affect the turbidity distribution (Fig. 9). For a flat, constant depth channel, the turbidity maximum monotonically moves upstream as river flow or tidal forcing (i.e., mixing) is decreased. The distribution becomes more spread, and the magnitude of the maximum decreases. When a bump is introduced, both salinity and turbidity becomes trapped downstream (to the left) of the bump for a number of different forcing conditions. As shown in Fig. 7, this occurs because of the feedbacks between depth, tidally averaged salinity intrusion, stratification, and circulation, which in turn affects turbidity. A topographic hole produces a convergence of sediment just upstream of the hole. The results in Fig. 8 are qualitatively similar to the observed MODIS profiles (Fig. 5): sediment moves upstream as tidal or river forcing is reduced, but is centered between river km 15-25 for a large parameter space, suggesting topographic influence. For extreme low flows, the salt wedge passes the topographic barrier, and the ETM occurs far upstream (Fig. 5 and 7). Over the next year, we will undergo additional sensitivity studies and further investigate the physical reasons for the observed turbidity profiles.
**Figure 9.** Surface turbidity transects during various river flow conditions (left) and stages of the neap/spring cycle (right) for domains with constant depth (top), topographic high (middle), and topographic hole (bottom).

**Lidar Tides:** Preliminary results for the Lidar Tides experiment are quite encouraging, and demonstrate that tides can be measured via airborne remote sensing (Fig. 10). Noise which remained in the signal after correcting for airplane pitch, roll, and altitude was filtered, and artifacts resulting from airplane movements (such as banking) were removed. The resultant elevations are shown as a function of time in Fig. 9, and clearly show Lidar measurements tracking the NOAA tide gauge measurements. Further improvement in the Lidar/gauge comparison is obtained by fitting a simple tidal model, consisting of a sinusoid with a K1 and M2 frequency, to the Lidar data. For locations with >10 independent Lidar measurements, the error between Lidar and tide gauge measurement was approximately 10cm rms. However, the goodness of fit in the upstream sections (e.g., Skamakowa, bottom panel) was not optimal because of the lack of independent measurements; essentially, the Lidar estimates on each individual transect were too close together in time to be independent of each other.

Applying our simple tidal model to the Lidar measurements at different locations, we are able to watch the progression of the tide as it moves up the estuary. Preliminary estimates of the phase speed agree well with tidal measurements (not shown), and our estimate of the mean depth from Lidar measurements, ~15.5 m, closely approximates the actual channel depth within the shipping channel. Similarly, estimates of the mean slope (not shown) approximate the slope measured by tide gauges.
IMPACT/APPLICATIONS

Our study is pioneering the use of ‘satellite climatology’ in estuaries, in which the full satellite record is being mined to define statistically representative states that vary over the full range of forcing. This approach addresses the problem of limited temporal resolution in satellite images, which is an important issue in highly variable estuarine environments. The resulting climatology yields data that can be used to help calibrate a numerical model and constrain its parameters, and provides a snapshot of spatio-temporal variability that is not possible with in-situ monitoring. A particular application is to apply satellite data to locations in which limited data is available.

Using Lidar to estimate tides is a simple way to remotely estimate tides and depth in areas in which insufficient data is available. Since water level data is a fundamental necessity for numerical models, remotely measuring tides could be used to help initialize and calibrate hydrodynamic and transport models in hard-to-measure areas such as shallow channels and tidal flats. Further, tides contain more
information than just water level: the rate of spatial damping is related to friction and river flow, while the tidal propagation speed is a function of depth, friction, and convergence. These known relationships can be inverted to estimate friction and depth.

RELATED PROJECTS

The ONR-sponsored “Shallow Turbulence in Rivers and Estuaries” project investigated large-scale eddies using in-situ, remotely-sensed, and modelled data. Some synergy and cross-over existed in that similar tools (the Delft3D model, satellite data) could be brought to bear on the distinct problems.

REFERENCES


**HONORS/AWARDS/PRIZES**

Outstanding Researcher Award, Sigma Xi (Portland Chapter), 2014 (Talke)

Faculty Research Excellence Award, Portland State University, 2014 (Zaron)