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# Coastal Shelf Visualization using VTK and OpenDX of Hydro-Informatic Numerical Models

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**Abstract**

*Scientific visualization has an important role in climate change analysis, especially by creating dynamic interactive environments. The earth sciences, such as oceanography, utilize many numerical models; experts wish to quickly try out different scenarios and explore various possible outcomes. However, many experts still rely upon two-dimensional slices and non-interactive computer graphics to perform their analysis. Subsequently, there is a strong argument to understand current practices, learn from other disciplines and develop appropriate interactive methods to visualize and explore complex hydro-informatics. First, this paper presents a discussion of two prototype visualization tools that were developed to represent coastal shelf tidal flow data where the data was simulated using TELEMAC-2D numerical model datasets. Prototype 1 was developed using OpenDX and Prototype 2 with VTK. Second, various strengths and and weaknesses of each system are discussed, especially in their use for exploratory oceanographic visualization. Finally, practical solutions of how both were implemented are described. Consequently, this paper provides practical and scientific guidelines that other oceanographic developers can utilize for future work.*

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications H.5.2 [Information Interfaces and Presentation]: User Interfaces

## 1. Introduction

Visualization is increasingly acknowledged as a valuable tool in scientific research, especially disciplines relying on the study and analysis of large, multi-disciplinary datasets, like the earth sciences and including ocean science. This paper focuses on the visualization of coastal shelf research, where coastal and estuarine flows are naturally very complex and unpredictable [WSG*00, LG05], thus presenting a challenge to meaningful inference. Accurately predicting coastal change is increasingly important in the context of climate change. In Wales, for example, DEFRA (Department for Environment, Food and Rural Affairs) predicts the net rate of sea level rise will exceed 10mm every year in the second half of C.21$^{st}$. So developing innovative methods to explore and analyse data is of increasing importance; especially to support more accurate models that aid the management of geographical areas which are increasingly prone to flooding. This is important as historic rates of changes to sea level may not be a reliable guide to predict future changes [BJK*06].

However, current practice within the ocean science community is to study the data using a post-processing methodology; where the data is saved from individual runs from the simulation software, processed and then visualized. E.g. this occurs in the Rubens module of TELEMAC (software commonly used by ocean scientists). Furthermore, the visualization modules tend to be limited: they utilize two-dimensional snapshots or contour plots; it is difficult to visualize multiple variables on the same plot; and little animation is provided. Additionally, the user has to switch from snapshot to

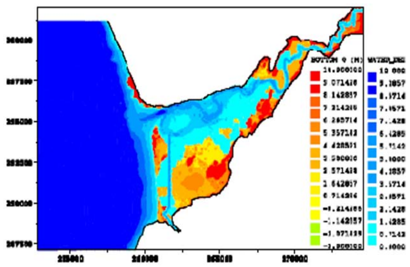

**Figure 1:** *An example of Rubens (graphics module) output [ROB08].*



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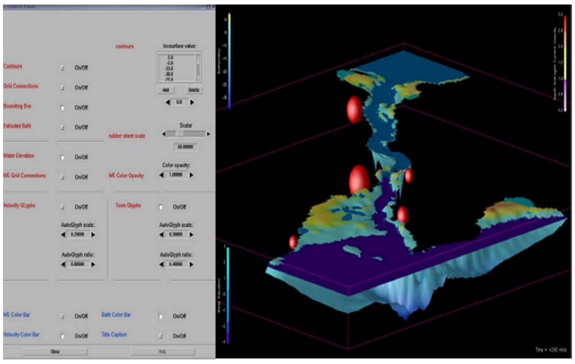

**Figure 2:** *A snapshot of Prototype 1, showing the data of the Menai Strait simulation.*

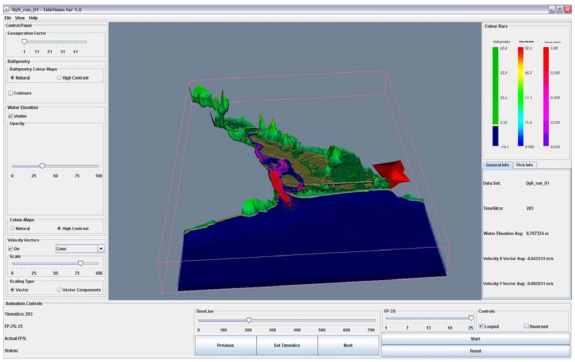

**Figure 3:** *A snapshot of Prototype 2, showing the same visualization as Figure 1, of the Dyfi Estuary simulation.*

snapshot to examine the data and so viewing static images simultaneously provides limited scope for comparison. This investigation is further complicated as the data is highly dynamic. For example, Figure 1 shows an example of a snapshot from the Rubens visualization of the TELEMAC-2D numerical model compared with a three-dimensional visualization from our tool(Figure 3). Our three dimensional tools (see Figure 2 and Figure 3) allows scientists to see all the variables in the same space and interact with the information. Developing interactive animated visualization tools that allow exploratory visualization, and visualize multiple variables in the same space, would enable scientists to interrogate the data more effectively, and integrate both large-scale hydrodynamics effects with the small scale hydrodynamics [SSB*00].

Visualization enables the large and complex datasets associated with coastal shelf science to be studied in their entirety, often revealing relationships not previously apparent, and facilitating the exchange of information [HPC*97, WSG*00], as visualization identifies spatial and temporal relationships within the data [BM00]. Furthermore, visualization may also contribute to understanding and help resolve other difficult issues relating to coastal shelf modelling and visualization, for example, paramaterisation, validation and uncertainty, which are important to achieving reliable predictions [BM00, BJK*06, SBM*05]. Setting the benefits of visualization alongside the challenge facing ocean scientists in accurately predicting changes to the coastline, there is thus a strong argument to develop more effective interrogation tools than those currently available and thus a motivation to find the most useful tool and develop the best practice.

This paper presents two prototype visualization tools. Prototype 1 (P1) was developed using OpenDX and Prototype 2 (P2) with VTK. Both tools were developed to represent coastal shelf tidal flow data, to gain an understanding of the challenges of visualizing coastal shelf models. They vary in complexity and apply two differing visualization systems to the same numerical model. P1 (the earlier prototype) focused on building a visualization tool to study aspects of a specific oceanographic domain, whilst P2 sought to develop a generic visualization tool. Much was learned about the relative strengths and weaknesses of the software used and a number of overall themes and challenges emerged in relation to ocean science visualization, which are helping to inform current research.

## 2. Background

Both prototypes visualize data that is generated from TELEMAC-2D, which is a widely used and well documented finite element hydro-informatic modelling system for coastal and estuarine studies. Although widely accepted to have a strong theoretical base, in common with all numerical modelling systems, there have been concerns of uncertainty and validation of the tool [FC00]. Its graphical post processor, Rubens, does not provide high levels of interaction and thus does not compare well against the high level of analysis possible with some scientific visualization tools.

Additionally, despite its wide use, there are few visualization tools for TELEMAC. EDF, the developers of TELEMAC, are currently working with VTK as part of the end-user simulation environment in a number of domains, but this is not related specifically to TELEMAC [HB08] and CETMEF (part of the French Ministry of Ecology and Sustainable Development) has produced a GUI for TELEMAC – Fudaa-Prepro [CET09]. However, no critical appraisal of this has been achieved. Although FUDAA does provide a Java front-end to TELEMAC, it supports limited interactivity. Thus, P2 was developed to gain an understanding of the challenges of producing a generic tool.

Prototype 2 was developed using VTK, Java and Java Swing. The aims were to develop a more general visualization tool to support TELEMAC-2D coastal shelf modelling, using scenarios of flooding over the Dyfi Estuary in Cardigan Bay. Early assessments are promising, with oceanographers positive as to the further opportunities that would be available with such a tool.

## 3. Prototype 1

Prototype 1 (P1) was developed using OpenDX to visualize datasets of the tidal flow of the Menai Strait, North Wales, and to assess whether visualization might provide greater insight into the physical processes than was provided by Rubens alone, see Figure 2. P1 was created to look at one specific coastal dataset. It would provide a tool that could be readily available to researchers, and which would also provide insight into the challenges of visualising coastal shelf data.

The Menai Strait was chosen for several reasons. It was important to select a complex area of oceanographic study, which might not be fully and effectively analysed through Rubens. The Menai Strait is widely recognised as one of the most intensely studied coastal areas in the UK, and there are a wealth of validated studies of the area using both field data and numerical modelling.

OpenDX was then selected as the software system, because of its flexibility and modular structure, and the fact that it is open source; so any visualizations would be freely available and easily distributable to oceanographic researchers. Although OpenDX has been used to visualize oceanographic data, a study of the literature shows that whilst there are many examples of systems developed to visualize specific oceanographic phenomenon, there are surprisingly few readily available general visualization tools for oceanographic visualization. In fact, it is widely regarded that tools which have been developed to visualize a specific oceanographic domain are not easily extensible for generic use [BEKE06], especially in an area such as coastal shelf science, where the domains are complex and geometry specific.

### 3.1. The Oceanographic Challenge

The tidal flow in the Menai Strait is extremely complex due to many factors, some of which affect only parts of the Strait, and there is an inter-relationship between depth, width, tidal flow, the differing types of sediment in varying sections of the Strait, and the nature of the sea bed. High tide is at different times at each end of the Menai; but the direction of the ebb and flow tide is not obvious, and the tide is seen to be asymmetric, with stronger currents on the ebb. The Swellies, a narrow, rocky channel are thought to have a strong influence on the tidal flow, as does the Isle of Anglesey on the timing of high tides. There is also a difference in tidal amplitude at the south western and north eastern entrances of the Strait [MAR06]. The tidal flow is illustrated in Figure 4. Thus, the tidal flow is complex. Specifically, Prototype 1 visualizes the data generated by Martin [MAR06], which was the first predictive model of tidal flow, water elevation and sediment transport for any point in the Strait.

### 3.2. Software Implementation and Challenges

As with many visualization systems, loading the data into the system proves to be a challenge. One of the challenges is that the TELEMAC-2D datasets are large; the output of the TELEMAC-2D hydro-informatic modelling software of the Menai Strait tidal flow analysis consists of six ASCII data files, where each file contains 50 time slices of 20967 points. In order to import the raw data using the OpenDX's General Array Importer a Java program was written to format and merge the separate TELEMAC-2D data files into bathymetry, water elevation and velocity data files. The challenge of using OpenDX to read raw data is a problem recognised by other users [SC04].

OpenDX's Visual Programming Editor (VPE) was used to create an appropriate visualization network. TELMAC-2D outputs unstructured scattered data, consequently as some of OpenDX's modules do not operate on scattered data, the data was transformed appropriately using the Connect and Autogrid modules to modify the data files. The Connect module connects the scattered data using a simple, unconstrained Delaunay triangulation (involving Voronoi tessellation of a plane) [TBF04], whereas the Autogrid module maps the unstructured grid of the bathymetry and the water elevation onto a a regular grid [TBF04], which was necessary for modules further down the visualization pipeline to operate. A useful feature of OpenDX was its ability to deal easily with coincident topology, which was to provide a major challenge in the subsequent VTK project. Finally, because the end user of the visualization was not the developer, interactors were used to provide a simple way of changing the parameter values of a module, thus the control panel had an easy to use interface with the visualization.

Speed was a major consideration. It was necessary to quickly generate a visualization, yet without compromising accuracy and quality. However, there are a number of factors that impinge upon the running speed. First, TELEMAC-2D datasets can be very large (1Gb plus) and take time to generate. Second, these large datasets take a long time to preprocess. Third, they take much time to load into the system. Fourth, the Connect and Autogrid modules are both time consuming – changing from scattered points to an unstructured grid, then to a structured grid requires a great deal of memory and consequently take time to process.

Various modules and configurations were investigated, with the aim to speed up the visualization. The solution was to split the process into two parts. First, the data was preprocessed and gridded, which was saved as an intermediate version; second the visualization loads this information to create the viewed result. In fact, the need for powerful computer resources and the requirement to balance data storage and rendering capacity to obtain the optimum outcome are widely recognised challenges by OpenDX users [SDM04]. Nevertheless, this prototype does prove that it is possible to develop visualizations of hydro-informatic models using personal computing facilities (an important factor bearing in mind the computing capacity normally available to ocean science researchers). However, to achieve interactive visualizations and investigate multiple scenarios quickly then more powerful computers and different computational methodology would be required.

One methodology could be to develop customised modules that may improve the throughput of the data and geometry through the visualization pipeline. The use of remote computing, grid and autonomic computing resources might have provided the basis for expansion of the visualization and also improved the speed of computation and thus the resolution of the visualization [BBC*07]. But, the reliance on external resources may not be suitable for long term usage of the systems as the resources may not be available, and may complicate the usability.

### 3.3. Results

Overall P1 was a success. OpenDX proved an effective way to develop an appropriate visualization tool, and the modular approach enabled the system to be incrementally developed which aided the oceanographers to view the progress and make comments as the visualization was developed. The system also permitted three-dimensional animations of the Menai Strait to be visualized. In particular, the way OpenDX controls color map, time controls, saving pictures and animations proved easily accessible and most convenient to the oceanographers.

Consequently, the visualization proved particularly useful for presentations by researchers to non ocean-science specialists, in its ability to show the complexities of the Menai Strait's tidal flow. It has been used by various users including Bangor's School of Ocean Sciences, and by Technium CAST (Centre of Advanced Software Technology) for demonstrations of oceanographic visualization to the Proudman Oceanographic Laboratory.

### 3.4. Discussion

The visualization provided the first opportunity for the data to be viewed in its entirety, (not previously possible due to the limitations of Rubens); this enabled the relationships between bathymetry, water elevation and velocity to be demonstrated and allowed researchers to view their data more clearly and interactively. The scope of this paper does not allow a detailed comparison of the visualization with the outcomes of Rubens, but one important issue was to demonstrate complex attributes of the tidal flow of the Menai Strait, which is achieved successfully in this prototype. In particular 'tidal convergence' – which can be seen along the stretch of water between Bangor and Caernarfon (Figure 4) can be demonstrated in P1. Prior work concluded that the water flow changes direction before the tide has finished rising, which may be due to the influence of The Swellies (a narrow rocky channel), as demonstrated in the contour plot (Figure 5) – a theory borne out by the visualization, where the feature is easier to identify in prototype 1, compared with the contour plot, or snapshots from Rubens, because the users can zoom in and explore this phenomena directly; Figure 6) depicts a snapshot from such an investigation, with two glyph markers depicting points of interest. By investigating the model, Figure 6 shows the flow travels in a south westerly direction (thought to be the ebb direction), yet the tide is still rising. Water travels around Anglesey and comes back down the Menai Strait from the north easterly end causing the flow of water to halt and subsequently change direction before the water has finished rising (shown by the glyphs).

### 3.5. Summary

OpenDX provides a convenient way to develop specific visualizations; the software is freely available to ocean science researchers, and users concluded that the visualizations added clarity and insight into their studies of the complexities of tidal flow in the Menai Strait, and has subsequently proved to be a valuable presentational tool. OpenDX enabled a prototype visualization to be developed quickly, although it was recognised that further developments through customised modules may be necessary to improve resolution and to enable users to interrogate their data more effectively and expand the scope of the visualization. Speed of operation – and the requirement to balance data storage and rendering capacity emerged as a key challenge. Further, this prototype was very specific to a particular dataset, and that further work was necessary to build on this to develop a tool relevant for generic use with the TELEMAC-2D numeric model.

## 4. Prototype 2

The work of Prototype 2 progressed on from Prototype 1. Again the aims were to develop a visualization tool for TELEMAC-2D, and visualize a complex oceanographic environment; it should be easily adapted to visualize different datasets and, based on the identified requirements of researchers, incorporate tools supporting enhanced interrogation of data, thus extending far beyond the capabilities of Rubens. A search of the literature had revealed validation and uncertainty issues in relation to numerical models, so it was hoped to gain some insight into this problem through the development of the visualization system. Because of the memory management and speed problems identified with Prototype 1, another objective was to try to identify means of managing these more effectively. Again, open source software would be used, to ensure the ready availability of the tool.

To broaden the application area (from the oceanographic study of the Menai Strait) and to compare and contrast the

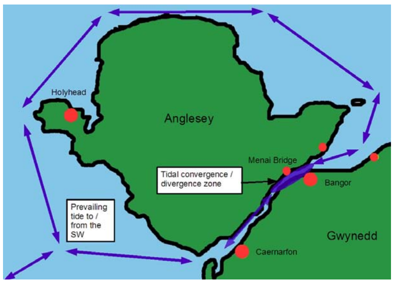


**Figure 4:** *The map demonstrates the tidal flow around Anglesey, which causes a number of complex effects; these include tidal convergence/divergence, various tidal ranges at different locations, and sediment transport.*

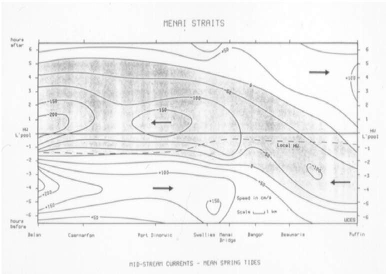


**Figure 5:** *Traditional oceanographic analysis of the tidal convergence/divergence that occurs along the Menai Straits. Image courtesy of Martin [MAR06].*

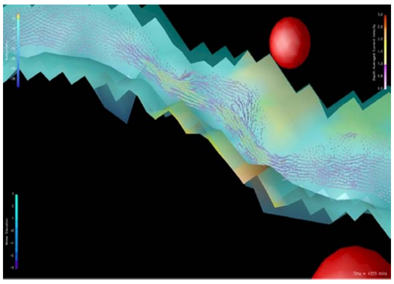

**Figure 6:** *Snapshot from P1 (OpenDX), with Bangor marked by the lower sphere glyph and the town of Menai Bridge marked with the higher glyph. The image demonstrates the flow moving in a South Westerly direction whilst the tide is still rising – a sign of tidal convergence.*

new prototype as a general tool, a new scenario was required. The study of flooding, and in particular flooding in the Dyfi Estuary using TELEMAC-2D met these criteria.

The decision to find an appropriate software system proved more complex than with Prototype 1. Originally, it was anticipated that Prototype 2 would be undertaken using OpenDX, but an early visualization of the datasets using OpenDX identified a problem. A major area of concern was undersampling at the mouth of the Dyfi Estuary, and for this reason, it was decided to look at visualization solutions other than OpenDX, which does not have undersampling detection. Using OpenDX, a visualization could only be produced by subdividing the meshes – by artificially adding points, and interpolating from those, but some holes remained. However, this was intuitive at best, and a more rigorously guaranteed outcome was necessary, using a system with constrained Delaunay triangulation, such as VTK.

A review of software solutions concluded that VTK was most likely to meet all the identified criteria: it has a large library of functions; is documented within the field of ocean science research, and is open source. A further reason was the availability of research into finite element numerical simulation, using VTK visualizations [SGM04, SBM*05]. Although implemented in C++, VTK supports Java, and other languages, thus permitting complex applications, rapid application prototyping and simple scripts. Whilst not providing any user interface components, it can be integrated with other interfaces, such as Java Swing.

The choice of Java and Java Swing for the project was largely a pragmatic one, made because of the developer's familiarity with that programming language. This meant the whole application could be built in Java, which would provide a cleaner end result. Furthermore, VTK is capable of handling very large datasets, yet it is possible to build applications quickly, and it supports a wide variety of interaction methods, which was felt to be important for obtaining the optimum results from the tool. Additionally, a relatively simple design was necessary, bearing in mind many ocean science users might not be very familiar with programming and visualization techniques.

### 4.1. The Oceanographic Challenges

The flood scenario datasets of the Dyfi Estuary, North Wales, form part of a major project in support of coastal zone management of an area increasingly prone to flooding. Estuaries are dynamic, and the complex inter-relationship between geological features, weather patterns, tidal flow, sediment transport, the nature of the sediment, and vegetation development, makes understanding the processes and predicting change a challenging task, particularly with the addition of another variable – sea level rise. In developing a generic TELEMAC-2D visualization tool, the VTK prototype also sought to demonstrate its effectiveness by adding to understanding of this complex oceanographic problem.

Whilst establishing user requirements for a visualization tool, several ocean scientists had commented on the inability of Rubens to compute instantaneous water and sediment flux (a key to understanding flooding scenarios) between defined points, leading to time consuming and complex computations. The development of a flux measurement device within the VTK visualization tool was a novel addition and would enable users to gain important new insight into their data, and a major objective of the project was to develop this.

### 4.2. Software implementation and challenges

VTK provides a completely different programming environment compared to that of the OpenDX's Visual Programming Editor. Initially, a data pre-processor, along with its own GUI was built to convert raw data into a format readable by VTK. Subsequently, building the viewer was split into two stages – loading the data and rendering. Whereas

OpenDX's system enabled the user interface to be built quite easily, with acceptable results, VTK involved programming the whole user interface, a more time consuming and complex process, and one where inherently, problems might, and did arise. We highlight three problems.

First, challenges occurred when the Java GUI was integrated with the VTK components; this resulted in an unresponsive program and was caused by blocked signals, which were generated by control panel items. This concurrency issue was caused by thread interference. However, resolution of this problem led to a further problem, such as lack of interaction by the GUI, when the animation was started. This was caused by problems relating to Swing, and effective Swing programming was needed to overcome this difficult. Furthermore, this solution had a detrimental effect on the performance of the animation, consequently speed of operation is a major issue requiring further work to resolve.

Second, the output data from TELEMAC-2D caused some geometry to be coincident. This coincident topology also proved difficult to resolve (unlike OpenDX which is able to handle multiple surfaces at the same point in 3D space). Although VTK provides methods to deal with this problem (z-buffer and polygon-offset), shifting the z-buffer was not effective in this case, and the polygon-offset has had mixed results. This is a documented problem, and the solution is to load a patch and recompile VTK using the latest version.

Third, there were challenges with selection (picking). The system uses a detailed, multi-point, high resolution unstructured grid, which presents challenges. Yet viewing geometry is an important element of visualization, and in the case of this tool, streamlining and the flux calculator were essential for effective data analysis (the flux calculator in particular). The flux calculator will interpolate new points over a cross sectional transect between start and end points, but to do so, needs to be able to 'pick' the start and stop points, which are sampled from the dataset with a set of points (the probe or picking took), to create a new dataset (output). However, due to coincident topology and the geometry created from importing the complex model, errors occurred and it was too easy to select incorrect positions. Thus, further research is necessary to produce an effective solution. Apart from solving the coincident topology issue, one solution could be to provide an interface that can cycle through picked points to select the desired one, alternatively widgets and indirect methods of selection could be employed to choose the point rather than directly picking on the display.

### 4.3. Results

A screenshot from Prototype 2 is shown in Figure 3, it shows the inter-relationship between the bathymetry, water elevation and velocity vectors. The prototype allows the user to manipulate the view, change different visualization parameters and run animations showing time varying properties of the water elevation and its velocity vectors and also allows images to be saved in various formats. At the current stage of development, it provides a framework for more innovative and novel modules to be incorporated into it – the flux calculator, measuring tools and sediment transport visualization.

### 4.4. Discussion

Early user testing of the visualization system, even at its current stage of evolution, highlights that oceanographers believe the tool, when completed, will have relevance to their work, will be validated to TELEMAC-2D datasets and will add to their ability to understand their data. Although the tool is not yet at a sufficient state of maturity of development for immediate use, ocean science researchers can see its potential. Users commented favourably on its applicability to different computational domains; its ability to complement existing data analysis techniques; the effectiveness of the user interface and ease of use and, intuitively, the apparent validity of the visualizations (although this remains to be tested rigorously). They were also able to see that it will be possible to add functionality to provide the tools they require to explore their data further and to demonstrate and explain their conclusions to others. However, speed proved to be a major challenge. Prototype 2 is still being developed and one of the focuses is to make the tool run efficiently: to provide quick animations in high resolution.

### 4.5. Summary

VTK has been successfully used to develop a generic visualization tool that supports and enhances the understanding of coastal shelf datasets modelled through TELEMAC-2D. The tool is more robust than prototype 1, and can be easily applied to various oceanographic domains. Although, P2 was more complex to develop and offered significant challenges, early user testing supports its use within the oceanographic domain. and suggests that the use of this prototype and in fact the use of VTK in general has considerable potential to support TELEMAC-2D studies of complex estuarine environments.

## 5. Discussion

Prototypes 1 and 2 demonstrated that OpenDX and VTK might be used to create relevant systems for visualizing coastal shelf datasets. Both enabled users to study tidal flow datasets in their entirety, rather than having to compare individual snapshots such as those generated by Rubens – and demonstrated it was possible to develop greater insight into the data than that provided simply by study of the numerical model. Prototype 2 was much more comprehensive in scope and thus provided a greater insight into the demands of visualizing ocean science data than Prototype 1. Nonetheless, the individual strengths and weaknesses of each system have been identified, some of the challenges of visualizing such highly complex data illustrated and common themes have emerged, which will inform future research. We highlight five key points: (1) Software and development issues; (2) Robustness; (3) Rendering Quality; (4) Data; (5) Further oceanographic applications.

### 5.1. Software and development issues

From the outset, and with both prototypes, it was decided to use open source software. This was to ensure that the visualization systems were freely available to ocean science researchers. However, VTK has a greater and more active support network, which proved invaluable for problem solving.

OpenDX provided a highly visual and design based interface, and produced a very quick result – it enabled a working visualization to be produced swiftly, because of its easily accessible library of modules. Nonetheless, it did have limitations – it is less flexible than VTK. This is because of the need to develop customised modules for complex tasks, which does not make it particularly suitable for use in developing an advanced, generic visualization tool.

VTK generally takes longer to achieve an outcome than OpenDX, but the end result is more flexible and capable of meeting the needs of researchers, as there is greater power and control. Whilst the system can be more time consuming and difficult to install than OpenDX, once the shared libraries are developed, then it is easy to integrate that copy of VTK with the visualization tool. Portability is essential if the tool is to be transferable between domains, and VTK is able to run on any system, because of its availability in a variety of different programming languages. It is thus more portable than OpenDX, which is sometimes difficult to set up on Windows (where Cygwin has to be used). Furthermore, the Mac version of OpenDX is not open source, but experience demonstrates that it is easy to set up on Linux – which, however, is not routinely used by ocean science researchers.

OpenDX's readily accessible tools meant a visualization could be created quickly, but in VTK the visualization had to be built using components, methods and filters within the system. E.g. the control panel for animation contains more parts than in OpenDX. This proved more time consuming - – but enabled the resulting tool to be tailored more closely to the needs of the researchers. The Use of VTKDesigner (similar to OpenDX) might provide a faster development environment, but it doesn't contain the same comprehensive modules and filters as VTK itself, and is not that intuitive – so it is limited in the same way as OpenDX.

Additionally, with VTK, it is easier to integrate new algorithms, because of the direct link to programming, than it is with OpenDX. Thus, as part of the development of the VTK tool, it was possible to provide additional visualization techniques to help resolve some of the limitations of the graphics post-processor. However, in fairness, this was not simply the result of the greater flexibility and power of VTK in comparison with OpenDX, but the facility to work alongside the Dyfi Estuary researchers, as the VTK project was undertaken in conjunction with continuing research into sea level rise. By working with the researchers it was possible to identify the problems they were experiencing with their data analysis, and suggest potential visualization solutions – for example the flux calculator and tidally averaged results.

Thus, it was concluded that the best use of OpenDX was as a prototypying tool. Given a reasonable knowledge of visualization systems, the pipelines can be built very quickly, especially as there are many tools readily available to the visualizer, enabling a rapid assessment of the visualization challenges of a project to be made. In fact, OpenDX was used effectively for this purpose in the second project, where it enabled a number of problems to be identified and solutions sought, notably undersampling within the mesh.

### 5.2. Robustness

To be able to use the visualization system for any TELEMAC-2D dataset, it must be demonstrably robust. It is important to be able to make comparisons between models and different model parameters (and users commented that they also wished the system to be developed such that variances between different datasets might be compared, through the visualization). As a test, the Dyfi data (from Prototype 2, VTK) was put into the OpenDX prototype, but it did not provide the correct results. However, when the Menai Strait data (from Protoype1) was put into Prototype 2, the system operated well. What might be concluded, therefore, was that the Open DX system was appropriate for the development of a visualization to support analysis of a particular oceanographic domain, (and likewise, so would VTK had it been used in such a project). However, testing the two prototypes as indicated demonstrated that the greater flexibility and complexity of VTK makes it a more suitable system for the larger scale project to develop a general oceaongraphic visualization tool.

### 5.3. Rendering Quality

With OpenDX, our experience was that the rendererd results were at a lower quality than compared with VTK. Also, users mentioned that the GUI has a dated look and feel (not ideal for the further development of a cutting edge tool). However, one of Open DX's major strengths was its ability to deal with coincident topology, which proved such a time consuming problem for the VTK project, but this did not outweigh its weaknesses. In fact, further development of OpenDX as a visualization tool for coastal shelf modelling would require modules to be written by the visualization developer to provide better rendering; to resolve other problems and to enable the system to run more quickly.

### 5.4. Data

Currently the TELEMAC-2D data was imported into Rubens to save the data in a usable format. Consequently, neither prototype, at their current stages of development, was able to replace Rubens, as both imported and formatted ASCII output from Rubens. Although it would be possible to write specific routines to input the data directly from TELEMAC-2D, this will be challenging as Rubens is used both to access the raw data and then to analyse it. A solution is more likely to achieved within VTK, rather than OpenDX because of VTK's greater flexibility in integrating with other systems, but there may be a further impact on speed of processing, which will need to be addressed, because more tools will slow down the system further. There are well documented difficulties in integrating OpenDX with other systems: as reported by various researchers; Severijns and Martino [SDM04] in relation to PRISM (Project for Integrated Earth Systems Modelling), and in regard to visualizing physics data [SC04]. In particular Szczesniak commented on the difficulties OpenDX experiences in importing extremely large datasets, due to the operating memory requirements, and the need to filter data [SC04]. Furthermore, often these data import solutions are not portable to other visualization environments. E.g., the attempts to apply the Prototype 1 visualization system to the Dyfi data were not successful, yet the development of a generic visualization tool requires a readily transferable solution to the problem of importing data.

Speed of data handling was an issue for both prototypes. OpenDX struggled to handle the large scale datasets, which was a major concern, as the visualization produced dealt only with M2 tidal data – the incorporation of other datasets such as S2 tidal component and sediment transport would have had an even greater impact on speed of operation. Solutions of parallel computation may be successfully used. For example, Brodlie et al. [BDG*04] use IRIS Explorer and OpenDX to demonstrate how various modules can be successfully run remotely in a grid computing environment, while running on parallel processors should reduce the preprocessing time [ALSM00]).

### 5.5. Further Oceanographic Applications

A complex and challenging problem in relation to coastal shelf numerical models, including finite element models, such as TELEMAC-2D is that of parameterisation, uncertainty and validation. In view of the increasing predictive need for such models, for example relating to sea level rise, finding solutions to this problem has greater immediacy. It is recognised that visualization may have an important role in this, and VTK's ability to integrate other algorithms will be important here [BM00, BJK*06, SBM*05]. The integration of other algorithms is also important in developing further tools to aid interrogation and analysis of data (e.g. side-by side comparison of visualizations of differing simulations and analysis of variances). VTK's flexibility is evidenced in other visualization demonstrations, such as the visualization of water quality in Chesapeake Bay [SSB*00], where researchers used a VTK visualization tool to visualize transport flux data and gain new understanding of boundary conditions in the upper part of the Bay – which in turn was used to restructure the numerical model used for data gathering.

## 6. Conclusions

From the case studies and two prototypes we conclude that the VTK prototype was more effective in providing ocean scientists with greater insight into their data. It is more robust and flexible; it is portable and has greater functionality, thus supporting its use for a wider range of projects than the OpenDX prototype – although it has to be recognised that the first prototype provided a valuable learning experience on which the second prototype could be built. Furthermore, the experience of conducting the first case study enabled a fuller trial and evaluation to be conducted with the second study.

Speed proved a major problem for both prototypes. However, the greater flexibility of the VTK system should enable this problem to be resolved. Re-implementing the DPP to be multi-threaded and run on parallel systems should reduce the pre-processing time, and Ahrens et al. [ALSM00] suggest that this approach for both task and pipeline parallelism appears to be successful. Other areas of exploration might be remote processing or DEX (dextrous data explorer) which focuses on selection of what is regarded as scientifically interesting data. This may achieve significant increases in processing speeds with VTK [SSBW05]. However, some caution with this approach in relation to coastal shelf modelling may be necessary in view of the uncertainty issues relating to numerical models, as it required modification of the data. Furthermore, VTK is more likely to meet the important criteria of performance (speed etc); portability, in its ability to support different languages and platforms and integrate with modelling software; and flexibility in developing interrogation tools meeting identified user needs.

Both OpenDX and VTK are able to provide effective presentational tools for use in oceaonographic presentations. Whilst acknowledging that these are primarily tools for scientific visualization, the outcomes of the research are routinely presented to non-academic clients – thus there is a need for simplification of the output. The use of the Menai Strait visualization by Bangor's Ocean Science department and Technium CAST for this purpose demonstrated the relevance of OpenDX, and undoubtedly VTK's flexibility would enable tools to be developed to ease understanding of the complex processes taking place.

Work is ongoing to develop a third prototype; learning from the two previous tools and developing solutions that are faster to render while still high quality. Our research is focusing on the same coastal oceanographic domain, and looks to solve the three challenges of (1) providing more interactivity and exploration functionality (2) allowing users to discover and explore various scenarios and different outcomes, and (3) to provide greater analysis tools, which would allow the user to measure and analyse various outcomes.

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