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Visual Analytics of the Hydrodynamic Flux for Coastal Flooding Prediction and Management

R. L. S. F. George[1], P. Robins[2], A. G. Davies[2] and J. C. Roberts[1]

[1]School of Computer Science, Bangor University
[2]Centre for Applied Marine Science, Bangor University

Abstract

Fifty percent of the earth's population lives within 60 kms of the shoreline. So preventing or mitigating against coastal or estuary flooding is important, especially because of the predicted sea level rise from climate change. A key calculation in simulating flooding over an estuary is hydrodynamic flux, but typically this is complex and tedious to compute and not easily undertaken with traditional visualization and analytical tools. We present a transect profiler and flux calculation algorithm which permits rapid, iterative exploration and comparison of the derived data. This profiler has been implemented and integrated in our multiple view visual analytics system VINCA.

Categories and Subject Descriptors (according to ACM CCS): J.2 [Computer Applications]: Physical Sciences and Engineering—Earth and atmospheric sciences

1. Introduction

Environmental and ocean scientists are addressing many challenges: one major challenge is to ascertain how climate change affects human habitation. This is of particular importance because 50% of the world's population lives within 60 kms of the shoreline [DT08]. It is widely accepted that a consequence of climate change is sea level rise [Dou91, Rah10], which increases the potential for storminess and flooding of the (often habited) coastal region.

Current practices provide many research challenges. Hydrodynamic studies rely on mathematical simulations that incorporate historic and observed data (e.g. rates of change to sea levels), but this data does not necessarily provide a reliable guide to predicting future changes [BJK*06]. The datasets are big, unstructured and are multi-field that cover long time periods. Furthermore, although high quality visualization techniques are used in a number of domains of physical sciences [LLC*11], predominantly they are non--interactive, and their analytical processes are *ad hoc* and time consuming. Coastal shelf researchers have traditionally used several visualization and analysis tools to display and study the information. To calculate the hydrodynamic flux our collaborators use MATLAB scripts for calculation, and a separate tool to visualize the results. These methods take many minutes to generate a single plot and require numerous intermediate files to be saved.

We have been working with coastal shelf scientists to develop a visual analytics approach to study modelled, estuarine hydrodynamic data used in flood prediction. One goal is to evaluate the sediment and hydrodynamic transport within the estuary. In particular, we wish to establish whether an estuary is filling with sediment or being eroded by the tides. This requires calculating the flux on several sections of the estuary and comparing different simulation runs. By providing interactive visual analytic tools, and automating part of this process, we can help ocean scientists make more timely flood predictions and support the development of theories about changes which lead to flooding.

In this paper we describe a transect profiler and hydrodynamic flux calculator, which provides derived diagnostic data for further detailed visual analysis, and significantly improves on the functionality of traditional calculation methodologies. We integrate these tools into our multiple-view oceanographic visualization system (VINCA).

2. Related Work

Coastal oceanographic flood simulations incorporate many phenomena, including spring tides, high storm surge, in-

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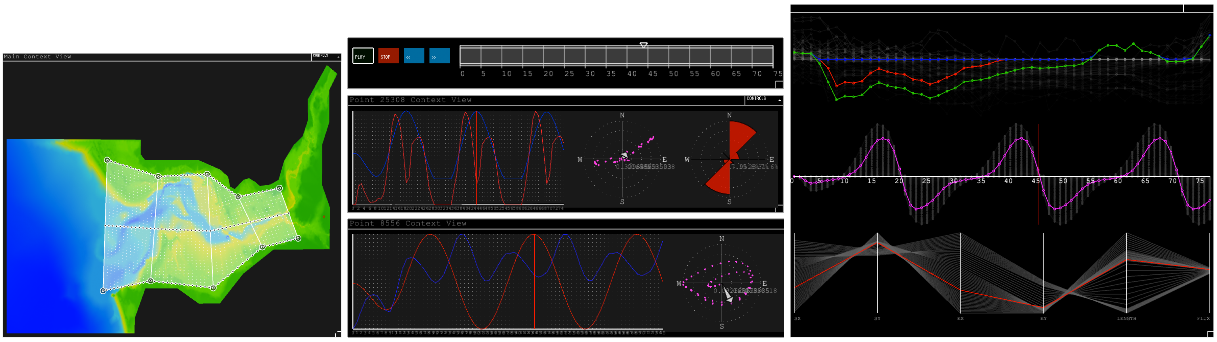

Figure 1: *Several views of our visualization system. From left to right: estuary, animation controls with two vector views, and finally the flux statistics view.*

creased freshwater run off, sediment erosion, other local factors and sea level rise [RDJ11]. But the models have limitations: they cannot currently provide a complete understanding of all the physical processes in the simulations, nor totally emulate the real world. Simulation tools such as TELEMAC-2D, used for our datasets, provide variables such as height of bed, water depth, speed and vector flow. But many of the required calculations are currently performed by separate tools: these tasks are not integrated into one workflow system.

What is required is for the data analysis to be tied more closely to the visual exploration. Furthermore, currently, the required diagnostic data is computationally expensive, which places further burdens on the tools and processes, which struggle to cope. In fact, Chave et al. [CAS*06] express the view that current tools are 'relatively primitive'. Our system, VINCA [GRDR12, Geo13]; provides a visual analytics interface, and incorporates several principles to enhance performance. These include: temporal caching of renderings to provide fast playback, hierarchical aggregation for quick exploration, and an interactive Parallel Coordinate Plot interface for quick non-spatial or spatial querying.

Our focus in this paper is the visual transect extractor and flux calculator. This research was performed collaboratively with marine scientists under an agile refinement methodology. Few solutions through visualization and visual analytics have been proposed for flux calculation, and specifically there are no solutions for flood management and prevention. One explanation of the lack of tools is given by Cotter and Gorman [CG08], who consider flux among the most complicated diagnostic quantity to calculate and visualize for modelled data, because of inherent difficulties with the data and the reliance on unstructured grids.

Measures of hydrodynamic flux are essential in understanding the potential for flooding, as they provide a detailed picture of the volume of water moving through an area, and give an indication of the net transport of water and sediment. Tidal flux calculations are also required to measure the *tidal prism* (the difference in the volume of water between high and low tide), regarded by oceanographers as one of the most important measurable parameters supporting insight into estuarine hydrodynamics [RDJ11]. Consequently, effective methods to calculate and visualize tidal (hydrodynamic) flux are relevant not only to flooding simulation, but also other environmental applications, such as water quality/pollution management and fisheries management.

While Cotter and Gorman [CG08] describe an algorithm to calculate flux in the water column (similar to our approach) their work focuses on unstructured, deep ocean data. Other researchers calculate flux for water quality and pollution evaluation. For its visualization, Stein et al. [SSB*00] used OpenGL to display transport flux data and to obtain insight into boundary conditions; Kitsiou et al. [KdMA01] visualized water quality data in the Gulf of Lyons, and Howe et al. [HLB*08] developed an interactive 3D tool to calculate salinity flux and analyse its impact on salmon stocks.

3. Calculating flux along an estuary

Hydrodynamic flux is the flow of water through a given surface per unit of time, calculated across a transect (cross–sectional profile of the geographic domain), and measured in cubic meters per second. Thus, if $U(x,y,t)$ is the depth averaged velocity component in the x direction, at time t and at point (x,y) in the domain, and a transect is taken across the channel in the y-direction at location $x = x_0$, then the instantaneous water flux, normal to this transect is given by:

$$Q(t) = \int_{y1}^{y2} U(x_0,y,t)[z_b(x_0,y) + \eta(x_0,y,t)]dy$$

Where $y2$ and $y1$ are the points of intersection of the water surface with dry land at time t, zb is the water depth below the Mean Water Level (MWL), and M is the tidally varying elevation around the MWL.

This simplified equation deals only with the x component of the velocity (where transects would all have to be vertical), so where the direction of the transect is arbitrary, the y component of the velocity and the cross sectional area must be included into the equation. In practice, this is implemented discretely, based upon the numerically simulated data.

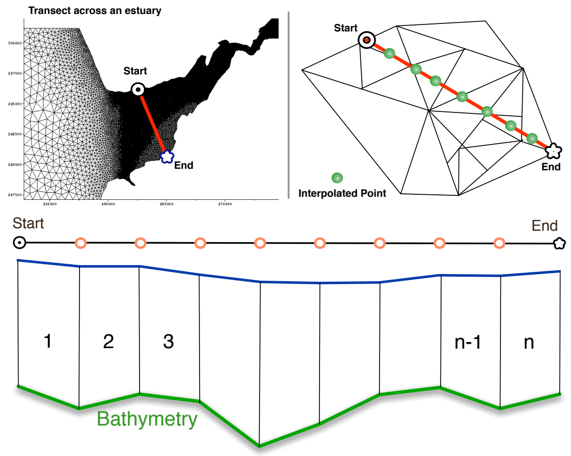

Figure 2: *The figure shows a typical transect cross-section (top left) that is divided into two end points and eight interpolated points.*

3.1. Methodology

The tool is designed to enable oceanographers to simulate field practice, by providing a number of transects and fluxes at multiple positions along an estuary or a bay. It offers two calculation methods: firstly, the user can select individual transects for investigation, but as with real surveying, this could be time consuming. Secondly, the user is able to define a range/boundary, from which the algorithm would generate multiple transects and fluxes, thus automatically calculating several fluxes within a boundary, rather than the time consuming individual calculations currently undertaken by researchers.

3.2. Transect Profiler and Flux Calculator

After defining a start and end point, the transect profiler cuts a straight line cross section from the mesh. Figure 2 depicts a typical transect cross–section. This is divided into m sample points, where m is determined by the length of the transect and a global resolution parameter (Gr). Gr is a relaxed parameter, usually set at between $1m$ and $10m$, depending on the resolution of the underlying data, to provide a whole number of sample points between the starting and ending points. Barycentric interpolation obtains the data values at each sample point along the transect line, providing an n segment transect where $n = m - 1$ (Figure 2). This piecewise description of the transect permits other important quantitative metrics to be calculated, e.g. the transect's length over ground and the cross-sectional area of the water column (area between the sea bed and water elevation).

The hydrodynamic flux is calculated along a user selected transect, producing an instantaneous calculation for all time-steps, and giving a temporal depiction of the transect's flux. It is calculated by multiplying the velocity, which moves perpendicular (normal) to the transect, by the cross–sectional area. This is calculated piecewise by multiplying the cross sectional areas of the n segments by their corresponding normal velocity, then summing individual fluxes to obtain the total flux across the complete estuary.

As the velocity data is depth averaged (average value for the velocity of the water column at that point), it is assumed that the velocity is the same at both the water surface and the sea bed. Thus, the depth averaged velocity vel_i, for each of the segments is an average of the two velocities from the interpolated sample points defining the segment. Calculating flux q_i, requires the normal component w_i of vel_i, to the transect cross section ($w_i = vel_i \times cos\theta_i$), where θ_i is the angle between vel_i and the normal to the transect segment. The flux for each segment q_i, can now be calculated as: $q_i = w_i \times Area_i$ The total flux Q can therefore be calculated as the summation of the n segments' fluxes q_i. $Q = \sum_{i=1}^{n} q_i$ Performing the calculation for all time-steps produces a time varying flux profile for the transect (Figure 1).

3.3. Flux through a domain

Comprehensive analysis of all the fluxes in the domain involves calculation at any transect through a continuous region running through the domain, necessitating an evenly spaced set of transects following the shape of the estuary/domain (not too asymmetric). These derived fluxes are visualized for further investigation, providing the user with the ability to analyse the data in a manner not previously possible. This represents a significant evolution from the few available examples of flux visualization and analytics described in the Related Work.

However establishing the continuous region can be problematical, as it must be defined to fit the shape and nature of the domain e.g. the domain may have several tributaries (affluents) – so which is the start? It may be braided into very small channels, meander or break into islands (bars) and re-join into several channels, and the curving channels often make one side longer than the other. Thus, generating a region bounding the skeleton of the domain is difficult to achieve automatically. There are several possible design solutions, which include development of a hill-climbing or gradient descent algorithm operating on the bathymetry data to generate a skeleton. This then queries the data to find points residing at the tidal maximum (highest tide contour) to generate the boundary.

However, our focus is a human-in-the-loop solution and utilizes a user defined skeleton and boundary. This gives the user complete control over the study area. The transects are automatically calculated by the system along the user-defined skeleton path. This solution is wholly appropriate because the researchers know the locations of the real-world observed data transects, and therefore the user of the visual analytics tool can mimic the position of the real-world loca-

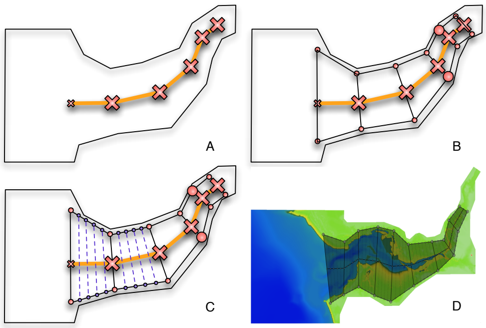

Figure 3: *Steps in calculation of the hydrodynamic flux of an estuary.*

tions to validate the tool against real world data. Our semi-automatic visual analytic approach is as follows:

Stage 1: User defines the skeleton, using a point and click strategy on key locations in the main view to define the shape, and create the desired piecewise-linear skeleton for producing the transects (Figure 3A).

Stage 2: Rectangular boundaries are generated around each segment of the skeleton, to align the boundary with the direction of the transect. The boundaries are the length of the skeleton segment and are initially set up with a constant width determined by the overall scale of dataset's spatial dimension.

Stage 3: The edges of the discontinuous rectangular boundaries are merged and edited to form a continuous, bounded trapezoid region, by averaging orthogonal components to obtain the average angle at joining ends of adjacent rectangular boundaries. The user may also move the boundary points in a constrained manner, if the boundary is not correctly fitted (Figure 3B).

Stage 4: Intermediate start and ending points are interpolated along the boundary to give a set of sample lines (Figure 3C). Intermediate points are automatically calculated using distance constant Cd, which allows for the maximum quantity of transects evenly spaced out between the control points.

Stage 5: Transects are generated for each of the sample lines (Figure 3D). Flux data is then calculated using the above methodology for all time-steps. Whilst iterating through all sample lines, the transect and flux data is stored to the database for visualization and analysis.

Stages 1-3 happen iteratively as the user defines the skeleton, with Stages 4 and 5 generating the results data when the user is satisfied with the skeleton and boundary fit.

3.4. Visualizing the Transect and Flux

The data generated through our flux calculator is stored in the database, which is then available for visualization in other view windows. Multiple windows are coordinated to enable expressive investigation and analysis of the data. We provide several views of the data. Figure 1 shows some of the views available in our system. Another design decision was to render the visualizations in a way that was suitable for screen and print display, thus requiring careful consideration of labels, scales and quality.

Figure 1 shows the line graphs that are used to represent a single transect and region based transects and the fluxes. The transect is a 2D cross sectional view, whereas the flux graph displays the data as a time varying flux curve. With the transect profile, and because the values are stored in our database, we are able to layer other information into the flux visualization, including tidal range and free surface range (and at a future date, bed evolution range). The user displays an envelope for water elevation and free surface to encode this information, but the actual value at the current time-step is still displayed.

The spatial view (top left) shows the location for all the generated transects and fluxes composited together. But the user can select one particular flux, which is displayed in a linked window. This is achieved by either direct selection in the main view (through a mouse click) or by using a slider attached to the view. The selected view is highlighted to the user, who is able to explore the data by creating fluxes, selecting particular results, displaying the statistical information in related views, altering the selection, or adapting the original flux calculation envelope. Users can also animate (the selection) of different fluxes, to view water volume changes up an estuary. Different datasets in several windows can be loaded and compared side-by-side to explore and compare different simulation parameterizations.

4. Discussion and conclusions

Our flux calculator provides a rapid, but rigorous method of extracting and analysing derived information, calculated from the underlying data. The close integration of the with the analysis, allows users to explore the information in a new way. In particular, the focus on the human-in-the-loop specification of the flux envelop, and the automatic creation of multiple fluxes, enables users to rapidly and effectively specify and explore multiple transect positions along an estuary, whereas traditionally, this was time-consuming to achieve. This supports quicker analysis, and has thus significantly speeded up an important knowledge discovery process. It also allows ocean science researchers to perform ocean science research instead of having to solve software engineering challenges in creating methodologies to perform these complex calculations.

The results generated by the tool in both the single and region based methods provide a publishable quality output suitable for screen and print display. The method has been tested by ocean scientists and proved to provide quicker and more comprehensive results. Furthermore, it is believed this method within the Vinca system currently provides both an elegant, and the speediest solution to extracting multiple transects and fluxes from modelled hydrodynamic data.

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