Interactive visual analytics of Hydrodynamic Flux for the Coastal zone

Richard L.S.F. George · Peter E. Robins · Alan G. Davies · Panagiotis D. Ritsos · Jonathan C. Roberts

Abstract Researchers wish to study the potential impact of sea level rise from climate change, and visual analytics tools can allow scientists to visually examine and explore different possible scenarios from simulation runs. In particular, hydrodynamic flux is calculated to understand the net movement of water; but typically this calculation is tedious and is not easily achieved with traditional visualization and analytic tools. We present a visual analytic method that incorporates a transect profiler and flux calculator. The analytic software is incorporated into our visual analytic tool Vinca, and generates multiple transects, which can be visualized and analyzed in several alternative visualizations; users can choose specific transects to compare against real-world data; users can explore how flux changes within a domain. In addition we report how ocean scientists have used our tool to display multiple-view views of their data and analyse hydrodynamic flux for the coastal zone.

Keywords Computer Applications · Physical Sciences and Engineering · Earth and atmospheric sciences

1 Introduction

Modelled simulations have assumed greater importance in recent years to environmental scientists seeking to understand the impact of climate change. For coastal shelf scientists, an important area of study is "sea level rise", which is an acknowledged consequence of climate change (Douglas,

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1991; Rahmstorf, 2010). Sea level rise brings the potential for increased storminess and extreme events such as hurricanes, storm surges and flooding (the latter two being the subject of the modelled data used in this paper).

Understanding how and when the sea level may rise is important, because a small rise in sea level could have a substantial impact on a significant part of the world's population. In fact, with half of the world's population living within $60km$ of the shoreline (Davies and Thorne, 2008), mathematical simulations that focus on coastal zone management are important for disaster planning and engineering, both to prevent flooding and mitigate its impact.

Coastal shelf scientists focus on the use of mathematical simulations because historic and observed data, (for example rates of change to sea levels) may not be reliable for predicting changes in the future (Brown et al, 2006). However, these simulations present specific challenges to effective analysis.

- One of the challenges to the researchers is that these mathematical simulations are 'complex' in nature. They are temporal, multi-field and multi-resolution (being derived from an unstructured grids). Such complex data is difficult to interact with, and time consuming to explore.
- There is an equally complex analytical process that needs to be managed. Calculations are made using scripts (for example with MATLAB) to process the data, and the results are stored in intermediate files. These are analysed using other scripts or visualized. While these scripts are certainly useful, researchers need to carefully manage the use of the scripts and especially the intermediate files. Therefore the process is time consuming and inhibits exploratory and interactive visualization.
- Scientists also need to explore different simulation runs that generates gigabytes or even terabytes of data, and need to be visually examined. Often one-hundred-year

simulations are made. These runs incorporate extreme weather conditions and enable scientists to compare and contrast different run parameterizations. Not only does the data need to be managed by the researcher, but visual exploration and visual comparison operations are difficult to achieve through current visual tools. Such detailed exploration and investigation is required to produce the predictions useful for coastal zone planning and management.

In fact the visualization tools that are currently used for the evaluation of hydrodynamic flux, in particular and over the coastal shelf in general, are static in nature and require considerable time to create the visualizations of multiple parameterisations. By using MATLAB it is possible to create one or two transects or sample plots (Nocke et al, 2007). While MATLAB is extremely powerful, in this instance it is difficult to create a dynamic and interactive visualization tool to explore multiple scenarios and automatically and comprehensively analyse the hydrodynamic flux in an interactive way. Interactive visual analytic tools have been created for other domains (Lipsa et al, 2012), however the multi field nature of the simulated data provides specific challenges for the domain.

For example, evaluating flooding simulation data to understand the volume of water flowing up the estuary requires calculations of tidal flux. Using traditional methodologies, we have developed a custom MATLAB script to calculate the hydrodynamic flux between two pre-defined points. But, the user needs to specifically determine the exact location of a transect. This data is then exported to a file, which is visualized at a later time, with a separate tool, using, for example Excel, GNUplot or a custom script. While this process works, it is time consuming – and depending on the size of the data can take several hours. Indeed, we have used it successfully to analyse the data, but it requires many intermediary files to be saved. In another variant, Blue Kenue (a post processing and visualization system developed for TELEMAC-2D) is used to calculate the hydrodynamic flux numerical model from the simulation data. However this process, is similarly complex and laborious and does not encourage exploratory examination.

In this paper, we describe an automated transect profiler and hydrodynamic flux calculator. Our techniques enable users to perform more timely calculations. In fact the system can automatically generate hundreds of transect calculations up an estuary. This analytic data is then stored for further detailed exploration and analysis using interactive visual analytics tools. Our techniques are developed as part of our Vinca visualization environment. Through such interaction and automation of analytic calculations, our techniques improve upon the functionality of the traditional methods mentioned above and supports the exploration of hypothesis about the changes which may lead to flooding.

This article extends a short paper that was presented at EnvirVis 2013 (George et al, 2013) workshop that was held alongside the Eurographics conference. We provide more detail of the flux calculator, our visual analytics tool and their processes, expand the related work section, explain the two case-study areas in detail, describe a pilot evaluation with ocean scientists and make a wider discussion of the work. The paper is therefore organised as follows: we describe background and the research context (Section 2), review related work (Section 3), and explain the two case-study areas (Section 4) that we have investigated for this work (the Dyfi and the Burry estuaries); we describe the flux calculation Section 5 and then our application design (Section 6); we have performed a pilot evaluation with ocean scientists, which is described in section Section 7 and finally reflect upon the work (Section 8) and conclude.

2 Background & Research context

Scientists are faced with an ever-increasing amount of complex data. Research scientists wish to add more variables, increase the dimensions, make more detailed simulation models and run these models for longer. This gives rise to a situation where there is too much data to visualize. This 'information overload' challenge (Keim et al, 2009) cannot be solved by traditional visualization techniques alone, nor by merely using analysis methods.

What is required is the mixture of visual solutions along with analytical solutions. Visual Analytic solutions support query driven tools enabling analytically important data to be identified and studied and data to be derived for further advanced study, creating an interactive, investigative environment (Thomas and Cook, 2006). While visual analytic methods have been used successfully in several domains, these systems are difficult to directly apply transfer into new fields. Specific tools for the oceanographic domain are needed to solve their challenges: tools that enable spatial, temporal, and multivariate data to be visualized, and tools that provide accurate and detailed statistical values to be presented to the user.

These requirements therefore motivate our research: to apply novel visual analytics solutions to real life coastal shelf research challenges. We have been developing a visual analytics tool called Vinca. The focus however of this paper is not the overarching visual analytics system, but one of its bespoke tools – the visual transect extractor and hydrodynamic flux calculator, researched and developed in collaboration with coastal shelf research colleagues using an agile refinement methodology.

Calculating hydrodynamic fluxes is fundamental to many aspects of oceanographic research, including understanding the potential for flooding, where the calculations provide a detailed picture of the volume of water moving through a

coastal area, giving an indication of the net transport of water and sediment. They are also relevant for other environmental applications, such as water quality, pollution management, understanding and conserving fisheries and other habitats.

In its most simple form, the flux of water in and out of an estuary is calculated to determine the estuarine tidal prism (i.e., the volume of water passing through every tidal cycle) and its flushing time (the time it takes for the total volume of water in the estuary to be replaced). The flux of a dissolved concentration substance in the water column, such as salinity or a pollutant, can be estimated in this way, enabling flushing times for a substance in an estuary to be calculated.

3 Related Work

We subdivide the related work into two parts (i) hydrodynamic flux and (ii) data visualization within the oceanographic context.

3.1 Hydrodynamic Flux

We have already highlighted the computational and visual computing challenges relating to simulated coastal shelf and estuarine data. Flooding simulations of the estuarine domain may typically incorporate spring tides, high storm surge, increased freshwater run off, sediment erosion, other local factors and sea level rise (Robins et al, 2011), together with variables such as height of bed, water depth, speed and vector flow. However, despite their undoubted capabilities, the models are also currently limited in their ability to provide complete understanding of all the physical processes in the simulations, and tidal flux calculation (the subject of this paper) is one of these limitations.

The fluxes of particulates in the water column, such as suspended and bedload sediments, can also be calculated. The net sediment transport flux in estuaries, over a lunar tidal cycle, is important for coastal management so that policy makers know whether an estuary is infilling with sand or eroding away. In the Dyfi Estuary located mid-Wales, Robins and Davies (2010) showed that the net flux of sand was controlled by the ratio of tidal amplitude and water depth; intertidal regions were generally infilling with sand, while deeper channels were eroding away. Such research has implications for the management of intertidal regions such as salt marsh ecosystems and organising navigation routes or dredging programmes.

Traditionally, time series measurements of velocity and salinity were needed to examine the salt flux of an ocean system, as was the case for Simpson et al (2001) when studying the Conwy Estuary in North Wales. By calculating the salt flux at regular transects along the estuary, Simpson et al

(2001) were able to establish the horizontal salt gradient and frontal position (e.g., where fresh water meets saline water), and show that the estuary undergoes tidal pumping of salt up-estuary, prior to rapid freshwater discharge during storm events. Simpson et al (2001) infer from their results that any dissolved constituent originating in the river system, such as inorganic carbon or nitrogen, may be retained in the estuary until high river discharge flushes the material offshore. These density-driven mixing processes are important for the local biodiversity of the estuary and surrounding catchments.

3.2 Data visualization

There are many ways to create visualizations. We have reviewed many visualization tools (George, 2013) in relation to the volume, flow and terrain visualization and presentational needs. We summarize their findings below.

Tools such as ESRI ArcGIS (Johnston et al, 2001), Fledermaus (Mayer et al, 2000), GeoZui3D and the GeoNav3D tool (Arsenault et al, 2004; Ware et al, 2001), GeoVR (Huang and Lin, 1999), GeoVRML (McCann, 2002), Vis5D (Hibbard et al, 1996), and X-VISION (Keen et al, 2001) all provide useful tools for oceanographic research.

In addition, tools such as the Virtual Geographic Information System (Lindstrom et al, 1997) include GIS capability, are capable of 3D visualization and can handle large datasets through Level of Detail algorithms.

However, Nocke et al (2007) qualifies the usefulness of many of the application systems mentioned above: they are quite old and possess limitations which hamper insight into hidden structures in multi-variate modelled data, as they focus on spatial visualization of individual models. Data visualization is certainly an accepted tool to analyze modelled simulations but few tools able to visualize data across multiple scales and numerous data sets (Szalay and Gray, 2006) or to support detailed exploration and comparison.

In fact, to support flood prevention and coastal zone management, researchers need to investigate several runs, different parameterizations and incorporate solutions that are specific to the analytic domain. Just looking at the calculation of flux. The current tools are neither simple nor swift. In fact, few visual analytics systems that focus on hydrodynamic flux have been proposed. A possible explanation as to why this problem has not been tackled with more enthusiasm is offered by Cotter and Gorman (2008) who regard flux as one of the most complicated diagnostic quantities to calculate and visualize for modelled simulations, because of inherent difficulties with the data, including the widespread use of unstructured grids. Cotter and Gorman's algorithm for calculating and visualizing flux in the water column for deep water data, however, demonstrates that it is possible to

calculate the flux of vector fields through isosurfaces, using flow data from an unstructured mesh finite element model, and furthermore that such methods are applicable to any unstructured grid oceanographic data.

There are a number of examples of the visualization of flux in studies of water quality and pollution, particularly in relation to coastal shelf and estuarine fisheries management, although these do not possess an integrated flux calculator. For instance, Stein et al (2000) present visualizations of modelled water quality data (including pollutants and contaminants) in Chesapeake Bay to support pollution studies for fisheries management. Hydrodynamic data was necessary to understand the transport of pollutants and their impact on fishery habitats. The model supplied vector constituent fields, with values reflecting fluxes entering and exiting, but did not display the transport flux data. OpenGL was used to develop a visualization tool, which provided insight into boundary conditions and their formulation. Similarly, Kitsiou et al (2001) incorporated flux visualization into their analytical tools studying water quality data in the Gulf of Lyons.

More recently, Howe et al (2008) describe a visualization system for understanding the factors affecting fish stocks and distribution in the Columbia River Estuary. A major concern was the impact of a salt intrusion on fishery stock, traditionally examined through selection (by trial and error) of 2D visualized slices of the salinity flux and studied as static plots. Howe et al's interactive 3D tool calculated salt flux, allowed users to sweep a plane through the field arbitrarily and visualized the salt flux vectors as barbs. This was acknowledged by researchers as providing greater insight than traditional study methods.

As described in the introduction, current methods often utilize several individual files, that are operated by scripts. Chave et al (2006), for example, describes these tools as 'relatively primitive' – and computationally expensive. This places yet more of a burden on current approaches and tools, which are already struggling to cope with the demands of analyzing complex data. Consequently there is a need to develop an integrated system that links data analysis to the visual exploration.

Our tool Vinca (Visualization and visual analytics) as introduced by George et al (2012), and developed from a previous tool iCove (George et al, 2010), incorporates a visual analytic interface together with methodologies to increase the performance. These performance enhancements include: temporal caching of renderings to provide fast playback, hierarchical aggregation for quick exploration, and an interactive parallel coordinate interface for quick non-spatial or spatial querying. The use of parallel coordinate plots, in a range of domains, is growing (Geng et al, 2011). The and provides a quick view of all the data points within the system. In addition, Vinca is a multiple coordinated view system (Roberts, 2007), where users can position windows anywhere on a canvas and link items in each view together.

Tidal flux is a fundamental element of understanding the changes to water flow (velocity), caused by the differing variables within each tidal/fluvial scenario, which Robins et al (Robins et al, 2011) considers to be a key to establishing the conditions which will result in flooding in different parts of the area of study. Tidal flux, whilst a valuable measure in its own right, is essential to the calculation of tidal prism considered by ocean scientists to be a single measurable parameter providing insight into the hydrodynamics and morphodynamics of an estuary (Robins et al, 2011), and thus in understanding the impact of simulated flood management strategies measures.

However, the suite of tools typically associated with an interactive visualization and visual analytics system is unlikely to support diagnostic data calculation tools such as tidal flux – hence the need for a customized tool if the system is truly to meet the needs of flood management research. The starting point for calculation of tidal flux is the transect - the cross sectional profile of the area of interest (in this case an estuary), thus the tool developed incorporates both an automated transect profiler and the flux calculator.

A set of requirements for the tool can be formed based on the challenges described, these are:

1. Ability to extract transects anywhere within the research domain.
2. Ability to calculate the flux across this transect.
3. To provide this in a method that is familiar to the ocean science researchers.
4. Visualize the results in a user friendly format.

4 The Case Studies

We present and utilize two case study areas: the Dyfi Estuary in Cardigan Bay, Mid Wales; and the Burry Inlet (Loughar Estuary) in South West Wales (Figure 1). Both of these locations are interesting to the environment scientists and are complex domains; these encompass which river channels, salt marshes, creeks and sandbanks.

Both estuaries urgently require management to reduce the flood risk, as these relatively shallow estuaries have been subject to previous heavy management, thus their natural tidal prisms have been reduced by earlier coastal realignment. As a result, coastal defences are increasingly overtopped, because of sea level rise, increased storm surges and high river flow. Furthermore, flood waters drain slowly, which has an impact both on their ecosystems and local infrastructure. Both estuaries have a main ebb dominant channel, flanked by extensive flood dominant tidal flats and salt marshes. The mouths of the estuaries are constricted by the
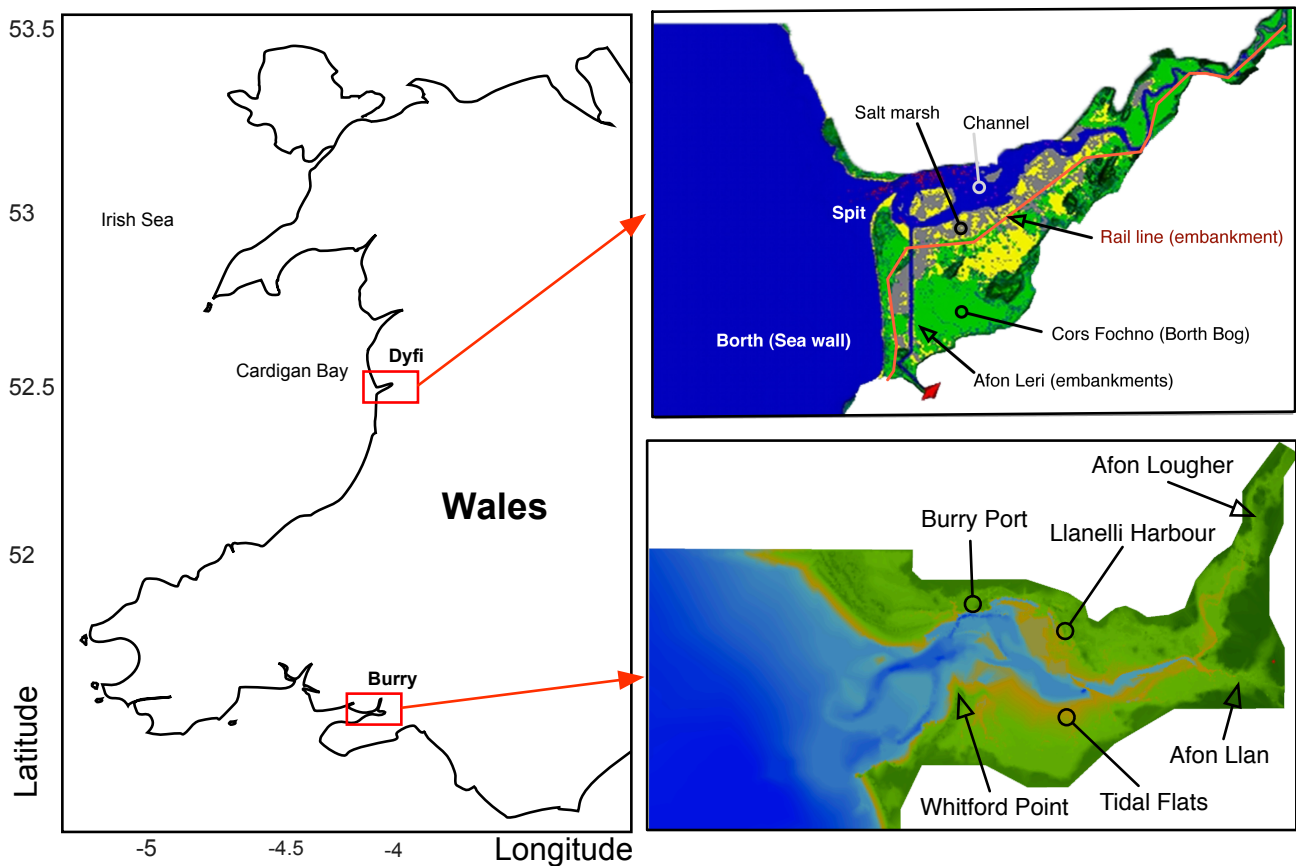
Fig. 1: Map of Wales highlighting the locations of the case study areas at the Dyfi and Burry.

presence of a spit, such that the strongest tidal flow is experienced though the mouth in both cases (Robins and Davies, 2011). These estuaries are explained in detail by Robins and Davies (2011), and Robins et al (2011).

4.1 The Dyfi

The Dyfi is a typical macro-tidal sandy estuary, (Figure 1) with extensive tidal flats and salt-marshes exposed at mid tide, contrasting with the deeper channels, which reach approximately seven metres at a high spring tide, whereas the tidal flats reach a maximum of two metres. It is some eight kms long, and two kms wide, with the width constrained to one km by the Ynyslas Spit at its mouth. This spit is composed of sand, shingle and more stable ships' ballast, dumped there. The waters of the estuary cover an area of approx $17.3km^2$. The two principle rivers which flow into the estuary – Afon Dyfi (mean flow rate $25m^3/s$) and Afon Leri (mean flow rate $5m^3/s$) – have been incorporated into the simulations and model domain includes all land below $10m$.

The size of the estuary was reduced considerably by the 19th century construction of the Borth-Dyfi Junction railway embankment, which currently acts as a sea defence for the southerly, low lying areas. Both the railway embankment, and other embankments on the river flood plains (protecting agricultural land), severely restrict the natural tidal prism. Furthermore, the embankments contribute to flooding at the town of Machynlleth, when high river flow coincides with high spring tides. Simulations are needed to support decisions on whether to reinforce the embankments to reduce flood risk, or realign them, which would threaten protected marsh ecosystems.

A particularly significant feature is the Borth Bog (Cors Forchno), a National Nature Reserve, SSSI and Special Area of Conservation, and one of the finest examples of a raised peat bog in the UK. However, it is at risk of flooding during extreme tidal and rainfall events, and its existence might be threatened by sea level rise, especially if flooding events become more frequent (Robins et al, 2011).

4.2 The Burry inlet

Sea level rise predictions around the Burry inlet (Figure 1) are similar to those of the Dyfi Estuary (Robins, 2009), but the Burry faces different coastal management issues. It too has protected ecosystems, including vast tidal flats, sand banks and extensive salt marshes on the south coast (SAC, SPA, SSSI, National Nature Reserve and others), which are at risk from increased tidal inundation, together with sediment erosion.

Larger than the Dyfi, the Burry inlet is $16km$ long with a spring tidal prism of $1 \times 10^{12}m^3$, but, unlike the Dyfi, it has a large, urbanised population on its north coast, together with rail networks and a sewage works at considerable risk of flooding. Afon Loughor (and its tributaries), and Afon Llan (including Afon Lliw) are its primary river systems, producing a mean freshwater discharge into the estuary of $1.1 \times 10^4 m/s$. The freshwater inputs, however, are insignificant when compared with the tidal prism. The tidal spit of the Burry is also threatened and might be breached, as a result of wave-induced erosion on its seaward side. This would expose the highly protected salt marsh to the open sea (Robins, 2009; Robins and Davies, 2011).

These profiles illustrate that the risks of flooding to populations and ecosystems in both areas are significant, and understanding the complex hydrodynamic factors at play is a key to flood prevention and management of the coastal zone.

5 Calculating flux along an estuary

Surveying the estuary involves standing in the middle of a channel to find the deepest point, or using differential GPS techniques. Multiple transects provide a visual depiction of the shape of the bed through the research area supporting calculation of quantitative metrics, such as cross sectional area of the water column, for use with other experimental or observational tools such as tide gauges and current profilers. Through these metrics, oceanographers are able to understand the dynamics throughout the whole research area.

Measuring flux in the field is hindered by temporal and spatial constraints. For example, to measure sediment transport fluxes, both velocity and transmissometry devices need to be installed along a transect and at high spatial and temporal resolution. To perform such an exercise at several locations and over long time scales is, therefore, impractical. Hydrodynamic and morphodynamic models can resolve this issue. However, in most packages additional (external) processing is required to calculate and visualize fluxes, as this procedure is not built into the software. This additional processing is time consuming and complex, and often the graphical outcomes are difficult to compare and contrast.

Because of these factors, frequently only a limited number of calculations are undertaken.

Figure 2 shows flux graphs comparing two modelled scenarios produced with traditional post processing methods (Robins, 2008). The top graph (a) represents a hypothetical model domain and the lower graph (b) the present day estuary shape. Cross-estuary profiles were calculated every $2km$ east from the mouth of the Dyfi (just five calculations per scenario, detailed by $A \ldots E$) for a hypothetical spring/neap tidal cycle (15 days). Whilst seeming identical, they are not, but it is difficult to identify the variations, without detailed and painstaking physical comparison of the graphs.

5.1 The hydrodynamic flux calculation

The hydrodynamic flux is the flow of a physical property, such as water, salt, or sand, through space per unit of time, measured in cubic metres per second. In oceanography, the flux is usually calculated across either a vertical plane (e.g. a transect across an estuary) or a horizontal plane (e.g. surface heat flux across the ocean surface). The instantaneous flux of water across a transect in the y direction at location $x = x_0$, is given by:

$$Q(t) = \int_{y1}^{y2} U(x_0,y,t)[z_b(x_0,y) + \eta(x_0,y,t)]dy \qquad (1)$$

Where $U(x;y;t)$ is the depth averaged velocity component in the x direction, at time t, and at point $(x;y)$, $y1$ and $y2$ are the points of intersection of the water surface with dry land at time t, z_b 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; other transect orientations require the flow normal to the plane to be calculated see Figure 3. In practice, this is implemented discretely, based upon the numerically simulated data.
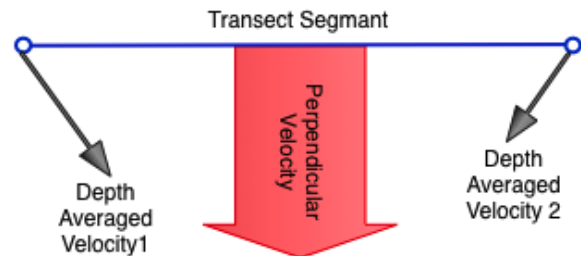

Fig. 3: For calculation of the flux on an arbitrary transect the flow normal to the plane needs to be used.
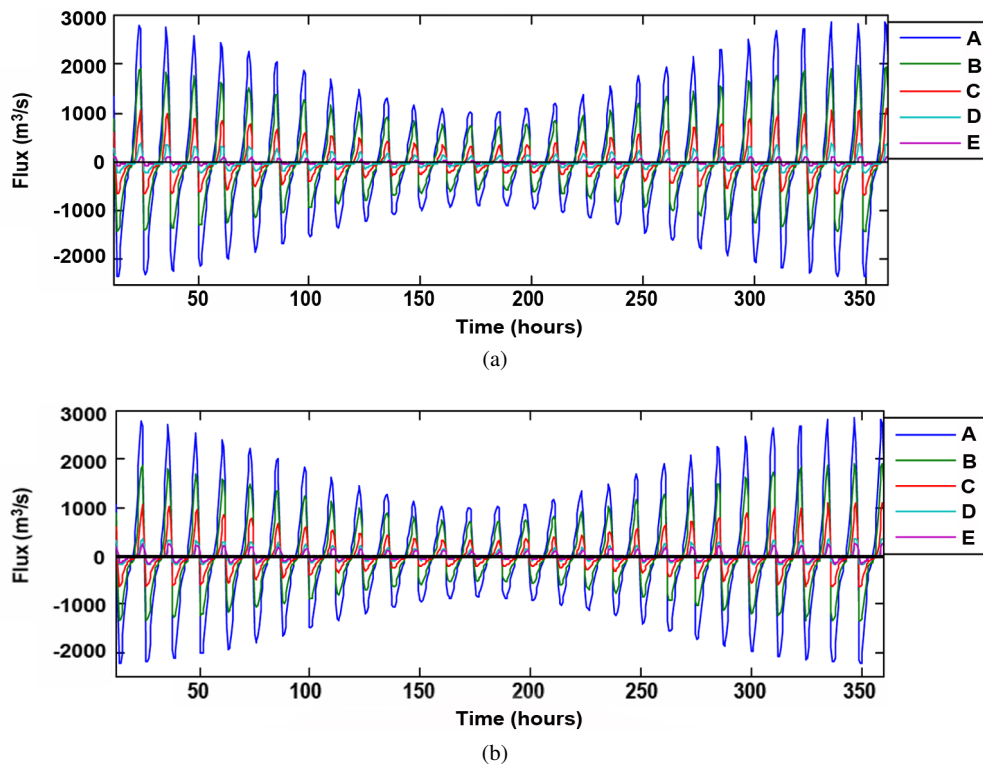
Fig. 2: Multiple fluxes from various locations in the Dyfi Estuary. (a) displays a hypothetical model, and (b) the present day estuary shape. Reproduced from Robins (2008).

The net sediment transport flux in estuaries, over a lunar tidal cycle, is important for coastal management so that policy makers know whether an estuary is infilling with sand or eroding away. For example, in the Dyfi Estuary Robins and Davies (Robins and Davies, 2010) showed that the net flux of sand was controlled by the ratio of tidal amplitude and water depth; intertidal regions were generally infilling with sand, while deeper channels were eroding away. Such research has implications for managing intertidal regions, such as salt marsh ecosystems, and also managing navigation routes or dredging programmes.

Traditionally, time series measurements of velocity and salinity were needed to examine the salt flux of an ocean system, as was the case for Simpson et al (2001) when studying the Conwy Estuary in North Wales. By calculating the salt flux at regular transects along the estuary, Simpson et al (2001) were able to establish the horizontal salt gradient and frontal position (e.g., where fresh water meets saline water), and show that the estuary undergoes tidal pumping of salt up-estuary, prior to rapid freshwater discharge during storm events. Simpson et al (2001) infer from their results that any dissolved constituent originating in the river system, such as inorganic carbon or nitrogen, may be retained in the estuary until high river discharge flushes the material offshore. These density-driven mixing processes are important for the local biodiversity of the estuary and surrounding catchment.

5.2 Tool Methodology

Our tool follows the field practice of the ocean scientists; through the provision of transects, and thus flux calculations at multiple positions along an estuary or bay. Two calculation methods enable the user to select either individual transects for investigation (but as with real surveying this can be time consuming), or else to define a range/boundary for investigating flux throughout the defined region. The algorithm automatically calculates multiple transects and fluxes within the boundary, providing a quicker solution to the problem than those currently available to ocean science researchers. A three stage process calculates flux at every position along the estuary:

1. A single transect is extracted and the flux is calculated along this transect.
2. Several *n* fluxes are calculated through a user interface which allows users to define the centre of the estuary, or the path across which fluxes will be calculated at regular distances;
3. The generated data is stored. From the stored data the user can create different visual depictions of the transect and flux; the user can filter and explore the data using different visual analytic tools within Vinca.
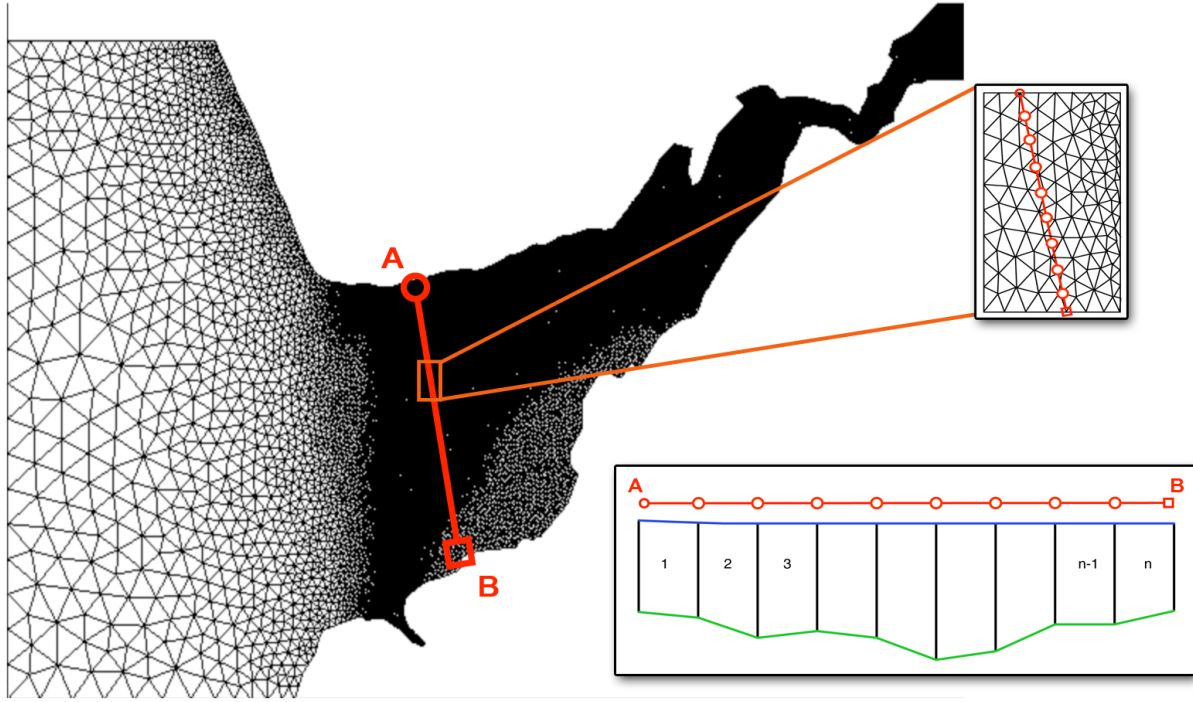
Fig. 4: The figure shows a typical transect cross-section of the dataset. The unstructured mesh is shown, demonstrating the dense (black) regions of the main estuary.

5.3 The user process

The user selects the start and end point for the transect pro-filer to cut a straight line cross section out of the mesh. Figure 4 shows a representative transect cross-section. The transect line is divided into m sample points where the length of the transect and a global resolution parameter (Gr) determines m. Gr enables a whole number of sample points between the start and end points to be selected. It is a relaxed parameter, usually set at between $1m$ and $10m$, depending on the resolution of the underlying data (which is also user assignable).

Barycentric interpolation provides data values for each sample point along the transect line, giving an n segment transect where $n = m - 1$ (Figure 4). Other important quantitative metrics may be calculated from this piecewise description of the transect. These metrics include the length of the transect over ground and the cross-sectional area of the water column (the wetted area between the sea bed and water elevation).

5.4 Flux Calculator

Hydrodynamic flux is calculated along the selected transect, using the quantitative metrics described above to produce an instantaneous calculation for all time-steps, also giving a temporal depiction of the flux across the transect. The calcu-lation is made by multiplying the velocity (which moves perpendicular – normal to the transect), by the cross-sectional area. This piecewise method requires the cross-sectional areas of the n segments to be multiplied by their corresponding normal velocity. It then sums individual fluxes to calculate the total flux across the entire selected area, for example the estuary.

For these simulations, the velocity data is depth averaged (i.e., an average value for the velocity of the water column at that point), thus it may be assumed that the velocity is the same at the water surface and the sea bed. Therefore, 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. The flux calculation q_i, requires the normal component w_i of vel_i to the transect cross section:

$$w_i = vel_i \times cos\theta_i \tag{2}$$

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:

$$q_i = w_i \times Area_i \tag{3}$$

The total flux Q can therefore be calculated as the summation of the n segments' fluxes q_i

$$Q = \sum_{i=1}^{n} q_i \tag{4}$$

Finally, a time varying flux profile for the transect is produced by performing the calculation for all time steps. The steps are shown in Figure 5 and the full screen of Vinca is shown in Figure 6.

6 Determining the flux domain in Vinca

To support comprehensive analysis of all the fluxes in the domain, transects through a continuous region running over the domain must be calculated. This necessitates us to create a set of evenly spaced transects that follow the shape of the estuary. The derived fluxes are placed in Vinca's database for further investigation using the system's visual analytics tools, such as temporal line graphs, Parallel Coordinate Plots and other views. This enables the coastal shelf researcher to visualize any of the generated transects, and compare any transects. This provides a convenient and fast way to make this analysis.

However, the requirement for a continuous region engenders several challenges. It must be defined to fit the shape and nature of the domain – for example where to start the region, as the domain may have several tributaries (affluents). There may be numerous very small channels, meanders, islands and then form larger channels and channel curvature frequently results in one side being longer than the other. This presents difficulties for automatic generation algorithms. Furthermore, changing sea-bed morphodynamics over time add to the difficulties: thus whilst the tool does not currently include sea bed evolution, an early improvement would be to incorporate a sediment transport model, to be able to progress from a fixed bathymetry.

A number of solutions to define the bounding skeleton of the test region were considered. For example, a hillclimbing or gradient descent algorithm operating on the bathymetry data could be used to generate a skeleton, with the user querying the data to find points at the tidal maximum (highest tide contour), to generate the boundary.

Our solution, however, was to focus on a human-in-the-loop solution. We utilize a user-defined skeleton to define the boundary. This enables the user to keep control over the whole study area. Transects are automatically calculated along the user-defined skeleton path – an appropriate solution as researchers will know where observed data transects were located. This means the visualization tool is able to mimic the position of the real-world locations and therefore we can validate the simulated data against real world data.

We adopt a semi-automatic visual analytic approach that allows the user to define key locations for calculating the fluxes. There are three principle stages, as described below, and demonstrated in Figure 5.

Stage 1: The user first defines a skeleton.

This is achieved through pointing and clicking on key locations to generate the main parts of the path. This process defines the principal shape of the estuary: it therefore creates a piecewise-linear skeleton. This is demonstrated in the schematic Figure 5a, and in the visualization window from Vinca in Figure 5d).

Stage 2: The second stage is to define the envelop of the analysis area.

Our tool, Vinca, first creates convex quadrilateral boundaries around each segment of the skeleton. The top and bottom axis of the trapezoids are parallel to the adjacent trapezoid, and the edges align the boundary with the direction of the transect. The sizes of these trapezoids are setup to fit in with the estuary. The edges of the discontinuous rectangular boundaries are merged to form a continuous and bounded trapezoid region by averaging orthogonal components to obtain the average angle at joining ends of adjacent rectangular boundaries.

This process generates an envelop over the domain. The user can move and edit the boundary points to better fit the envelop. This is shown in (Figure 5b and Figure 5e).

Stage 3: The transects are calculated along the estuary.

One challenge is that we wish to constrain the location of some transects such to match these with transects from real-world situations. From these defined transects, Vinca then calculates a series of key transects. Intermediate start and ending points are interpolated along the boundary to give a set of sample lines (Figure 5c and Figure 5f). Intermediate points are automatically calculated using distance constant Cd, which allows for the maximum quantity of transects evenly spaced out between the control points.

Transects are generated for each of the sample lines (Figure 5c). Flux data is then calculated for *all* time-steps. Whilst iterating through all sample lines, the transect and flux data is stored to the database for visualization and analysis. This then allows the user to investigate any time period.

6.1 Visualizing the Transect and Flux in Vinca

Data generated by the flux calculator is stored in Vinca's database and is thus available for visualization in any of the view windows. The coordinated multiple windows in our Vinca tool enable expressive investigation and analysis of the data. This is demonstrated in the screenshot from our Vinca visual analytic tool (Figure 6). We describe the views in a clockwise manner.
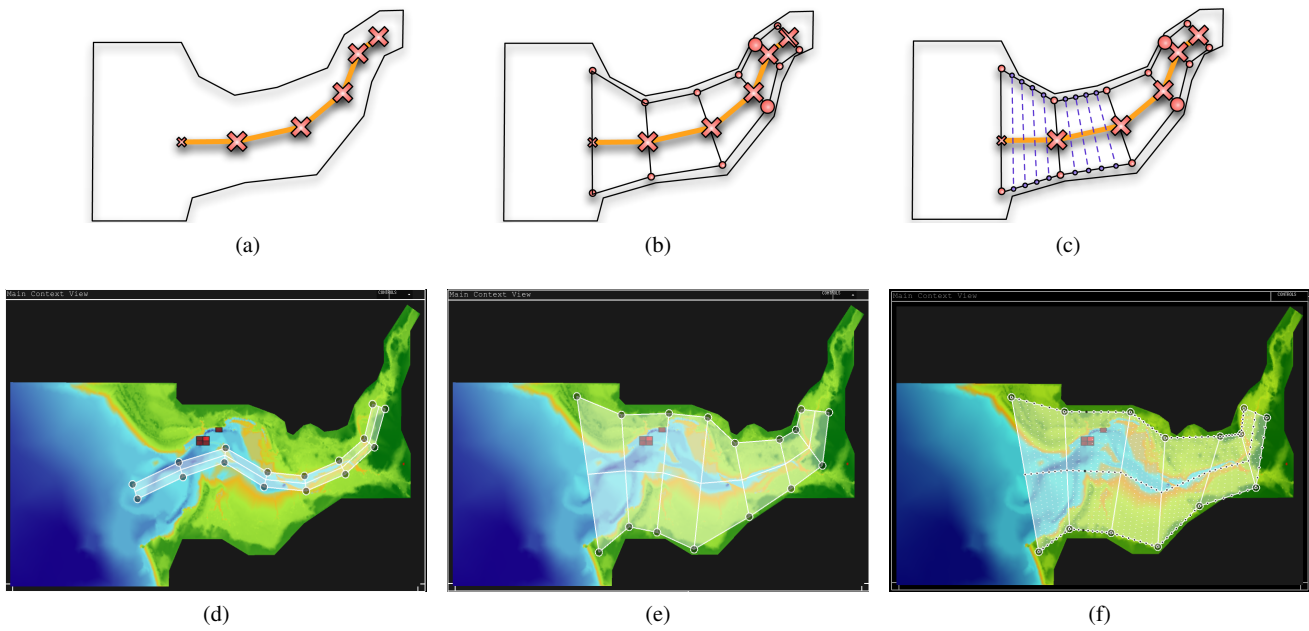
Fig. 5: There are three principle stages to define the envelop of the test area along the estuary. First the user creates the outline skeleton by defining key locations along the estuary that defines the skeleton path (5a, 5d). Second an envelop is expanded by the user to define the area (5b and 5e). Finally, the tool is direct to automatically create the transects and hydrodynamic fluxes along the estuary (5c and 5f).

It is important to investigate the data over time. The control panel (Figure 6a) allows users to control the animation of the data. Users can move to specific time points and replay temporal sequences. Because it may take a few miliseconds to render some of the views, each of the visualizations are cached in image forms, when they are first rendered. This means that the visualizations animate in real-time when subsequently replayed.

Map visualization (Figure 6b) is extremely important for ocean scientists. The map window provides facility to change colourmaps, add layers, investigate flows over time through time. High quality renderings are possible with Vinca and a few screen shots are displayed in this article. This view also shows the transects, and allows the user to alter the envelop; select and zoom into areas of interest, select single fluxes, or animate the visualization through time. This animation allows the user to view how the water volume changes up an estuary. Data from a selection operation is instantly highlighted in all the other linked views.

The two windows on the right (shown as Figure 6c) represent the Point Graph View (PGV). This allows the user to see the data from an chosen location from the 2d map view. The window shows two PGV panels demonstrating two different locations (marked by the red squares in Figure 6b). This panel has the ability to depict a temporal graph of all the time points (shown), and a temporal polar vector partition showing a vector trail, which leads to an understanding of the tidal ellipse (shown) and a polar vector rose partition

to provide a frequency based view of the vector data held at this point (not shown).

The transect profiler (Figure 6d, e and f) contains three different graphs. Figure 6f shows the Transect profile. The graph overlays each of the calculated transects, and one is selected, which is shown in a green line. The second graph is the flux curve. Again all the fluxes are shown, but the previously profile that was selected in Figure 6f is made bold and is shown in purple. Finally the third part of this window is a Parallel Coordinate Plot to demonstrate of all the parameters that are associated with the transects and fluxes. This enables the user to filter specific ranges of the data. E.g., to display all the shallow water transects. Different datasets in several windows are able to be loaded and compared side-by-side to explore and compare different simulation parameterizations.

Finally the Parallel Coordinate Plot view is shown in (Figure 6g). The vertical axis (shown as vertical lines) represent the variables of the data (such as location, salinity, temperature etc). The polylines that are connected between the axis represent the data. Potentially every data point in the database, could be shown on this plot. However, because there is a huge amount of data, we display the denser regions by a brighter colour, and the less dense areas with a light colour. This enables the points that are more frequent to be shown more brightly. Users can also constrain the range of a particular dimension, by changing the range slider positions that are located on each axis.
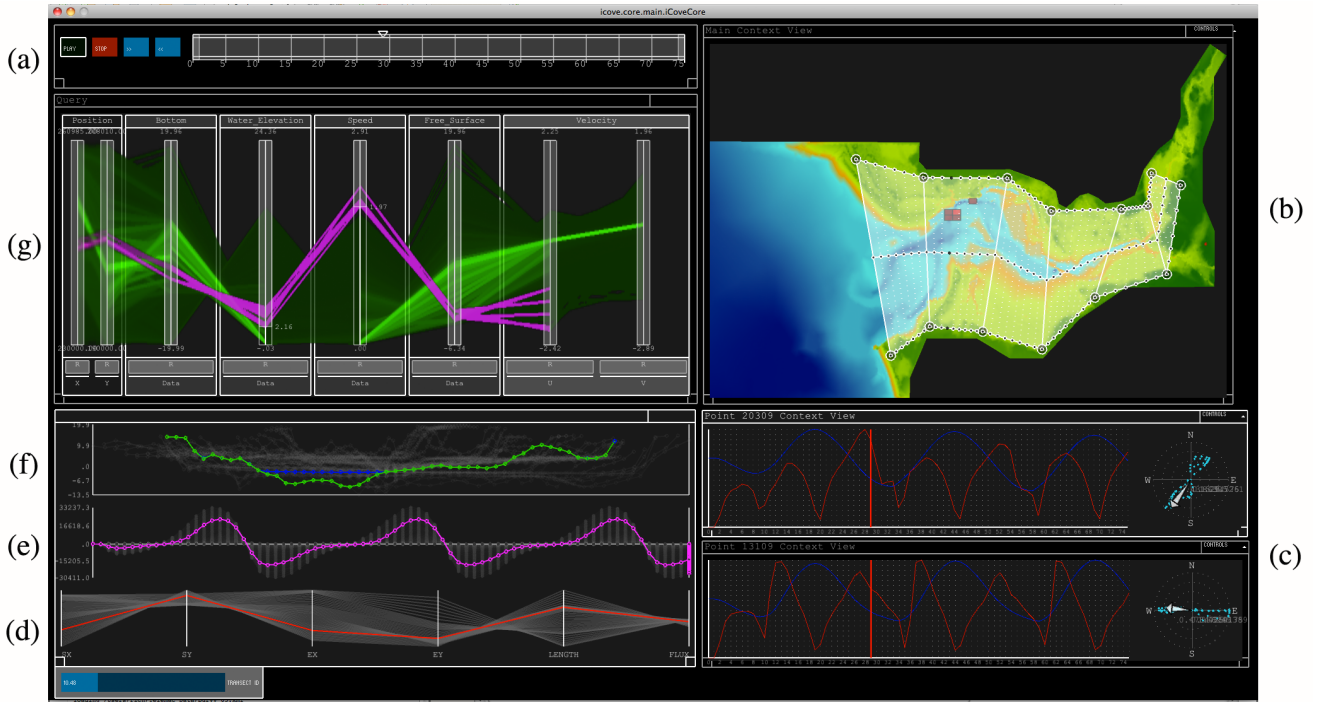
Fig. 6: The figure shows shows a full screen shot of Vinca. This includes several coordinated windows, as follows (a) the time controller, (b) map view, (c) point attribute graph, (d,e and f) transect profiler showing three parts of the calculated transects, flux curve, and parallel coordinate plot view. Finally, (g) shows the main parallel coordinate plot view.

7 Evaluation

We performed a formative evaluation of the use of Vinca to calculate and investigate Hydrodynamic flux. This was achieved using a series of think-aloud sessions (Van Someren et al, 1994) by two experienced ocean scientist users. It serves as a pilot study for further assessment in the future. Our goal was to assess Vinca's overall usability to perform this task, and to solve some of the data analysis challenges confronted in coastal shelf and estuarine research.

7.1 Evaluation methodology

The evaluation was conducted using a provided laptop with the application installed. A brief post-session questionnaire (see Table 1) was used to elicit information on specific points. We followed a protocol of introducing the project, describing the assessment procedure and obtaining written consent for participation. A background questionnaire gathered information about the participants' age, gender and expertise with computers, visual analytics and oceanographic analysis. User's where encouraged to comment on Vinca during task completion and filled in the questionnaire once the tasks where complete. Last but not least, the evaluation facilitator recorded observations on the participant's use of Vinca.

Table 1: Open-ended Questionnaire

Q.1	Describe some positive aspects of Vinca
Q.2	Describe some negative aspects of Vinca
Q.3	Briefly describe any type of enhancement that you would like to see in Vinca
Q.4	Explain whether you think Vinca will be a useful tool for aiding coastal oceanographic researchers knowledge discovery?
Q.5	What is your opinion of using an interactive visual oceanographic analytics environment, such as Vinca?
Q.6	What is your opinion on the future of interactive visual oceanographic analytic environments?

The user was given an overarching task. In our experiment their task was to identify whether their modelled scenarios may lead to coastal zone flooding. In this case, the oceanographers need to understand the net movement of water within the estuary. There are a number of key factors influencing this, such as fresh water (riverine) input and the tidal elevation. By calculating and analysing the net transport of water at different points in the domain, the user is able to predict sediment transport and assess whether parts of the domain are in-filling or out-filling and if the risk of flooding may increase.
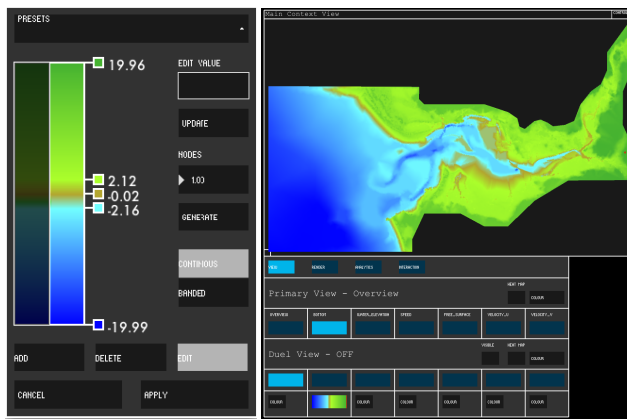
Fig. 7: The colourmap changer allows users to control how the data is mapped to colour. The mapping of each parameter can be changed. The table of parameters (bottom right) show the range of the data from blue,brown to green, as chosen by the user.
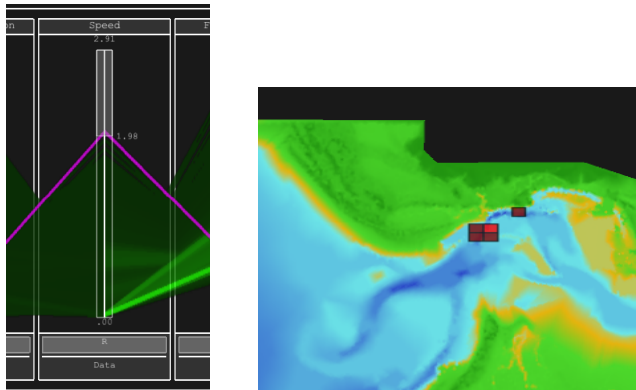

Fig. 8: The figures are cropped images of windows from our Vinca visual analytic tool. The user selects the range of the data values to explore (left) on the Parallel Coordinate Plot, which are displayed as a series of rectangles on the map (right).

7.2 Observation of the Oceanographers doing the task

We observed the users performing the task. They each followed a similar process, and hence we record this below. On reflection they performed the investigation in three parts: preparation, exploration and flux calculation.

Preparation: To prepare the data and to load the main visualization windows, the oceanographers initially loaded the data into Vinca. They then select the map view from the menu to display the map of the data. The users then changed the default colour of the mapped data into a banded colour combination (see Figure 7). Users can change the parameters of any variable. The values of these parameters are shown in a table interface (Figure 7, bottom right), where it is possible to see a thumbnail of the created colourmap. This
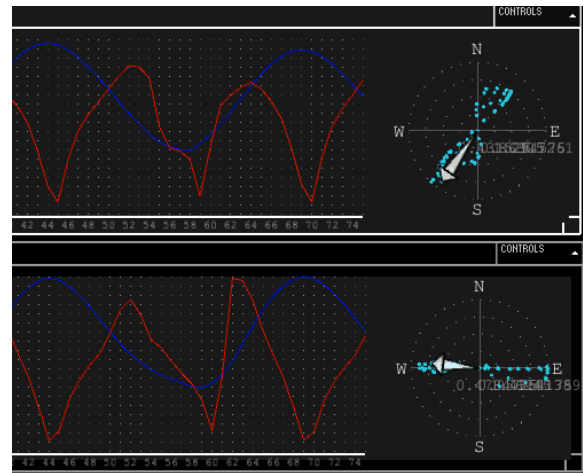

Fig. 9: The point attribute graph shows a temporal plot of the values, which were selected in Figure 8

colourmap provides a clear representation of the bathymetry and the water flow. Features such as channels or sand banks could be more easily identified by the users.

Exploration. Once coloured, the experts explored candidate positions within the estuary where the greatest volume of water flows. This was achieved by loading the Parallel Coordinate Plot (PCP) view (see Figure 6g and also Figure 8). These views are automatically linked together, such that any operation in one view effects the linked view. We note that this view can potentially display every data point in the system. The vertical bars (axis) represent the parameters, and one horizontal polyline is one data point. However, because the data is huge, the polylines would be overplotted, and difficult to interpret, therefore we use a frequency driven algorithm to highlight where the polylines are more frequent. Shades of green realize this frequency, with brighter green colour meaning that more polylines (more data points) have that range. Purple is used to highlight selected points.

The researchers then investigated areas in the data that could be considered as channels (e.g., where the water elevation was above 2m). They achieved this by selecting a range on the PCP. Areas that contain the selected data are denoted by squares on the related map view (two areas are shown, in Figure 8 right).

To study the flow, the users clicked on the selected regions in the map view (the two red squares) which loads a point attribute graph (Figure 9) which shows the tidal harmonics and polar vector trace indicating the direction of the flow. By performing these visualizations they were able to locate the fastest moving water. Therefore, they are now able to use the transect and flux calculator tool to support their analysis of the volume and flow of water in the various parts of the estuary.

Flux calculation. Finally the users created a set of transects and flux profile curves running through the domain. They followed the procedure, as explained in Section 6 and displayed in Figure 5. The oceanographers were careful to create the points running through the areas of high water flow shown on the filtered subset heat-map. Transect and flux profile curves are then generated from which researchers are able to identify and study transects and fluxes of interest, i.e., the ones running through the areas of higher water flow. By viewing these flux profiles the researchers are able to identify the areas of highest water flow, and thus sediment transport, within the estuary, and use these measures to inform their flood predictions.

7.2.1 Users comments of our tool

We follow the order of the questions, as detailed above.

Positive. Overall the ocean scientists were positive. They believed that Vinca can be a very useful tool to aid coastal oceanographic researchers. They provided several positive comments. One researcher said: "The application is well thought out with the original selection of brushed data integrated into each feature perfectly". The other said "it is a good idea but it needs a team to make a professional tool. It is good at this stage and has potential". They commented favourably on the rendering speed, ease of the manipulation and placement of the visualizations, and especially the ease by which the Transect and Flux visualizations could be displayed and manipulated. They were also keen to see how this tool could be extended to other study areas.

The *Negative* comments that were received tended to be specific to the interface. For instance, they commented on the dark colouring scheme for the GUI, the need for more control over the animations, and a wish to have a programmable interface to do more 'powerful' tasks. Changing the colour and adding more functionality to the animation tool bar are minor improvements. However the requirement for a full programming interface (such that Matlab would offer) was out of scope of the project.

Enhancements. The oceanographers appeared to be excited about our tools because we had a long discussion over future enhancements of Vinca. Ideas included, grid generation, 3d renderings and three-dimensional bathymetry views.

Use of Vinca for discovery. One of our original goals was to help the user to perform these (often) tedious tasks in an easier way. Indeed, one of the researchers said "the system is extremely well implemented with clear visual links and an easy to use workflow embedded within." "The flux and transect options are very useful for visualizing the 3d data in time".

Opinion of visual analytic tools. The users were again positive over the use of VA tools in this domain saying "indeed it [Vinca] will be helpful - visualization tools are much faster in allowing analysts to see effects and behaviours. It is a matter of speed, compared to the alternatives".

Finally the users commented on the *future of tools for oceanographic analysis*. In fact they were keen to suggest several improvements to the tool such as 3d views, methods to handle more simulation runs, and certainly positive over its potential. One researcher said "if more ocean scientists learn computing and build and use tools such as these, them I'm sure the domain will benefit greatly".

8 Discussions & Conclusions

There are certainly limitations with this pilot study, particularly with the small number of participants. However the results from this initial study were positive. Certainly it would be ideal to incorporate Vinca into the day-to-day workflow of the oceanographers; and we are planning to achieve this.

Indeed, our preliminary assessment showed that Vinca can be a useful tool for coastal shelf and estuarine researchers with many powerful features in terms of visualizing information. However, it was also evident that targeted enhancements could increase the tool's user friendliness even more, such as changing the colour of the user interface and adding three-dimensional visualizations.

Our flux calculator provides a rapid and effective method to extract and analyse derived information that is calculated from the underlying data. The close integration of the visualization capability along 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 the user to specify and explore multiple transect positions along an estuary in a way that was traditionally time-consuming to achieve. This enables a quicker analysis process, and has thus significantly sped up an important knowledge discovery process, whilst also allowing ocean science researchers to perform ocean science research instead of having to solve software engineering challenges in creating methodologies to perform these complex calculations.

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