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Author(s)	Fallon, David; Nash, Stephen
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Galway Bay Bathymetry Comparison from Admiralty Chart & LiDAR Datasets

David Fallon,[1] Dr Stephen Nash,[1]
[1]National University of Ireland, Galway, Connacht, Ireland

Abstract
The primary objective of this paper was to test the sensitivity of numerical models to bathymetry datasets. Bathymetric datasets used were from; 1) Admiralty Charts and 2) LiDAR & Multi-Beam Echo Sounder surveys. The bathymetries were examined by comparing the contour maps, mudflat extents, basin volumes at various stages of the tide, tidal current velocities, current direction, and water surface elevations. The model results indicate that the main effect of bathymetry accuracy seems to be on the magnitude of current velocity and negligible effects on current directions and water surface elevations.

Keywords: Admiralty Chart, Bathymetry, Current Velocities, DIVAST and LiDAR

Introduction

Historically, the coastal zone has been the most heavily populated region worldwide; today it constitutes home to approximately 60% of the global population. Practically all land-derived materials such as water, sediments, and nutrients enter the near-shore waters by means of surface run-off and groundwater flow, large quantities of matter and subsequent energy mixes and circulates with the open ocean. Consequently, it is considered to be one of the most energetic areas of the biosphere, due to diverse geochemical and biological activity it supports (Nash, 2010). Therefore, numerical modelling of near-shore waters is an important management tool with regard to the correct monitoring of nutrients discharged, as well as the impacts of climate change and inevitable coastal flooding. In addition, models can simulate the effects that hydraulic structures have on flows and solute transport and can also be used to predict the impacts associated with energy harvesting which can impede tidal flows.

The traditional source of bathymetric data has been Admiralty Charts; however, they can be quite old and the seabed profile can change over time. A more advanced and accurate source comes from LiDAR (Light Detection and Ranging) and Multi-Beam Echo Sounder surveys. Tidal flows are influenced by tidal forcing (tide, wind, freshwater inflows), bathymetry and coastline topography. Bathymetry and the shape of the coastline have a considerable impact on tidal flows, when water depths decrease as it approaches the shore, the tide shoals result in an increase in tidal amplitude (Cornett 2008).

The purpose of the present research was to determine the sensitivity of model-simulated tidal flows to changes in bathymetric data, and in particular to improvements in the accuracy of a bathymetric dataset. In the present research, two different bathymetric datasets were input to a numerical model and the results compared to determine differences in the resulting tidal flows. The first dataset was obtained from Admiralty Charts and the second from LiDAR surveys. For the purpose of this paper LiDAR refers to data acquired from Light Detection and Ranging and Multi-Beam Echo Sounder surveys. To the Authors' knowledge this is the first sensitivity study of this kind as it is quite rare to have accurate surveyed data for the full extents of a model's domain. More commonly Admiralty Chart data is used to fill in the gaps in a surveyed bathymetry dataset.

This research was undertaken to establish the effects of different bathymetric datasets on hydrodynamic circulation in Galway Bay. Bathymetric datasets were developed using Admiralty Chart data and LiDAR data, a height/depth acquisition system. A comparative study of the datasets involved the analysis of the bathymetric models developed from both datasets; basin volumes were calculated and compared at different stages of the tide. The mudflat extents at low tide were also compared as these areas are important for management of nutrient discharges. The bathymetric models were included in a numerical model to simulate the tidal regime within Galway Bay. The numerical model was used to compute current velocities, current directions and water surface elevations throughout the model domain.

Methodology

Numerical Model

The model used for this research was DIVAST (Depth Integrated Velocities and Solute Transport), a two-dimensional, depth integrated, finite difference model developed for hydrodynamic modelling of shallow, near-shore waters in the coastal zone. The model is comprised of two linked modules: 1) a hydrodynamic module which simulates currents and water surface elevations, and 2) a solute transport module which simulates the transport and fate of up to twelve different water quality parameters. This research was only concerned with the hydrodynamic module. This module is based on the solution of the Navier-Stokes equations and takes account of the effects of local and advective accelerations, earth's rotation, barotropic and free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model.

The model employs an implicit finite difference scheme based upon the *Alternating Direction Implicit* (ADI) technique to solve the governing differential equations. This technique divides each time step into two half-time steps, enabling a two-dimensional implicit scheme to be applied; however, only one dimension is considered implicitly for each half-time step. The major advantage with this approach is that it eradicates the requirement for solving a complete two-dimensional matrix and reduces the computational cost (Falconer et. al., 2001). The model carries out computations on a uniform rectilinear grid with equivalent grid spacing's in the x and y planes.

The governing differential equations employed by the model to ascertain the water surface elevation and depth integrated velocity fields in the horizontal plane are based on integrating the Navier-Stokes and continuity equations (three-dimensional) throughout the depth of the water column. Full details of the model formulations can be found in (Hartnett et. al., 2011).

Study Area

Galway Bay was used as the study area for this research. It is a large bay situated on the west coast of Ireland bordered by County Galway to the north/east and County Clare to the south. The bay in entirety is 62 kilometres long and extends from the Brannock Islands (west of Aran Islands, denoted as A in Figure 1) to Oranmore (B) in the east. At its largest extent, the mouth of the bay is 33 kilometres wide and extends from Doolin (C) to Lettermullan (D), but it contracts to

10 kilometres from Black Head (E) to Leac na Gibeoige (F). The bay is separated into two sections; the inner bay and the outer bay (approaches to Galway Bay). The inner bay is reasonably shallow with depths under 30m below Mean High Water Spring (MHWS). The outer bay extends seaward towards the Aran Islands which dominates and protects the bay. The outer bay gradually deepens to 60 metres to the northwest and southeast of the islands where it reaches proximity to the Atlantic Ocean (INFOMAR.ie).

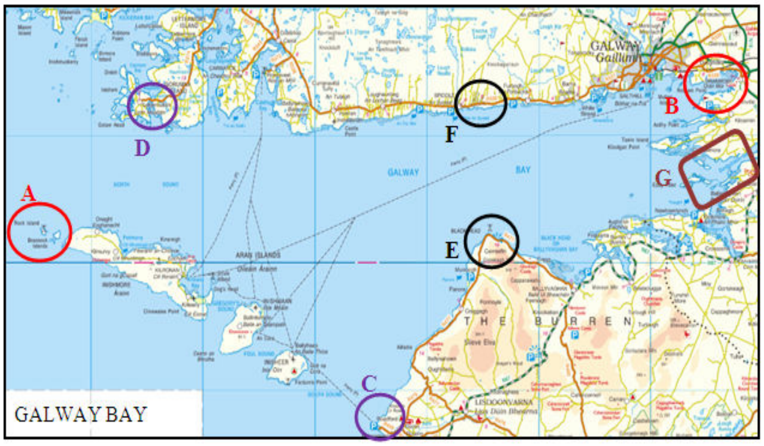

Figure 1 Map of Galway Bay (courtesy of Geolives software)

Bathymetric Datasets

The aim of this research was to determine the effects of different bathymetric datasets on simulated tidal flows in Galway Bay. The first dataset was sourced from Admiralty Charts. Two different Admiralty Charts were used to generate a dataset containing Irish National Grid coordinates and water depths, an inner bay chart and an outer bay chart. The inner bay chart (Chart N^{o} 1984, published 1980) was mapped at a scale of 1:30,000 and the depths were recorded in metres below chart datum, taken as the level of lowest astronomical tide (LAT). The outer bay chart (Chart N^{o} 3339, published 1903) was mapped at a scale of 1:48,450 and depth soundings were recorded in fathoms. The two Admiralty Charts were georeferenced and digitised in ArcGIS 10. The digitisation process involved tracing the coastline and the various depth contours and entering spot depth readings. The inner bay and approaches to Galway Bay had 1,462 and 5,995 spot depths alone to be digitised respectively. When the digitization process was completed the raw data was output and a contouring software package used to interpolate the unordered data onto a regular grid with a 270m grid resolution in both the x and y directions.

LiDAR (Light Detection and Ranging), is a remote sensing technology that uses laser scanning to measure the distance from a LiDAR sensor to distant objects (OSi). An airborne LiDAR sensor accumulates information in X, Y, Z (easting, northing and depth in this case) when the sensor is flown over the area of interest. The laser sensor emits 150,000 pulses per second towards the surface of the Earth. Each laser pulse is reflected off any objects it encounters on its journey to the ground and returns to the airborne laser sensor. The sensor measures the time it takes each laser pulse to reach the surface terrain or the seafloor and back and this information can be used to produce a three-dimensional representation of the topography surveyed. The **IN**tegrated Mapping FOr the Sustainable Development of Ireland's MArine Resource (INFOMAR) programme was a joint venture between the Geological Survey of Ireland and the Marine

Institute. The project succeeded the Irish National Seabed Survey (INSS) and their task was to generate a range of integrated mapping products of the physical, chemical and biological features of the seafloor in the near-shore area (INFOMAR.ie).

The INFOMAR surveys commenced in 2006, a LiDAR survey of the region along the southern coast of the bay from Oranmore Bay to Black Head was undertaken. The research vessel the Celtic Voyager continued a Multi-Beam Echo Sounder survey in an easterly direction from the Aran Islands to beyond Black Head. In 2007, a hydrographic and geophysical survey of the inner part of Galway Bay was conducted by IMAR Surveys Ltd. A further LiDAR survey was undertaken along the northern coastline of the Bay and the eastern periphery of the Aran Islands in 2008. The Celtic Voyager were tasked with completing any gaps that existed between the LiDAR and earlier Multi-Beam surveys to the south of the bay off the County Clare coast and alongside the eastern coast of the Aran Islands. These combined surveys resulted in an accurate merging of formerly acquired data (Figure 2) into one meticulous dataset (INFOMAR.ie).

The LiDAR and Multi-Beam data used in this research were in ASCII file format and were based on the Irish National Grid 1965, which is a projected coordinate system. The spatial resolution for the data was 270m. The ASCII file was then imported into Golden Software's SURFER^{TM} software and a grid file and contour maps were produced. The grid extents were synchronised with the coordinates of the Admiralty Chart data, which ensured that all coordinates were the same on both sets of grids.

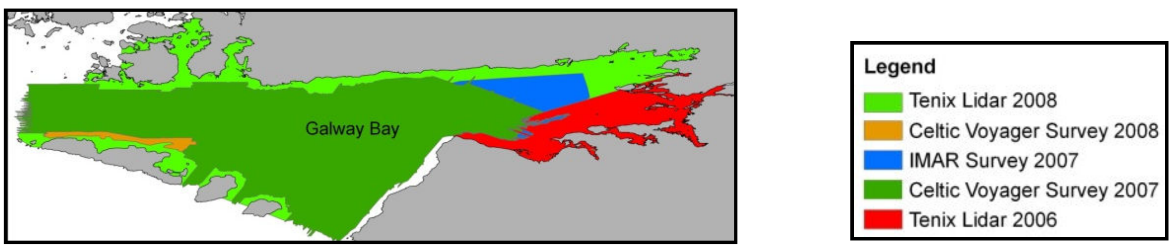

Figure 2 Map showing the coverage from all surveys involved in the INFOMAR project (INFOMAR, 2008)

Modelling

Two numerical models of Galway Bay were developed, one using the Admiralty Chart bathymetry, the other using the LiDAR bathymetry. The digitised data from the Admiralty Chart and the LiDAR ASCII XYZ file was interpolated and subsequently gridded using Golden's SURFER^{TM} software, resulting in a finite difference grid for each dataset. The grid spacing for both had equal spacing of 270m x 270m in two orthogonal directions. A total of 45,828 grid points were used to define the bathymetry for both models. The water body extent was defined by stipulating land boundaries. Water elevation boundaries were specified at western and southern limits of the model domain. These boundary conditions were the principal forcing functions that induced water circulation within Galway Bay. The same physical parameters were specified in both models.

The hydrodynamic model was used to calculate current velocities, direction and water surface elevations over a constant spring tidal cycle. The model start time corresponded to high water on spring tides and ran for two tidal cycles (25 hours). Eight time-trace locations were specified in the model (see Figure 3) at which tidal current velocities, directions and water surface elevations were output. The full model domain is shown in red in Figure 3 and the inner bay area is shown in dashed black.

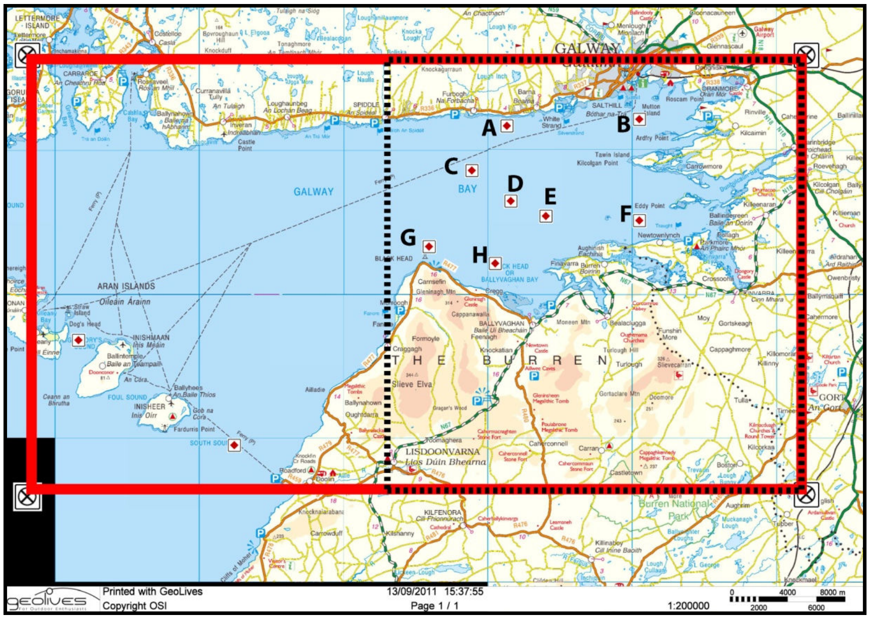

Figure 3 Galway Bay map illustrating the time trace locations

Results

Results from both numerical models were compared to determine differences in the bathymetric datasets and in the computed current velocities and water surface elevations. Two- and three-dimensional bathymetric contour plots were used to calculate basin volumes and compare the extents of inter-tidal mudflats, while time series of the hydrodynamic variables were analysed to ascertain differences in the hydrodynamic regimes.

Comparative Analysis of Bathymetric Datasets

3-D bathymetry contour plots are presented in Figures 4 and 5 which accurately correspond to the 2-D plots (Figures 6 & 7). Both the 2-D and 3-D contour plots highlight the bathymetry and the yellow coloured contour indicates the mudflat area. The contour maps from both datasets clearly indicate that the inner bay is relatively shallow with water depths 30 m or less. The LiDAR surveys, which are typically effective in depths not exceeding 15 m in Irish coastal waters (INFOMAR) were deemed suitable for large sections of the inner bay. These results portray that the bay gradually deepens as it extends westward, and depths reach 60 m at two distinctive areas; 1) between Inishmore and Connemara (the North Sound), and 2) between Inisheer and Co. Clare (the South Sound). Furthermore, there are two straits of deeper water between the Aran Islands known as Gregory Sound (between Inishmore and Inishmaan) and Foul Sound (between Inishmaan and Inisheer) where water depths were measured at 30 - 40 m. The contour maps from both datasets are generally in good agreement, although, there are some minor differences in small pockets of areas.

Mudflats are coastal wetlands formed by mud, silt and clay and are exposed as the land dries out at spring low tide, the greatest extent of mudflats. The contour plots in Figures 5 and 6 reveal that they are quite similar for both datasets. However, we can assume that LiDAR data is more accurate than Admiralty chart data because the mudflat profile would have changed since they were first charted. Therefore, LiDAR data would provide more accurate modelling in the near-shore regions.

To further quantify differences in the bathymetric datasets, the volume of water in the tidal basin was calculated for both the full model domain and the inner bay. The basin volumes were calculated for three stages of the tide: Mean Spring High Water (MHWS), Mean Water Level and Mean Low Water spring (MLWS). Basin volumes were calculated according to:

$$Basin\ Volume = \sum (H_{i,j} \times grid\ cell\ area)$$

… for all grid cells in area of interest

The volumes calculated from the LiDAR dataset were greater than the Admiralty Chart dataset for each water level for both model domains (Table 1). The percentage difference for all three water levels was less than 5% and 9% for the complete and inner bay domains respectively. The two model domains compare well, however, the LiDAR volumes are assumed to be more accurate because of the changes to the seafloor topography and mudflat extents since the Admiralty Charts were charted.

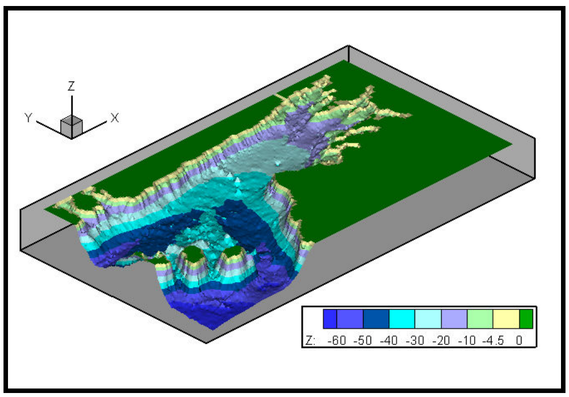

Figure 4 Admiralty Chart contour plot (3-D)

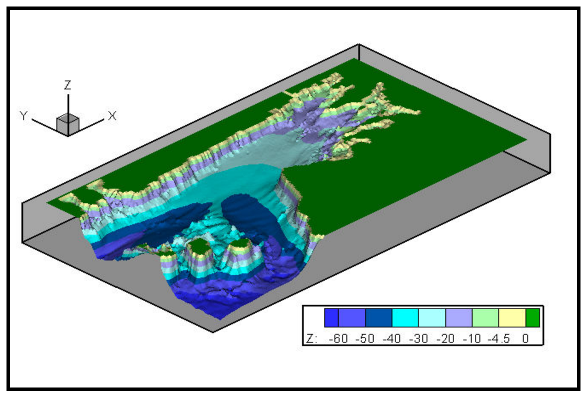

Figure 5 LiDAR contour plot (3-D)

Comparative Analysis of Hydrodynamics

The results from the model simulation are presented as time series analyses at two of the 8 cell locations specified throughout the model domain (Figure 3). Time trace plots (Figure 8) for both datasets illustrating the variation of current velocities and water surface elevations over time were output during the simulation. The remaining 6 locations A, C, E, F, G and H produced comparable results for both models, but the largest differences occurred in areas nearest the mudflats (Loc B). Moreover, the percentage difference in water depths between the two datasets at location B and D was 5.95% and 2.35% respectively, therefore, water depth accuracy is a significant parameter for the model simulation. The water surface elevations and current directions (see Figure 9) for all 8 locations produced near identical results. Consequently, the time series locations were specified in the deeper areas of the inner bay and near the coastal mudflats to provide a representative analysis of the tidal flow variations. The main effect of bathymetry accuracy seems to be on current velocity magnitude while it has little or no effect on current directions and water surface elevations.

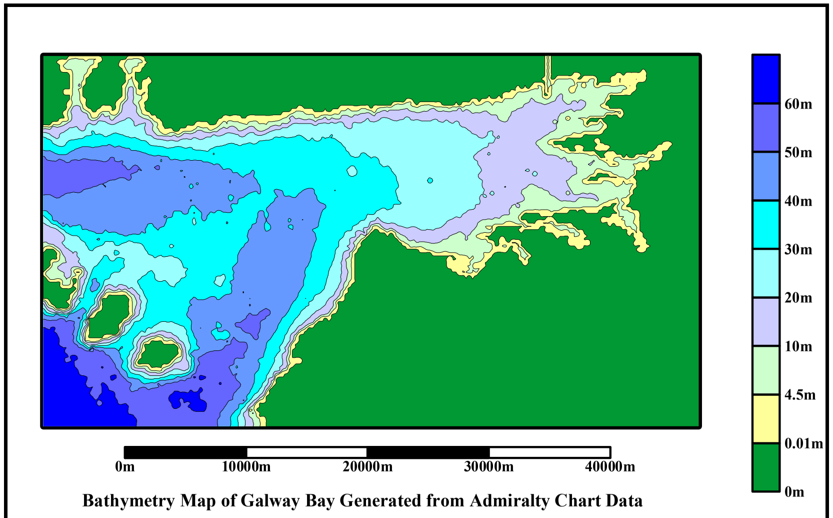

Figure 6 Contour Map of Galway Bay from Admiralty Chart Data

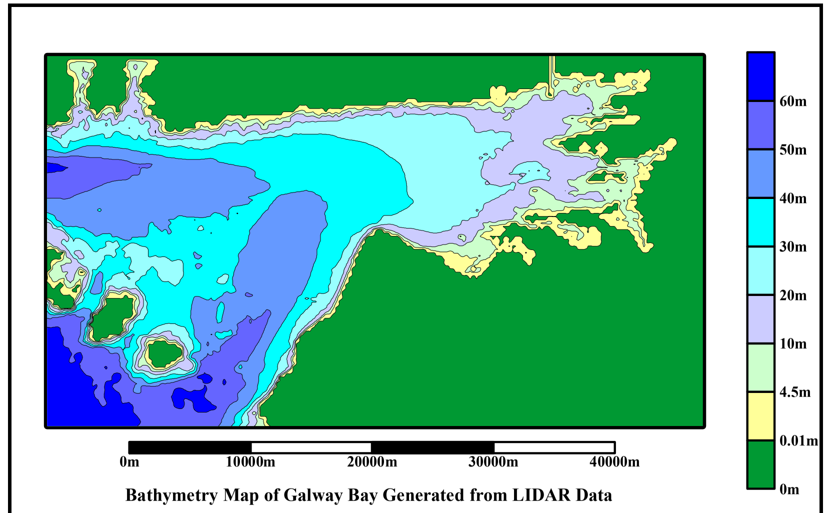

Figure 7 Contour Map of Galway Bay from LiDAR Data

	Complete Model Domain			Inner Bay Model Domain		
Basin Volumes Calculated at Various Water Levels	Basin Volume Calculated from Admiralty Chart Data (m^3)	Basin Volume Calculated from LiDAR Data (m^3)	% Difference	Basin Volume Calculated from Admiralty Chart Data (m^3)	Basin Volume Calculated from LiDAR Data (m^3)	% Difference
MHWS	26158787399.608	27141918930.116	**3.62**	4034035588.487	4423959754.153	**8.81**
MSL	24253581912.201	25239728295.160	**3.91**	1539508816.077	1577093060.672	**2.38**
MLWS	22389956981.017	23390533554.315	**4.28**	1315703377.729	1334547752.260	**1.41**

Table 1 Basin volumes at three stages of the tide for both the complete and inner bay model domains

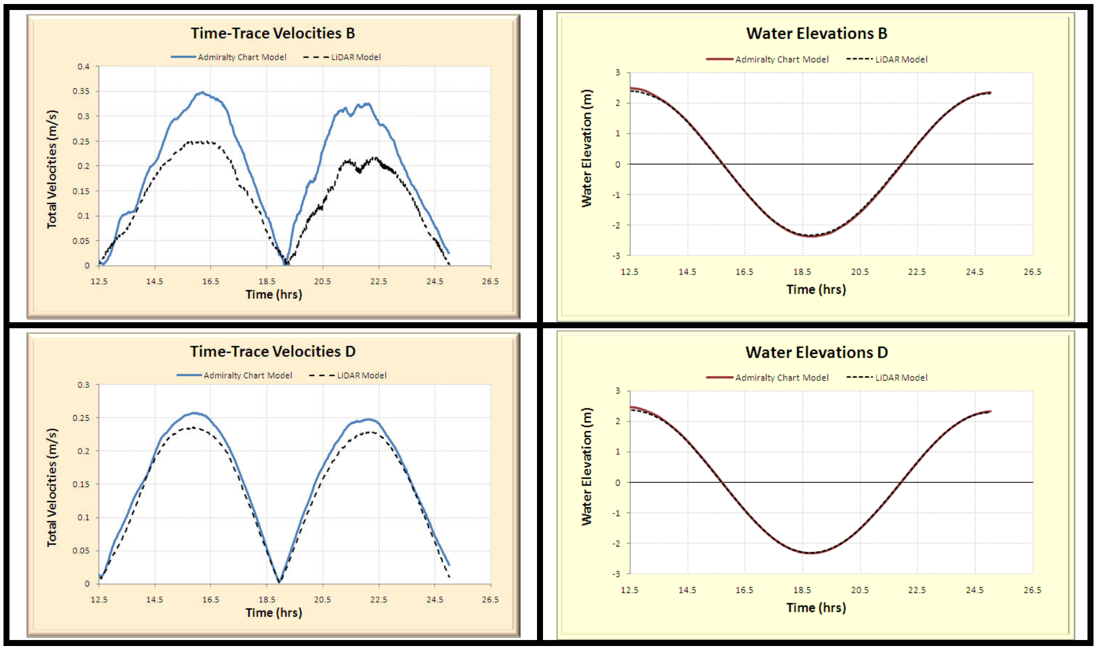

Figure 8 Time trace velocities and water surface elevations (A & D)

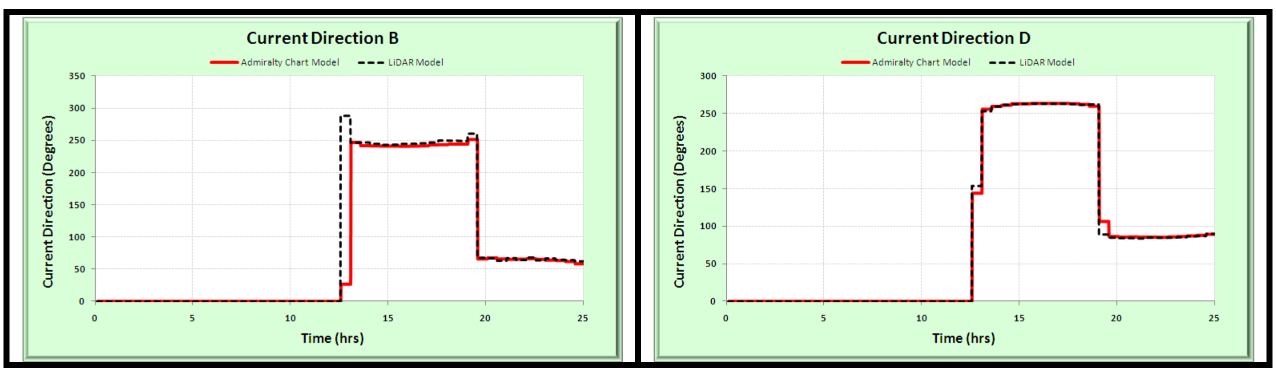

Figure 9 Current direction plots at time trace locations (B & D)

Summary & Conclusion

The aim of this research was to determine the sensitivity of a tidal flow model to bathymetric data obtained from two different sources: Admiralty Charts and bathymetric surveys. Admiralty Chart data for the study area, Galway Bay, was obtained from two charts (Charts 1984 & 3339). These charts were digitized in ArcGIS 10 software and the data exported to Golden's SURFER™ software where the data was interpolated and a grid file generated. The LiDAR data was obtained from the Infomar project and was in ASCII XYZ file format. This was also imported into SURFER™ to produce a grid file.

Bathymetric contour maps were generated illustrating depth contours from 0 to 60 m. The contour range from 0.01 to 4.5 m represents the mudflat extent around the coastal zone. The mudflat areas were relatively similar but it is assumed that LiDAR data is more authentic and would provide more comprehensive modelling of near-shore areas. Basin volumes at MHWS, MSL and MLWS were ascertained from the grid files, and the bay was segregated into complete and inner bays for comparison. The percentage difference at each tidal water level was below 5% for the complete domain modeled and less than 9% for the inner bay model domain.

DIVAST was the model of choice used to generate the results from both models. The models output current velocities, water surface elevations and current directions at 8 time series locations. Generally, the results of current velocities were reasonably similar apart from some notable differences which occurred at locations nearest mudflat areas. The results show that current direction and water surface elevation are relatively independent of the bathymetric data. In deeper water, the current magnitudes were also quite insensitive to the different bathymetric datasets; however, in shallower near-shore waters velocity magnitudes were quite sensitive to the bathymetric data specified. This finding has particular consequences for the use of numerical models for the simulation of near-shore discharges and for their use in near-shore coastal management.

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