Appendix L5

Extracts from HR Wallingford Report
Hydrodynamic Modelling of Sruwaddacon Bay

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1. Introduction

This report was prepared by HR Wallingford for RPS Consulting Engineers, on behalf of Shell E&P Ireland Ltd to inform their planning application for the onshore section of the Corrib Gas Field pipeline, County Mayo, on the west coast of Ireland.

A number of options are under consideration by Shell of the route for the onshore section of the pipeline, which will carry gas from the deepwater Corrib field to the onshore gas treatment terminal. Where the route passes through and/or adjacent to Sruwaddacon Bay there is a need for information and data on the flow regime in the Bay. The data will support assessment of the route selection and evaluation of the works required for construction of the onshore section of the pipeline. This assessment will take place in Stage 2 of the present study.

This report describes the results from Stage 1 of the present study: namely, a review of the available survey data for the Bay, and the set-up and validation of a two-dimensional, depth-averaged, numerical hydrodynamic model for Sruwaddacon Bay. A comparison between the model predictions and time-series measurements of water depth, flow speed and direction is presented at four locations where measurements were made.

2. Scope of Work

The following items are included in the Scope of Work whereby HR Wallingford would assist in the assessment of the potential impact of the onshore part of the Corrib Gas Field pipeline. The work required to support selection of the optimal pipeline route and design for the proposed sections crossing Sruwaddacon Bay were grouped into two Stages, as summarised hereafter.

2.1 STAGE 1

1.1 Review of field data made available by RPS (bathymetry, water levels, flow measurements, river discharge, seabed cores, particle size distributions);
1.2 Preparation of the field data to serve as model input or model validation data, in cooperation with RPS;
1.3 Set-up of the baseline two-dimensional, depth-averaged, numerical hydrodynamic model to cover the area shown in Figure 1;
1.4 Validation of the hydrodynamic model on the basis of the field data for three periods of one tidal cycle: a neap tide, an average tide and a spring tide;
1.5 Production of the underlying Technical Note summarising the results of Stage 1.

2.2 STAGE 2

2.1 Identification of the pipeline routes and construction methods in consultation with Shell and RPS, and agreement of the scenarios and deliverables of Stage 2 in a kick-off meeting;
2.2 Set-up and simulation of the agreed scenarios with the validated numerical hydrodynamic model for the same three periods simulated for the baseline;
2.3 Assessment of the impact of the construction works on the hydrodynamics and sediment dynamics on the short and long term, and footprint of the construction works on a local and bay-wide scale;
2.4 Production of an interim statement on the outcomes to serve as basis for a meeting with RPS and Shell;
2.5 Production of a Draft Report, including a non-technical summary to feed into the Environmental Impact Assessment.

3. Review of the Field Data

3.1 BATHYMETRY

Bathymetric data for Sruwaddacon Bay and Curraunboy Bay was made available by RPS. This multi-beam echo sounder data was collected by vessel-based surveys. Figure 1 shows the coverage of the bathymetric measurements.

The horizontal spacing of the provided data varies between 2m in the deeper channels and 150m to 200m on the for the survey vessel less accessible tidal flats. Due to the observed limited relief on the tidal flats interpolation between observations on these flats is likely to give acceptable results.

The received data covers most of the proposed model domain (refer to Figure 1), albeit with somewhat lower resolution on some tidal flats and parts of the northern Curraunboy Bay, as well as in the river reach at the southeastern end of Sruwaddacon Bay up to the model open boundary directly downstream of the confluence of Glenamoy and Muingnabo River, and on the sand bank along the southern bank near the northwestern entrance of Sruwaddacon Bay.

RPS provided further information based on digitised contours from an aerial photograph representing high water mark contours and outlines of water features, which proved helpful in the interpretation of the bay morphology.

Although the bathymetric data does not provide full coverage, realistic assumptions for the bed levels in the identified areas with lower resolution could be made on the basis of the additionally provided information and interpretation of further aerial photographs. The resolution of the data in areas covered was sufficient for interpolation onto the defined model mesh to create the baseline model bathymetry for Sruwaddacon and Curraunboy bays (see Section 4.1).

3.2 WATER LEVELS

RPS provided water level information obtained from pressure sensors at four locations within the model domain, covering a period of approximately 15 days, from 25 July through 8 August 2007. Figure 2 shows the locations of the Moorings.

The data show a semi-diurnal tide with a tidal range varying from approximately 1.4m during neap tides up to about 3.8m during spring tides. Whilst travelling in a southeastern direction through Sruwaddacon Bay the tidal curve is deformed as a result of the local bathymetry and bottom friction. Near the entrance of the bay the tidal curve has a fairly sinusoidal shape, whereas the shape of the curve becomes more triangular, with relatively short slack water periods, i.e. periods with little variation in water level near Low and High Water. The tidal range gradually reduces towards the southeast, which is likely to be a result of the bottom friction the tidal wave experiences whilst progressing through the bay.

It is noted that the instrument at Mooring 4 was buried by sand during the second half of the observation period (approximately from 1 August 2007), which is likely to have affected the resulting recorded pressures, which have therefore not been used for model validation.

3.3 FLOW MEASUREMENTS

Acoustic flow measurements were made for the same observation period as for the water level observations, and at the same locations (shown in Figure 2). The instruments were positioned at 0.18m above the seabed and recorded flow velocities at 0.1m intervals in the water column. The flow velocities in u- and v-direction were determined on the basis of Doppler shifts in frequency of an acoustic signal reflecting on suspended sediment particles in the water column. Some irregularities in the vertical velocity profiles due to interference with the water surface could be identified in approximately the top 10% of the water column. The measurements start at 0.38m above the bed as a result of the positioning and settings of the acoustic device. A graphical representation of the flow velocity magnitudes and directions at the four Moorings, provided by RPS, has been included in Appendix A.

The recorded flow velocities and directions were averaged over the water column to produce estimates of the depth-averaged values for the model validation. Although this method produces smoother records than the original data at specific depth levels, it is noted that the resulting time series (see Chapter 5) continue to show short-period fluctuations. These may be related to local turbulent flow as well as to the accuracy of the hydrodynamic measurements as a result of the relatively fast flows in combination with the limited water depths.

The depth-averaged time series show a lengthened ebb phase and shortened flood phase for each of the measurement locations. The depth-averaged flows reach velocities up to approximately 1.1m/s at Mooring 4 during spring tides and gradually decrease towards the southeast, with maxima of about 0.6m/s at Mooring 3.

3.4 METEOROLOGICAL DATA

Meteorological data covering a period from 1 July 2007 until 15 August 2007 were provided by RPS, containing hourly records of air pressure, wind speed and direction at Belmullet. These data show that, during the hydrodynamic measurement period, the wind speeds were generally moderate (less than 12m/s) and no persistent wind direction over longer periods, with a few short-duration peaks up to a maximum of 14m/s.

A number of short-period peaks in the rainfall were identified from the rainfall records. These peaks were below 6mm in July and less than 14mm in August. It is noted that during the selected periods for model validation (see Section 0) the peaks in rainfall were below 3mm.

3.5 SEA BED CORES AND SEDIMENT DATA

The results of sediment sample analyses for a number of locations in Sruwaddacon and Curraunboy Bays were provided by Shell (see Figure 3). A preliminary review of these data show mean sediment grain sizes ranging from 120 to 340µm, with few outliers up to 8.6mm. The number of locations and spread over both bays is likely to give a relatively good insight of the horizontal distribution and variation of sediment sizes, although this obviously depends on the level of uniformity throughout the area.

The sediment information will be reviewed in more detail in Stage 2, once the routes to be studied and exact locations of the sediment samples are made available to HR Wallingford.

4. Set-up of the baseline Hydrodynamic Model

4.1 MODEL MESH AND BASELINE BATHYMETRY

On the basis of the provided bathymetric information presented in Section 3.1, a finite-element model mesh has been generated. This mesh consists of triangular elements, allowing for a flexible variation of the resolution throughout the model domain. Hydrodynamic quantities (e.g. water levels, current magnitude and direction) are computed at each node.

In areas where strong variations are expected in these quantities, the distance between the nodes needs to be smaller than in relatively uniform areas. Figure 4 shows the resulting model mesh, with high resolution along the deeper tidal channels (node distance in the order of 20m) and moderate resolution for relatively uniform tidal flats (distance of order 60m) and relatively remote areas, e.g. in Curraunboy Bay (distance up to 100m).

The bathymetric data has been interpolated onto the model mesh, resulting in the model bathymetry shown in Figure 5. The model bathymetry shows a good resemblance with the original data (Figure 1). This confirms that the defined resolution of the mesh is sufficient for a proper representation of the bathymetry.

On the sandbank in the vicinity of the western entrance of Sruwaddacon Bay limited bathymetric data was available. Through interpolation of the surrounding data, a model bathymetry could be generated nevertheless. It is noted that the water depths are limited and the main flow occurs in the deep channel adjacent to this sandbank. Therefore, the lack of bathymetric data at this sandbank is likely to have only minor effects on the performance of the model. It is noted that the validated model shows good performance at the nearby Moorings 1 and 4, thus suggesting that the bathymetry is generally well schematised in the hydrodynamic model.

4.2 OPEN BOUNDARY CONDITIONS

Figure 4 shows the location of the model open boundaries, i.e. the boundaries through which flow is allowed. One open boundary is located at the western model boundary to account for interaction between the model domain and the open sea; the second is located at the southeastern boundary, where the discharge of the Glenamoy River flows into the model domain. At these open boundaries, time series of the tidal signal (western boundary) and of the river discharge (southeastern boundary) have been imposed.

To generate the time series of the tidal signal for the western boundary, the records of water elevation at Mooring 4 (refer to Figure 2 for its location) has been analysed. An iterative procedure was used to determine the phase difference between the western boundary and Mooring 4 (i.e. the time lag between specific stages of the tidal cycle, e.g. High Water at the western boundary and High Water at Mooring 4). Subsequently, the water level record was corrected for this phase difference and imposed on the western open boundary.

To date no information was made available for the river discharge of the Glenamoy River. A constant fluvial discharge of $2.5 m^3/s$ has been assumed to be representative at the southeastern boundary. Sensitivity tests have been conducted with alternative fluvial discharges. Analysis of the model results indicated a limited impact, which could only be detected at Mooring 3.

4.3 SELECTION OF TIDAL CYCLES FOR VALIDATION

The oceanographic measurements at the four Moorings, discussed in Chapter 3, cover a period of about two weeks, starting and ending at an approximate neap tide. From the resulting records of water levels three periods of two tidal cycles were selected, with neap, average and spring tide conditions. Since the device at Mooring 4 was buried by sand during approximately the second half of the observation period, all three periods were selected from the first week of the measurement period. Table 1 lists the details of the selected periods.

Table 1 Selected periods for model validation

Tide	Tidal range (m)	Start	End
Neap tide	1.6	25/07/2007, 2nd HW	26/07/2007, 2nd HW
Average tide	2.7	28/07/2007, 2nd HW	30/07/2007, 1st HW
Spring tide	3.2	31/07/2007, 1st HW	01/08/2007, 1st HW

5. Hydrodynamic Model Validation

Simulations were made for each of the periods defined in Section 0. Each of this periods was simulated with an approximate 12-hour spin-up time to minimise initialisation effects, e.g. artificial water movements due to inaccuracies in the assumed conditions at the start of the simulations. The model was calibrated for several parameters and settings, including the definition of the seabed friction and the formulation and settings of the turbulence model.

The depth-averaged model results were compared to the depth-averaged observed records of water level, current magnitude and direction through analysis of time series plots. Further investigation of the model performance was carried out by use of scatter plots, in which the observed results were plotted against the modelled values. Ideally these scatter plots show a cloud along the 45-degree line, which has been added to each plot.

The results of the three simulated periods with the validated model are presented in the following Sections.

5.1 NEAP TIDE

A comparison between the modelled and observed time series of the water levels at Moorings 1 through 4 for the neap tide shows that agreement at Mooring 4 is excellent. This is due to the short distance between this location and the northwestern open boundary, and the applied method for generating the open boundary conditions, which were based on the water level records at Mooring 4. This agreement does confirm however, that the open boundary conditions have been adjusted and imposed correctly.

The water levels at the remaining three locations, i.e. Mooring 1, 2 and 3, show similarly good results. Although some discrepancies can be seen, the deformation of the tidal curve from a sinusoidal towards a somewhat triangular shape is reproduced in a good manner.

The observed modelled water levels have been plotted against the values in a scatter plot for all four Moorings. The cloud of scatter points are located very close to the 45-degree line, indicating a very good performance of the model.

Observed and modelled flow magnitude and direction shows good general agreement between the magnitudes and directions, including the reproduction of the lengthened ebb phase and shortened flood phase. Discrepancies between observed and modelled values are inherent to small scale variations in the actual bathymetry, e.g. small gullies and other irregularities in bed levels, and subsequently in the hydrodynamics which would adapt to these variations.

Reproduction of these fluctuations was not expected since the model does not resolve processes at such a small scale. An example is the deviation in the current direction during slack water, where the observed values show a turning of the flow rather than the modelled bi-modal directions. In the model the flow slows down, comes to an approximate halt and then starts flowing in the opposite direction, whereas the observed directions indicate a turning of the flow direction.

It is noted that the change of direction occurs at times of limited flow and does therefore not reduce confidence in the model, especially since the model will be used for assessment of design conditions that will concentrate on maxima in the flow velocity rather than conditions at slack water.

Observed versus modelled flow direction and magnitude confirms the results shown in the time series, with a slight underprediction of the velocity magnitude for Mooring 2 for higher velocities. The scatter of points away from the 45-degree line in the directions are related to the deviation in modelled and observed direction during slack water conditions.

5.2 AVERAGE TIDE

The results of modelled and observed water levels for the average tide show a generally good agreement. The model predicts the first High Water to occur slightly earlier than what has been observed at Moorings 1 through 3. The actual levels are well produced, as is the deformation of the tidal curve when travelling through Sruwaddacon Bay.

Observed versus modelled water levels shows a cloud of points to be close to the 45-degree line. The slightly oval shape along this line is the result of the small phase difference noted in the time series plot. This effect becomes somewhat more pronounced towards Mooring 3 in the southeast of the bay.

Fore the flow magnitude and direction, apart from the phase difference, the model captured the hydrodynamics well. The modelled maxima in flow velocity at Moorings 1 and 4 are very close to the observed values, whereas an underprediction is seen at Mooring 2 and during the ebb stage at Mooring 3. The latter may be a result of the interference of the fluvial discharge with the tidal flow and of differences in the model and the actual bathymetry upstream of this location. The short-term fluctuations in the observed records (discussed in Section 0), which are possibly due to inaccuracies in the measurements or small-scale processes, are not reproduced by the model (and this was not expected since the model and model bathymetry did not resolve processes at this scale).

Comparison of modelled versus observed flow magnitude and direction showed a clouds of points to be centred along the 45-degree lines and show an overall good agreement. The small velocities at Mooring 3 are slightly overpredicted by the model. This is likely be related to the schematised bathymetry upstream of this location, leading to a possibly more concentrated flow.

5.3 SPRING TIDE

The model reproduces the observed water levels well, with the minima and maxima of the correct magnitude. A small forward shift in phase is seen for High Water at Moorings 1 through 3, leading to a slightly lengthened ebb phase. It is likely that differences between the model bathymetry and the actual bathymetry, especially on the higher tidal flats, are the reason for these discrepancies. During a spring tide the water levels are higher than for other tides, thus allowing for more flow over the tidal flats. Differences between the model and actual bathymetry may thus be the reason for a different deformation of the tidal curve whilst travelling through the bay.

Observed versus modelled water levels show a slightly oval shape, centred well along the 45-degree line, is the result of the phase difference of High Water between model and observations. The levels at Low and High Water are reproduced in a good manner by the model.

For flow magnitude and direction on the spring tide, the lengthened ebb phase and shortened flood phase are well reproduced, subject to the shift in phase noted in the water levels. The maxima in current magnitude are somewhat underpredicted at Mooring 2 and Mooring 3, where at the latter location this is again likely to be related to the uncertainties in upstream bathymetry and the actual fluvial discharge at the time of the observations. It is seen that the flow directions are reproduced in a good manner.

Flow magnitude versus direction show the data to be centred well around the 45-degree lines, with the exception of Mooring 2 where the slight underprediction of the current magnitudes is apparent. The scatter plot of direction evidences a good agreement at all Moorings, apart from the variation in observed direction during slack waters.

6. Conclusions

The following conclusions were reached in this study:

- The provided bathymetry data shows a coverage of Sruwaddacon and Curraunboy Bay with spacing in the order of 2m in the main channels, gradually increasing on the tidal flats, and up to 200m in relatively remote areas. Coverage of the data extends over most of the model domain, with relatively low resolution in an area in the southeastern part of Sruwaddacon Bay up to the confluence of the Glenamoy and Muingnabo Rivers, and near the sandbank at the western entrance of Sruwaddacon Bay;

- Water level and current data from observations at four Moorings cover a period of about two weeks, starting and ending at approximate neap tides, with the exception of Mooring 4 where the instrument was buried during the second week. The water level records show the deformation of the tidal curve from an approximately sinusoidal curve at Mooring 4, near the western entrance of the bay, to a somewhat triangular shape towards the southeastern Mooring 3. The current data show short-term fluctuations, which could be reduced, but not entirely removed in the process of depth-averaging of the data;

- The meteorological data from the station Belmullet confirmed that no periods of prolonged and/or intense rainfall, nor periods of strong and/or persistent winds occurred during the hydrodynamic measurements;

- An initial assessment of the results of laboratory analysis of sediment samples at various locations in Sruwaddacon and Curraunboy Bay showed that mean grain sizes generally vary between 120 and 340µm, with few outliers up to 8.6mm. Further assessment of these data formed part of Stage 2;

- The constructed model mesh has a spacing of 20m in the vicinity of the main channels, 60m on the tidal flats, and up to 200m for relatively remote areas. Comparison of the interpolated model bathymetry with the original data showed good agreement, confirming that the defined resolution of the model mesh allows for a proper representation of the bathymetry;

- The recorded water levels at Mooring 4 were shifted in time to generate water level time series at the northwestern open boundary. The high level of agreement between the model results and observed water levels at Mooring 4 confirmed this approach. Due to the absence of actual river discharge data, sensitivity tests were made with several constant river discharges. This resulted in the assumption of a constant discharge boundary condition of Glenamoy River of 2.5m^3/s, imposed at the southeastern open boundary;

- Three periods of two tidal cycles, representing a neap (with a tidal range of 1.6m), an average (with a tidal range of 2.7m) and a spring tide (with a tidal range of 3.2m), were selected for the model validation. The model was validated for these periods, varying several parameter and model settings, including the bed friction and definition of the turbulence formulation;

- The results of the validation showed that, although in some cases slight phase differences were noted, the model was able to reproduce the water levels, current magnitudes and directions in good manner at all four Moorings. The observed tidal deformation whilst progressing through Sruwaddacon Bay was generally seen to be predicted by the model. Discrepancies in the flow magnitudes at Mooring 3, located nearby the river reach, were likely to be related to the lack of bathymetric data towards the southeastern model boundary and uncertainties about the river discharge at the time of the hydrodynamic measurements. The minima and maxima of the water levels were reproduced, and in most cases the peaks in current magnitudes were captured well;

- The comparison between data and model were considered to demonstrate an appropriate level of validation of the hydrodynamic model for Stage 2 of the project.

Figures

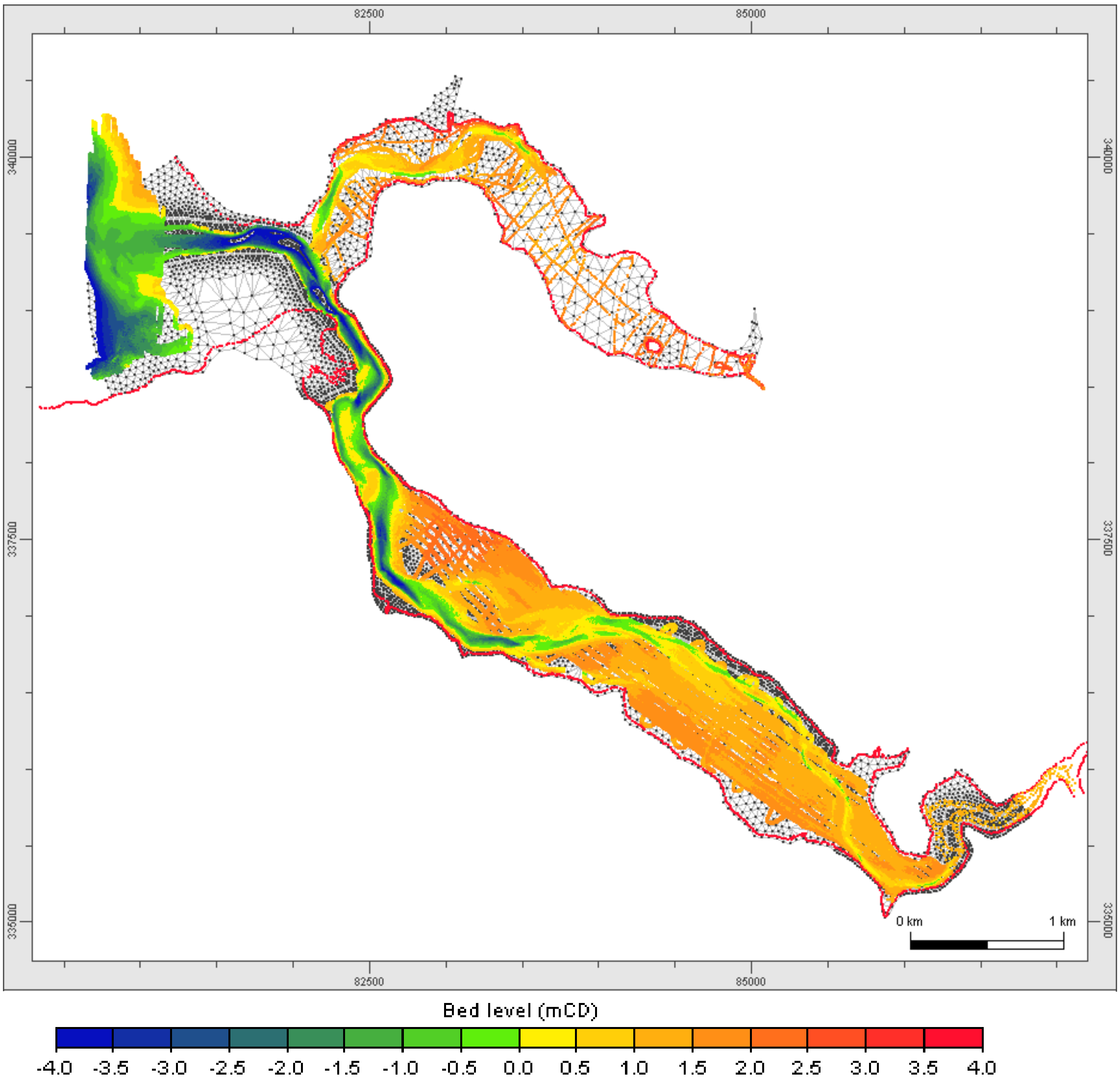

Figure 1 Model mesh and bathymetric data coverage

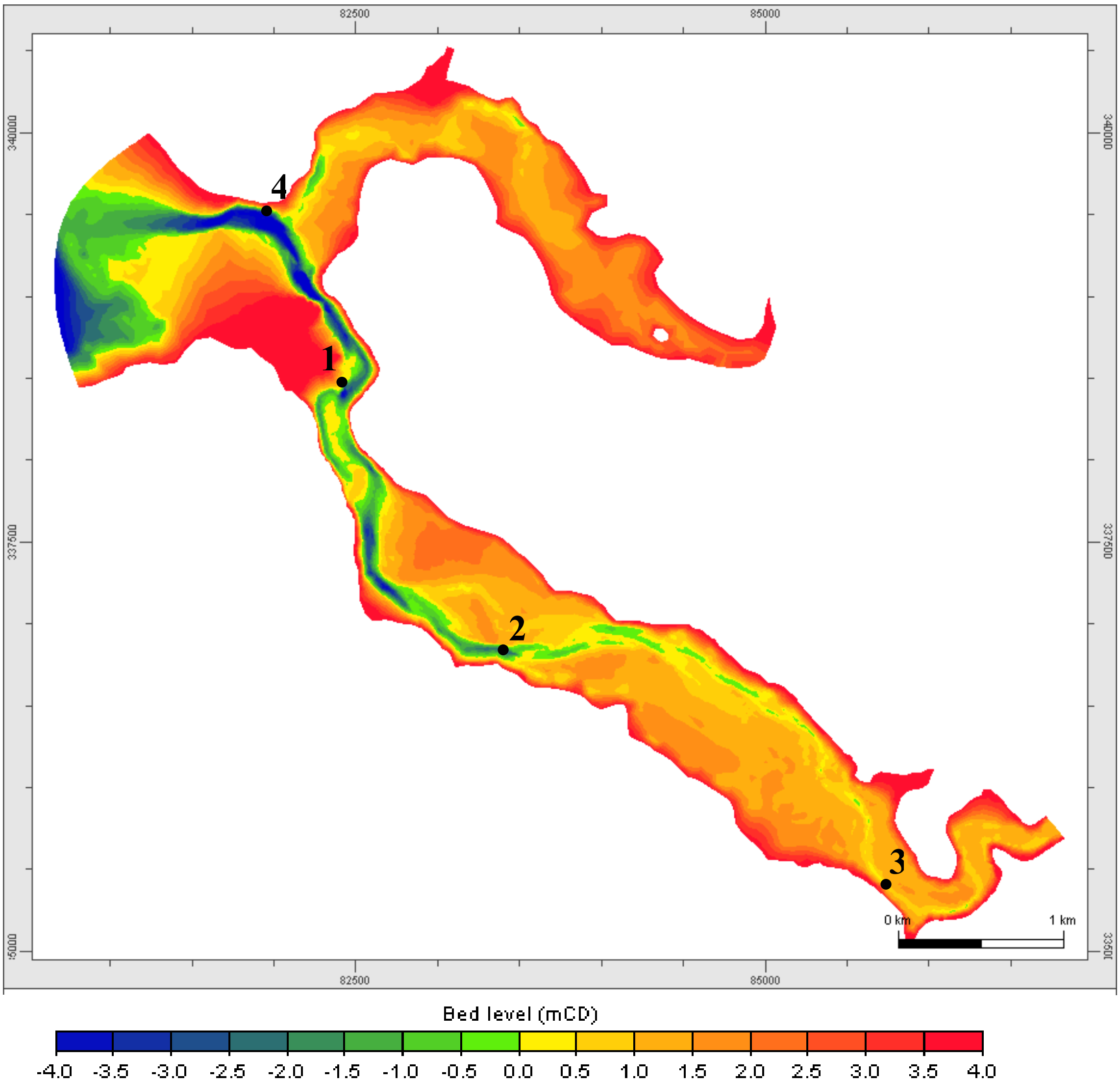

Figure 2 Location of the hydrodynamic observations

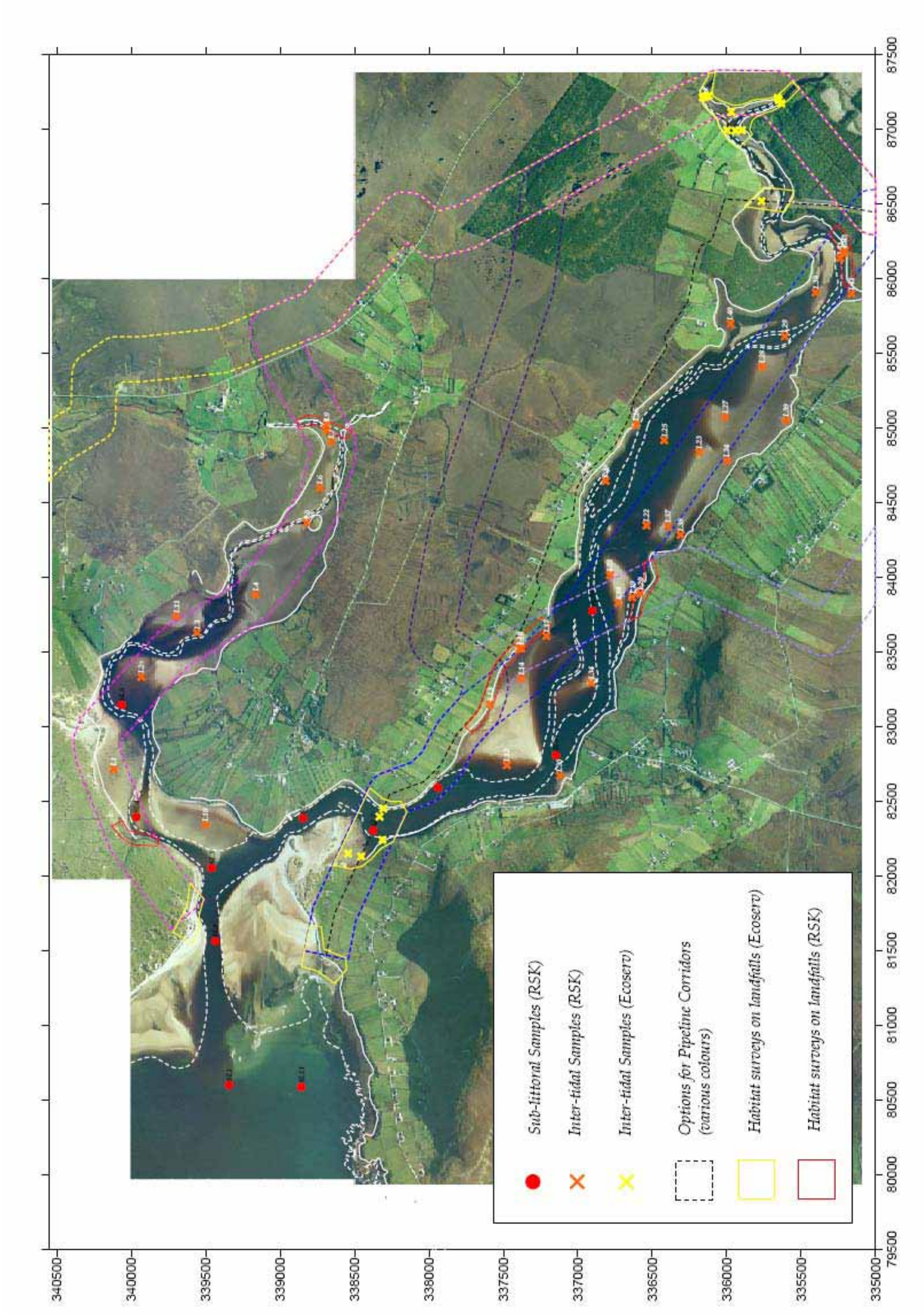

Figure 3 Location of the sediment sampling

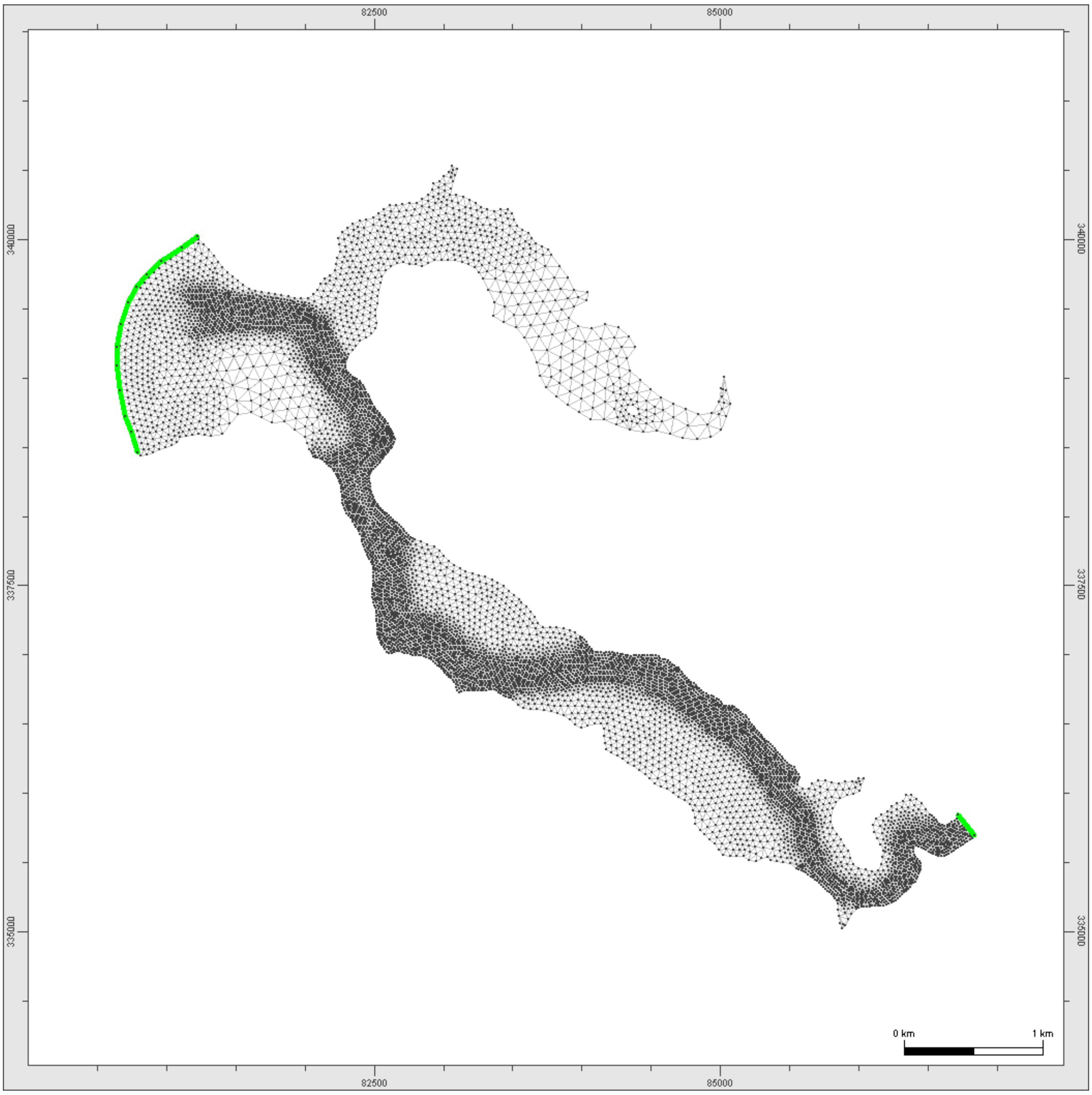

Figure 4 Model mesh with location of the open boundaries (in green)

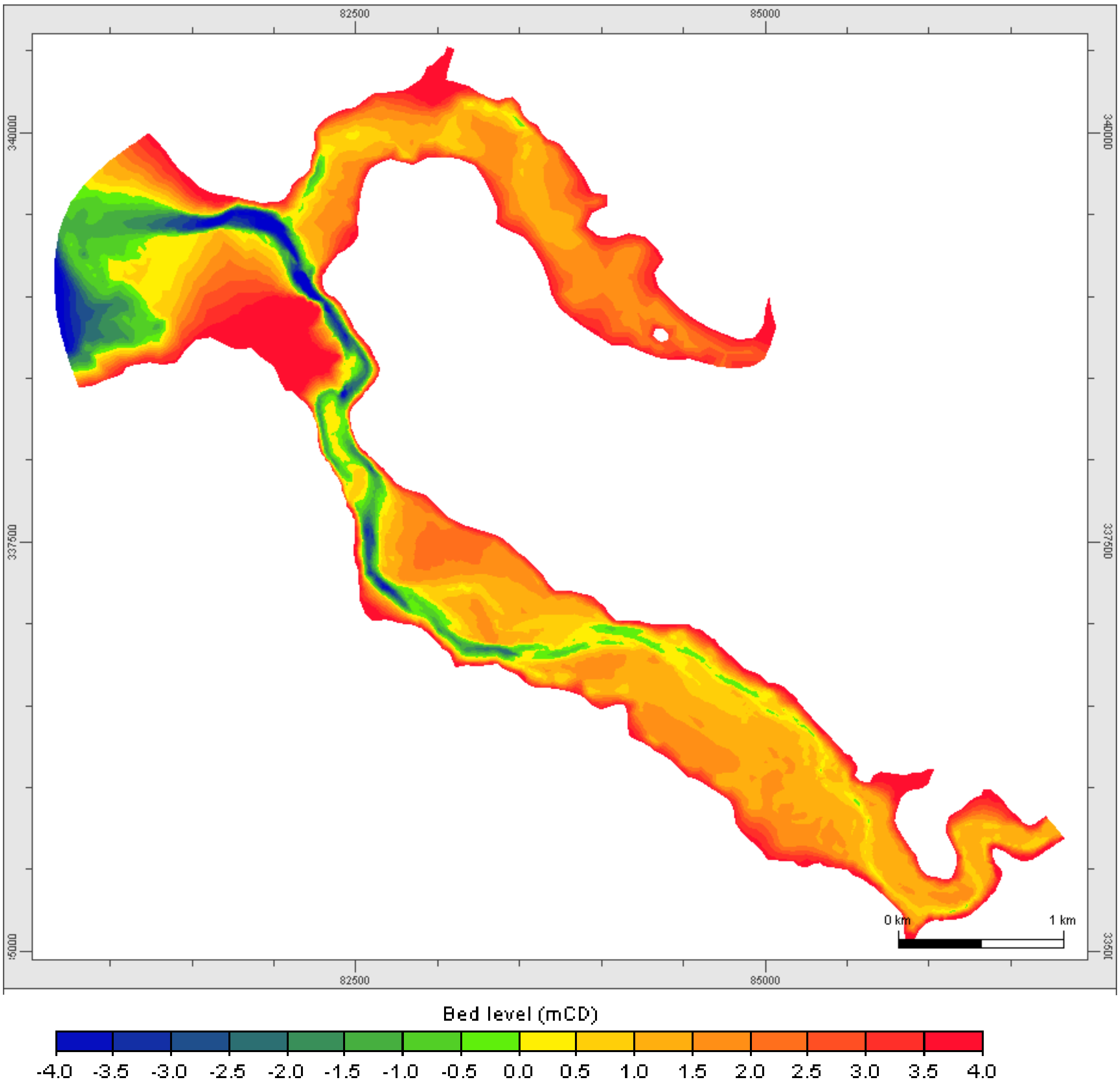

Figure 5 Baseline model bathymetry