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Bathymetric Control of Front Generation in a Tidal River

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Abstract

A persistent tidal front is observed on ebb tide in the vicinity of the Nanjemoy Creek diversion on the Potomac River in Maryland. This front forms along the boundary between the creek water mass and the main river water mass and is evidence of low lateral mixing in the area of the front. An accurate numerical model of the river-creek geometry is able to reproduce this feature using realistic tidal and river forcing. Further investigation with an idealized model shows the importance of downstream (ebb) mudflats and shoals in generating this persistent flow structure.

1. Introduction

Short lived fronts, with a duration of a few hours, are common features in estuaries and tidal rivers and are often caused by small spatial scale bathymetric features modifying the bulk flow (Sarabun, 1993). They are generally the result of tidal processes creating strong lateral density gradients (O'Donnell, 1993) and are observable on the surface as flotsam, spume or water color changes indicating the presence of convergent, divergent or shear zones separating differing water masses (Huzzey and Brubaker, 1988). They tend to form and dissipate quickly at either the dominant tidal frequency (on flood or ebb) or twice the dominant tidal frequency (on both flood and ebb or on both slack waters). While generally short lived, their periodic nature makes them important to local biological processes and sediment dynamics (Largier, 1993).

Tidal creeks are small costal inlets or else side channels or tributaries of tidal rivers, the flow in which is dominated by the ebb and flood of the tides and through which no significant surface or ground water flows. Often associated with salt marshes, they form important linkages between the land margin and the coastal ocean serving as major export pathways for terrigenous sediment (Childers and Day,1990a; Cavorta et al., 2003), nutrients (Childers and Day, 1990b) and as refuge and nursery for many species.

This paper investigates a recurrent front generated on ebb tide at the mouth of a tidal creek on the Potomac River. Starting by identifying the recurrent front in aerial imagery, we are able to replicate the important features of the front using a detailed numerical model of the region. A series of simplified and idealized models are then used to investigate the important bathymetric and flow conditions that generate this front.

2. Nanjemoy Creek and the Ebb Tidal Front

Nanjemoy Creek (see Figure 1) is a large tidal creek that acts as a diversion from the main channel of the Potomac River in Maryland (38.40N 77.12W). Joining the Potomac on a reach where the river is approximately 5 km wide and 12 m deep on the thalweg, Nanjemoy Creek is approximately 1.4 km wide at the mouth and extends straight away from the river for 5 km before making a turn and meandering for another 5 km of much narrower channel. It averages 4 m deep and has an extensive mud flat in the ebb (down river) direction. The Potomac River here is tidally influenced but is above the region of maximum salt penetration so buoyancy effects are minimal. There is no flow in through Nanjemoy Creek other than some possible slow seepage of groundwater.

This reach of the Potomac is affected by semi-diurnal mixed tides primarily at the M2 frequency with significant contributions from the M4 and higher shallow water harmonics that serve to distort the tidal wave. Tidal range on spring tides is approximately 1.2 m compared to 0.8 m on neap tide. River discharge past Nanjemoy Creek can vary between 17 and 13,700 m^3/s with a mean value of 300 m^3/s (Patrick, 1995)

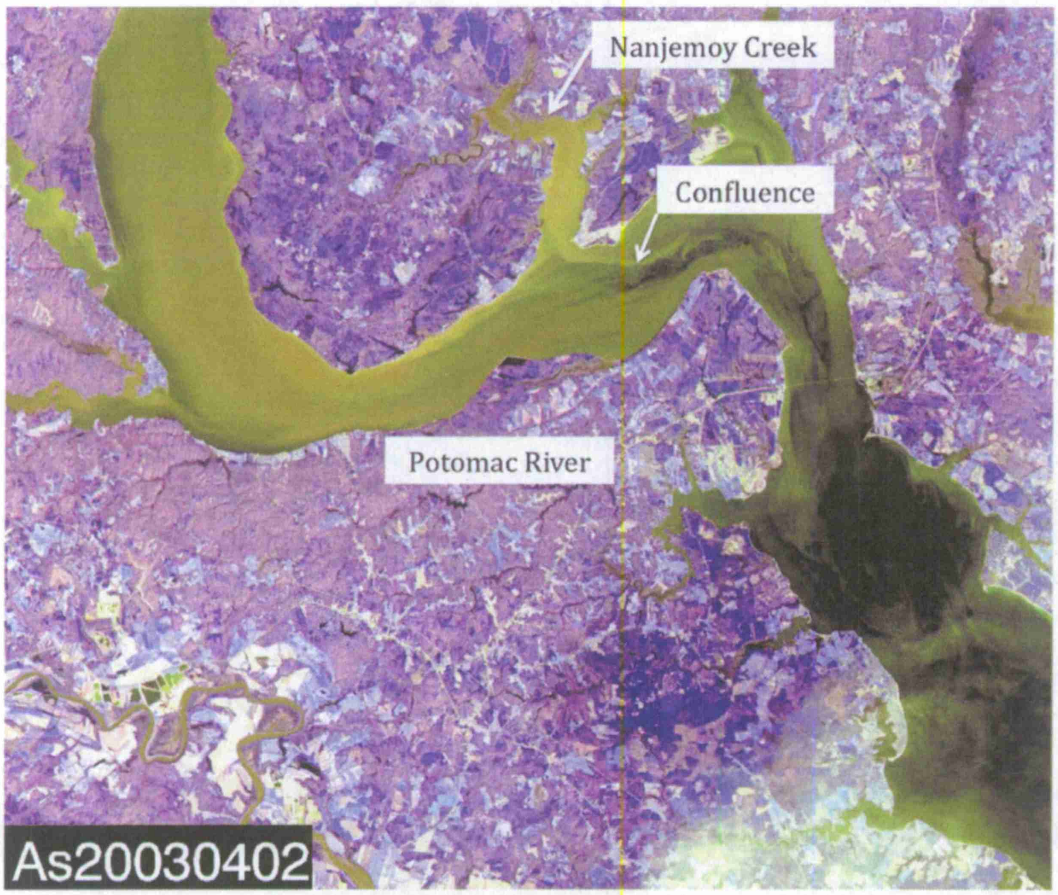

Figure 1: An ASTER image from April 2, 2003 depicting the Potomac River, Nanjemoy Creek, and the confluence line between the two. The tide phase corresponds to 3:49 (hh:mm) after slack water before ebb.

Figure 1 shows an ASTER image of Nanjemoy Creek 3h 49m into an ebb on April 2, 2003. A front is clearly visible between the water ebbing out of the creek and the ebbing river water that roughly corresponds to the edge of the downstream shoals associated with the creek. As ebb continues this front will begin to corrugate and eventually break up at the end of ebb as the water masses mix laterally. On flood tide an intrusion front is briefly seen as river water floods into the creek before mixing but no similar front occurs in the river channel proper.

3. Modeling the Front

Creating a realistic numerical model of the river-creek region allows the formation and dissipation of the front to be examined in light of changing tidal and river forcing and for water surface elevation and currents to be examined in detail.

3.1 Mesh Description

A region of the river was selected for modelling running from approximately 30 km upstream of the creek to 20 km downstream for a total modelled reach of 50 km. While extensive databases of world coastlines are available for use in numerical modelling, such a database does not exist for river banks. The bank locations needed to define the boundaries of the model were extracted from orthorectified and georeferenced aerial imagery of the region using a Navy developed image processing technique which segments the image based on relative levels of image information entropy (described by McKay et al. (2011)). Bathymetry was taken from NOAA 30 m resolution multi-beam surveys conducted in 2001. A 50 km upstream channel extension was added to remove the upstream (river flux) boundary condition far from the region of interest and thus minimize contamination of the solution by boundary effects (Luettich, 2003).

The river edge data and bathymetry were imported into the Naval Research Lab's in house meshing tool, MeshGUI (Blain et al., 2008), and an unstructured triangular finite element mesh of 378,549 nodes and 740,286 elements was generated. An unstructured mesh uses elements of varying size, allowing elements to cluster in areas of interest while maintaining much greater nodal spacing along the open boundaries and away from the area of interest. Nodal spacing ranges from 50 m on the open boundaries to 1 m in the area of the anticipated front. The full mesh is shown in Figure 2 with a detail showing triangular elements in the area of the front in the inset plot.

3.2 ADCIRC Model

The non-linear ADvanced CIRCulation (ADCIRC) model (Luettich et al., 1992; Luettich and Westerink, 2004) has an extensive record of use in predicting tidal circulation and storm surge in coastal seas and estuaries and has recently been applied to modeling rivers (McKay et al., 2009; Blain et al., 2009). ADCIRC solves the shallow water wave equation, cast in the form of the generalized wave continuity equation (GWCE), on an unstructured triangular finite element mesh. The model produces three-dimensional currents and water surface elevations at discreet time steps, saving the results at user defined intervals.

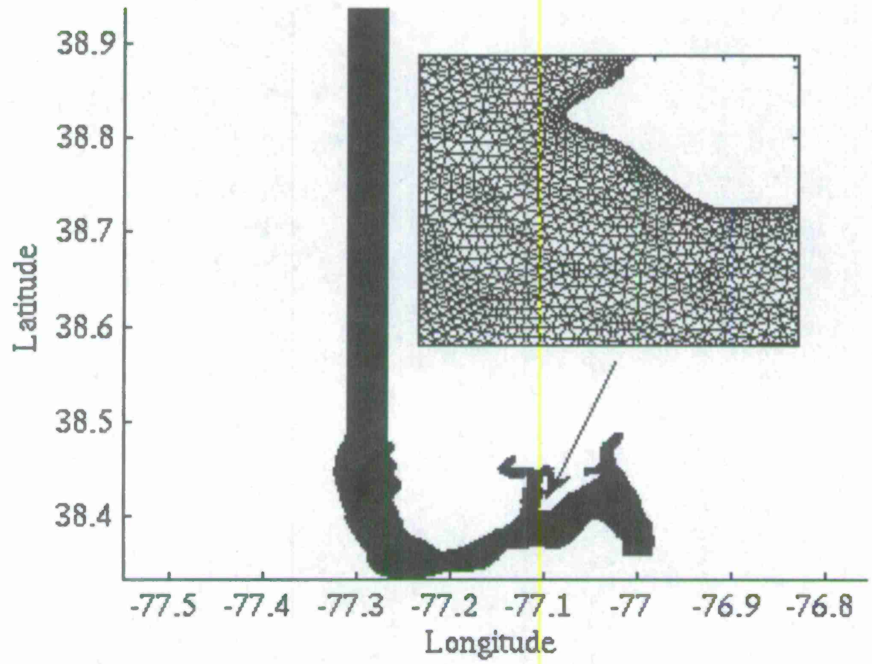

Figure 2: The unstructured finite element mesh of a 50 km reach of the Potomac River with a 50 km straight extension added to the upstream boundary. The inset image shows details of the mesh in the area of interest.

3.3 Model Run Parameters

The model was run in barotropic mode assuming constant water density. The small element size dictated a time step of 0.5 s. Ten evenly spaced σ-layers were used to resolve the vertical dimension allowing the modelling of any three-dimensional circulation in the system.

The model was forced with a combination of tidal elevations at the downstream boundary and time-varying river flux at the upstream boundary. Tidal forcing was applied using six component harmonic tides (Q1, O1, K1, N2, M2, K2) taken from the Grenoble FES99 database (Lefevre et al., 2002) with a time lag introduced to account for the time required to propagate upstream from the ocean. River flux was taken from the USGS Gauging Station 01646500 located near the upstream boundary of the mesh, at Little Falls, which reports instantaneous hourly values. Bottom friction was set to a value of CD = 0.003, representing a typical quadratic bottom drag coefficient for a muddy bottom. After a seven day spin up, the full u, v and w velocity fields and water surface elevation were written every ten minutes of simulation time for several tidal cycles.

3.3 Results

The initial run was set to span the period around April 2, 2003 with observed river fluxes and harmonic tides as forcing. The resulting physical front is shown in Figure 1. The simulation shows very similar behaviour and replicates the observed behaviour closely.

On flood, river water is diverted over the mud flats and into the creek. Water builds up in the creek and the surface elevation increases. Due to the likely presence of M4 and higher shallow water harmonics, the tidal wave in the Potomac shows qualities of a progressive, rather than a pure standing, wave and flood continues in the main river channel even as the water level begins to drop. This results in a water surface slope along the axis of Nanjemoy Creek on the order of 1E-4 that drives water out of the creek. Thus the creek begins to ebb while the main river channel is flooding. The ebbing creek water stays closely over the downstream shoals and does not readily mix with the river water, establishing a clear front. Shear instabilities appear at the diving line between the two masses and the front begins to dissipate and is completely eliminated on flood.

Figure 3 shows the location of various colored tracers introduced into the flow on ebb tide. A clear front can be seen between the water ebbing out of Nanjemoy Creek and the water ebbing past it on the main river channel. This closely follows the contours of the mud flats and shoals downstream of the creek. Figure 4 shows a vector plot of the surface currents in a wider region at this same time. A dividing line can be clearly seen that the vectors do not cross. This indicates that there is little to no lateral mixing across this front on ebb.

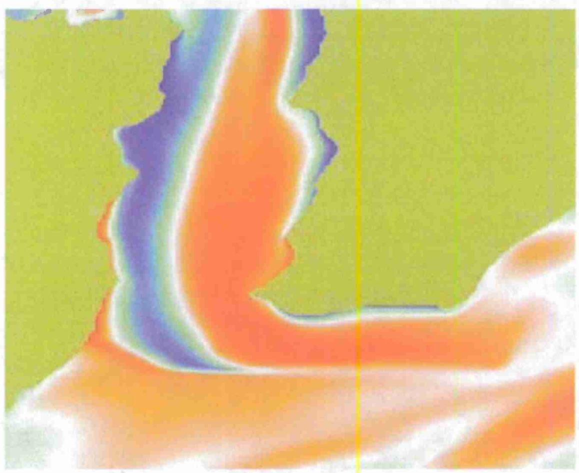

Figure 3: Colored tracers in the modelled flow around the mouth of Nanjemoy Creek on ebb. A clear front can be seen between tracers exported from the creek and tracers already in the river channel.

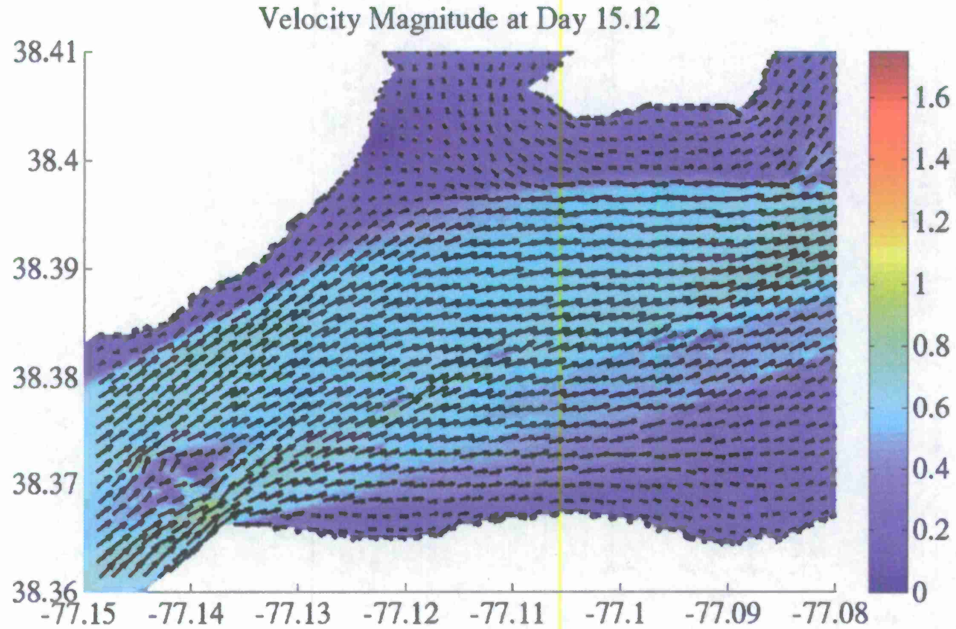

Figure 4: A down sampled vector plot showing the modelled surface flow field in the Potomac River approximately 3 hours after start of ebb under conditions matching those of April 2, 2003. The background color is the flow speed. A clear front can be seen near the edge of the downstream shoals that the flow vectors do not cross.

3.4 Idealized Modeling

By creating an idealized model of a similar river-creek system and manipulating both forcing and geometry we are able to explore the factors responsible for creating this ebb tide front. To accomplish this, an artificial straight sided, flat bottomed river mesh was created. This channel is 100 km long (to account for the Potomac's length and the extension) with a depth of 12 m (the mean depth along the thalweg of the Potomac in our area of interest). A side creek with a width of 1.5 km joins the main channel at a 90 degree angle and stretches for a length of 5 km. Initially it is set at a depth of 12 m and no shoals are present. The idealized model is forced with constant river flux and a pure M2 tide with a 1 m tidal range.

The simplest representation of the side creek has a flat bottom set at the same depth as the main channel and no shoals. Water flowing past this on either ebb or flood behaves like a lid driven cavity flow. There is a slight diversion into the cavity where the water flows straight across and smoothly exits. Rotational flow is set up in the creek (clockwise on flood and counterclockwise on ebb) and there appears to be little to no mixing between the water masses. As this case is trivial no further investigation was made of it.

The real Nanjemoy Creek is shallower than the main river channel, averaging 4 m deep. Starting at 12 m and progressively making it shallower until it was 1 m deep slightly altered the flow. The shallower it got the further river water penetrated into the creek, as the increased bottom friction caused it to turn further into the creek, but the dominant flow pattern was still that of lid driven cavity flow and no mixing between water masses was apparent.

Next, the effect of the downstream shoals was examined. The creek was held at 4 m deep and a shallow region was created extending out 500 m from the bank and running from the centreline of the creek to a distance of 1 km downstream. This shoal radically altered the flow patterns and created a flow very similar to the observed flow in Nanjemoy Creek.

On flood, water flowing over the shoals encountered greater friction and began to slow. It then turned into the slower water of the creek and flowed in. As the tidal wave passed the creek and water levels in the main channel began to drop, despite the fact that it was still flood tide in the main channel, the resulting water surface slope along the axis of the creek drove water out as the creek began to ebb earlier than the river. This water then flowed over the ebb shoals and did not mix with the river water until it exited the shoals. This pattern persisted until slack after ebb and then repeated. Figure 5 is a vector plot showing a close view of flow instabilities in a small area along the ebb front for this case.

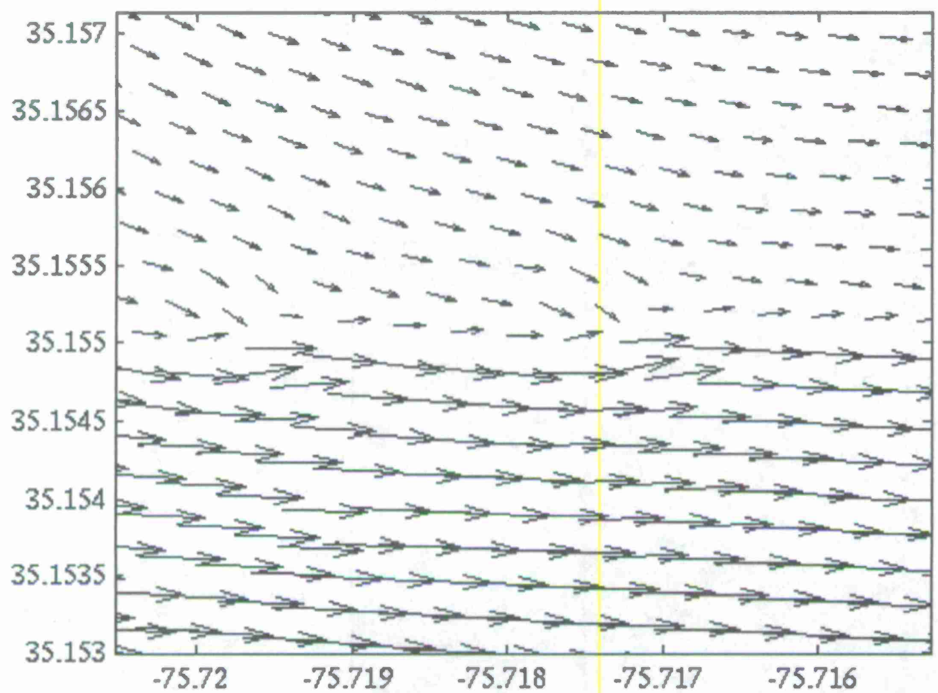

Figure 5: Vector plot showing flow instabilities developing along the line of the ebb front in the idealized case.

Manipulating the length of the shoal downstream and the breadth of it across channel showed that this is responsible for the horizontal extent and location of the front. Making the shoal deeper than the creek diverted less water into the creek on flood and shortened the duration of the front. Similar effects were seen when making the shoal shallower than the creek.

Extending it upstream of the creek had no effect on the flow at all. However, having a shoal only on the upstream side (a morphologically unlikely scenario) caused the flow to revert back to a form of lid driven cavity flow and no fronts were observed.

Altering tidal range affected the duration of the front and the time at which the tide turned in the creek. This is largely a function of the volume of water pumped into the creek on flood. Decreasing river flux increased the duration of the front while increasing it decreased it. The front was effectively gone when river flow was ¾ the tidal flow and completely gone when river flow exceeded tidal flow.

4. Conclusion

An accurate numerical model of the confluence of Nanjemoy Creek and the Potomac River is able to duplicate the persistent ebb tide front observed at this location. Idealized modelling shows that this front is due to the effect of shoals and mudflats downstream of the creek mouth forcing water into the creek on flood and constraining it as it exits on ebb. The location of the front is controlled by the horizontal extent of the shoals while its duration and timing are controlled by the shallowness of the shoals compared to the creek as well as to the relative strengths of the tidal flows and the river flows.

As the river water picks up much sediment in the shallow side creek, the action of the shoals to constrain the water on ebb to a certain region enhances the likelihood of this sediment being deposited on the shoals. Thus while the shoals serve to create the front it is also true that the front serves to enhance and build the shoals.

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