The Scottish Government
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# The Scottish Shelf Model.
# Part 5: Wider Loch Linnhe System Sub-Domain


## Scottish Marine and Freshwater Science Vol 7 No 7



D Price, C Stuiver, H Johnson, A Gallego, R O' Hara Murray


marine scotland

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Published by Marine Scotland Science

ISSN: 2043-7722
DOI: 10.7489/1696-1

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# Document history

## The Scottish Shelf Model. Part 5: Wider Loch Linnhe System sub-domain

Marine Scotland

This document has been issued and amended as follows:

| Version | Date | Description | Created by | Verified by | Approved by |
|---|---|---|---|---|---|
| 1.0 | 15/03/2013 | Draft report including only data review section. | Maurice McCabe, Darren Price | | |
| 1.1 | 31/3/2015 | Draft including calibration/validation | Darren Price | Hakeem Johnson | |
| 1.2 | 04/09/2015 | Calibration/Validation updated;<br>Climatology, 2011 and 1991 results added;<br>Discussion added | Caroline Stuiver | Hakeem Johnson | John Debenham |
| 1.3 | 18/09/2015 | Final edits based on client comments | Caroline Stuiver | Hakeem Johnson | John Debenham |

**The Scottish Shelf Model. Part 5: Wider Loch Linnhe sub-domain.**

Authors: Darren Price, Caroline Stuiver, Hakeem Johnson, Alejandro Gallego, Rory O'Hara Murray.

**Acknowledgements:**

The Scottish Shelf Model (SSM) contract was funded by the Scottish Government.

The FVCOM model has been developed by the Marine Ecosystem Dynamics Modeling Laboratory at the School for Marine Science and Technology, University of Massachusetts, Dartmouth, led by Dr Changsheng Chen. We would like to acknowledge Dr Chen for authorising the project team to use FVCOM for the development of the Scottish Shelf Model.

We would like to thank the SSM Steering Group for their contribution. In particular, Tracy McCollin (Marine Scotland) as the Project Manager, John Debenham (CH2M HILL) and Alan Hills (Scottish Environment Protection Agency). Daniel Pendrey and Kate Smith (Marine Scotland) and Andrew Berkeley (SEPA) also participated in the Steering Group. We also wish to acknowledge the contribution of Fiona McLay, Maurice McCabe, Ilektra Apostololidou and Elysia Ward (CH2M HILL).

The Grid2Grid freshwater runoff data were supplied under contract by the Centre for Ecology and Hydrography. We would like to thank Robert Moore and his colleagues at CEH for those data.

Many individuals and organisations, too numerous to list individually, made data and data products used in the development of this model available free of charge. All relevant data sources are acknowledged through the text of these reports and we refer the readers to that information.

# Contents

# Abbreviations

| Abbreviation | meaning |
|---|---|
| ADCP | Acoustic Doppler Current Profiler |
| AMM | Atlantic Margin Model |
| BODC | British Oceanographic Data Centre |
| CEFAS | Centre for Environment, Fisheries and Aquaculture Science |
| CEH | Centre for Ecology and Hydrology |
| CTD | Conductivity, Temperature and Depth instrument |
| DHI | Danish Hydraulic Institute |
| DTM | Digital Terrain Model |
| ECMWF | European Centre for Medium range Weather Forecasting |
| ECLH | East Coast of Lewis and Harris |
| EMODNet | European Marine Observation and Data Network |
| G2G | Grid-to-Grid |
| GEBCO | General Bathymetric Chart of the Oceans |
| GSHHS | Global Self-consistent, Hierarchical, High-resolution Shoreline |
| ICES | International Council for the Exploration of the Sea |

| Abbreviation | meaning |
|---|---|
| MHW | Mean High Water |
| MHWS | Mean High Water Spring |
| MS | Marine Scotland |
| MSL | Mean sea level |
| NGDC | National Geophysical Data Centre |
| NOAA | US National Oceanic and Atmospheric Administration |
| NOC-L | National Oceanography Centre - Liverpool |
| NODB | National Oceanographic Database |
| NTSLF | National Tide and Sea Level Facility |
| ODYSSEA | Ocean Data analYsis System for SEA |
| OS | Ordnance Survey |
| PFOW | Pentland Firth and Orkney Waters |
| SEPA | Scottish Environment Protection Agency |
| UKHO | United Kingdom Hydrographic Office |
| ULL | Upper Loch Linnhe |
| WLLS | Wider Loch Linnhe System |
| WVS | World Vector Shoreline |

# 1 Introduction

## 1.1 Background

Halcrow Group Ltd. (a CH2M Company) was commissioned by Scottish Ministers to develop a 'Hydrodynamic model of Scottish Shelf waters'. The contract was commissioned under the Scottish Government Framework Contract for the Provision of Strategic Environmental Assessment, Appropriate Assessment and Marine Planning Services and Advice to Support Sustainable Economic Development in Scottish Marine Waters (REF: 177895) – Call Off Number 11 - Provision of a Hydrodynamic Model of Scottish Shelf waters – 16 May 2012. The project was managed on behalf of the Scottish Ministers by Marine Scotland.

The Scottish Government is committed to the development of a successful marine renewable energy industry in Scotland, which is currently also the largest producer of farmed Atlantic salmon in the EU and third largest globally. To achieve the sustainable development of both the offshore renewable energy industry and the aquaculture sector, Marine Scotland has adopted a planning approach to identify potential developmental areas.

Both of these factors are drivers for the development of a regional hydrodynamic model of the Scottish Shelf Waters and four more localised models which will be used to inform their planning approach. Marine Scotland will take ownership of the hydrodynamic models at the end of the study enabling them and other community organisations they work with, to undertake simulations and further development to meet their planning and research needs.

This report forms part of a series of reports that were produced during the lifetime of the project whilst developing hydrodynamic models of the Scottish shelf waters.

## 1.2 Study areas

The overall study area includes all of the Scottish shelf waters out to the 200m depth contour at the edge of the continental shelf. A Scottish shelf waters model covering this study area was developed to simulate the hydrodynamic conditions in three-dimensions, including meteorological and tidal forcings. The model resolution is variable and matched to the processes and bathymetry that are required for the simulations.

Within this region-wide shelf waters model, four local three-dimensional models were setup providing higher resolution to resolve key bathymetry, coastline and physical processes over smaller more local areas. These four model areas have been defined as case studies and cover the following regions:-

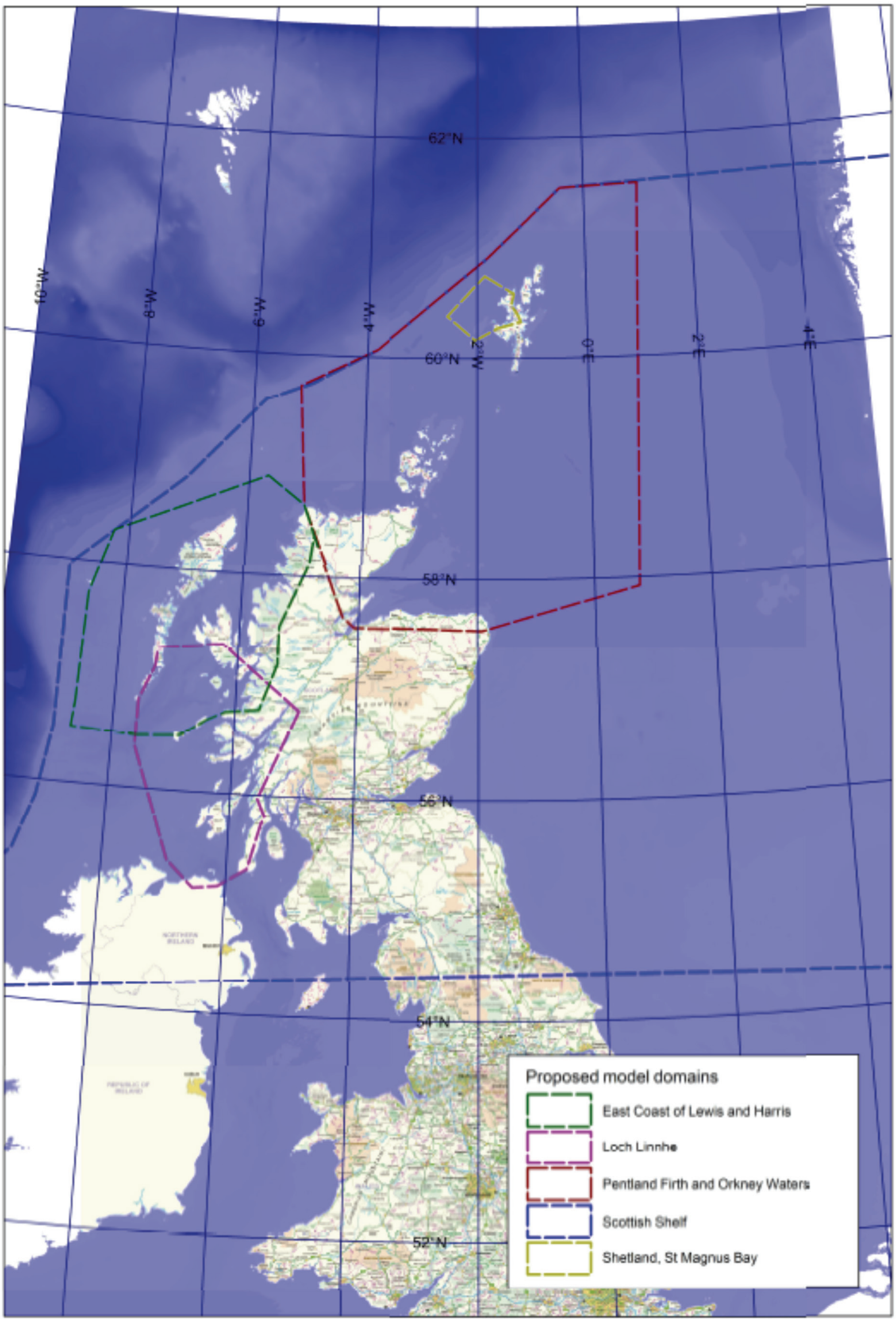
Case Study 1: Pentland Firth and Orkney Waters (PFOW)

Case Study 2: Wider Loch Linnhe System (WLLS)

Case Study 3: East Coast of Lewis and Harris (ECLH)

Case Study 4: Northwest Shetland mainland – St Magnus Bay area (SMB)

The locations and approximate areas of these models are shown in Figure 1-1, note that these model domains are not the final model domains but an approximation.






| Client | Consulting Engineer | Project: | Figure 1-1 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of the Shelf and individual case study model domains |

## 1.3 Aims and scope of numerical modelling works

The main aims of the project are to: 1) develop a validated three dimensional hydrodynamic model for the Scottish shelf waters; 2) develop a validated three dimensional hydrodynamic model for each of the four identified case studies. In addition, to develop a validated wave model for the Pentland Firth and Orkney Waters (Case Study 1); and 3) integrate the case study sub-models into the wider domain shelf model.

The modelling is aimed at providing a quantitative description of marine currents and water properties for the whole of Scottish waters on a range of spatial scales. The outputs of this study comprise validated hydrodynamic models (shelf model and local case study models) capable of predicting tidal and non-tidal currents for the whole of the Scottish shelf and inshore waters and include a more accurate assessment of the connectivity of different regions; and the available energy resources in those regions. It also includes description of methods for assessing the impact of extracting some of that energy upon the physical environment.

The modelling is undertaken using an open-source three-dimensional (3D) hydrodynamic model called FVCOM.  One of the reasons behind the choice of this modelling software is that the models developed in this project will be freely available to others at the end of the Project. Marine Scotland's vision is that the models will be used and developed further by Marine Scotland staff and the marine modelling community as more data becomes available and/or other needs are identified.

## 1.4 Project Team

The project team delivering this study consists of:

- Halcrow Group Ltd as the main contractor, responsible for co-ordination of team and development of the hydrodynamic models for the four case studies.
- National Oceanography Laboratory, Liverpool (NOC-L) as subcontractor, responsible for development of the Scottish shelf model.
- Centre for Ecology and Hydrology (CEH) responsible for delivering river outflow discharge data covering the entire Scottish waters and Northern Ireland using the Grid to Grid model.

- Prof. Chen of University of Massachusetts, USA, responsible for providing technical support on the application of the FVCOM software.
- Prof. Christina Sommerville of University of Stirling, UK, responsible for providing technical support on sea lice and development of connectivity indices.

## 1.5 This Report

This report documents the work carried out in developing the Wider Loch Linnhe System (WLLS) model. This work includes: data collated and/or identified for the numerical modelling, setup and calibration of the flow model, and the longer term simulations required for this study. It is noted that the data section in this report is a summary of the overall Data Review report (Halcrow, 2012) that is relevant to the WLLS area.

This report is Volume 1 of the WLLS model report. A companion volume (Volume 2) contains additional details on model development (data preparation, mesh generation, preparation of model setup files, how to run the model, etc.).

## 1.6 Datums

Unless explicitly stated otherwise the following reference datums are used in this study:

- All horizontal co-ordinates are referenced to latitude and longitude.
- All vertical levels are relative to MSL.

## 1.7 Acknowledgments

We gratefully acknowledge with thanks the contributions of the following organisations and individuals to this project.

- Marine Scotland (Alejandro Gallego, Rory O'Hara Murray, George Slesser and Berit Rabe) for providing, requesting and collecting available data.
- UKHO for the bathymetry datasets we have received.
- BODC/NOC-L for the wide range of oceanographic data and metadata; this is a great source of data. Thanks to Polly Hadziabdic at BODC for helping us with our enquiries.
- SEPA for providing tide gauge data, which was very useful for this study.

- CEH (Robert Moore and team) for their work towards providing river discharges data using the Grid-to-Grid model for this study.
- Professor Chen at the University of Massachusetts (Dartmouth) and his team for making the FVCOM software available for this project.

We also acknowledge with thanks the owners of the internet websites mentioned below for the valuable data downloaded from them for this study.

- Tide gauge data (class 'A') from the National Tide and Sea Level Facility (NTSLF – available from www.pol.ac.uk/ntslf) were downloaded and used for calibration purposes.
- ICES database (http://ocean.ices.dk/) which proved to be a good source of data.
- Bathymetric metadata and Digital Terrain Model data products have been derived from the EMODNet Hydrography portal - http://www.emodnet-hydrography.eu. This portal was initiated by the European Commission as part of developing the **European Marine Observation and Data Network** (EMODNet).

# 2 Available data for model development

## 2.1 Introduction

In order to carry out the numerical modelling works for the Wider Loch Linnhe System (WLLS), the following data have been collated:

- Bathymetry data, required for creating the bathymetry for the numerical model.
- Forcing data, required for specifying the forcing conditions in the numerical flow models.
- Calibration and validation data, required for calibrating and validating the numerical models.

This section of the report describes the data collated for the WLLS model area. Where appropriate, reference is made to the overall project data review report (Halcrow, 2012). Note that the proposed model domains shown in this section are not the final model domains but an approximation.

## 2.2 Bathymetric Data

### 2.2.1 Coastline Data

Two coastline data sets have been obtained for use in this study. These are: the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) distributed by National Geophysical Data Centre (NGDC) in the US, and Ordnance Survey Mapping.

The GSHHS coastline comes in different resolutions. For the UK, the best resolution available is the World Vector Shoreline (WVS) designed to be used at a resolution of 1:250,000. The GSHHS coastlines have been data processed to ensure they are free of internal inconsistencies such as erratic points and crossing segments.

The Ordnance Survey (OS) Vector Map District contains tidal boundary polylines, which are at Mean High Water Spring level (MHWS) in Scotland and MHW in England and Wales. The GSHHS data is considered appropriate for use in areas where the model resolution is coarse, the OS vector map district MHWS line should be used in areas of higher resolution.

### 2.2.2 Global/Regional Gridded Data Sets

Three existing coarse resolution bathymetry data sets have been identified which cover the study area the GEBCO_08, the ETOPO-1 grid and the EMODnet grid. These are described briefly below. Details regarding these datasets are provided in Halcrow (2012).

### 2.2.3 General Bathymetric Chart of the Oceans (GEBCO)

The GEBCO_08 data set is a global DTM at 0.5 minute resolution generated from a database of bathymetric soundings with interpolation between soundings guided by satellite-derived gravity data. The dataset is produced by GEBCO (http://www.gebco.net).

Known errors or discontinuities in the data set occur between regions where data is derived from satellite data and detailed bathymetric survey – this is evident in a grid pattern in the Southern North Sea Region, and a discontinuity at 0°E. Marine Scotland has highlighted errors where false banks occur on the shelf around the Shetland Isles (Hughes, 2014).

Figure 2-1 shows the GEBCO_08 bathymetry for the British Shelf and the source of the data. The discontinuity at 0°E and the grid pattern in the North Sea are clearly visible although this does not affect this model.

#### 2.2.3.1 ETOPO-1

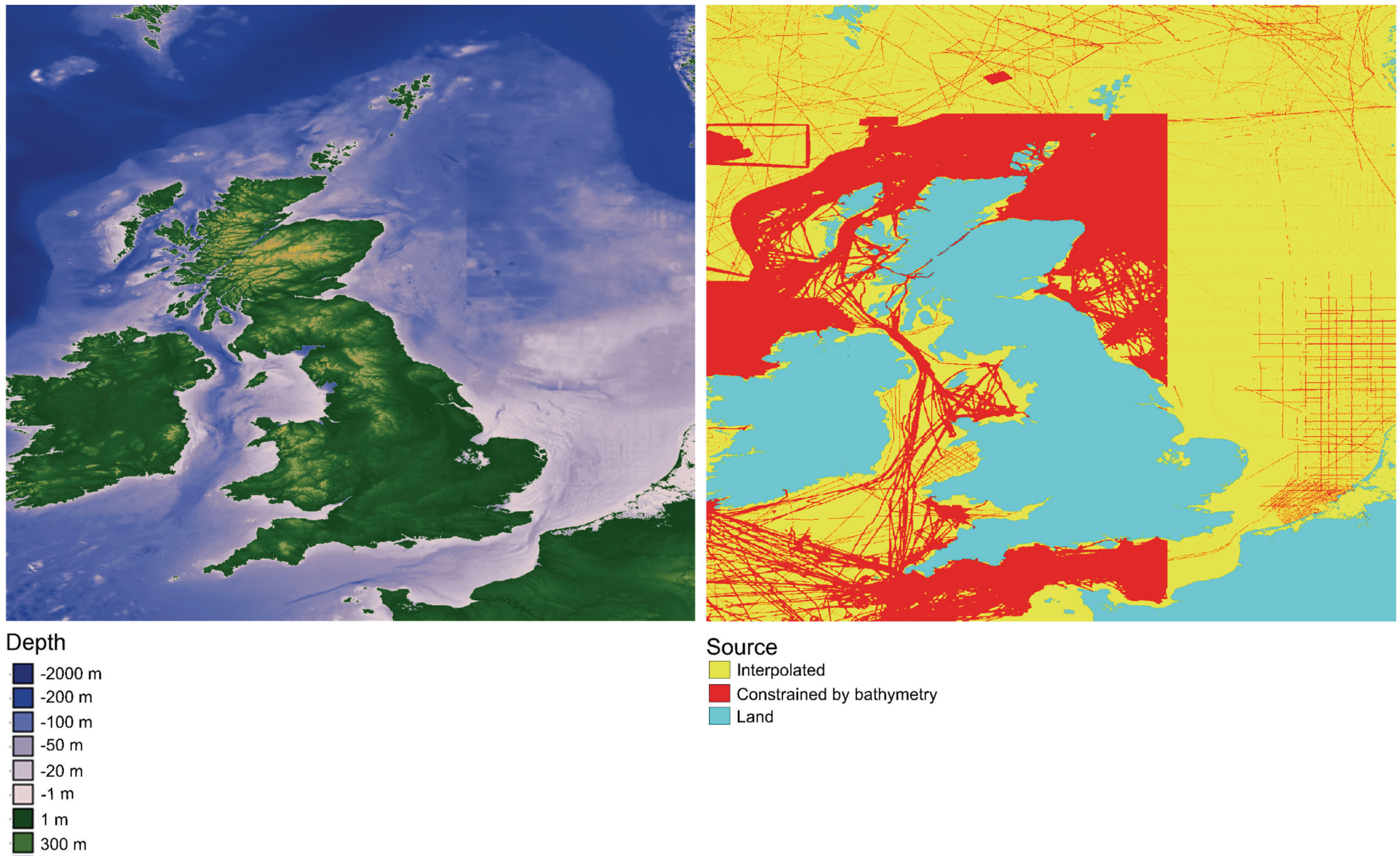
ETOPO-1 is a global DTM at 1 minute resolution produced by NOAA National Geophysical Data Center. The documentation states that this uses the GEBCO_08 data set for the British Shelf. Due to the lower resolution this dataset has not been considered further.

#### 2.2.3.2 European Marine Observation and Data Network (EMODnet)

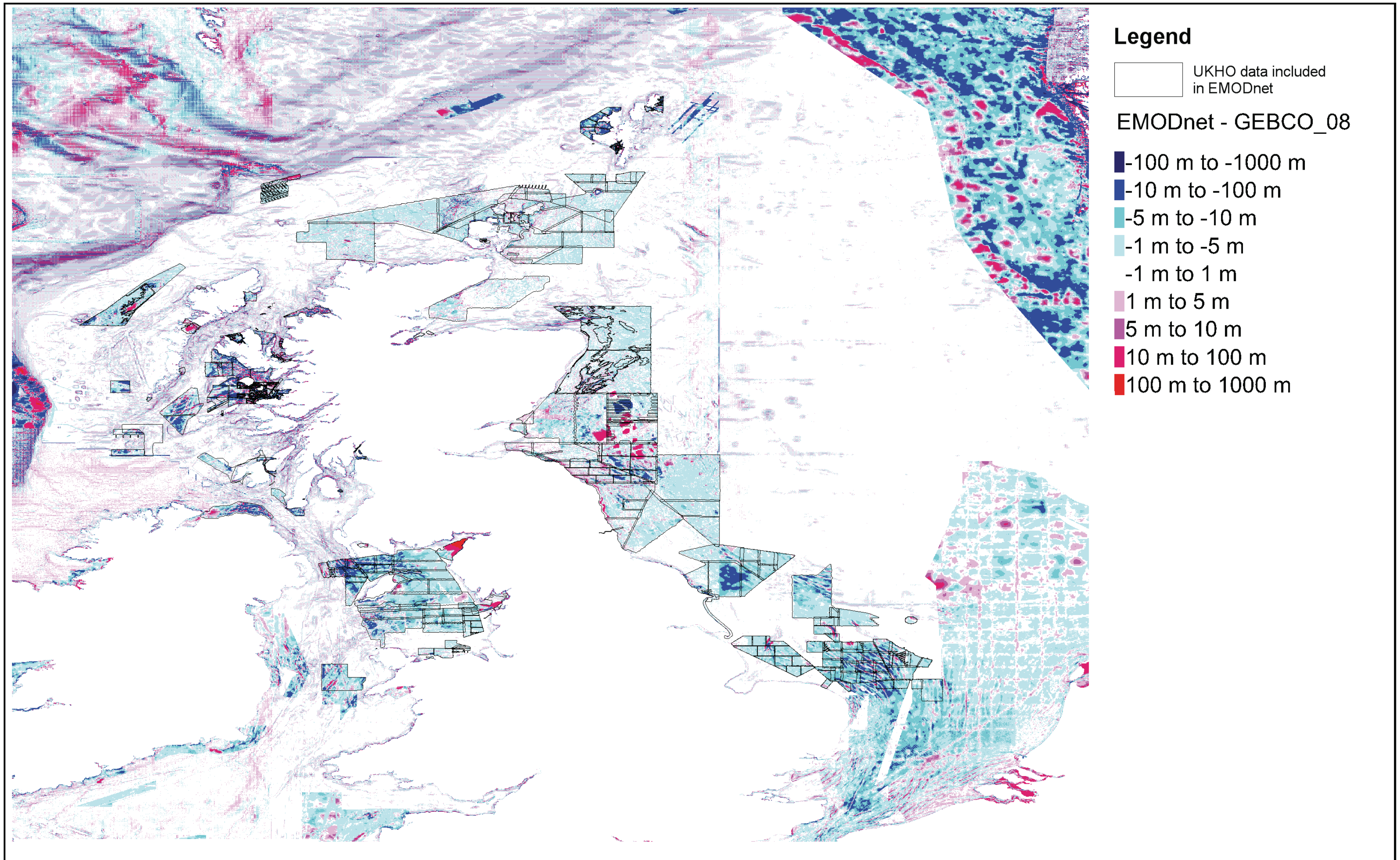
The European Marine Observation and Data Network (EMODnet) have produced DTMs for the Greater North Sea and Celtic Seas at 0.25 minute resolution (about 250m east-west direction and 450m north-south directions). The grids are based on bathymetric surveys and terrain models developed by external data providers including the UK Hydrographic Office (UKHO), and the GEBCO_08 Grid 0.5 minute resolution dataset where no other data is available. Data sets are made available through the EMODnet website http://www.emodnet-hydrography.eu/. Further details of EMODnet are provided in Halcrow (2012).

Figure 2-2 shows where UK Hydrographic office data has been incorporated into the EMODnet dataset and the differences between the EMODnet and GEBCO_08 bathymetry. Comparison of the EMODnet and GEBCO_08 data sets shows significant differences where the data from the UKHO and other hydrographic offices has been included. Differences are generally greater in areas where the GEBCO_08 has been interpolated, and the UKHO data has been used in the EMODnet bathymetry, for example around 1.5°W 56.3°N, due east of the Firth of Tay. The large differences west of Norway are due to incorporation of Norwegian hydrographic office data. There are also differences north west of the British Shelf around Iceland, where the EMODnet data is sourced from the GEBCO_08 grid. However these have not been investigated as they are not considered important for the study area.

Due to the inclusion of the majority of the UKHO data, ***the EMODnet bathymetry is considered appropriate for use as the base bathymetry for model construction in areas where the resolution will be in the order of one kilometre.*** Higher resolution bathymetry data is however required in areas where the model mesh is finer to represent bed or flow features. Therefore other datasets are required as described below.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-1 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Data sources used in the GEBCO data set. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-2 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | EMODnet data sources and difference between EMODnet and GEBCO_08 bathymetry. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

### 2.2.4 Hydrographic Data

Three sources of hydrographic survey data have been identified; the United Kingdom Hydrographic Office (UKHO), the International Council for Exploration of the Sea (ICES) and Marine Scotland's data sets.

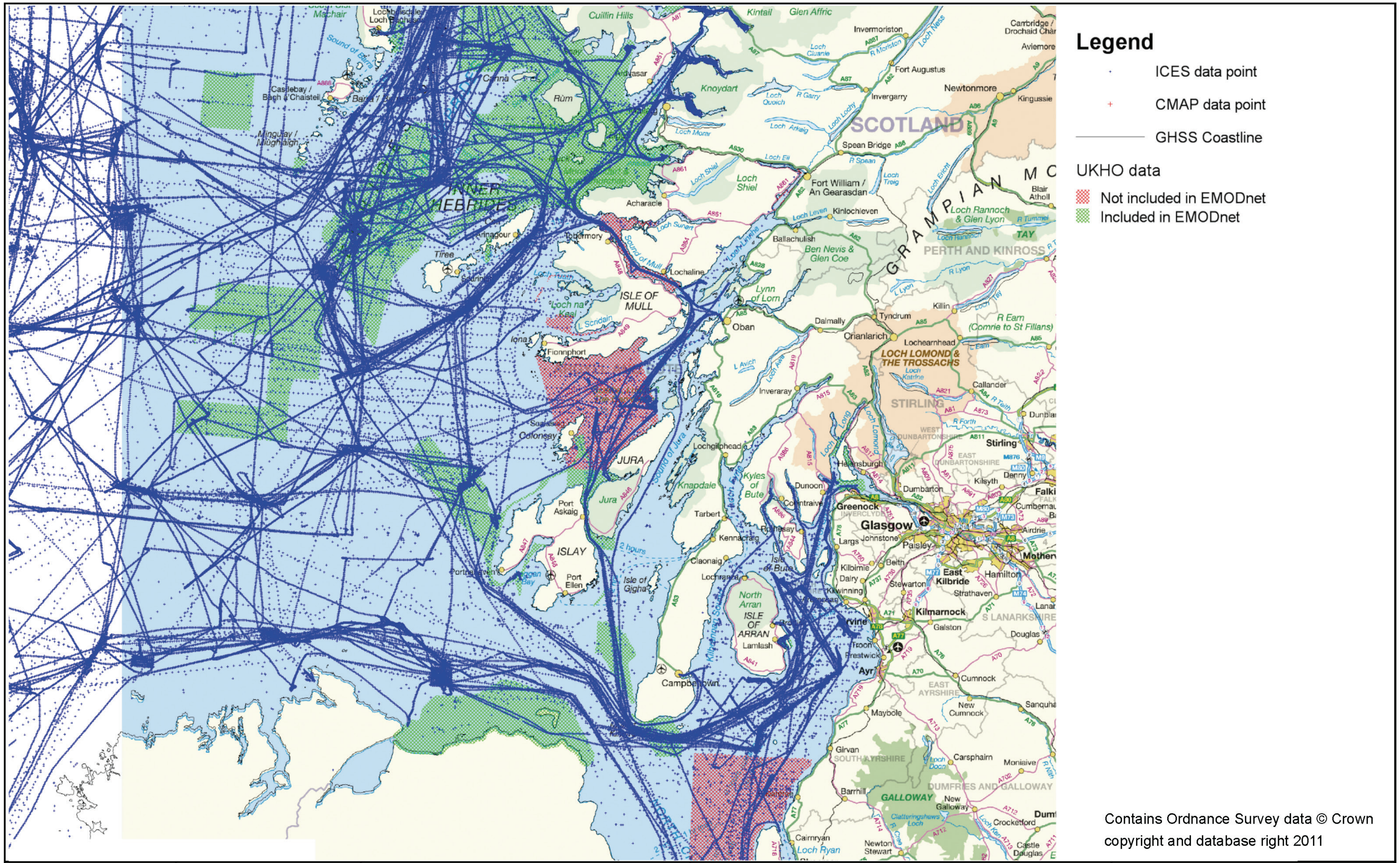
The UKHO have a memorandum of understanding with Marine Scotland making their high resolution bathymetric survey available. Most of these data have already been incorporated into the EMODnet bathymetry, however further data has since become available. The location of the UKHO data in the WLLS model domain is shown in Figure 2-3a where it has been indicated on top of the EMODnet data. A closer view of Loch Linnhe is provided in Figure 2-3b.

The ICES surface dataset holds over 100 years of ship based observations, including soundings. There are over 2 million data points in the ICES data set within the study area, providing a good coverage over most areas. The ICES website (http://ocean.ices.dk/) states that data are quality controlled by contributing organisation and visually inspected by experienced staff to further improve the quality of these data. However it is expected that due to the age of some of the sounding data and the differences in measurement methods, data logging and processing that there may be significant differences or scatter between the soundings. Marine Scotland used the ICES dataset to identify and correct anomalies in the GEBCO_08 data set off the coast of Shetland. See Halcrow, 2012, for more detail regarding hydrographic data and the differences observed between datasets.

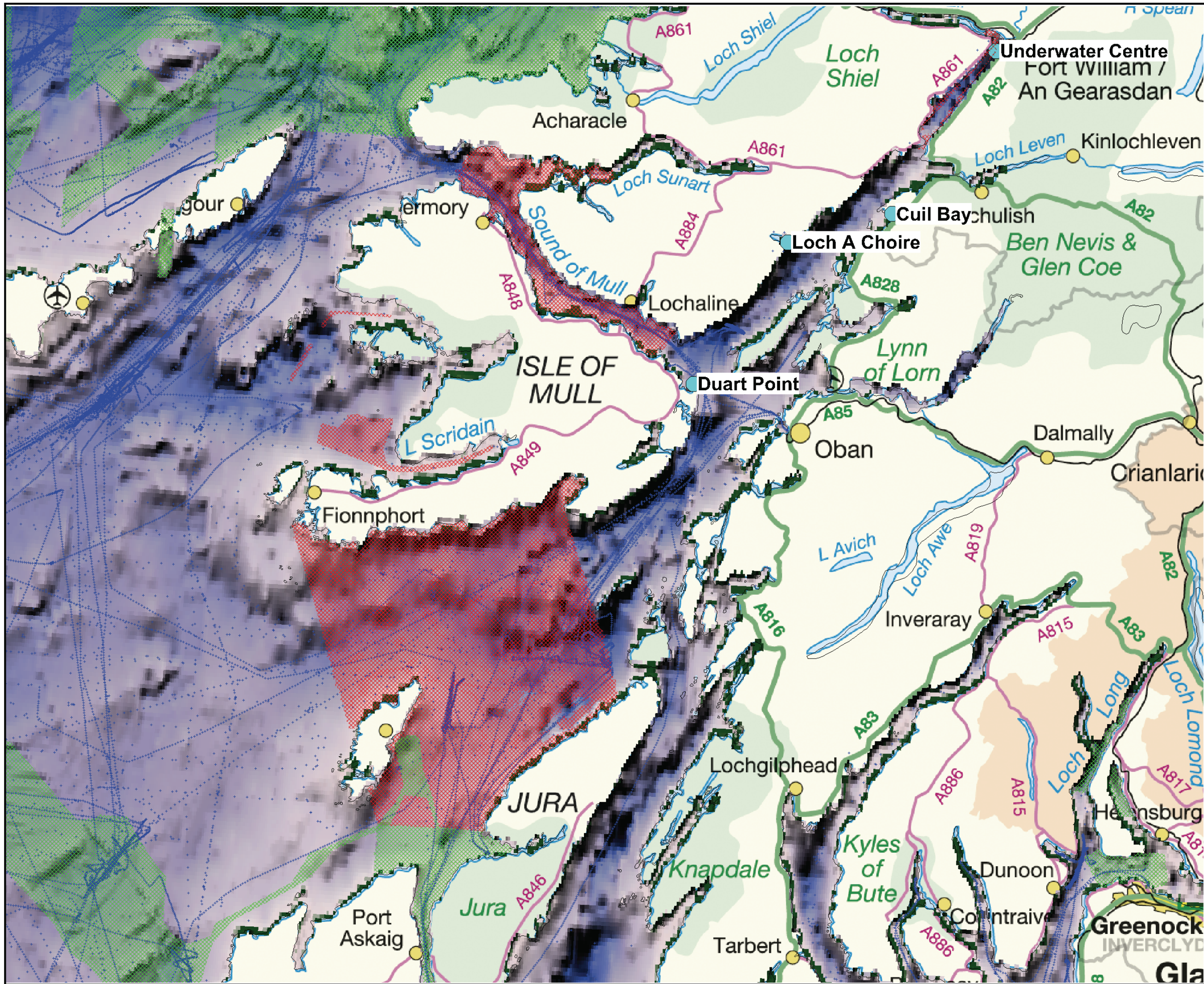
### 2.2.5 NOOS 1.0

NOOS 1.0: A gridded dataset for the UK continental shelf at 1 arc-minute resolution was produced under the aegis of NOOS (an operational oceanography organisation for the NW European Shelf (see Halcrow, 2012 for more information). The NOOS bathymetry incorporates local datasets made available by oceanographic institutions in countries around the North Sea, however no detailed source attribution information is available for the bathymetry, and it was last revised in 2004. Bathymetric surveys collected by the UKHO post 2004 are therefore not incorporated in to the bathymetry, and it is uncertain to what extent earlier UKHO and other national hydrographic office datasets were incorporated.

After consideration of this data and comparison against other datasets (Halcrow, 2012) it was concluded that the NOOS bathymetry should not be used west of 0°E and has therefore not been used for the WLLS model.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-3a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Available bathymetry for the wider Loch Linnhe Area | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




## Legend

ICES data point

GHSS Coastline

UKHO data

Not included in EMODnet

Included in EMODnet

Meteorological Station 2011

Depth **EMODnet bathymetry**

- -2000 m
- -200 m
- -100 m
- -50 m
- -20 m
- -1 m
- 1 m
- 300 m



| Client | Consulting Engineer | Project: | Figure Title: | Figure 2-3b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Available bathymetry for Loch Linnhe. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

### 2.2.6 Other data sources

Other identified data sources include digital Admiralty charts (C-MAP) and SeaZone. However, these datasets were not used for this study due to licensing restrictions as discussed fully in Halcrow (2012). A licence enabling Halcrow to digitise the required Admiralty Charts was obtained from the Hydrographic Office and the digitising undertaken. This allows the data to be used into the future for this project without paying a licence fee every year. The digitised Admiralty Charts are used to fill the gaps in the digital bathymetry data available for the ECLH model.

### 2.2.7 Summary of bathymetry data availability for the Wider Loch Linnhe Area

Figures 2-3a shows data availability for the wider Loch Linnhe system; there is detailed bathymetric survey for the Sound of Mull, and Firth of Lorn, but not for the Firth of Jura. Figure 2-3b shows data availability within Loch Linnhe itself; there are some ICES ship tracks but no detailed bathymetric survey from the UKHO. Loch Linnhe and Loch Sunart are covered by Admiralty Charts. Figure 2-3 in Halcrow (2012), shows that there are considerable differences between the EMODnet bathymetry and the GEBCO_08 bathymetry where UKHO data has been incorporated into the EMODnet dataset in this region. In the outer Loch Linnhe system there is no additional bathymetry available from the UKHO in the EMODnet data, therefore based on differences found elsewhere there would be some uncertainty with the depths in this area. Both datasets are too coarse resolution to model the loch and surrounding lochs. Inaccuracies in the EMODnet bathymetry where it is derived from GEBCO_08 data mean that it will be necessary to correct and modify the coarse resolution data at the boundaries of the model domain.

SAMS has undertaken a number of bathymetric surveys in the years 2009-2011, including Loch Linnhe and Loch Etive and the Civil Hydrography Programme (CHP) have planned surveys of Loch Linnhe, the sound of Jura, the Passage of Tiree, the outer approaches to the Firth of Lorne. These data sets apart from the Passage of Tiree were not available at the time of the mesh generation and were not used. Admiralty Chart data was used for Loch Linnhe and surrounding areas with limited bathymetry data.

## 2.3 Forcing Data

### 2.3.1 Introduction

Forcing data is required for a yearlong climatological model run of the WLLS flow model, for six month long runs May to October 2011 and May to October 1991, and for calibration using observed data for approximate 1 month periods. The following forcing data is required;

- meteorological - including wind speed/stress, atmospheric pressure, surface heat flux, precipitation and evaporation
- hydrological - river flux
- oceanic open boundaries – including temperature, salinity and velocity
- tides

In addition, surface winds and offshore wave boundary data are required for the wave model.

### 2.3.2 Meteorological forcing

#### 2.3.2.1 UK Met Office Model Data

Two data streams from the Met Office forecast models have been archived at NOC (Liverpool) for operational modelling:

- for operational tide-surge modelling on the continental shelf, using the 2d tide-surge model (CS3 and CS3X).
    - These data comprise of surface wind and atmospheric pressure only, at 1-h intervals, from Mid-May 1991 to present. From 1991 to 1995 the data is at 50 km resolution, post 1995 the data is at 12 km resolution.
- for Irish Sea Observatory operational modelling system, running the 3d baroclinic hydrodynamic model, POLCOMS, on (i) the Atlantic Margin Model (AMM, ~12km) and (ii) the nested Irish Sea model (IRS, ~2km). The data comprise the following, from 2004 to 2007 with some gaps, and continuously from 2007 to 2011, all at 12 km resolution:
    - Global model output for the Atlantic at 6-hour intervals – 10m wind (E and N components); sea level pressure; low, medium and high level cloud coverage; specific humidity at 1.5m, air temperature at 1.5m; total accumulated precipitation;

  - Mesoscale model output at 3-hour intervals – same variables

#### 2.3.2.2 ECMWF Data

Additional meteorological forcing data was taken from the ERA (ECMWF Re-Analysis) - Interim dataset http://www.ecmwf.int/en/forecasts/datasets. This data includes:

- Downwards longwave radiation and downwards shortwave radiation on a 0.75° grid, accumulated over 12 hours from midnight and noon. Available from 1989 to present.
- Evaporation and precipitation on a 0.75° grid, accumulated over 12 hours from midnight and noon. Available from 1989 to present, used in 1991 runs.
- Air temperature, sea level pressure, dew point temperature on a 0.125° grid at 6 hourly. Available from 1989 to present. Note that dew point temperature was used along with air temperature to calculate the relative humidity in the 1991 runs.
- U and V components of wind on a 0.125° grid at 6 hourly interval. Available from 1989 to present, used to fill in the gaps in the Met Office wind data in the 1991 runs.

#### 2.3.2.3 Climatological Forcing

Climatological forcing was derived from the ERA40 and ERA-Interim datasets, which were used to force the POLCOMS AMM (~12km) model for the 45 year hindcast (1960-2004). See Wakelin et al. (2012) and Holt et al., (2012). A licence to use these data has been provided by the European Centre for Medium range Weather Forecasting (ECMWF) for this study. A one-year climatological forcing for the temperature and salinity (i.e. heat flux and precipitation) has been derived.

### 2.3.3 Meteorological observations

Loch Linnhe is approximately 6km wide and surrounded by mountains. The highest resolution Met office model output is at 4 km and local scale variations in the wind in this area is unlikely to be captured in the model. Therefore, the use of local measurements will also be made.

Local wind measurements around the Loch Linnhe system were made by Marine Scotland in 2011 and 2012 as part of an intensive measurement campaign in the Loch. Data is also available from 1991.

- Davis weather station data on Underwater Centre Pier in Fort William between July – November 2011
- Davis weather station data on Duart Point, Loch A'Choire and Cuil Bay between April – November 2011

In addition there is meteorological data for one station in 1991, as part of a previous intensive measurement campaign.

There are Met Office weather stations at Dunstaffnage, Aonach Mor, Colonsay and Tiree (although Aonach Mor is at high altitude). The Scottish Association of Marine Science (SAMS) also maintain a weather station in Dunstaffnage http://dalriada.sams.ac.uk/sams_weather/.

The number of sites in 2011 are sufficient to carry out a correlation analysis for the wind conditions between the available data locations (obtained in 2011), to provide relationships of wind speed and direction for a range of directional sectors between these sites and data from the Met Office Mesoscale model.

Meteorological data at four weather stations around Loch Sunart were provided by Marine Scotland. However there was no overlap with the 2011 data, therefore this data could not be included in the main wind correlation analysis, however some consideration of the topographic influence on wind within Loch Sunart have been made.

Met Office model data from May 1991 is archived at NOCL at 25 km resolution, but no temperature and salinity forcing data are available for this time. For 2011 full forcing data from the Met Office models is archived at NOCL at 12km resolution.

### 2.3.4 Hydrological Data (Fresh Water Inflows)

In order to simulate the effect that river flow has upon salinity in coastal waters, river flux data are required. The Centre for Ecology and Hydrology (CEH) Grid-to-Grid (G2G) model was used to supply freshwater inflows to the various coastal models for this study.

The output that CEH provided from the G2G model were:

1. River discharge data (time series data) at all coastal locations in Scottish waters with the G2G model. The data cover 1 March 2007 to 30 September 2010 at 15 minute intervals.
2. River discharge data (time series data) at all coastal locations around Shetland and Northern Ireland with the G2G model. The data cover 1 March 2007 to 30 September 2010.

3. River discharge climatological data (long term daily/seasonal discharge data) at all coastal locations for Scotland (including Shetland) and Northern Ireland with the G2G model. Daily averaged data was provided, the averaging period covered 1962-2011.

In addition, Marine Scotland also provided the following river data sets for 1991.

1. River flux data for 3 rivers (River Lochy, River Nevis and Loch A’Choire)
2. Diffuse river inputs for Loch Linnhe and all side lochs
3. River temperature data (calculated using an empirical relationship relating the air temperature at Oban to river temperatures).

### 2.3.5 Tide

For the WLLS Model, the boundary data was derived from NOC-L’s Atlantic Margin Model (AMM) with a 12km resolution. Water levels along with temperature and salinity timeseries are applied at the model boundaries for specific periods coincident with times that calibration data is available. For the 1991 runs, boundary came from the POLCOMS model on a 12km grid. The WLLS climatology runs were forced using results from the Scottish Shelf model climatology run.

## 2.4 Calibration Data

### 2.4.1 Introduction

Model calibration was undertaken against observation datasets for periods of up to 1 month. Calibration is required for water level, currents, temperature and salinity. In addition, the result of the 1 year climatology runs are compared against accepted general flow characteristics including current speed and direction (seasonal variability) and seasonal temperature and salinity cycles. Sections 2.4.2 to 2.4.4 present data found in freely available sources, however section 2.4.5 presents data from specific surveys targeting Loch Linnhe.

### 2.4.2 Water Level

Figure 2-4 shows all the locations of water level observations that are available in the WLLS region. These come from three main sources: tide gauge data from the BODC National Oceanographic Database (NODB); bottom pressure data from the NODB, and analysed tidal data from NOC.

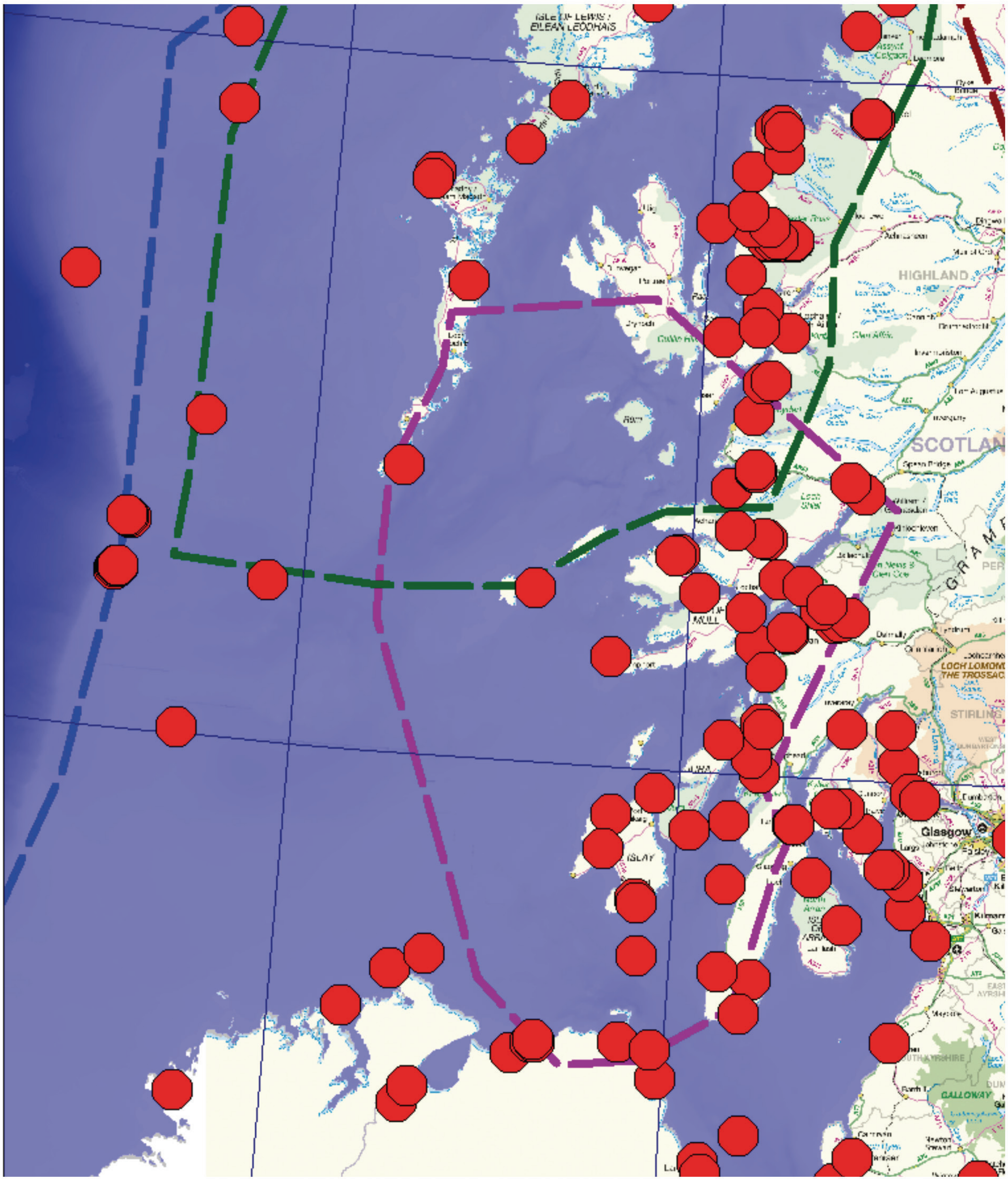
In addition, we have access to tidal data from TotalTide - a digital version of the UK Admiralty tide tables, from the UK Hydrographic Office. The locations of these datasets are shown in Figure 2-5. Because these data are based on harmonic analyses, water level estimates for any past or future date are obtainable, or via the use of constituents from the Admiralty tide tables. All available water level data available post year 2000 are shown in Figure 2-6.

### 2.4.3 Currents

Datasets on currents have been found from a number of sources; all locations are shown in Figure 2-7. These come from the BODC National Oceanographic Database (NODB) and the TotalTide software, from UK Hydrographic Office. As Figure 2-8 shows, there are only a few datasets from the BODC National Oceanographic Database since year 2000. In some cases, vertical current profiles are available; these are shown in Figure 2-9.

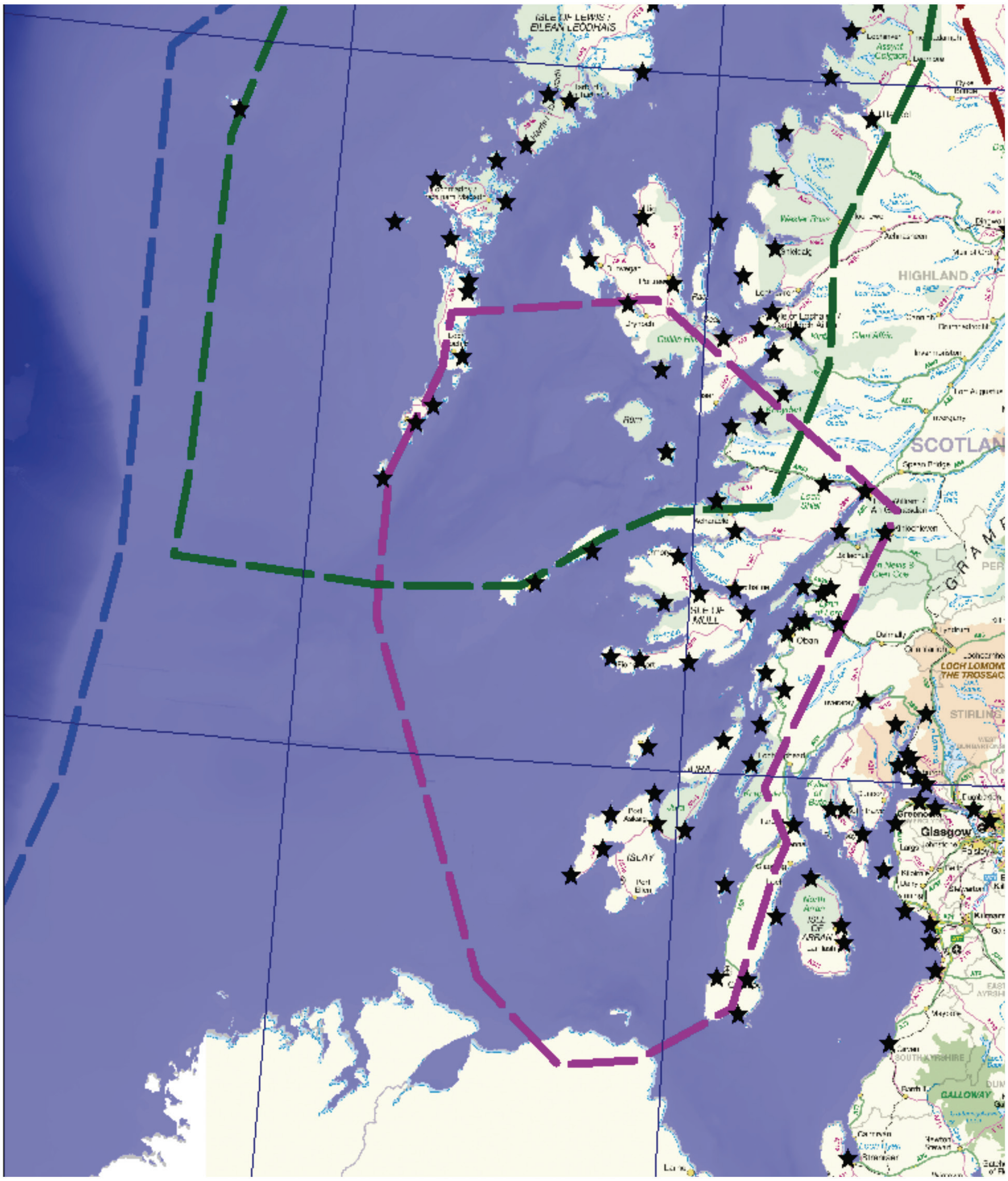
The methodology used by TotalTide for calculating currents is not known. In addition, these data have been estimated for the use of shipping; therefore, a greater weighting may be placed on surface currents than currents near the sea bed.

The Atlas of UK Marine Renewable Energy Resources (www.renewables-atlas.info) contains information on peak tidal current speeds over a mean spring and a mean neap tide. The dataset was derived from the POL HRCS Model, with peak spring and neap current speeds calculated from the major 2 or 4 tidal harmonics. Although this dataset is limited, it is freely available on a 0.0167° x 0.025° (latitude x longitude) grid throughout the region shown in Figure 2-10.






| Client | Consulting Engineer | Project: | **Figure 2-4** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level observations within the WLLS model domain |




Water level observations

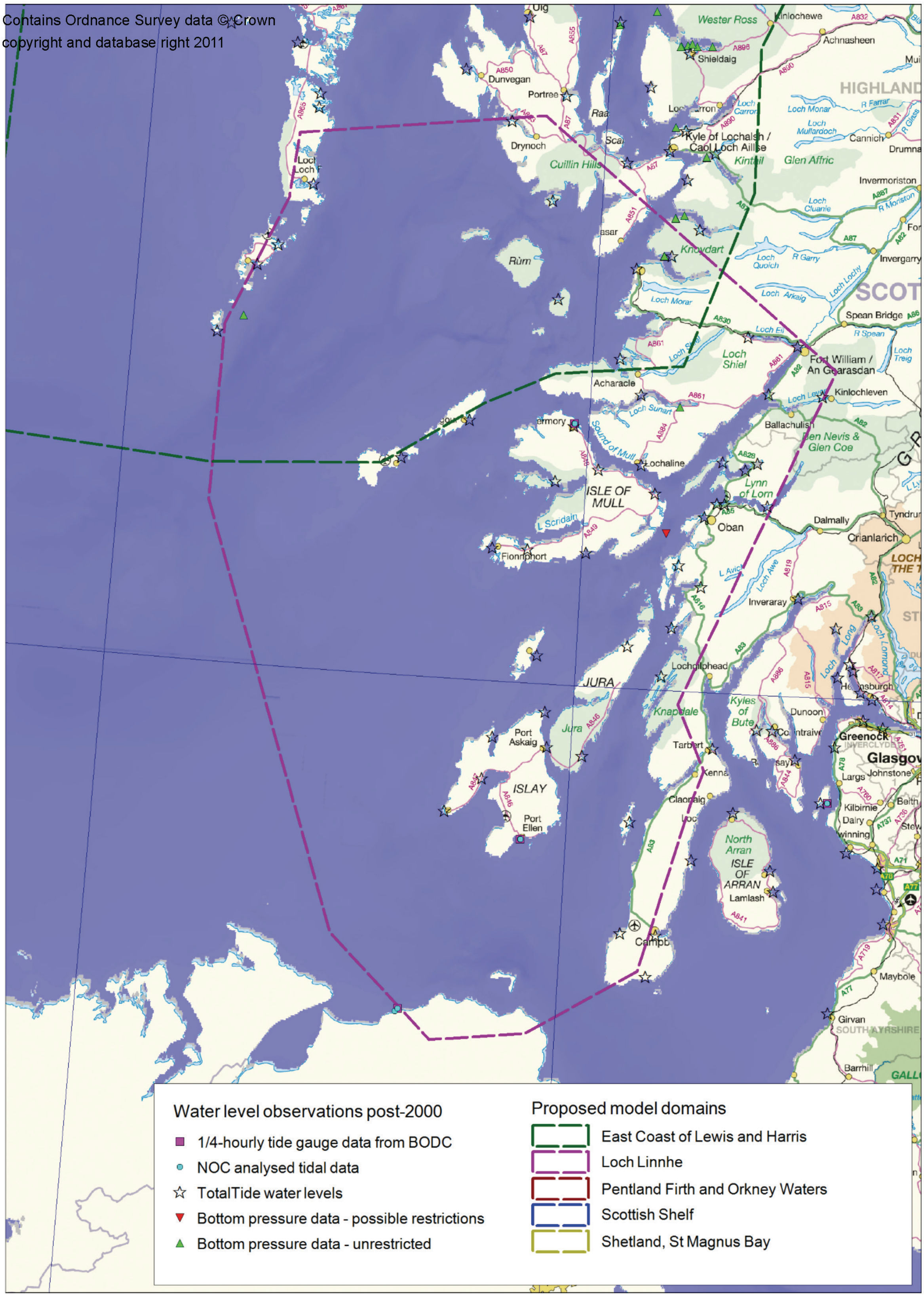
★ TotalTide water levels

Proposed model domains

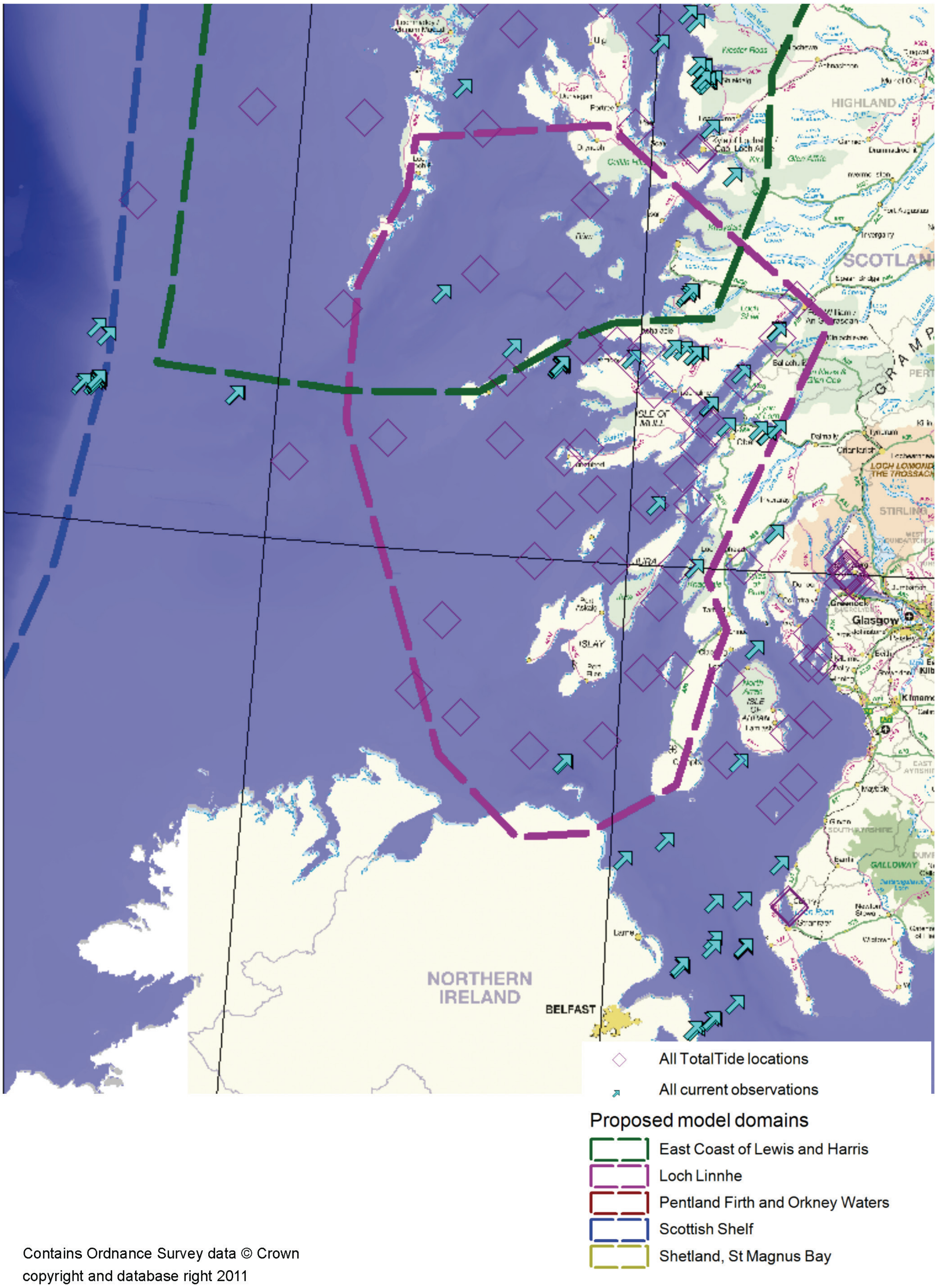
- East Coast of Lewis and Harris
- Loch Linnhe
- Pentland Firth and Orkney Waters
- Scottish Shelf
- Shetland, St Magnus Bay



| Client | Consulting Engineer | Project: | Figure 2-5 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Total-tide water level locations |

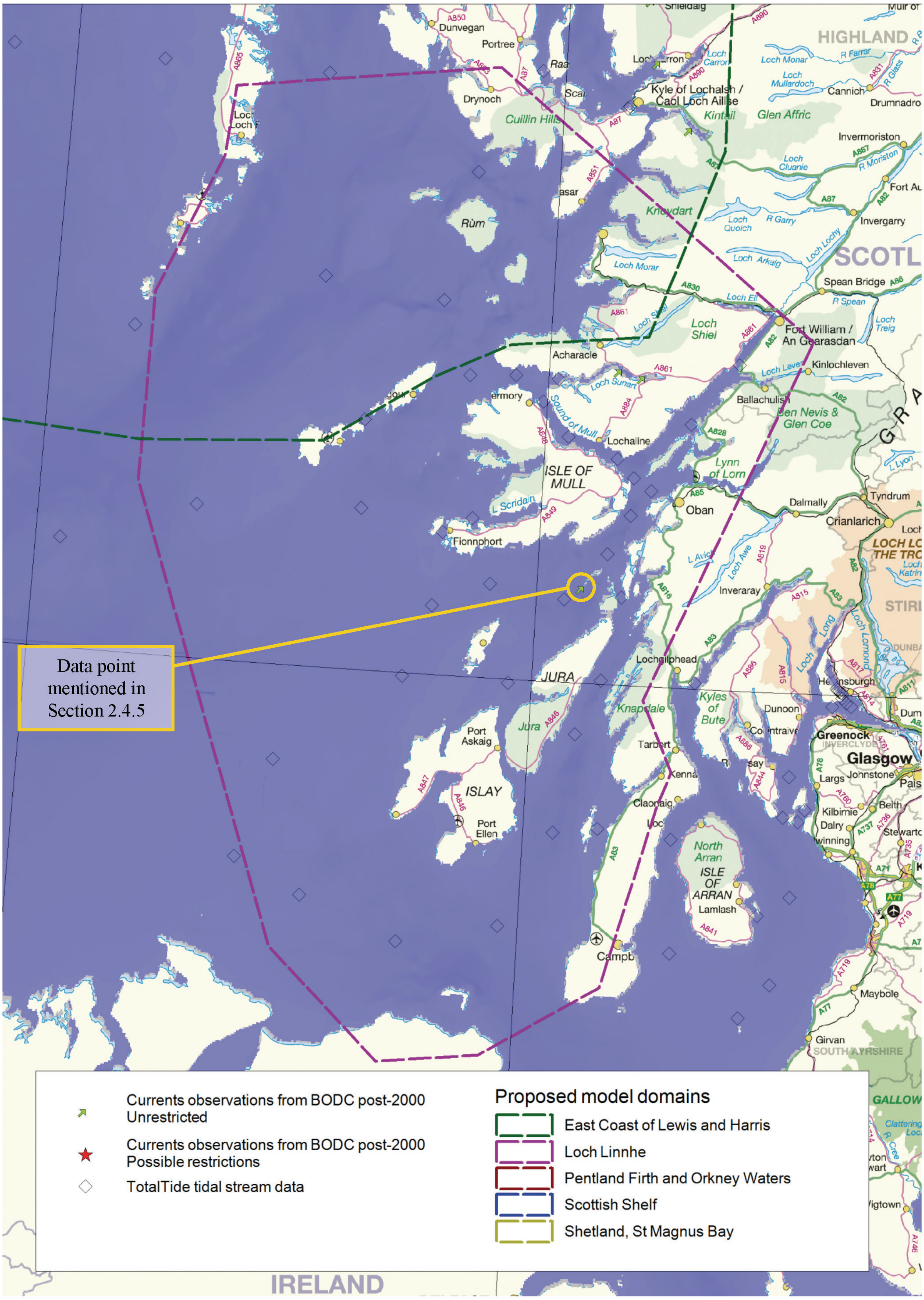



| Client | Consulting Engineer | Project: | Figure 2-6 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Post-2000 water level observations in the Wider Loch Linnhe System area |

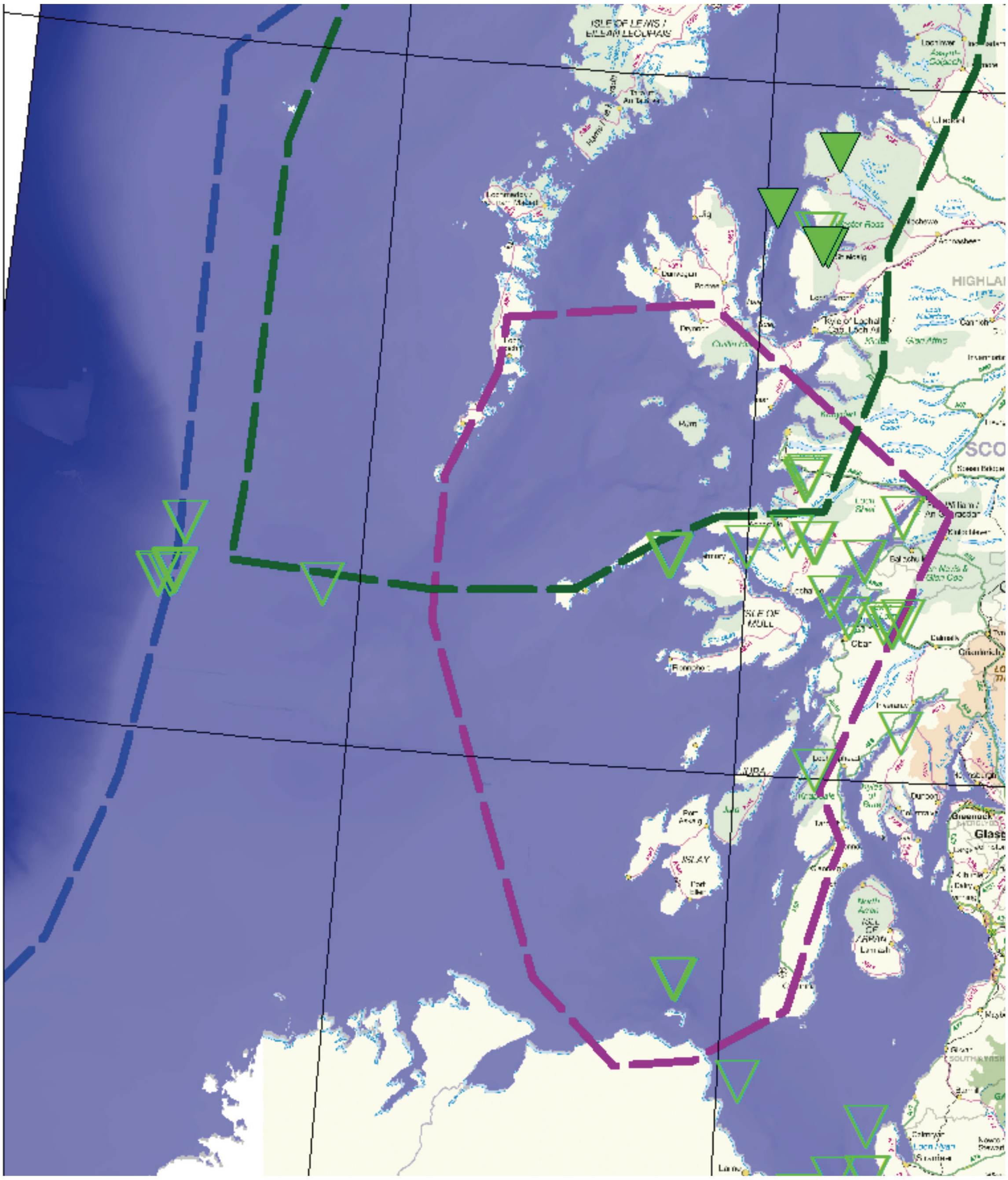





| Client | Consulting Engineer | Project: | Figure 2-7 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | All current observations and TotalTide tidal stream locations |




| Client | Consulting Engineer | Project: | **Figure 2-8** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Post-2000 current observations in the Wider Loch Linnhe System Area |




- ▼ Current profiles, post-2000 - unrestricted
- ▽ Current profiles, pre-2000 only - unrestricted
- ★ Current profiles, post-2000 - possible restrictions
- ☆ Current profiles, pre-2000 only - possible restrictions



**Proposed model domains**

- East Coast of Lewis and Harris
- Loch Linnhe
- Pentland Firth and Orkney Waters
- Scottish Shelf
- Shetland, St Magnus Bay

| Client | Consulting Engineer | Project: | **Figure 2-9** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Pre and Post-2000 current profiles |

### 2.4.4 Temperature and Salinity

Temperature and salinity validation was carried out using selected hydrographic stations which were identified from the British Oceanographic Data Centre data holdings for UK. There are a very large number of datasets from CTD (Conductivity, Temperature and Depth) and bottle casts, both from the BODC National Oceanographic Database and the ICES database. Additionally, some of the CEFAS WaveNet buoys record sea surface temperature.

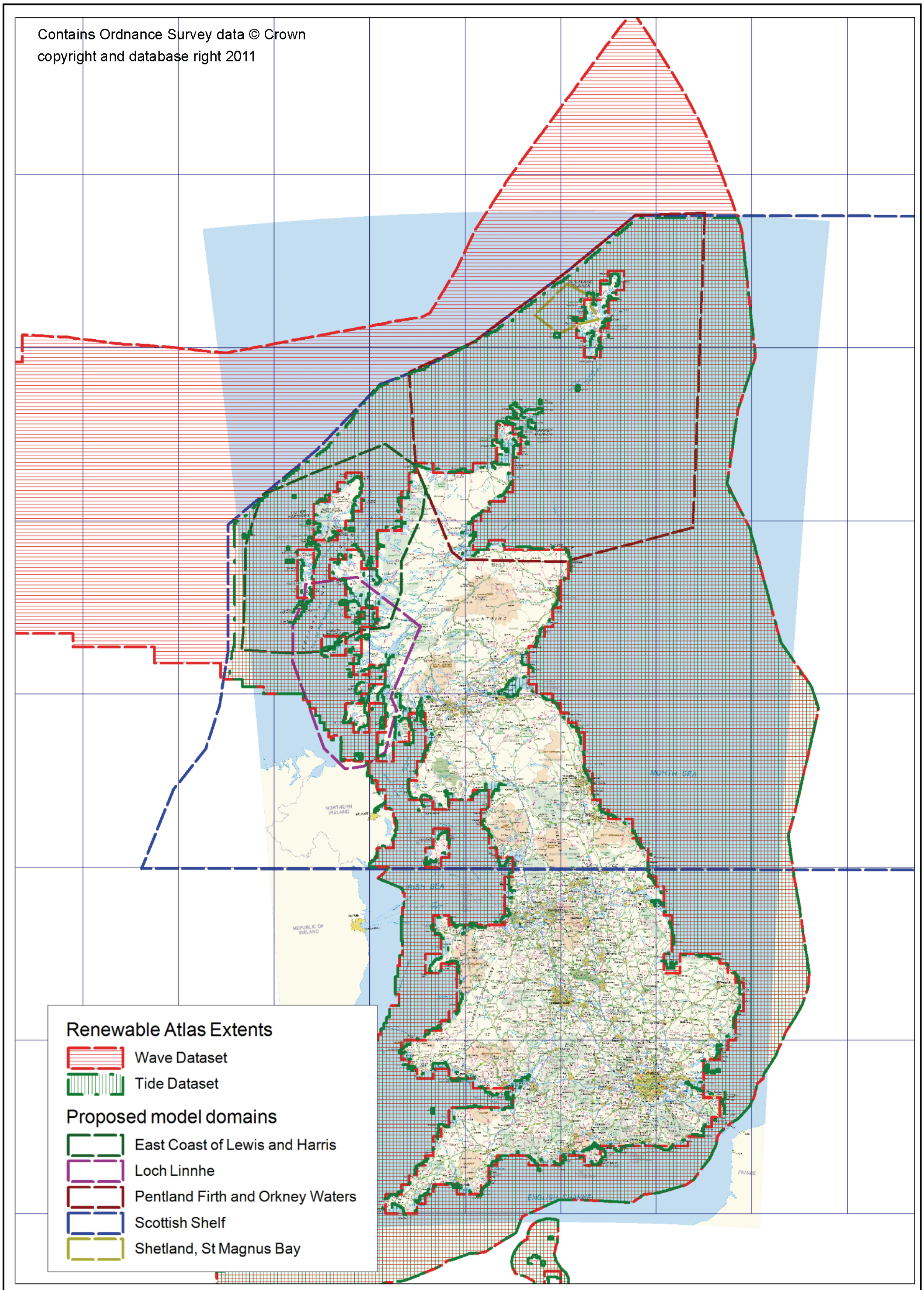
Figure 2-11 shows the locations of the temperature observations and Figure 2-12 shows the locations of the salinity observations. As Figure 2-13 shows, the temperature and salinity observations have occurred throughout the last two decades, with many observations throughout the model domain having occurred over the last two years. Figure 2-14 shows which of these observations include profiles over the entire water depth. Most temperature and salinity observations occurred at the same location and time.

In addition, the Ocean Data analYsis System for SEA (ODYSSEA) dataset is a re-analysis of satellite observations of sea surface temperature. Daily mean average sea surface temperatures since 01/10/2007 have been obtained, on a 0.1° x 0.1° grid.

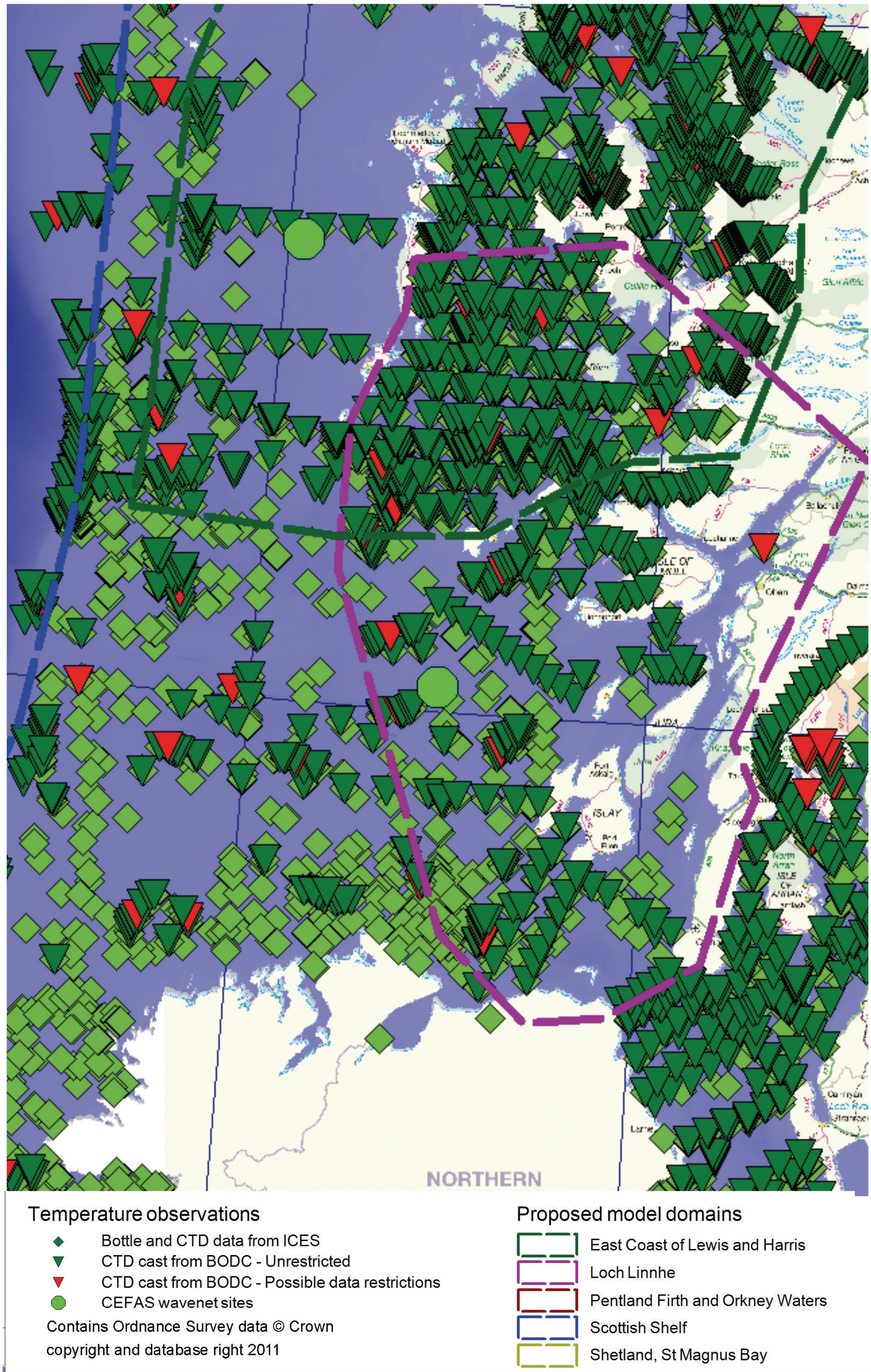
The results from the climatic run were compared with climatological atlas information for temperature and salinity, from the World Ocean Atlas (WOA) and International Council for Exploration of the Seas (ICES) climatological datasets.

### 2.4.5 Summary of data availability for the WLLS model including site specific survey data from 1991and 2011

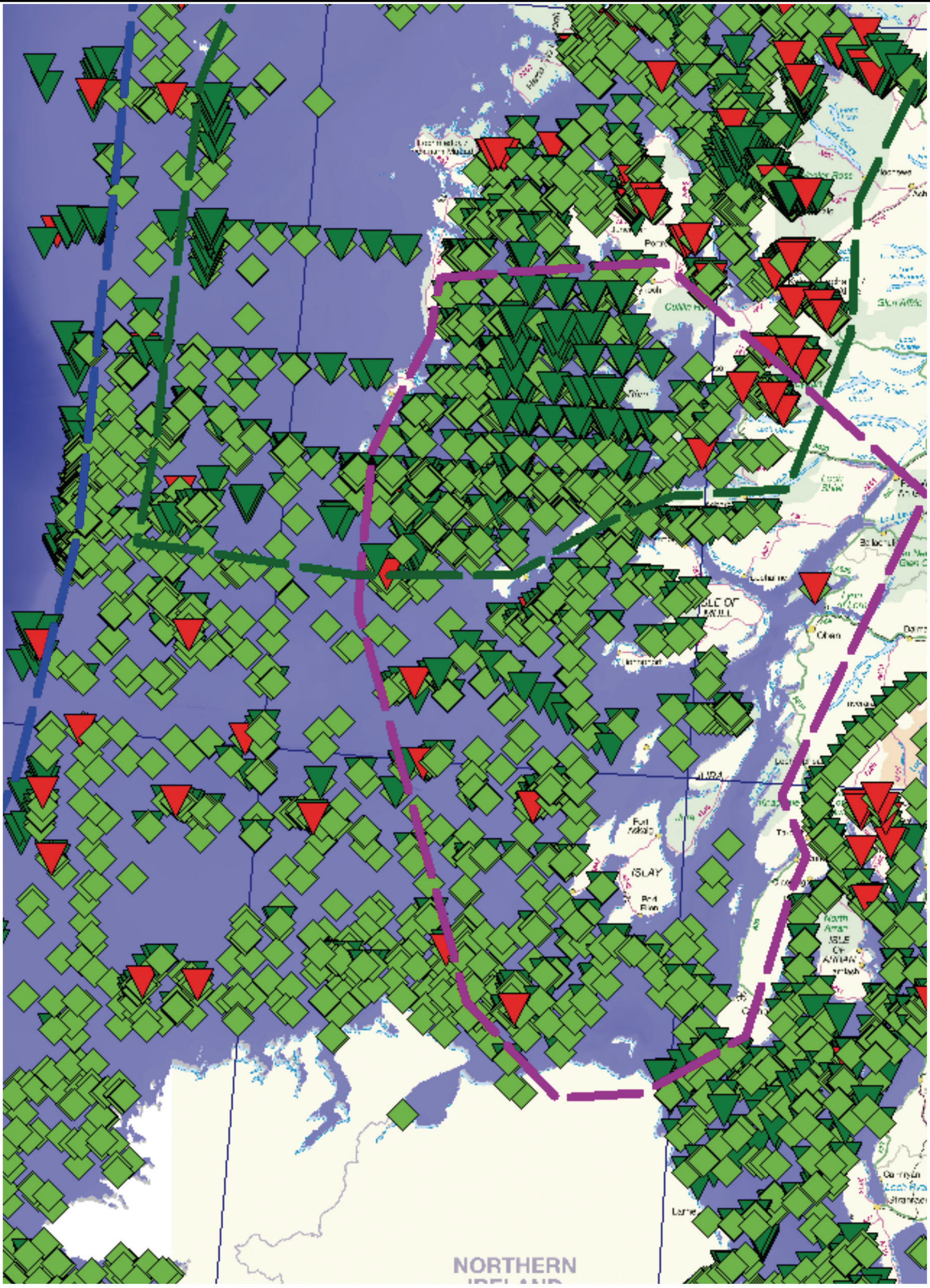
Very few water level observations have been found near Loch Linnhe. Figure 2-6 shows water level observations since 2000; the majority of these data come from TotalTide. Tide levels at Tobermory, Mull exist since 1990. The “restricted” data point shown on Figure 2-6 between Mull and Oban is pressure recorder data collected between June and August 2010 by Marine Scotland.




| Client | Consulting Engineer | Project: | **Figure 2-10** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Wave and tidal domains from the Renewables Atlas |




| Client | Consulting Engineer | Project: | Figure 2-11 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | All temperature observations |



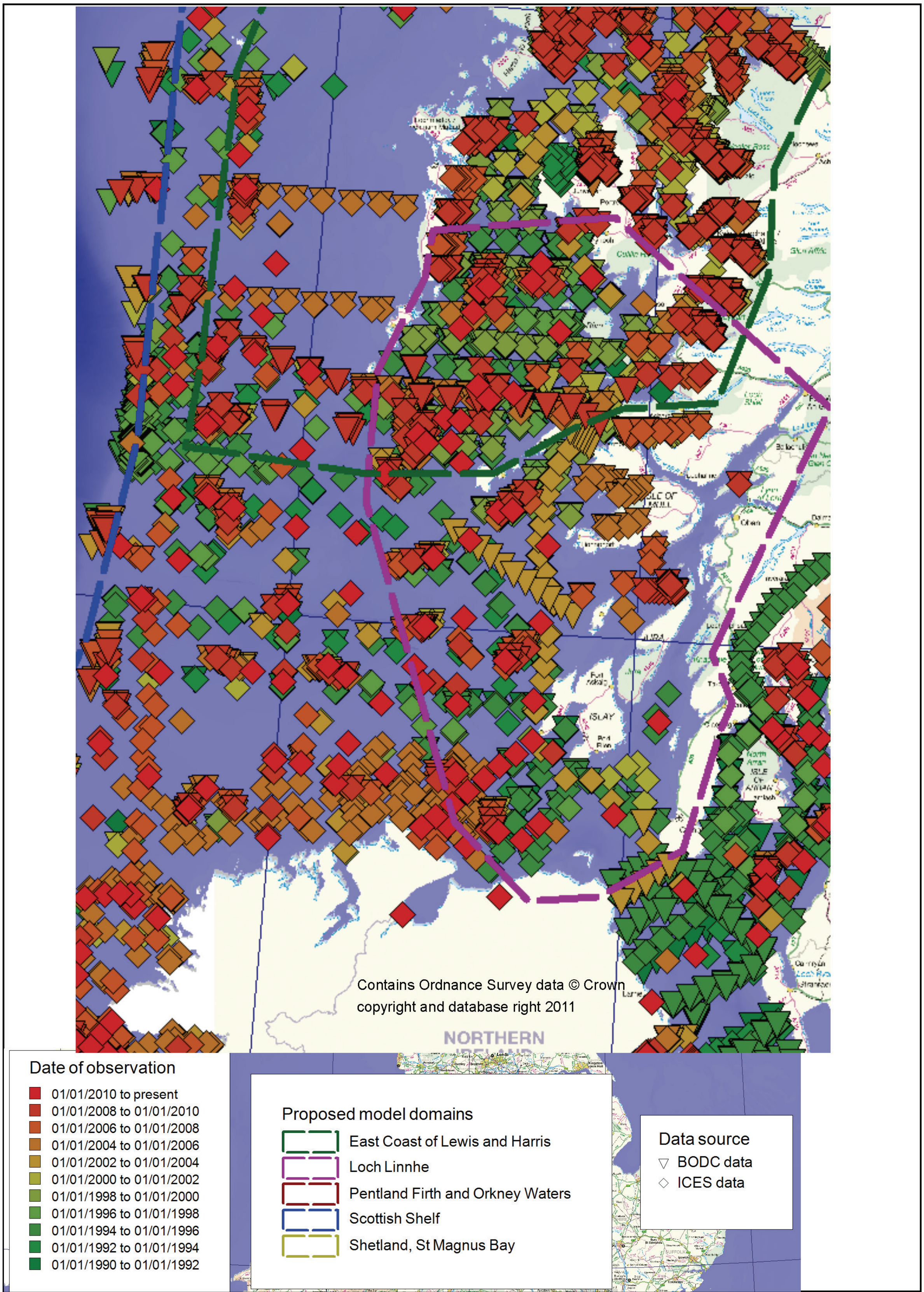

Salinity observations

- BODC data - unrestricted
- BODC data - possible restrictions
- ICES data

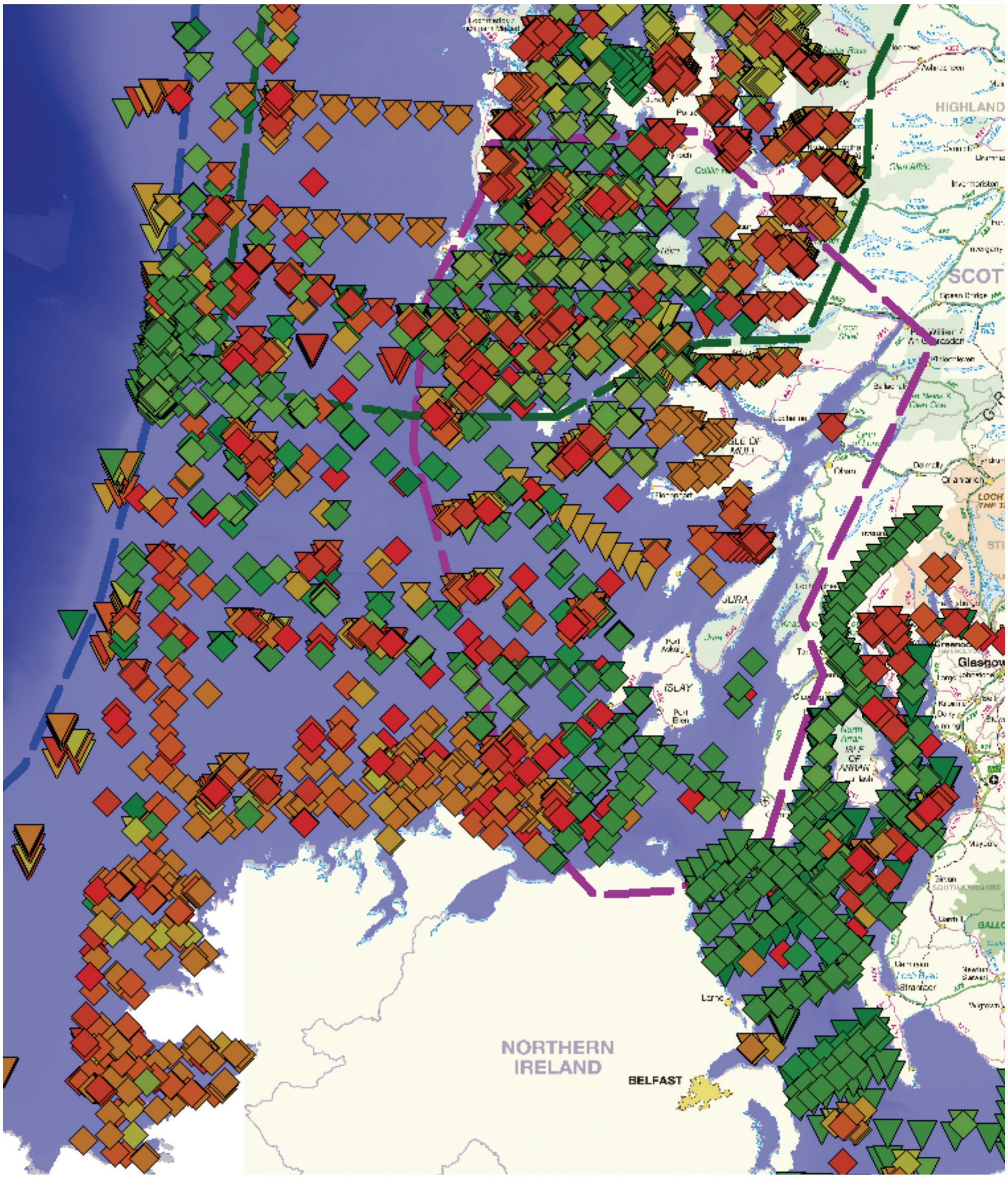
Proposed model domains

- East Coast of Lewis and Harris
- Loch Linnhe
- Pentland Firth and Orkney Waters
- Scottish Shelf

| Client | Consulting Engineer | Project: | Figure 2-12 |
|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | All salinity observations |




| Client | Consulting Engineer | Project: | **Figure 2-13** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Temperature and salinity observations by date, including surface observations and profiles |




Date of observation

- 01/01/2010 to present
- 01/01/2008 to 01/01/2010
- 01/01/2006 to 01/01/2008
- 01/01/2004 to 01/01/2006
- 01/01/2002 to 01/01/2004
- 01/01/2000 to 01/01/2002
- 01/01/1998 to 01/01/2000
- 01/01/1996 to 01/01/1998
- 01/01/1994 to 01/01/1996
- 01/01/1992 to 01/01/1994
- 01/01/1990 to 01/01/1992

Proposed model domains

- East Coast of Lewis and Harris
- Loch Linnhe
- Pentland Firth and Orkney Waters
- Scottish Shelf
- Shetland, St Magnus Bay

Data source

- ▽ BODC data
- ◇ ICES data



| Client | Consulting Engineer | Project: | **Figure 2-14** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Temperature and salinity profile observations by date |

Intensive measurement campaigns were undertaken in 1991, 2011 and 2012 and will be useful for the Loch Linnhe case study area. A summary of the data available in 2011 and 2012 is provided in Figure 2-15. The data collected consists of:

**1991 Measurement campaign:**

- CTD deployments from summer cruises in 1987-1991
- 1991, monthly repeated stations throughout the loch and monthly undulating tows in Loch Linnhe
- Current meters, 13 single-point current meter data mostly in the upper basin (1987-91) but in 1991 also in middle and outer basins. One ADCP instrument data from 1991
- Water level recorder data from four instruments in 1987, 1989, 1990 and 1991
- One thermistor chain data from 1990
- Thermistor chain data from 1991 from various locations in the loch

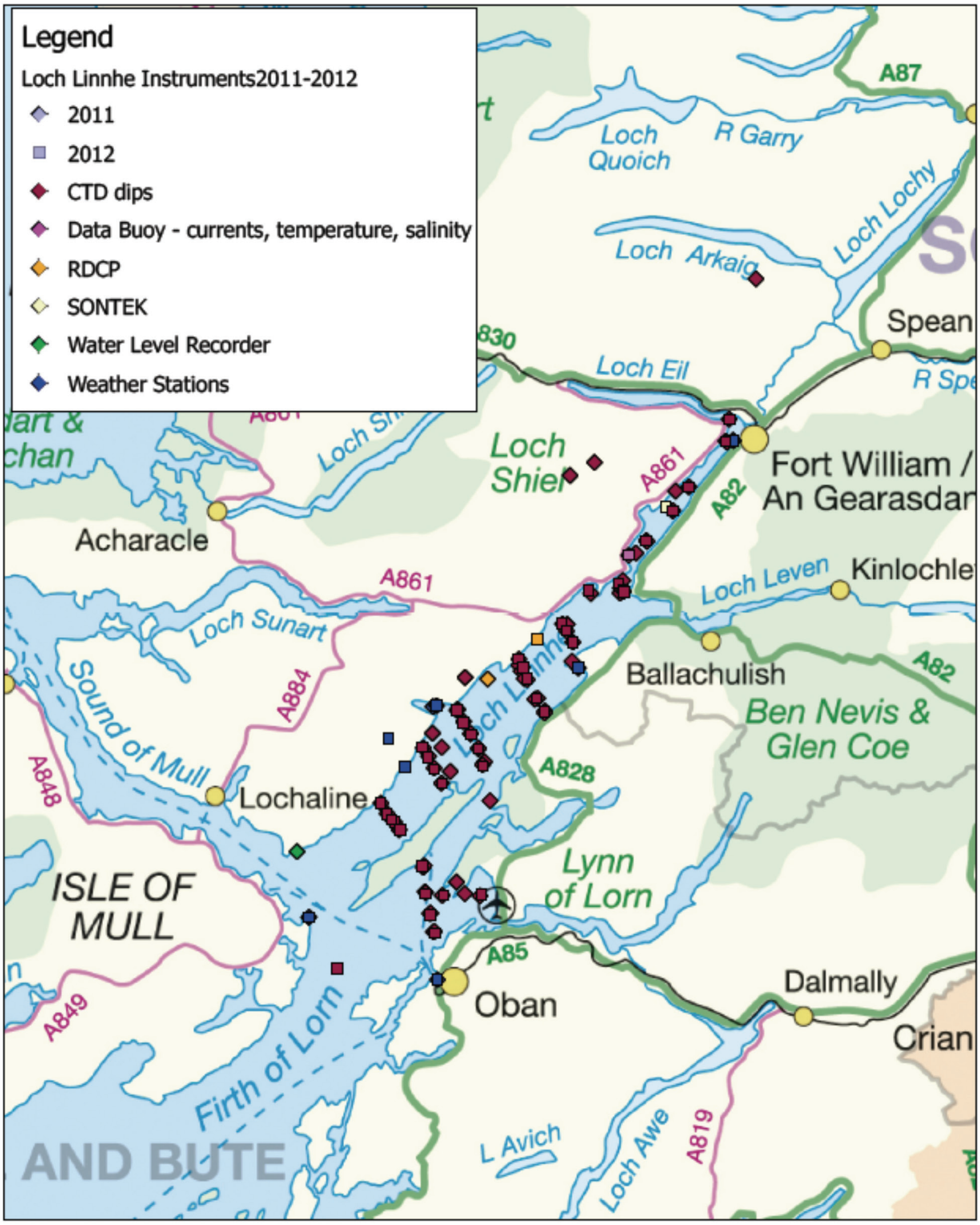
**2011 measurement campaign:**

From a dedicated field campaign carried out in 2011 (May and October) as part of the MSS sealice dispersal project:

- Repeat of main 1991 sampling locations
- Cross-sections in Upper and Lower Loch Linnhe
- At most plankton sampling sites
- CTD data from plankton sampling sites in December 2010
- Tracks of drifters, deployed during July and October 2011 field campaigns. and possibly in 2012
- Single-point current meter data at nine locations around the loch close to shore within 2 week periods in May and October 2011
- One profiling current meter for May and October 2011 close to Loch A'Choire
- Multi-parameter buoy surface current data North of the Corran Narrows from April – December 2011
- ADCP data at model boundaries, as described above

- Water level data from two pressure sensors deployed from April - November 2011 close to Sound of Mull and Fort William

All datasets have been made available.






| Client | Consulting Engineer | Project: | Figure 2-15 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Data available in Loch Linnhe from the 2011 and 2012 surveys |

Figure 2-8 shows the availability of other current data in this area since 2000 which was not part of the intensive measurement campaigns. In addition to the TotalTide data, the point shown between Mull and Jura represents ADCP (circled in orange on Figure 2-8) current measurements collected December 2008 and January 2009. These data appears to have been collected near the bed only.

Table 2-1 summarises the available data for two periods. Given that there exists meteorological forcing in 2011 as well as CTD and current measurements, this would suggest that a period or periods within 2011 would be the most suitable for model calibration. Calibration for temperature and salinity for the 1991 measurement campaign would be harder as the meteorological data held by NOC-L only has wind and pressure for this period (May 1991- present).

Therefore to conclude it is felt that there is sufficient data available for calibration and validation of the local Loch Linnhe model.

## 2.5 Conclusions and Recommendations

A review has been undertaken to identify data that are relevant to the setting up, forcing and calibration of the WLLS model. It has been found that there are datasets available providing coverage over a wide spatial and temporal field.

### 2.5.1 Bathymetry

The EMODnet data is considered appropriate for use as the base bathymetry for model construction. This data formed our base coarser resolution data but was supplemented with higher resolution data.

Further UKHO data and other higher resolution datasets from ICES and Marine Scotland have been used to replace the coarser resolution data in areas that they overlap, with appropriate checks for consistency. However even with these data there are areas which have been identified in the data review report (Halcrow, 2012) as not having sufficient bathymetry data at a fine enough resolution. In this case data from digitised Admiralty Charts have been used.

### 2.5.2 Forcing data

For this case study **tidal forcing, temperature and salinity data** have been obtained from the NOC-L AMM model to provide boundary conditions to the WLLS model.

**Meteorological forcing** for the WLLS model will be derived from the Met Office model data that NOC-L holds. For Loch Linnhe, more localised wind data will also be used to develop an improved picture of the local variability in wind strength and direction by analysing observed wind data available in the locality and correlating with the coarser wind data thus providing higher resolution variability within the WLLS model domain.

The Met Office data provides wind data from 1991 to present day, however other parameters such as sea level pressure, low, medium and high level cloud coverage, specific humidity at 1.5m, air temperature at 1.5m, total accumulated precipitation and sensible heat flux are only available from 2007 to 2011. Data is available from ECMWF ERA-Interim datasets for the 1991 period.

**Fluvial inputs** are taken from G2G river flow data obtained from CEH for the WLLS area. CEH also carried out G2G runs to provide river data for 2011. Flux and temperature data for 3 rivers with in Loch Linnhe have been provided by Marine Scotland for the 1991 runs.

### 2.5.3 Calibration Data

In general there is sufficient data with which to undertake calibration for water level, currents, temperature and salinity by using the 2011 survey data. A summary of the dates where suitable calibration data is available is provided in Table 2-1.

In summary we conclude that there are sufficient data for the calibration of the WLLS model using the data in 2011 and 1991; Figure 2-15 summarises the data available in 2011.

*Table 2-1 Available data*

| Sub model | Year | Water level | Currents | Temperature /salinity | Meteorological | Wind | River |
|---|---|---|---|---|---|---|---|
| Loch Linnhe Wider system | 1991 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ (3) |
| | 2011 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ (151) |

# 3 Hydrodynamic Model Development

## 3.1 Introduction

This section of the report describes the setting up of the WLLS model mesh, bathymetry and the calibration of the flow model. Model documentation and lessons learnt during this process have been captured in Volume 2 of this report.

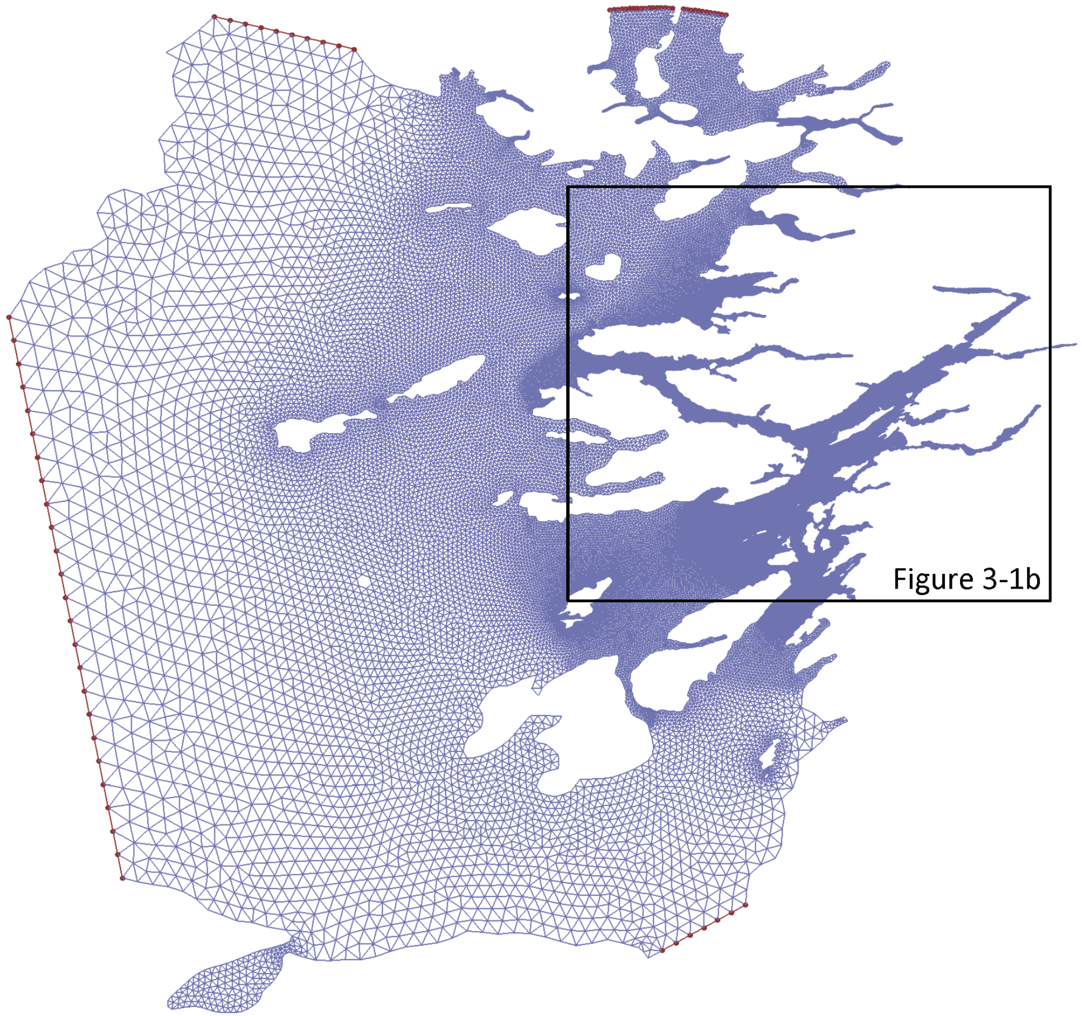
## 3.2 WLLS flow model setup

### 3.2.1 Model mesh

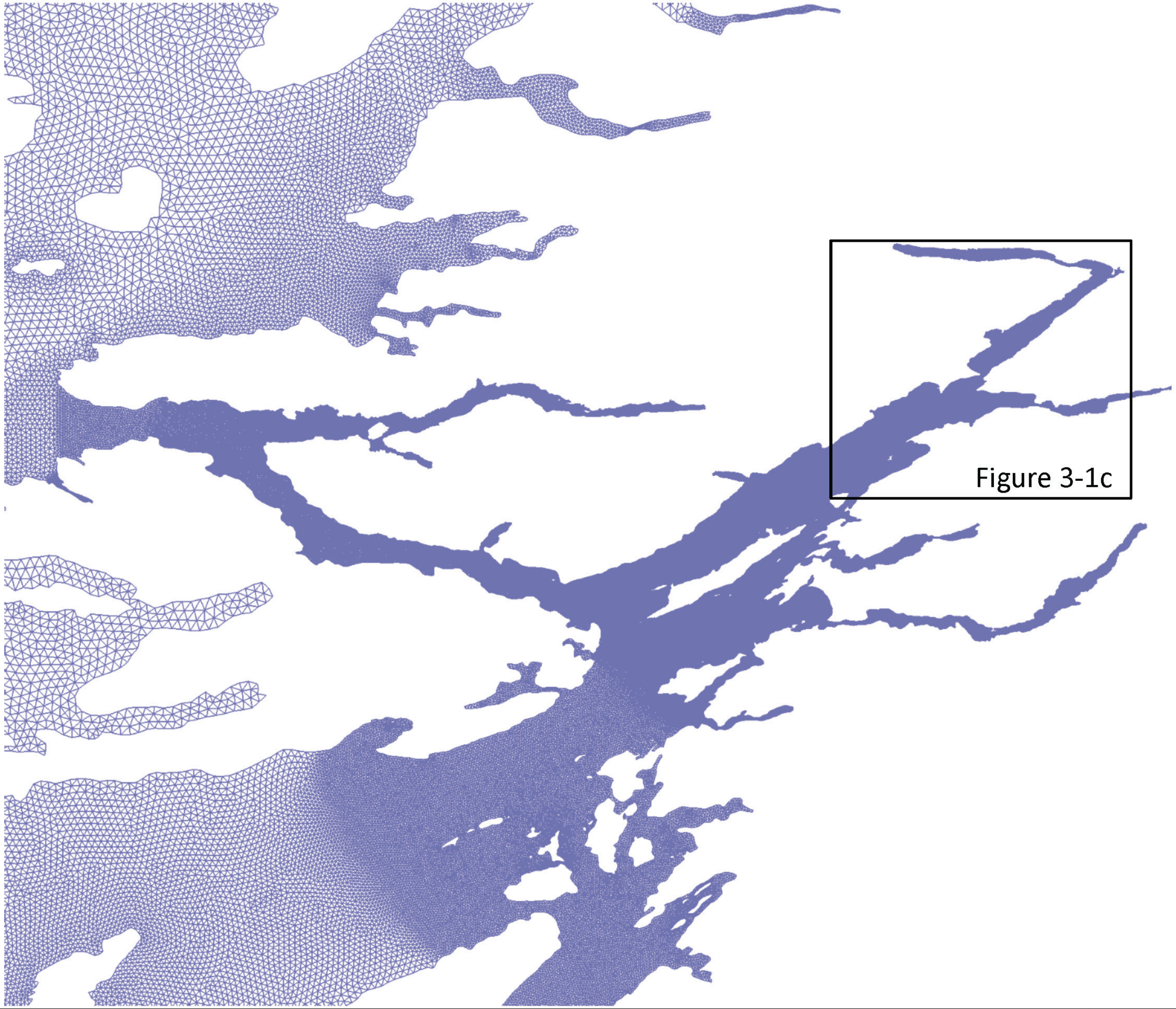
The model mesh developed for the WLLS model has been created using the SMS mesh generator. The horizontal coordinate system used has been latitude and longitude with a vertical datum of mean sea level (MSL). Ten vertical layers have been employed within the model simulations, these were initially equally spaced sigma layers but were later set to be mixed with equal layers in depths less than 13 metres and variable for deeper depths. The variable depths had two layers at the surface which are 1m thick, and two layers at the bottom each being 2.5m thick. The remaining 6 layers are equally spaced. The reason for this setup was to be able to resolve better the freshwater outflow in the upper Loch Linnhe.

The SMS Mesh generator requires coastline and boundary data to define the extent of the active and inactive mesh. Additional information is provided regarding the resolution required in user-specified domains. The resolution is based upon modelling experience, bathymetry gradient/resolution, geographical features and requirements for the study. Although the mesh generator is able to create meshes with triangular or quadrilateral elements, FVCOM requires only triangular elements.

Mesh generation can be an iterative process in order to get a mesh that varies smoothly, with triangles that do not have angles that are too acute and resolution that does not require an overly small model timestep. SMS has a number of features to allow for a smooth resolution change throughout the model domain so that adjacent element volumes do not differ by more than a factor of 0.5. Additionally the minimum interior angle was set as 30 degrees, maximum interior angle set as 130 degrees and the maximum number of connecting elements was set as 8. These values were obtained from the FVCOM manual. It had been found previously that the volume factor and the number of connecting nodes did effect the model stability. Figure 3-1a-c show the mesh at different zoom levels.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-1a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Entire model mesh | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-1b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Model mesh. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-1c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Model mesh. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

### 3.2.2 Model bathymetry

The WLLS model mesh was created using the SMS mesh generator. The area of the mesh is contained within the Atlantic Margin Model (AMM – developed by NOC-L) from which boundary conditions have been obtained.

The bathymetry used for the WLLS model was derived from the same sources as the other case study models, namely:

- EMODNET (coarser and generally offshore),
- higher resolution survey bathymetry (data and other higher resolution datasets from ICES and Marine Scotland) and
- digitised Admiralty Chart data where no other data was available.

The coastline was derived from Ordnance survey coastline data.

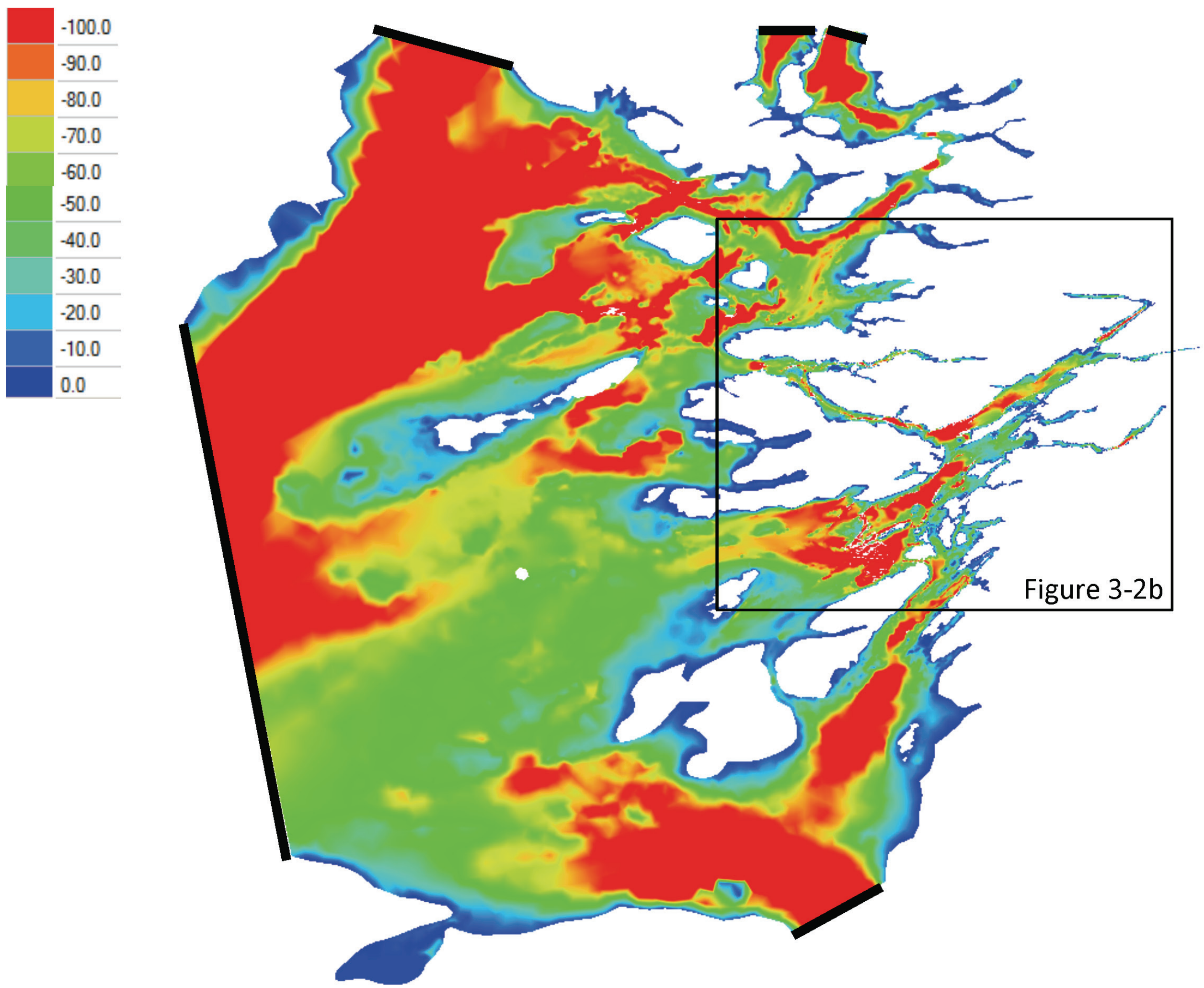
This bathymetry was combined to a common datum of MSL and interpolated onto the model mesh within the SMS mesh generator. Figures 3-2a-c shows the extent of the model domain with various zoomed in views showing detail in Loch Sunart, Mull Sound and Loch Linnhe. The open boundaries are highlighted in black. The contours on these images are of the model bathymetry which is relative to MSL.

### 3.2.3 Boundary data

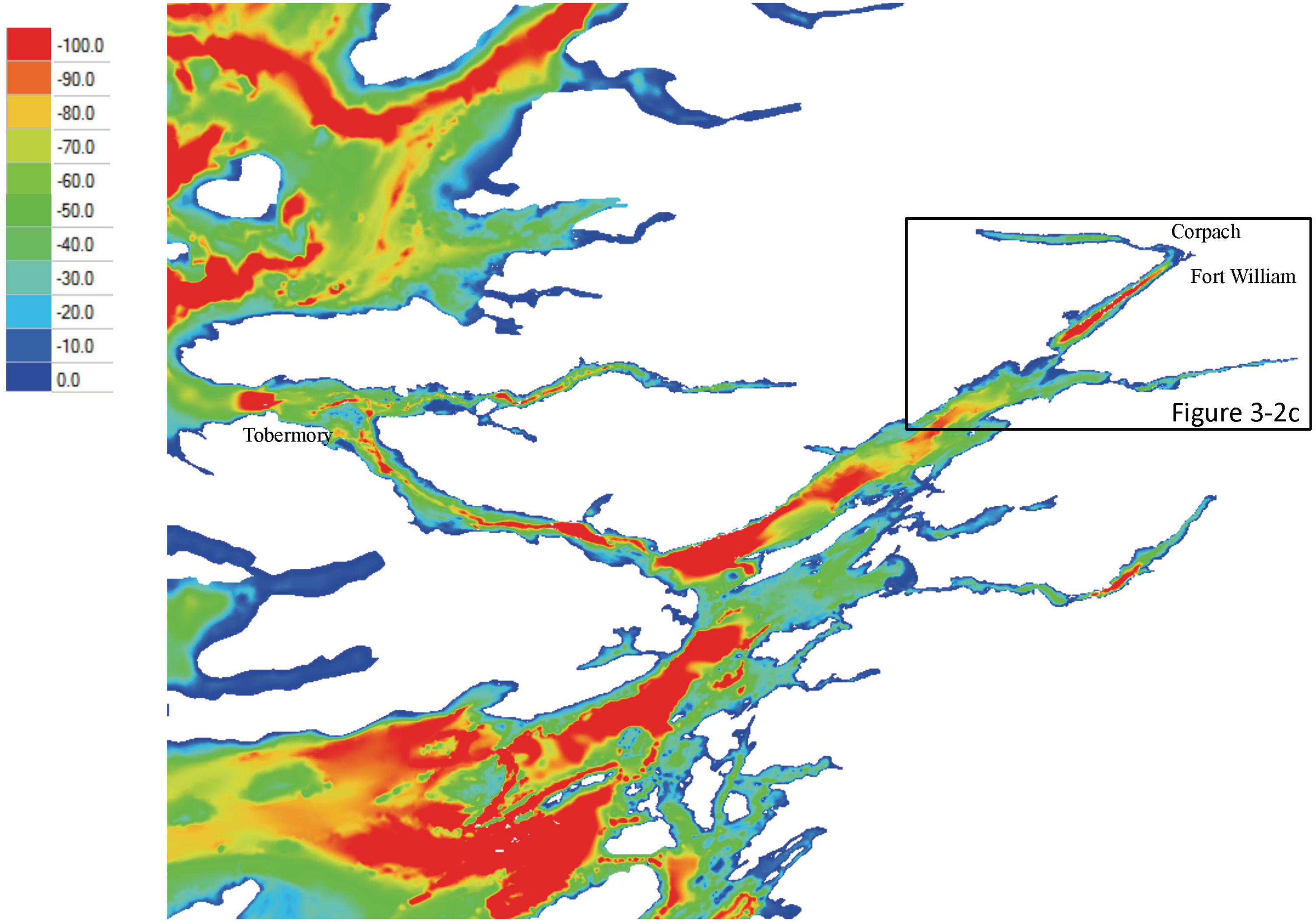
The WLLS model utilises the FVCOM TYPE 3 nesting boundaries, the location of which can be seen in Figures 3-2 a-c. The boundary data are derived from the AMM model results supplied by NOC-L. TYPE 3 nesting boundaries supply the model with water level, current speed components, temperature and salinity at the nodes/element centres of all of the elements attached to the model boundaries. In addition a weighting is also applied so that a combination of the boundary conditions and the values within the model domain can be determined and applied at the model boundaries. The weighting at the element centres was set as 0.5, whereas the weighting on the nodes along the boundary were set as 0.75, and the nodes inside the model domain set as 0.25.

Two periods for the model calibration and validation were chosen based upon available data (current, temperature and salinity measurements) for comparisons along with data used as forcing for the model (AMM model availability, met forcing, local wind conditions, river flows from CEH). These were May and October 2011.

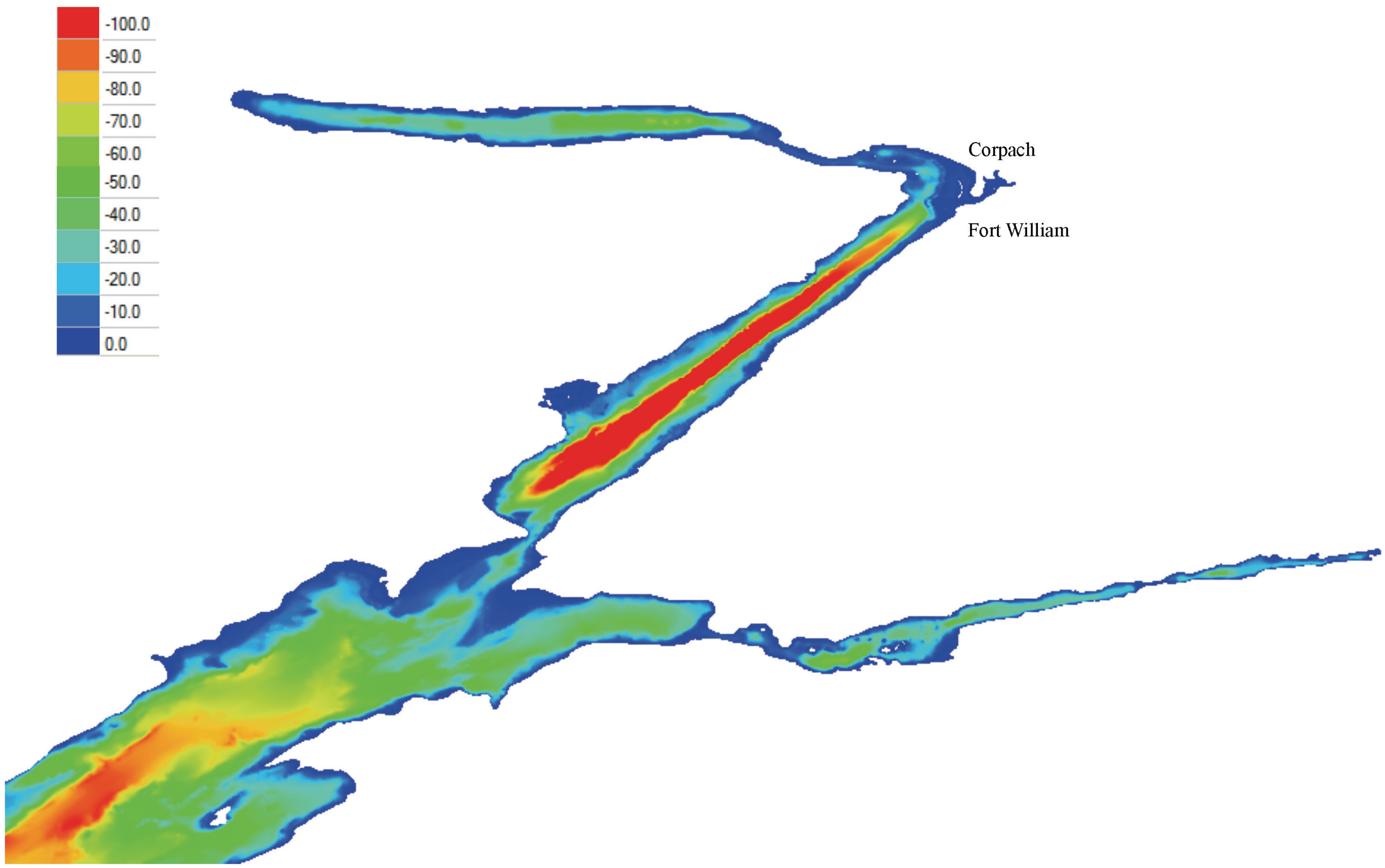
The WLLS model is run initially with constant temperature and salinity for a short warm-up period, this outputs a hotstart file which contains information about water levels, current speed and temperature/salinity. To reduce the warm-up period for the temperature and salinity, a Matlab script has been used which writes AMM or Scottish Shelf model temperature and salinity results to the hotstart file (over-writing the constant values in the hotstart file). This allows the follow-on WLLS model hot start conditions to match those applied at the boundary and to have suitable temperature/salinity within the model domain. The external timestep used in the simulations was 0.3 seconds, with ISPLIT set as 5 (ratio of internal timestep to external timestep). Many tests were undertaken to reduce the run times, but due to the high velocities in the side loch sills within Loch Linnhe, this was the largest timestep possible even though some coarsening of the mesh in these areas was also included in the mesh.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Entire Model bathymetry<br>Black lines represent the model open boundaries | Checked<br>DMP | Scale<br>Not to scale | Rev.<br>0 |
| | | | | Designed<br>FML | Drawn | Date<br>14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Entire Model bathymetry | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-2c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Entire Model bathymetry | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

### 3.2.4 Meteorological forcing data

There are two option when including heat input into the FVCOM model; either the heat inputs are provided by way of netcdf files (from data provided by the Met Office), or FVCOM calculates it internally. NOC-L found that the Scottish Shelf model was heating up too much with the former approach over a 4-month simulation. Furthermore, they found that this overheating problem was solved by allowing FVCOM to calculate the heat inputs internally. The reason for the overheating problem is due to the difference in sea surface temperature used in the Met Office model and the AMM model used for deriving initial conditions.

It is therefore advantageous to follow the NOC-L approach and have the heating calculated within the model so this is the method employed for this case study. The AMM model outputs for 2011 contained only air temperature, sea level pressure, total precipitation and the U and V wind components. The relative humidity and short wave and longwave downward solar radiation were taken from the ECMWF interim data set. It is important to note that the radiation terms from the ECMWF are given as an accumulated total which is reset every 12 hours at midnight and midday. These datasets were processed and a Matlab tool produced which provided the necessary meteorological file for FVCOM.

There were some issues with the meteorological forcing data with rain falling on dry elements, some negative evaporation (and precipitation) as well as cooling of elements that were disconnected from the main water body (at a few places along the coastline). Additionally the Met data grid did not always overlap fully the WLLS model. In order to remove issues associated with these problems, the met data was post-processed to make the values zero in these locations. It was felt that this would not have a significant impact upon the overall model results.

### 3.2.5 Initial conditions

To avoid long warm-up periods to allow temperature and salinity to reach dynamic equilibrium the shelf model climatology results were used. The AMM results were considered but due to the low resolution (12km) compared to Loch Linnhe it was not used. First the hydrodynamic model is run from cold with constant temperature and salinity. The warmed up water level sand currents are saved in a restart file. This restart file is processed using a MATLAB scripts that interpolates the temperature and salinity from the Scottish Shelf model climatology results on to the WLLS mesh and writes this into the restart file, replacing the constant values.

### 3.2.6 Local wind condition derivation

It has been observed that the complex hydrodynamics within Loch Linnhe can be affected by the local wind conditions and therefore some consideration of this was included in the modelling. This section briefly explains what has been done to adjust the relatively coarse (compared with Loch Linnhe dimensions) met forcing wind data described in the previous section to account for the effect that the local topography has upon the wind speeds over Loch Linnhe. For a more detailed explanation of the process, see the Technical Note in Appendix A.

The approach used was to obtain wind speed/direction from a number of sites in and around WLLS and correlate for different speeds and directions against a reference site away from the complex topography. This allowed the prediction of wind speeds within Loch Linnhe given wind conditions outside. The criteria for choosing suitable wind stations were: a) data availability, and b) a good spread within the estuary as well as a point outside.

Data for 2011-2012 were available from the following sources:

- MS Data: Duart, Fort William, Cuil Bay and Kingair Loch
- SAMS Data: Oban (Dunstaffnage data were available only until 2010)

Duart and Oban were the two possible reference stations towards the mouth of Loch Linnhe. The other stations are inside Loch Linnhe, and were used for the correlation. The common data periods for 2011-2012 were July-December 2011 and April-October 2012.

After analysis of the data, Duart at the mouth of Loch Linnhe was chosen to be the reference station, whilst Cuil Bay and Fort William were chosen to describe the variation of wind speed and direction relative to Duart; these were located midway and at the head of the Loch respectively. The other location (Kingair Loch) was not used after analysis of the data suggested that it is not entirely suitable due to local topographic features and localised features in the wind conditions. It was felt therefore that accounting for the acceleration of wind blowing up the loch from the sea (as shown in the data) and vice-versa would be our main focus as this may have an effect of holding up the freshwater in the Upper Loch Linnhe. This approach takes account of the increase/decrease in wind speeds along the length of the Loch for different directional sectors. Using the Met Office wind speeds at Duart, these are scaled and interpolated onto the model mesh within Loch Linnhe.

The three locations used were corrected for altitude, then ratios of wind speed relative to Duart calculated for Fort William and Cuil Bay for 22.5 degree sectors. Likewise the direction deviation in wind direction compared with Duart are calculated at these two locations for the same directional sectors. The values obtained for the two sites are shown in Table 3-1. It can be seen that for winds blowing up the Loch from the sea, wind speeds at Cuil Bay are 1.2 times greater, and at Fort William are 1.6 times greater than the wind speeds at Duart. For wind blowing down the Loch from the land, the wind speed ratios at Fort William and Cuil Bay relative to Duart (1.0) are 0.7 and 0.8 respectively. Following on from the calculation of the wind speed scaling and direction shifts, the speeds/directions at Duart within the met data are interpolated linearly along the length of the estuary replacing the wind speeds within the original met file that had been created previously.

*Table 3-1 wind speed ratios and wind direction shifts for Cuil Bay and Fort William relative to Duart*

| Loch Linnhe Station | Cuil Bay | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 1.0 | 1.0 | 0.9 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.3 | 1.2 | 1.1 | 1.0 | 0.9 | 0.8 | 0.9 | 1.0 |
| Wind Direction Difference | 3.5 | 3.9 | -4.6 | -12.7 | 17.7 | -1.1 | 21.5 | 12.2 | -16.6 | -33.0 | -33.8 | -27.3 | -11.4 | 26.6 | 20.3 | 16.1 | 3.5 |

| Loch Linnhe Station | Fort William | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 0.9 | 0.8 | 0.7 | 0.7 | 0.6 | 0.9 | 1.0 | 1.1 | 1.3 | 1.6 | 1.6 | 1.6 | 1.3 | 0.9 | 0.9 | 0.9 | 0.9 |
| Wind Direction Difference | -48.8 | -10.1 | -2.4 | -10.2 | -28.7 | -21.0 | -16.2 | 0.9 | 1.2 | -16.6 | -32.7 | -32.6 | -42.0 | -15.6 | -4.5 | -42.9 | -48.8 |

## 3.3 River input

River data was obtained from CEH and encompassed all of 2011 at 15 minute intervals. This data was processed using a MATLAB tool that determined which mesh node to apply the river flow to. It also moved the location of a river node to the nearest land node if it was connected to two other land nodes in the same element (if connected in this way, then the river flow cannot escape the element and water levels build up artificially too high).

A river namelist file was produced along with a netcdf file for each of the rivers named in it. On further application of the Scottish Shelf model it was found that reading in over 500 river files impacted upon model performance (input/output overhead). Therefore only one namelist and river file were employed for this study, encompassing all of the rivers within the model domain.

The salinity in the river flow was set to 0 psu, and the temperature was initially set to 7 degrees Celsius as this was appropriate for the nearshore temperatures from the AMM model, but was increased to 10 degrees Celsius for the final calibration runs.

The river flow is distributed equally amongst all of the vertical layers. In the upper Loch Linnhe and other side lochs, the Grid2Grid model (CEH) did not resolve the river sources, however the discharge for tributaries further upstream were included in the furthest points upstream in each of these water bodies. Therefore to include the river discharges in the correct place, the river flow was redistributed according to the catchment area of the upstream tributaries.

## 3.4 Initial Sensitivity runs

A number of sensitivity runs were carried out during calibration of the WLLS model. These include sensitivity to wind scaling, vertical mixing and the number of layers used. Please note that these sensitivity comparisons are not from the final calibration run, and some changes in the initial conditions were made to these runs.

### 3.4.1 Wind scaling

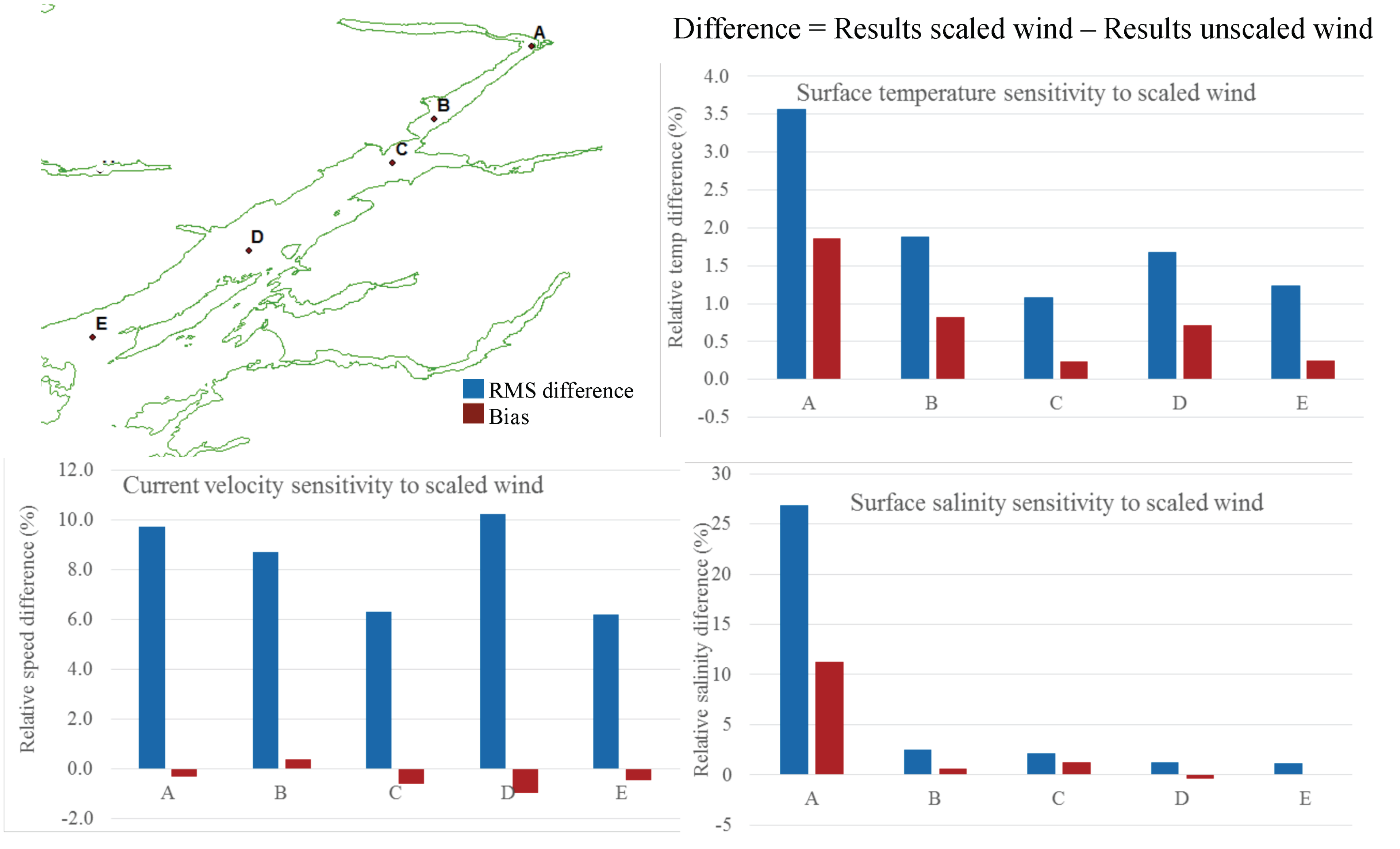
The sensitivity of the model results to the scaled wind at a number of locations around Loch Linnhe and Loch Sunart for the May 2011 run is presented in Figure 3-3a. Figure 3-3b shows the scaled wind speed and direction at location A, C and E and the unscaled wind at E as a reference. This shows that when winds are directed up the Loch (winds blowing from SSE to WSW) the wind speed increases up the Loch this is most significant for winds from the SW. The influence of the scaled wind on sea surface temperature and salinity is small, with the RMS difference and bias less than 2% at all stations except A which is where the increase in wind speed is highest and is close to the outflow of River Lochy and River Nevis which have a high combined discharge rate. At station A the temperature and salinity bias is positive showing a 1.9% or 0.2°C and 11% or 1.2psu increase respectively. The channelling of the wind up the Loch in the scaled wind is likely to hold back or alter the flow of the incoming fresh water at Station A causing a slight increase in temperature and salinity at that location. The RMS difference in current flows is up to 10% in Loch Linnhe, little difference is seen in Loch Sunart as the scaled wind is not applied there. The bias in the data in Loch Linnhe and the sound of Mull is however very small. Please note these sensitivity test were not carried out on the final calibration run but during the calibration process.

### 3.4.2 Vertical mixing

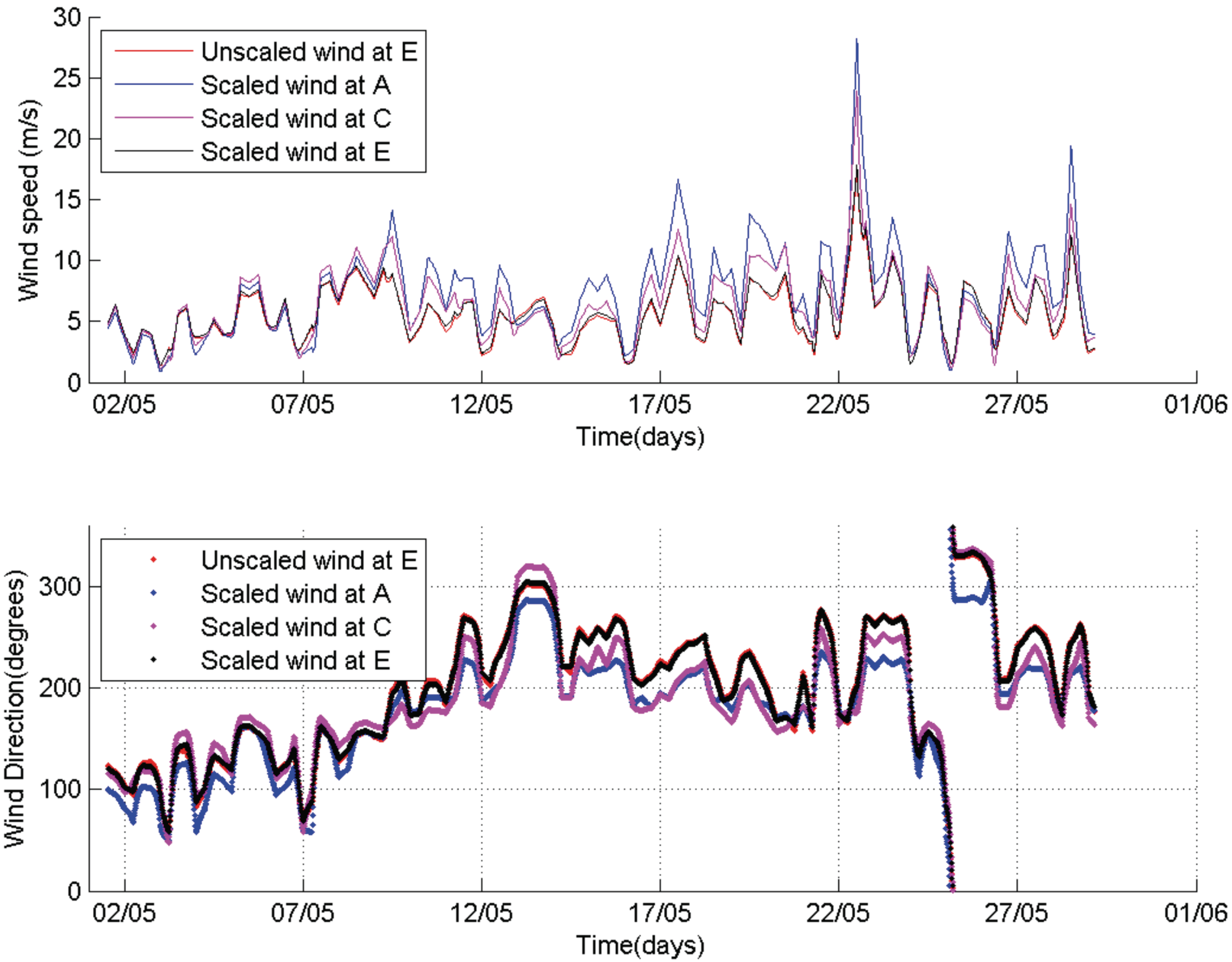
To test the sensitivity of the model results to vertical mixing the vertical mixing coefficient and vertical Prandtl number were reduced by a factor of 10 from the default values used in the three other local models, i.e. from 1E-5 to 1E-6 and from 1.0 to 0.1 respectively. Figure 3-4 shows the model sensitivity for May 2011 at a number of locations around Loch Linnhe and Loch Sunart. The largest impact is seen in salinity at Location A, close to the outflow of River Lochy and River Nevis, here the reduction in vertical mixing lead to an increase in the bias of salinity of around 24% (2.7 psu). At all other locations the bias in salinity is small (<1.5%), as is the bias in temperature (<1.5%) and current speeds (<6.2%).

### 3.4.3 Vertical layer schematisation

A sensitivity run to the number of vertical layers was carried out. A 12 layer model was set up in an attempt to capture the drop in salinity seen at the data buoy, an extra two layers were added to the surface layers so the top four layers had a thickness of 0.2, 0.4, 0.6 and 0.8m respectively the lower 8 layers remained as they were in the 10 layer model. The comparison with the 10 layer model and the data is shown in Figure 3-5. Increasing the number of layers and reducing the thickness of the upper layers had the opposite effect to what was expected. During periods of low or no river flow the results were similar, however during periods of high river flow the surface salinity increased relative to the 10 layer model. The surface temperature did drop slightly relative to the 10 layer model.

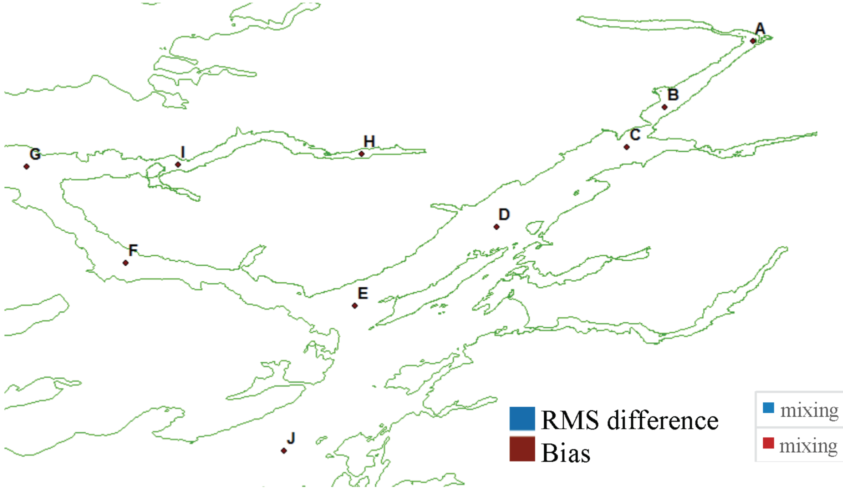


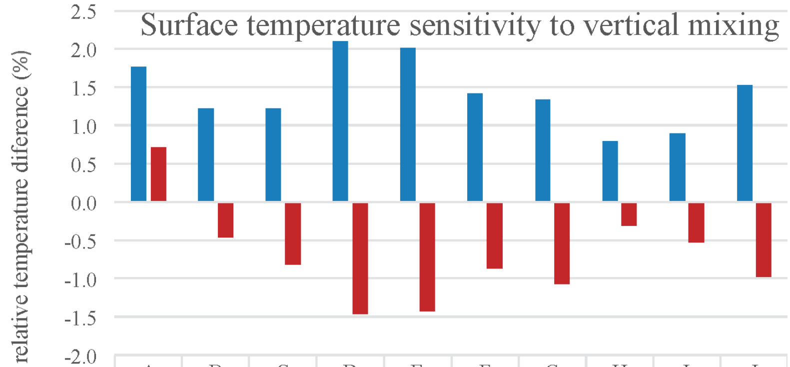

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | RMS difference and bias between scaled and unscaled wind at a number of locations in Loch Linnhe where scaled wind is used | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



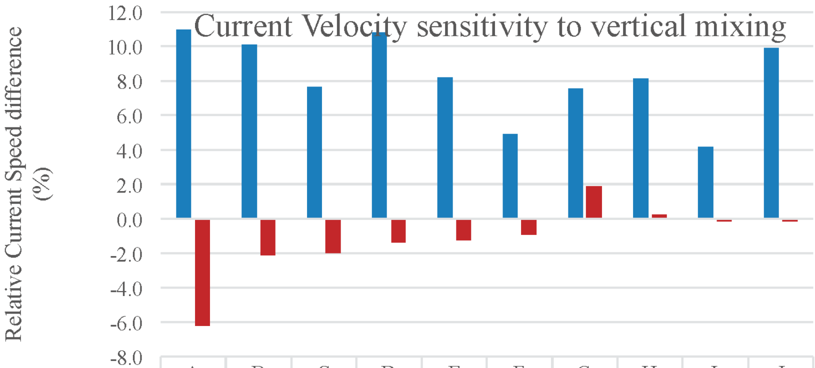

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-3b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Changes in scaled wind speed and direction though Loch Linnhe | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

Difference = Results lower vertical mixing – Results higher vertical mixing

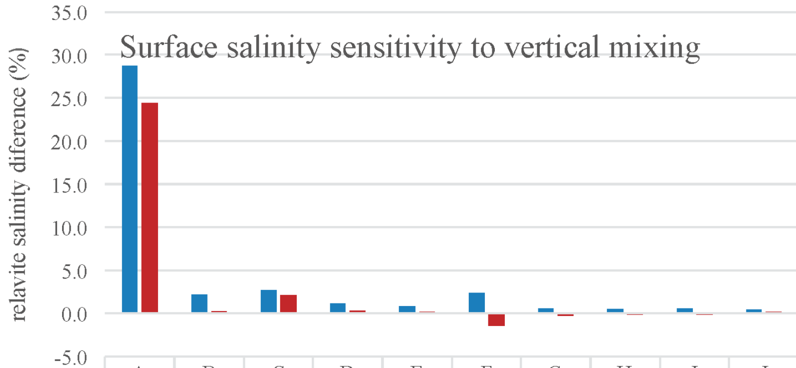



| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| mixing rms surface | 1.8 | 1.2 | 1.2 | 2.1 | 2.0 | 1.4 | 1.3 | 0.8 | 0.9 | 1.5 |
| mixing bias surface | 0.7 | -0.5 | -0.8 | -1.5 | -1.4 | -0.9 | -1.1 | -0.3 | -0.5 | -1.0 |

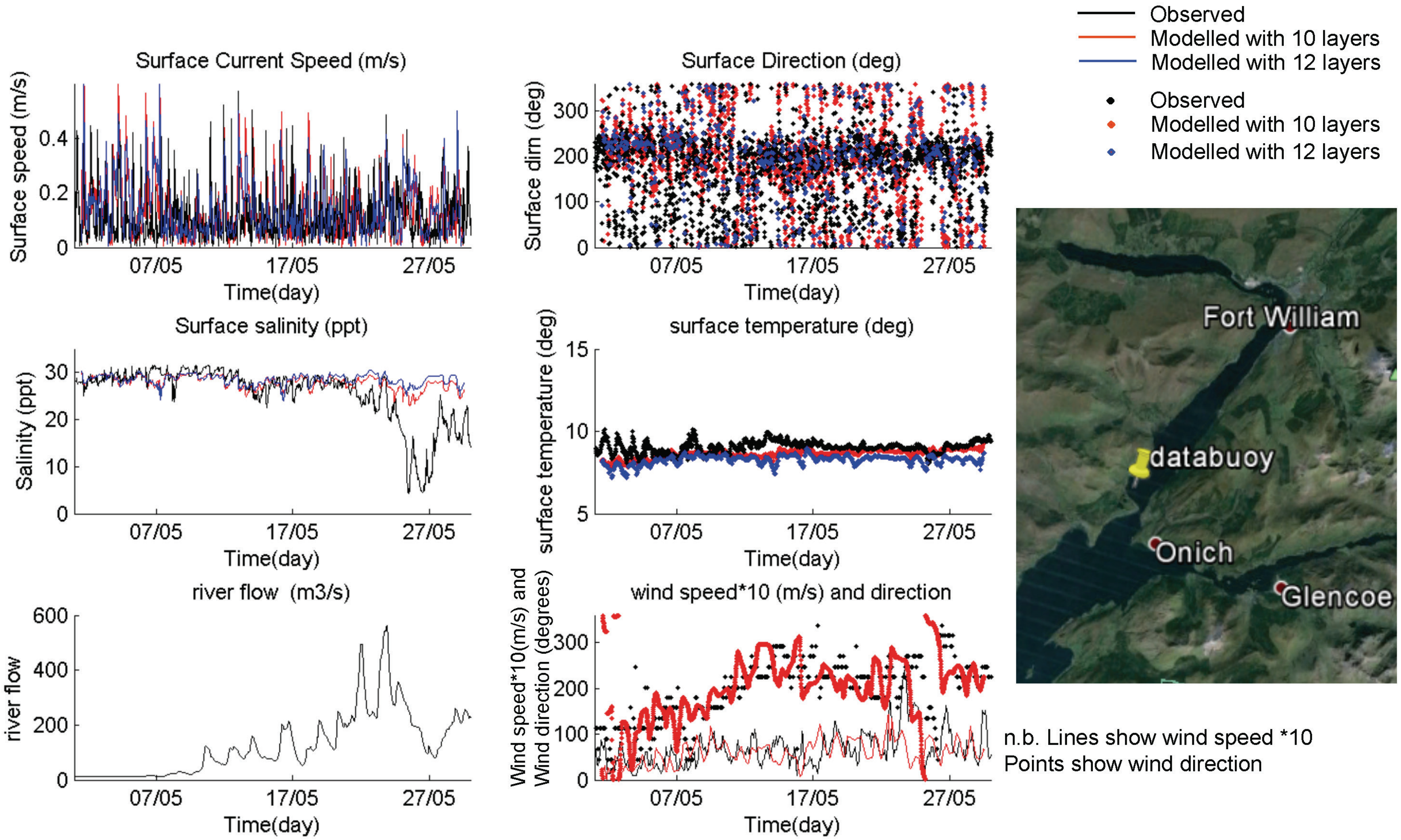



| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| mixing rms | 11.0 | 10.1 | 7.6 | 10.8 | 8.2 | 4.9 | 7.5 | 8.1 | 4.1 | 9.9 |
| mixing bias | -6.2 | -2.1 | -2.0 | -1.4 | -1.2 | -0.9 | 1.9 | 0.3 | -0.1 | -0.1 |




| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| mixing rms surface | 28.7 | 2.2 | 2.7 | 1.1 | 0.9 | 2.3 | 0.6 | 0.5 | 0.6 | 0.4 |
| mixing bias surface | 24.4 | 0.2 | 2.1 | 0.3 | 0.1 | -1.5 | -0.3 | -0.1 | -0.1 | 0.1 |

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-4 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | RMS difference and bias between two values for vertical mixing at a number of locations around Loch Linnhe | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-5 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of model with 10 and 12 layers and Databuoy measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

## 3.5 Flow model calibration

A range of datasets were available with which to calibrate the WLLS hydrodynamic model. Water level data were available for long periods at Tobermory and Corpach, with 6 month records at the southern end of Loch Linnhe and Fort William. Currents, CTD profiles and longer term temperature and salinity measurements were available at a range of locations within Loch Linnhe from a survey undertaken by Marine Scotland in 2011 during the months of May and October, although some instruments covered all of the period between these two months. Additionally MS undertook a short survey to record current speeds and temperature/salinity in June 2013 in the Mull Sound and entrance to Loch Sunart.

The different timeframes at which the various current measurements were available, combined with the periods when we had suitable boundary and meteorological forcing data meant that it was difficult to run the model with all of the met forcing and coincident boundary conditions to that of the available data; boundary conditions were available for 2011, as was the met data and therefore May and October 2011 were used for the calibration and validation periods respectively. Current data obtained during other timeframes were compared with the May 2011 model results following harmonic analysis of both data and model results.

Initially the model was run for the month of May 2011, with river input and full met forcing. The results of which were compared with water levels, currents and temperature/salinity.

Many tests were undertaken with both the initial conditions, the river flow distribution (in the Upper Loch Linnhe (ULL) tributaries) and the vertical resolution to try and get the salinity to drop during high fluvial flow conditions to match the measurements at the Data buoy in ULL. The best results were obtained with a variable vertical resolution.

To keep runtimes at a sensible limit, 10 layers was found to be appropriate. However as will be seen later, the Data buoy in ULL showed large drops in salinity during high freshwater flow periods. Although a drop in the salinity was seen in the model, but the modelled drop was not as large as measured. It was felt that 10 uniform sigma layers did not provide sufficient near-surface resolution and therefore a variable vertical resolution was employed. For depths less than 13m, 10 vertical, equally spaced sigma layers were used. For depths greater than this, the top two layers had a thickness of 1.0m, and the bottom two layers had a thickness of 2.5m, with the remaining 6 layers split amongst the remaining thickness of water. This allowed greater resolution near to the surface in the deeper water as well as close to the bed. It was felt that the freshwater from the rivers would spread out as thin as possible on the surface of ULL, if the surface layers were too thick then this would not be resolved and the predicted salinity would be too high.

The model parameters applied to the FVCOM WLLS model were as follows:-

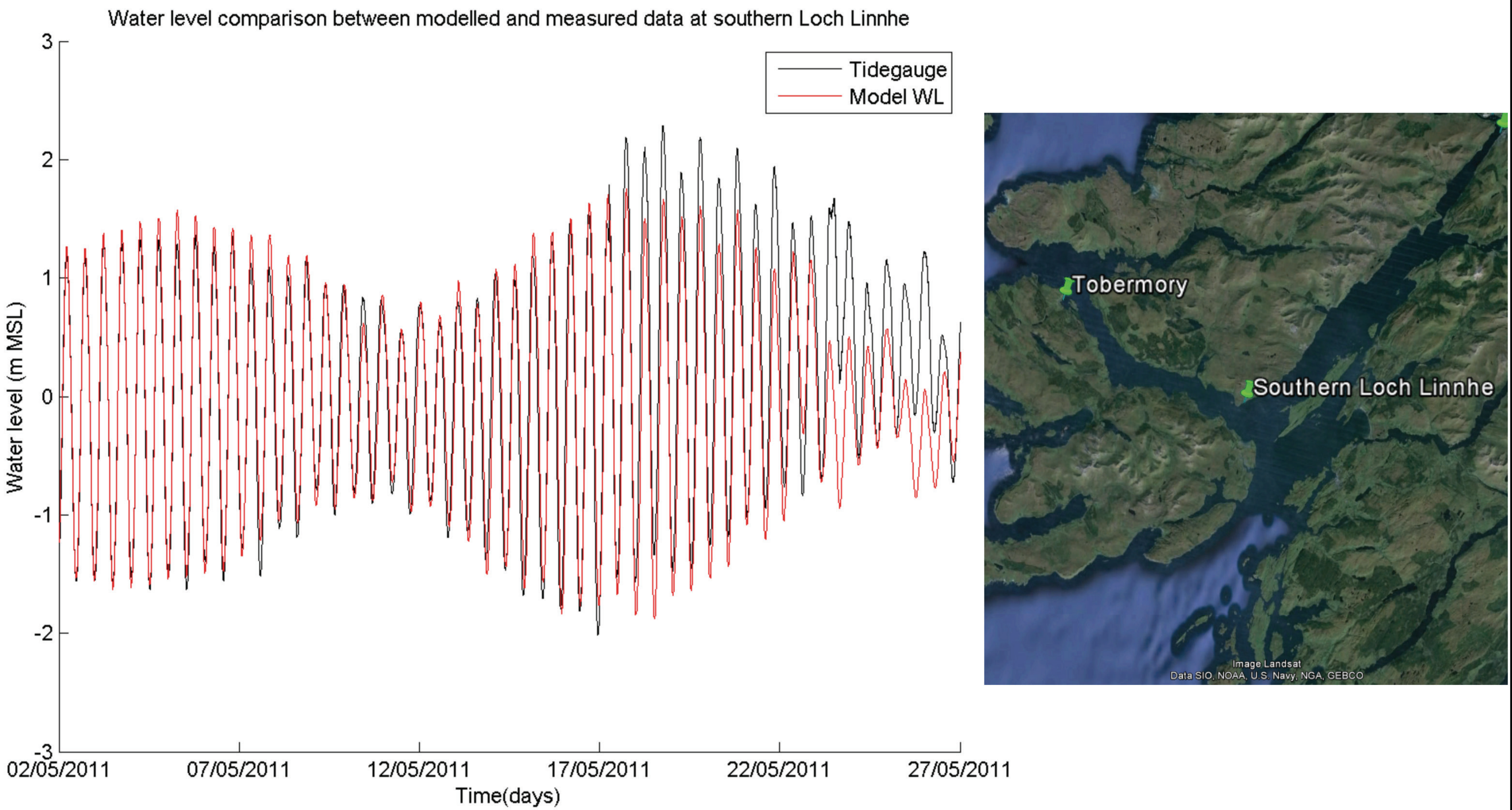
| | | |
|---|---|---|
| follows:- | *Horizontal mixing coefficient* | *= 0.3* |
| | *Horizontal Prandtl number* | *= 1.0* |
| | *Vertical mixing coefficient* | *= 1E-6* |
| | *Vertical Prandtl number* | *= 0.1* |
| | *Bed roughness* | *= 0.1* |

The calibration of the model was undertaken for the month of May 2011. Comparisons between the simulated model results and observed water levels can be seen in Figures 3-6a-d for the southern end of Loch Linnhe, Tobermory, Fort William and Corpach. The model simulation included full met forcing, river input and adjusted wind speeds within the Loch. It can be seen that for the majority of the month the predicted water levels are a good match with the observed data. However from the 18/5/2011, it can be seen in Figure 3-6a that there is a vertical shift in the observed water levels. Consultation with MS revealed that the shift was due to the mooring sliding down the steep slope it was deployed on. However around the 24-25$^{th}$ May 2011 there appears to be a vertical shift in water levels at all of the gauges, especially at Fort William and Corpach. The reason for this shift is unclear.

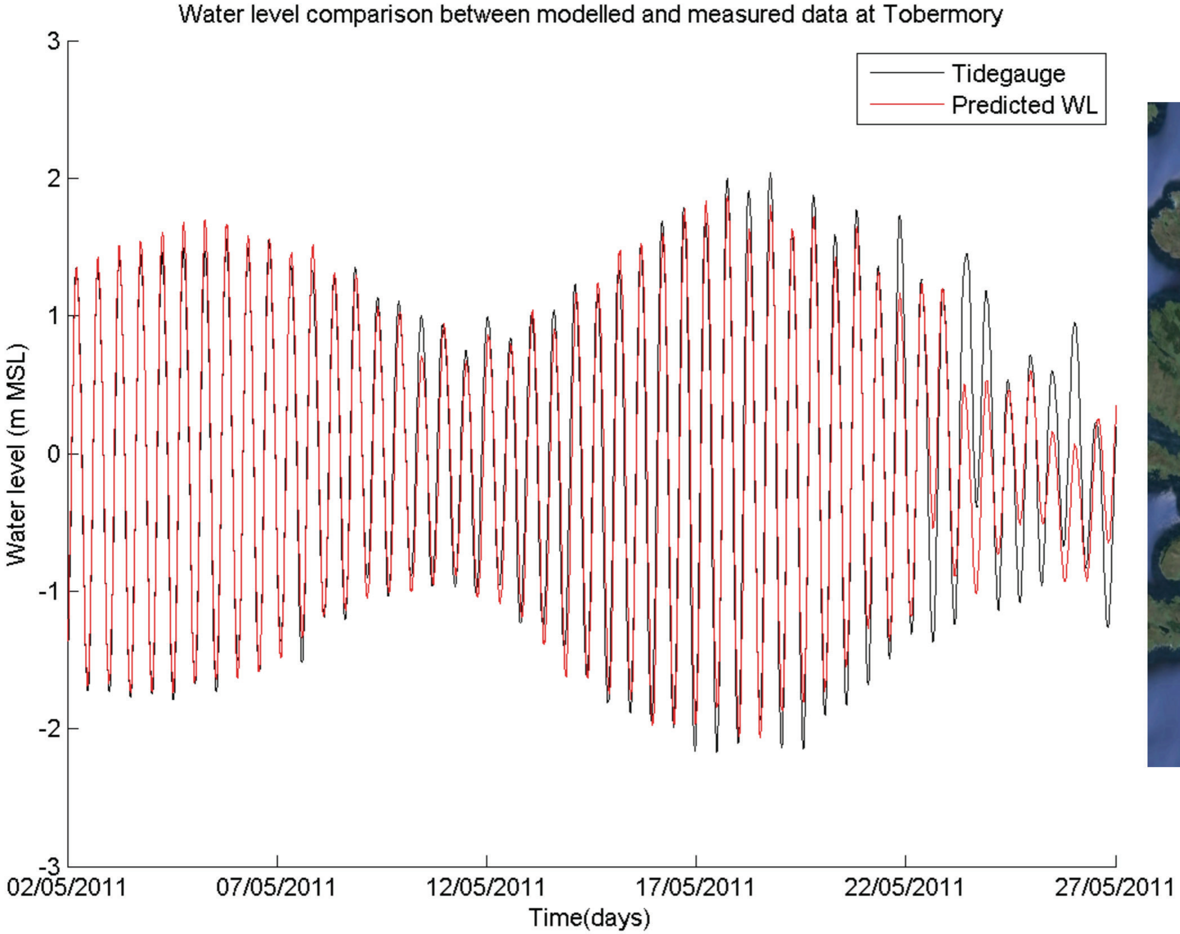
Without including this period, and only using the first 20 days of the simulation, the RMS errors from three of the locations are:-

***Tobermory***
*RMS error = 0.29m*
*Bias error = -0.10m*
***Corpach***
*RMS error = 0.27m*
*Bias error = -0.05m*
***Fort William***
*RMS error = 0.28m*
*Bias error = -0.06m*

This shows an average RMS error of 0.22m, which given the tidal range of 2-4m, gives an approximate percentage RMS error relative to the tidal ranges of between 7-15% which is within the bounds required for this type of modelling (i.e. it is within the EA guidelines).

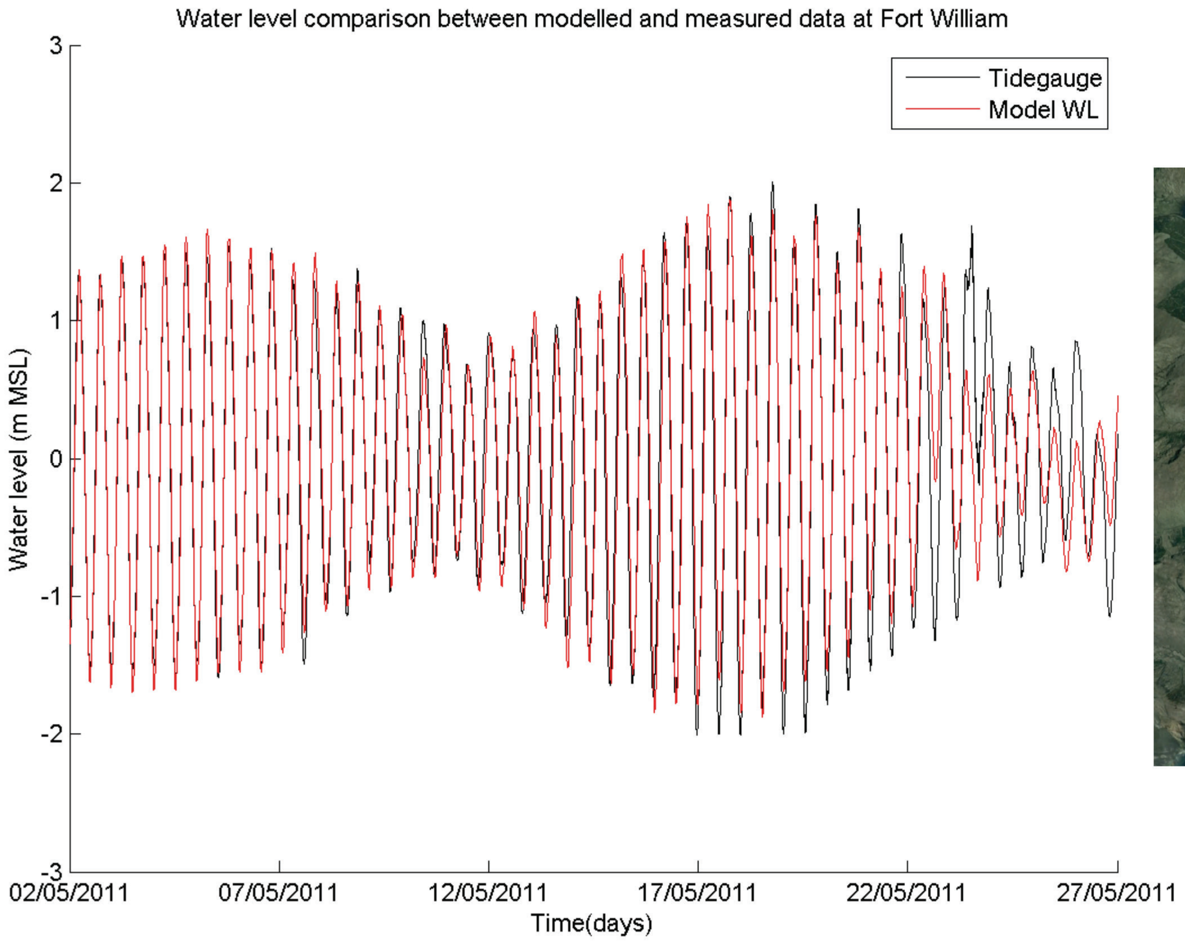



| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at the southern end of Loch Linnhe. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



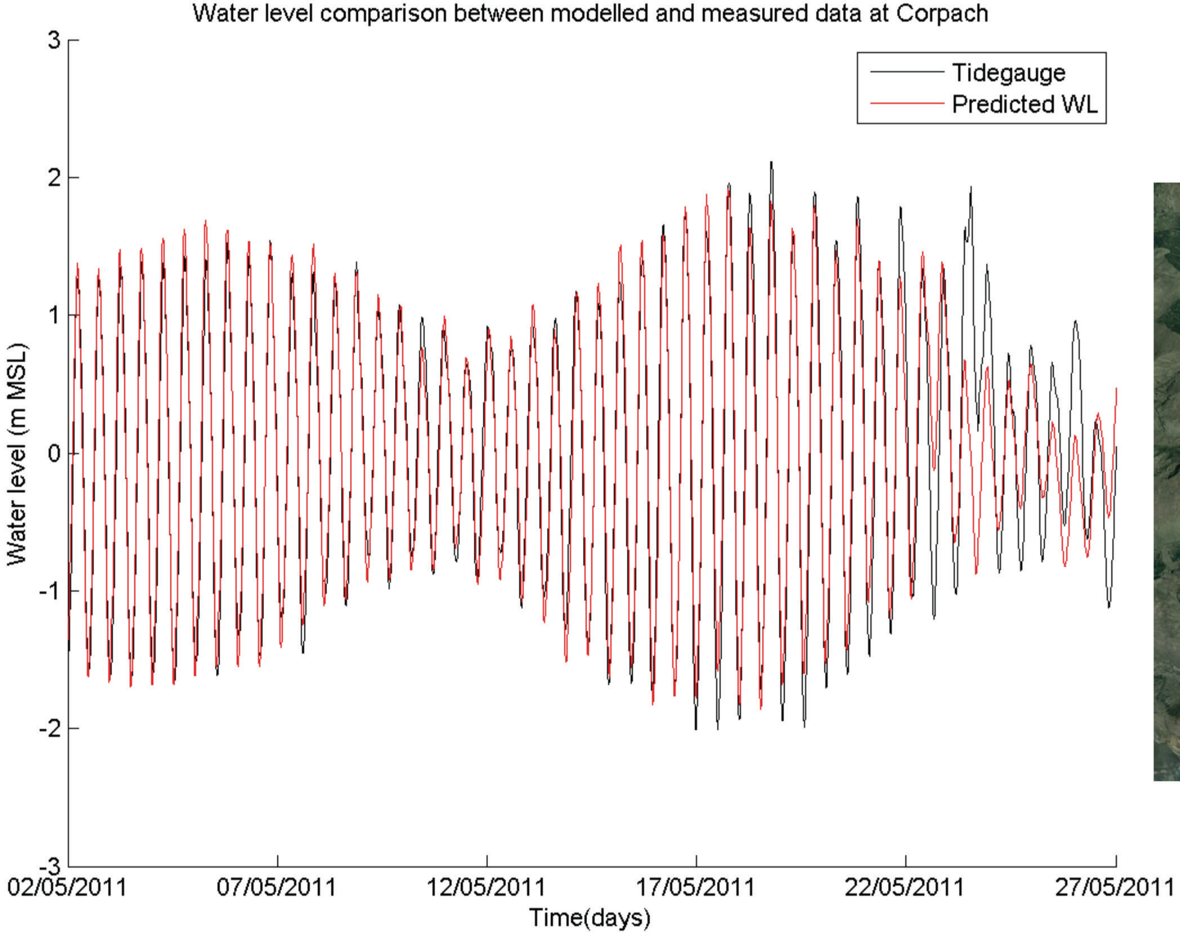


| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Tobermory (western end of Mull Sound). | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |





| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Fort William. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

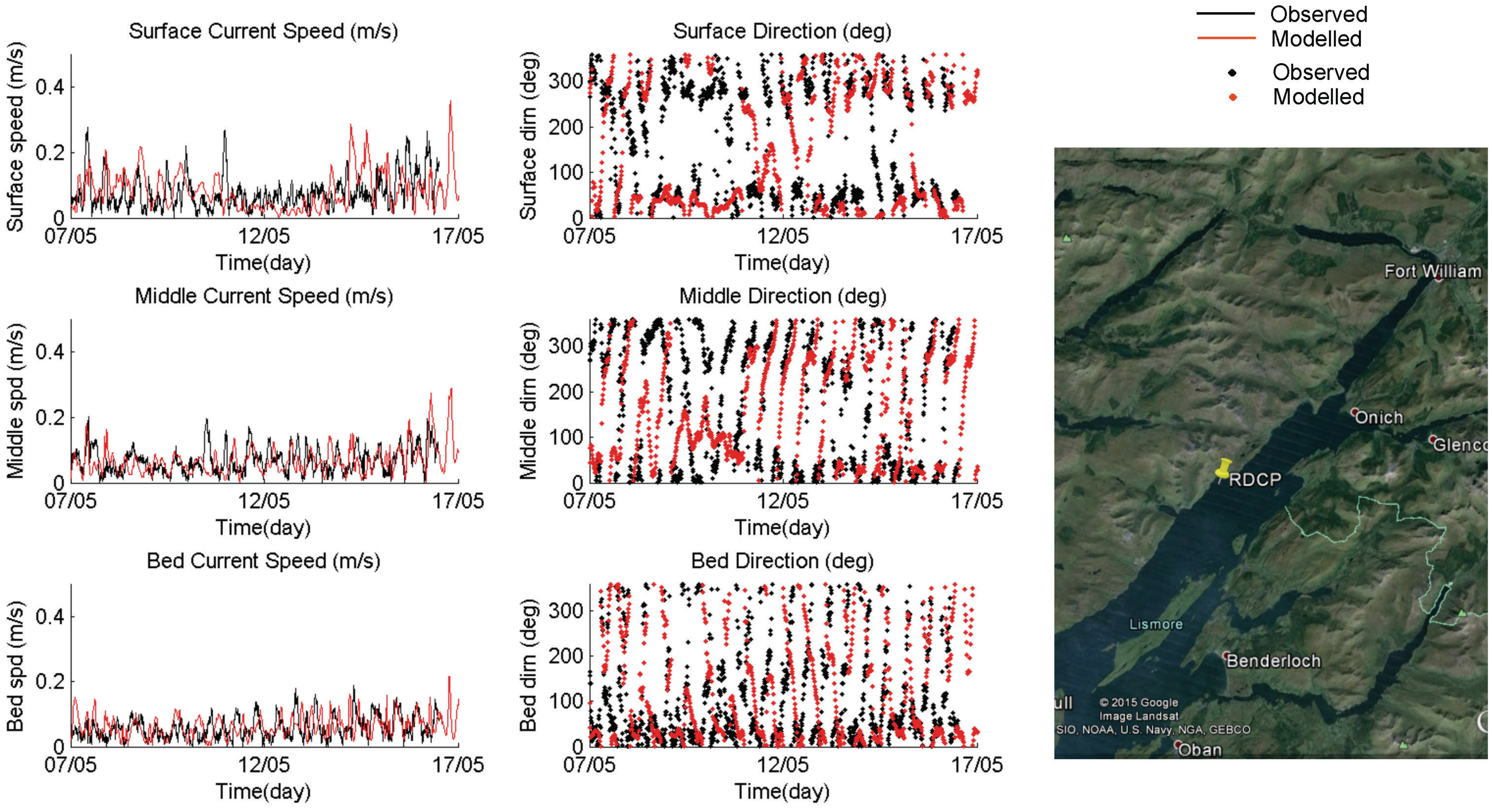




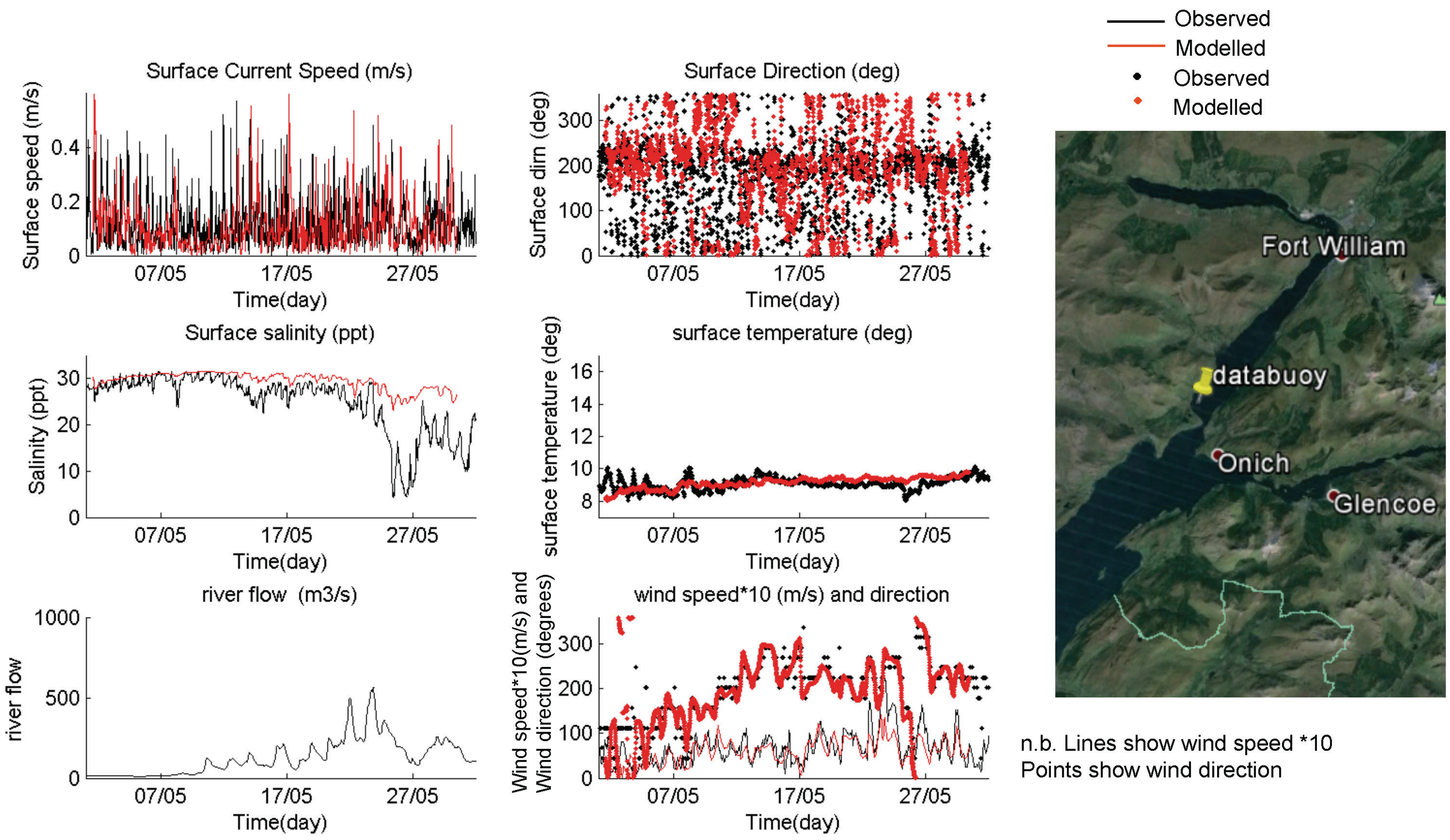
| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-6d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Water level comparison at Corpach. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

Current measurements available during the month of May 2011 and within Loch Linnhe took the form of RDCP measurements (Figure 3-7) and surface data buoy measurements of current speed/direction, temperature and salinity (Figure 3-8). The comparisons between model current speeds (red) and the observed speeds (black) recorded by the RDCP can be seen in Figure 3-7 for surface (at 5.2m), mid-depth (at 14.8m) and bed (at 26m). The instrument was within an eddy which encompasses the bay in which the RDCP was located. This makes it quite difficult to get an exact match with the timing of the peak currents as it can be quite difficult to reproduce the effect of eddies exactly the same as observed. The data was provided at layers within the water columns. For comparison purposes, Figure 3-7 shows the comparisons at the surface, middle and near bottom of the water column. Although the exact timing of the peak speeds has not been predicted exactly, the general variation in current speed both through time and through the vertical shows a good reproduction of the current magnitudes and the variation of those measured. In general the current directions are also reproduced well at this scale. When examined more closely, the current speeds closest to the bed produced the best comparison with the data.

The data buoy recorded data (currents, temperature and salinity) at the surface of the water column. Figure 3-8 shows the comparisons with near-surface currents speed, salinity and temperature at the data buoy, along with the river flow and wind speeds/directions applied to the model compared with measurements at Fort William. The current speed peaks show a reasonable comparison with the data although when examined in more detail the peaks do not always match up exactly. The location of the data buoy is also within an eddy at the southern end of ULL which adds additional difficulty in getting a closer match with peak speeds and direction. The model is very sensitive to salinity conditions within the model which can affect the surface current speeds greatly. The comparison of salinity measurements with the model predictions shows a good agreement for most of the time until river flows into ULL starts to go above 200 cumecs for about 7 days at which point the salinity in the surface of the model does not drop as much as has been measured. It is hypothesised that the fresher water will be a thin buoyant layer that is not adequately resolved with the 1.0m thick top layer in the model (although this was the aim in reducing the surface layer thickness). However the temperature predicted by the model is in good agreement with the model throughout the period of the simulation, this may be partly due to the convective nature of heat in the water as well as input from radiation.



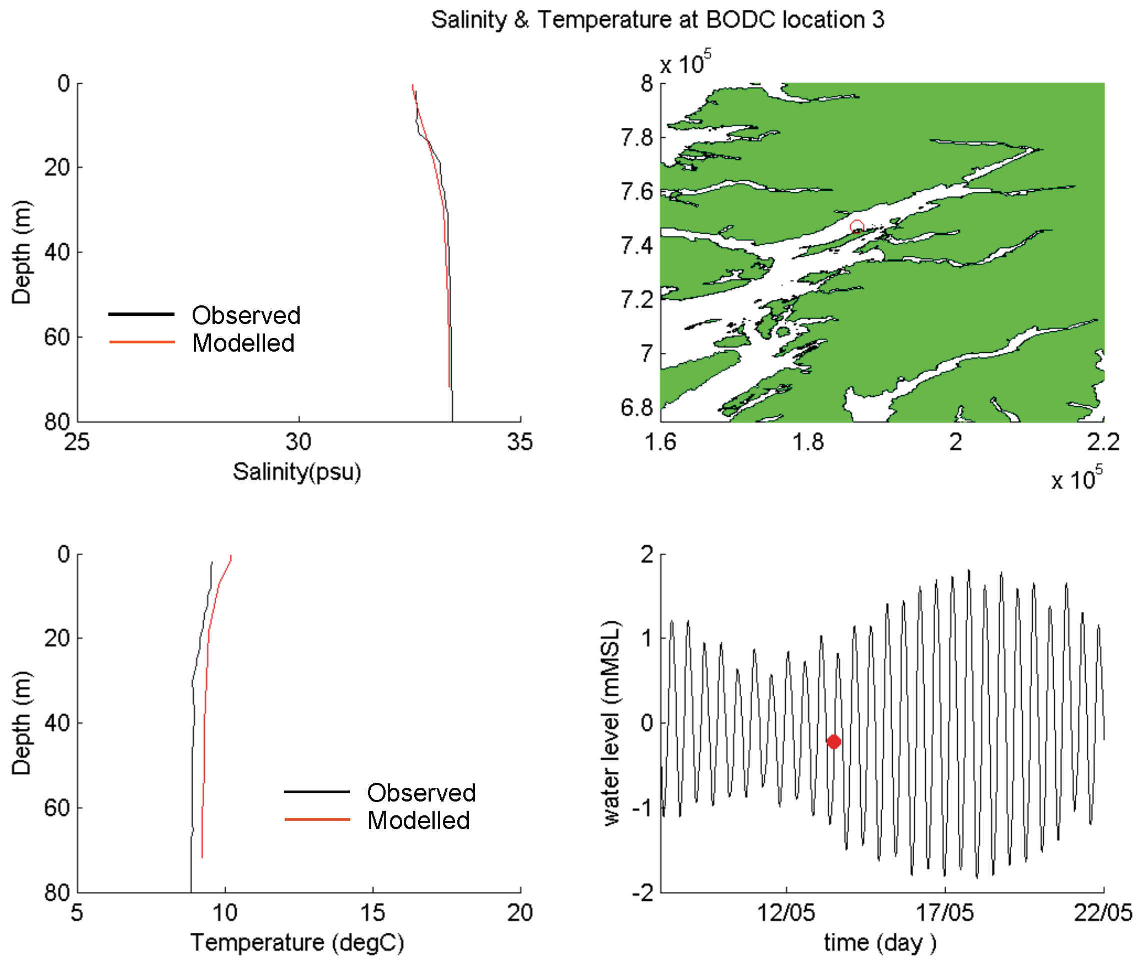

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-7 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and RDCP data at surface (5.2m), mid (14.8m) and bottom (26m) levels. Water depth 30.1m | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



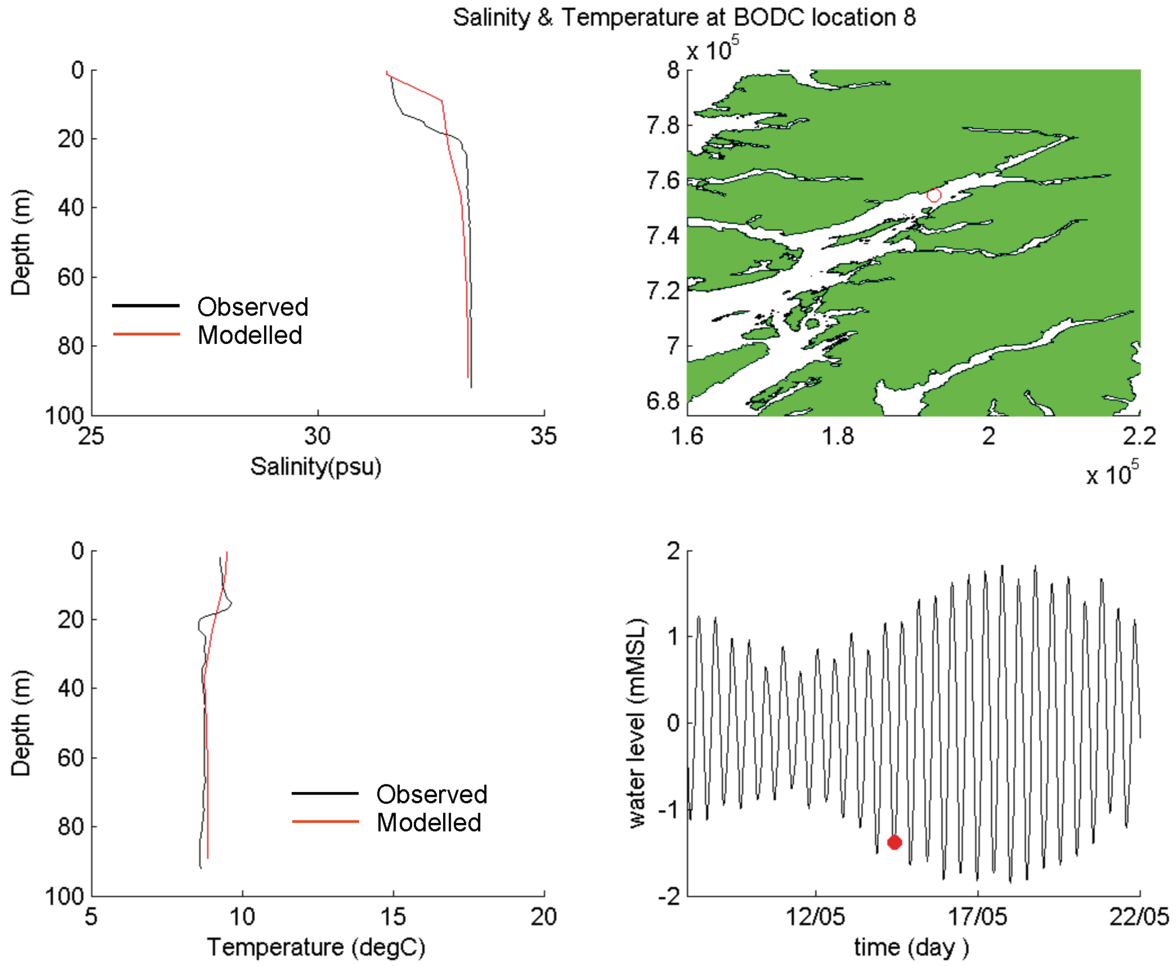

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-8 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and databuoy – surface measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

Further salinity and temperature measurements were made in the form of vertical profiles made at a range of locations by way of dropping a CTD probe through the water column and then bringing it back up to the surface again. Figures 3-9a-j show the vertical profile comparisons (red – model, black – observed) for salinity and temperature along with the position in the tidal cycle and the location within Loch Linnhe. The comparison between the observed and modelled temperature and salinity is good. Near surface salinities show a reduction close to the surface which is picked up by the model. There are instances however where the observed temperature close to the surface is higher than in deeper depths showing a distinct thermocline at about 20m depth. This is not picked up by the model to the same extent although this feature is still evident. However a river water temperature of 7 degrees Celsius has been assumed, this may have an effect on the near surface temperature if this differs significantly from the actual value (which is unknown).

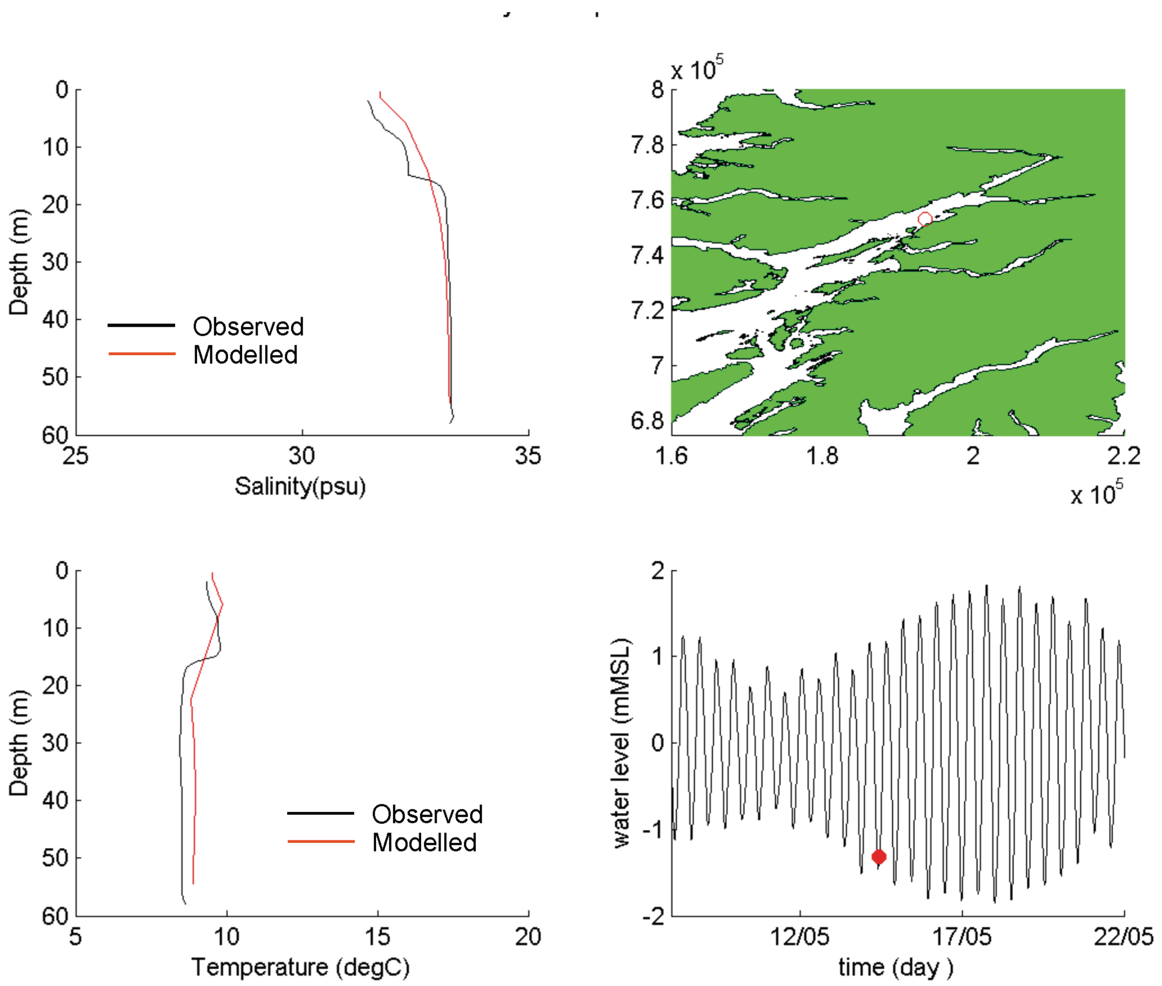
To conclude the model has been calibrated against available data within Loch Linnhe, comprising water levels, current speeds, temperature and salinity. It has been shown that in general the model is able to reproduce the measurements within a reasonable magnitude. 5-11% for tidal levels (compared with tidal range), current speeds within 0.1m/s and temperature, salinity generally within 1 degrees and 1ppt, although the salinity is not reproduced well at the surface during high fluvial flow; it was initially thought that this is partly due to the resolution not being fine enough in the vertical, however the 12 layer model sensitivity test proved to have the opposite effect, increasing salinity relative to the 10 layer model. It is not clear what caused this increase in salinity.



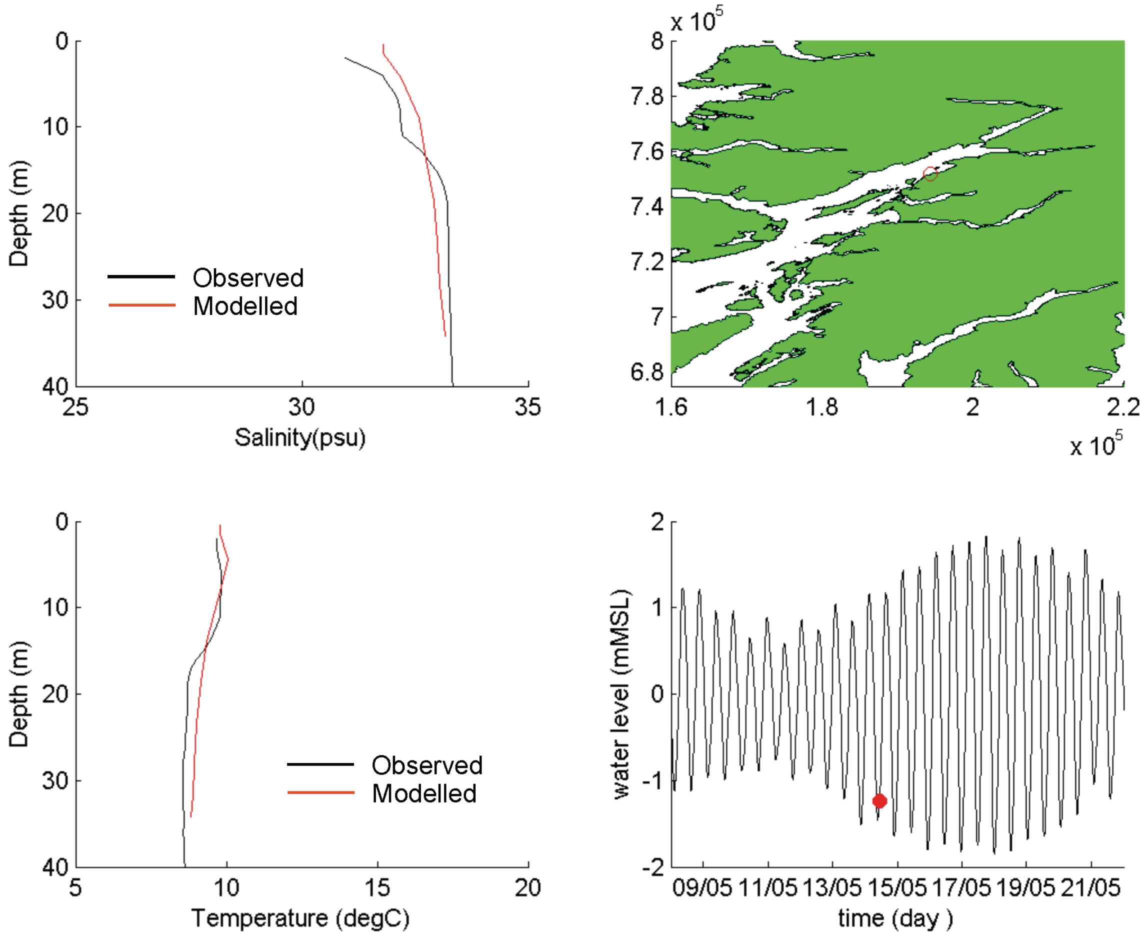

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Cross section through the Corran Narrows | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



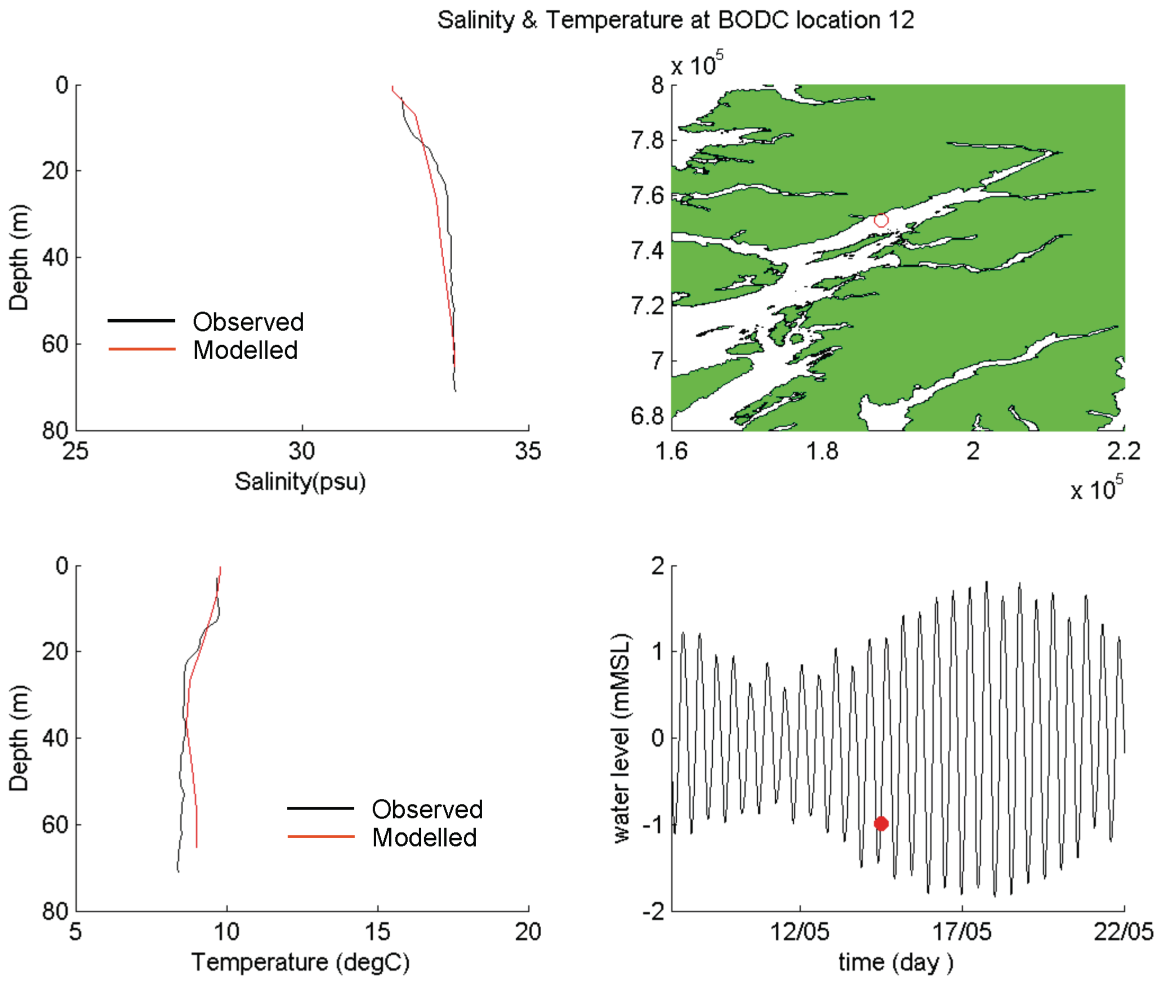

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



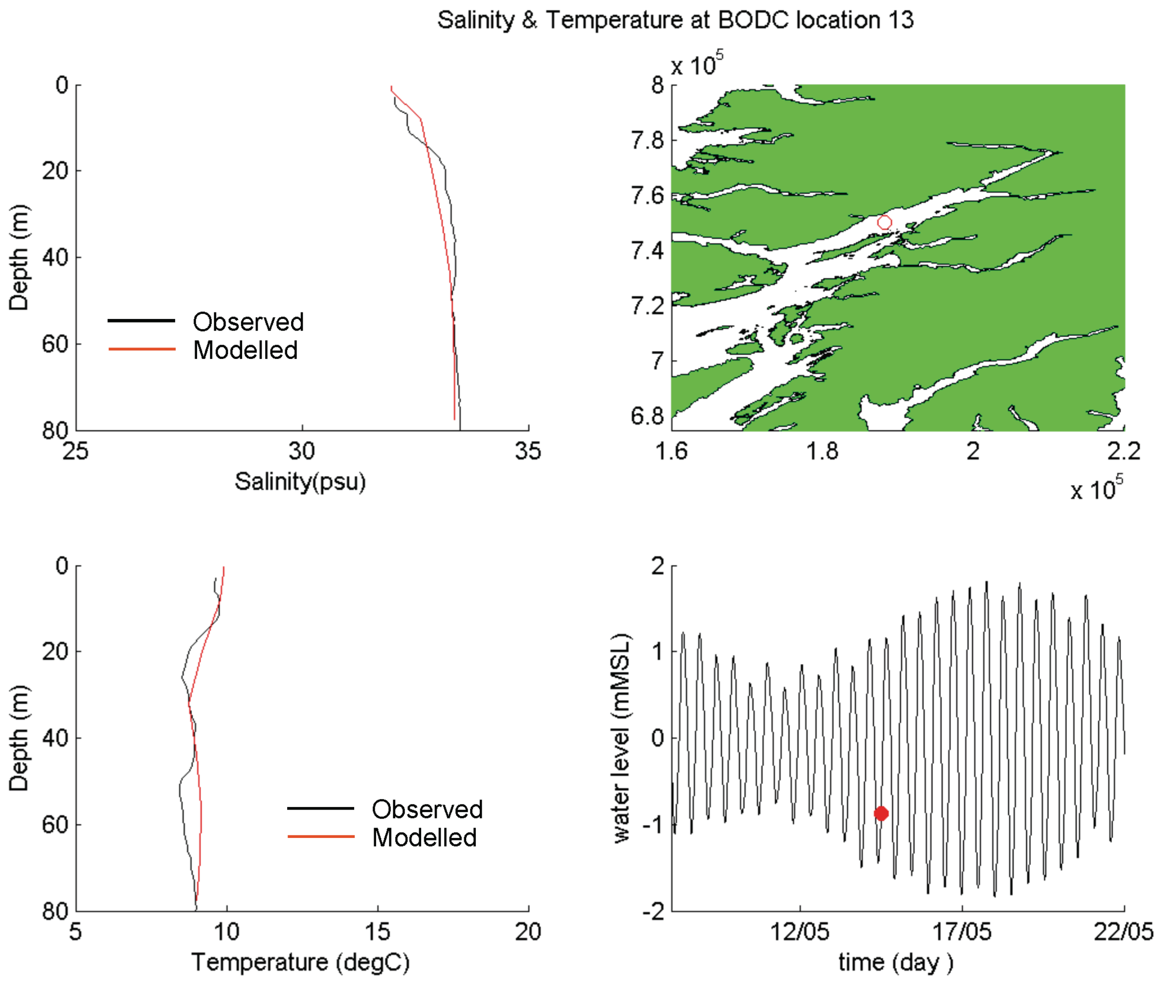

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



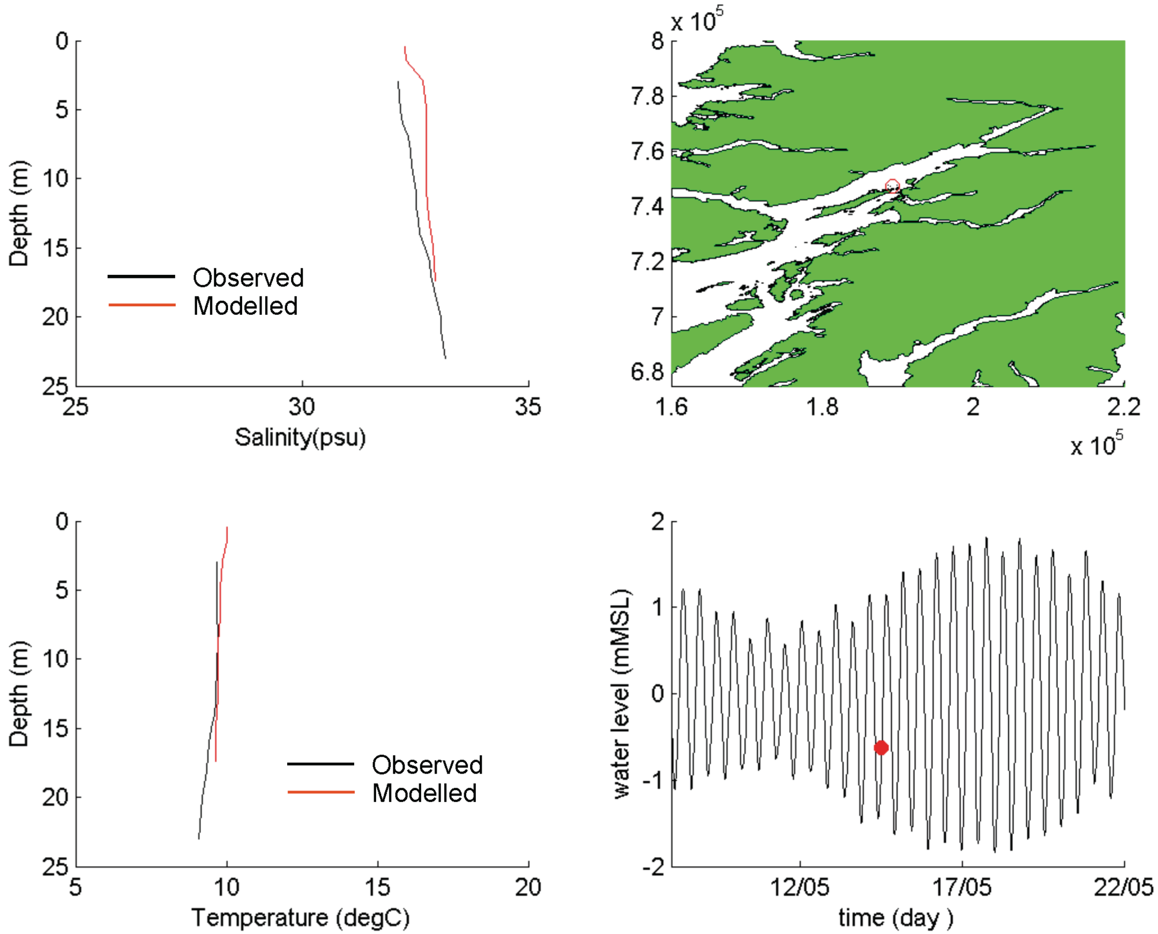

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



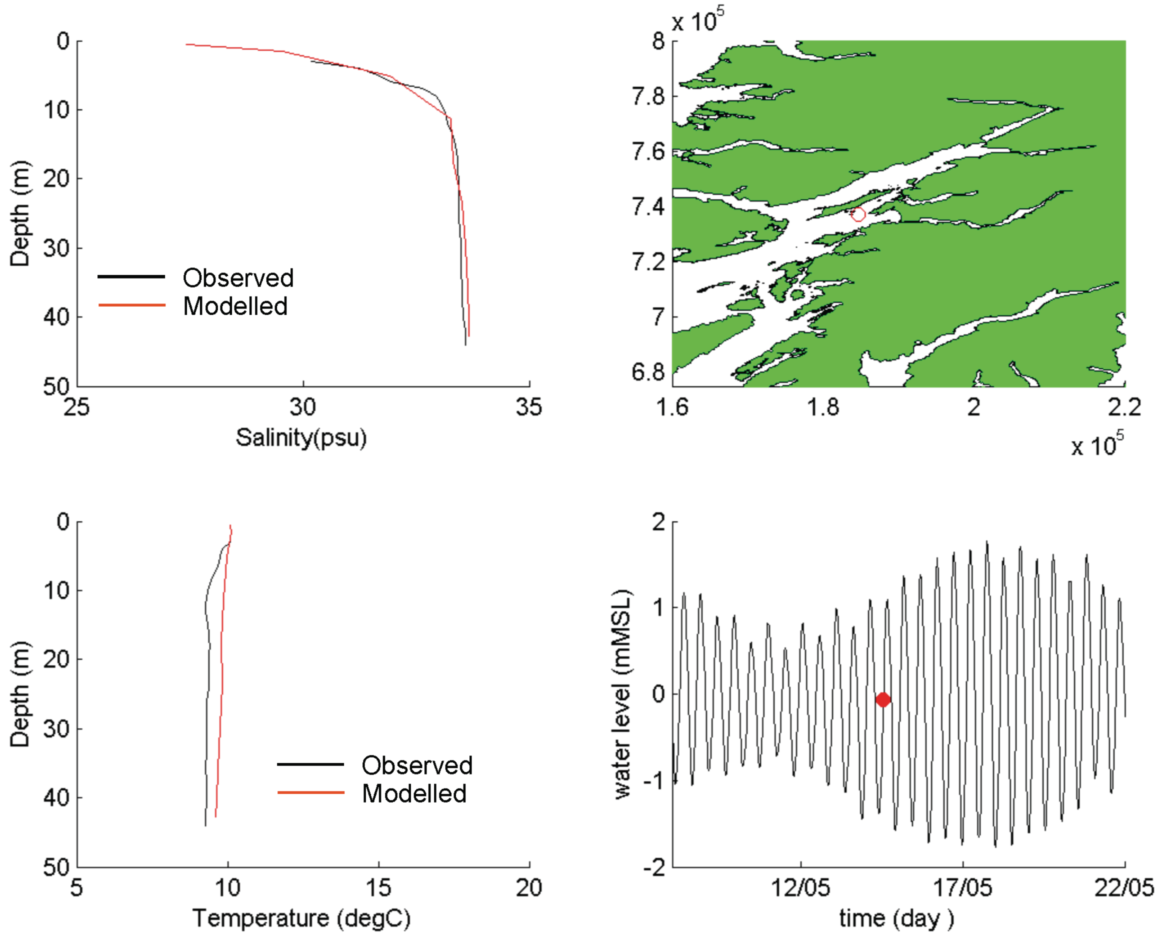

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



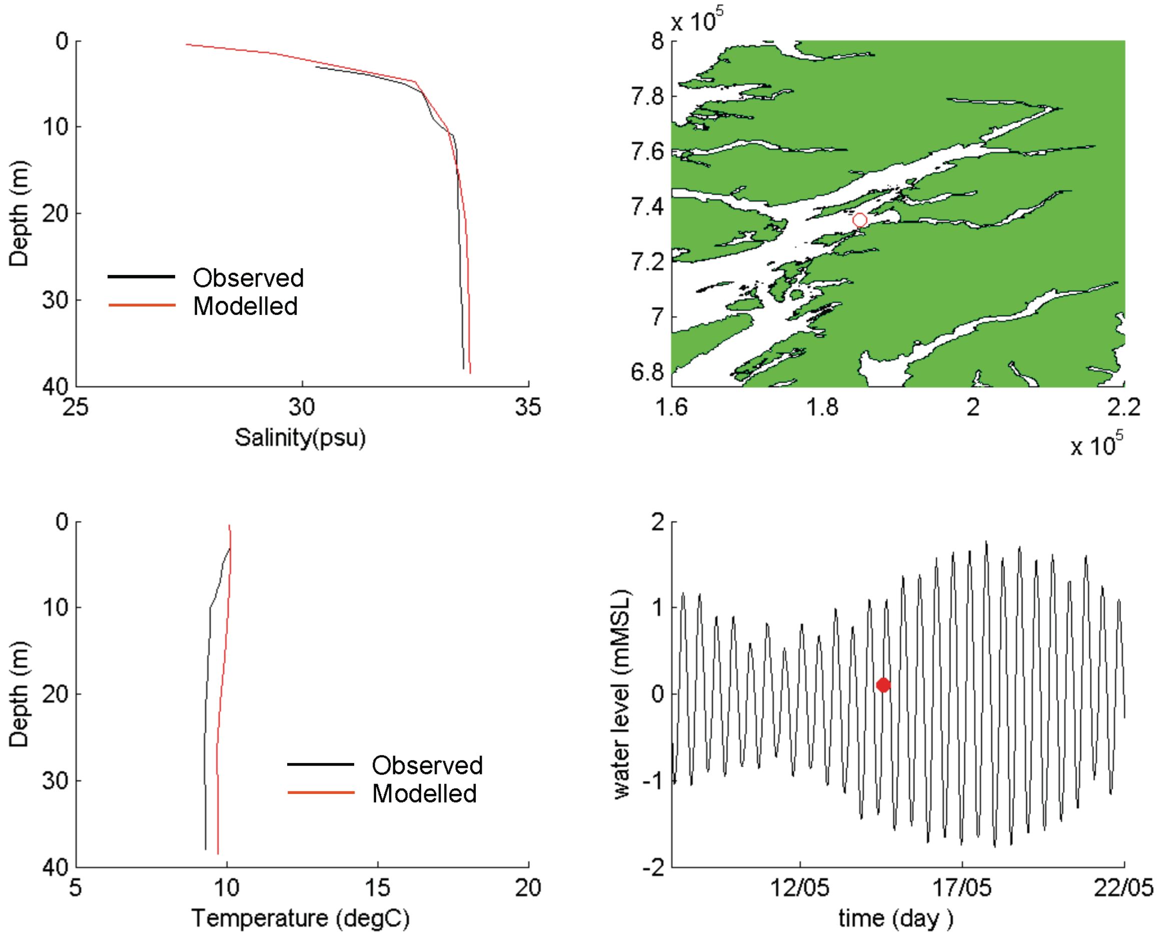

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



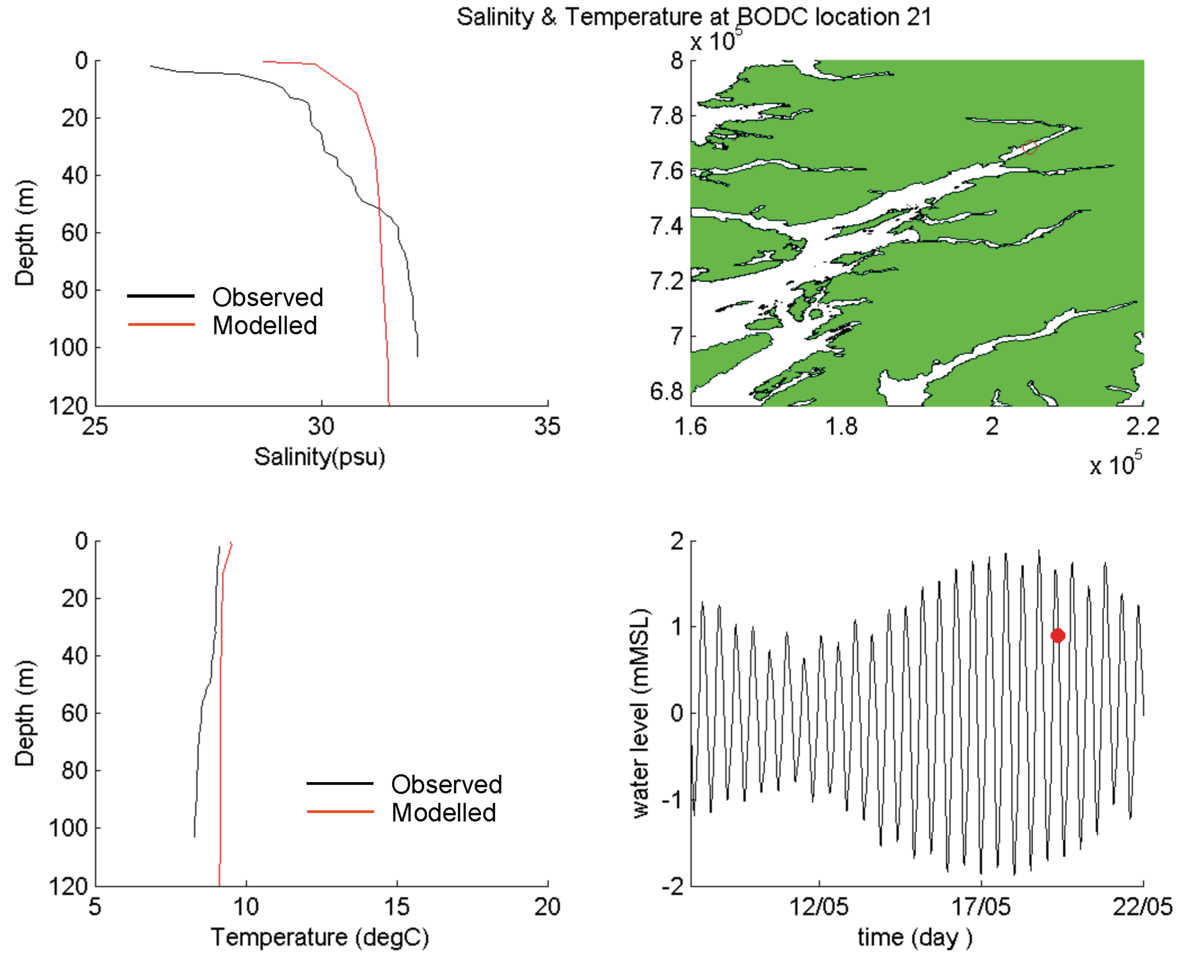

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9h | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9i | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-9j | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

## 3.6 Flow Model Validation

Following on from the model calibration, it is good practice to validate the model against a different period of data, using the same model parameters and setup as used for the calibration simulation. For this purpose, we selected data from the October 2011 survey, combined with additional tide gauge and current data obtained from other surveys.

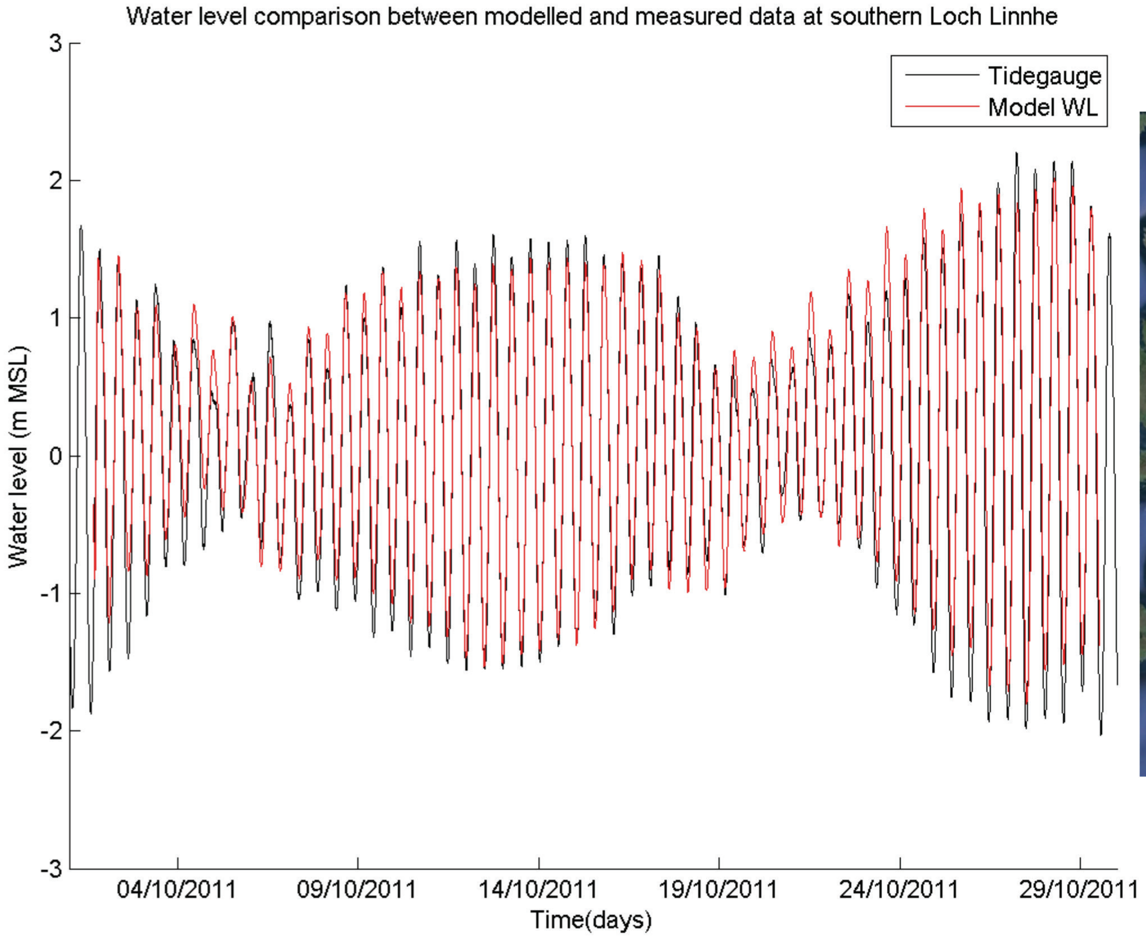
Boundary conditions were taken from the AMM results. As with the calibration run the model was run from a cold with constant temperature and salinity to ramp up the hydrodynamic before adding the temperature and salinity initial conditions from the Scottish Shelf model climatology run for the corresponding time step.

Figures 3-10a-e present the comparisons between observed water levels and those predicted by the model. The RMS errors and bias for three of the locations are as follows:-

***Tobermory***
*RMS error = 0.27m*
*Bias error = -0.17m*
***Corpach***
*RMS error = 0.27m*
*Bias error = 0.12m*
***Fort William***
*RMS error = 0.24m*
*Bias error = 0.10m*

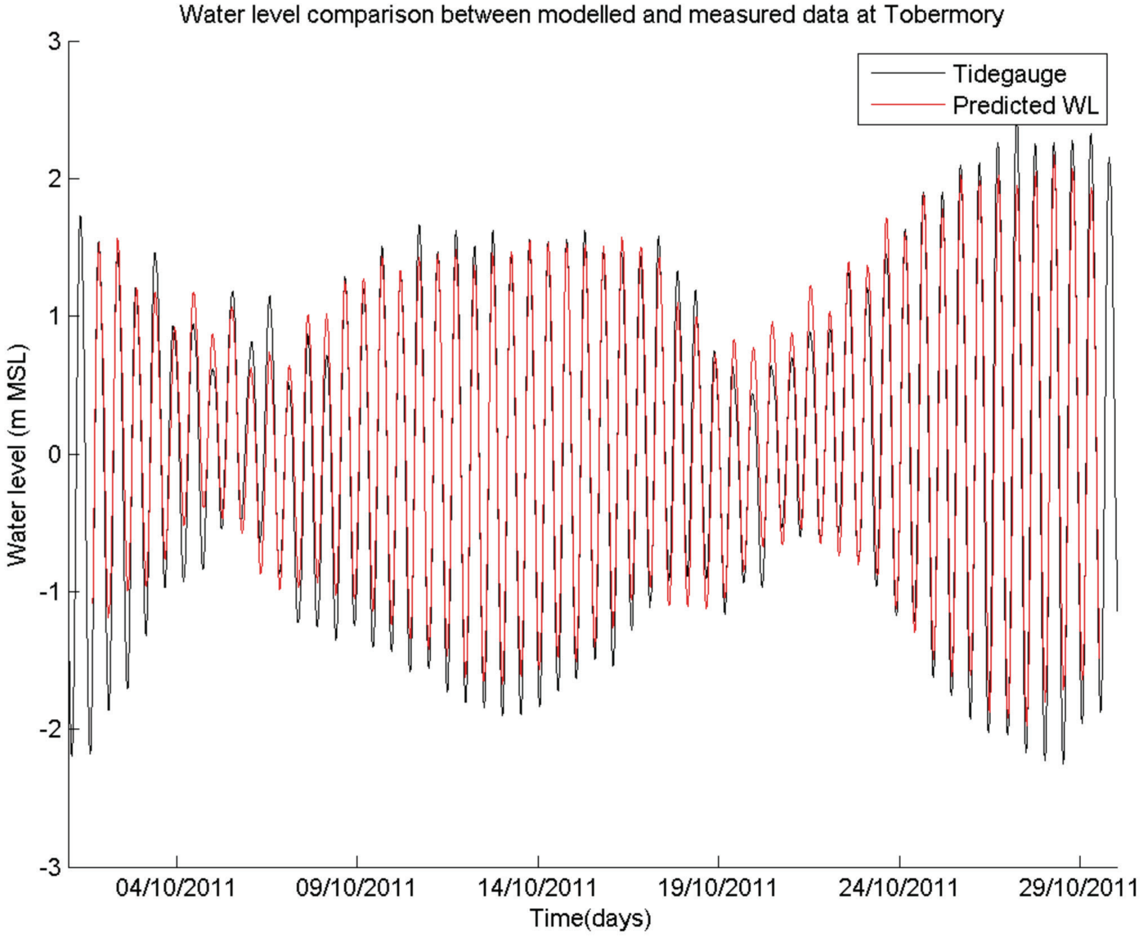
These are very similar in magnitude to those calculated for the calibration simulation for May 2011 giving a percentage relative to the tidal range at these locations of approximately 6-14% which is within the limits set within our proposal and used for the other case study models.

Figure 3-11 shows the location of the data buoy within ULL and the comparison between the model (red) and data (black). Both the salinity and the temperature comparison seems to replicate the general pattern seen in the observations. However, for both parameters the impact of the river flow is less pronounced in the model compared to the measurements. One possibility is that the river discharge spreads over a thin surface layer, which is not well reproduced in the model. However the vertical profile plots appear to show overall fair agreement with data.





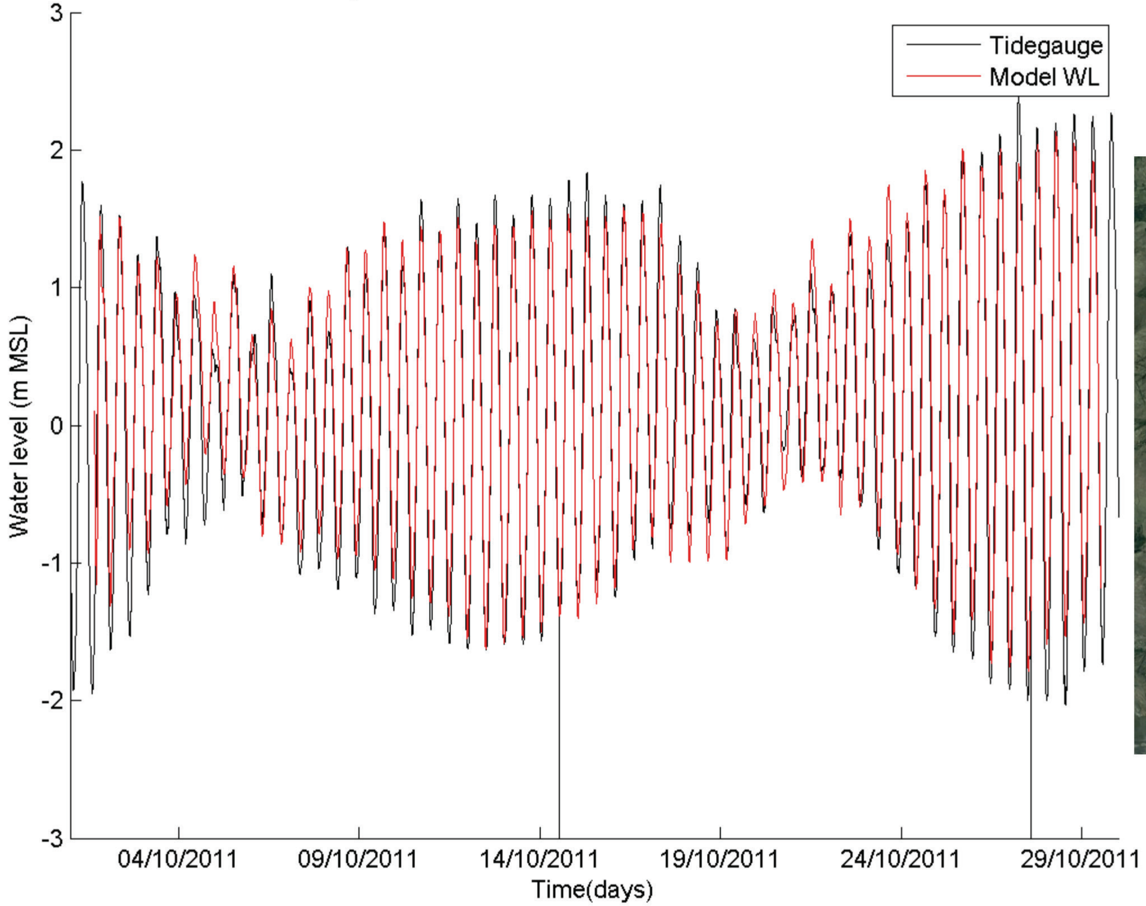
| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-10a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at the southern end of Loch Linnhe. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |





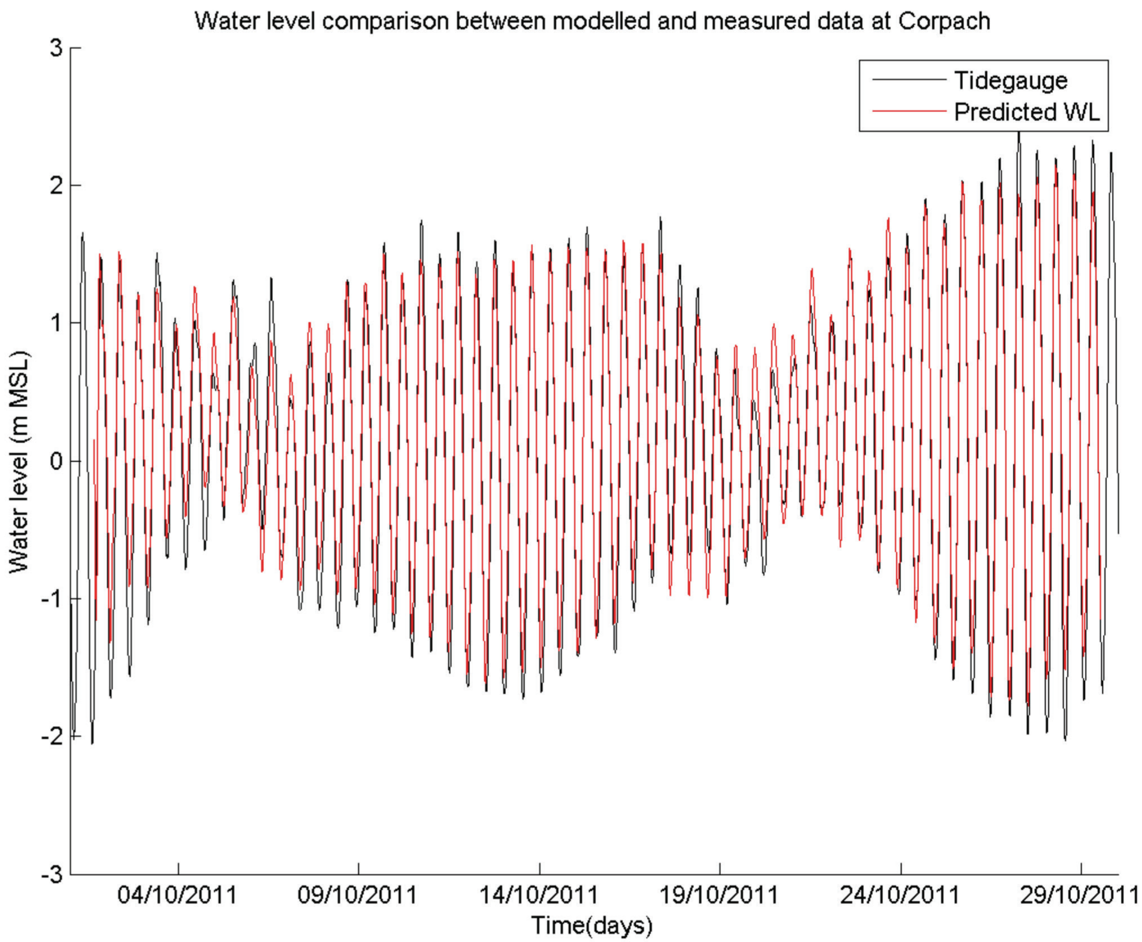
| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-10b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Tobermory (western end of Mull Sound). | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

Water level comparison between modelled and measured data at Fort William



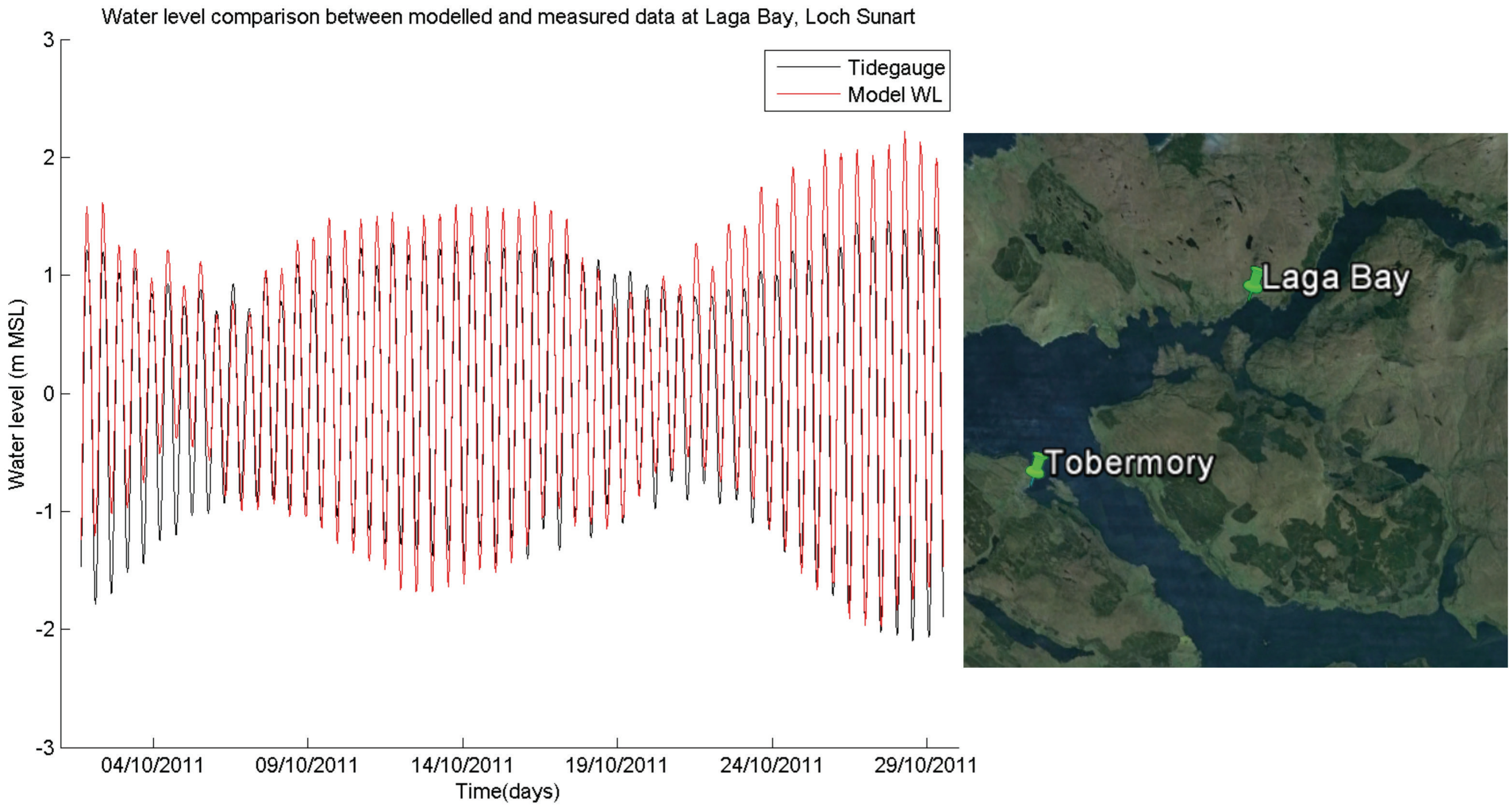


| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-10c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Fort William. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

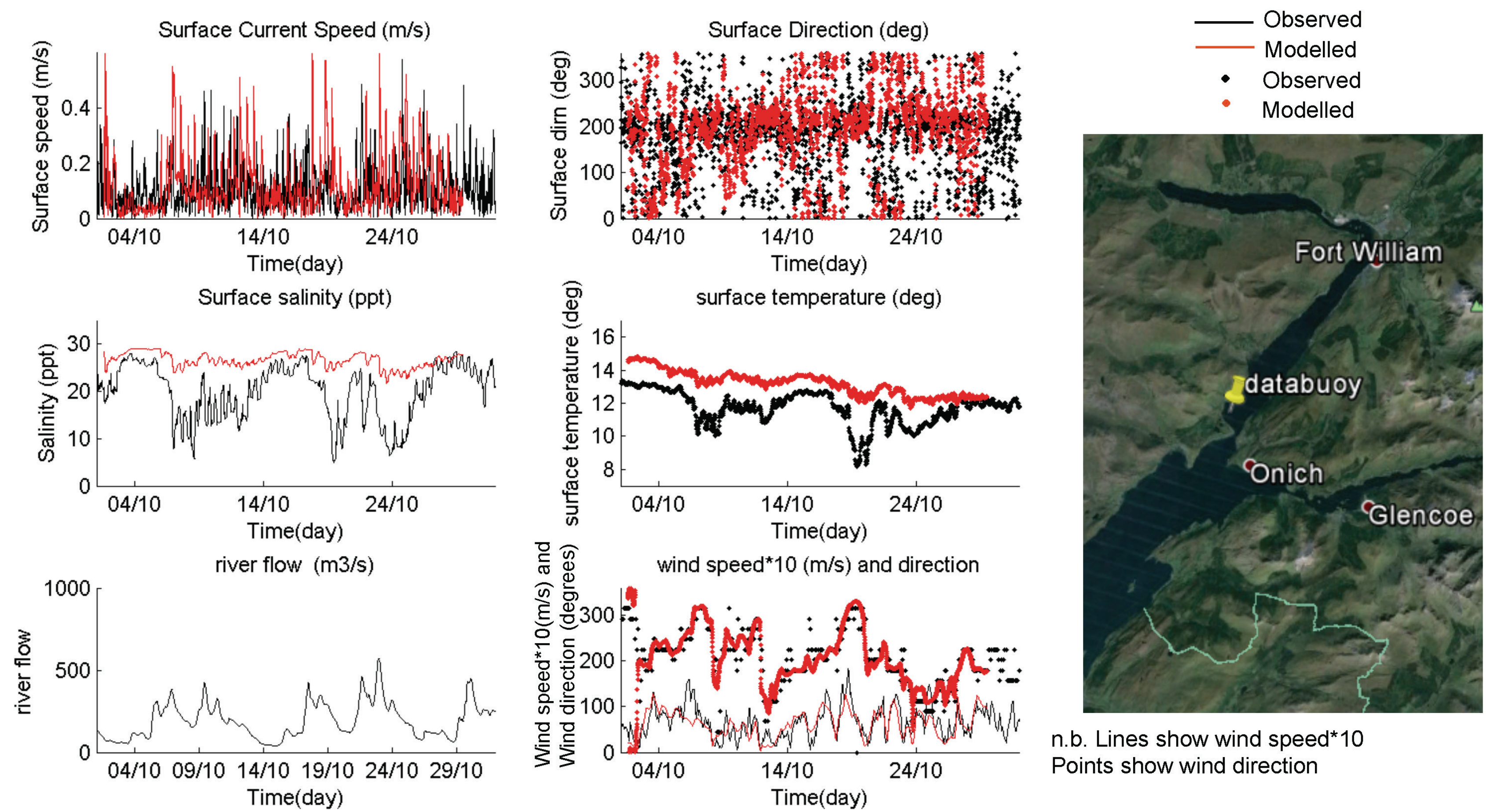




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-10d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Corpach. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-10e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Laga Bay. | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-11 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparison between model and databuoy – surface measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

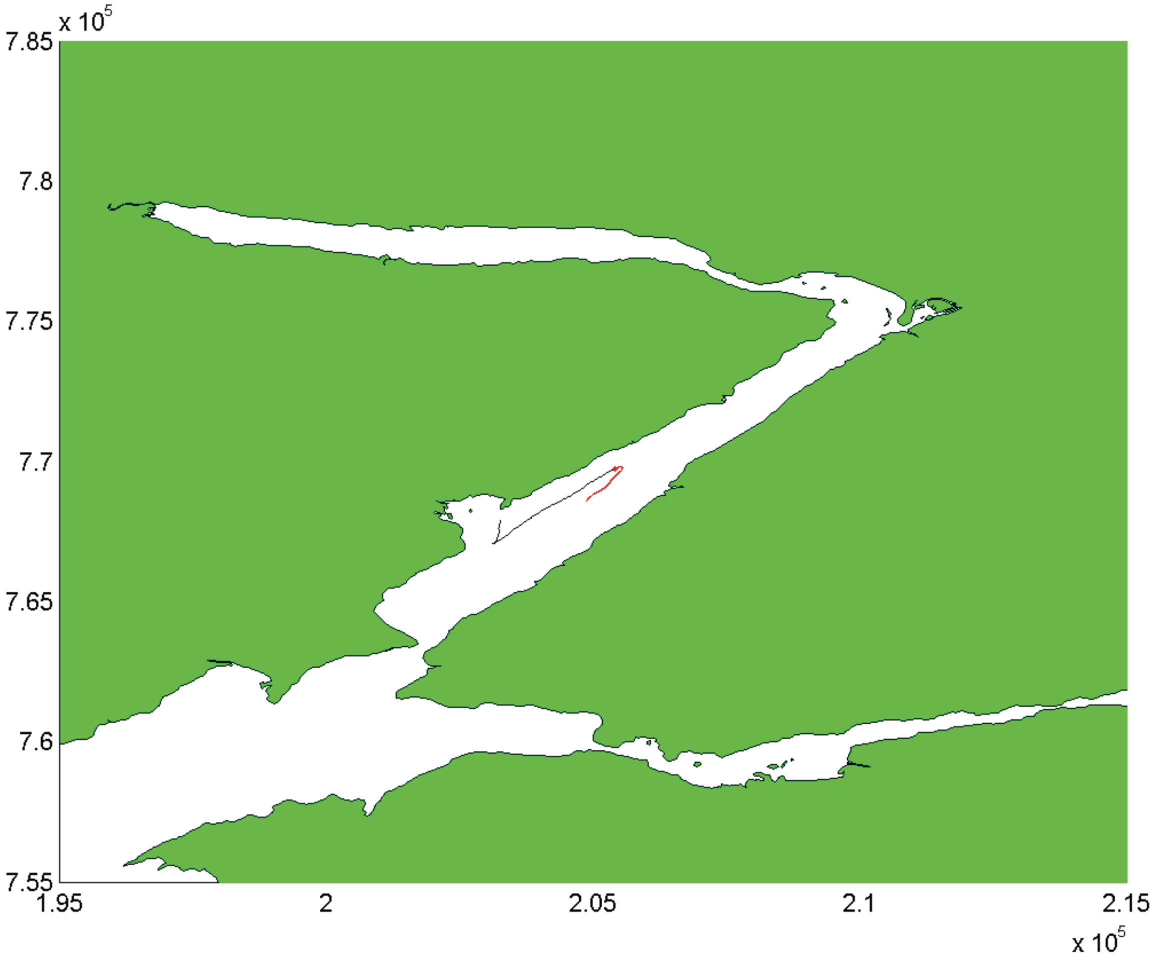
Three drogues were tracked as part of the survey. The comparisons with the model can be seen in Figures 3-12a-c. The first two Comparisons show poor reproduction of the drogue track in terms of the length of movement and time to the turn, whereas the third comparison is better with the drogue travelling further than the previous two but still fails to turn at the correct time.

Figures 3-13a-j present comparisons between observed CTD profiles and modelled profiles of temperature and salinity. The modelled temperature shows good agreement with the measured and picks up the stratification in the water column well at a number of locations (Figure 3-13d-f). The salinity profiles also show good agreement. The stratification in the salinity is also reproduced well by the model outside of ULL. In ULL the model under predicts the salinity levels by around 2psu below the surface but over predicts it at the surface indicating that the ULL in the model is more mixed in the vertical than the observations suggest. This may be related to the high river flows into ULL during October.

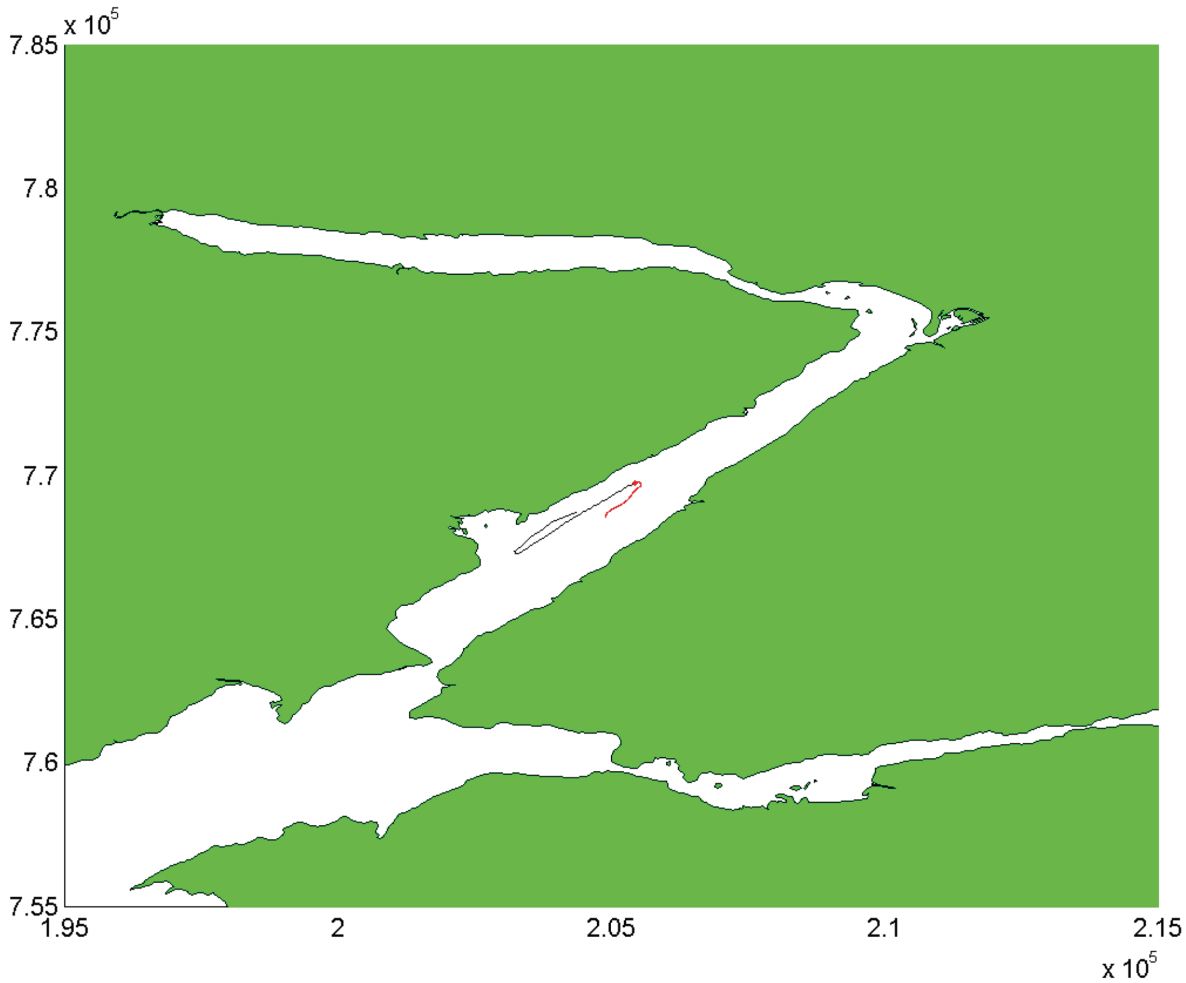
A short survey was undertaken by MS in June 2013 in the entrance to Loch Sunart. The ADCP data at a fixed station recorded current speeds and directions throughout the water column.  This data was depth-averaged and a harmonic analysis carried out so that the tidal component of the flows could be plotted. The depth-averaged current speeds from the model at the same location were also harmonically analysed and repredicted for the same period as the data. The comparisons can be seen in Figures 3-14 a-c, these show the same data but at three different timescales so that the overall comparisons can be made along with more detailed ones.

Differences in speed are generally less than 0.05m/s, with the model being able to reproduce the general change in current speed throughout the tidal and spring-neap cycle. Although not an exact match, comparisons with directions are also good.

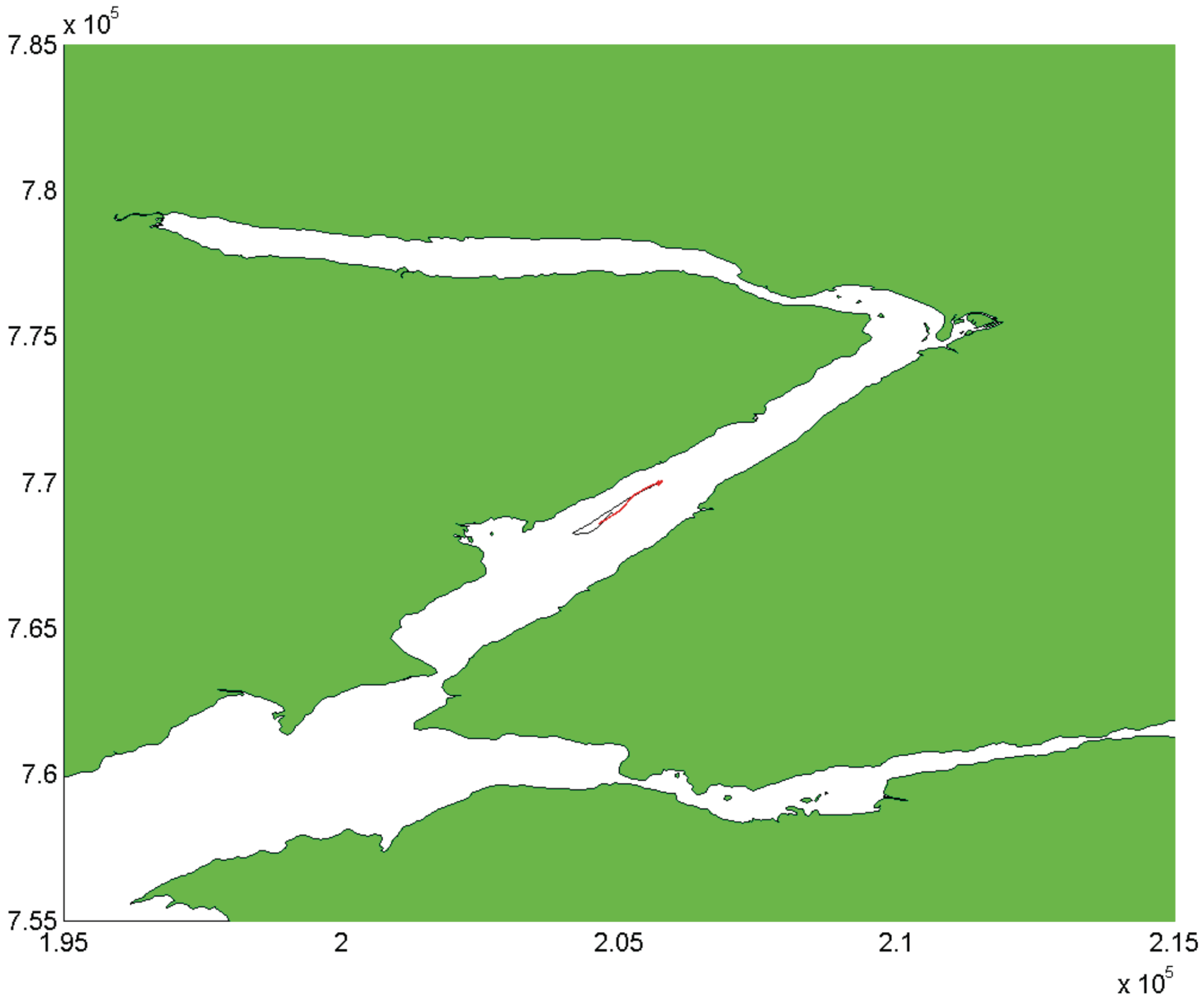
In addition to the fixed station, four transects were also undertaken within the Mull sound and the entrance to Loch Sunart. These were traversed at regular intervals throughout a tide. The results from the model have been compared with the recorded transect data by first undertaking a harmonic analysis on the current speed components for both the data and model results. The speeds/directions were then re-predicted and compared in Figures 3-15 a-h. In general the features and magnitude of the flow is reproduced by the model which gives confidence in its use within the Wider Loch Linnhe System outside of Loch Linnhe.



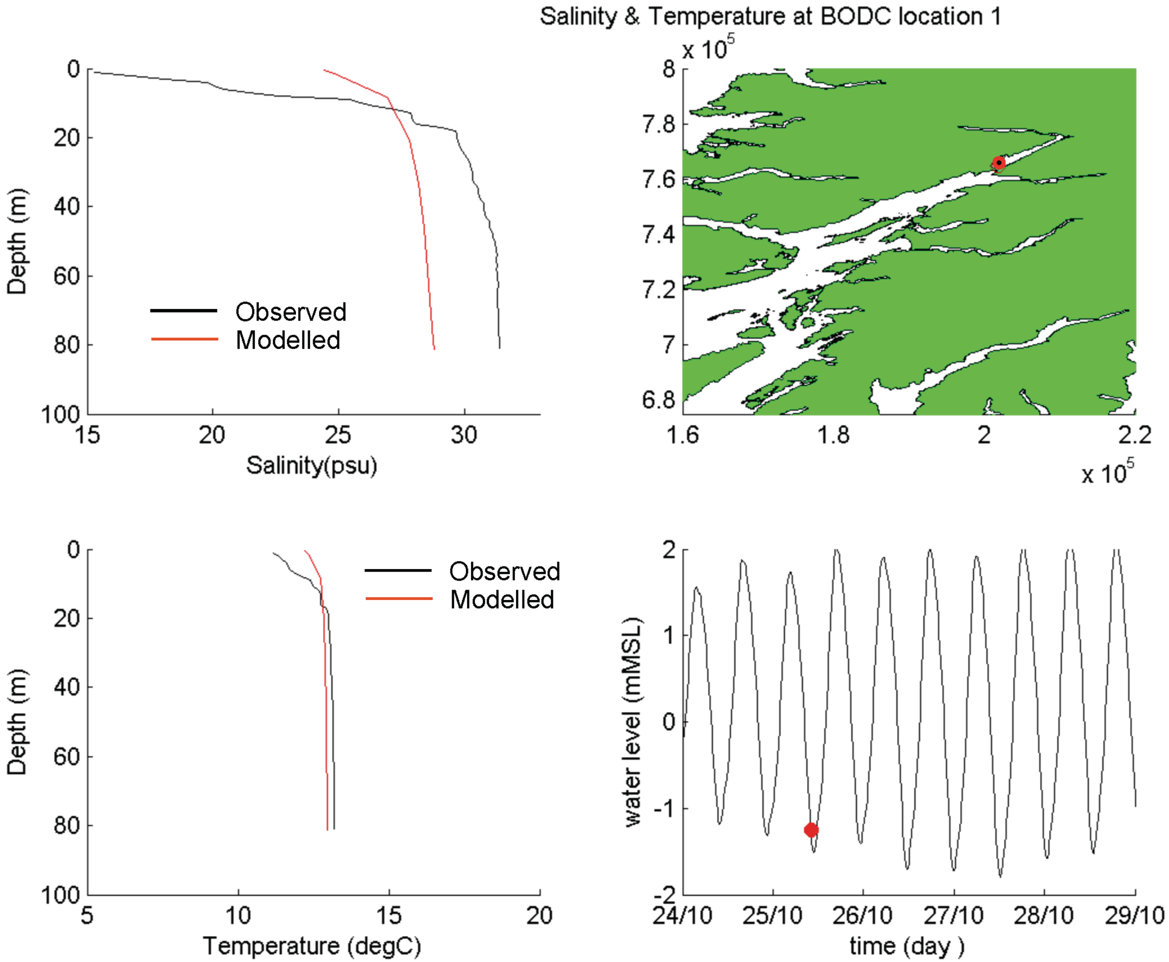

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-12a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Drogue track comparison<br>Observed – black<br>Model - red | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



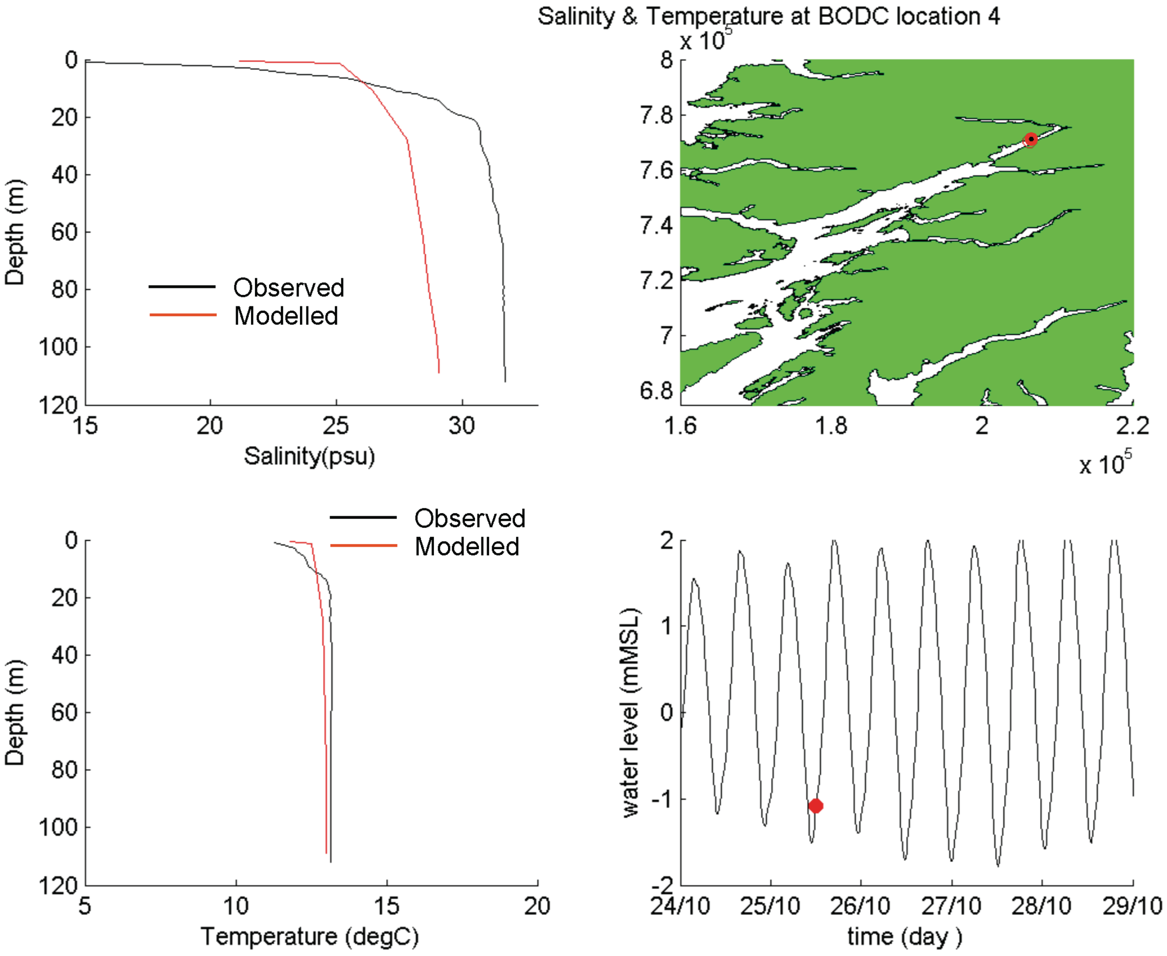

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-12b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Drogue track comparison<br>Observed – black<br>Model - red | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



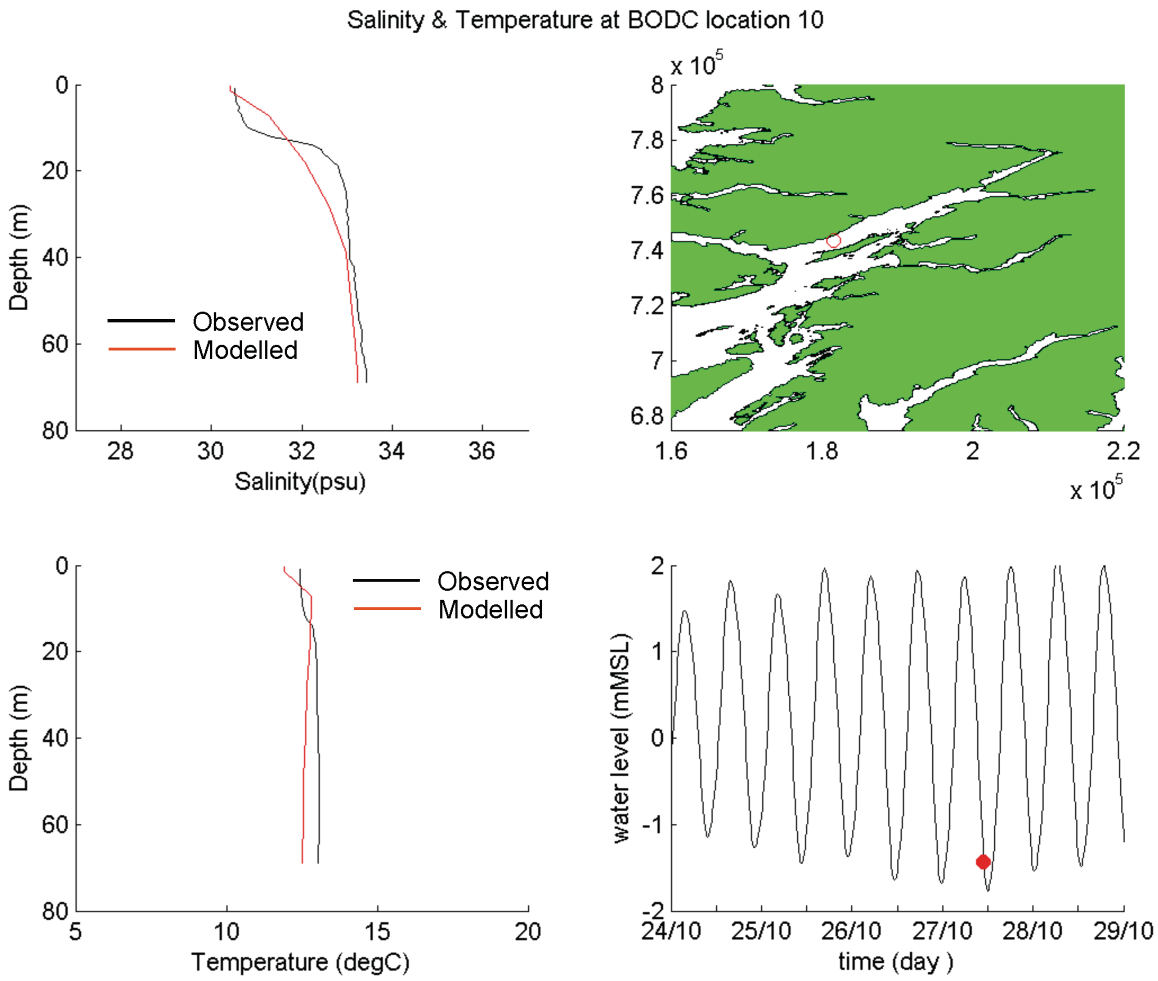

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-12c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Drogue track comparison<br>Observed – black<br>Model - red | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
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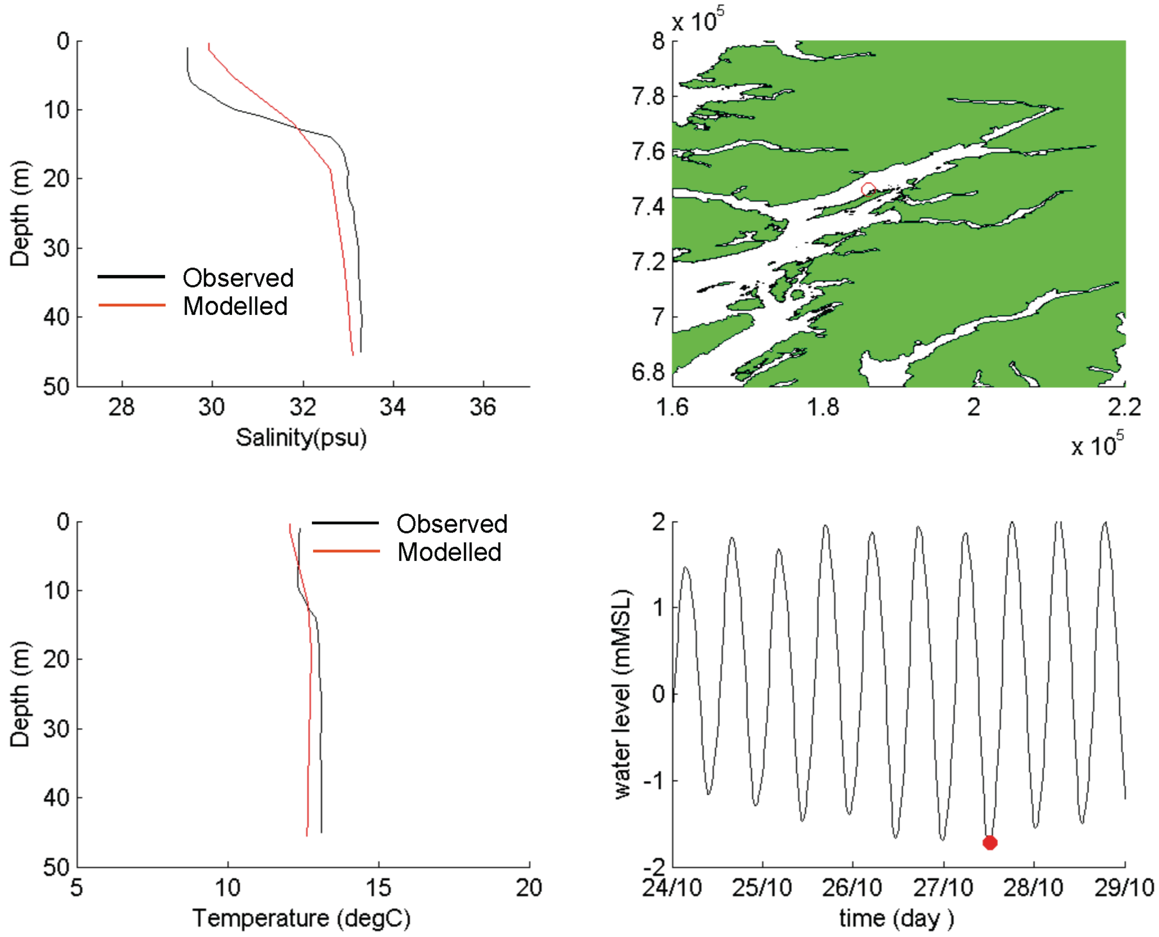
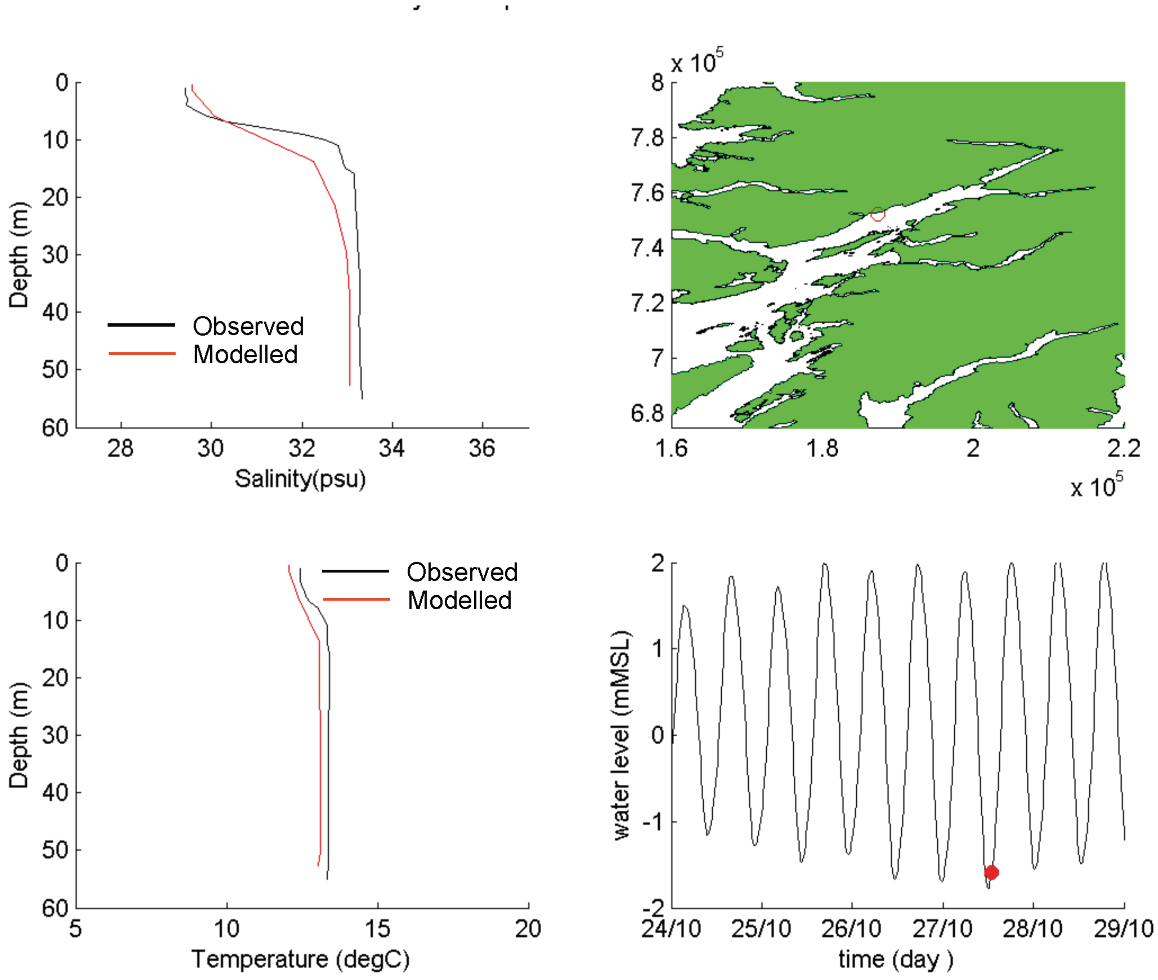
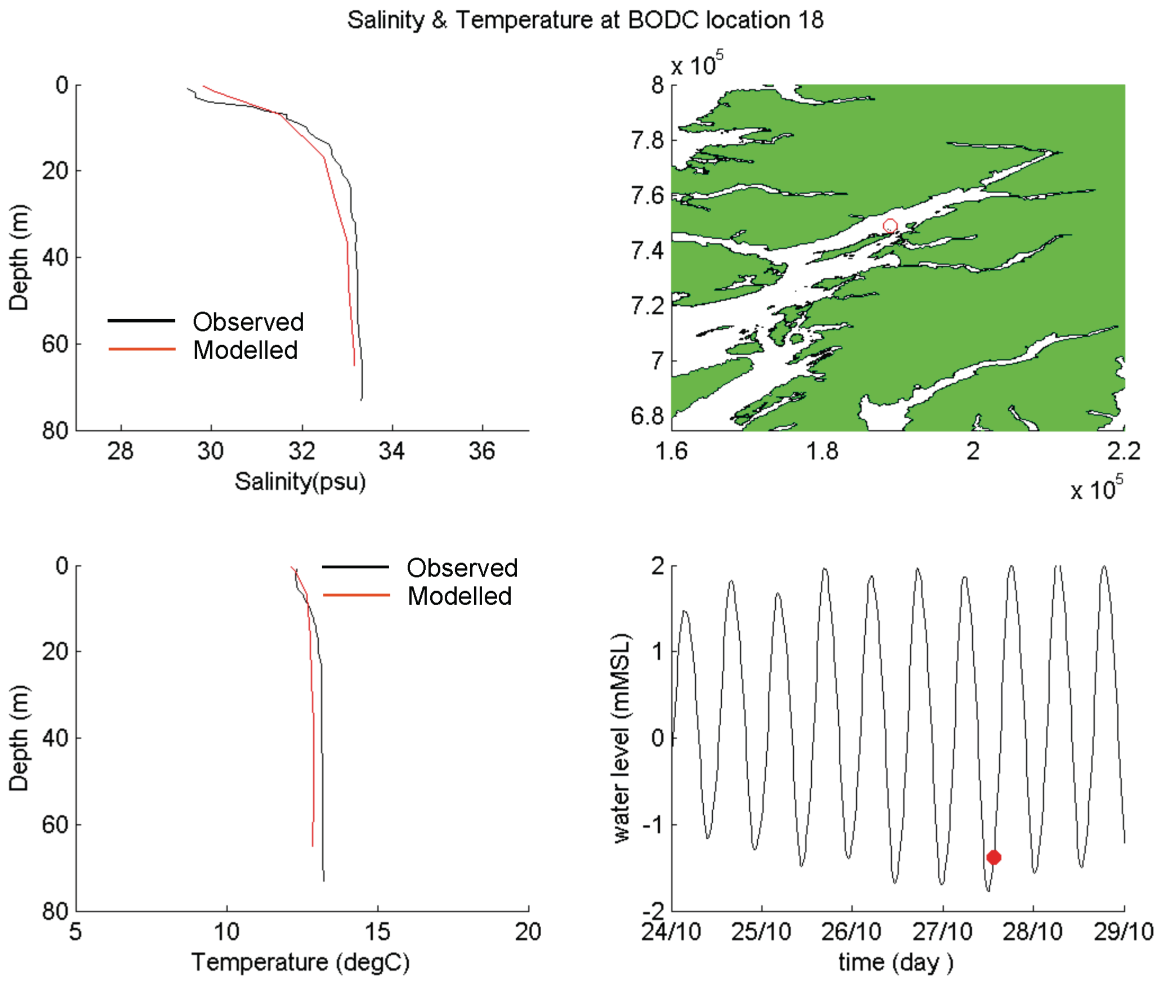


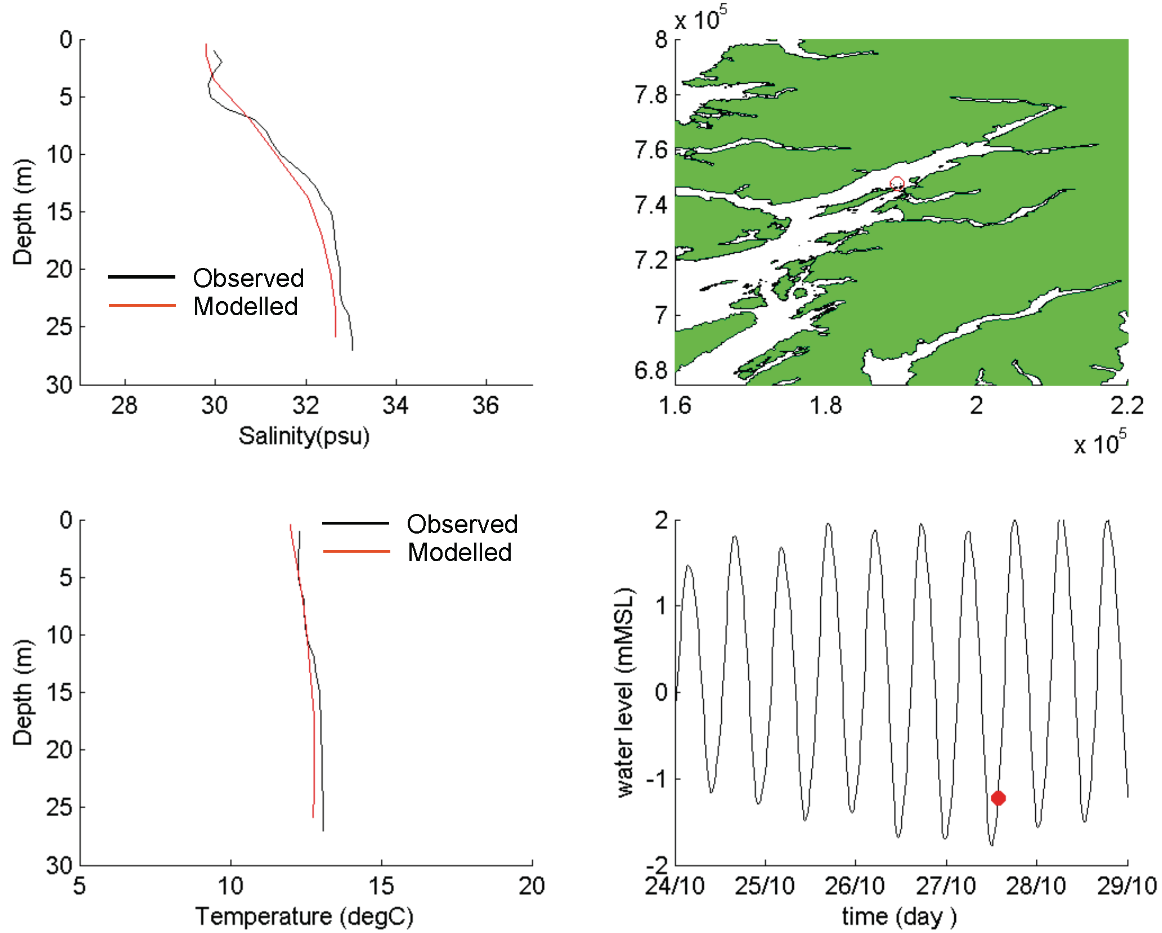

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



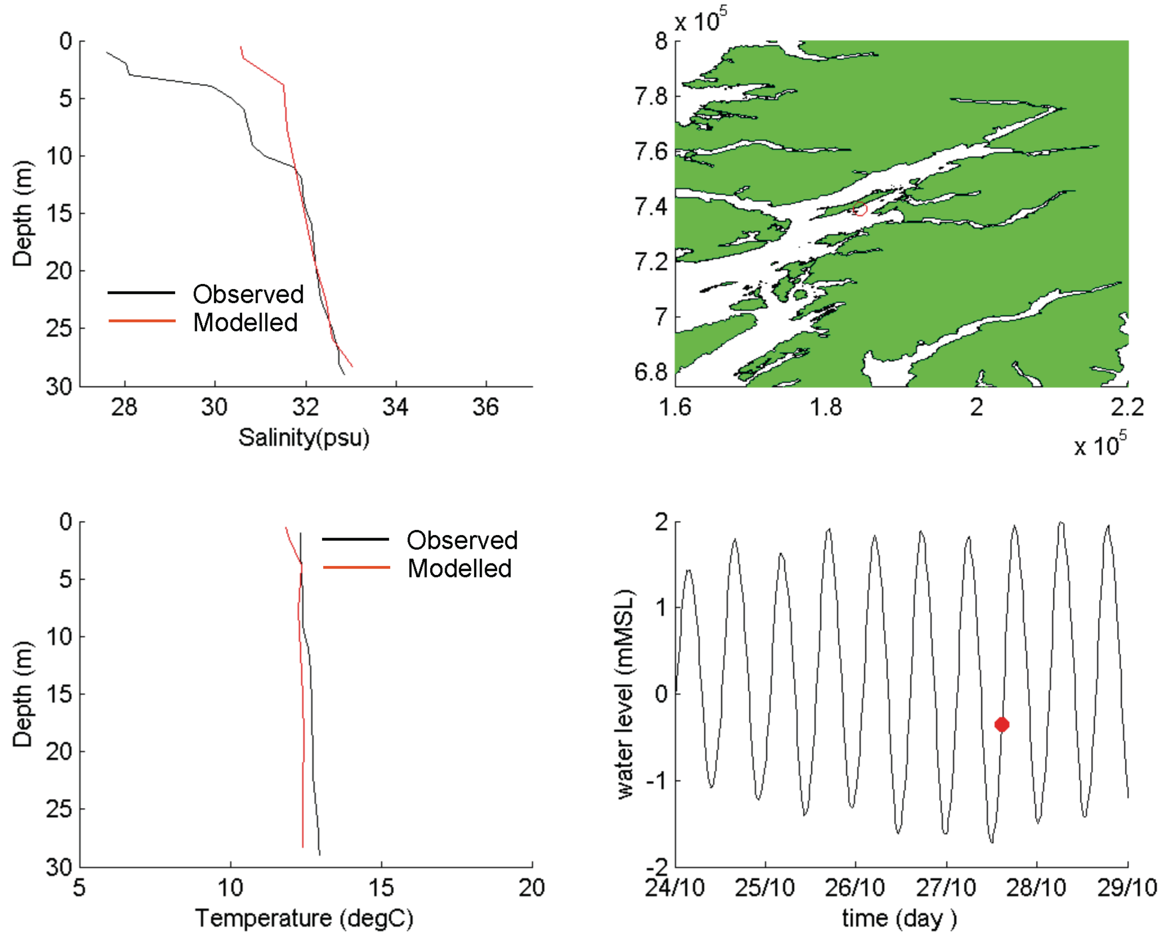

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



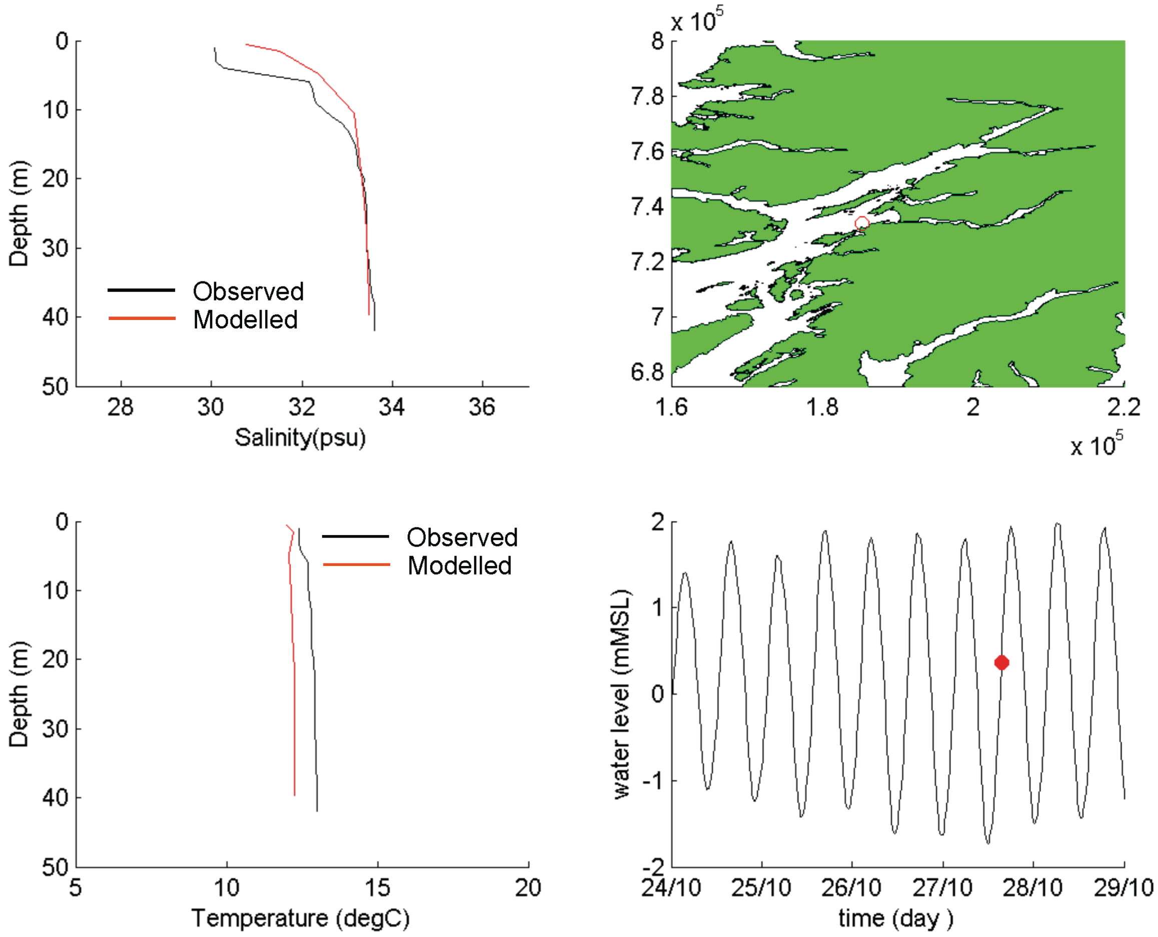

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



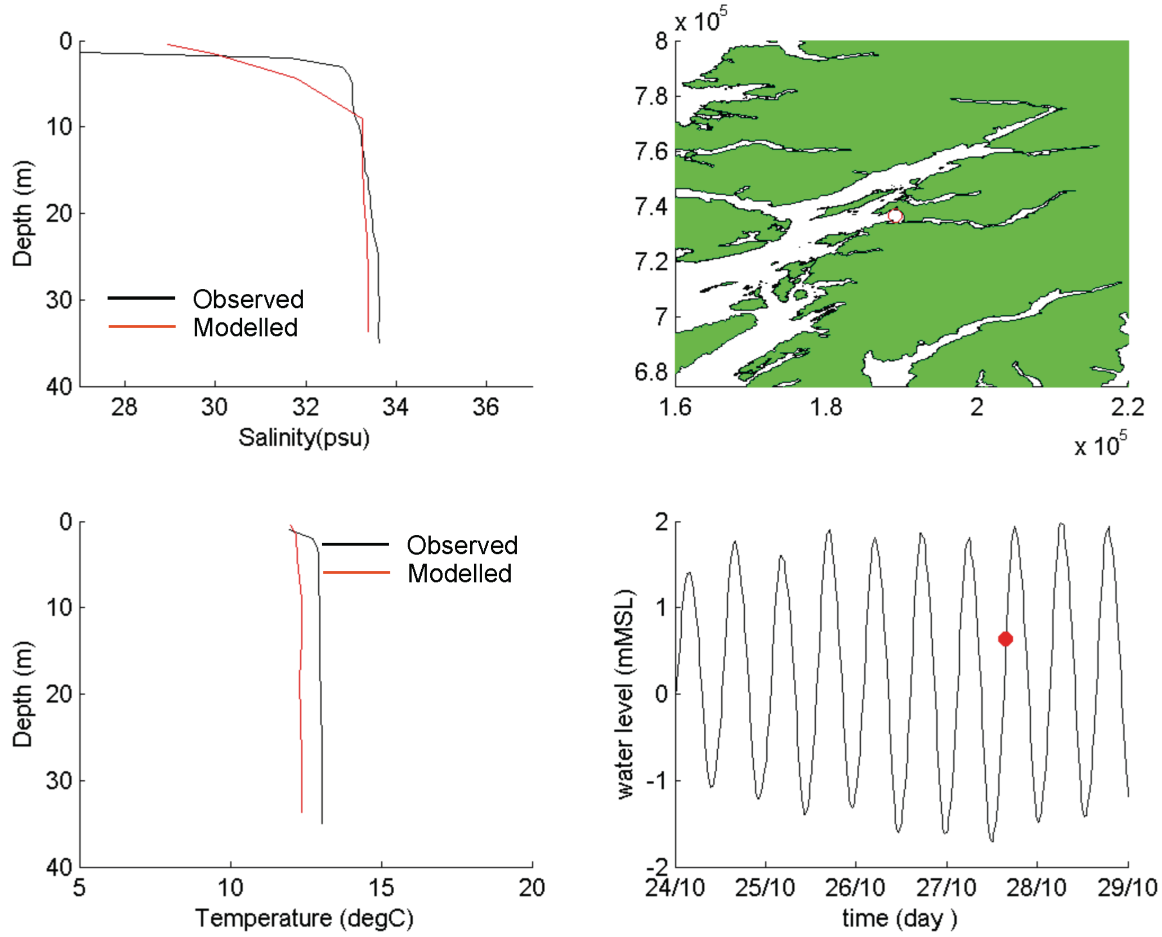

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



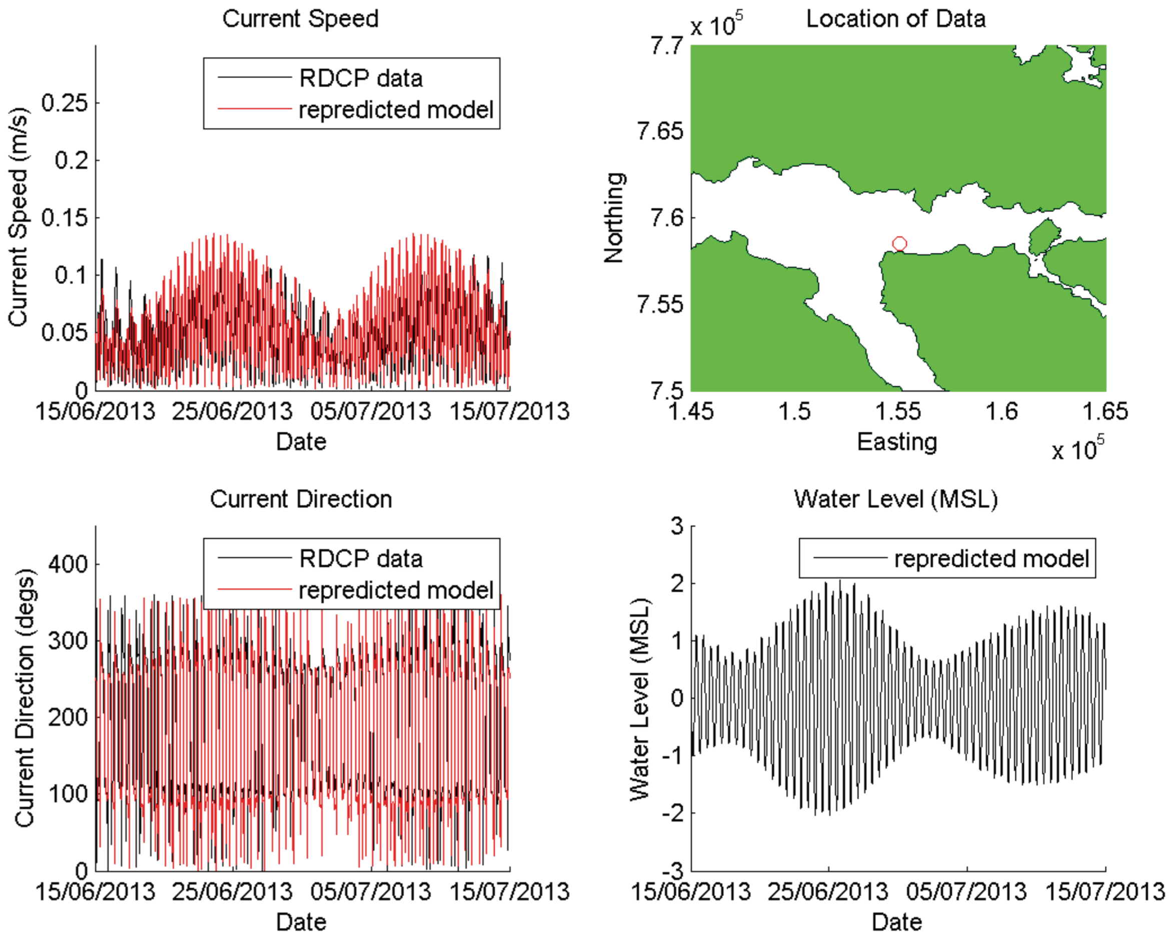

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13h | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



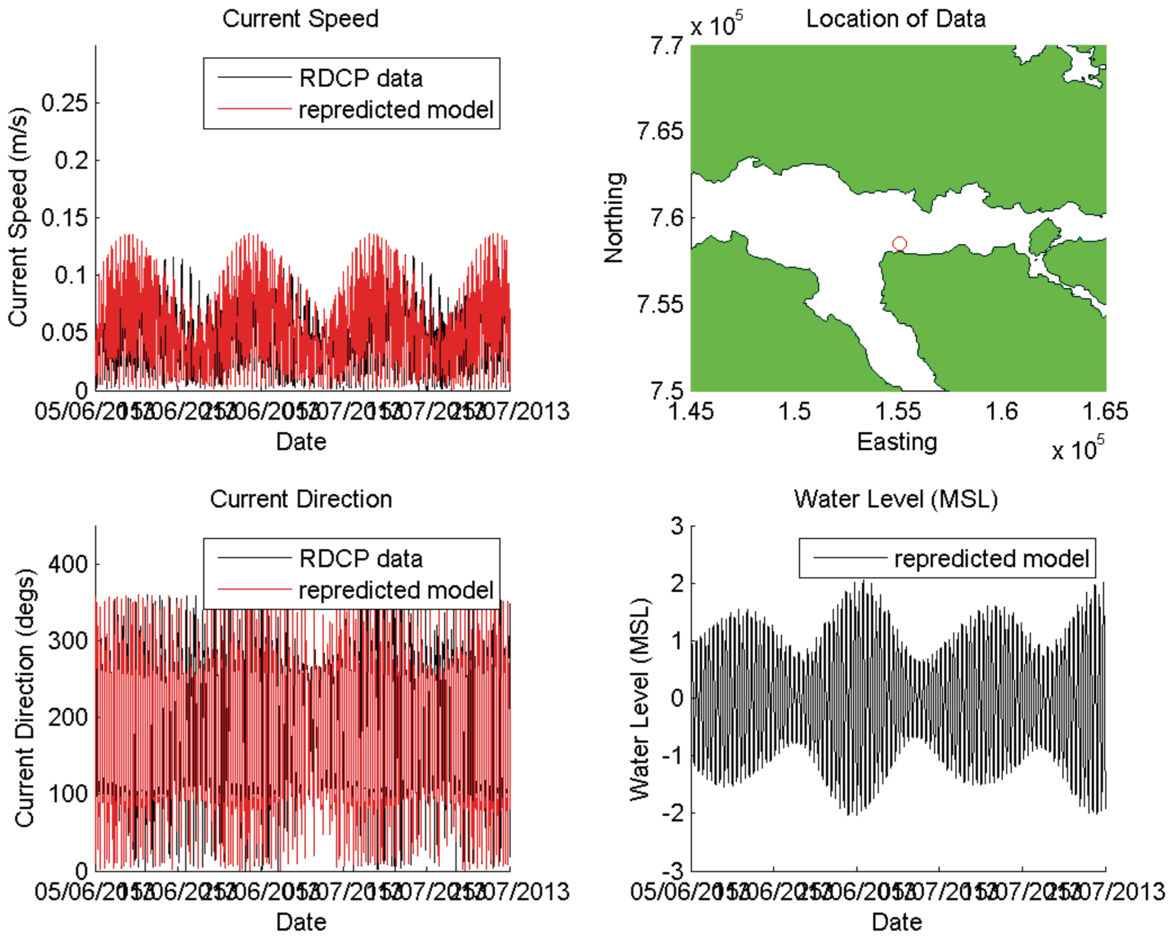

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13i | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



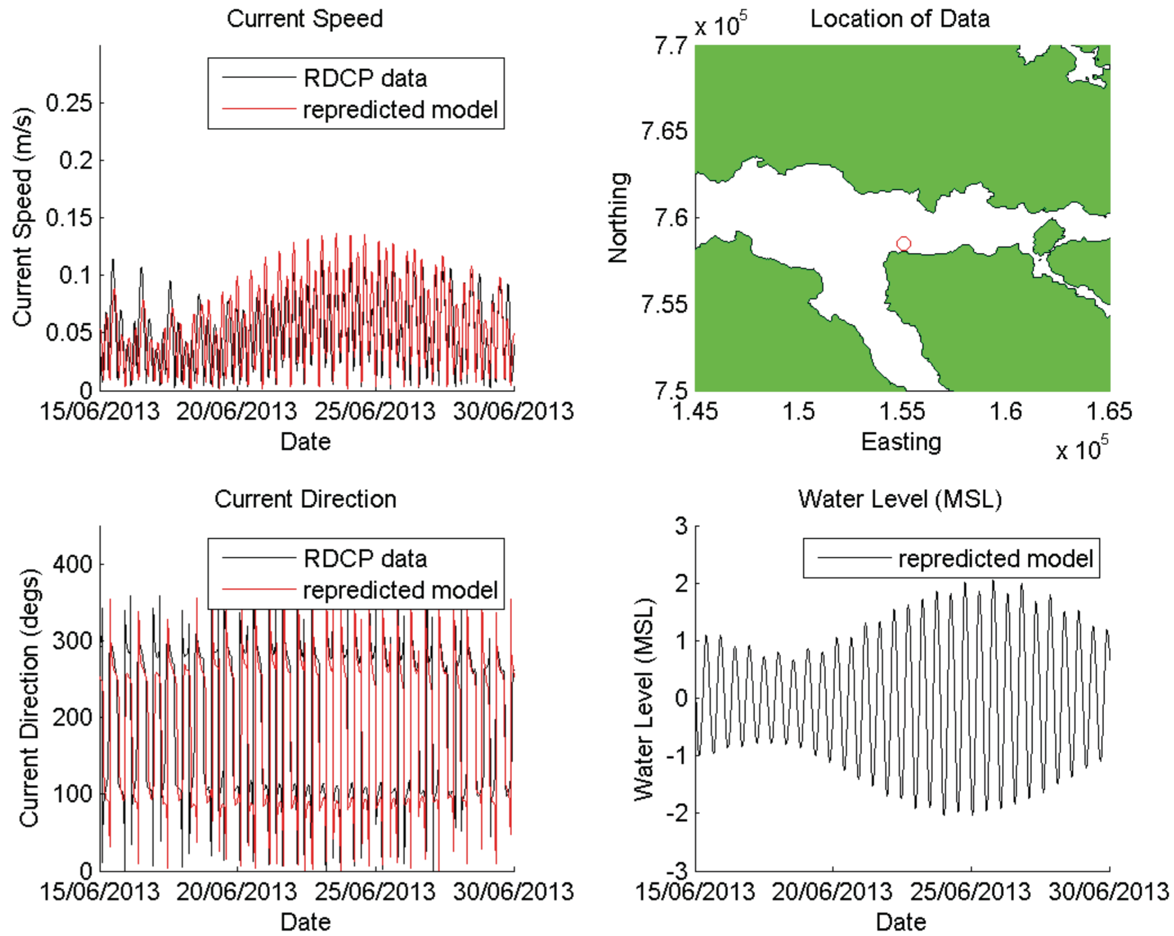

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-13j | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



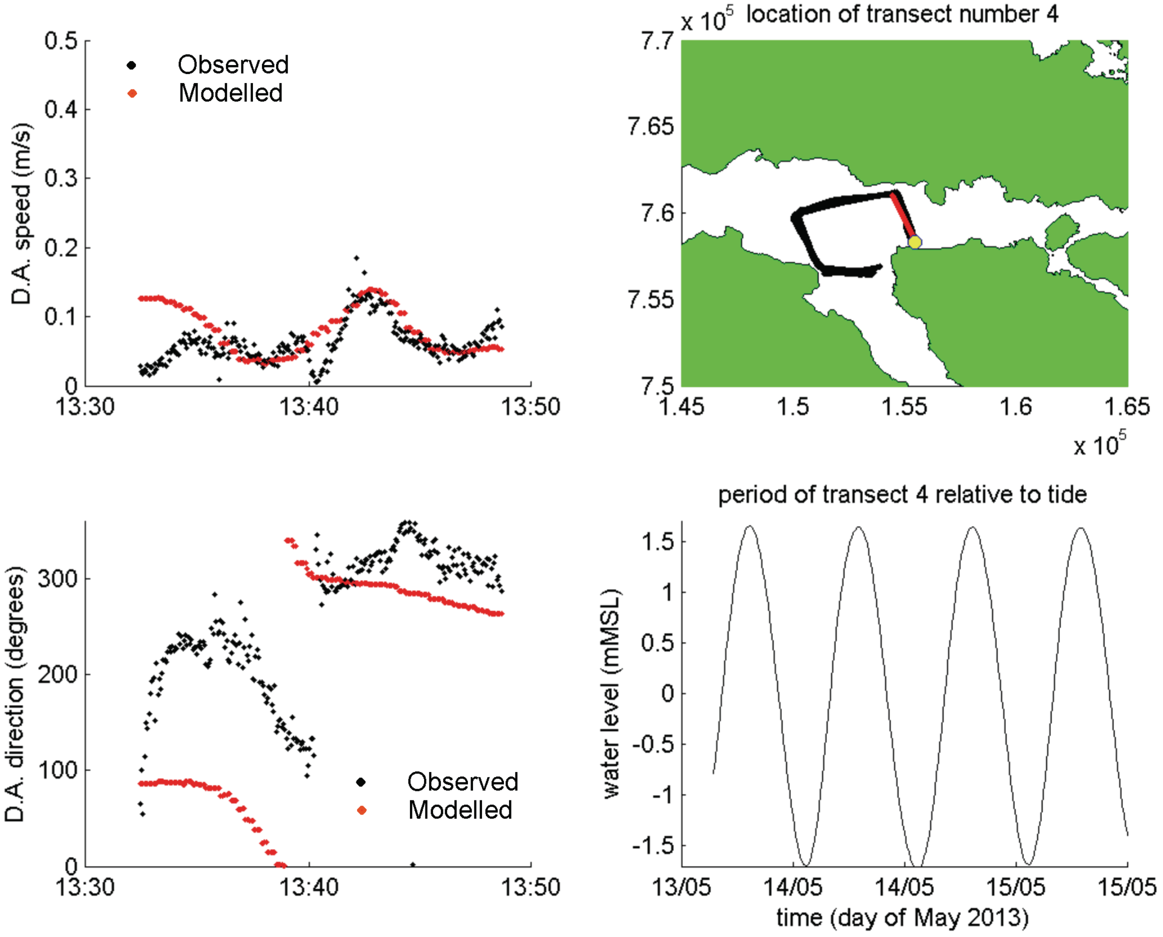

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-14a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed RDCP depth-averaged current data in Loch Sunart entrance. Harmonic analysis and reprediction undertaken with both datasets – zoom1 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



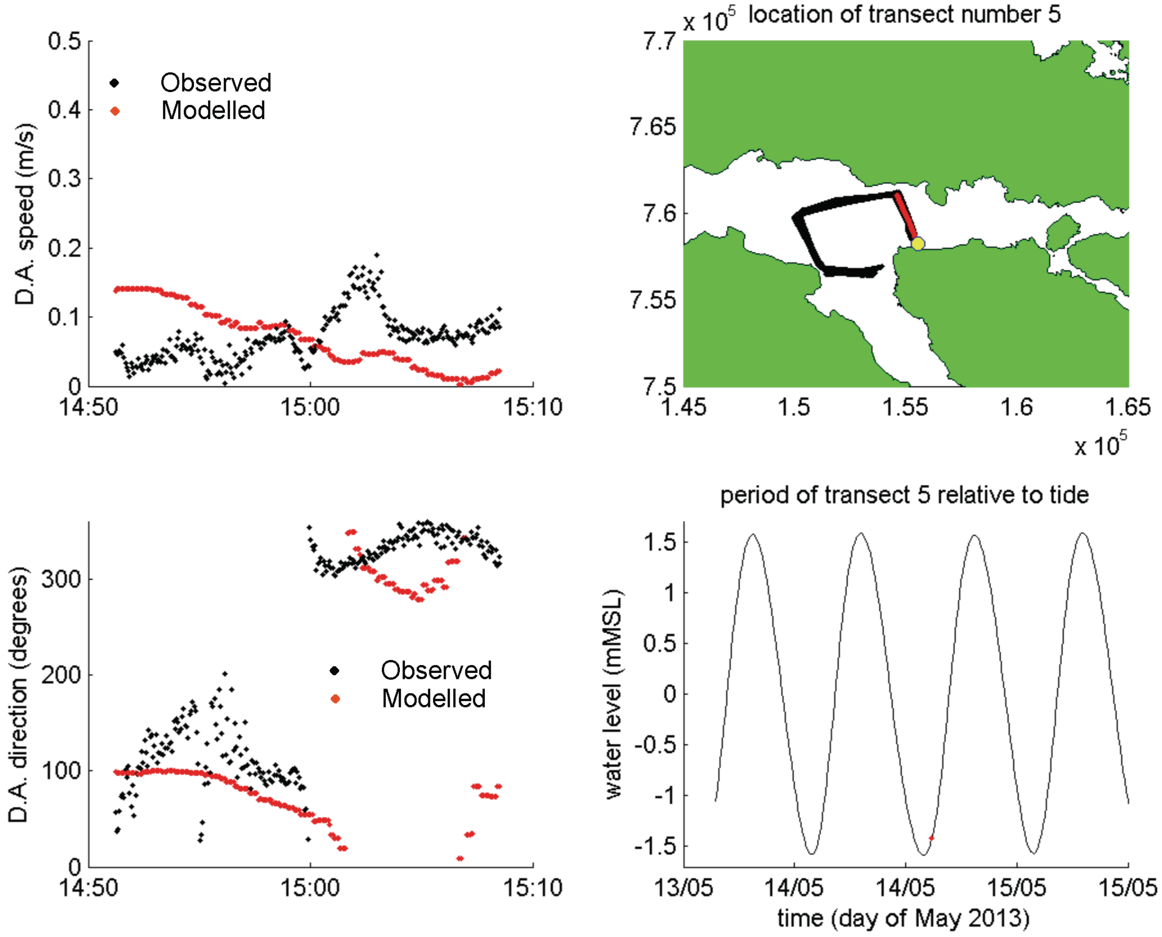

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-14b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparison between model and observed RDCP depth-averaged current data in Loch Sunart entrance. Harmonic analysis and reprediction undertaken with both datasets – zoom2 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



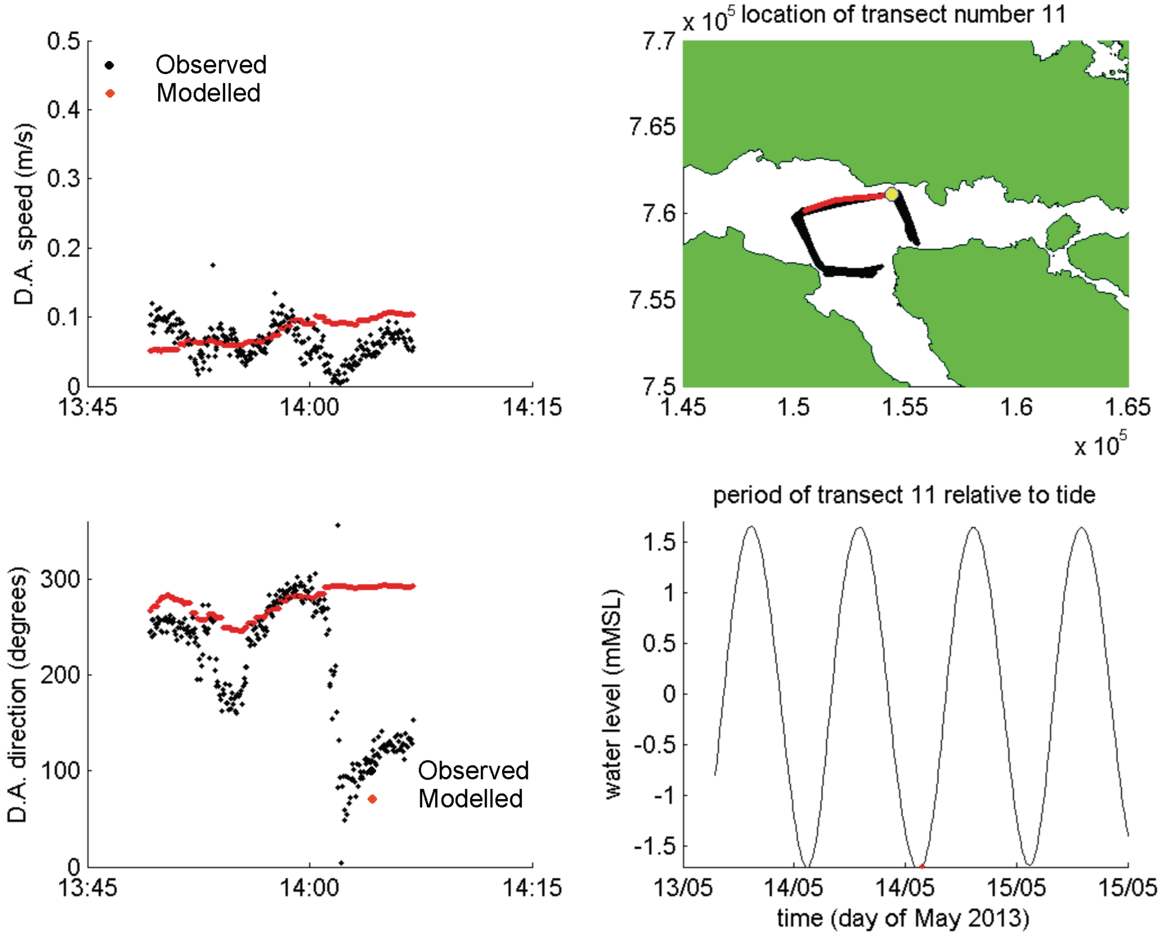

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-14c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed RDCP depth-averaged current data in Loch Sunart entrance. Harmonic analysis and reprediction undertaken with both datasets – zoom3 | Checked: DMP | Scale: Not to scale | Rev.: 0 |
| | | | | Designed: FML | Drawn: | Date: 14/112012 |



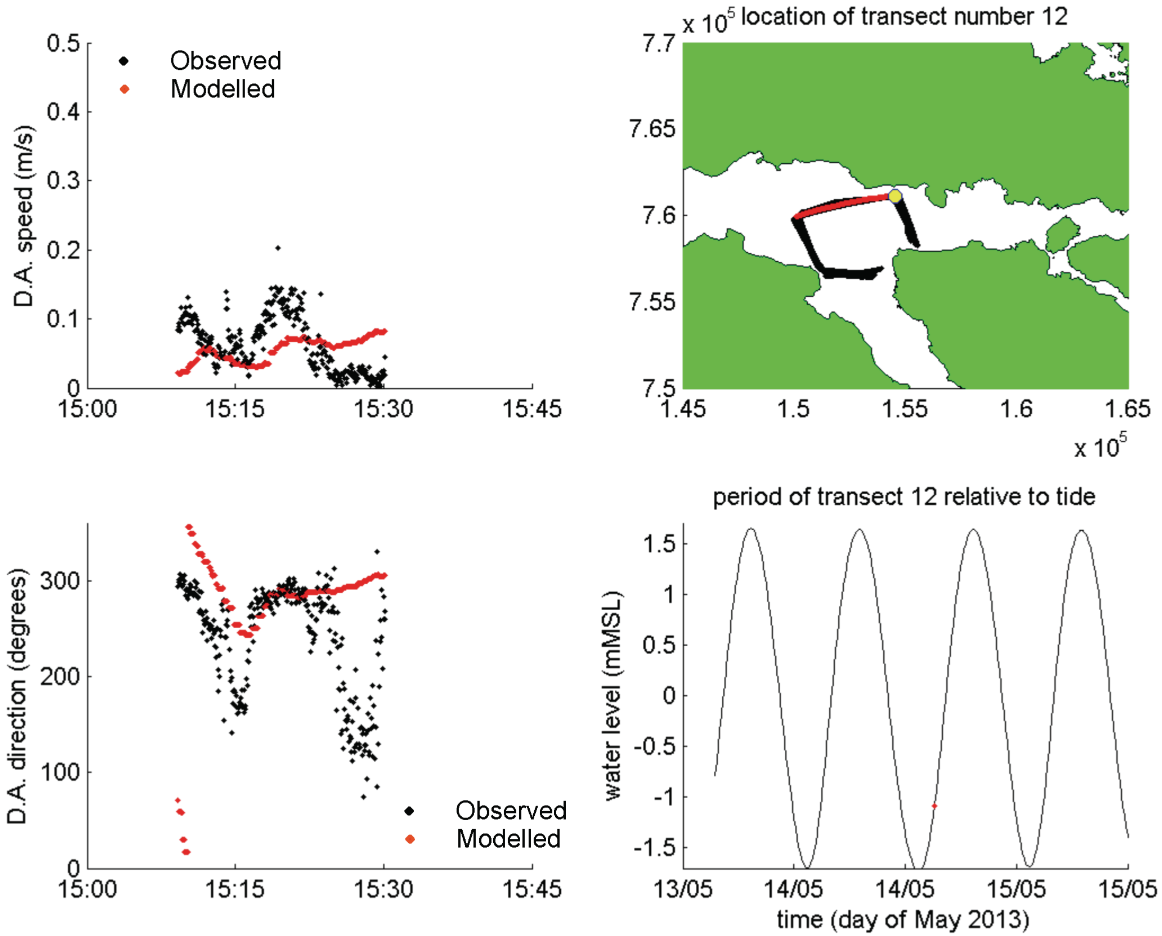

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



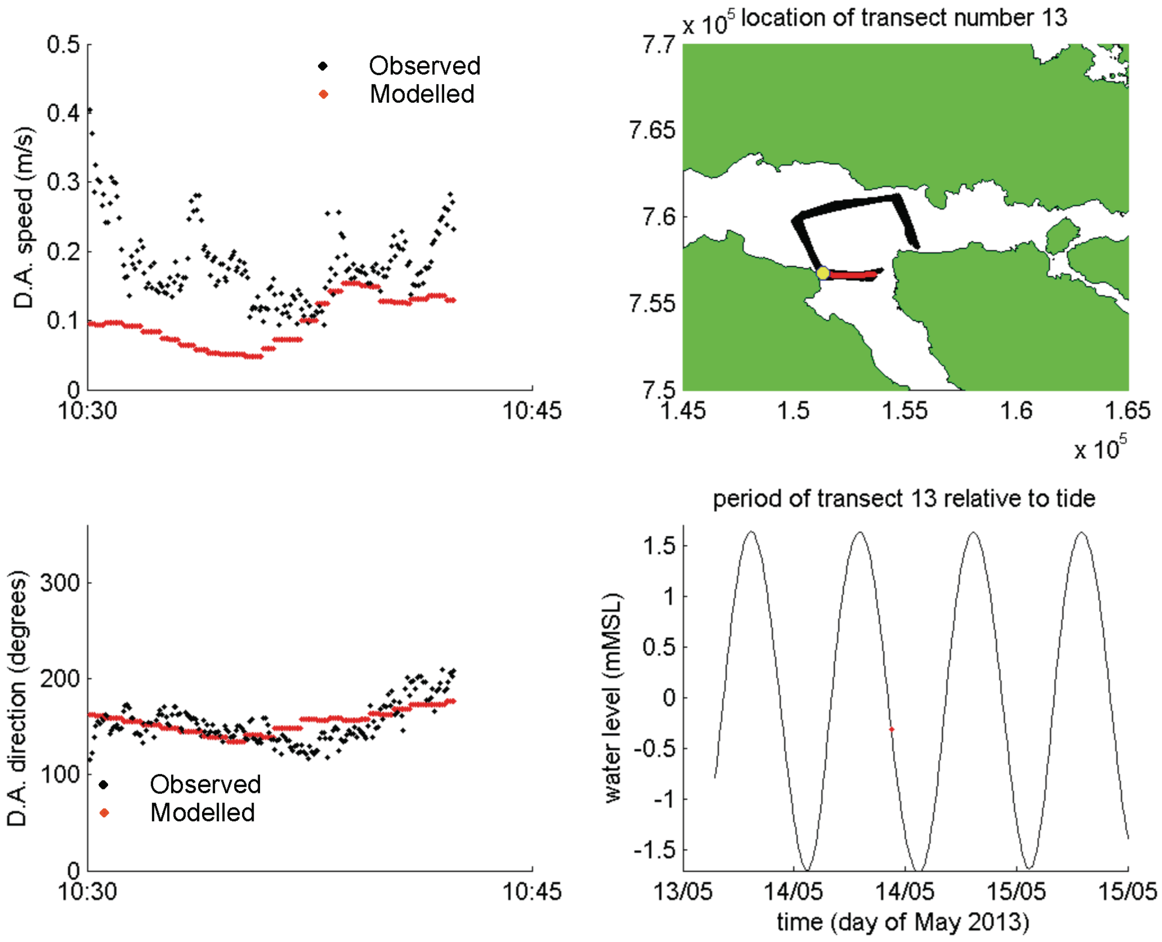

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



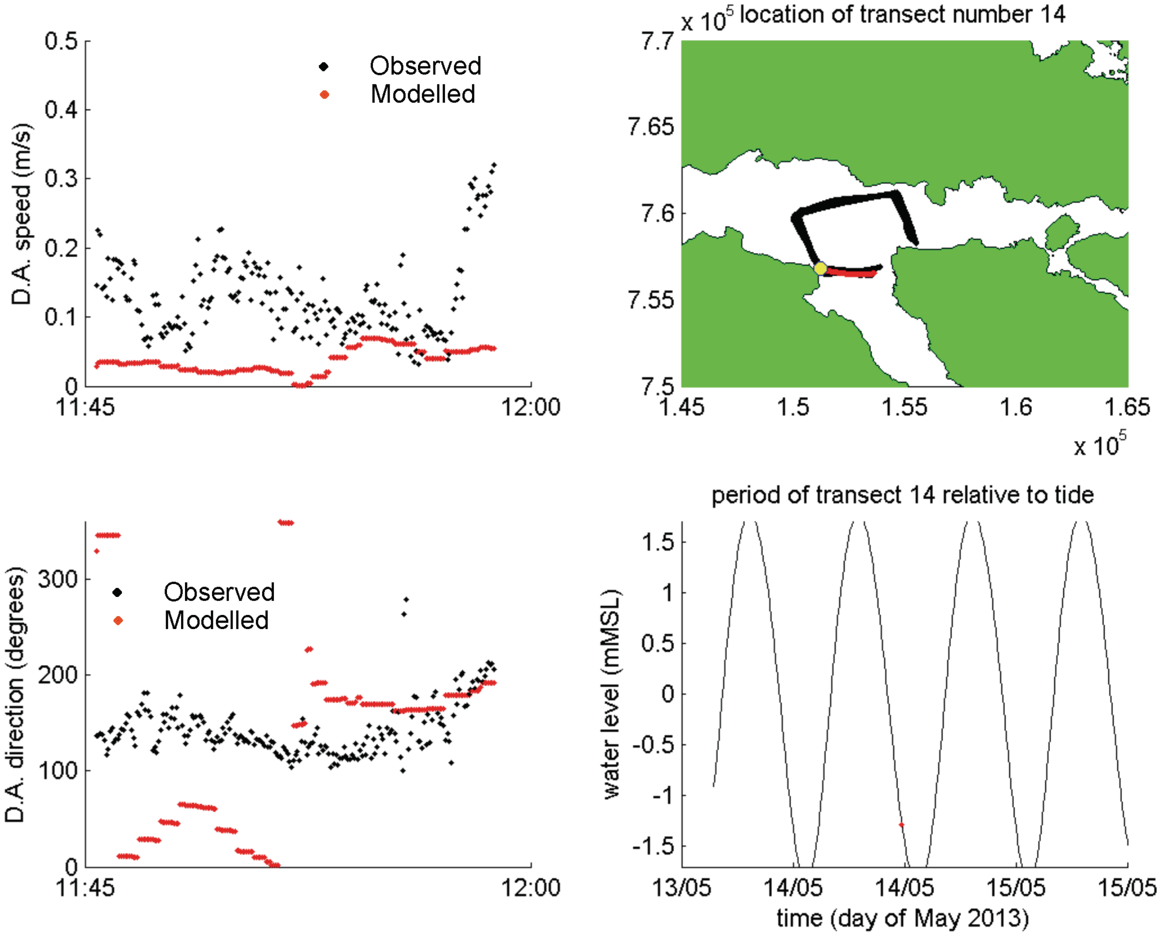

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



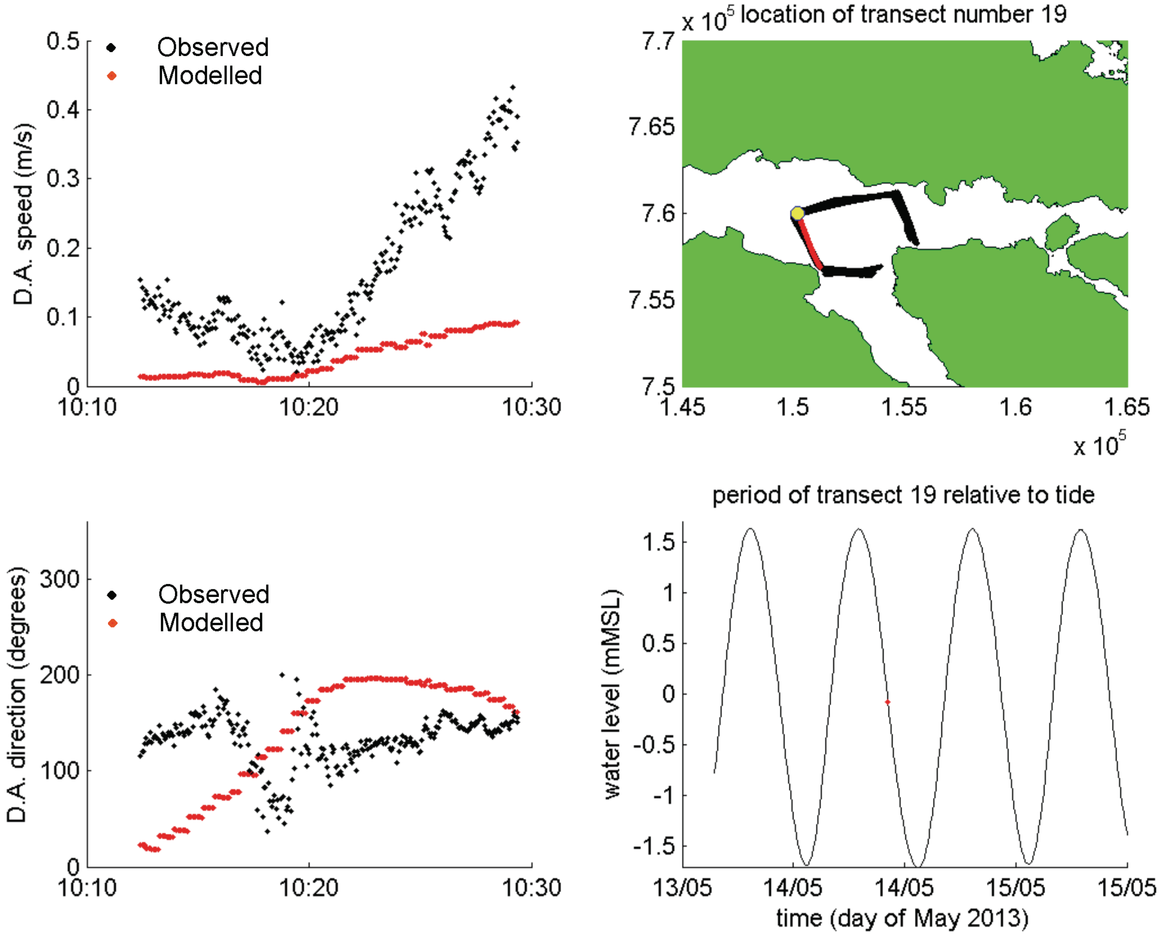

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



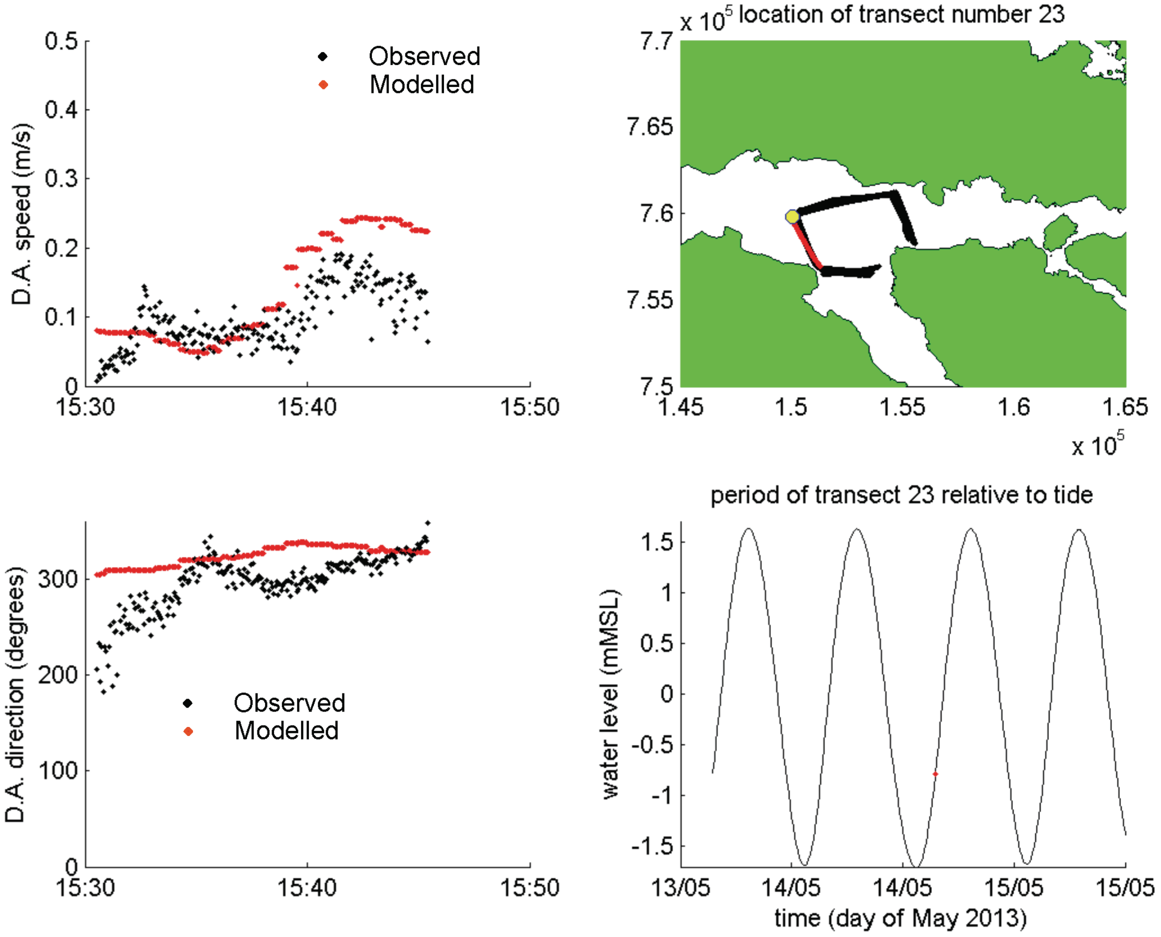

| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 3-15h | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

## 3.7 Summary for model calibration and validation

The WLLS model has been setup for the purposes of simulating the tidal and meteorological forced flows within the wider Loch Linnhe System, encompassing Loch Linnhe, Loch Sunart, Mull Sound and all side lochs within. Vertical resolution varied in order to try and capture the near surface freshwater plume during high fluvial events, especially in Upper Loch Linnhe. This was partially successful, although it is believed that to capture this correctly would require higher resolution in the near surface layers.

Water levels predicted by the model are in general good within the WLLS area. Similarly temperature and salinity are reproduced well, especially for the May 2011 calibration period. Current speeds are also reproduced well in terms of magnitude at the two sites within Loch Linnhe, although timing of the peaks is not always good; both sites are located in circulations which make this more difficult to achieve.

Comparisons with currents and direction in Mull Sound and Loch Sunart entrance are good with speeds of a similar order of magnitude, with the majority of the transect comparisons showing similar features in the model as was measured. It is concluded that this model has achieved a suitable level of calibration and validation.

# 4 Flow model simulations

## 4.1 2011 Simulations

### 4.1.1 Input Data

The input data for the 2011 runs was taken from the same sources as the calibration runs and processed using the same methods. The main difference is that the six month run was started on the 6th of April giving a 24 day warmup period for temperature and salinity. Initial conditions were also taken from the Scottish Shelf model climatology run but for the 6th of April not the 1st of May. Selected results from the 6 months are presented below, including comparisons with the calibration runs to consider the influence of initial conditions and warm up length.

### 4.1.2 Results

#### 4.1.2.1 Data Buoy

Comparisons with near-surface currents speed and direction, salinity and temperature at the data buoy, along with the river flow and water level for May, July, September and October are presented in Figure 4-1a-d. In general the comparison in current speeds is reasonable, there is some variation in the timing of the peak flows but speed are of a similar order of magnitude. As stated in the calibration section (Section 3.4) the data buoy is located in an eddy making it difficult to reproduce the measured currents in the model. As with the calibration runs the surface salinity responds to the fresh water inflow from the rivers quite well but does not drop down to the same levels measured by the data buoy, even in September when the river flow reaches in excess of 900 m/s. The model also fails to pick up the rapid variations in surface temperature seen in July and October but does follow the correct trends in warming and cooling through the six month period. The model appears to heat up at a higher rate than the measured data at the data buoy during the summer months, this is reflected in the over estimation of surface temperature during July (Figure 4-1b) and September (Figure 4-1c), the temperature does reduce again in October back in line with the measured data (Figure 4-1d).

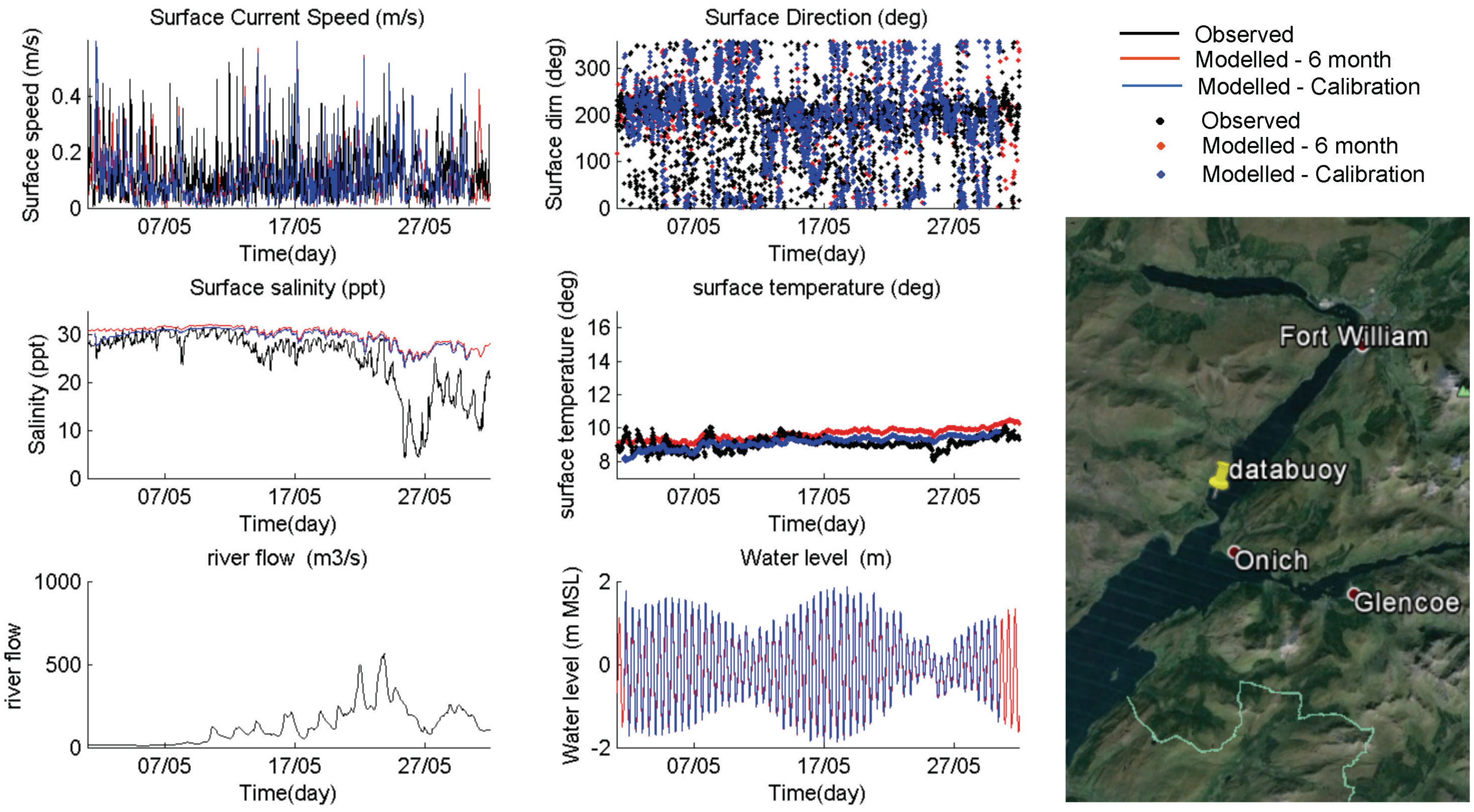
The plots for May and October also include the calibration run results. The difference in initial conditions can be seen in the temperature and salinity at the start of May (Figure 4-1a). The difference in the salinity of the calibration and six month runs reduced over the first 7 days of the run. This variation in salinity is reflected in the variations in current speeds between the two models, confirming that the model sensitivity to salinity discussed in Section 3.4. The initial difference in the temperature, however, remains throughout the month.

#### 4.1.2.2 CTD Profiles

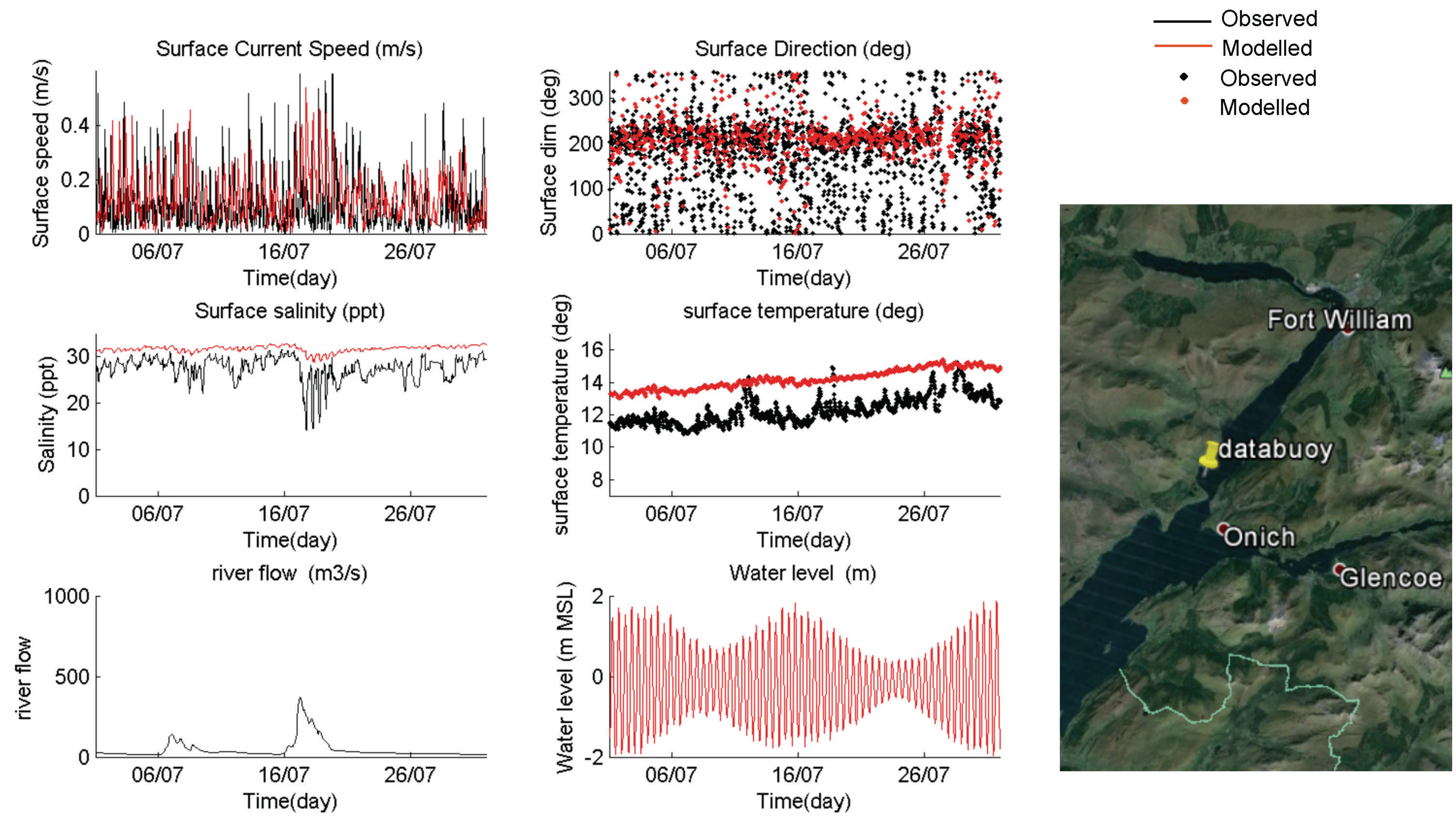
The measured CTD profiles were also plotted with the calibration run and six month run results for May and October in Figure 4-2a-d and Figure 4-2e-h respectively. Note that the red dot on the water level series is repeated in some cases this is simply due to the difference in timestep between the two runs. The calibration data is output every 15 minutes while the six month run is output at hourly intervals, therefore the maximum time difference between the data from the two models is 30 minutes. In May both the temperature and salinity are higher in the six month run than the calibration run. This highlights the influence initial conditions and warmup period can have on model results. However this is also partly due to the increase in the salinity and temperature after the April spin-up, a trend that continues throughout the summer. The calibration profile comparisons using initial conditions for the start of May 2001 are closer to the measured data. In October the salinity from the six month run is higher than that the calibration run but the temperature difference between the two models is very small, and both model are lower than the measured temperature (<1°C).

### 4.1.3 Summary

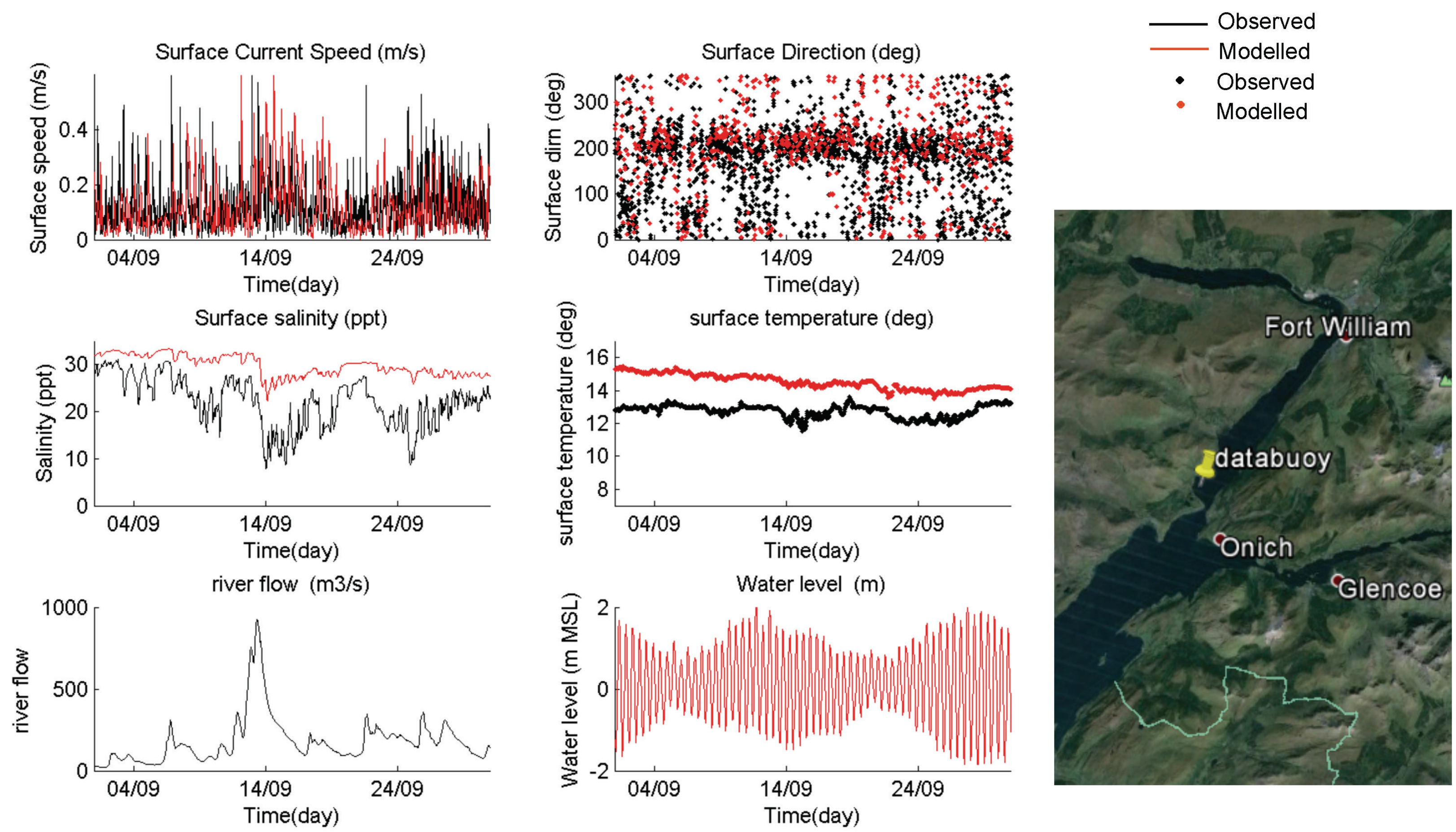
The 2011 runs show reasonable comparisons with surface currents, temperature and salinity at the data buoy. The temperature was overestimated in the summer month but ok in October, this indicated that the model is heating and cooling at a slightly greater rate than that indicated by the measured data. In the CTD profiles the salinity was overestimated by the six month run in May (approx. 1psu) and October (approx. 2psu). The temperature was overestimated in May (1°C) but underestimated slightly in October (<1°C). This highlights the influence initial conditions and warm up period can have on temperature and salinity in the model. Another possibility is that the input of fresh water is underestimated in the model. This may be due to underestimation from the G2G model or the method used to redistribute the G2G flows to the main rivers discharging into Loch Etive, Loch Leven and the top end of Loch Linnhe.



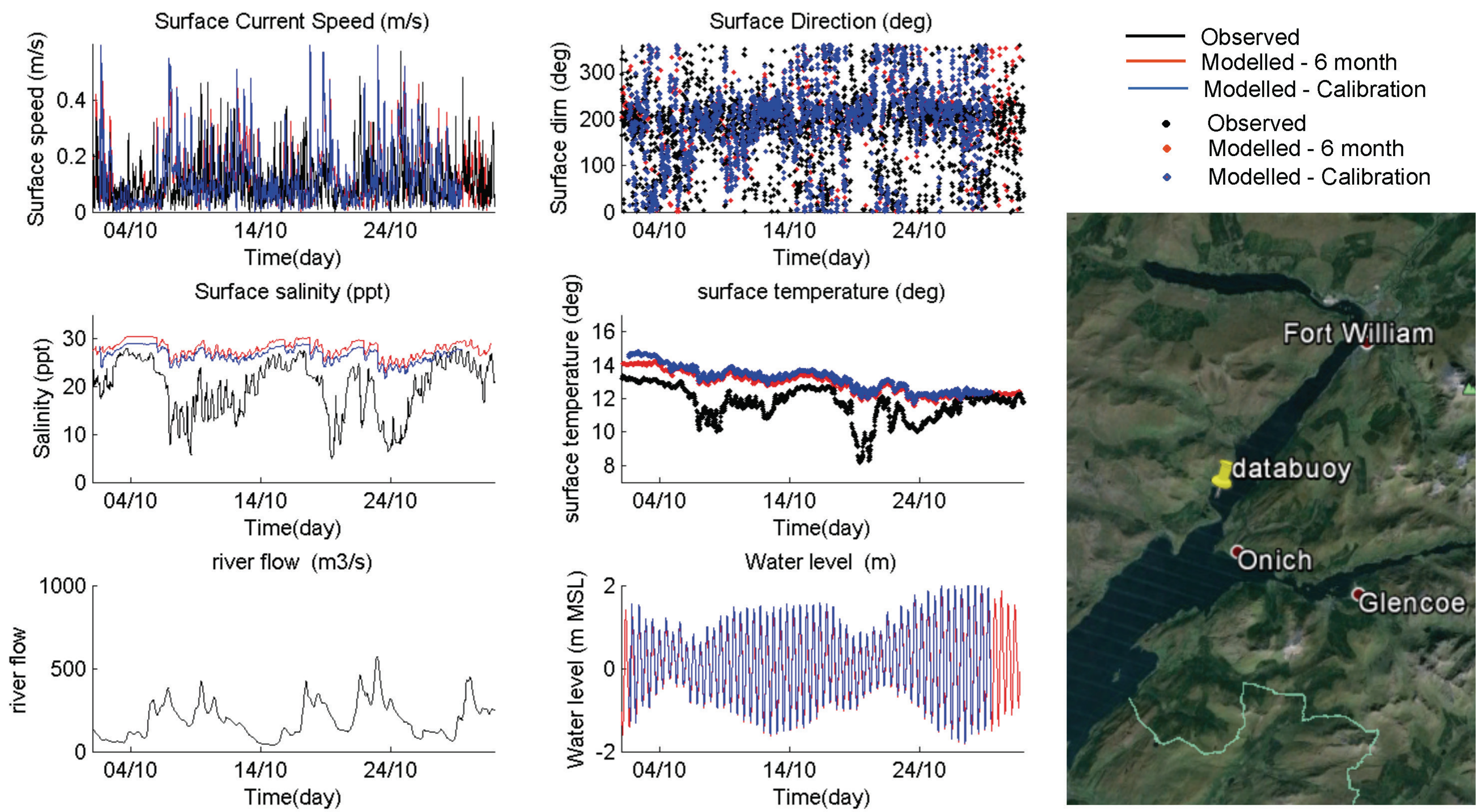

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-1a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model calibration and 6 month run and data buoy – surface measurements for May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



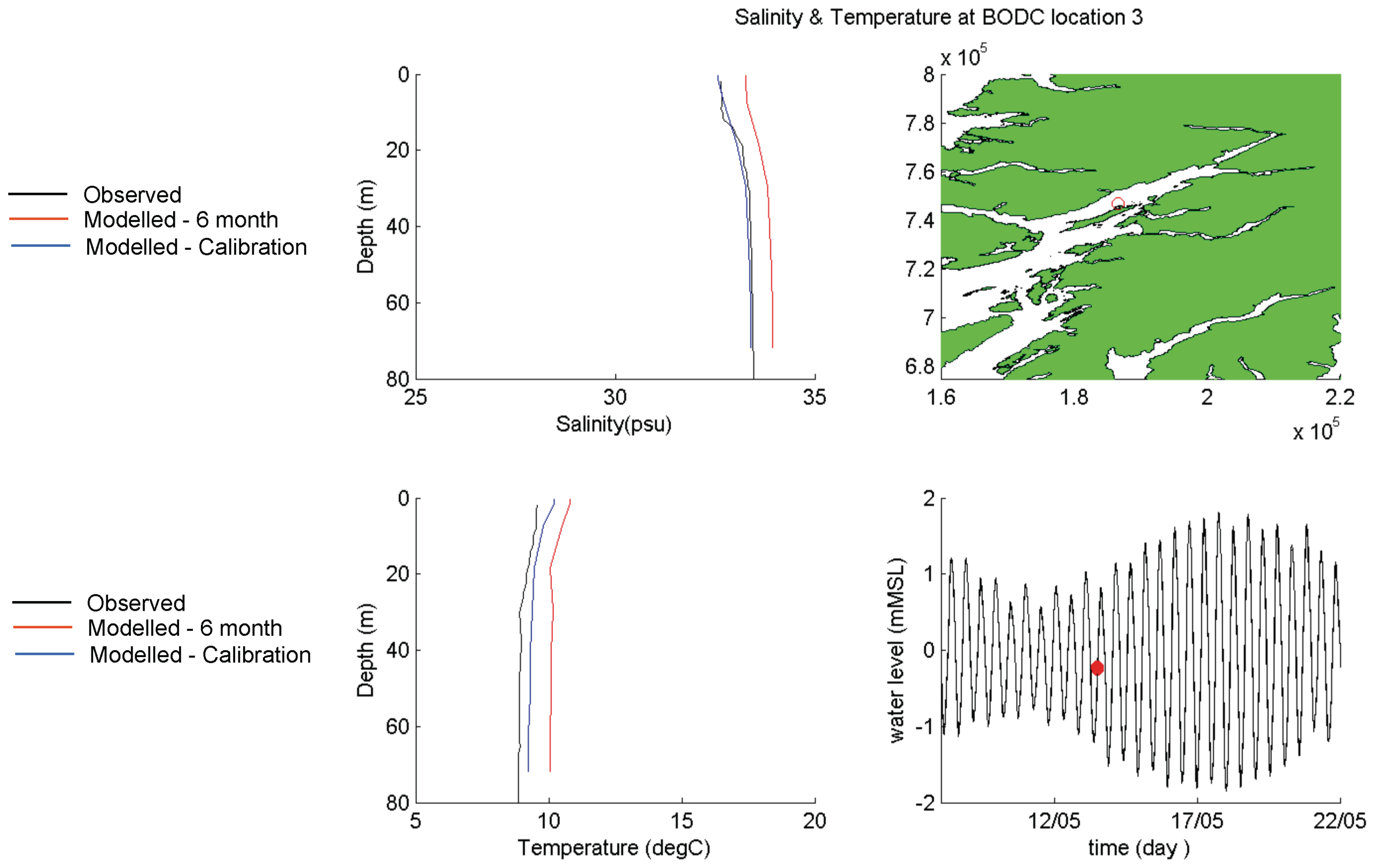

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-1b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and data buoy – surface measurements for July 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



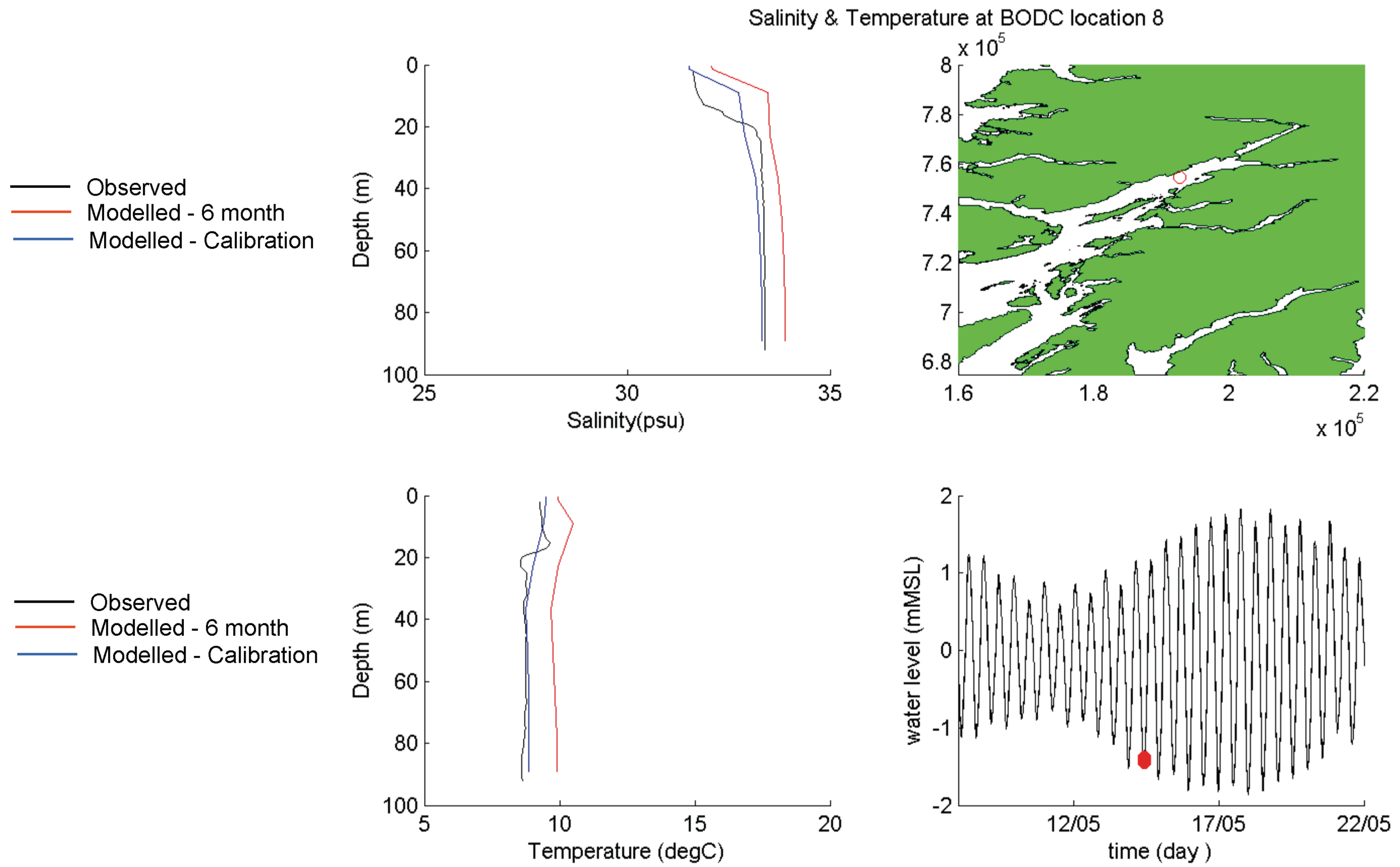

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-1c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and data buoy – surface measurements for September 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



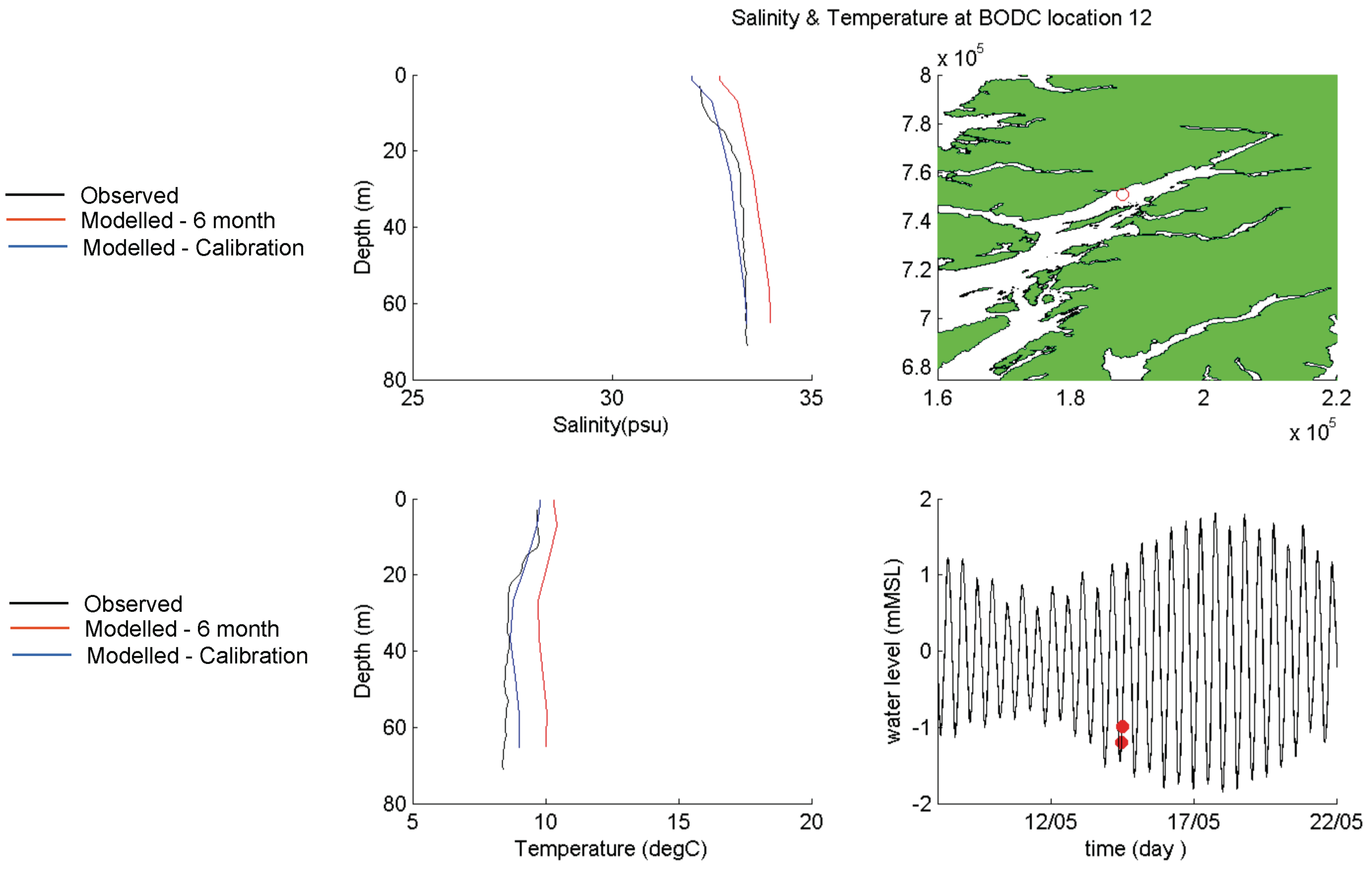

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-1d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model calibration and 6 month run and data buoy – surface measurements for October 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



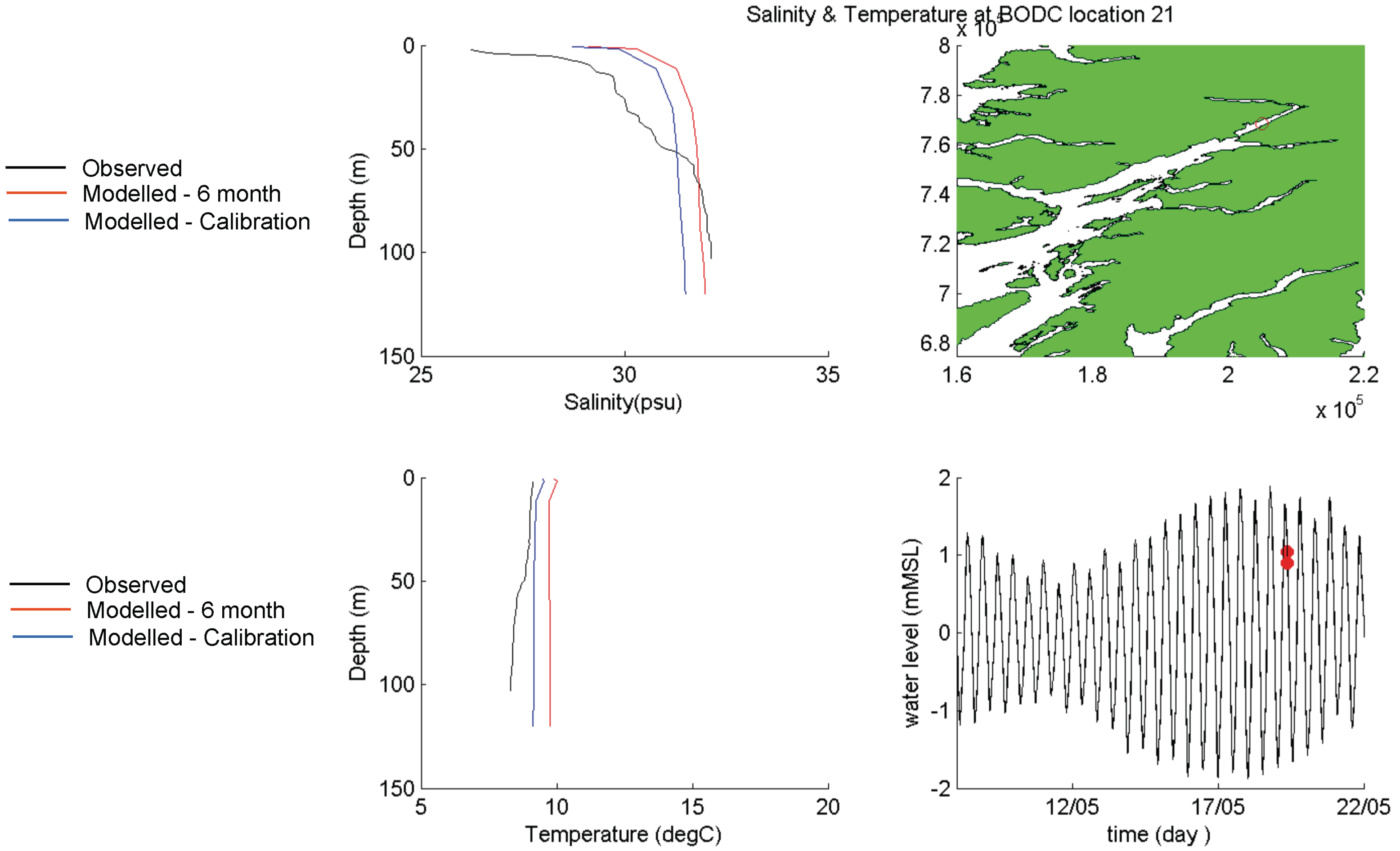

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



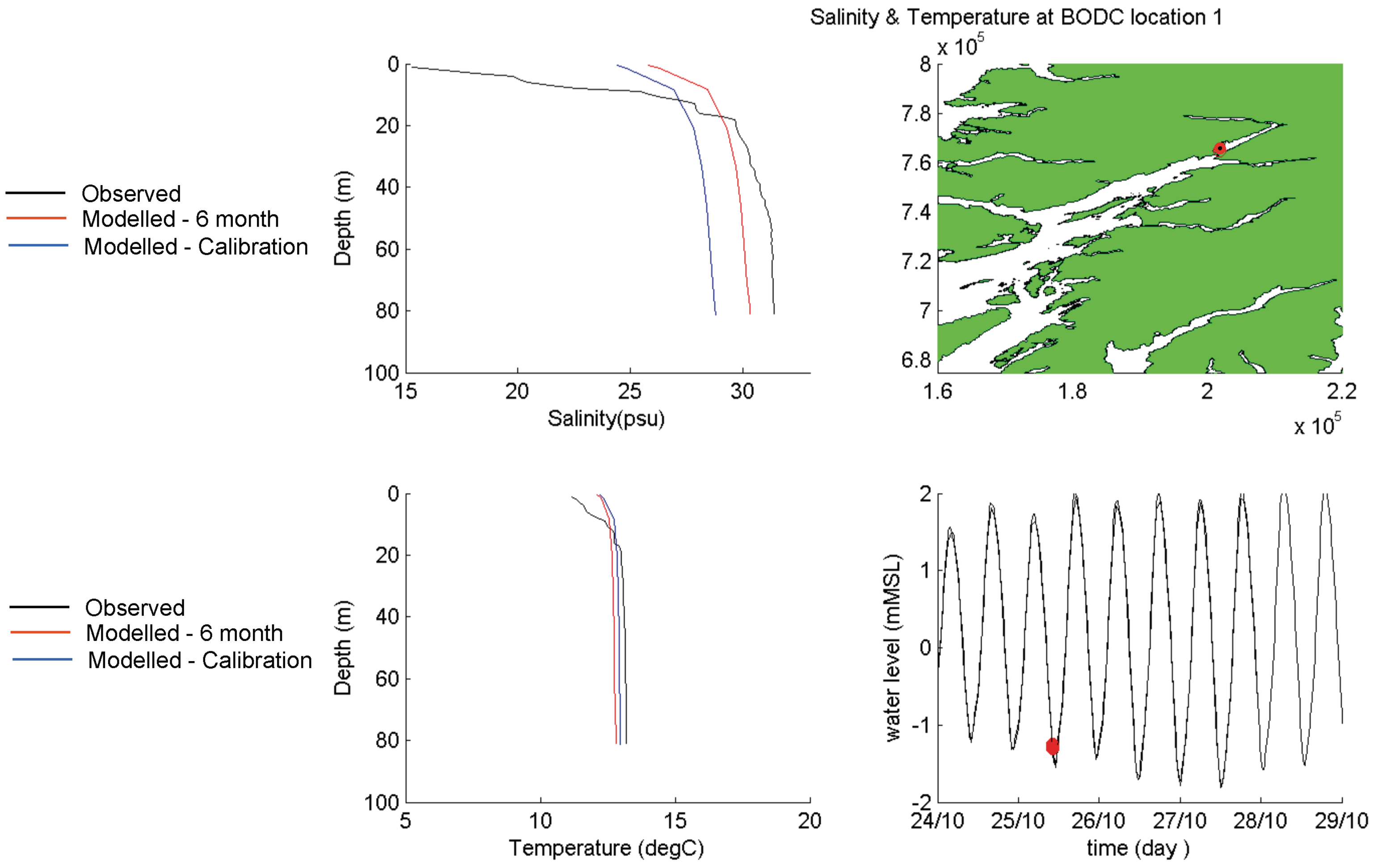

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



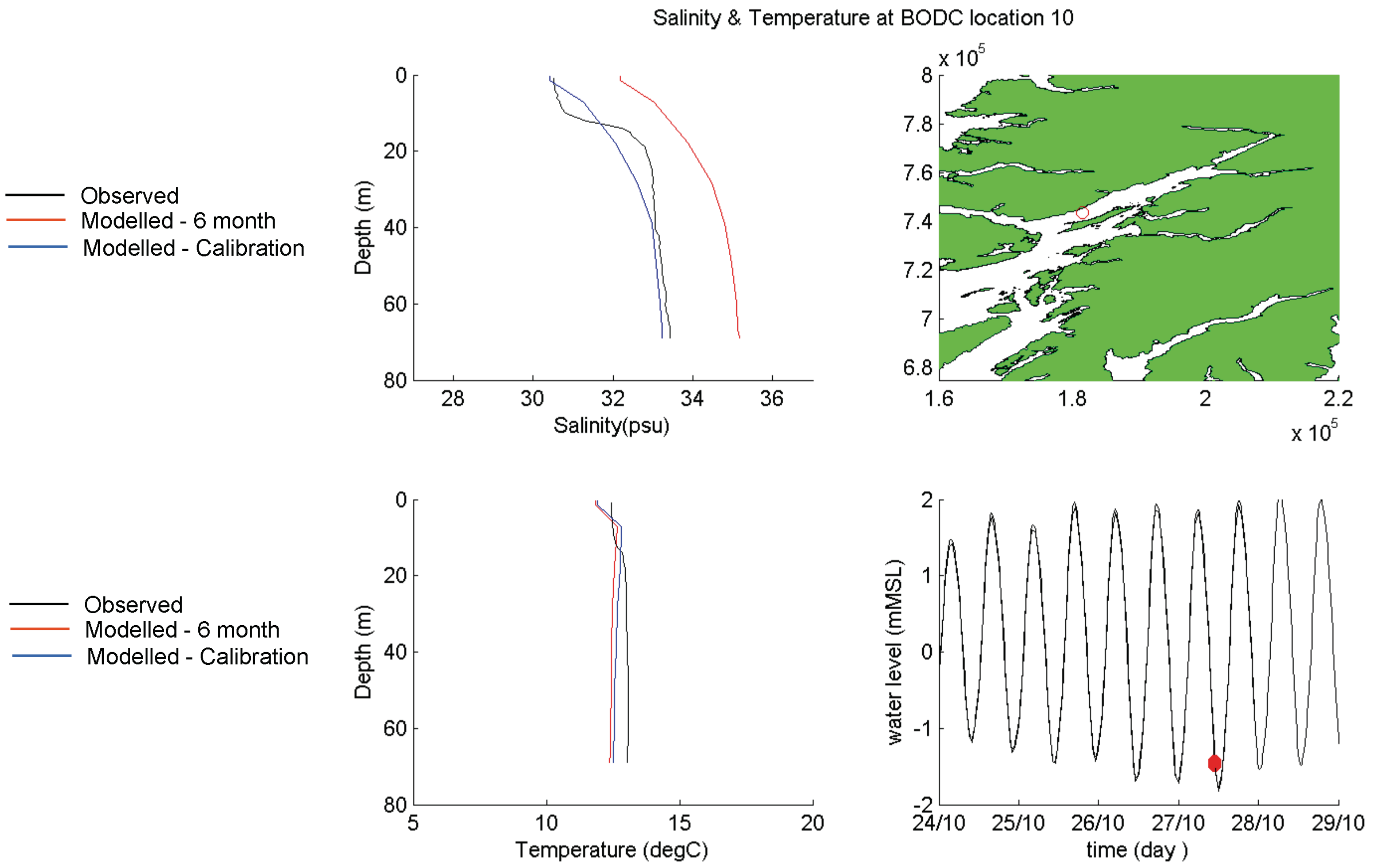

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

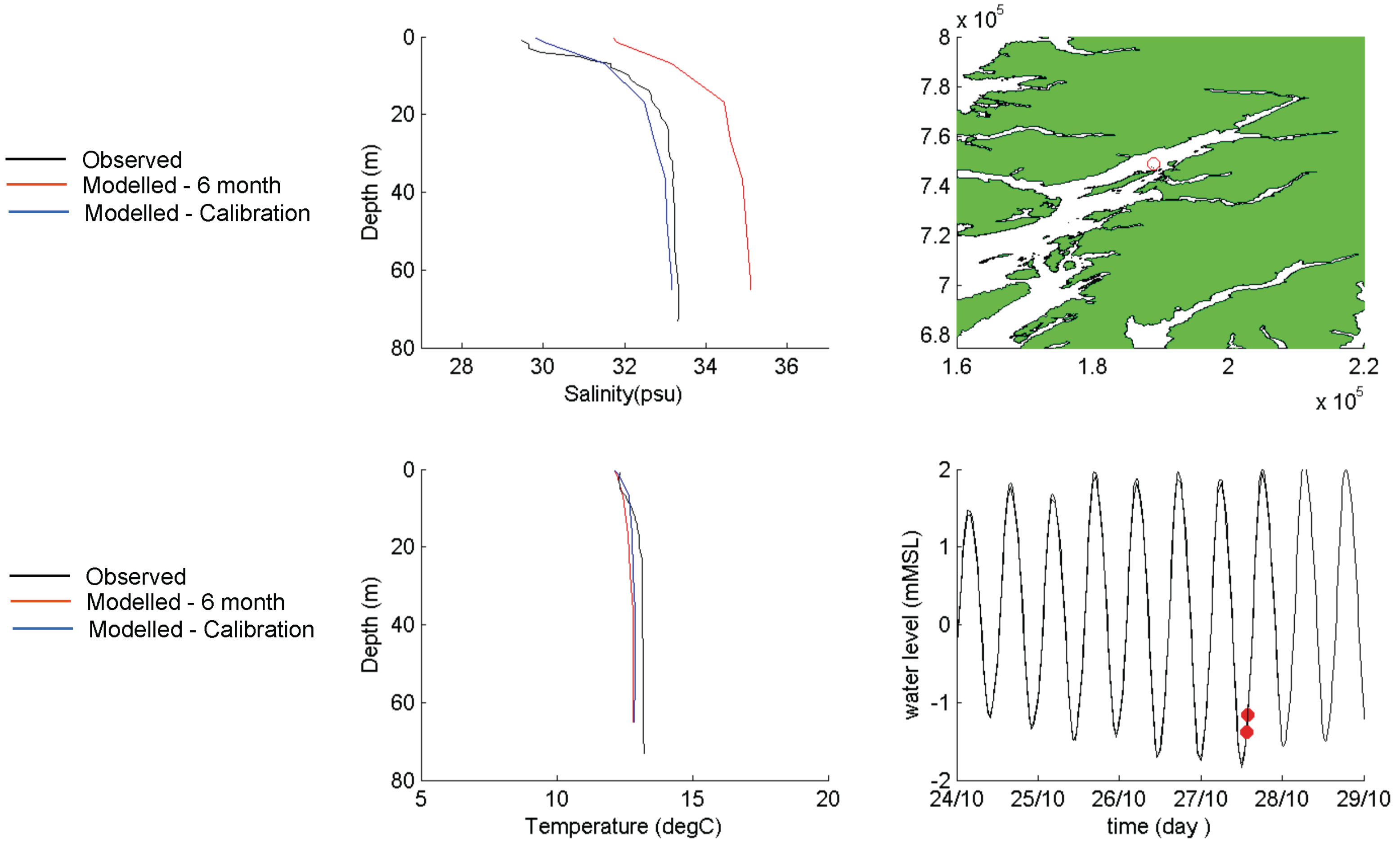



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements October 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

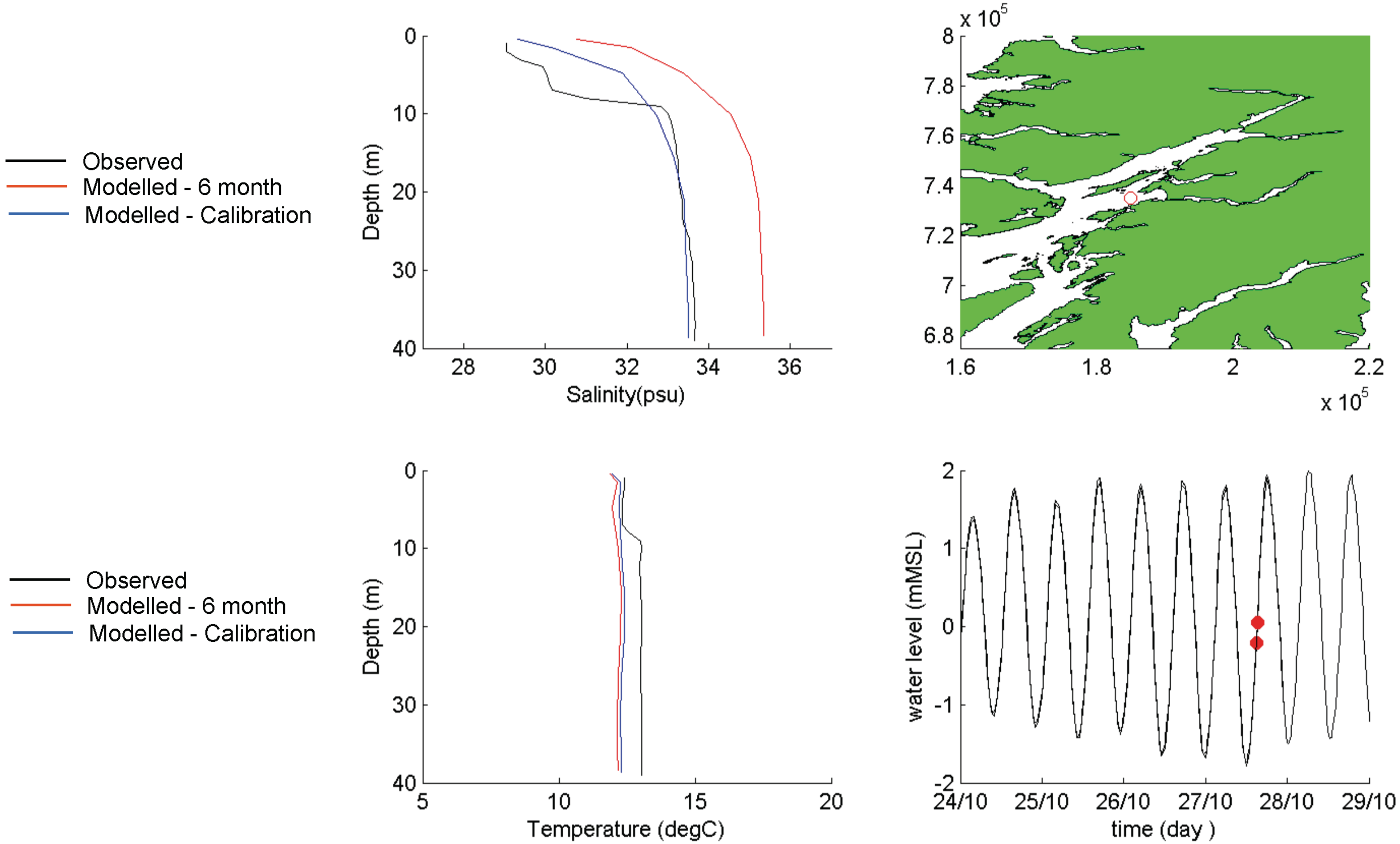



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements October 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

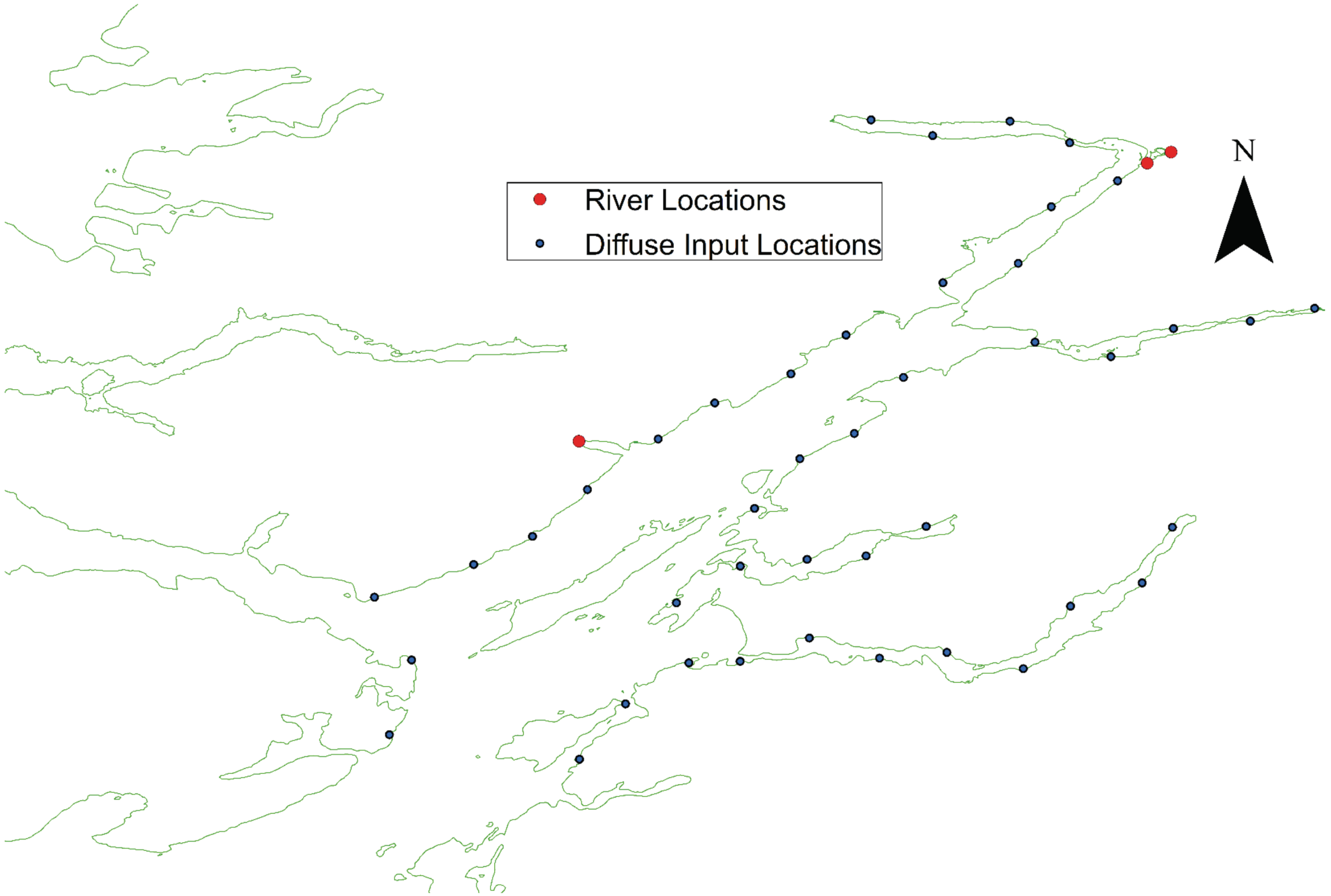
Salinity & Temperature at BODC location 18




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements October 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-2h | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and six month run with vertical profile CTD measurements October 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-3 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Locations of rivers (Red) and diffuse inputs (blue) used in the 1991 model runs | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

## 4.2 1991 Simulations

### 4.2.1 Input Data

The data sources for 1991 vary from those used in 2011. The water level, current, temperature and salinity data came from the POLCOMS 12km model provided by NOC-L. No met data was available from the AMM model so all parameters apart from wind data (wind speed and directions) were taken from the ECMWF interim datasets, i.e. shortwave and long wave downwards solar radiation, precipitation and evaporation (accumulated totals at 12 hourly time steps) and air temperature, sea level pressure (instantaneous at 6 hourly time steps). Relative humidity was calculated from air temperature and dew-point temperature. Wind data was available from the met office model at hourly intervals on a 50km grid. The data set was not complete and gaps were filled using the ECMWF interim dataset interpolated to hourly time steps from 6 hourly data. The wind file was put through the Matlab script developed in the calibration runs to take into account the topographic steering of the wind in Loch Linnhe. Finally the G2G river data was not available for 1991, instead data was provided by Marine Scotland for three rivers in Upper Loch Linnhe, River Nevis, River Lochy and Loch A'Choire. Diffuse inputs from the other catchments not included in the rivers was also provided and input into the model as a number of point source inputs as shown in Figure 4-3. River temperature derived from measured air temperature at Oban was also available from Marine Scotland, temperatures were applied to the rivers using a 7 day moving average of the data.

### 4.2.2 Results

An extensive field measurement campaign was carried out by Marine Scotland in Loch Linnhe during 1991. The data has been provided for comparison with model results, the comparisons are presented below.

#### 4.2.2.1 Water Levels

Tide gauge data from BODC at Tobermory and pressure gauge data at two points in Loch Linnhe from Marine Scotland are available. The depth of the pressure gauges within the files from Marine Scotland are not correct, following discussion it was thought that due to the steep slope on which these recorders were deployed the depth of the sounding may not match the depth of deployment. Therefore the MS data has been manually adjusted to match the modelled water levels. Figure 4-4a shows the location of the measurements while Figure 4-4b-g shows the water level comparison at those locations for May and

October. The RMS error and bias at Tobermory for the 6 month simulation was as 0.24m and 0.16m respectively.

#### 4.2.2.2 Currents

Current measurements are available at three locations (Figure 4-5a) and a range of depths. The current speed and direction comparisons at location 1 during October, location 2 during July and location 4 during September are shown in Figure 4-5b-d respectively. At all locations the modelled current speeds are the same order of magnitude as the measured data. At times the size and shape of the peaks in current speed and the changes in flow directions are well replicated in the modelled data at location 1 and 2, particularly the mid and deep water comparisons. At MS current data location 4 in upper Loch Linnhe, where complex mixing occurs the comparison is not as strong, however the order of magnitude is the same.

#### 4.2.2.3 Temperature and Salinity

Two thermistor chains were deployed by Marine Scotland one in the upper loch at and one in the lower loch (Figure 4-6a). Figure 4-6b and c show the temperature comparison at 1m, 31m and 61m at thermistor location 1 and 2 respectively for the entire model run. From May to September the model temperature is slightly higher than that measured at both locations and at all levels. This difference in temperature is more pronounced at MS thermistor location 2, located in the Upper Loch. From May to September the temperature of the model and the measurements increases, the model temperature increases at a slightly higher rate. From September the measured temperature either becomes constant or starts to decrease, at the same time the model temperature begins to decrease but, again, at a higher rate.

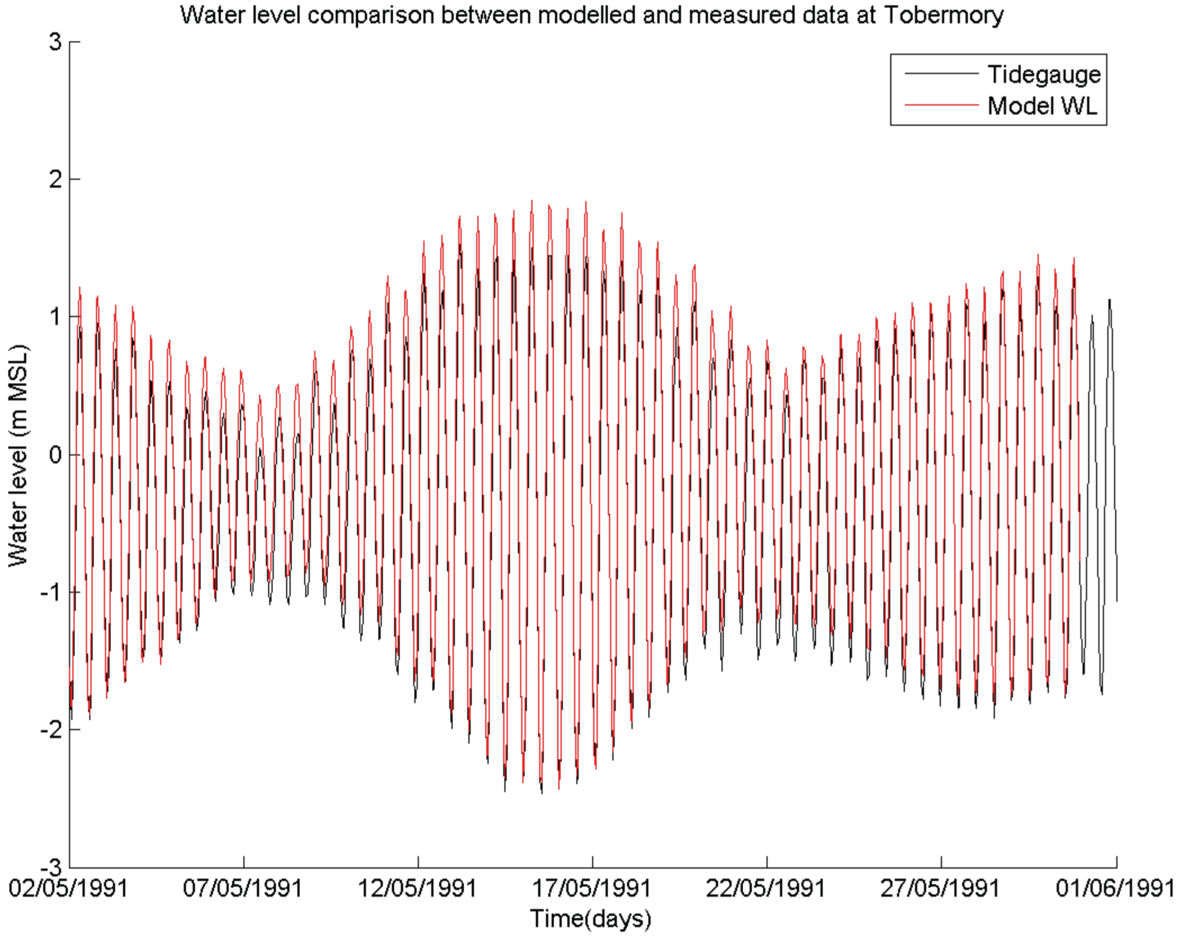
A number of CTD dips were also made during 1991, comparisons of a selection of the CTD dips from three zones (Figure 4-7a), are presented in Figure 4-7b-j. the variations in temperature seen in the thermistor data are replicated in the CTD data, with the temperature of the model being higher in May (approximately 1°C) and that temperature difference increasing towards September (approximately 2°C), then dropping to levels lower than the measured in October (approximately 1.5°C).

The salinity comparisons are very good, less than 1psu, up to October even replicating some of the stratification seen in the measure data. In October the difference increased to around 2psu in some locations, this may be due to the increase in river input during this time.

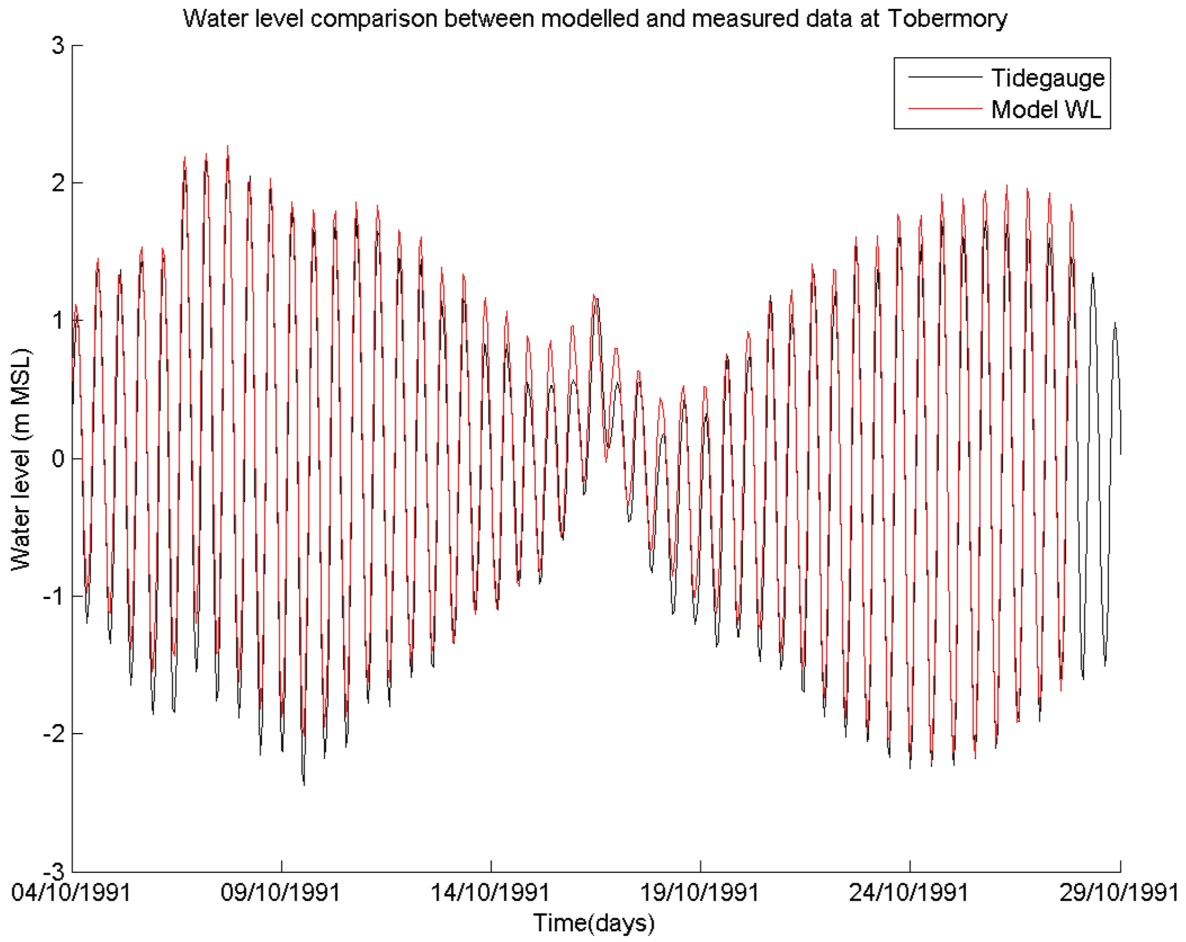
### 4.2.3 Summary

Overall the 1991 model runs replicate the water levels, currents and salinity in the WLLS well. The temperature comparisons were not as good, with the model heating up and cooling down at a higher rate than seen in the measured data.

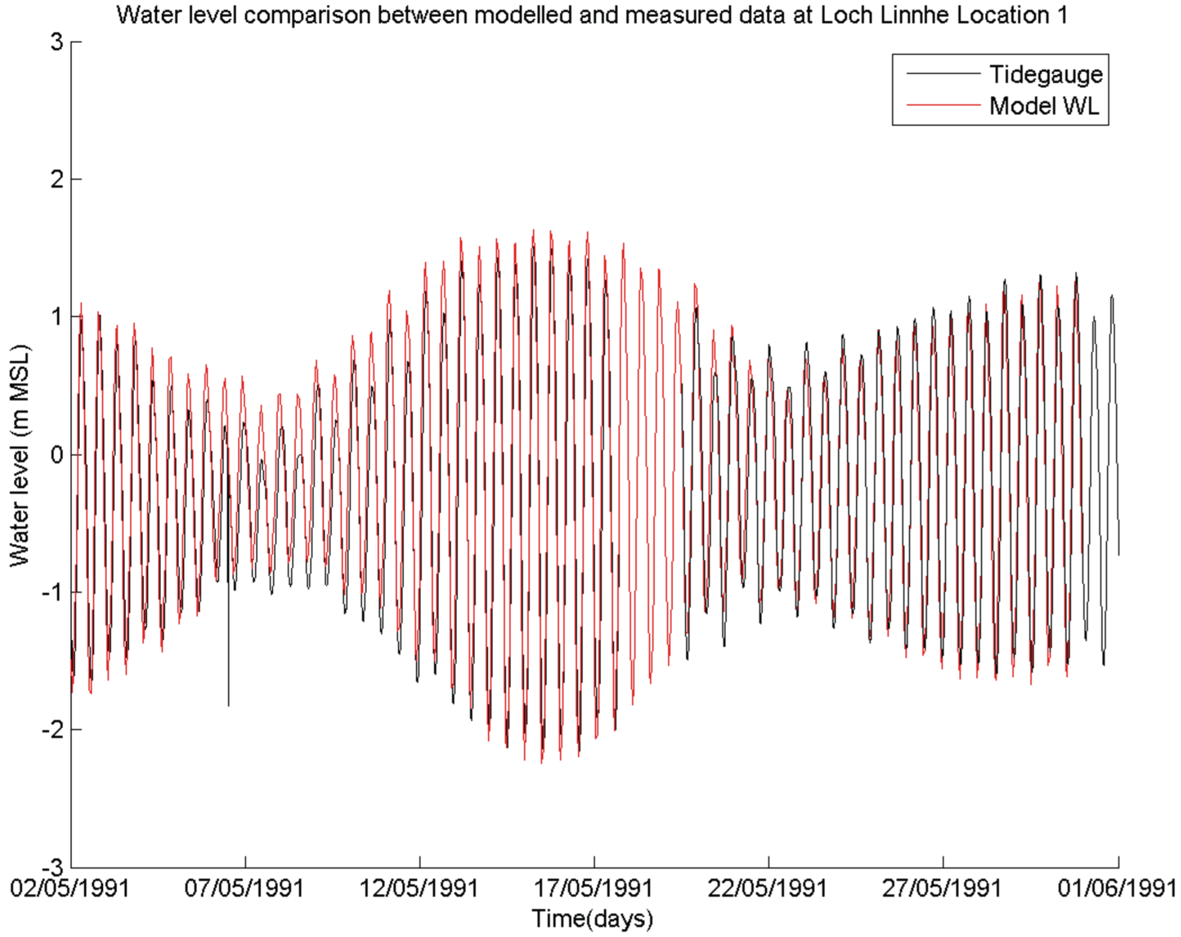

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of water level measurements for 1991 model comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



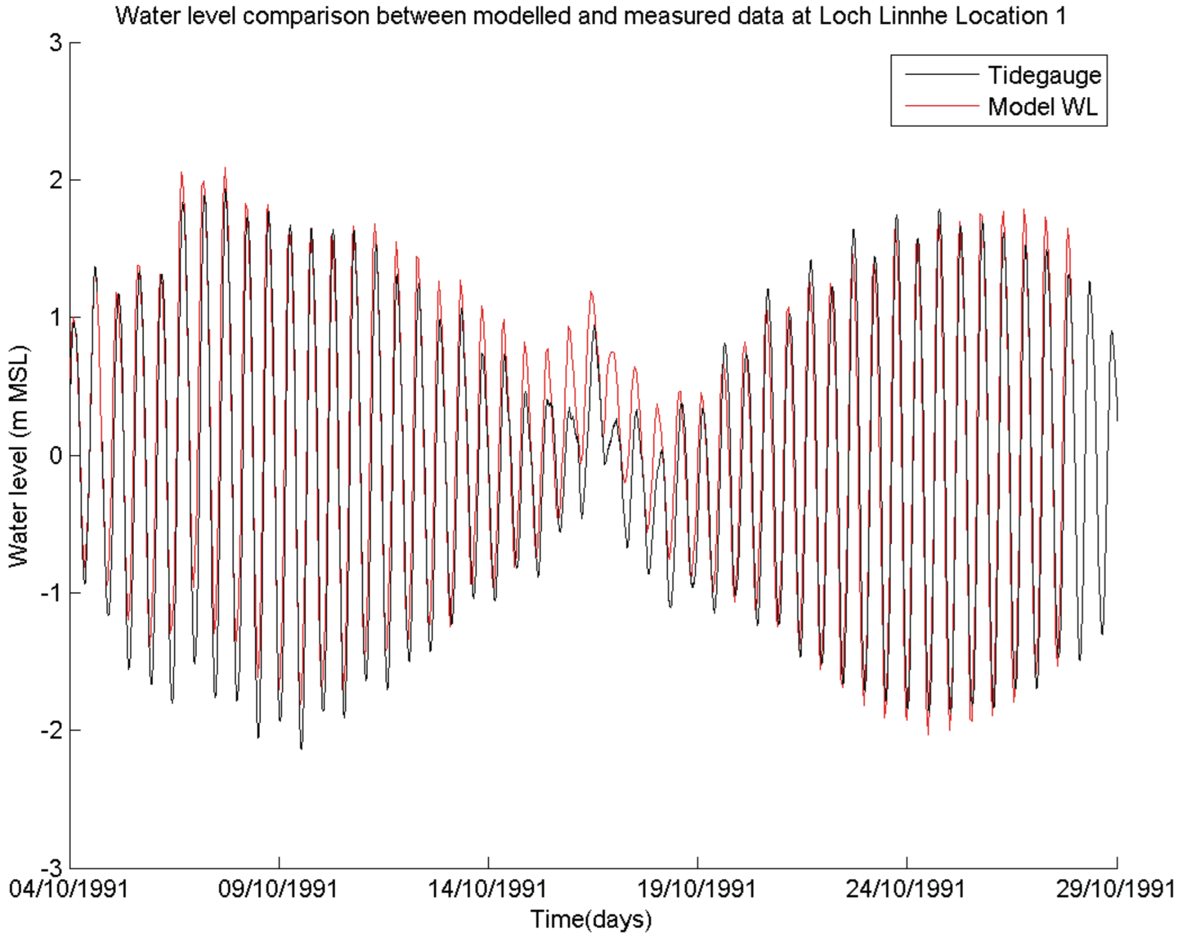

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Tobermory for May 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



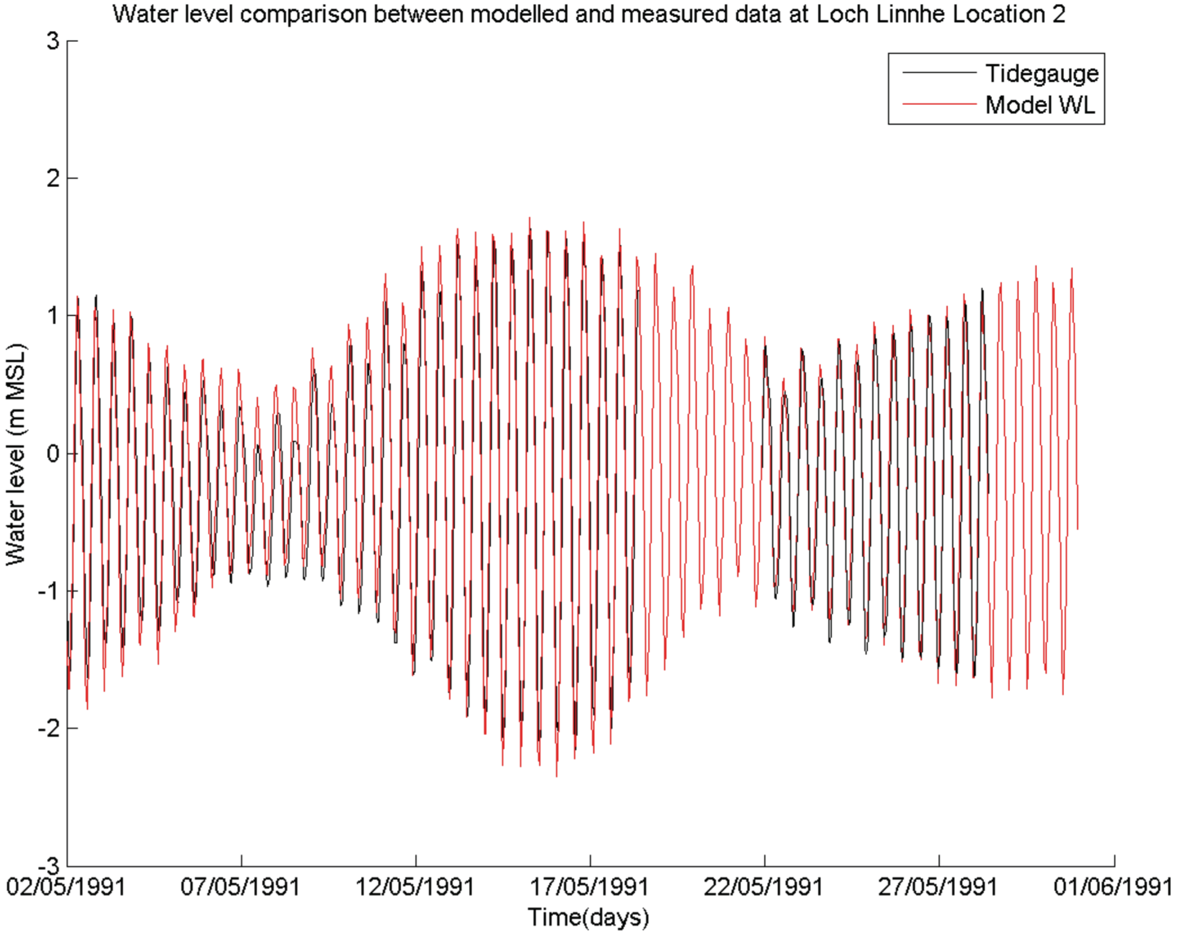

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Tobermory for October 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



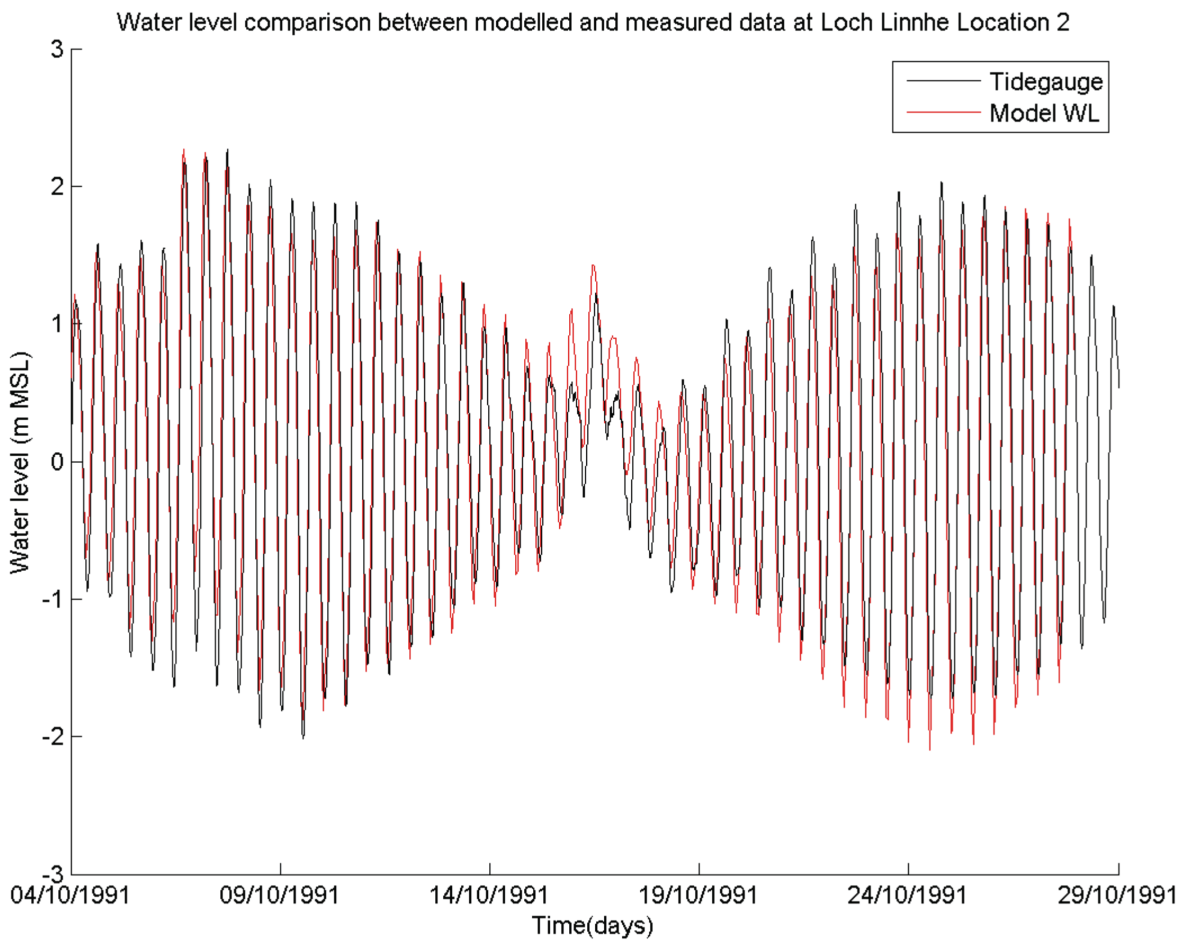

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Loch Linnhe Location 1 for May 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



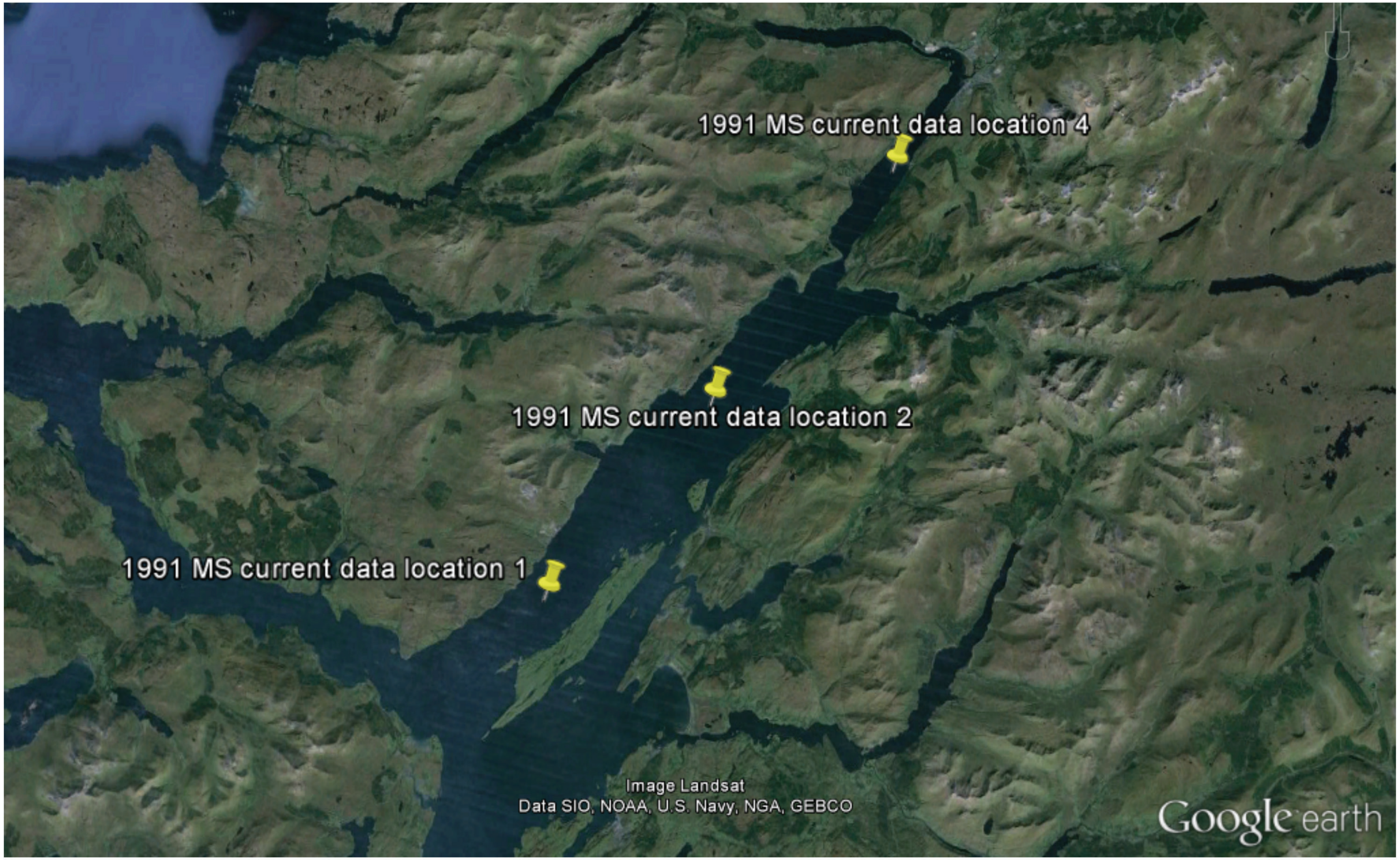

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Water level comparison at Loch Linnhe Location 1 for October 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



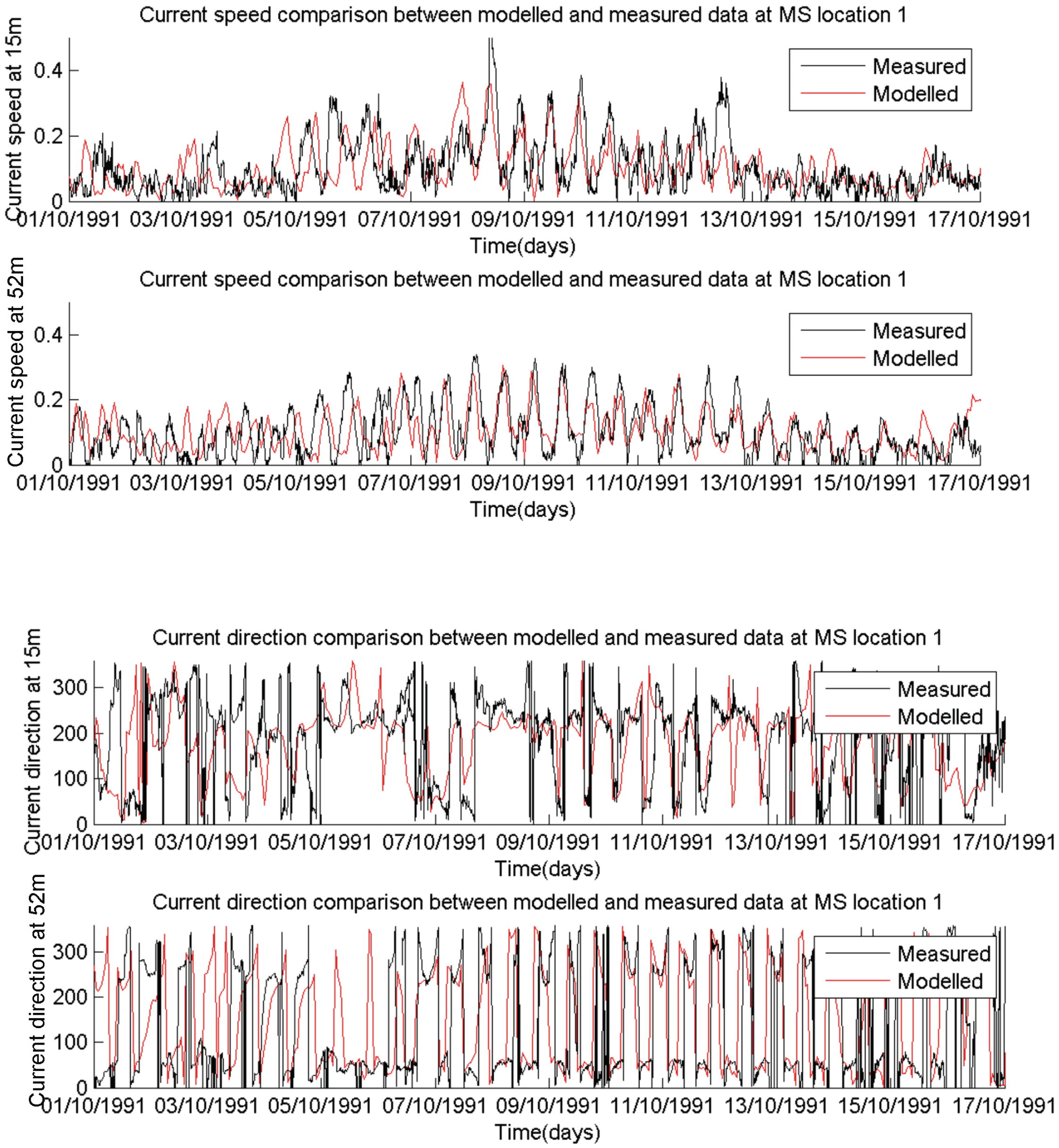

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Water level comparison at Loch Linnhe Location 2 for May 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



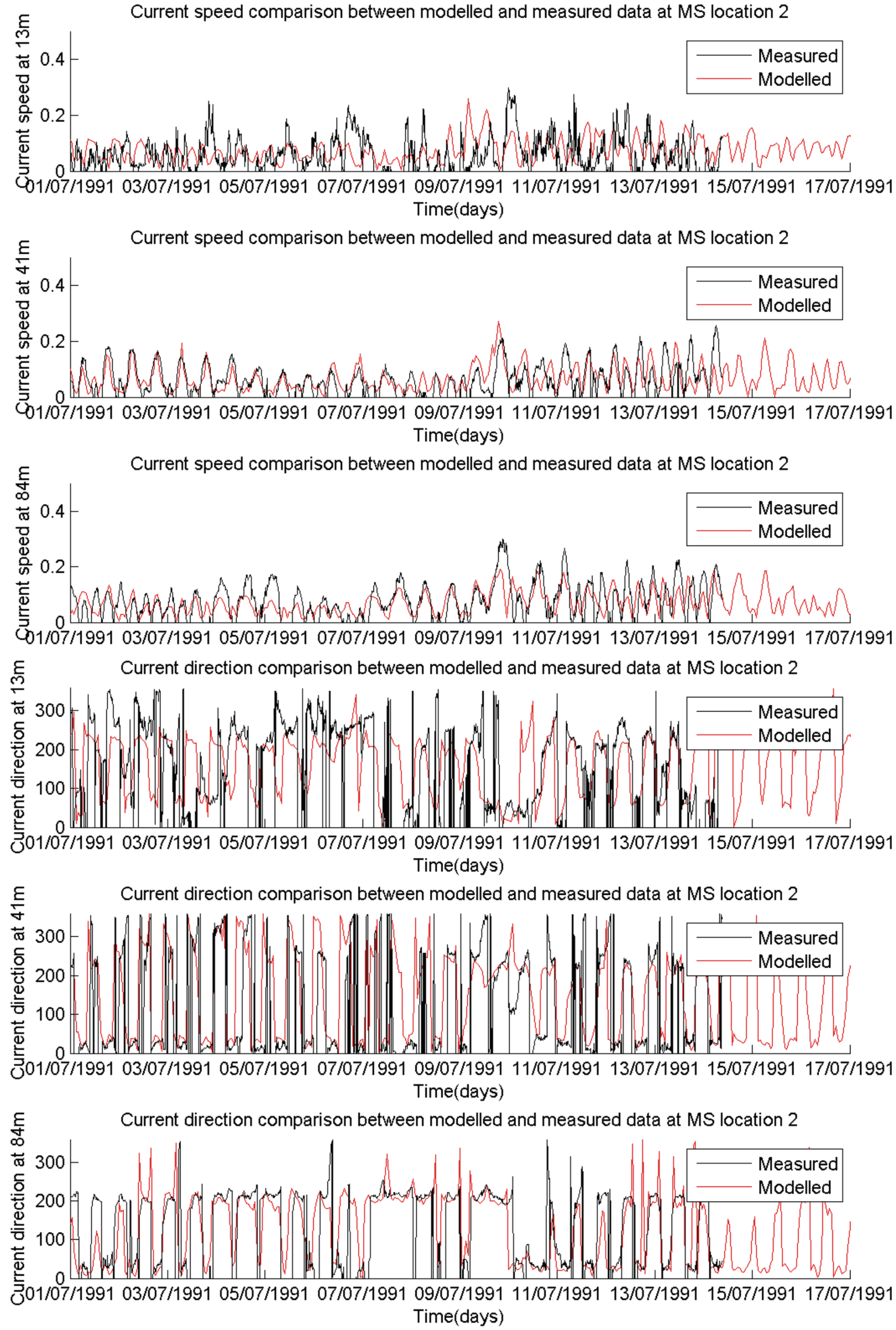

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-4g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Water level comparison at Loch Linnhe Location 2 for October 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



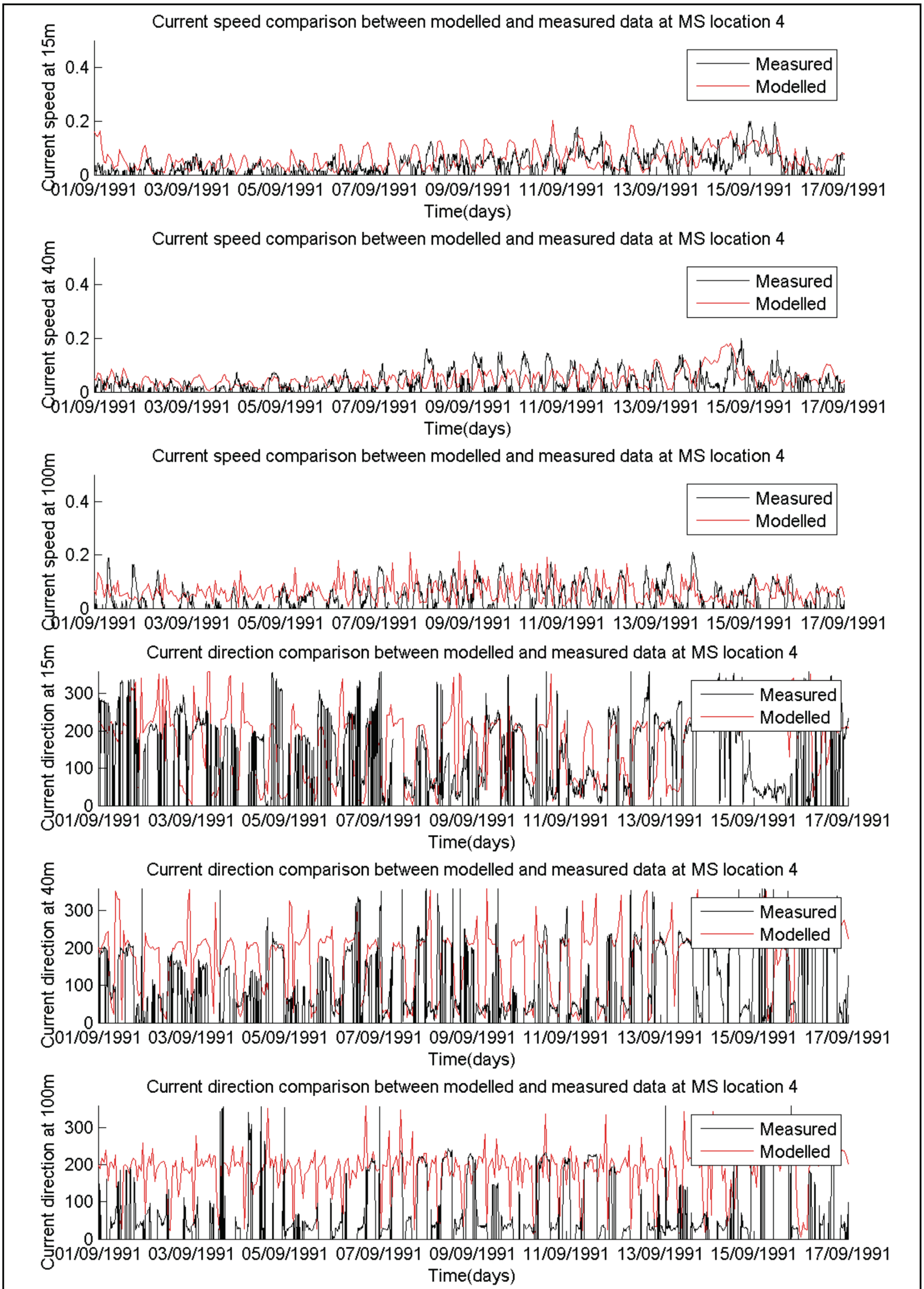

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-5a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of current measurements for 1991 model comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



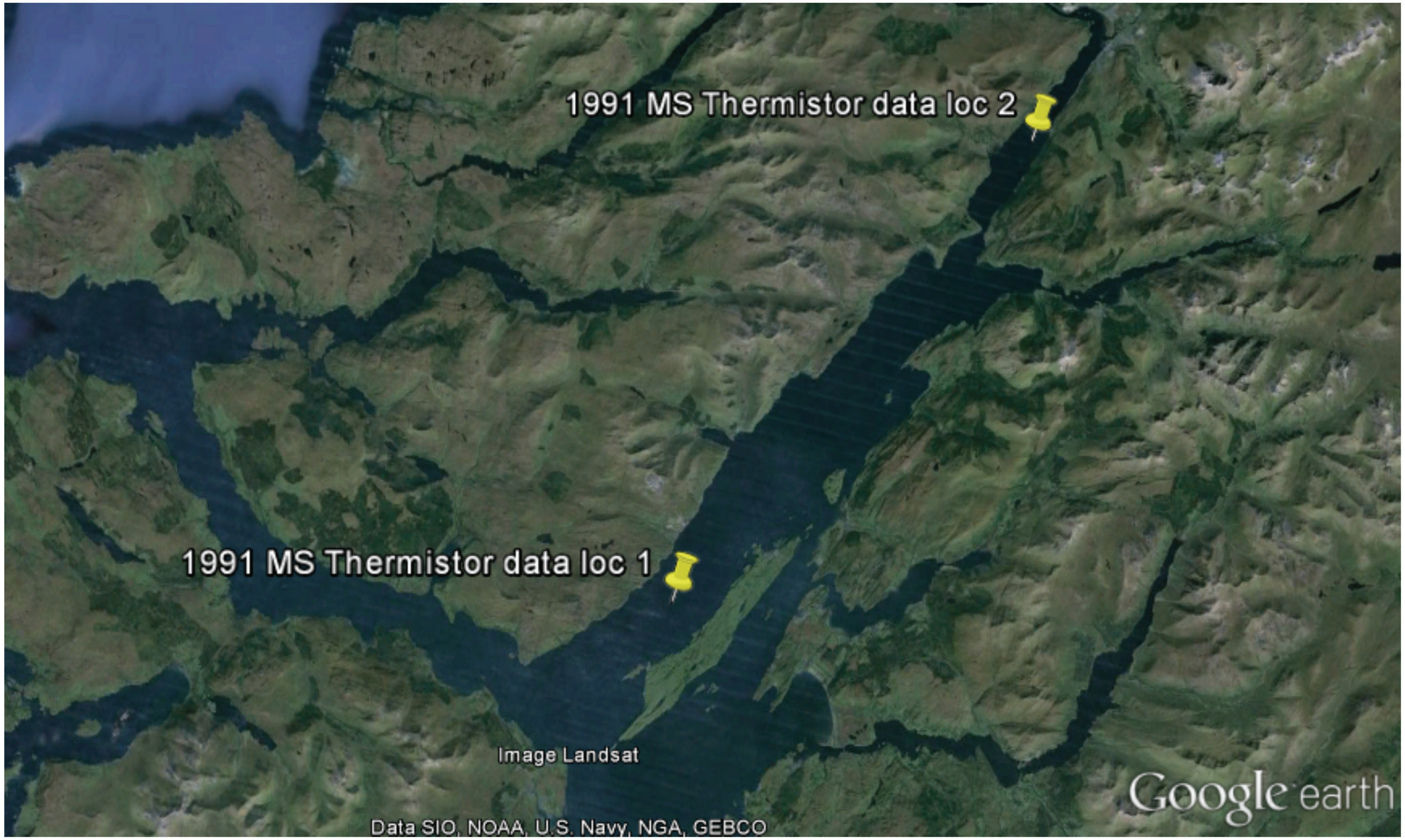

| Client | Consulting Engineer | Project: | **Figure** 4-5b |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Current comparisons at Location 1 during October 1991 |



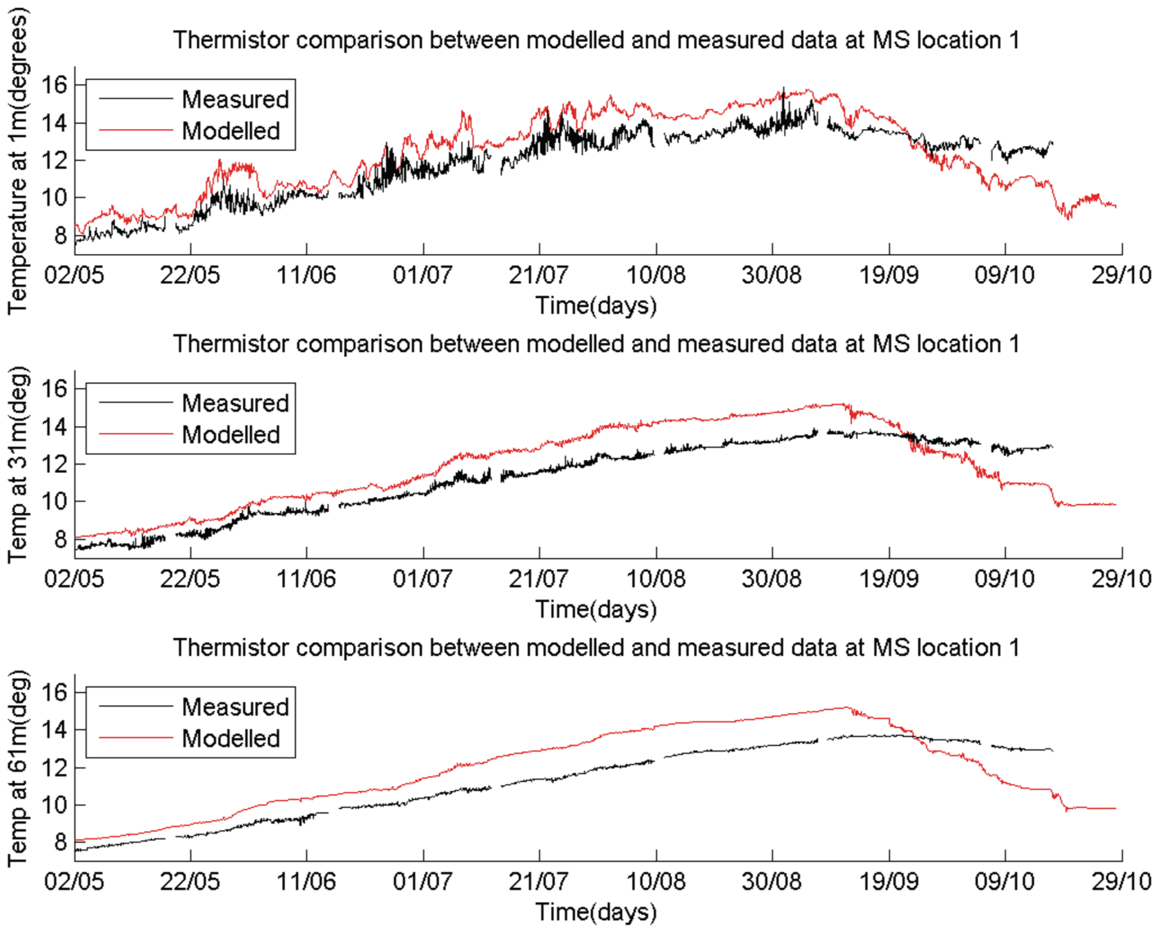

| Client | Consulting Engineer | Project: | **Figure 4-5c** |
|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Current comparisons at Location 2 during July 1991 |



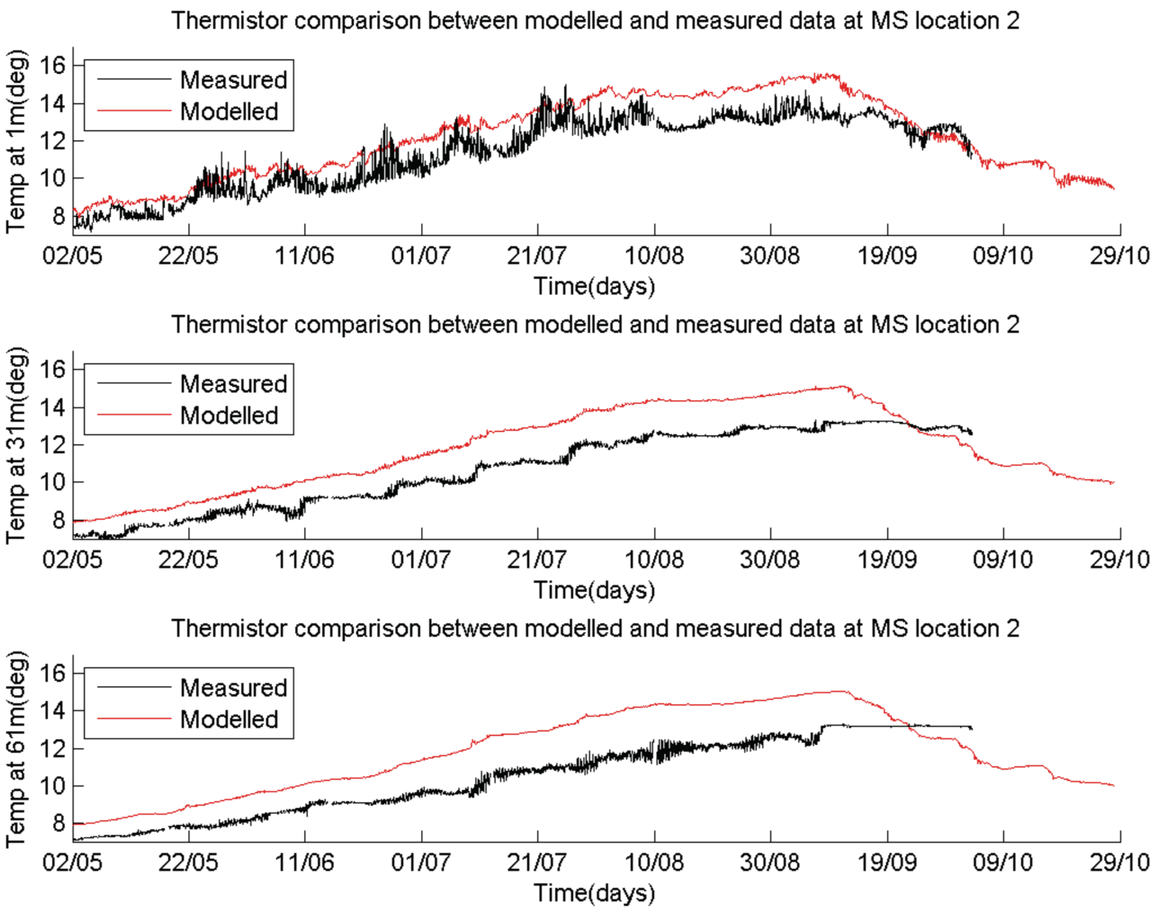

| Client | Consulting Engineer | Project: | **Figure 4-5d** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Current comparisons at Location 4 during September 1991 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-6a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of thermistor measurements for 1991 model comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

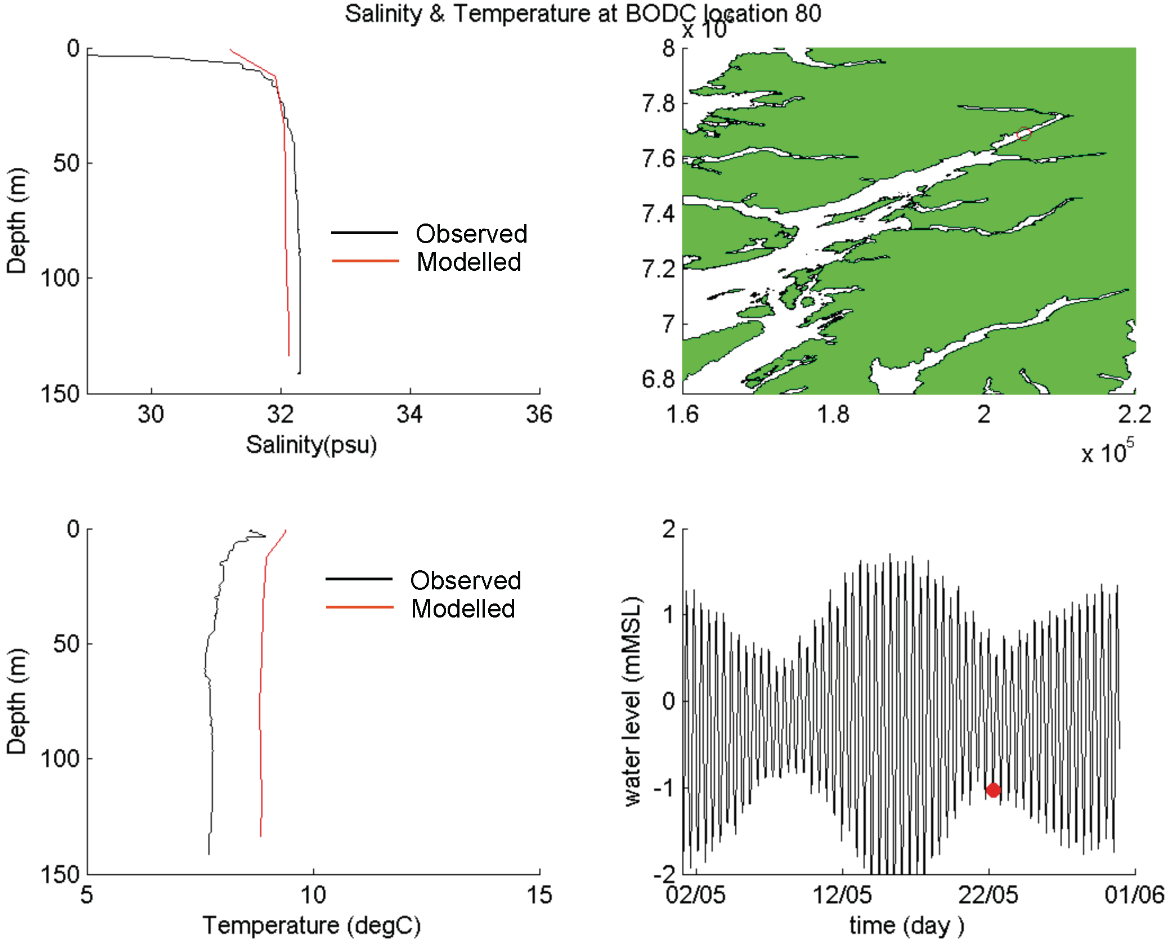



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-6b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Temperature comparison at MS thermistor location 1 from May to October 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

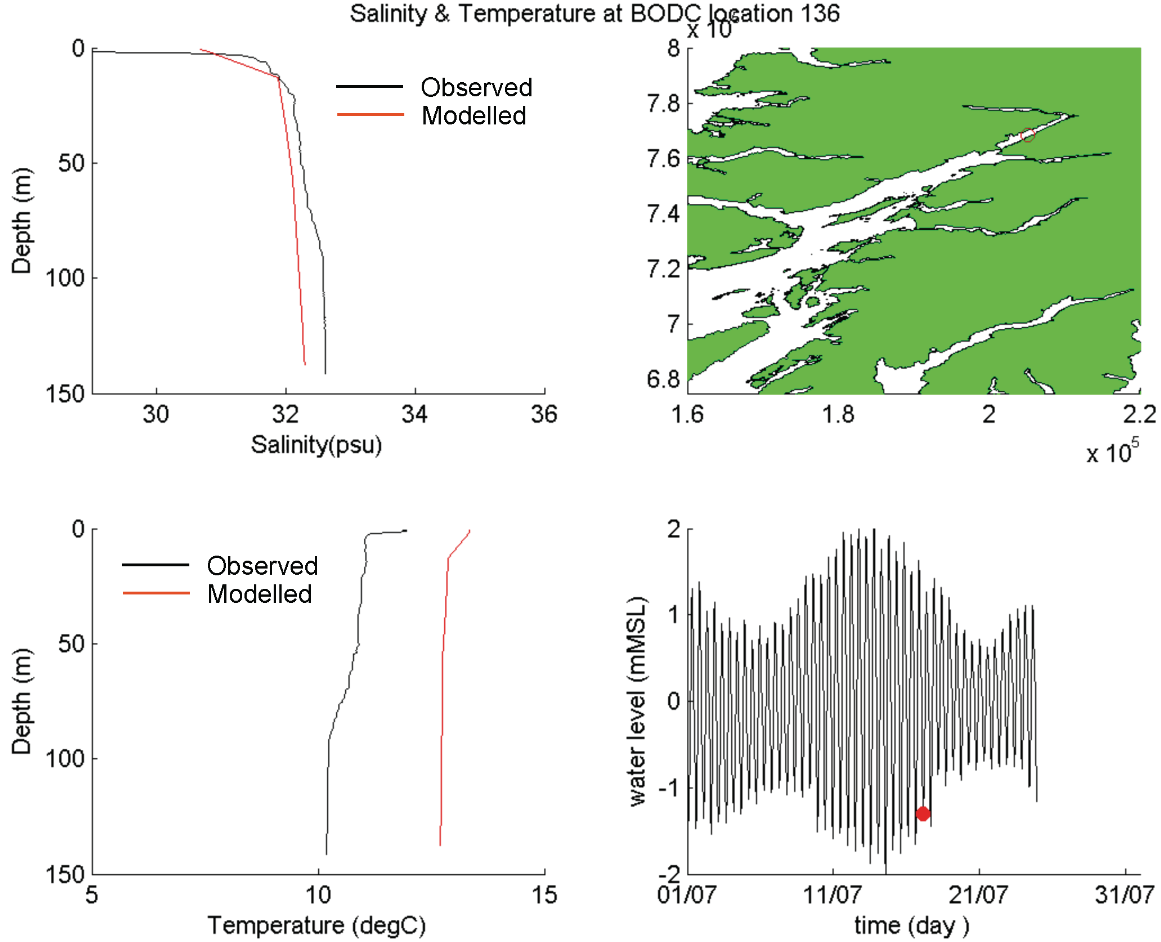



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-6c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Temperature comparison at MS thermistor location 2 from May to October 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |


| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of CTD measurements for 1991 model comparison | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements May 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements July 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
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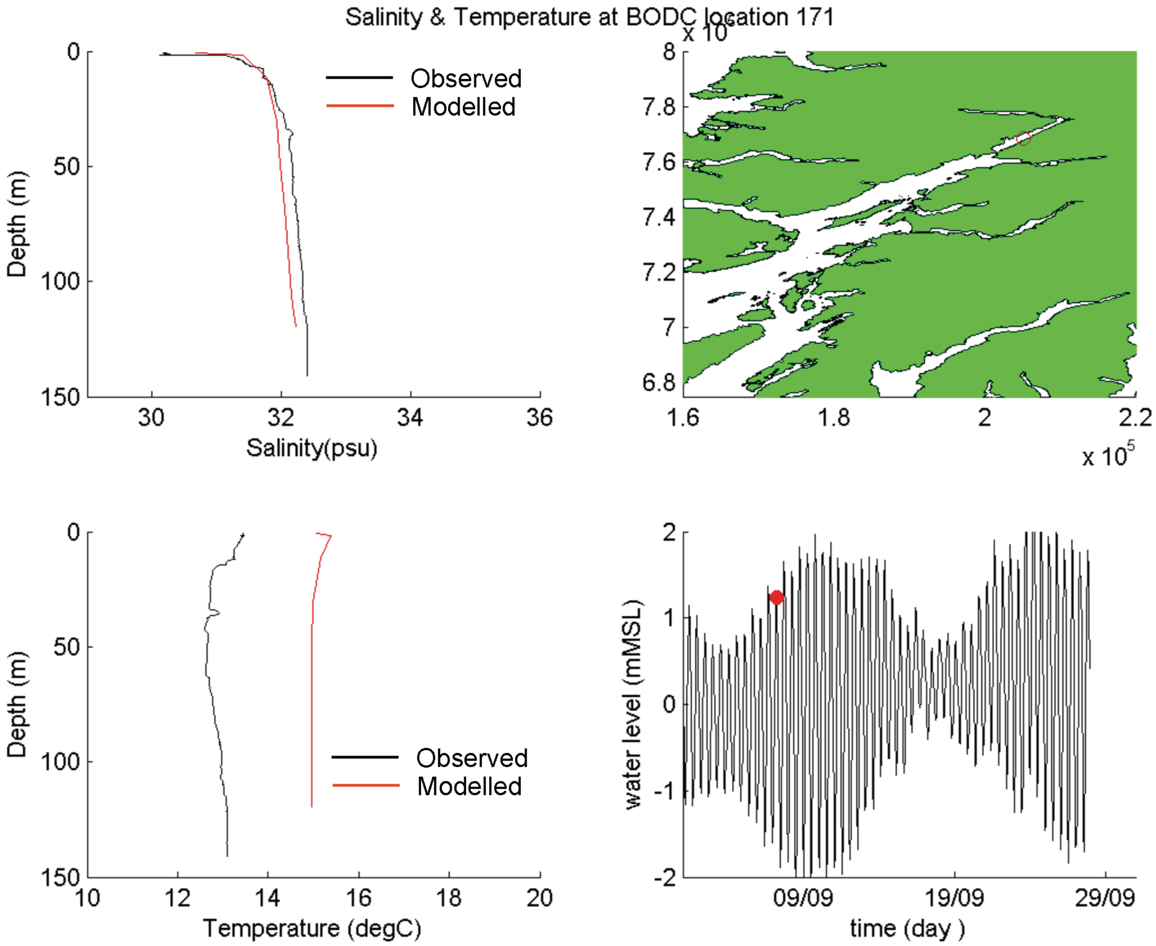


| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7d | | |
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| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements September 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
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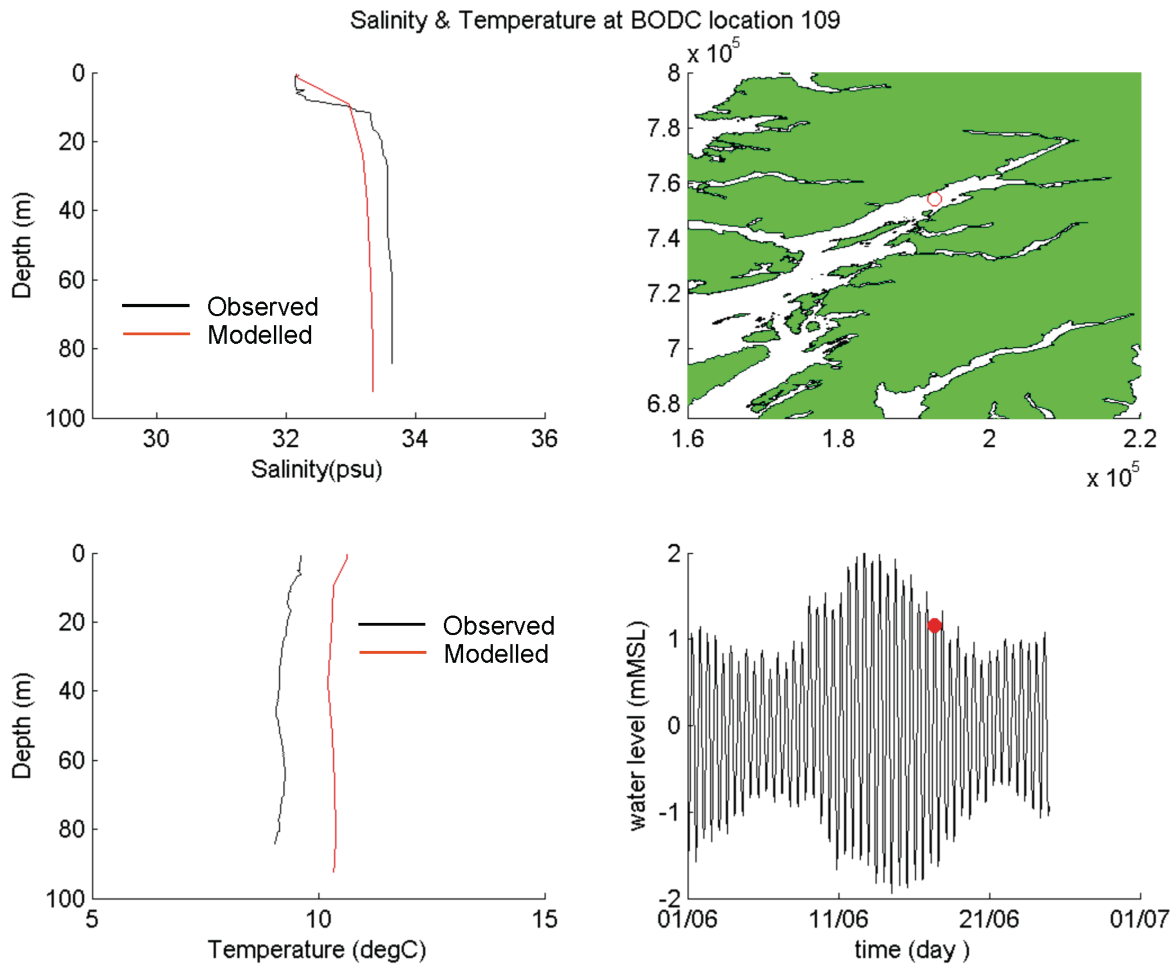
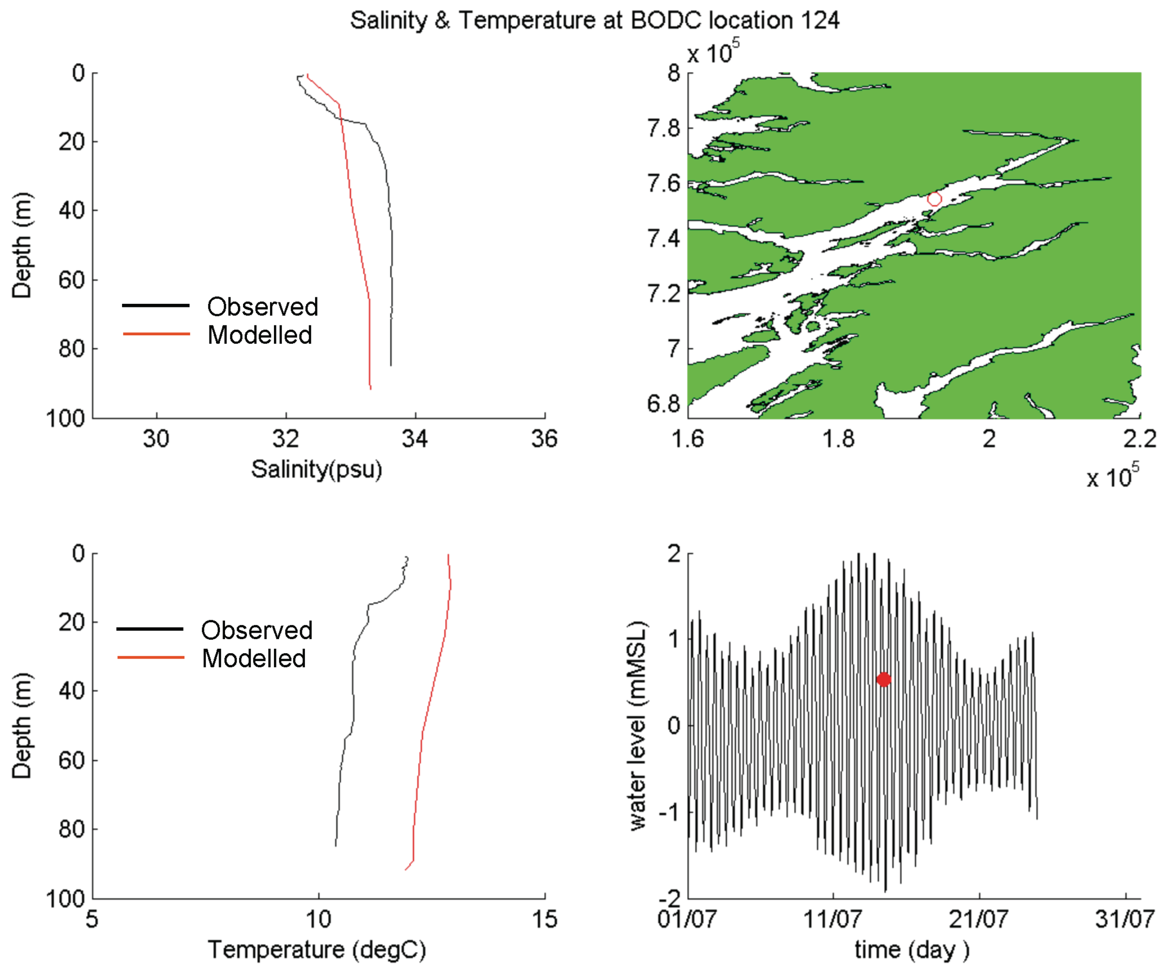
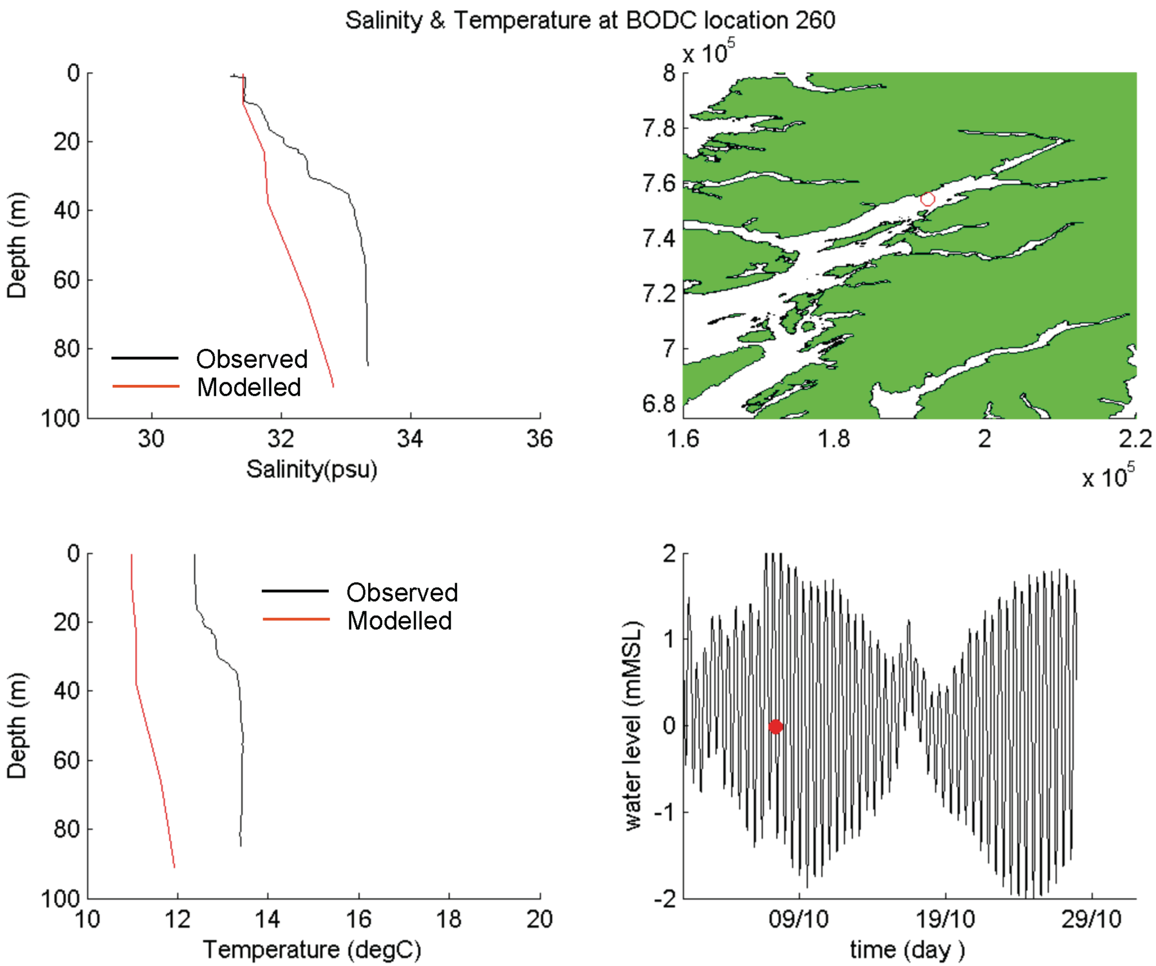



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements June 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7f | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements July 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7g | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements October 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
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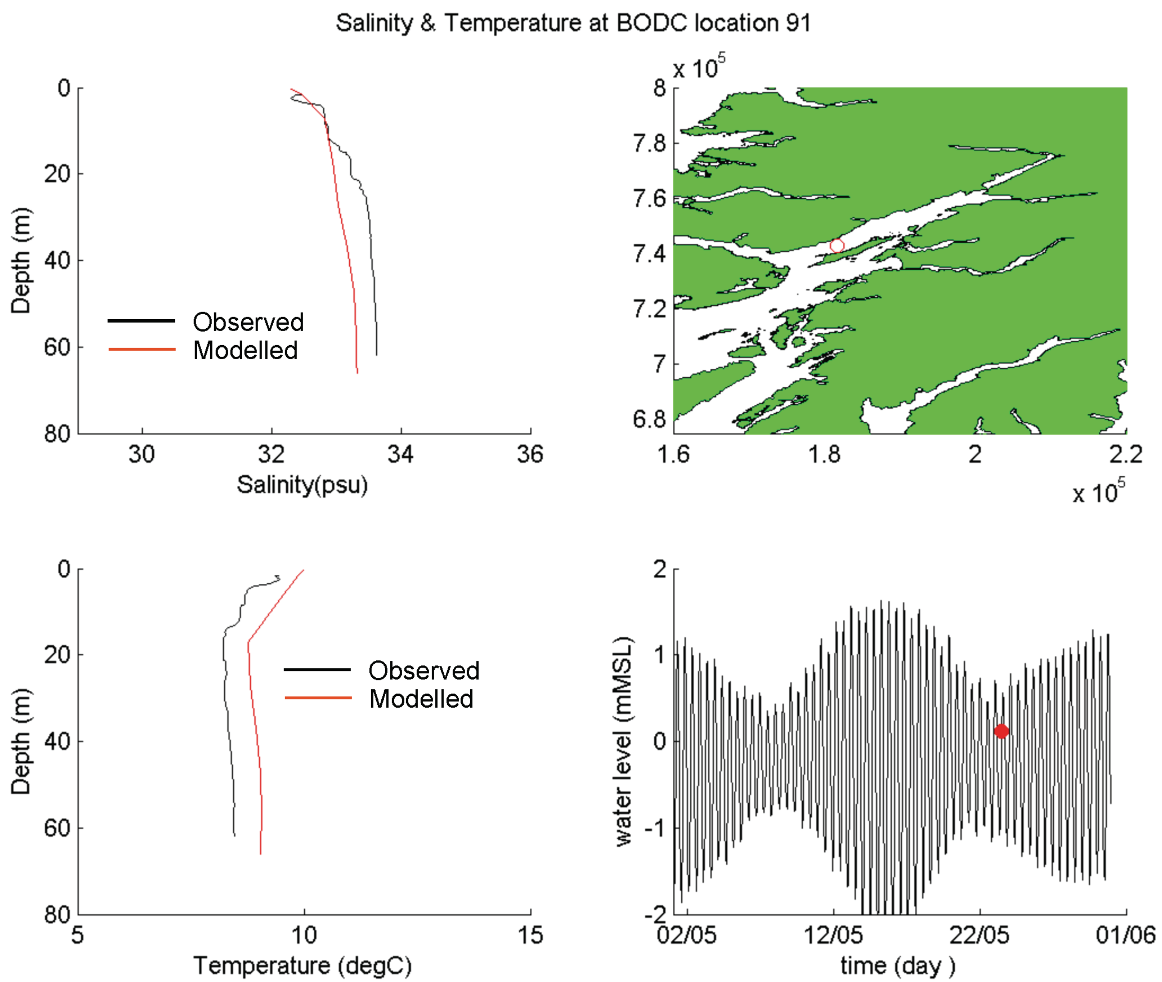


| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7h | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements May 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
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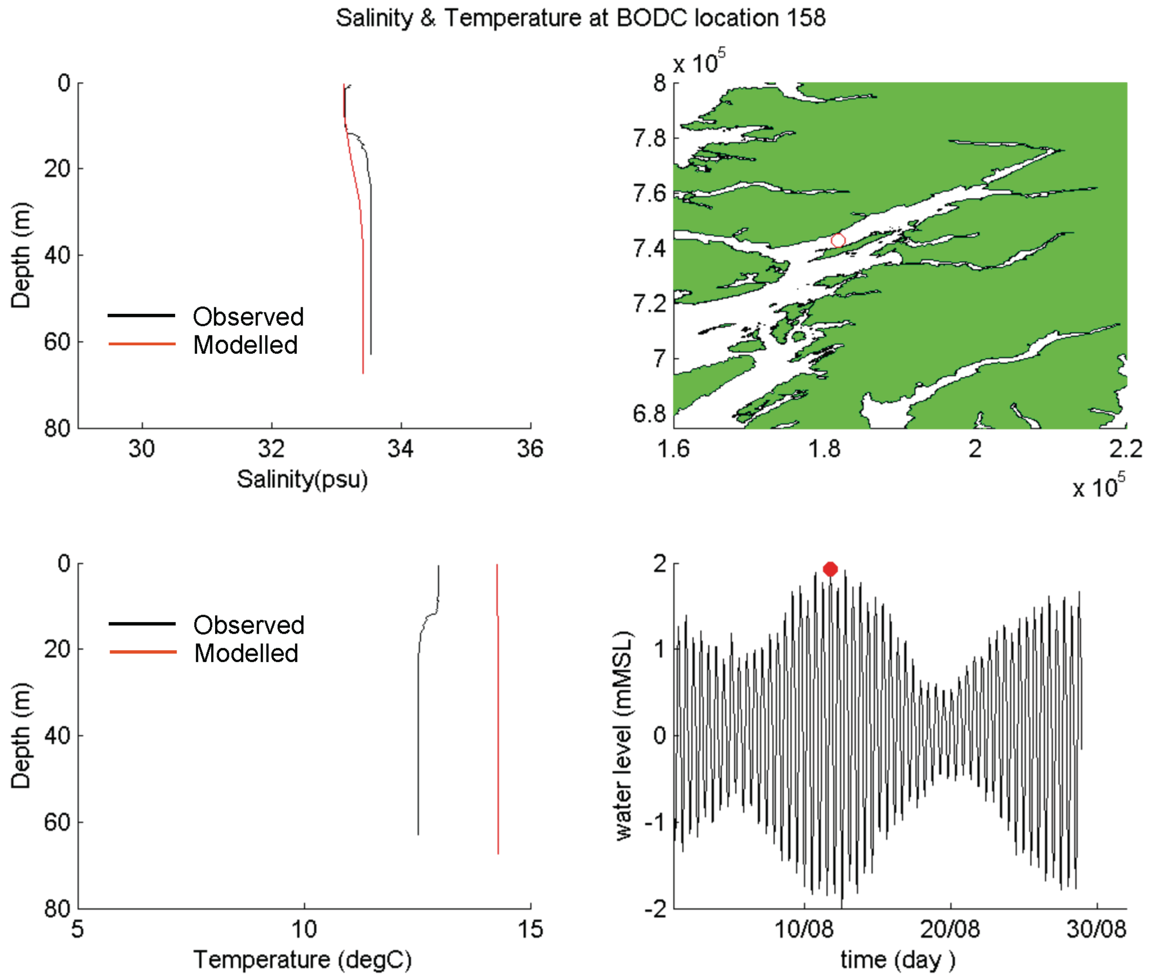
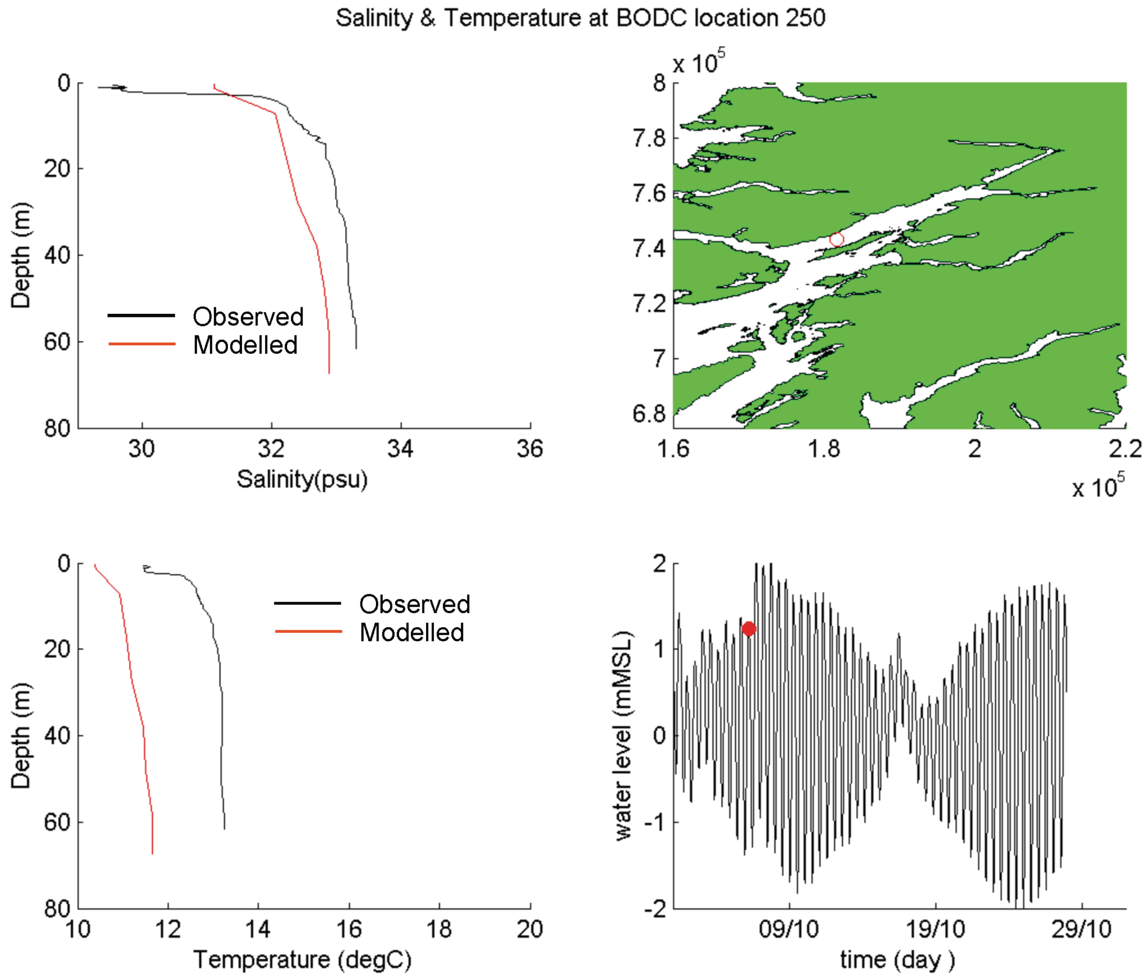



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7i | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements August 1991 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-7j | | |
|---|---|---|---|---|---|---|
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| | | | | Designed | Drawn | Date 14/112012 |

## 4.3 Climatology simulations

### 4.3.1 Introduction

This section of the report describes the climatology runs of the flow model for the Wider Loch Linnhe System (WLLS). The model set up used has been described in the calibration section. The requirement was to produce a one year climatology run, from January to December, based on climatological forcing, representing a typical annual climate. The simulation was carried out using the Scottish Shelf model climatology results as initial conditions as well as for boundary conditions. The input data sets for climatological meteorological forcing and climatological river fluxes used in the Scottish Shelf model were also used for the WLLS model. For a full description of the input data, the sources and how it was processed for climatology runs see the Scottish Shelf Modelling report (Wolf et al. 2015)

The results from the climatology run will be used for particle tracking and to develop connectivity indices. The results have been compared with climatological atlas information for temperature, salinity and currents. The neap and spring tidal ranges and peak flows are also compared with the ABPmer tidal atlas.

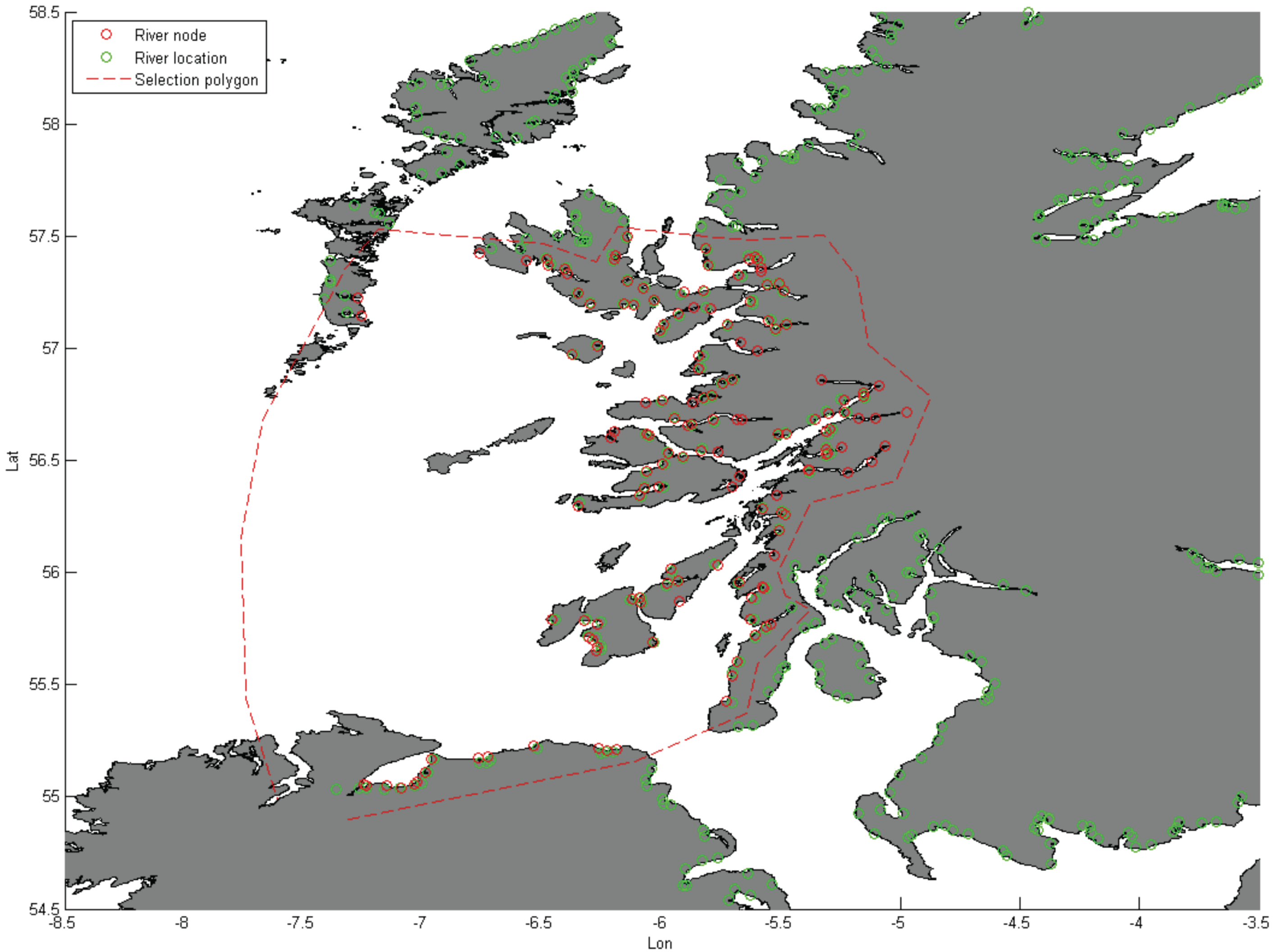
### 4.3.2 Climatology Input Data

#### 4.3.2.1 Boundary conditions

Boundary forcing for water levels (mean yearly tides), currents, temperature and salinity were taken from the Scottish Shelf model climatology results. Hourly results were interpolated on to the nested boundary nodes and elements using a Matlab script. Because the Scottish Shelf model was run with 20 layers whilst the WLLS model has been run with 10 variable layers it was also necessary to interpolate the current components, temperature and salinity from 20 even layers to 10 variable thickness layers. This was also carried out in the Matlab script.

#### 4.3.2.2 River input

River climatology data was processed by NOC-L from two sources: (i) a reconstructed river climatology derived by reference to the E-HYPE model (126 Scottish rivers, 1980-2012 provided by the Swedish Meteorological and Hydrological Institute, SMHI), distributed across the 508 G2G river discharge locations for the Scottish mainland, as originally provided by CEH for March 2007 – Sep 2010 (see below) (ii) G2G river climatology (1962-2011, 577 rivers) provided by CEH in August 2014 and updated in October 2014. For full details of how the river data was reconstructed to give climatological daily averages, see the Scottish Shelf Modelling Report (Wolf et al. 2015). Only 151 of these rivers fall within the WLLS model domain. The rivers were processed in the same way as those for the baroclinic calibration model runs. Figure 4-8 shows the location of the rivers and the location of the nodes the rivers were applied at.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-8 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Locations of rivers (Green) and the node locations at which the river flows were applied at (red) used in the Climatology runs | Checked DMP | Scale Not to scale | Rev. 0 |
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#### 4.3.2.3 Meteorological forcing

Met forcing data for the climatology simulations were interpolated on to the WLLS mesh from the Scottish Shelf model met forcing input files at 6 hourly intervals. The met forcing was derived by the NOC-L from ECMWF (ERA-40 and ERA-Interim, licence granted). The ERA-interim data cover 1989 – present, and ERA-40 data cover 1957 to 2002. These data were processed to derive monthly mean wind-stress, pressures, heating and “evaporation minus precipitation” for the period 1981-2010, to match the boundary forcing period.

The met forcing were derived as monthly means, which were specified at the middle of the month i.e. mean February data were applied at the middle of February; then mean March data were applied mid-March etc. The data are then linearly interpolated to 6-hourly smoothed forcing data for each grid-point in the FVCOM model. For full details see the Scottish Shelf Modelling report (Wolf et al. 2015).

### 4.3.3 Validation

#### 4.3.3.1 Temperature and Salinity Comparisons

Average monthly sea surface temperature (SST) and sea surface salinity (SSS) observations are available from two sources:

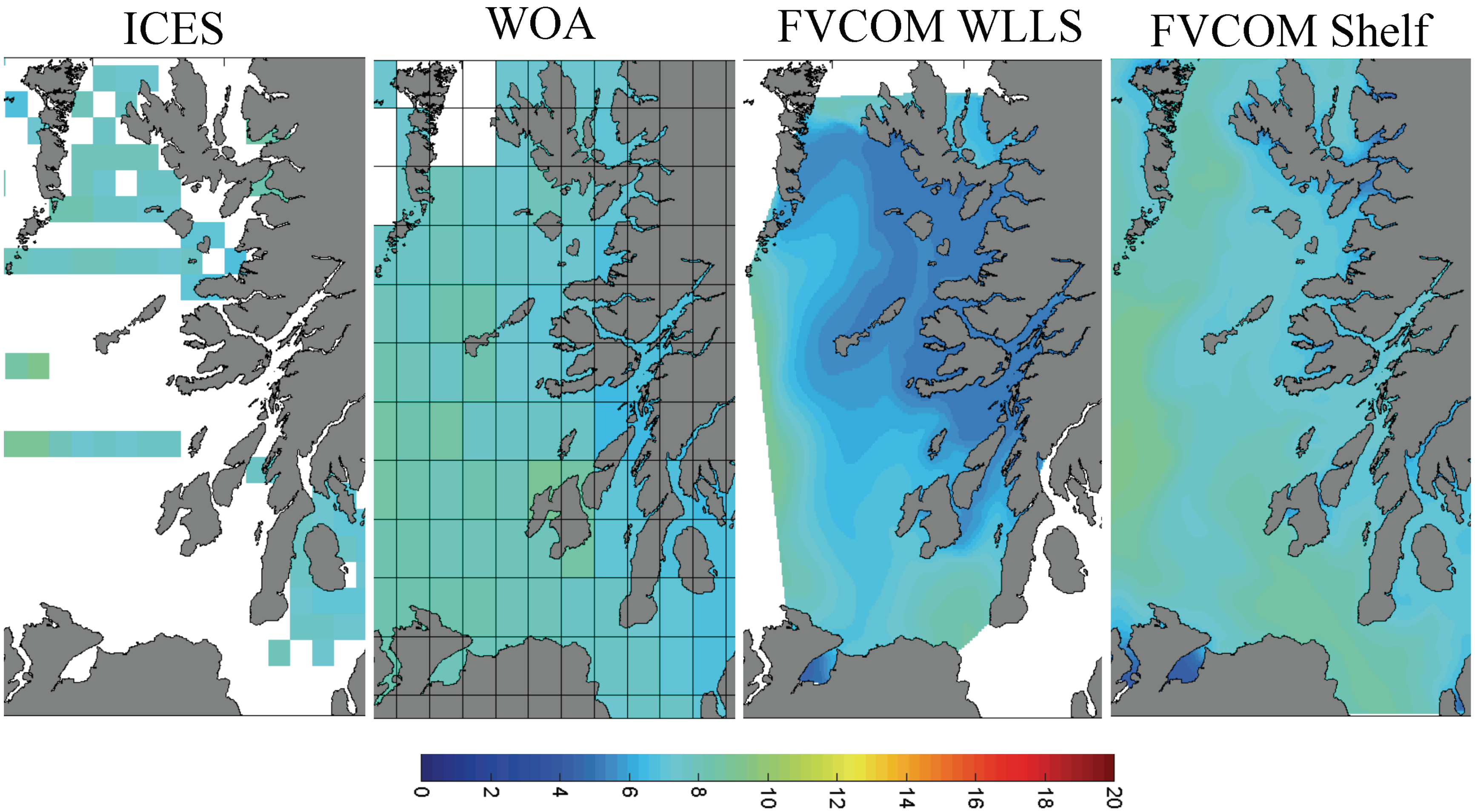
1) The ICES (International Council of the Exploration of the Sea) dataset (http://www.ices.dk/marine-data/data-portals/Pages/ocean.aspx) gridded and averaged for 1960-2004 (45 years) by Jason Holt (NOC-L). Data are also available from the NOAA/NDBC World Ocean Atlas (2013);

2) The WOA (World Ocean Atlas) http://www.nodc.noaa.gov/OC5/woa13/) based on over 100 years of observations interpolated on to a 0.25° resolution grid.

These datasets are used for qualitative comparison with the WLLS FVCOM results for February and August. These months were chosen based on the findings of Berx and Hughes (2009) that the maximum and minimum of the SST occur in February and August.

Figures 4-9a-b shows the comparison of SST for February and August respectively. The SST in the interior of the WLLS model is lower than both the validation data sets (ICES and WOA) and the Scottish Shelf model, by around 2°C. The cause for this difference has been investigated and is thought to be due to a number of factors. Firstly the river temperature in the WLLS model was set to 7°C to be in line with the calibration runs, while the river temperatures in the Scottish Shelf model are set to 10 °C. Table 4-1 shows the quarterly mean river temperature for 15 rivers across Scotland, from Sparks et al., 2006. The annual mean is 9.4°C which is closer to the value used in the Scottish Shelf model, while the average for January to March is 7.2°C which is in line with the value used in the WLLS model. The other factor that may be influencing the temperature of the model is the difference in the spatial resolution of the model both in term of the horizontal mesh and vertical layers.

# Sea Surface Temperature February




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-9a | | |
|---|---|---|---|---|---|---|
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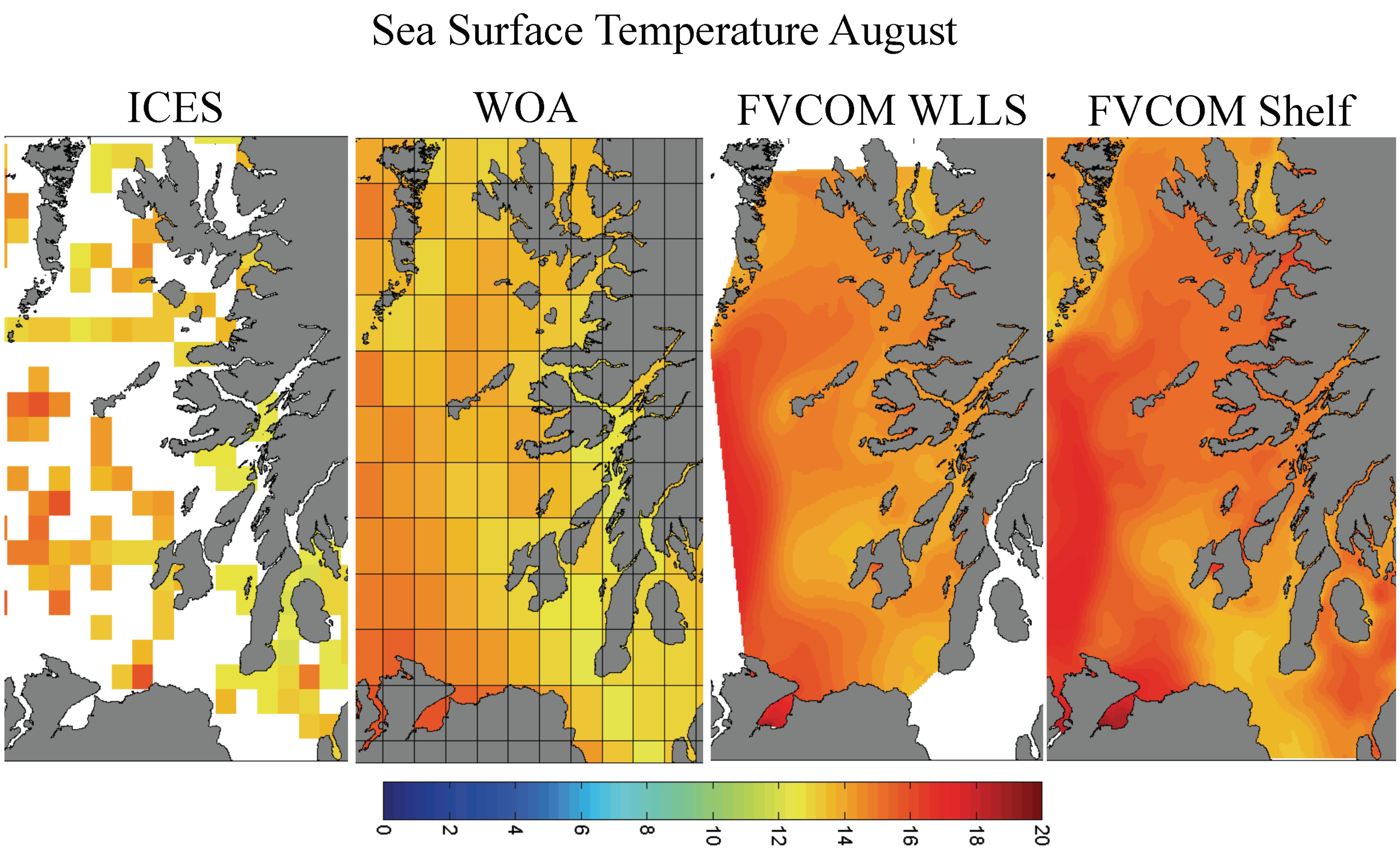


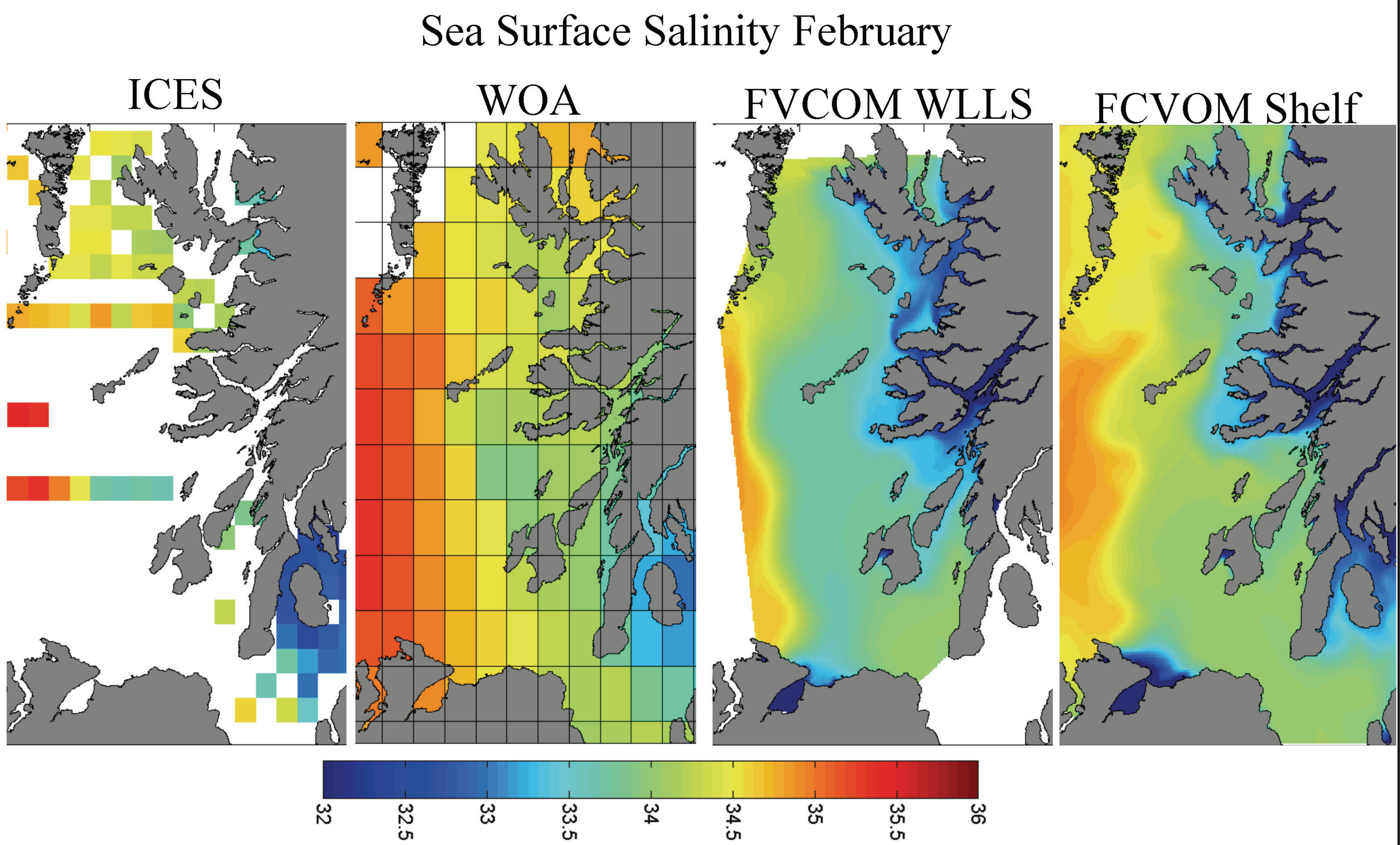

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-9b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

*Table 4-1: Quarterly mean river temperatures (°C) for 15 rivers across Scotland 1975-2003. From Sparks et al., 2006.*

| Quarter | Mean river temperature (°C) |
|---|---|
| Jan/Feb/Mar | 7.2 |
| Apr/May/Jun | 14.8 |
| Jul/Aug/Sep | 11.1 |
| Oct/Nov/Dec | 4.3 |
| Annual mean | 9.4 |

The comparison of SST in August is better than February, the WLLS results are higher than those of the ICES and WOA but are closer to the Scottish Shelf results from which it took its boundary conditions and forcing data. This improvement in the comparison in August when river discharges are low supports the theory that the difference seen in February, when discharge is high, is related to the temperature difference in the rivers.

Figure 4-10a-b shows the SSS comparisons for February and August respectively. In both the WLLS model and Scottish Shelf model the influence of river discharge is seen close to land in February and August, with the area of low salinity surface water reducing from February to August. In February the FVCOM models show lower SSS levels that the WOA data across the model domain. In August the salinity in the FVCOM models is higher in the offshore areas. The ICES coverage in the WLLS area is poor.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-10a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | | Checked DMP | Scale Not to scale | Rev. 0 |
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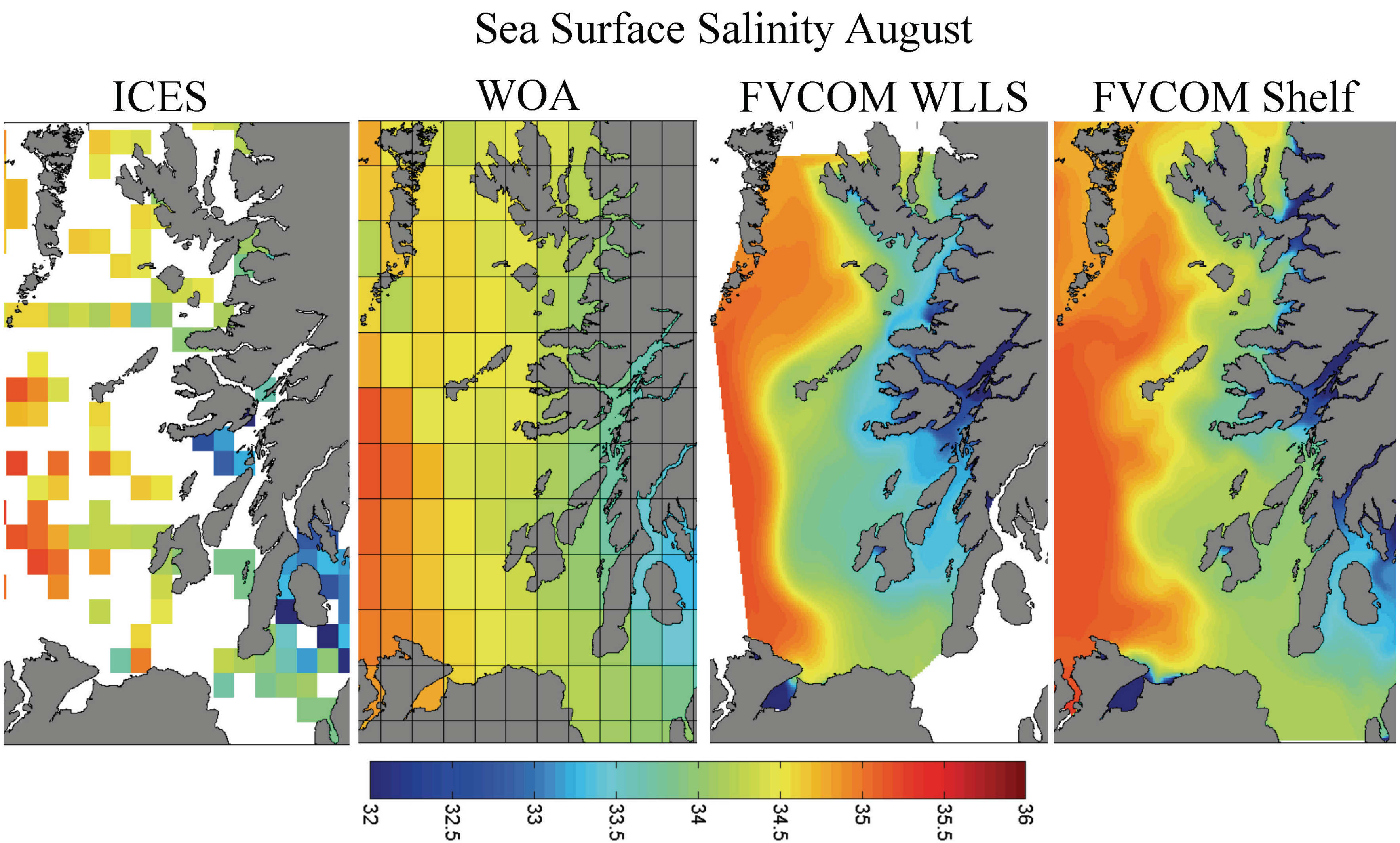


| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-10b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | | Checked DMP | Scale Not to scale | Rev. 0 |
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#### 4.3.3.2 Mean Spring/Neap Tidal Range

Average monthly sea surface temperature (SST) and sea surface salinity (SSS) observations are available from two sources:

Mean spring tidal ranges have been computed directly from the two principal semi-diurnal components $M_2$ and $S_2$ based on the following equations from Pugh (1987):

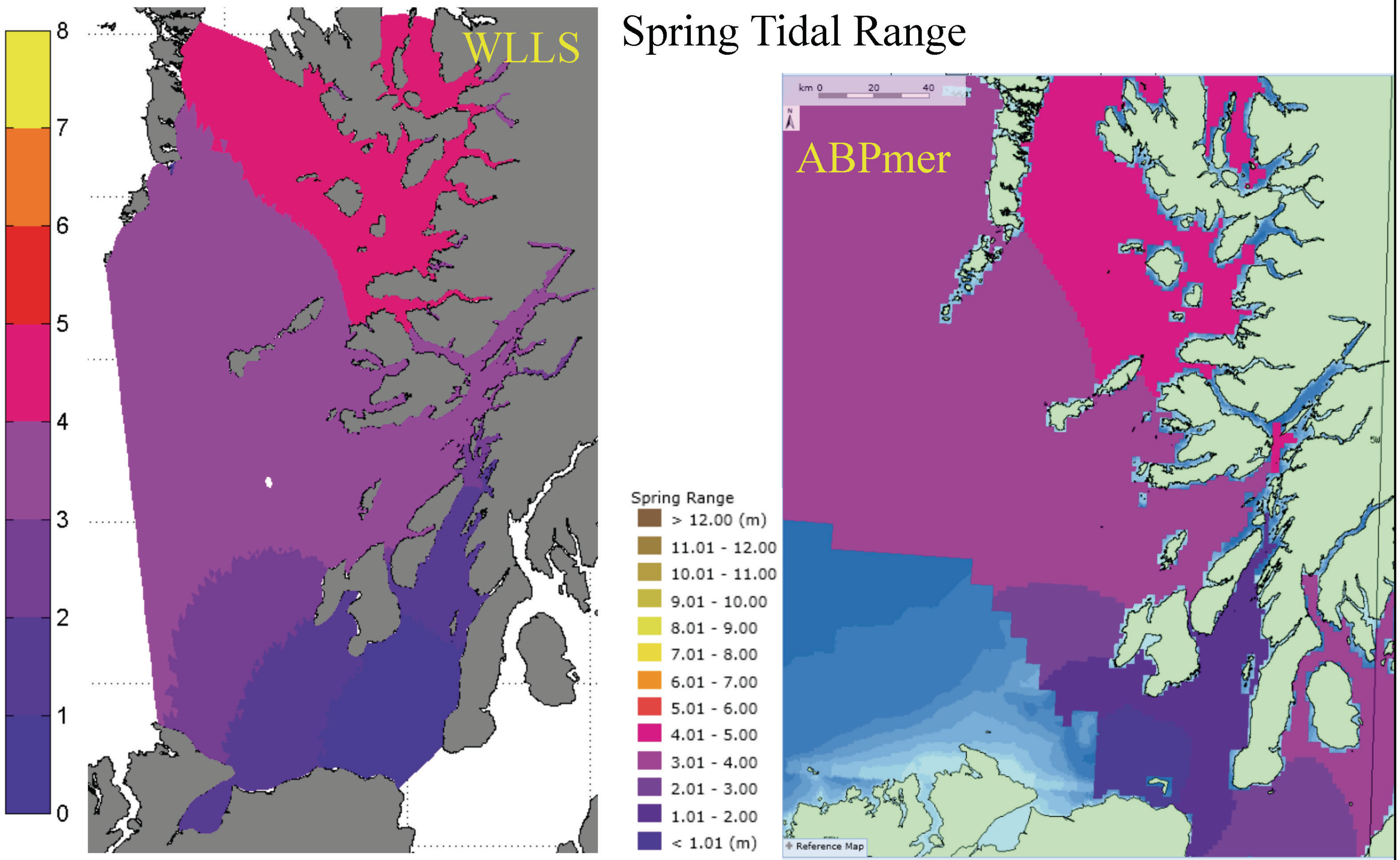
*mean high-water springs* = $Z_0 + (H_{M2} + H_{S2})$
*mean low-water springs* = $Z_0 - ( H_{M2} + H_{S2})$
*spring tidal range = mean high-water springs – mean low-water springs*

Values for these constituents were obtained from a harmonic analysis of 60 days' worth of data from the WLLS climatology run (01/Jan - 01/March). These harmonic components control the timing of the spring-neap cycle, and their combination is considered to give a good measure of average spring (and neap) tides. The data was also used to calculate the mean neap tidal range as:

*mean high-water neaps* = $Z_0 + (H_{M2} - H_{S2})$
*mean low-water neaps* = $Z_0 - (H_{M2} - H_{S2})$
*neap tidal range = mean high-water neaps – mean low-water neaps*

A map of the mean spring results are shown, along with the equivalent tidal range from the ABPmer / NOC Atlas of Marine Energy Resources (http://www.renewables-atlas.info/) in Figure 4-11a. The corresponding plots for mean neap tidal range are shown in Figure 4-11b. The magnitude of the spring tidal range in the WLLS FVCOM model shows good agreement with the ABPmer Atlas. There are some differences in the location of the contours, with the 4m contour further northeast in the FCVOM model and the area of less than 1m shifted to the east. This is likely to be related to the increased resolution of the FVCOM model. In the ABPmer model the islands of Skye, Mull and Jura are connected to the mainland. The neap tidal range comparison shows good agreement between the two models in both the magnitude and location of tidal range contours.

Further comparisons were made at a number of locations where the M2 and S2 constituents are available from the Admiralty tide tables (Figure 4-12a). Due to the lower resolution of the ABPmer model, comparison was not possible at a number of points. In general the FVCOM WLLS tidal range is greater than the Admiralty tidal ranges, both spring and neap (Figure 4-12b and Figure 4-12c respectively). In the locations with available ABPmer data the tidal ranges are the same or greater than the FVCOM WLLS ranges.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-11a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparison of Mean Spring Tidal range calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
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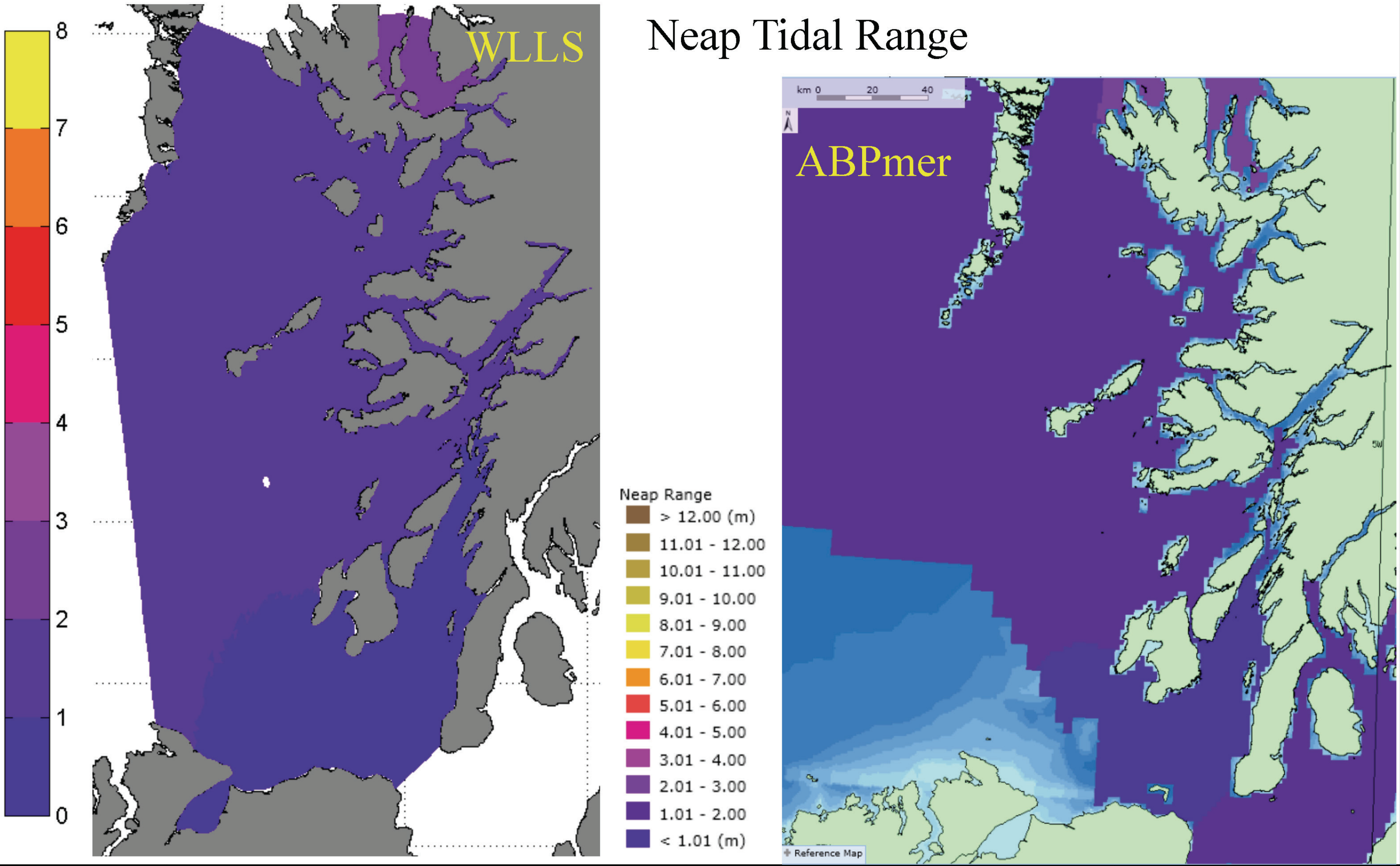


| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-11b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of Mean Neap Tidal range calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
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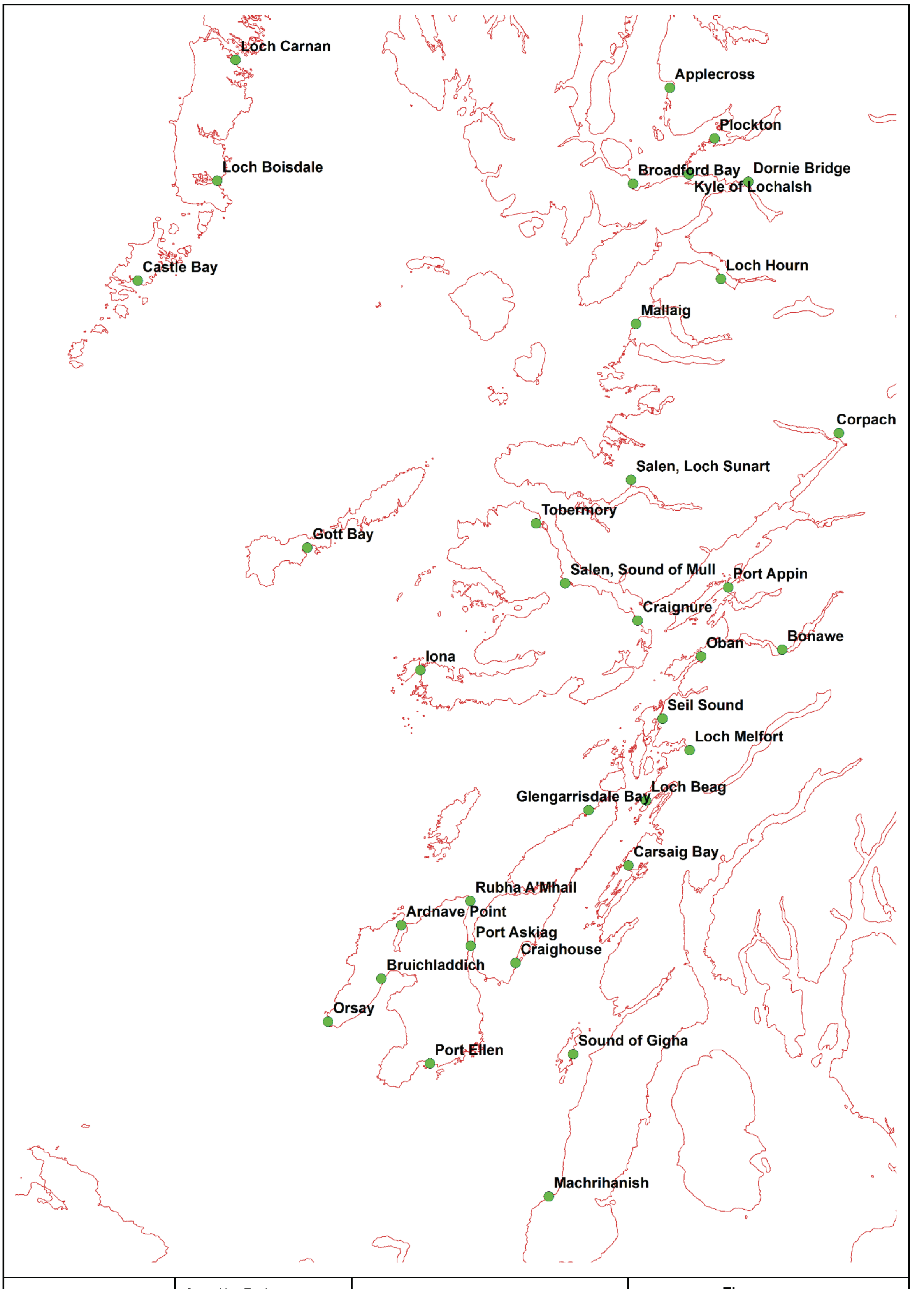
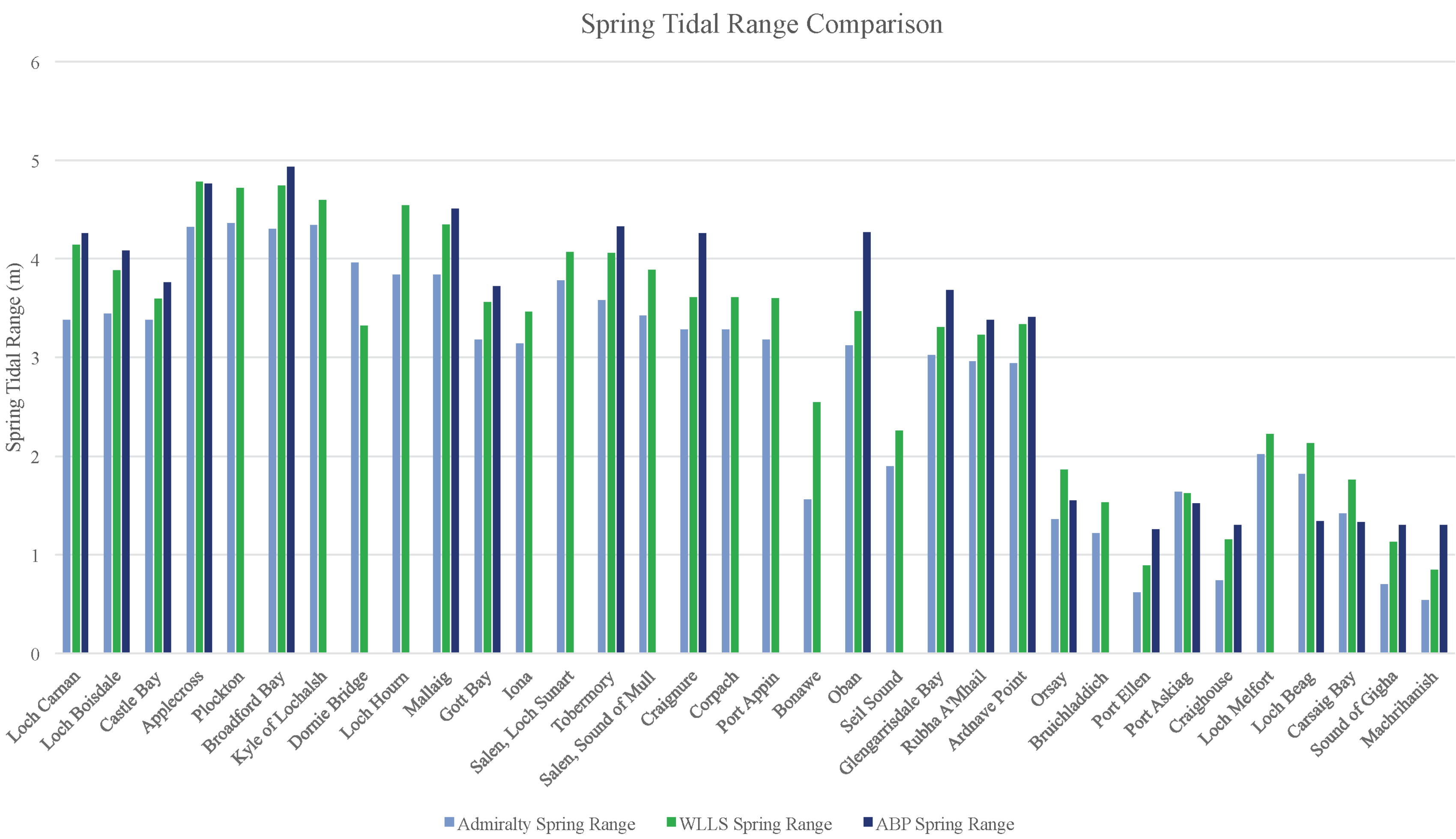
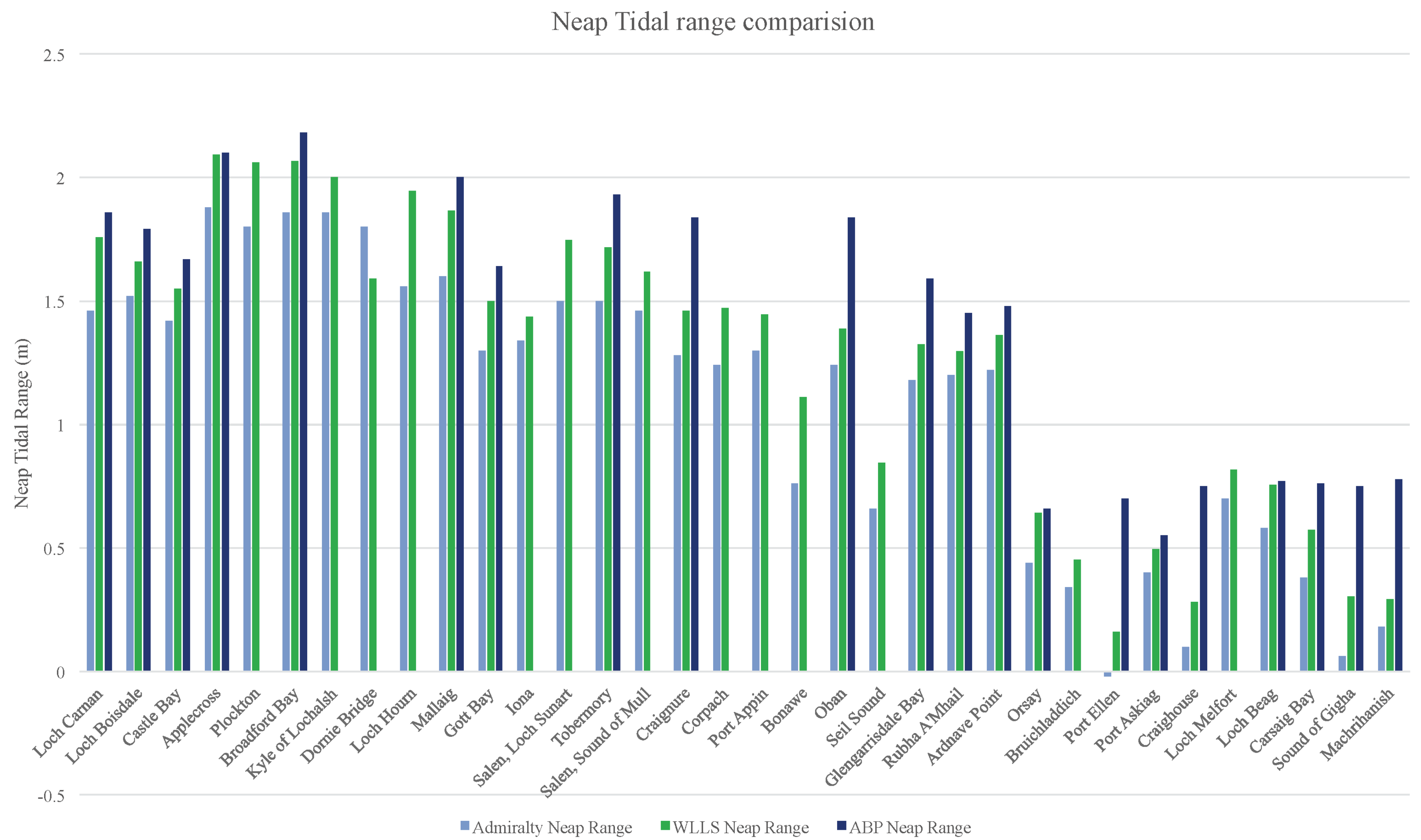



| Client | Consulting Engineer | Project: | Figure 4-12a |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of Admiralty Tidal data |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-12b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of Mean Spring Tidal range calculated from the Admiralty tide tables, FVCOM model and the ABPmer/ NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-12c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of Mean Neap Tidal range calculated from the Admiralty tide tables, FVCOM model and the ABPmer/ NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

#### 4.3.3.3 Mean Spring/Neap Currents

Mean peak current speeds have been calculated from a harmonic analysis of 60 days (01/January – 01/March) of depth averaged tidal velocities, from the WLLS climatology run. In line with the methodology used for the ABPmer / NOC Atlas, a mid-depth velocity was used for the calculations. The east and west components of velocity were analysed using T_TIDE to give the $M_2$ and $S_2$ amplitudes and phases. These were in turn analysed to give the semi-major axis amplitudes for each ellipse. The mean peak spring current was then computed as:

*mean peak spring current = amplitude semi-major axis* $M_2$ + *amplitude semi-major axis* $S_2$

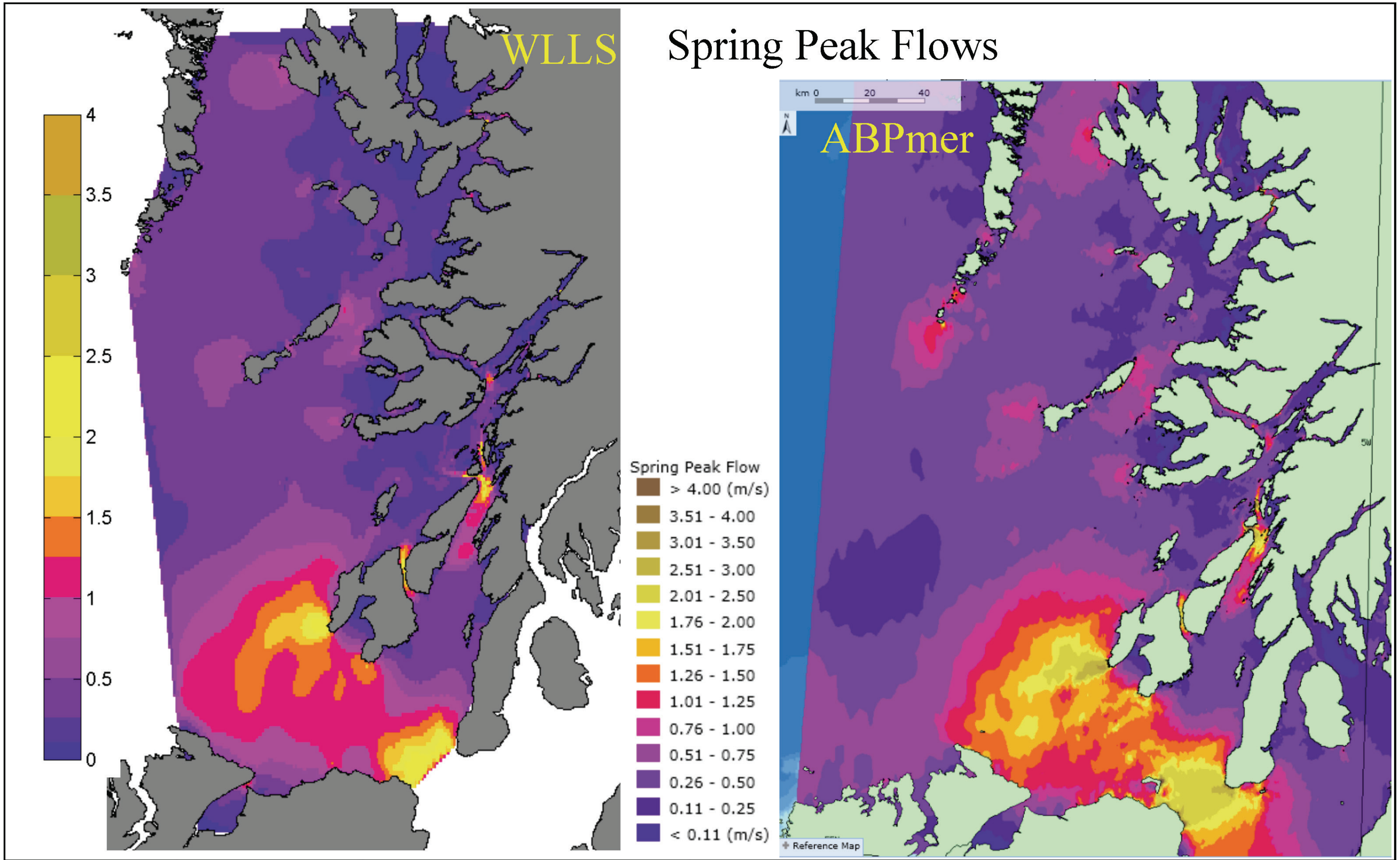
The mean neap spring current was computed as:

*mean peak neap current = amplitude semi-major axis* $M_2$ – *amplitude semi-major axis* $S_2$

A map of the results for mean spring current is shown, along with the equivalent peak currents from the ABPmer / NOC Atlas of Marine Energy Resources, in Figure 4-13a. Corresponding plots for the mean neap current are shown in Figure 4-13b. The peak spring flow data from the ABPmer Atlas is taken from a higher resolution flexible mesh model which includes many of the Sounds and Lochs that are omitted from the regular grid model. The spatial variations in spring peak speeds are consistent between the two models, the peak speeds are seen to the northeast of Jura and through the North Channel of the Irish Sea. However the ABPmer model gives a slightly higher estimate of the peak flows. The comparison of the neap peak flows, using the lower resolution, regular grid ABPmer model shows good spatial agreement on the location of peak flows. Again the ABPmer results show higher peak flows.

#### 4.3.3.4 Residual Currents

The residual surface currents from WLLS and the Scottish Shelf model are displayed in Figure 4-14 for February and August. In all cases the residual flow is to the north, which is in line with existing knowledge of the residual current in this area. The speed of the residual currents in the WLLS FVCOM model is greater than that from the Scottish Shelf model. For both the Scottish Shelf and the WLLS FVCOM model the residuals are stronger in August than February and location of the peak residual speeds are broadly the same in both models, i.e. through the passage of Tiree, the south Minch, to the north of Jura and south of Islay.




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-13a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of Mean Spring Peak Currents calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
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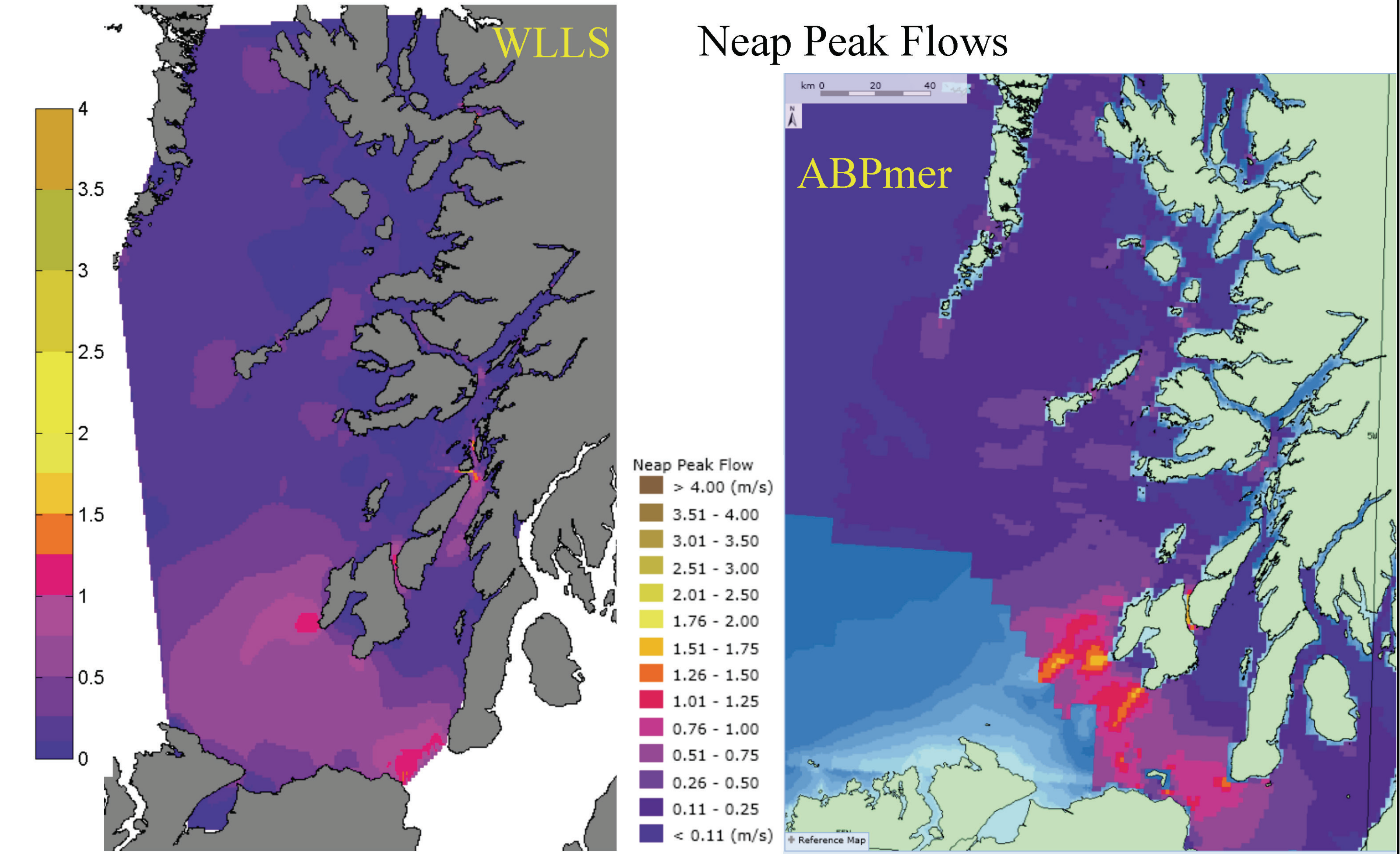


| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-13b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of Mean Neap Peak Currents calculated from the FVCOM model and the ABPmer/NOC Atlas of Marine Energy Resources | Checked DMP | Scale Not to scale | Rev. 0 |
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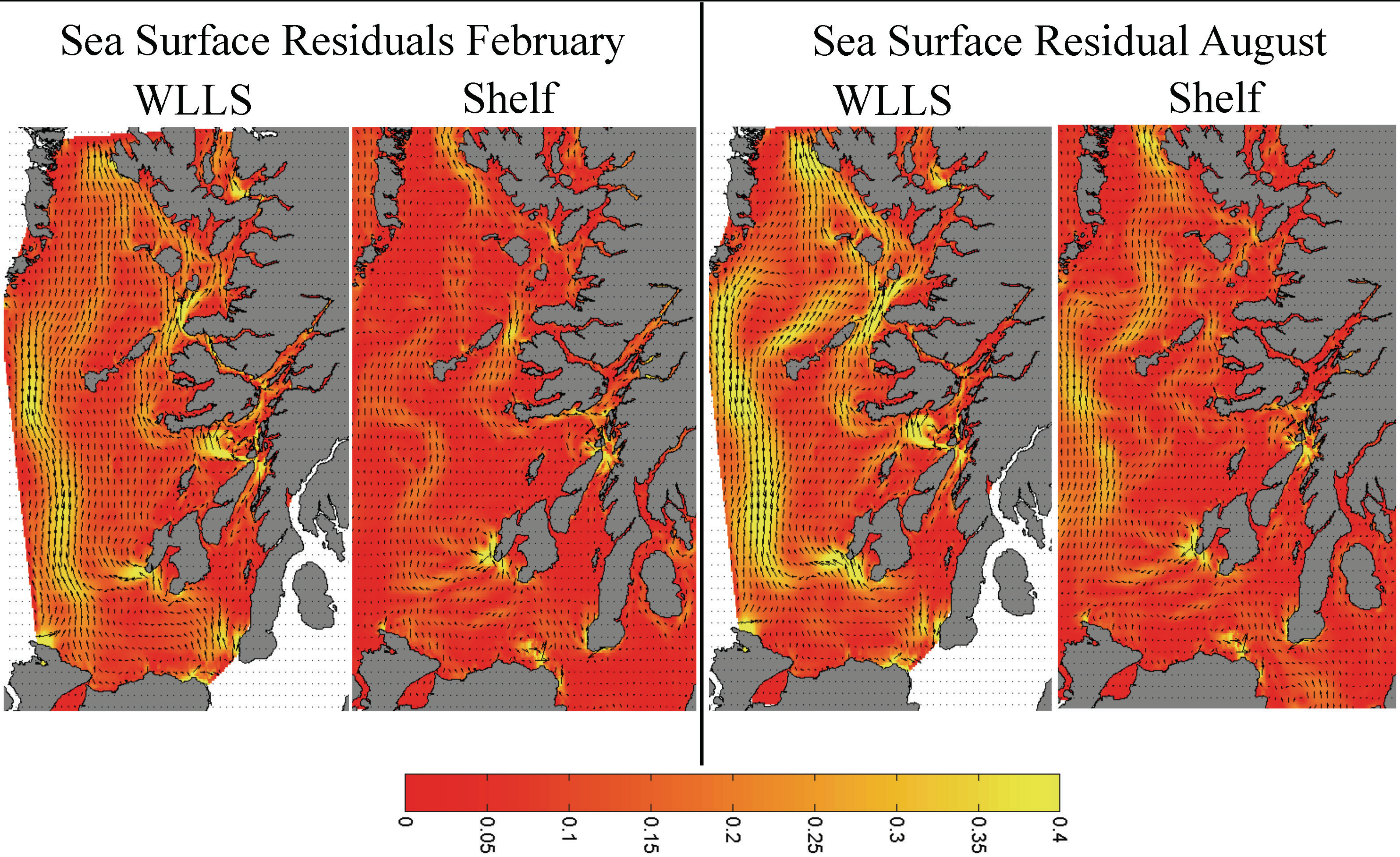


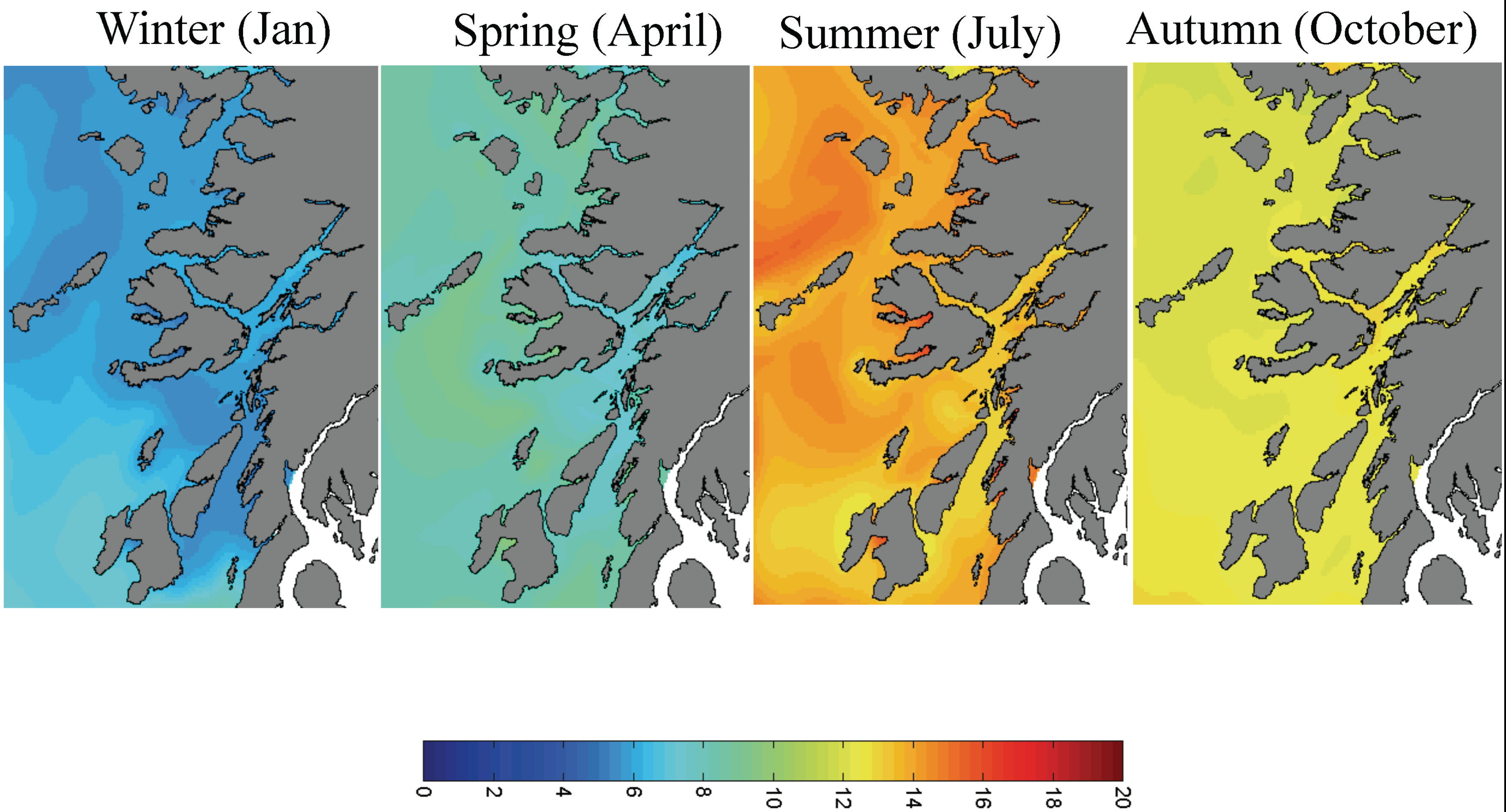

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-14 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison of surface residual currents in the WLLS with the shelf model for Febuary and August | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

#### 4.3.3.5 Seasonal Variations

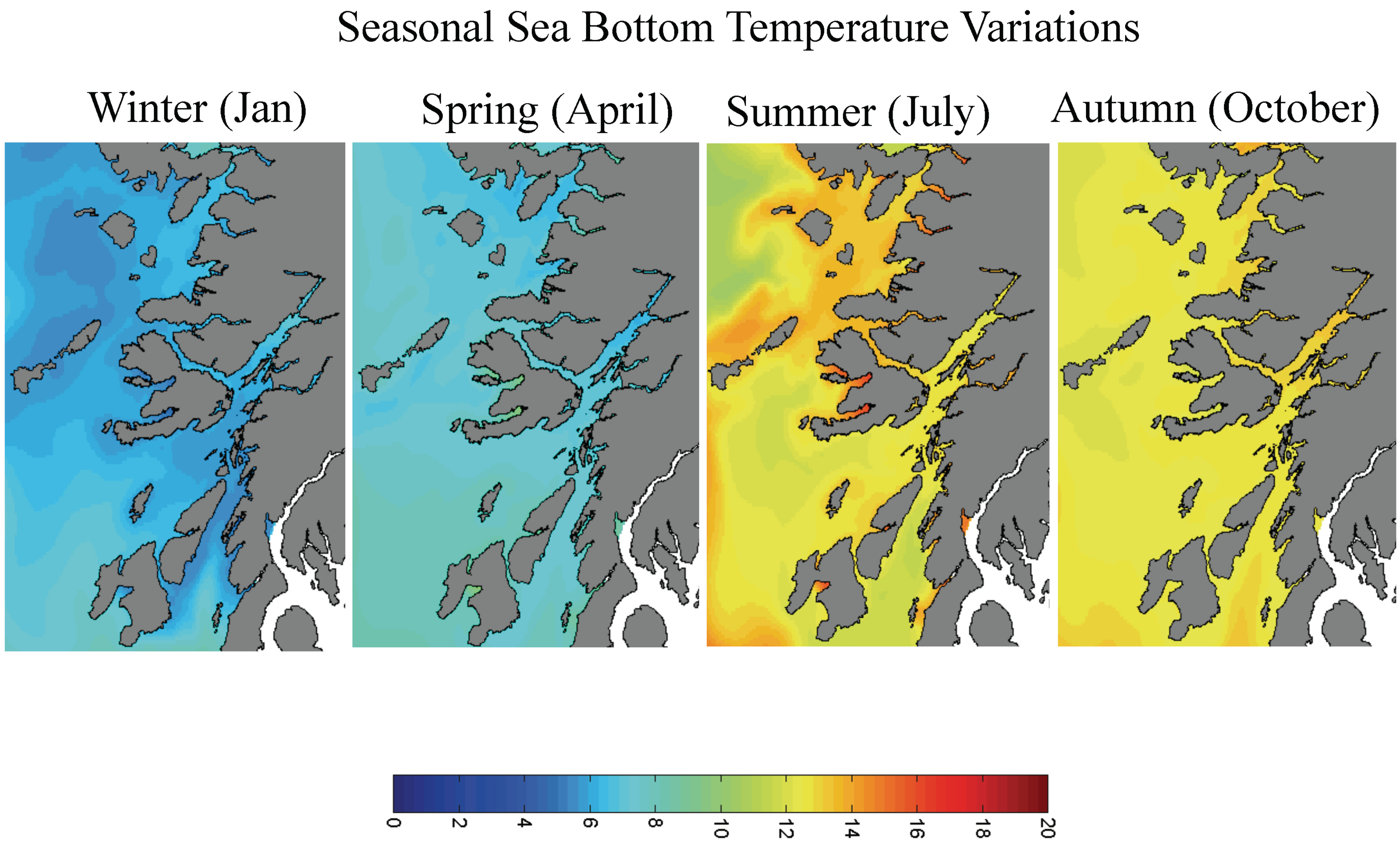
Seasonal variations in sea surface temperature and salinity are shown in Figures 4-15a-b and 4-16a-b. Sea surface and bottom temperatures are at their lowest in January and highest in July, and warmer in the autumn than the spring as would be expected. The areas with higher sea bed temperature in July coincide with relatively shallow areas. The difference between sea surface and bottom temperature throughout the year is shown in Figure 4-15c. It gives an indication of the stratification of the water column. In autumn and winter, there is very little difference in temperature implying there is little or no stratification, while in spring and summer the surface temperature is slightly higher in Loch Linnhe and higher generally off shore. The temperature difference in Loch Sunart and Loch Etive is not as pronounced.

The salinity in the model is lower close to land both at the sea surface and bottom all year round, due to fresh water inputs to the system. The salinity at the surface in these areas is always lower. During the summer and autumn an incursion of high salinity Atlantic water can be seen north of Tiree and Col. As with the temperature difference plots the salinity difference plots give an indication of the water column stratification (Figure 4-16c). Note the pale green areas though the sound of Mull (A), around Jura (B) and Islay (C), Loch Sunart (D) and in the upper end of Loch Etive (E) in both Figure 4-15c and 4-16c which indicate low stratification potential. The reason for the low potential varies at the different locations. The high flows through the Sound of Mull and around Jura and Islay mean the water column is likely to be well mixed in those areas. However the low stratification potential in the Lochs is more to do with the low river flows in Loch Sunart and into the top end of Loch Etive within the model.

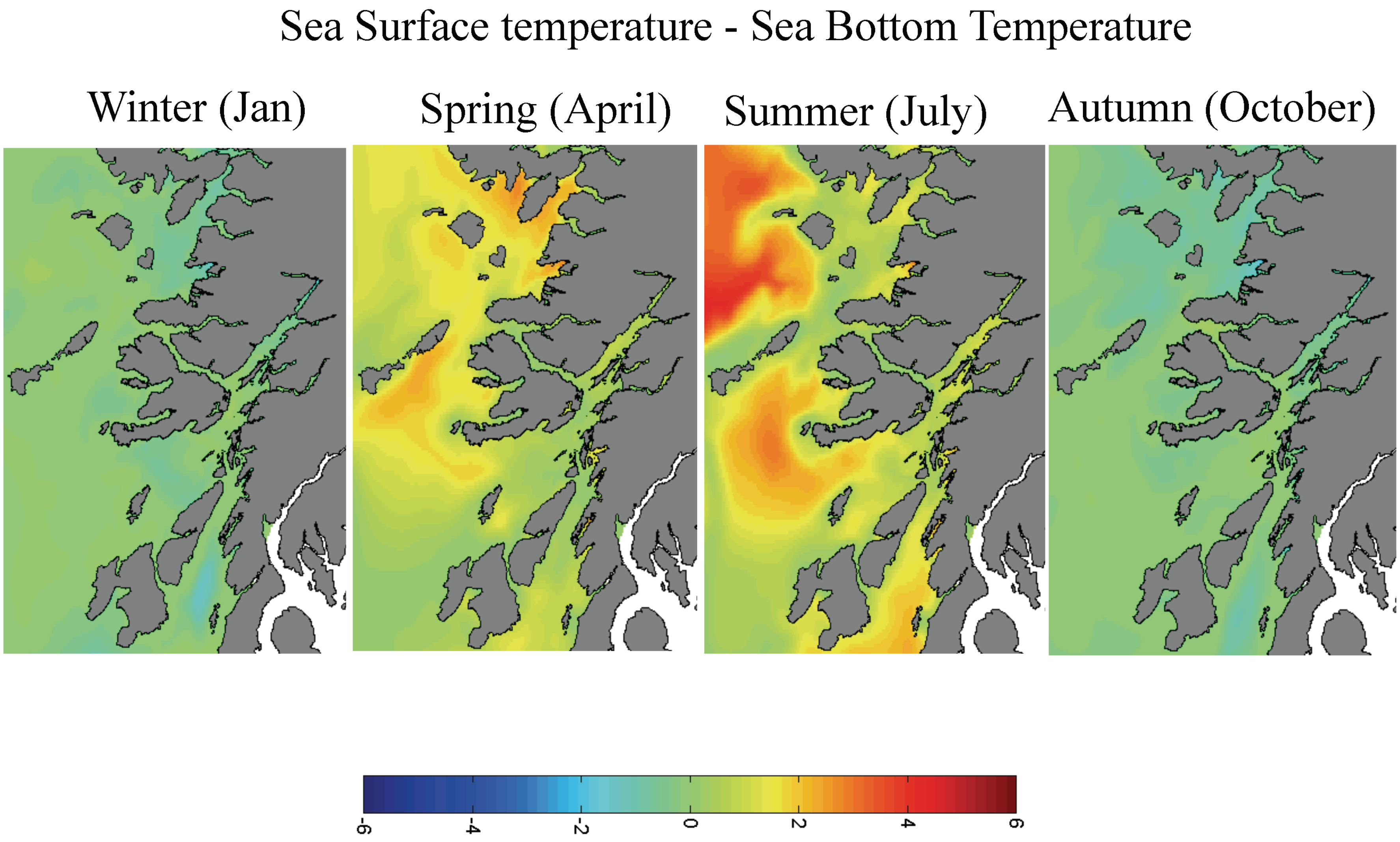
# Seasonal Sea Surface Temperature Variations



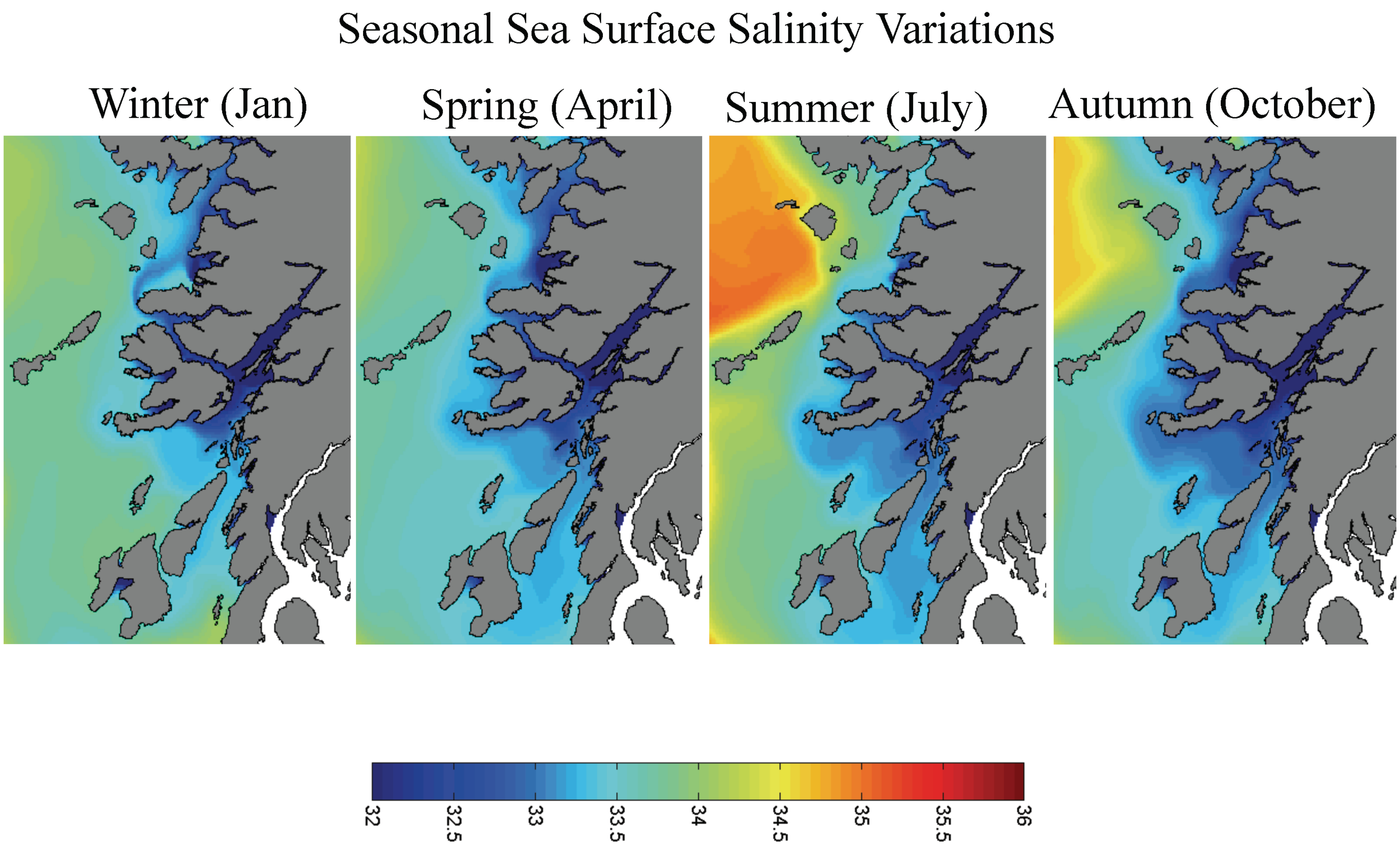

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-15a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Seasonal variations in the monthly average sea surface temperature from the WLLS model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-15b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Seasonal variations in the monthly average sea bed temperature from the WLLS model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

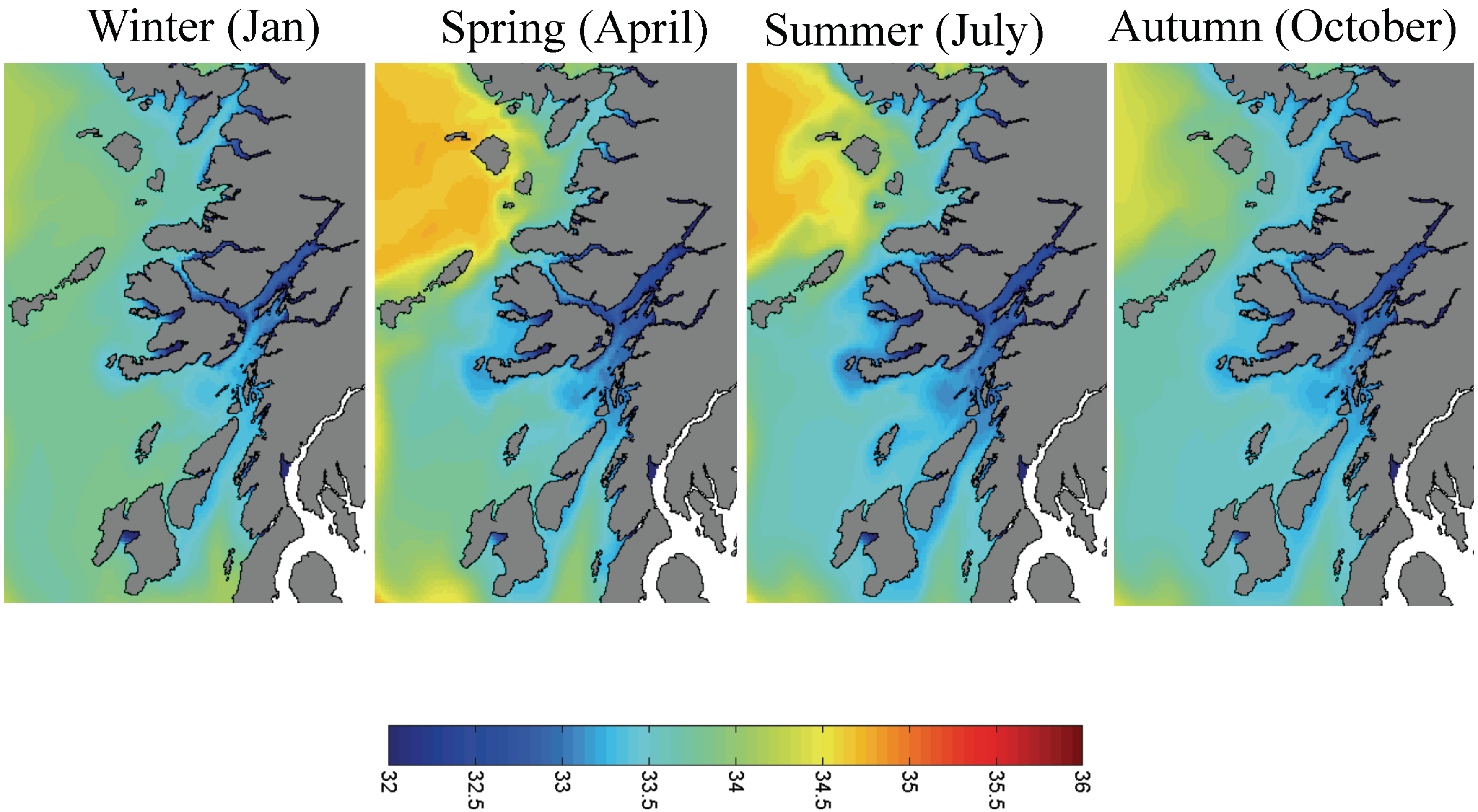



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-15c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Seasonal variations in the difference in monthly average sea surface and sea bottom temperature from the WLLS model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

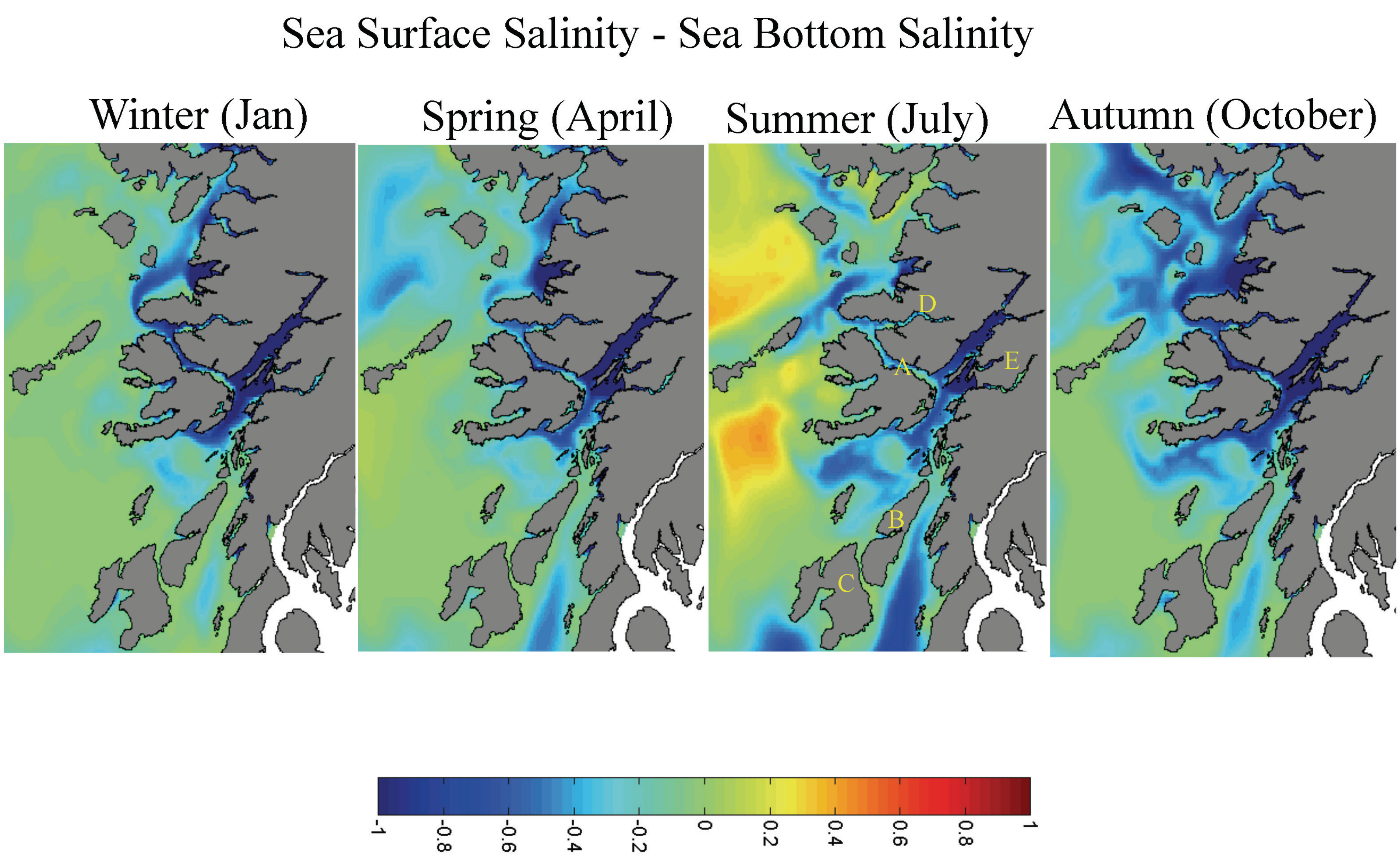



| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-16a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Seasonal variations in the monthly average sea surface salinity from the WLLS model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

# Seasonal Sea Bottom Salinity Variations




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-16b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Seasonal variations in the monthly average sea bed salinity from the WLLS model | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



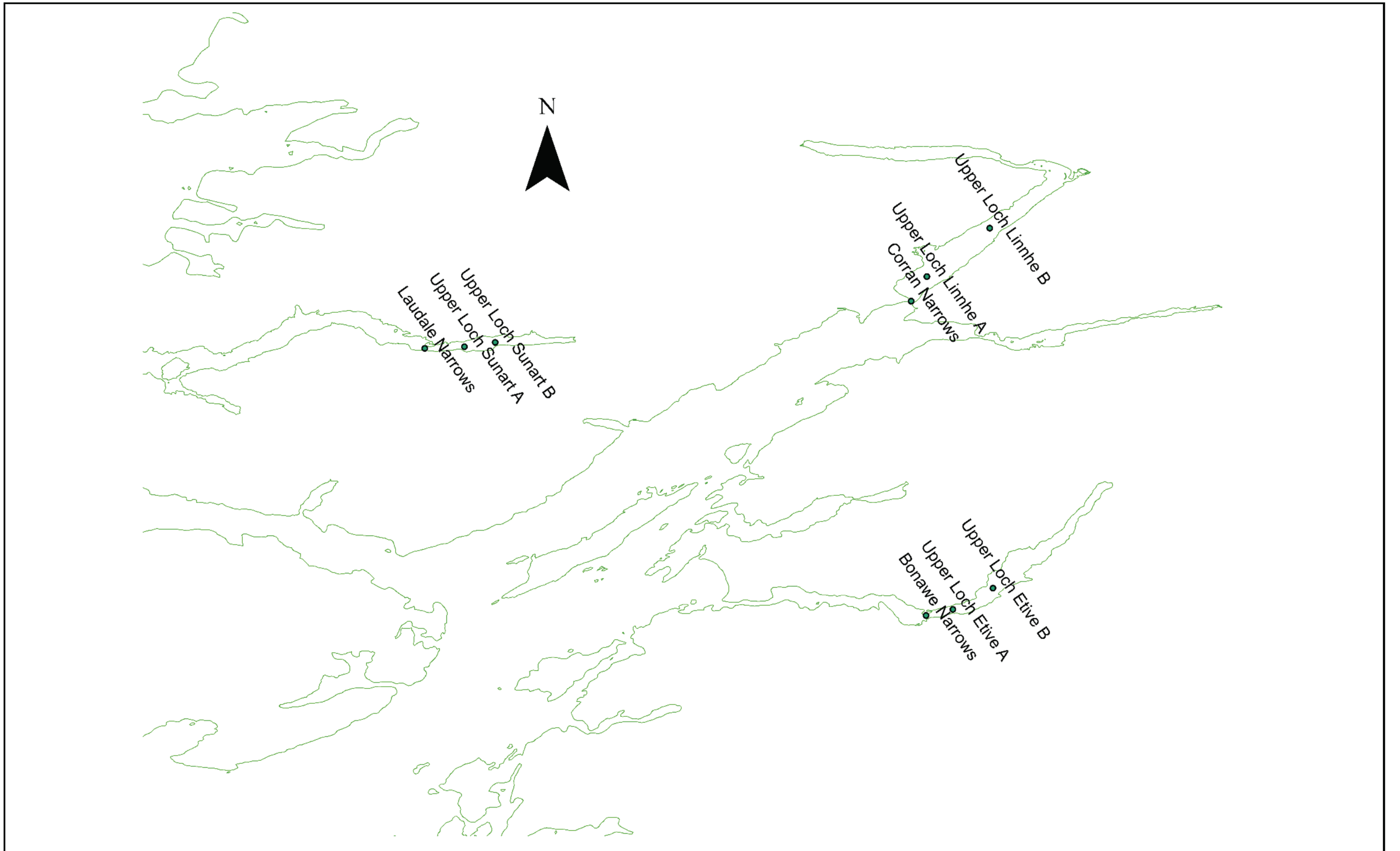

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-16c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Seasonal variations in the difference in monthly average sea surface and sea bottom salinity from the WLLS model. A- Sound of Mull, B-Jura, C-Islay, D-Loch Sunart and E-Loch Etive | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

## 4.4 Discussion

The Wider Loch Linnhe system contains a number of fjordic sea lochs characterised by deep, often stratified, semi enclosed basins separated from the sea by a shallow sill at the mouth. Circulation in these sea lochs is controlled by freshwater inflow and meteorological forcing. Previous research has revealed a number of mechanisms for deep water mixing and renewal within these sea lochs landward of the sills including deep water inflows and internal tides. Evidence of deep water inflows of denser saline water from the sea in Upper Loch Linnhe, Loch Sunart and Loch Etive is presented in Allen and Simpson (1998a and 2002), Austin and Inall (2002) and Gillibrand et al. (1995). Allen and Simpson (1998b) also identified an internal tide in Upper Loch Linnhe, a feature that persisted over the 7 months of measurements.

The occurrence of deep water inflows is controlled by freshwater inputs, tidal range and wind conditions. Low freshwater input and high tidal range combined with strong seaward winds increase the likelihood of inflows, while high freshwater discharge rates, low tidal range and landward winds have the opposite effect (Allen and Simpson, 1998a, Gillibrand et al. (1995). The seaward winds move low salinity water away from the sill and enhance estuarine circulation in the lower loch, increasing the density of the deeper water over the sill (Gillibrand et al., 1995). Inflows are likely to occur when the density at the sill is greater than that of the deep water in the upper loch. They are characterised by an increase in the near bed velocity compared to the depth averaged velocity, an increase in the deep water salinity and at times rapid changes in temperature. A rapid change in temperature is not always seen, but only when the temperature of the inflowing dense water differs from the deep water temperature.

To test whether the model is capable of replicating these deep water inflows a number of parameters (i.e. salinity, temperature, current speeds and $\sigma_T$ ($\rho(S, T)$-1000kg/m$^3$ – i.e. a measure of density of sea water at a given temperature)) were extracted on the sill and in the upper loch near the bed of Loch Linnhe, Loch Sunart and Loch Etive (Figure 4-17).




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-17 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Location of data extraction points | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

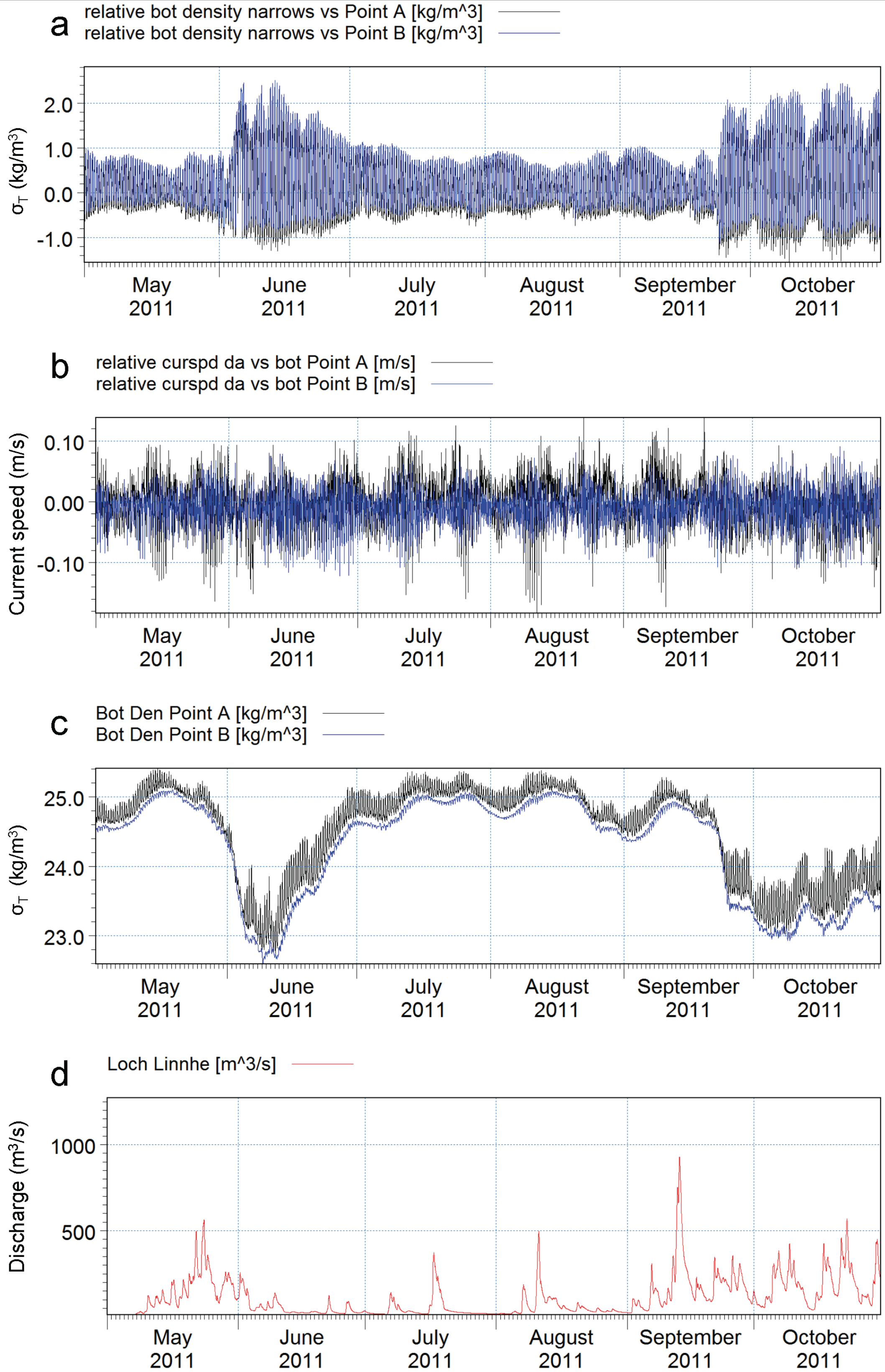
### 4.4.1 Loch Linnhe

Data for May to October at Loch Linnhe is presented in Figure 4-18. Panel a shows the difference in the near bed $\sigma_T$ on the sill to point A and B in the Upper Loch, positive values indicate that the density at the sill is greater than the deep water in the Loch and there is potential for deep water inflows. Panel b shows the depth average current speed minus the near bed current speed at points A and B. Negative values indicate that the flow at the bed is greater than the average and is an indication of deep water inflows of higher density water. Panel c shows the $\sigma_T$ variations near the bed at points A and B and panel d shows the river discharge into the upper loch. These plots reveal the influence of both river discharge to reduce the density in the upper loch through vertical mixing and of inflows of higher density water over the sill at Corran Narrows. The drop in $\sigma_T$ in late May/early June and towards the end of September occur several days after high river flows into the upper loch, while the increase in $\sigma_T$ during June occurs when the $\sigma_T$ difference between the narrows and the deep water in the upper loch is at its highest. This coincides with a time when densities in the upper loch have been reduced by freshwater inputs increasing the potential for inflows over the sill. Despite the increased potential in inflows seen in October, the $\sigma_T$ of the deep water in the upper loch does not increase at the rate seen in June, most likely due to the sustained input of fresh water during that time.

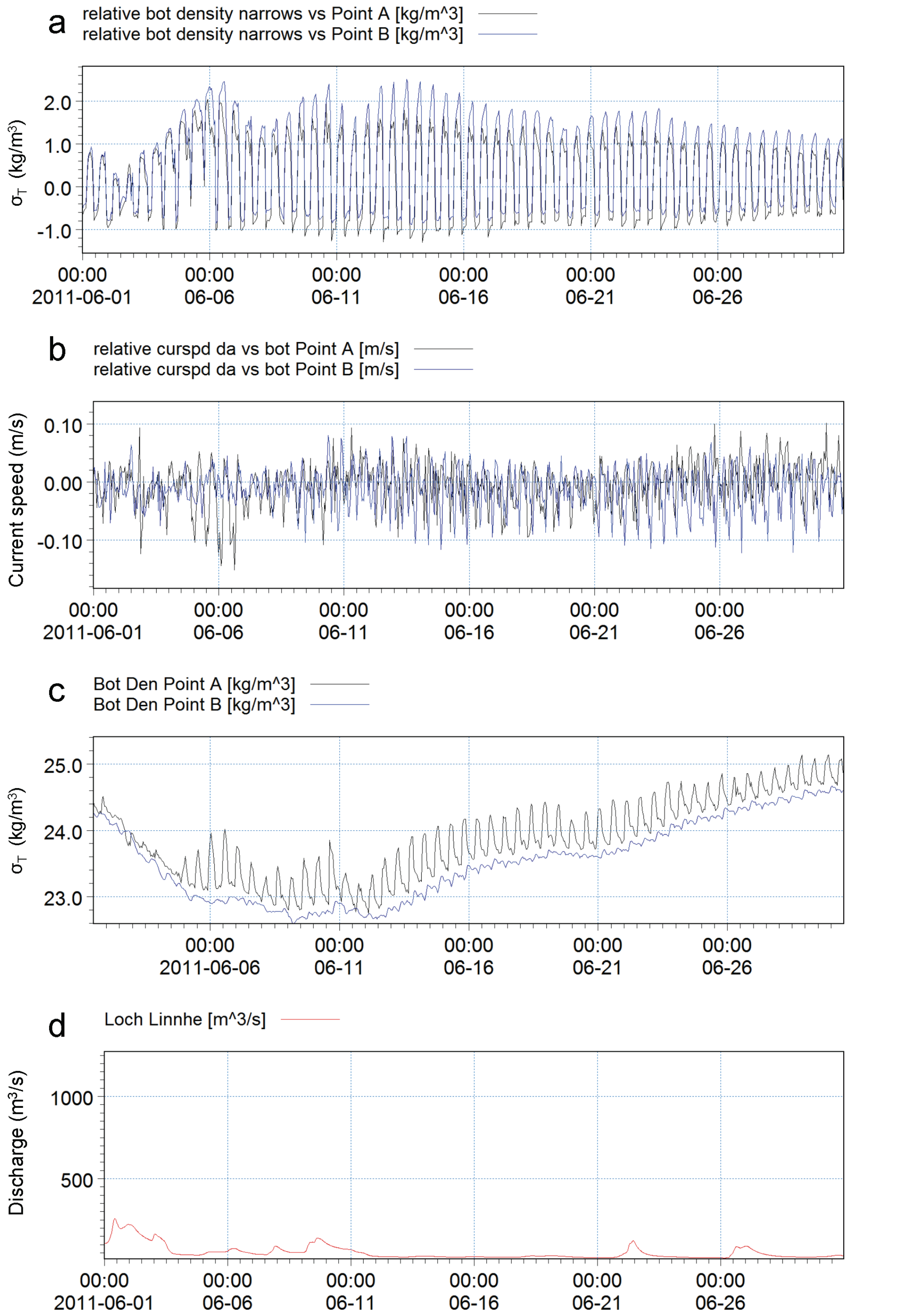
Allen and Simpson (1998) describe deep water inflows as pulses of denser water being advected into the loch on successive tides over a period of several days. By zooming in to June the tidal signal and the gradual increase in $\sigma_T$ in the deep water of the upper loch as semi diurnal pluses can be clearly seen (Figure 4-19). In October the increase in $\sigma_T$ is tempered by the sustained river flow, with any increases in $\sigma_T$ occurring during periods of relatively low river flow (Figure 4-20).

### 4.4.2 Loch Sunart

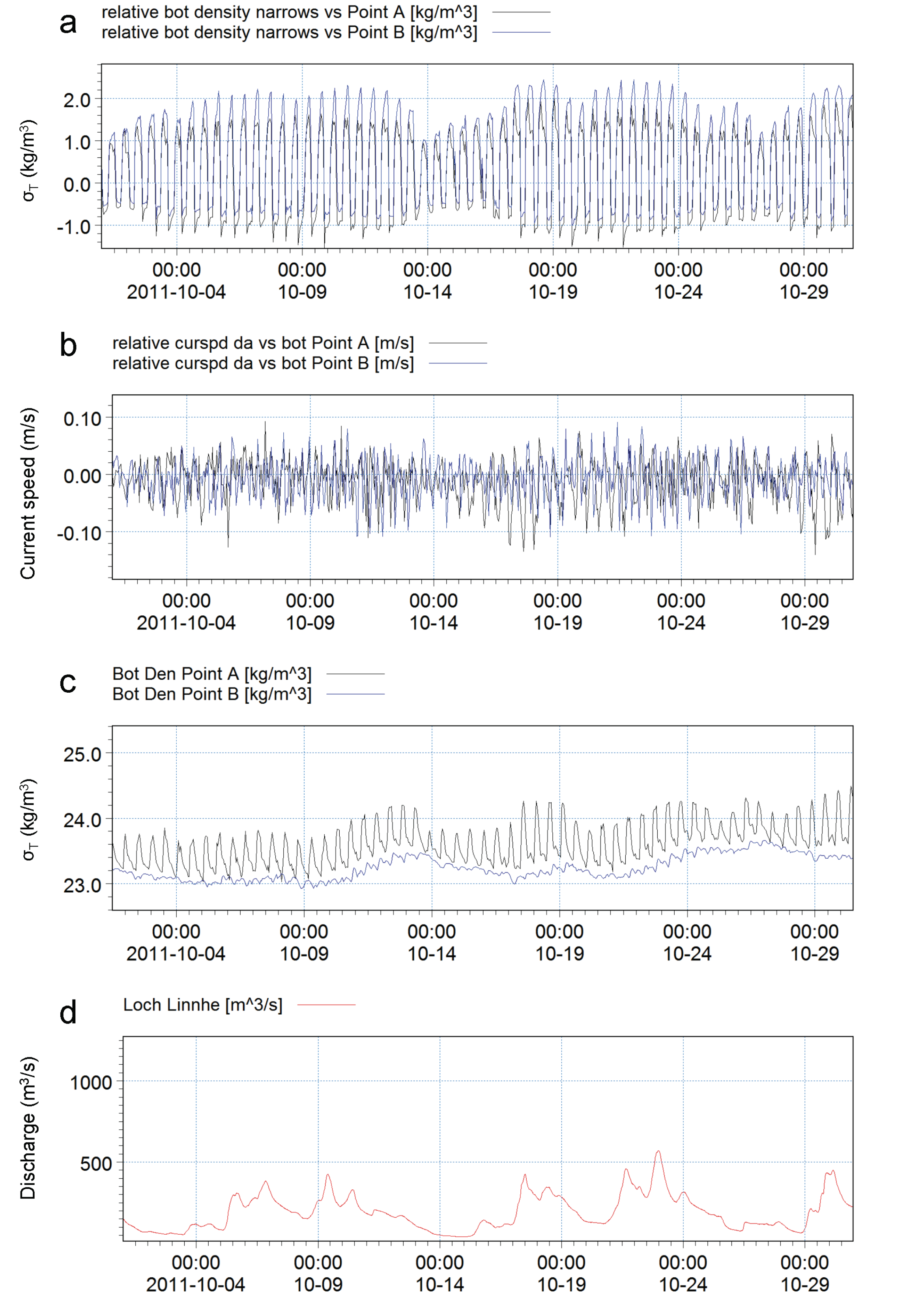
The upper basin of Loch Sunart is subject to much lower river discharge than upper Loch Linnhe and therefore has a higher potential for deep water inflows. A previous study by Gillibrand et al. (1995), found that deep water inflows occurred frequently, at least once a month. The results at Loch Sunart are shown in Figure 4-21 for May to October 2011 and, zoomed into July and August in Figure 4-22, the parameters presented are the same as those in Figure 4-18 with the addition of water level at the Laudale Narrows. The $\sigma_T$ changes seen in Loch Sunart are much cleaner than those seen in Loch Linnhe especially at Point A. The relative $\sigma_T$ at the narrow and deep water also shows a more defined signal relating to increases in $\sigma_T$ and relative near bed current speeds. The increased clarity of the signals is likely to be due to the lower fresh water input into the upper loch. The relationship between freshwater input, reducing density and inflow of higher density water over the sill is clearly seen. Another relationship is apparent in the data, that of tidal range and inflow. Many of the inflow events, characterised by an increase in near bed density coincide with spring tides, supporting the assertion in the literature that increased tidal range increases the potential for deep water inflows (Allen and Simpson, 1998a and 2002, Austin and Inall, 2002 and Gillibrand et al., 1995).



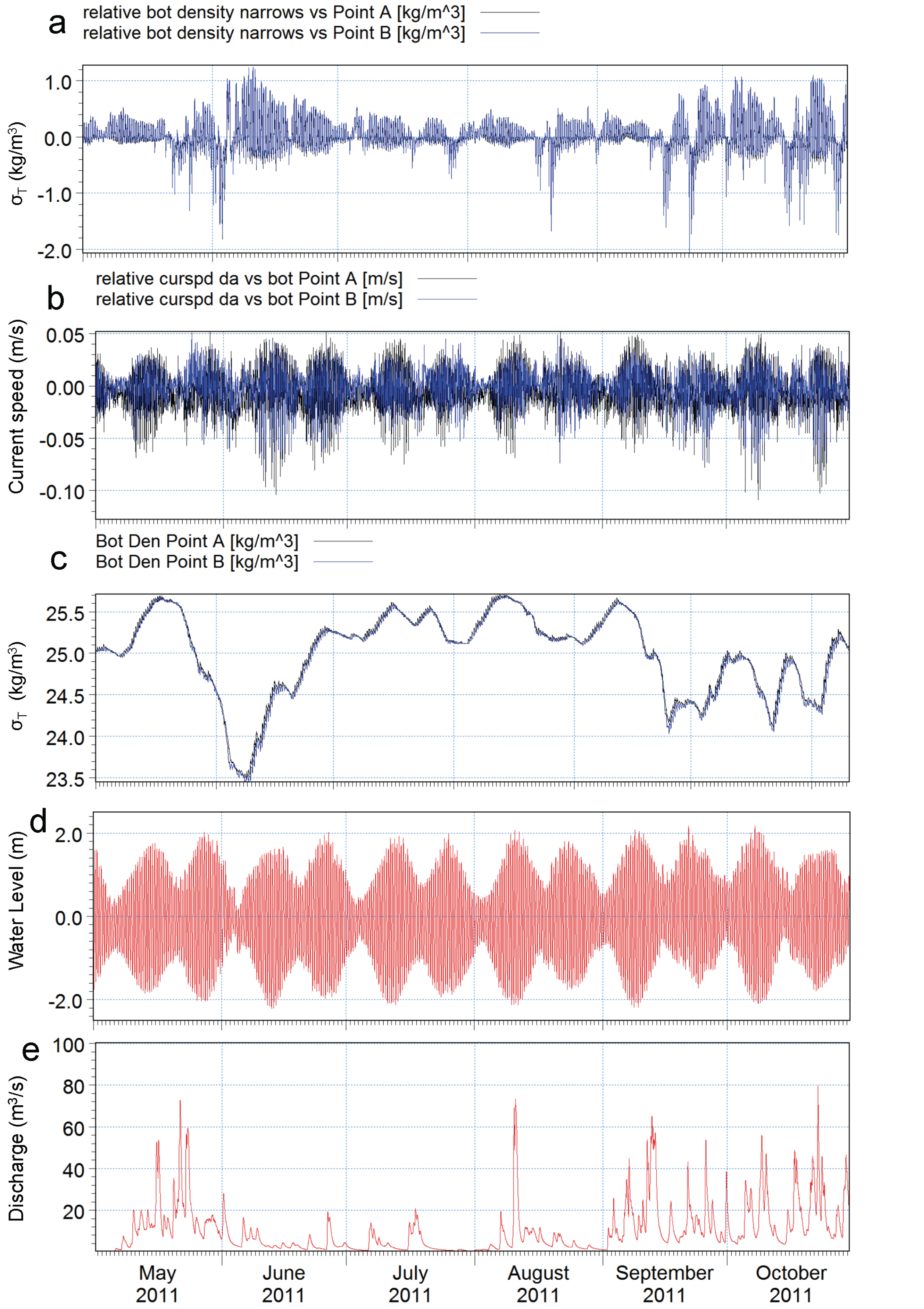

| Client | Consulting Engineer | Project: | **Figure** 4-18 |
|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Time series indicating the potential for deep water inflows across the Corran Narrows in to upper Loch Linnhe, May to October 2011 |



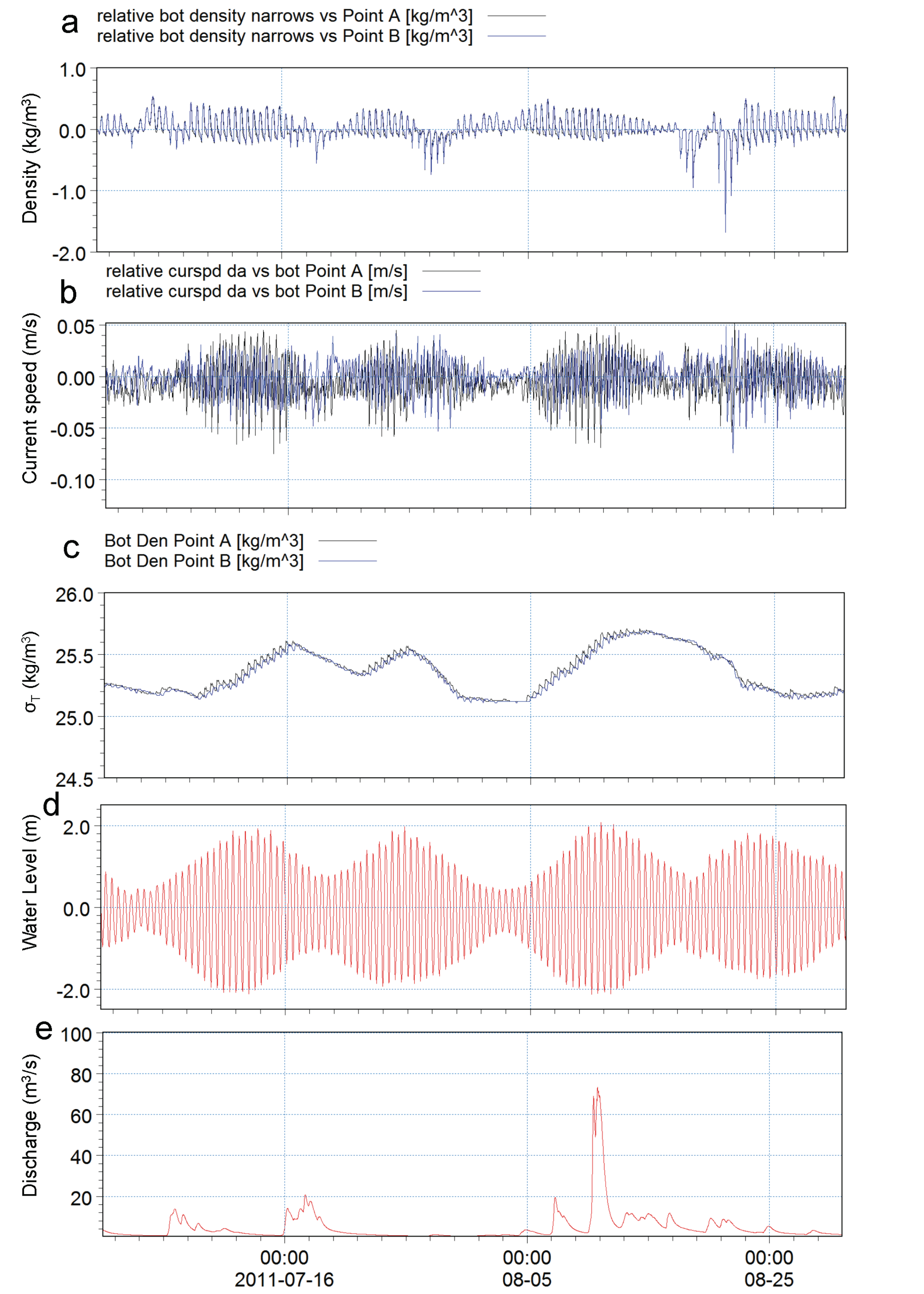

| Client | Consulting Engineer | Project: | **Figure 4-19** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Time series indicating the potential for deep water inflows across the Corran Narrows in to upper Loch Linnhe during June 2011 |




| Client | Consulting Engineer | Project: | **Figure 4-20** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Time series indicating the potential for deep water inflows across the Corran Narrows in to upper Loch Linnhe during October 2011 |




| Client | Consulting Engineer | Project: | **Figure 4-21** |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Time series indicating the potential for deep water inflows across the Laudale Narrows in to upper Loch Sunart, May to October 2011 |




| Client | Consulting Engineer | Project: | Figure 4-22 |
|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Time series indicating the potential for deep water inflows across the Laudale Narrows in to upper Loch Sunart, July to August 2011 |

### 4.4.3 Loch Etive

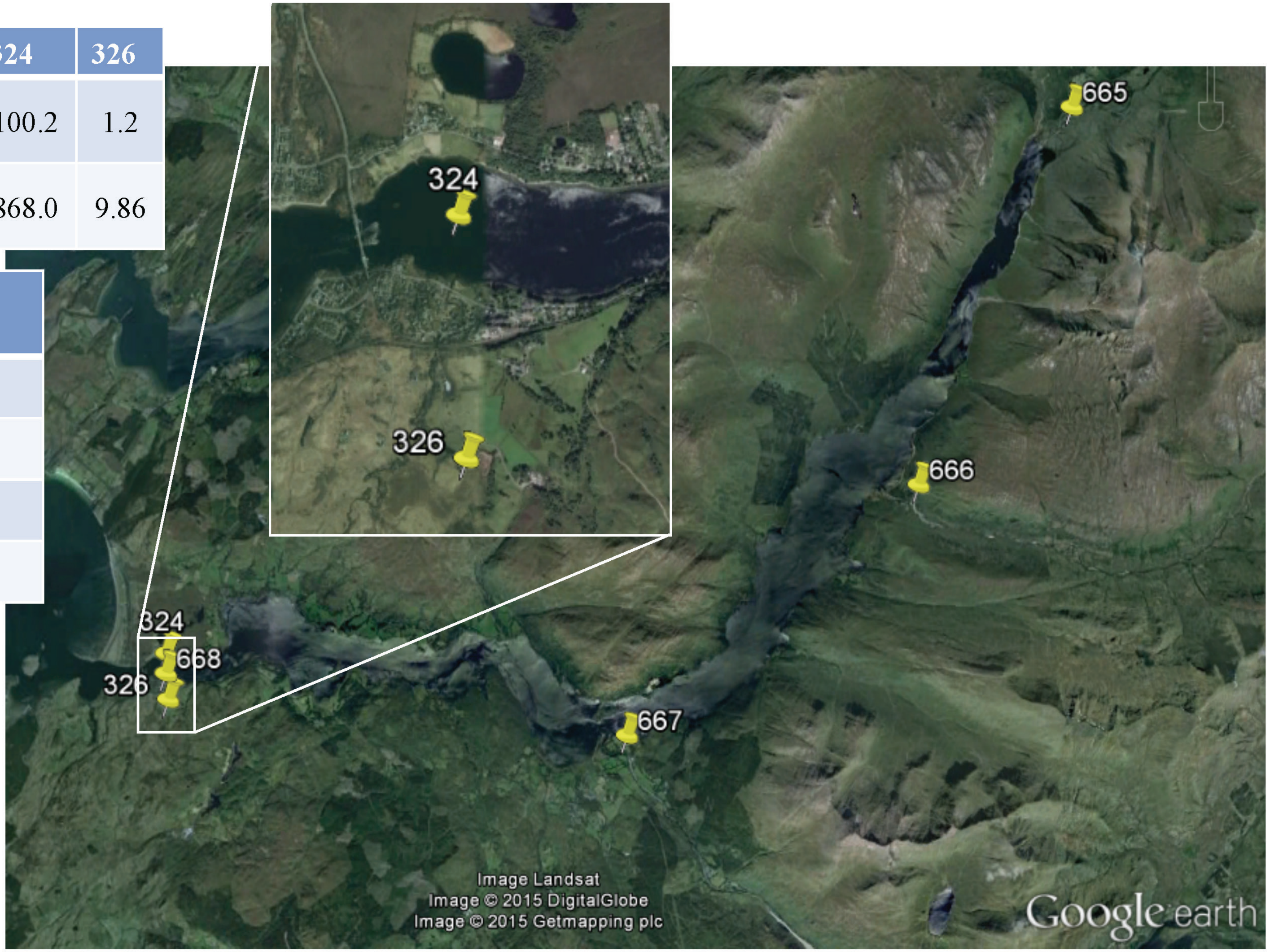
Analysis of the Loch Etive results revealed an error in the way the rivers have been applied to the model within this loch. All the rivers flowing into Loch Etive were provided as a single output at the mouth of the loch in the G2G data provided by CEH. Therefore it was necessary to redistribute the flows using the catchment area ratios shown in Figure 4-23 from the river specified at the mouth (324) to the individual rivers within the loch (665-668). However, due to a mix up in the river numbers provided by CEH, flows from the wrong river (326) were redistributed to rivers 665 to 668. The mean and maximum discharges of the two rivers are also shown in Figure 4-23. The total freshwater input to the model was correct but the distribution in Loch Etive was not. This means the results for temperature and salinity within Loch Etive are not valid and the results in this region are not presented in terms of the potential for deep water inflows.

A sensitivity test was carried out for May 2011 with the correct river redistributed. Time series of water level and depth averaged current speed, and surface, mid and near bed temperature and salinity were extracted at a number of locations around the mouth of Loch Etive from both the May calibration run and the sensitivity run with the corrected river distribution. The RMS (root mean square) difference and bias between the two runs was calculated. The RMS difference and bias for water level and current speed was less than 0.006m and 0.07m/s respectively at all locations. The temperature and salinity RMS difference and bias are presented in Figure 4-24 and 4-25 respectively along with the extraction locations. The RMS difference in temperature is very small less than 0.15 degrees Celsius at all locations and depths, the bias is even smaller, not exceeding 0.06 degrees Celsius. There is no obvious pattern in the data, i.e. the RMS difference is not greater close to the mouth of Loch Etive.

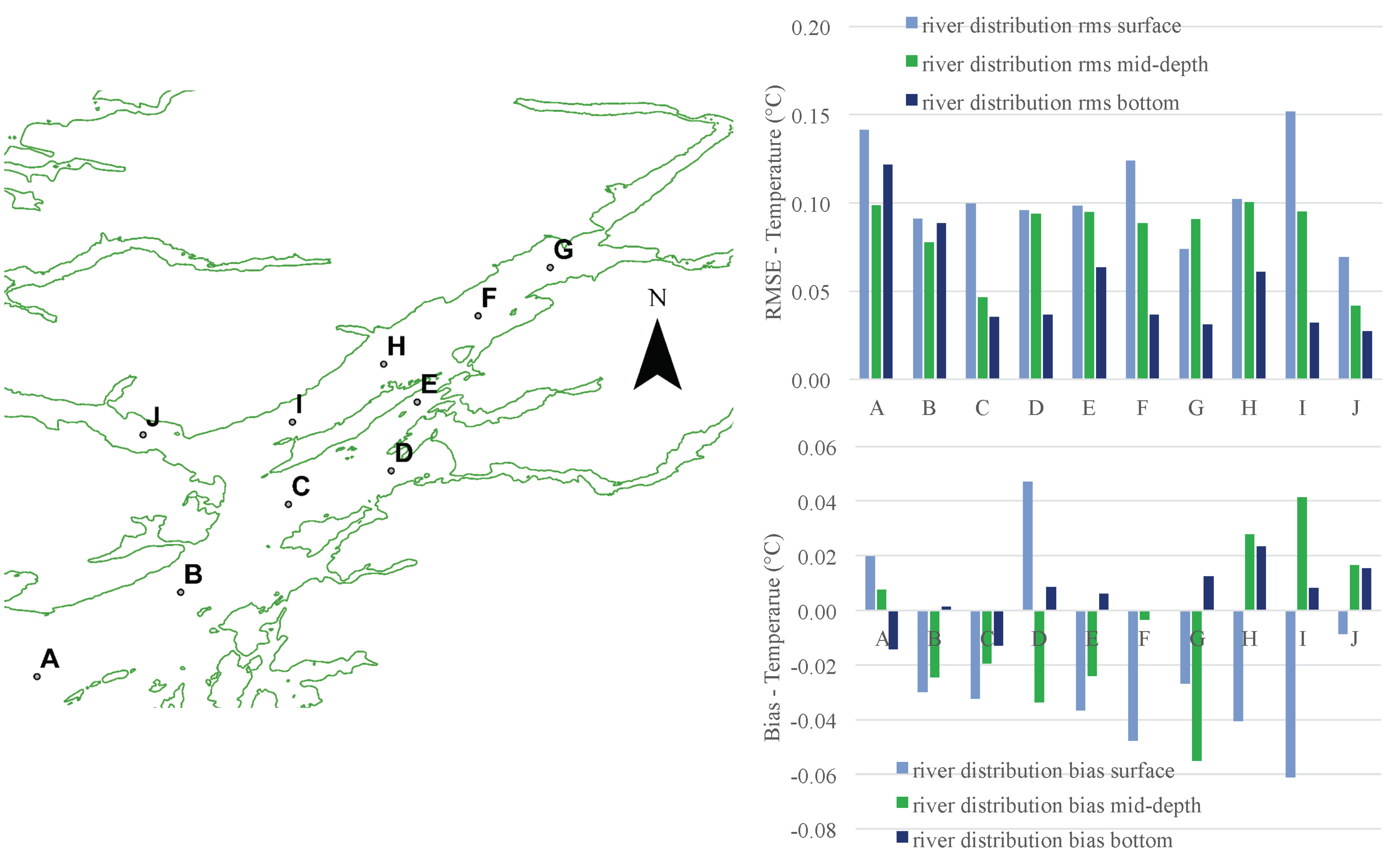
The salinity comparisons however, show clearly the influence of the distribution of the rivers. The maximum RMS difference and bias are seen at location D (2.4 and 1.7 psu) and E (1.3 and 1 psu) in the surface waters. This can be expected due to the increase in the distance the fresh water must travel before reaching these point when redistributed further up the Loch. In the mid bed level measurements the RMS difference and bias do not exceed 0.5 and 0.4 psu, and in the deep water the difference and bias do not exceed 0.1 and 0.05 psu. Away from the mouth of Loch Etive the influence is small even at the surface with RMS difference and bias less than 0.3 and 0.2 psu respectively at any level or location. A number of CTD comparisons with measured data and the calibration and sensitivity run are shown in Figure 4-26a-e, these plots support the argument that the change in temperature is minimal and the change in salinity is most significant near to the Loch mouth at the surface.

| | 324 | 326 |
|---|---|---|
| Mean discharge ($m^3/s$) | 100.2 | 1.2 |
| Max discharge ($m^3/s$) | 868.0 | 9.86 |

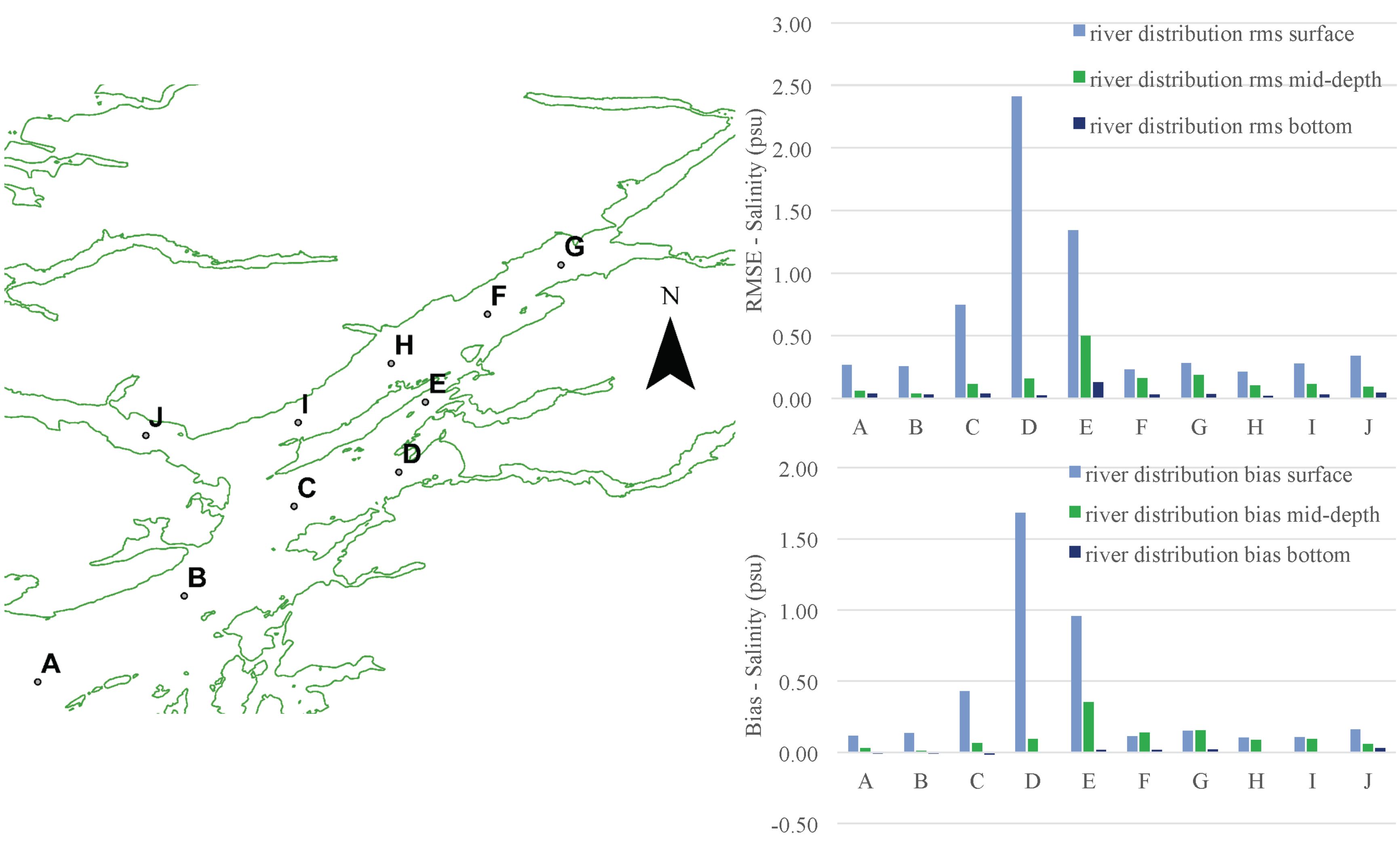
| River Number | Area Ratio |
|---|---|
| 665 | 0.14 |
| 666 | 0.09 |
| 667 | 0.76 |
| 668 | 0.02 |



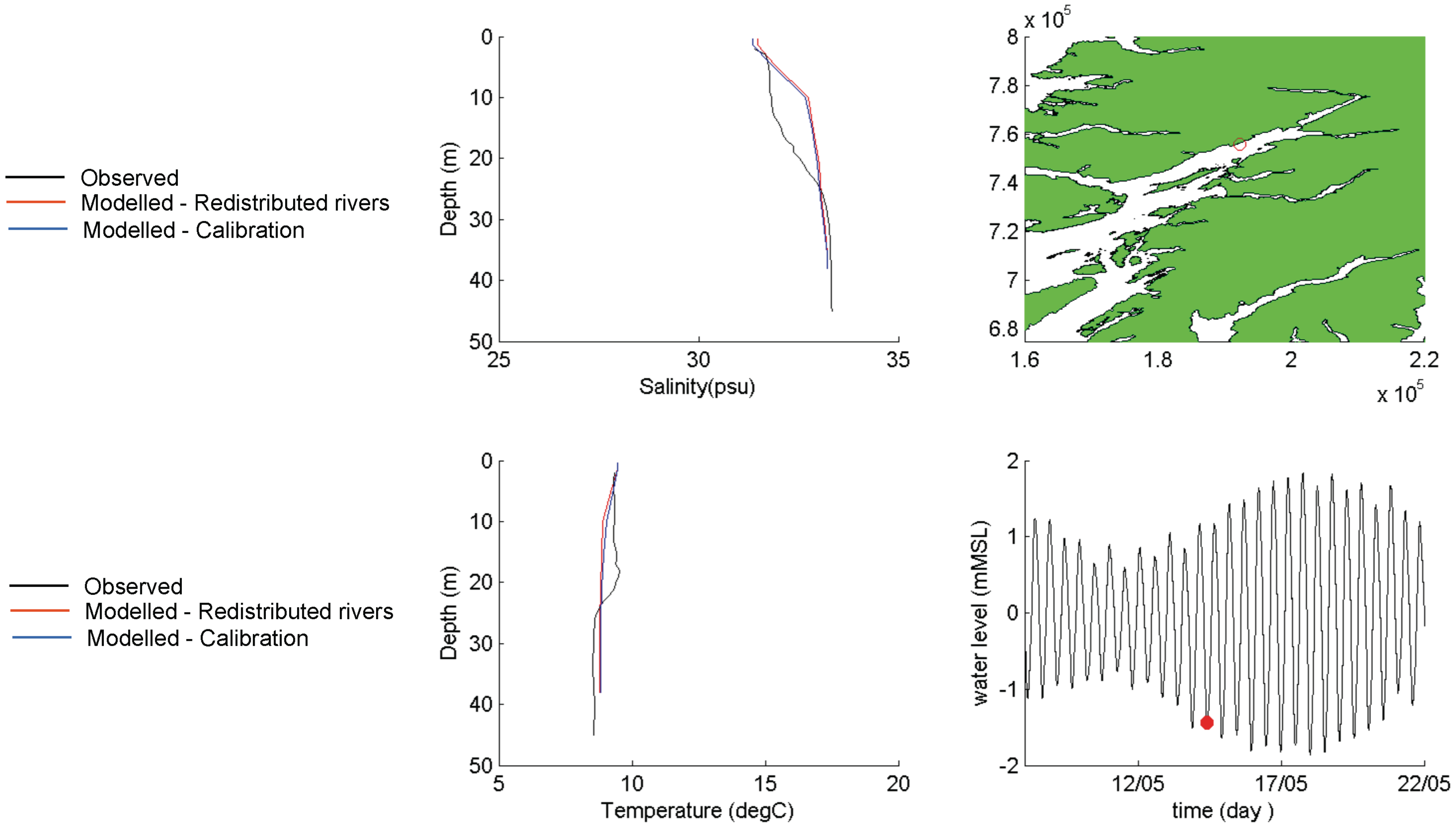

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-23 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | River locations 665 to 668 show the location of the redistributed flows. River 326 was mistakenly redistributed instead of river 324 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



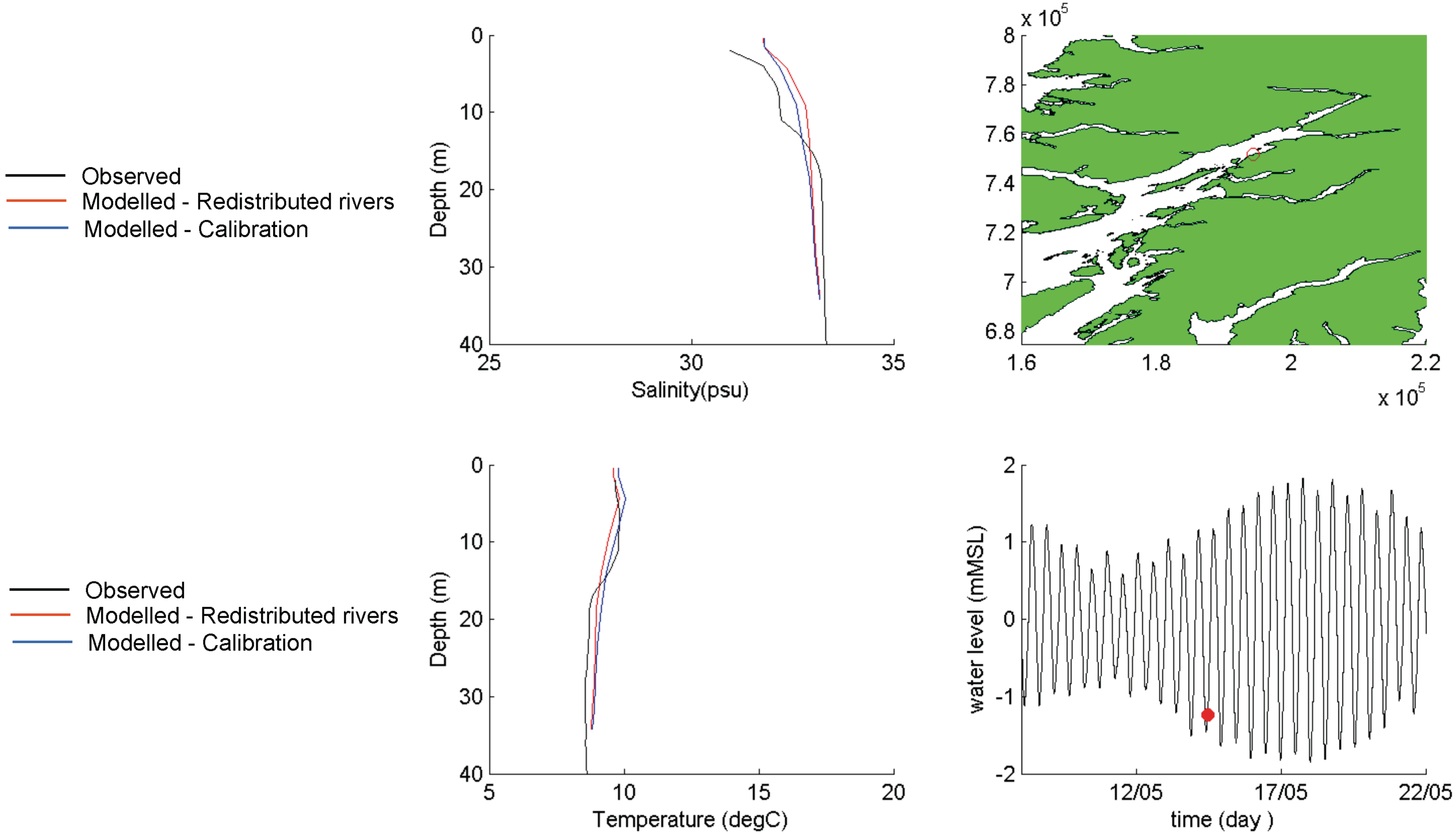

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-24 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Temperature sensitivity to river distribution at a number of locations around the mouth of Loch Etive | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



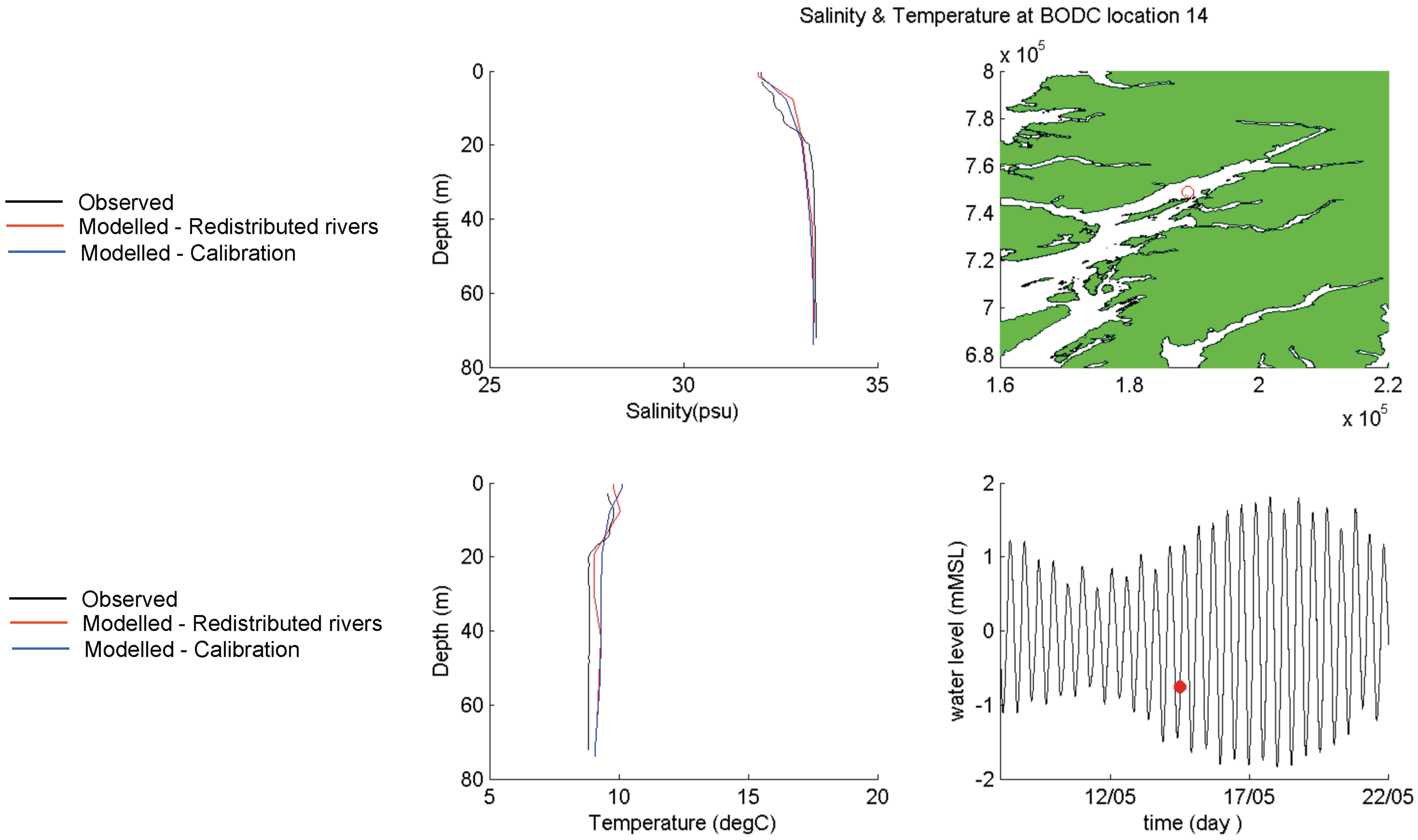

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-25 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Salinity sensitivity to river distribution at a number of locations around the mouth of Loch Etive | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



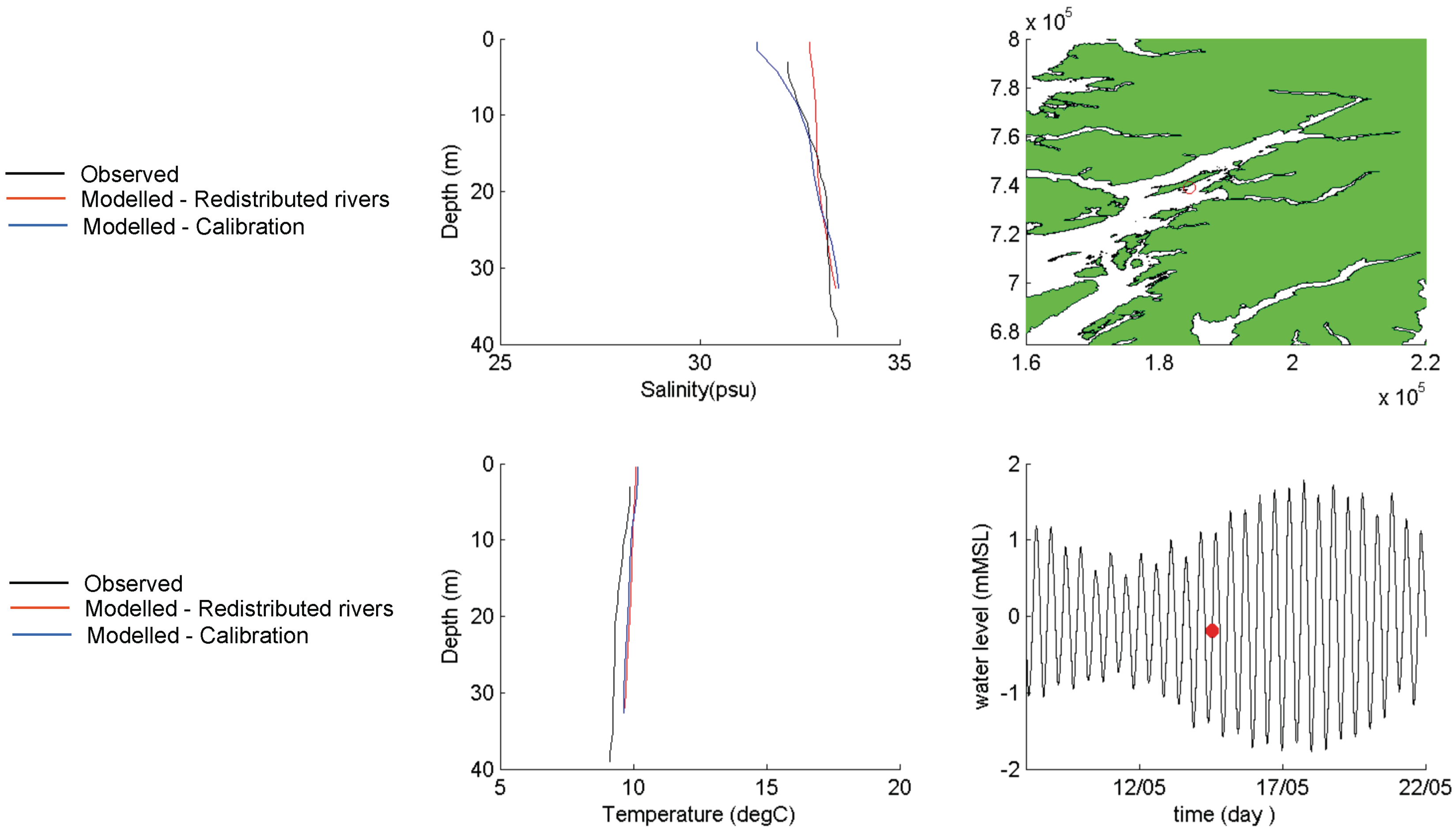

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-26a | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparisons of calibration and corrected river distribution in lich Etive with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |



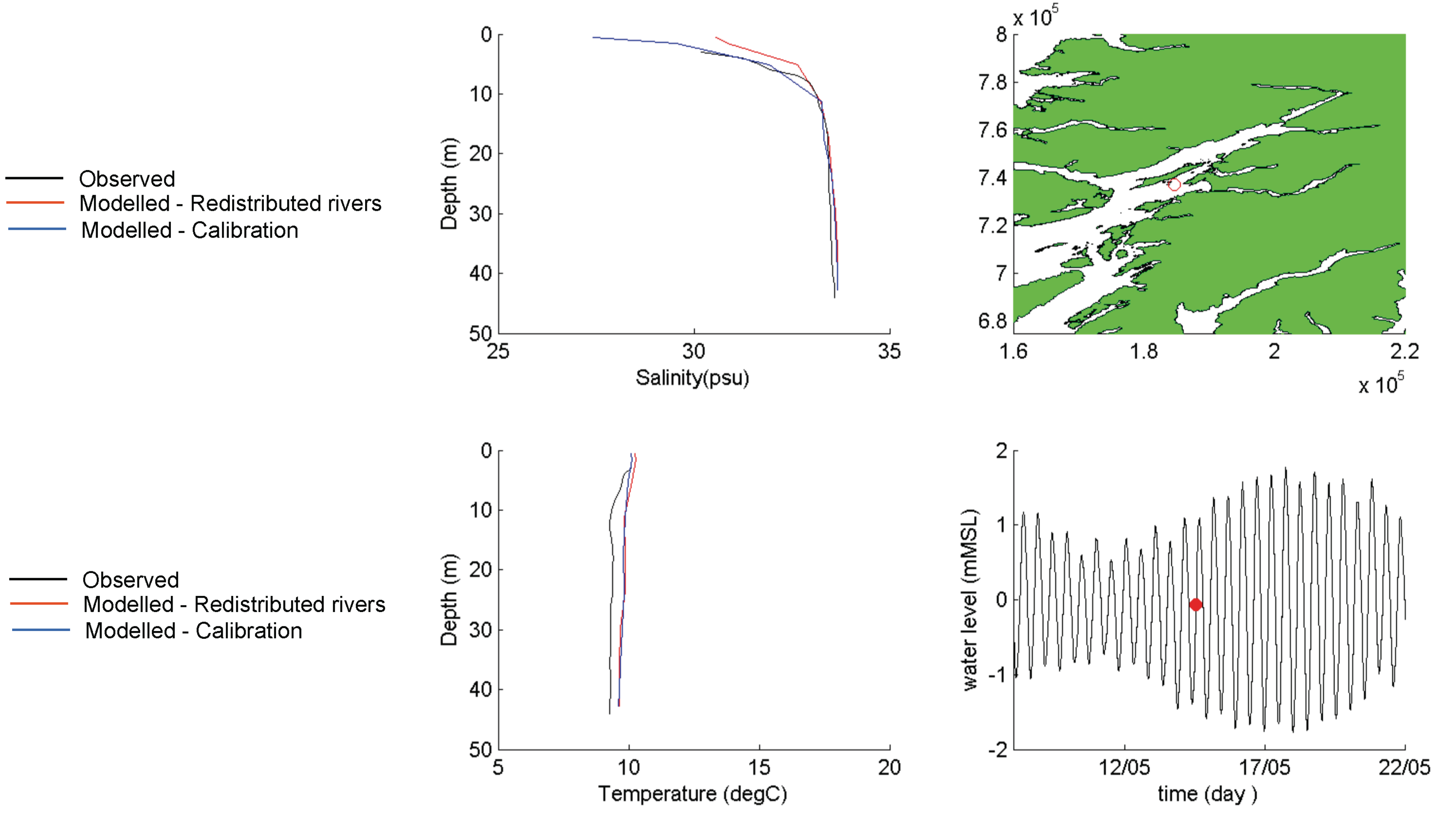

| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-26b | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and corrected river distribution in lich Etive with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-26c | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and corrected river distribution in lich Etive with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-26d | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparisons of calibration and corrected river distribution in lich Etive with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure 4-26e | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons of calibration and corrected river distribution in lich Etive with vertical profile CTD measurements May 2011 | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed | Drawn | Date 14/112012 |

# 5 Summary and Conclusions

## 5.1 Introduction

This report documents the work carried out in developing the Wider Loch Linnhe System (WLLS) model. This work includes: data collated for the numerical modelling, setup, calibration and validation of the flow model, and longer term (six month) simulations for 2011 and 1991 and the year-long climatology simulation required for this study.

The FVCOM model was chosen because of its capabilities as well as it being freely available, which then fulfils the aim for this and other models developed under the same project to become community models.

## 5.2 Hydrodynamic model calibration and validation

The WLLS hydrodynamic model was setup using bathymetry taken from a number of sources, from the freely available but coarser EMODnet/NOOS data, to the UKHO and Marine Scotland higher resolution datasets. Where data from these sources was not readily available, Admiralty Charts were digitised (with permission from the Hydrographic office) to fill in any gaps. All bathymetry was reduced to mean sea level as the common datum.

The model mesh was created with the SMS mesh generator using a spherical coordinate system (latitude and longitude). The model was run with 10 vertical sigma layers of variable thickness with a vertical datum of Mean Sea Level (MSL). The variable depths had two layers at the surface which are 1m thick, and two layers at the bottom each being 2.5m thick. The remaining 6 layers were equally spaced.

An analysis of the data available for forcing the hydrodynamic (HD) model showed that periods in 2011 were the most appropriate as calibration and validation periods, as all of the necessary forcing data required by the model are available. Datasets for calibration and validation of the model in the form of timeseries of water levels and current speeds were also available within Loch Linnhe and Loch Sunart. Additionally temperature and salinity profiles were available for comparisons with the model.

Boundary conditions for water levels, depth-averaged currents, temperature and salinity were taken from the Atlantic Margin Model (AMM) developed by NOC-L. These were applied using a nested boundary approach. Water levels and currents were provided at hourly intervals, whereas the temperature and salinity were provided at daily intervals for each of the 40 layers in the AMM. Much of the meteorological forcing was provided by NOC-L and derived from the Met Office model (i.e. wind components, air temperature, air pressure and precipitation. The remaining parameters came from the ECMWF (i.e. radiation, evaporation, relative humidity). The heating input was calculated internally by FVCOM rather than provided externally. This was found to provide the best results for sea surface temperature. River flow data was provided by CEH from their Grid to Grid model. At three of the large lochs where river flow was specified at the mouth in the CEH dataset, the flows were redistributed to all the rivers feeding the Lochs. River salinity was set at 0 psu, and temperature at 7 degrees Celsius, which was felt appropriate when considering the observed nearshore water temperatures. This was later increased to 10 degrees Celsius after consideration of the climatology results and based on limited published data on annual mean temperature in Scottish rivers. Therefore all 2011 simulations have been run with a river temperature of 10 degrees Celsius and the climatology simulations have been run with a river temperature of 7 degrees Celsius.

Comparisons between the model results and measurements of water level and current speeds showed reasonable agreement, the location of measured data within eddies made it difficult to exactly replicate the timing and direction of peak flows. Comparisons of the 10 layer baroclinic model showed that salinity comparisons with data were generally within 1 psu and the temperature comparisons were within 0.5 Celsius in line with our target.

## 5.3 2011 simulations

A six month simulation of May to October 2011 was required. The inputs used in this model run are from the same sources as the calibration and validation runs. As with those runs the comparison with surface currents, temperature and salinity at the data buoy were reasonable considering the location of the data buoy within an eddy. Temperatures were overestimated during the summer months but fell back in line with measured temperatures for October. This implies that the model heats and cools at a higher rate than seen in measured data. The salinity CTD comparisons show an increase in salinity during May (1 psu) and October (2 psu) compared to the calibration and validation runs. This illustrates the importance of the initial conditions on the results. Alternatively, it may also suggest that the input of fresh water during this period is underestimated by the G2G model data.

## 5.4 1991 simulation

A six month simulation of May to October 1991 was also required. The data sources for 1991 vary from those used in 2011. The water level, current, temperature and salinity data came from the POLCOMS 12km model provided by NOC-L. No met forcing was available from the AMM model, so all parameters apart from wind were taken from the ECMWF interim datasets. Wind data was available from the met office model at hourly intervals on a 50km grid. River flow data from Marine Scotland for 3 rivers in Upper Loch Linnhe and diffuse inputs for the other catchments were used.

Overall the 1991 model runs replicate the water levels, currents and salinity in the WLLS well. The current comparisons in particular were an improvement on the data buoy comparisons for 2011. This supports the suggestion that the location of the data buoy has an influence on the current comparisons. The temperature comparisons were not as good, with the model heating up and cooling down at a higher rate than seen in the measured data. The stratification of the water column was picked up well by the model even though in some cases the absolute values were 1-2 degrees Celsius and 1-2 psu.

## 5.5 Climatology simulations

Another requirement of this study was to produce a one year climatic run based upon climatological forcing to represent a typical annual cycle. The model was therefore run for the period January to December. Mean boundary forcing for water levels (mean yearly tides), currents, temperature and salinity were taken from the Scottish Waters Shelf Model climatology results. An efficient method was developed to interpolate the forcing data onto the nested boundary nodes and elements. River climatology was also provided by CEH and used for this study following analysis by NOC-L, river salinity was set at 0psu and temperature at 7 degrees Celsius. Meteorological forcing was derived by NOC-L from ECMWF (ERA-Interim) averaged data to provide monthly mean wind-stress, pressures, heating and evaporation minus precipitation from the period 1981-2010.

Average monthly temperature and salinity simulated by the model were compared against sea surface temperature and salinity climatological datasets and residual currents for the months of February and August; the results showed lower surface temperature in February but slightly higher temperatures in August. The salinity close to land was slightly lower than the comparison data in both months.

Mean spring and neap tidal ranges and currents were also calculated using M2 and S2 water level and current constituents and then compared against ABPmer model of the area. Comparisons are generally good, with the main difference found between the Outer Hebrides and Tiree, and at the mouth of Loch Linnhe. The ABPmer model does not resolve the channel between Skye and Mull and the mainland and the full extent of Loch Linnhe. The WLLS model does however resolve this channel and therefore this is likely to be the reason for the differences observed and the benefit of the finer resolution WLLS model.

# 6 References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# Appendix A

## Technical Note: Local wind conditions derivation

# WLLS Wind Analysis

PREPARED FOR: Marine Scotland

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DATE: 04-Sep-2015

PROJECT NUMBER: 462000

# 1. Part 1: Loch Linnhe

## 2. Introduction

One of the aims of the WLLS study was to include spatially and temporally variable wind in Loch Linnhe. The proposed approach was to obtain wind speed/direction from a number of sites in and around WLLS. The wind speeds and directions at the different sites are correlated against a reference site away from the complex topography. The result of this analysis is then used to determine the spatial variation of wind data within Loch Linnhe.

This note describes the procedure followed for the Wider Loch Linnhe System (WLLS) Wind Analysis and presents the main outcomes.

## 3. Data Overview

Data for 2011-2012 were available from the following sources:

- **MARLAB Data:** Duart, Fort William, Cuil Bay and Kingair Loch
- **SAMS Data:** Oban (Dunstaffnage data were available only until 2010 so were not considered)

A location map is shown in Figure 1. Duart and Oban are the two possible reference stations towards the mouth of Loch Linnhe. The rest (inside Loch Linnhe) are used for the correlation.

The common data periods for 2011-2012 were:

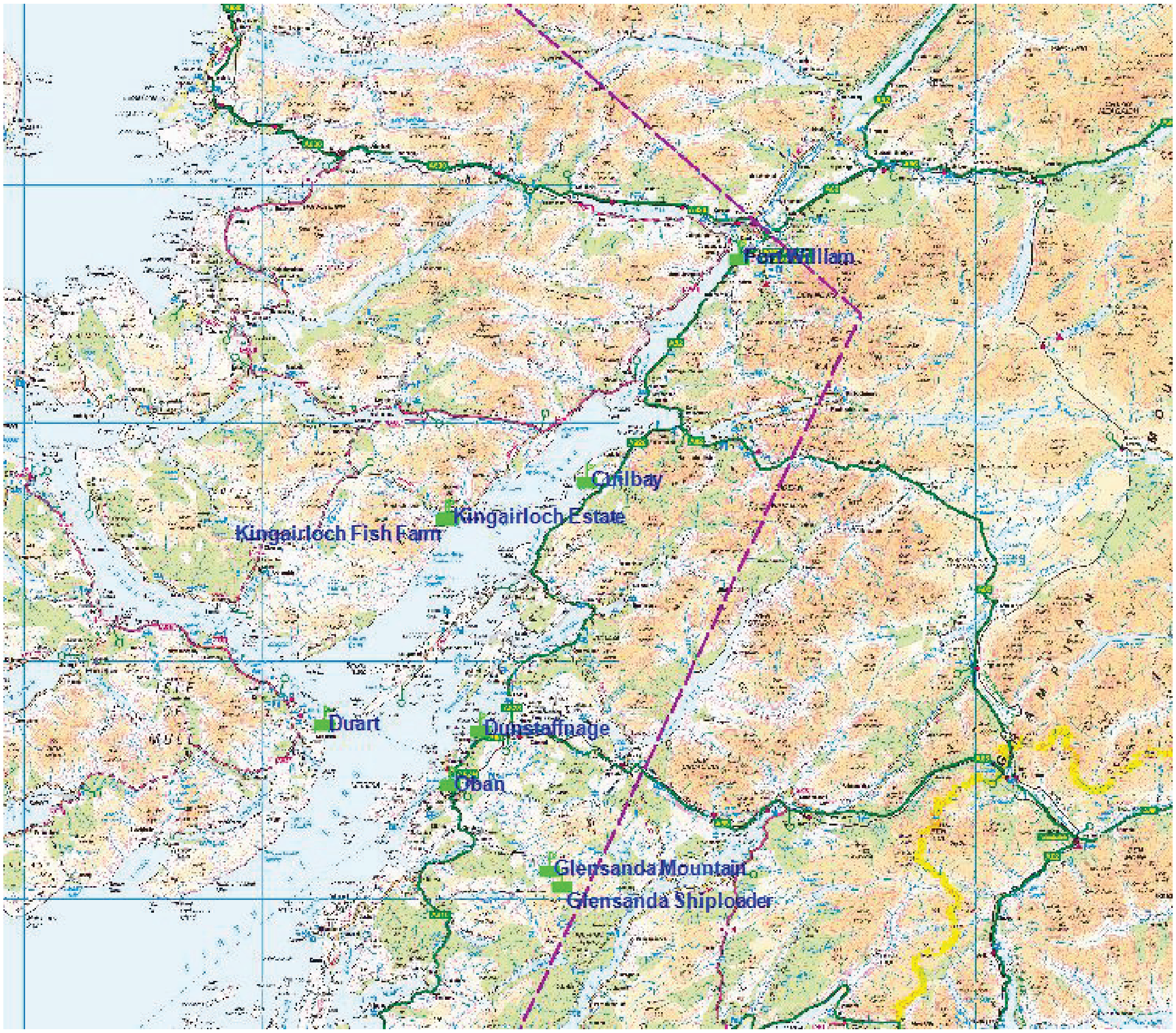
- **Dataset 1:** July-December 2011
- **Dataset 2:** April-October 2012

Adjustments to the wind speed data were carried out to correct the wind data at all stations to 2-hour averaged wind speeds and a common elevation of 10m above MSL. The adjustments are described below.

FIGURE 1

- **WLLS Stations Location Map**

*'Contains Ordnance Survey data © Crown copyright and database right 2013'.*




## 4. Wind speed adjustments

- For each station the following corrections were applied:
    - 2-hours averaged values (wind speeds and directions) were calculated for Oban (as the data were in 10min intervals) and in order to match the MARLAB stations and facilitate the correlation (conversion with a factor of 0.92 was applied as calculated per Figure II-2-1 in Coastal Engineering Manual – Part II – Chapter 2).

- Wind speeds adjustment for altitude to common height of 10m above sea level, by applying the “1/7” rule (see again CEM – Part II – Chapter 2). This approximation is given as

$$U_{10} = U_z \left(\frac{10}{z}\right)^{\frac{1}{7}} \qquad \text{(Eq. 1)}$$

- where z is measured in meters. The elevation of each station is detailed in Table 1.

- Land-based wind speeds were not adjusted for over sea wind speeds, as all the locations are near the shore.

TABLE 1
**WLLS Weather Stations Elevation and data Averaged Time**

| Station | Elevation (mASL) | Data averaged time (h) | Period Data Available | Source of Data |
|---|---|---|---|---|
| CuilBay | 4 | 2 | 19/04/2011-06/12/2011 and 26/03/201-23/10/2012 | MARLAB |
| Fort William | 8 | 2 | 25/07/2011-05/12/2011 and 01/01/2012-25/10/2012 | MARLAB |
| KingairLoch | 24 | 2 | 19/04/2011-02/12/2011 and 07/06/2012-29/08/2012 | MARLAB |
| Duart | 40 | 2 | 27/04/2011-06/12/2011 and 27/03/2012-24/10/2012 | MARLAB |
| Oban | 13 | 0.17 | 01/01/2011-30/12/2011 and 01/01/2012-28/11/2012 | SAMS |

The adjusted data are plotted in Figures 2 and 3 for the respective data periods. The Fort William values from April till August 2012 were considerably higher (probably equipment fault) and were excluded from the analysis.

FIGURE 2

- **WLLS Wind Speed Data 2011**

*Data period: July to December 2011.*

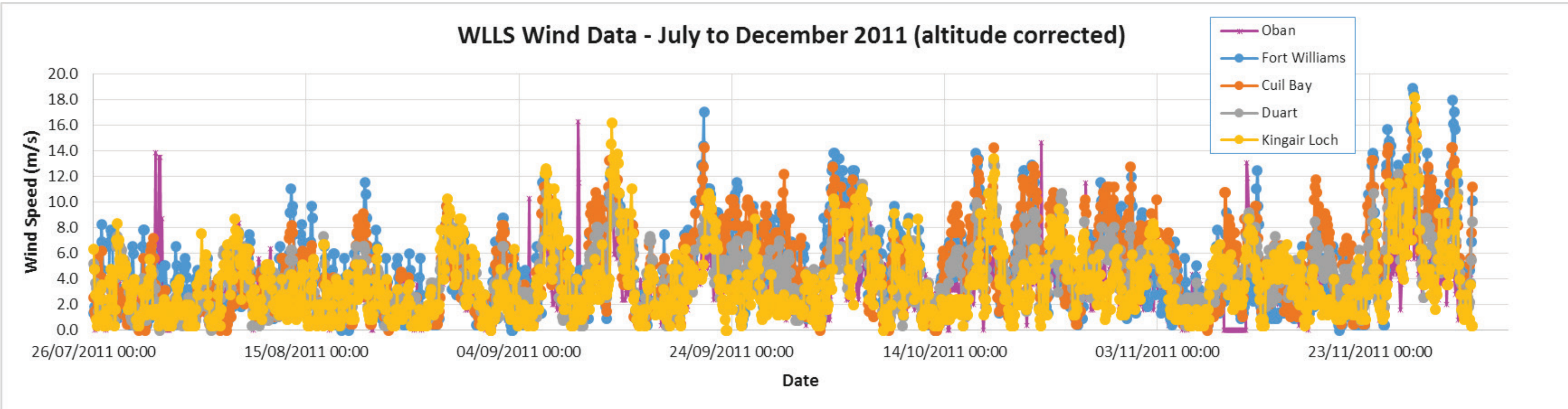
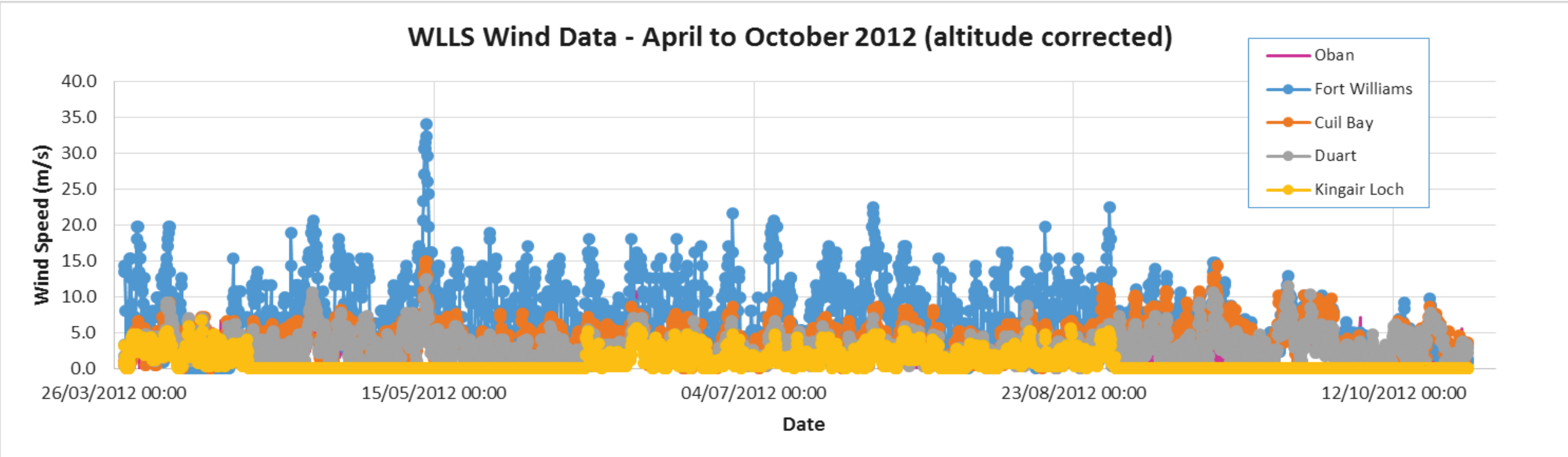


FIGURE 3

- **WLLS Wind Speed Data 2012**

*Data period: April to October 2012.*



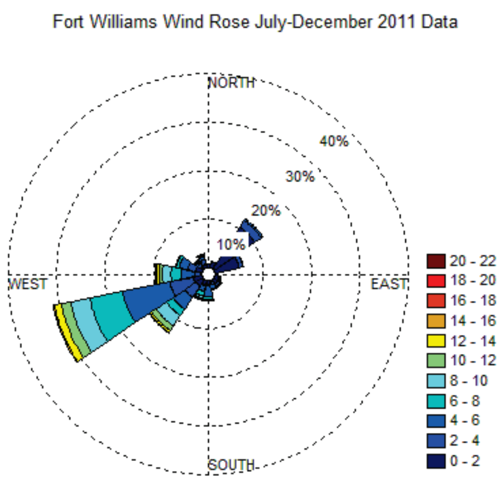
## 5. Wind roses

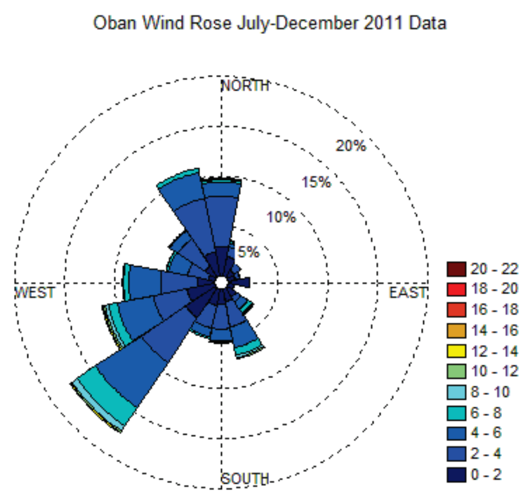
- Wind roses for each of the sites were plotted, making sure they cover same period so that comparison is fair. The wind roses for Datasets 1 and 2 are shown in Figures 4 and 5 respectively. In Dataset 1 South-West winds were predominant, probably due to the Loch Linnhe orientation. In Dataset 2 for almost all the stations mostly North-East and South-West wind directions can be observed except for Oban (East winds).

FIGURE 4

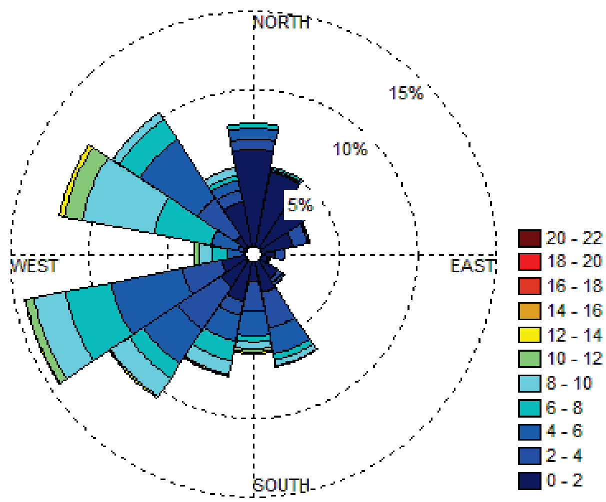
- **WLLS Wind Roses 2011**

*Data period: July to December 2011.*

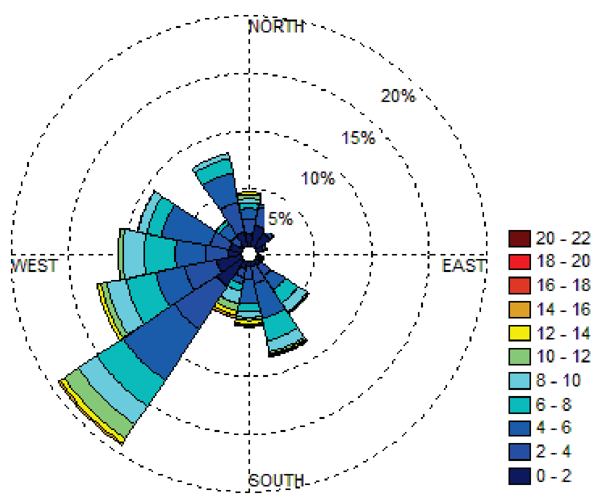


Cuil Bay Wind Rose July-December 2011 Data




Duart Wind Rose July-December 2011 Data




Kingair Loch Wind Rose July-December 2011 Data

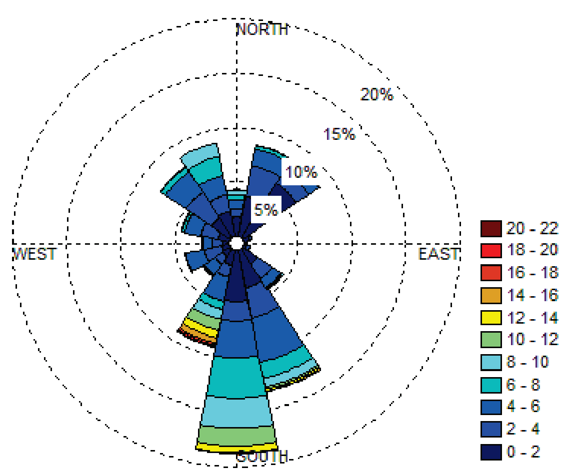
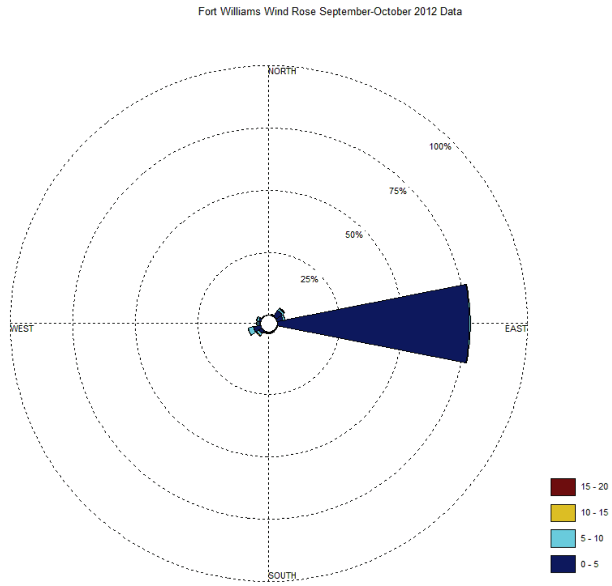
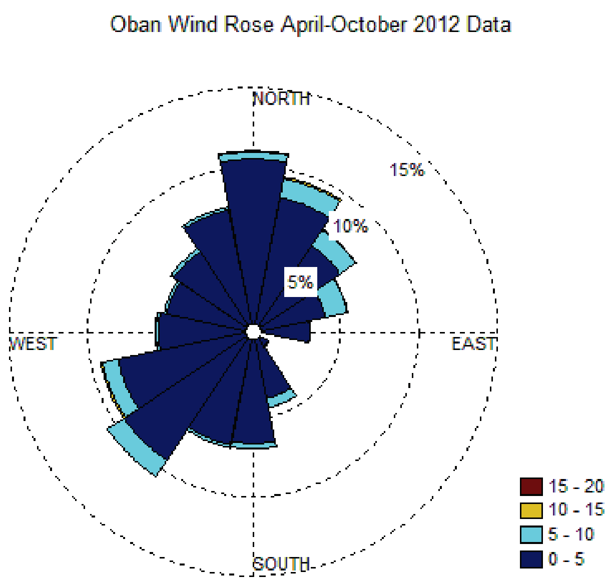


FIGURE 5

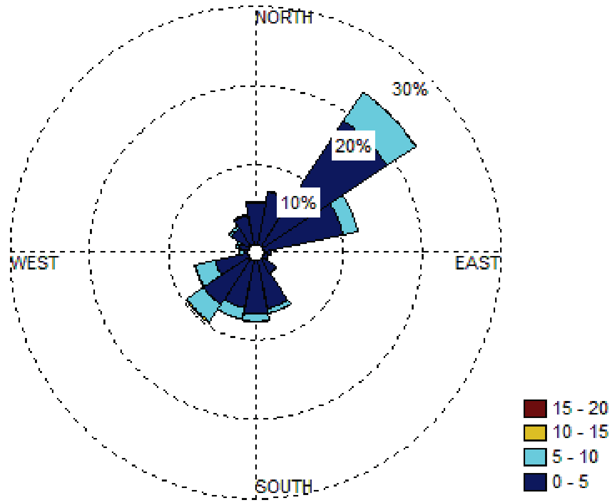
- **WLLS Wind Roses 2012**

*Data period: April to October 2012 (Kingair Loch data only from July to August 2012)*

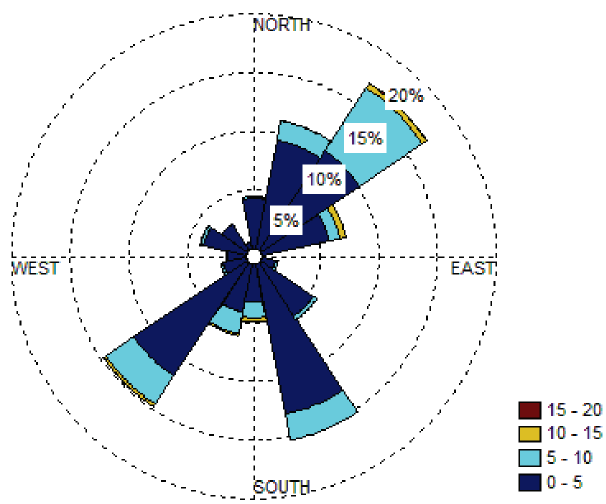


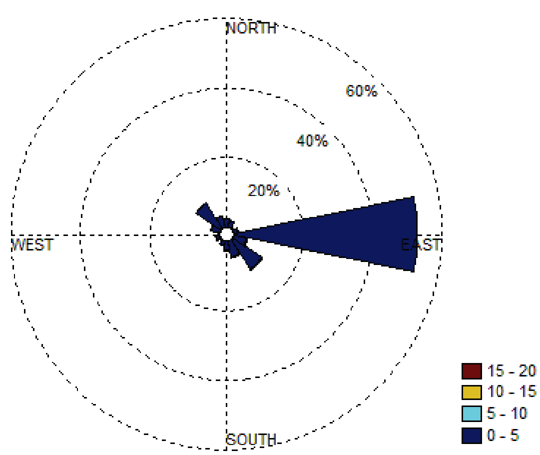
Cuil Bay Wind Rose April-October 2012 Data




Duart Wind Rose April-October 2012 Data




Kingair Loch Wind Rose July-August 2012 Data



## 6. Methodology

The methodology used for the wind analysis is outlined as follows:

- For each station inside the loch, wind speed ratio (wind speed at station / wind speed at reference station) and wind direction difference (wind direction at station - wind direction at reference station) are calculated for each of the 16 direction sectors. The reference station is selected as a station in a relatively exposed location outside the loch.
- A distance weighted algorithm is used to determine the map of wind speed and directions in the loch based on wind conditions at the reference station and the calculated wind speed ratio and wind direction differences.

The methodology is presented in more detail in the sub-sections below.

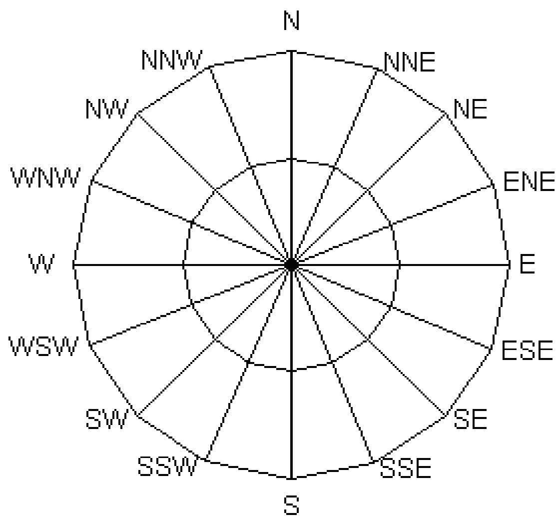
- The correlation for wind speed is done for a number of directional sectors. Because the original MARLAB data were given in cardinal directions they were converted in degrees according to Table 2 and Figure 6, resulting to 16 directional sectors. This obviously has a limitation for the directional correlation.

TABLE 2
**Reference table for wind direction conversion from cardinal to decimal**

| Wind Direction and Degrees | | |
|---|---|---|
| **Cardinal Direction** | **Direction sector (degrees)** | **Average wind direction (degrees)** |
| N | 348.75 - 11.25 | 0 |
| NNE | 11.25 - 33.75 | 22.5 |
| NE | 33.75 - 56.25 | 45 |
| ENE | 56.25 - 78.75 | 67.5 |
| E | 78.75 - 101.25 | 90 |
| ESE | 101.25 - 123.75 | 112.5 |
| SE | 123.75 - 146.25 | 135 |
| SSE | 146.25 - 168.75 | 157.5 |
| S | 168.75 - 191.25 | 180 |
| SSW | 191.25 - 213.75 | 202.5 |
| SW | 213.75 - 236.25 | 225 |
| WSW | 236.25 - 258.75 | 247.5 |
| W | 258.75 - 281.25 | 270 |
| WNW | 281.25 - 303.75 | 292.5 |
| NW | 303.75 - 326.25 | 315 |
| NNW | 326.25 - 348.75 | 337.5 |

FIGURE 6

- **Cardinal System for Wind Direction Index**




- The correlation analysis resulted to 18 spreadsheets – look up tables: 2 possible reference stations outside Loch Linnhe (Duart and Oban) and 3 station inside Loch Linnhe (Fort William, Cuil Bay and Kingair Loch) for 3 datasets (Dataset 1, Dataset 2 and combined Datasets 1 and 2).
- For each station inside Loch Linnhe the following were calculated:
  - Average wind speed ratio (wind speed at station / wind speed at reference station) for each of the 16 direction sectors.
  - Average wind direction difference (wind direction at station - wind direction at reference station) for each of the 16 direction sectors.
- For each station, the following plots were produced:
  - Average wind speed ratio versus wind direction at reference station (1 plot for each correlation pair).
  - Average wind direction difference versus wind direction at reference station (1 plot for each correlation pair).

- The correlation plots with Duart as reference point for Datasets 1 and 2 combined are included in Appendix A and the XY plots (wind speed at Loch Linnhe stations against wind speed at Duart) are included in Appendix B.

- For each station and data period, a look up table was produced. The look-up tables derived using Dataset 1 are shown in Tables 3 and 4 for Duart and Oban (as reference stations) respectively.

TABLE 3

**Look up  table with Duart as reference station (Dataset 1)**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference Station | Duart | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Loch Linnhe Station | Cuil Bay | | | | | | | | | | | | | | | | |
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 1.2 | 1.0 | 1.0 | 0.8 | 0.9 | 0.9 | 1.2 | 1.1 | 1.3 | 1.3 | 1.2 | 1.2 | 1.0 | 0.7 | 0.7 | 0.8 | 1.2 |
| Wind Direction Differ | 3.5 | 3.9 | -4.6 | -12.7 | 17.7 | -1.1 | 21.5 | 12.2 | -16.6 | -33.0 | -33.8 | -27.3 | -11.4 | 26.6 | 20.3 | 16.1 | 3.5 |
| | | | | | | | | | | | | | | | | | |
| Loch Linnhe Station | Fort William | | | | | | | | | | | | | | | | |
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 1.4 | 0.9 | 0.7 | 0.7 | 0.6 | 0.9 | 1.0 | 1.0 | 1.3 | 1.6 | 1.6 | 1.6 | 1.3 | 0.9 | 0.9 | 1.2 | 1.4 |
| Wind Direction Differ | -48.8 | -10.1 | -2.4 | -10.2 | -28.7 | -21.0 | -16.2 | 0.9 | 1.2 | -16.6 | -32.7 | -32.6 | -42.0 | -15.6 | -4.5 | -42.9 | -48.8 |
| | | | | | | | | | | | | | | | | | |
| Loch Linnhe Station | Kingair Loch | | | | | | | | | | | | | | | | |
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 1.8 | 0.5 | 0.6 | 0.8 | 0.9 | 1.1 | 1.3 | 0.7 | 0.5 | 0.6 | 0.9 | 1.3 | 1.1 | 1.0 | 0.9 | 1.3 | 1.8 |
| Wind Direction Differ | 19.4 | -1.2 | -21.7 | -6.3 | 4.9 | -5.1 | -15.6 | -40.2 | -49.9 | -18.0 | 5.0 | 15.7 | 20.8 | -2.8 | -14.8 | 4.4 | 19.4 |

TABLE 4

**Look up table with Oban as reference station (Dataset 1)**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference Station | Oban | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| Loch Linnhe Station | Cuil Bay | | | | | | | | | | | | | | | | |
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 1.3 | 1.3 | 1.5 | 1.1 | 1.1 | 1.4 | 1.7 | 2.0 | 2.1 | 1.6 | 1.5 | 1.7 | 1.4 | 0.9 | 0.8 | 1.3 | 1.3 |
| Wind Direction Differ | 54.0 | 19.8 | -4.3 | -21.2 | -19.5 | -4.9 | 10.6 | -18.8 | -18.8 | -17.2 | -0.1 | 24.3 | 21.3 | 19.8 | 13.7 | 21.9 | 54.0 |
| | | | | | | | | | | | | | | | | | |
| Loch Linnhe Station | Fort William | | | | | | | | | | | | | | | | |
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 2.9 | 2.5 | 2.6 | 1.9 | 1.6 | 1.6 | 1.9 | 2.3 | 2.5 | 2.3 | 2.5 | 3.1 | 2.5 | 1.8 | 1.0 | 0.8 | 2.9 |
| Wind Direction Differ | 21.6 | 5.7 | -8.6 | 2.0 | 2.0 | 17.5 | 27.0 | 28.5 | 16.7 | 13.5 | 17.2 | 20.8 | 14.2 | 24.7 | 3.4 | -28.8 | 21.6 |
| | | | | | | | | | | | | | | | | | |
| Loch Linnhe Station | Kingair Loch | | | | | | | | | | | | | | | | |
| Look up Table | | | | | | | | | | | | | | | | | |
| From Direction (dgr) | 0.0 | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 |
| To Direction (dgr) | 11.3 | 33.8 | 56.3 | 78.8 | 101.3 | 123.8 | 146.3 | 168.8 | 191.3 | 213.8 | 236.3 | 258.8 | 281.3 | 303.8 | 326.3 | 348.8 | 360.0 |
| Wind Speed ratio | 0.7 | 0.8 | 0.8 | 0.7 | 1.0 | 1.1 | 0.8 | 0.8 | 0.9 | 0.9 | 1.3 | 1.8 | 1.7 | 1.3 | 1.3 | 2.2 | 0.7 |
| Wind Direction Differ | -19.8 | -22.5 | -35.2 | -41.5 | -18.9 | -21.5 | -23.4 | -7.3 | -2.9 | 10.3 | 21.8 | 17.1 | -8.0 | -23.1 | -0.9 | 18.1 | -19.8 |

- For validation, the look up tables derived using Dataset 1 and both Oban and Duart as reference stations were used to predict Dataset 2 and the results were compared to the observed values. The comparison plots are shown in Figures 8, 9 and 10. The RMS Error and the Bias were calculated as listed in Table 5.
- The results show that the errors with Duart as reference station is lower. Thus, Duart is used as reference station for the prediction of the wind speed and directions inside Loch Linnhe. For this purpose the combined Datasets 1 and 2 were used to calculate the wind speed ratios and wind direction differences.

TABLE 5

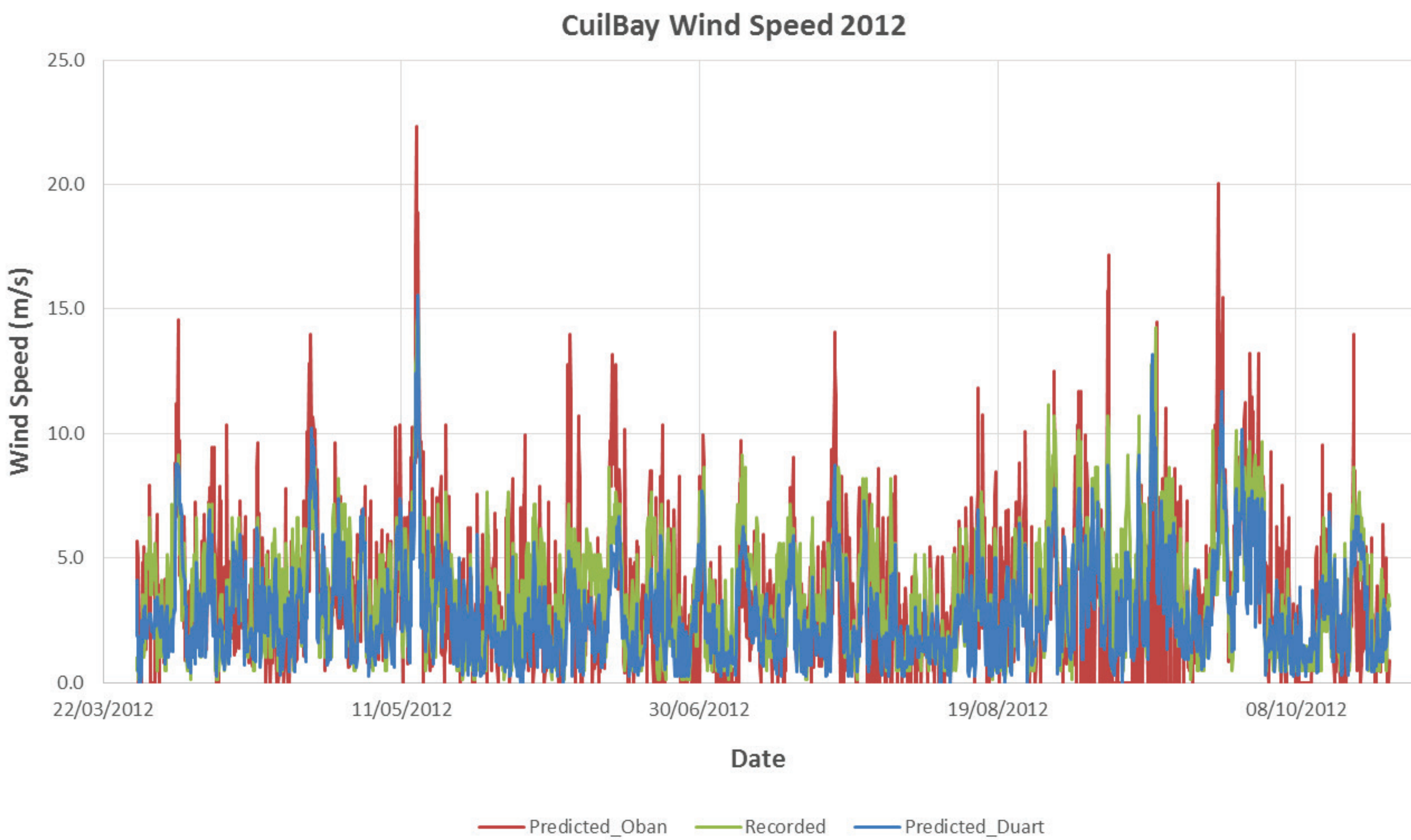
**RMS Error and Bias for the predicted Dataset 2 values (wind speed and wind direction)**

| | Wind Speed | | Wind Direction | |
|---|---|---|---|---|
| **RMS Error** | **Reference Station** | | **Reference Station** | |
| **Loch Linnhe Station** | **Duart** | **Oban** | **Duart** | **Oban** |
| **Cuil Bay** | 2 | 3 | 69 | 78 |
| **Fort William** | 2 | 5 | 59 | 88 |
| **KingairLoch** | 1 | 2 | 135 | 143 |

| **Bias** | **Reference Station** | | **Reference Station** | |
|---|---|---|---|---|
| **Loch Linnhe Station** | **Duart** | **Oban** | **Duart** | **Oban** |
| **Cuil Bay** | -1 | 0 | -3 | 0 |
| **Fort William** | -1 | 0 | 3 | 23 |
| **KingairLoch** | 0 | 1 | 1 | -2 |

FIGURE 8

- **Comparison between predicted and recorded Dataset 2 values for Cuil Bay**
-



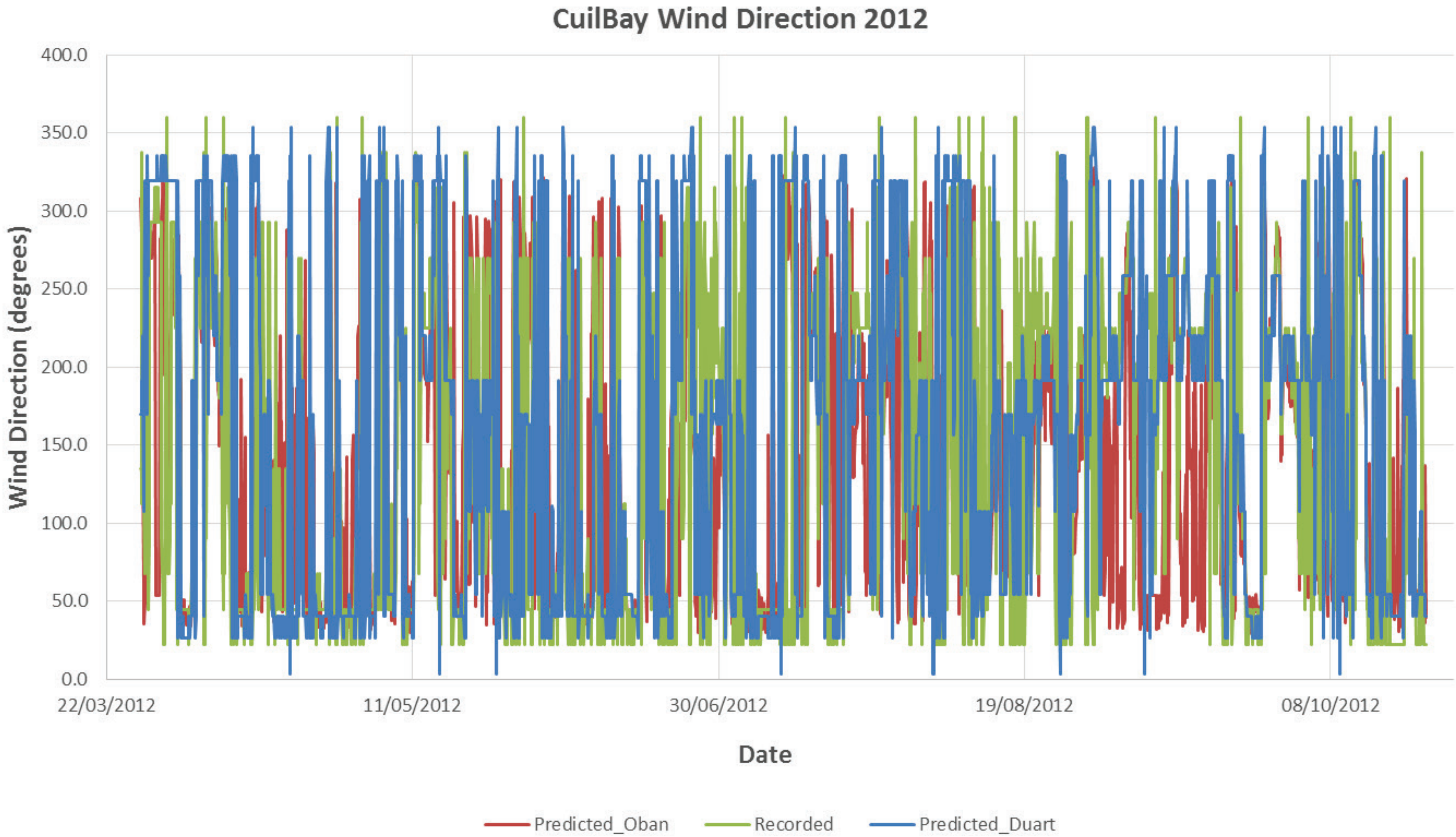
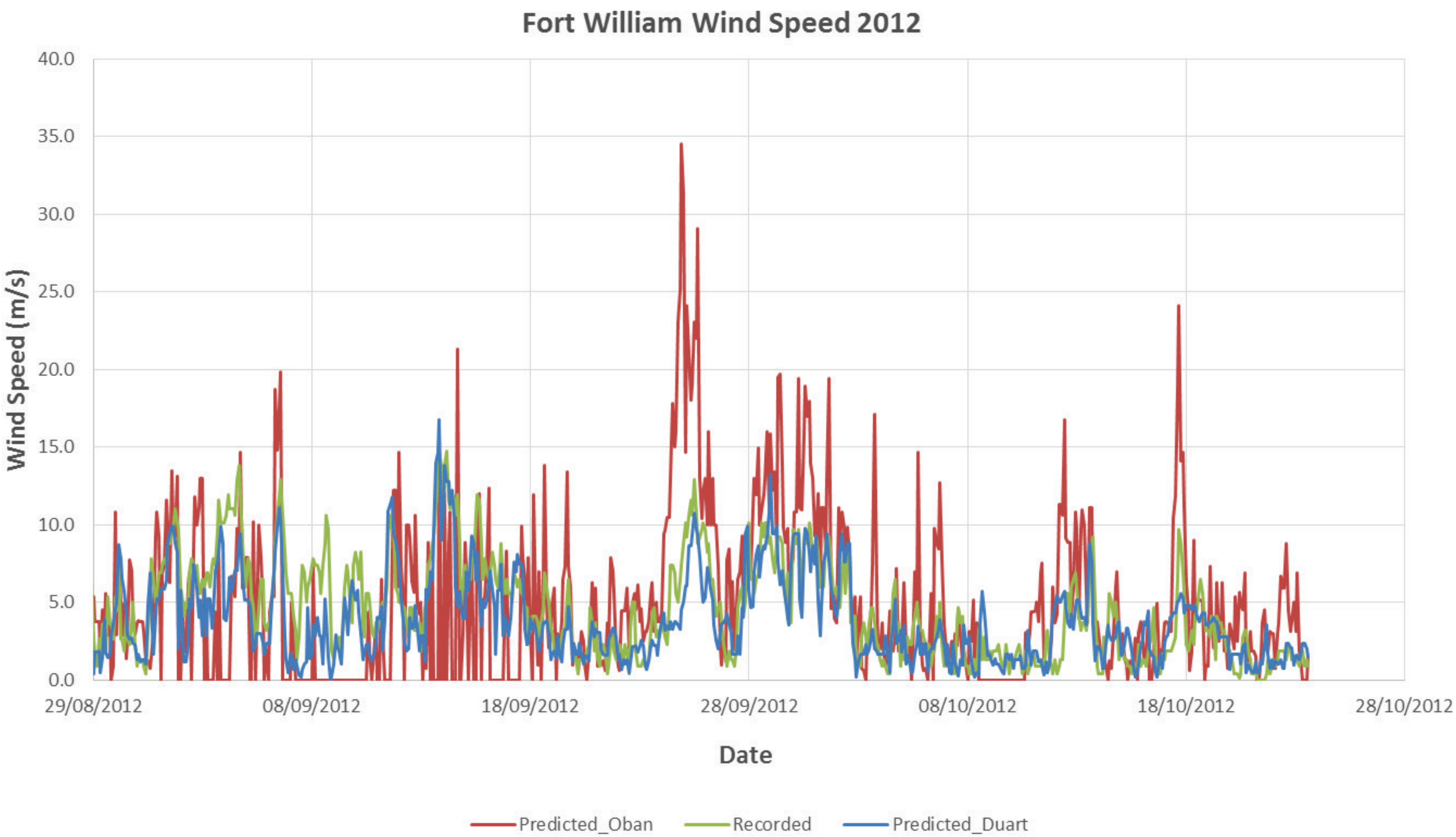

CuilBay Wind Direction 2012
Wind Direction (degrees)
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
22/03/2012
11/05/2012
30/06/2012
19/08/2012
08/10/2012
Date
Predicted_Oban
Recorded
Predicted_Duart

FIGURE 9

- **Comparison between predicted and recorded Dataset 2 values for Fort William**



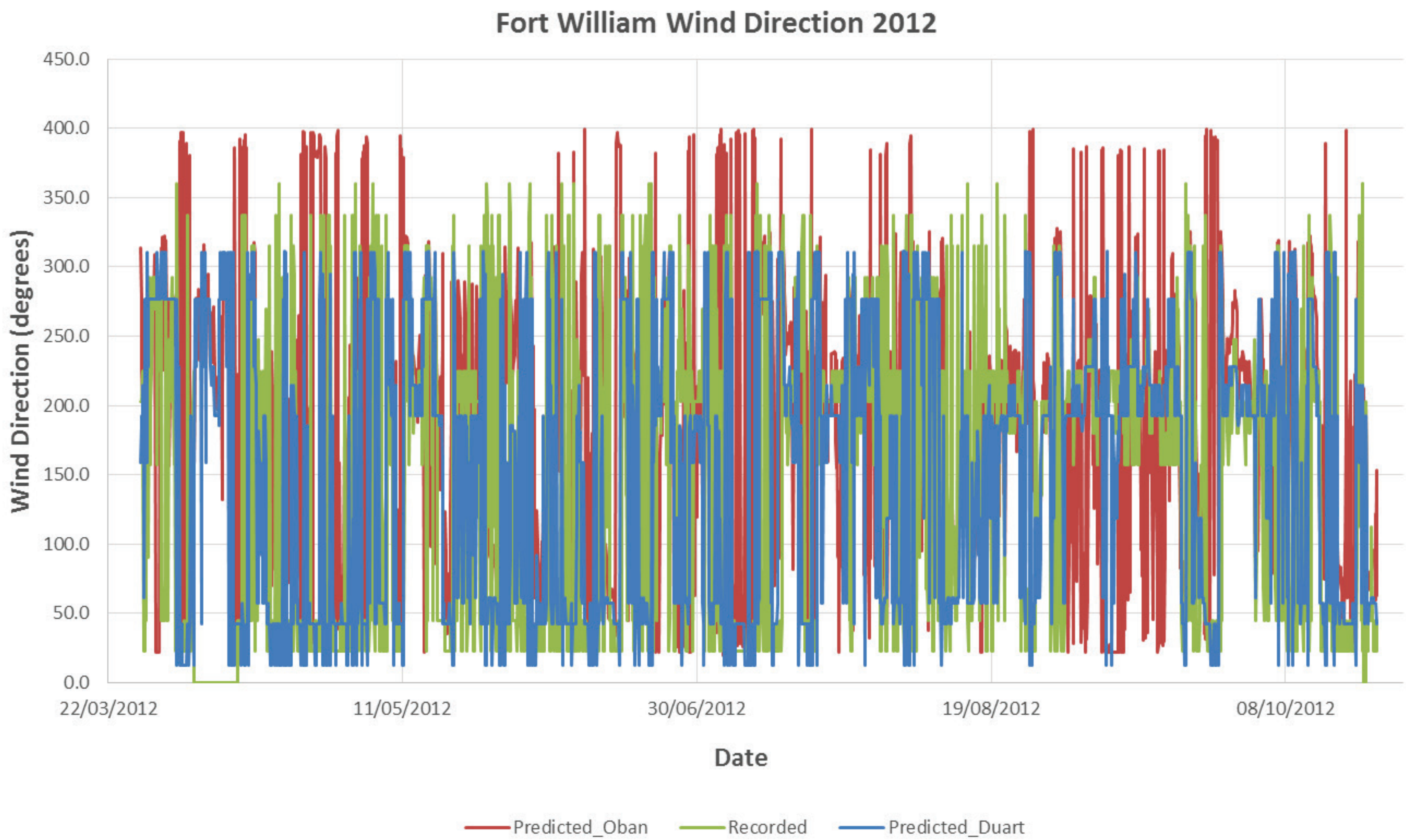
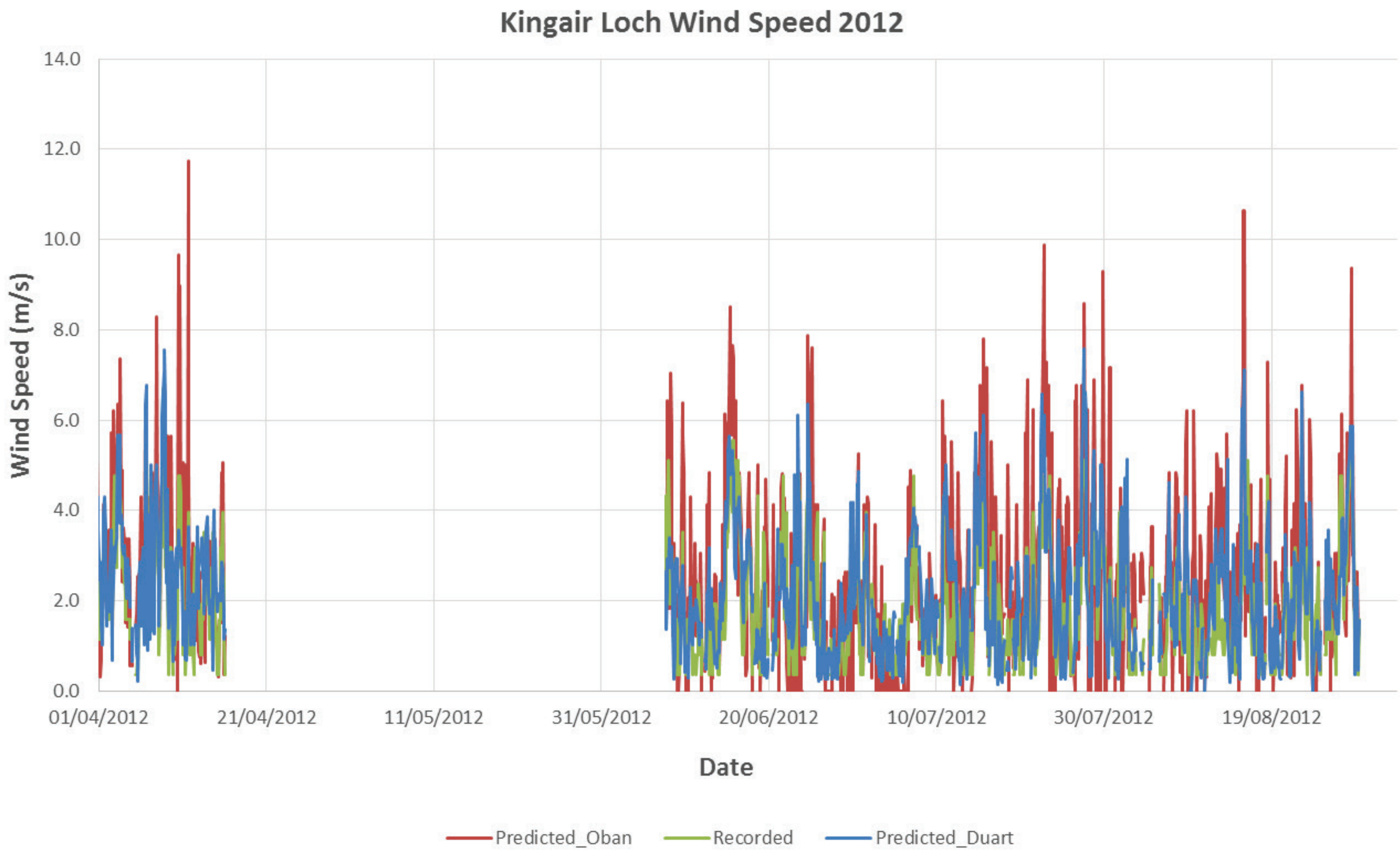
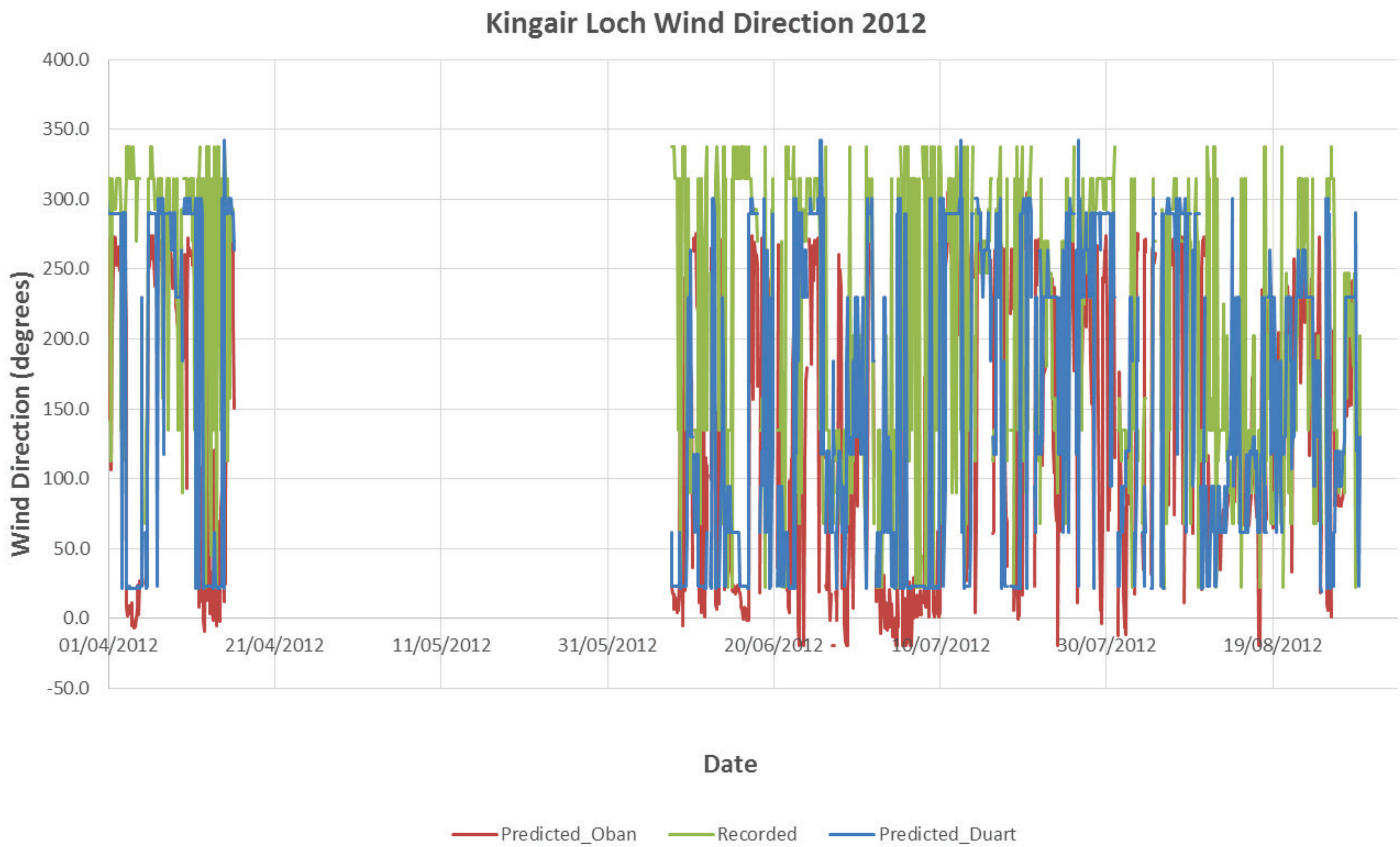

Fort William Wind Direction 2012
Wind Direction (degrees)
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
22/03/2012
11/05/2012
30/06/2012
19/08/2012
08/10/2012
Date
Predicted_Oban
Recorded
Predicted_Duart

FIGURE 10

- **Comparison between predicted and recorded Dataset 2 values for Kingair Loch**





Kingair Loch Wind Direction 2012
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
-50.0
Wind Direction (degrees)
01/04/2012
21/04/2012
11/05/2012
31/05/2012
20/06/2012
10/07/2012
30/07/2012
19/08/2012
Date
Predicted_Oban
Recorded
Predicted_Duart

## 7. Modified map of wind data over Loch Linnhe

## 8. Comparison of observed and UK met office wind data at Duart

For carrying out the model simulations, the primary data available is the meteorological data file provided by the UK Met Office. This data is modified over Loch Linnhe using the directionally dependent wind speed ratios and wind direction differences derived from stations in Loch Linnhe.

First, the wind speed and direction data extracted from the meteorological file at Duart are compared with the MARLAB data for the same station, as shown in Figures 11 and 12 below. These figures show that the wind data extracted from the Met Office is broadly consistent with the measured wind data at Duart.

FIGURE 11

- **Comparison between Duart wind speed – Met file vs MARLAB**

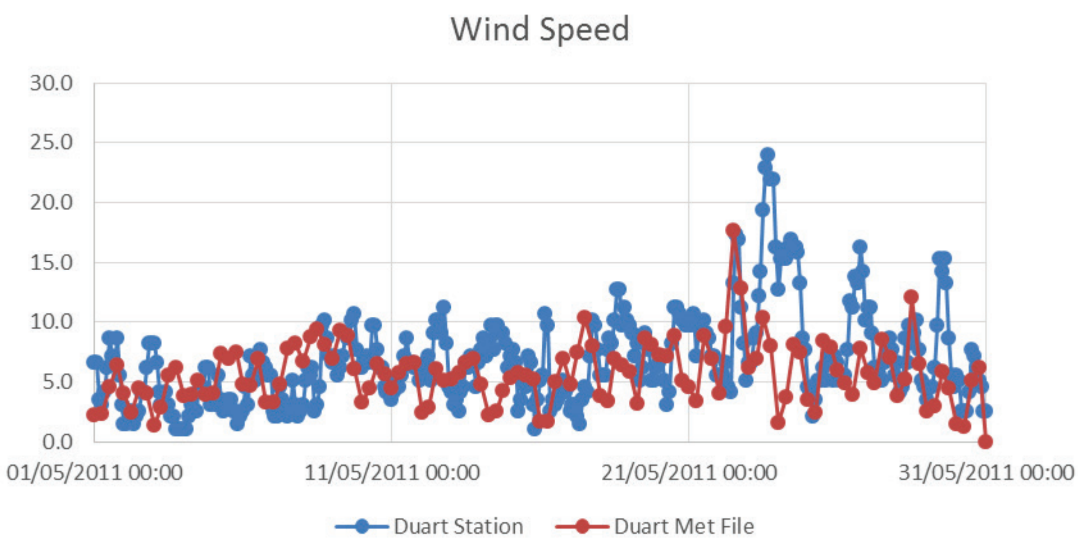
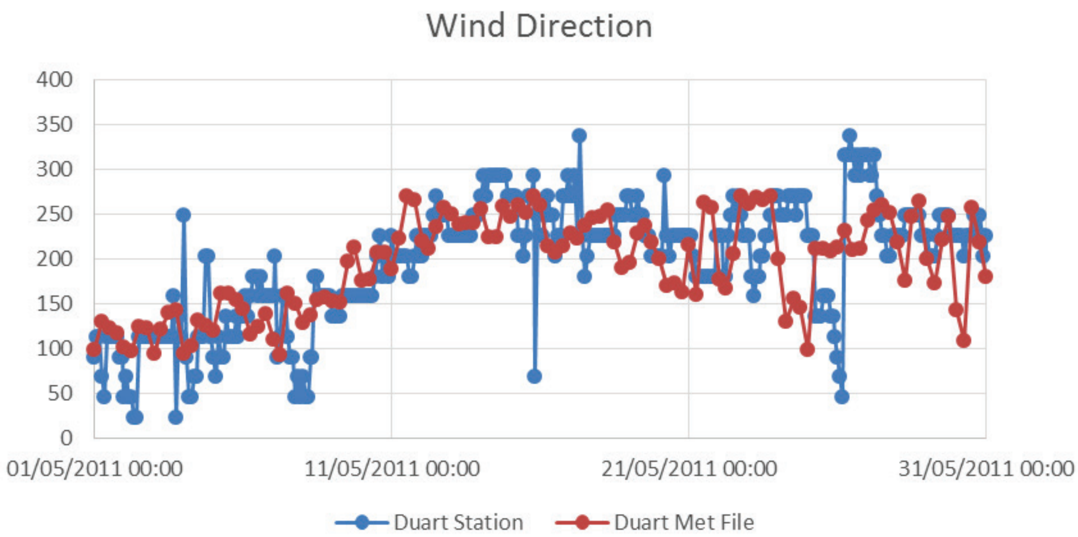


FIGURE 12

- **Comparison between Duart wind direction – Met file vs MARLAB**




## 9. Spatial variation of observed wind data in Loch Linnhe

The spatial variation of wind speed ratios in Loch Linnhe is illustrated in Figures 13 and 14 using the directional wind speed ratios at Fort William and Cuil bay. In both figures, the blue lines represent the calculated wind speed ratios, while the red lines represent the schematised variation. The key results are summarised in Table 6. This shows that for wind directions from 270 to 135 $^{o}$N (clockwise), the wind speed generally increases from Fort William through Cuil bay to Duart. On the other hand, for wind directions from 135 to 270 $^{o}$N, the wind speed increases from Duart through Cuil bay to Fort William.

The calculated wind speed ratios for Kingair loch station is shown in Appendix A. This location exhibits double peaks (peaks of about 1.2 for wind direction of 135 and 255 $^{o}$N) in the variation of wind speed ratios with directions at Duart. In particular, for wind directions from 135 to 255 $^{o}$N, the wind speed is lower at Kingair loch, in contrast to observations at Cuil Bay or Fort William. It is considered that this behaviour is due to localised topography at this station, hence this station was excluded from further analysis.

TABLE 6

**Variation in observed wind data at stations within Loch Linnhe**

| Direction Sector | Fort William | Cuil Bay |
|---|---|---|
| 0 – 135 $^{o}$N | Wind speed at Fort William is lower than at Duart. Minimum ratio of 0.65 for wind from 70 +/- 20 $^{o}$N. | Wind speed at Cuil Bay is lower than at Duart. Minimum ratio of 0.80 for wind from 70 $^{o}$N. |
| 135 – 270 $^{o}$N | Wind speed at Fort William is higher than at Duart. Maximum ratio of 1.55 for wind from 200 - 250 $^{o}$N. | Wind speed at Cuil Bay is higher than at Duart. Maximum ratio of 1.25 for wind from 150 - 250 $^{o}$N. |
| 270 – 360 $^{o}$N | Wind speed at Fort William is about 90% of wind speed at Duart. | Wind speed at Cuil Bay increases from 0.7 (270 $^{o}$N) to 1.0 (360 $^{o}$N) of the speed at Duart. |

Figure 15 shows in green the sector where the wind speed in Loch Linnhe is greater than wind speed at Duart and in red the sector where the wind speed in Loch Linnhe is lower than wind speed at Duart. For wind directions from 270 $^{o}$ N to 135 $^{o}$N (clockwise), the wind speeds over Loch Linnhe are lower than wind speed at Duart. This is due to Duart being relatively exposed, while Cuil Bay and Fort William are sheltered from these directions (due to the hills). For wind direction from about NW (wind blowing offshore along the alignment of Loch Linnhe), wind speed is expected to increase from Fort William to Cuil Bay and to Duart. This is reproduced in the data. For wind direction from SW (wind blowing onshore along Long Linnhe), wind speed accelerates within Loch Linnhe, and increases towards Fort William.

FIGURE 13

- **Simplification of Spatial Wind Speed Variation – Fort William**

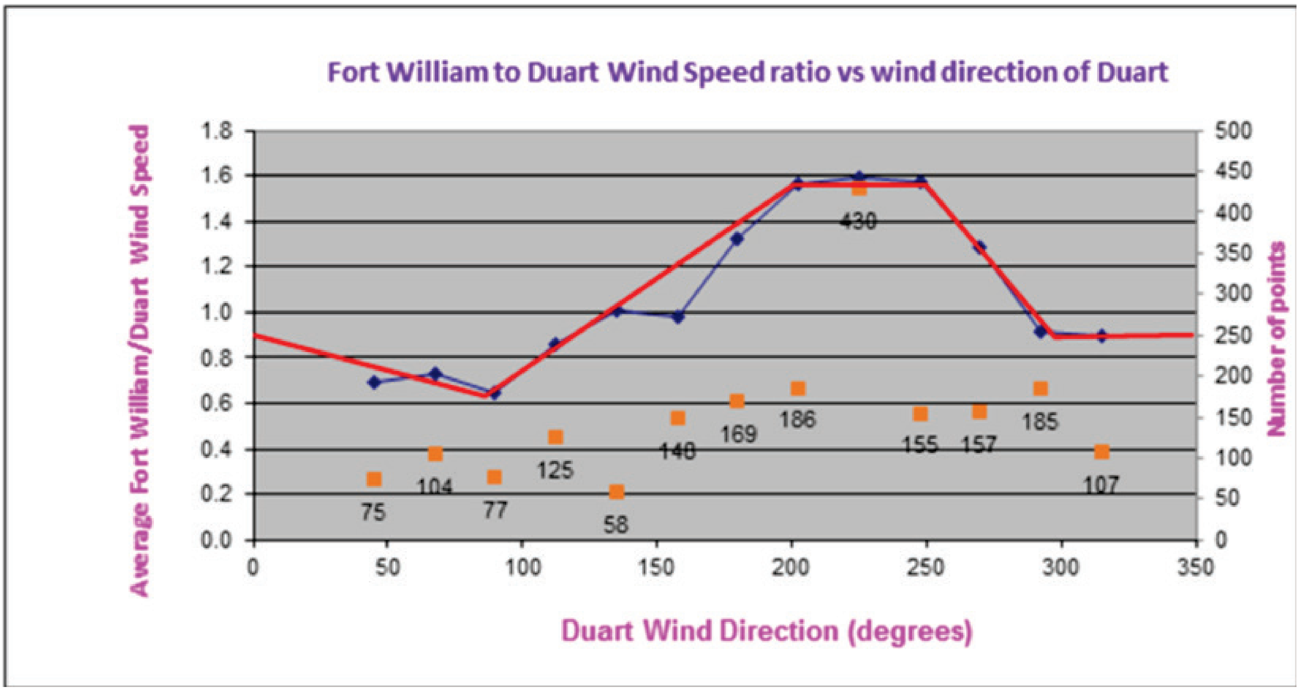



FIGURE 14

- **Simplification of Spatial Wind Speed Variation – Cuil Bay**

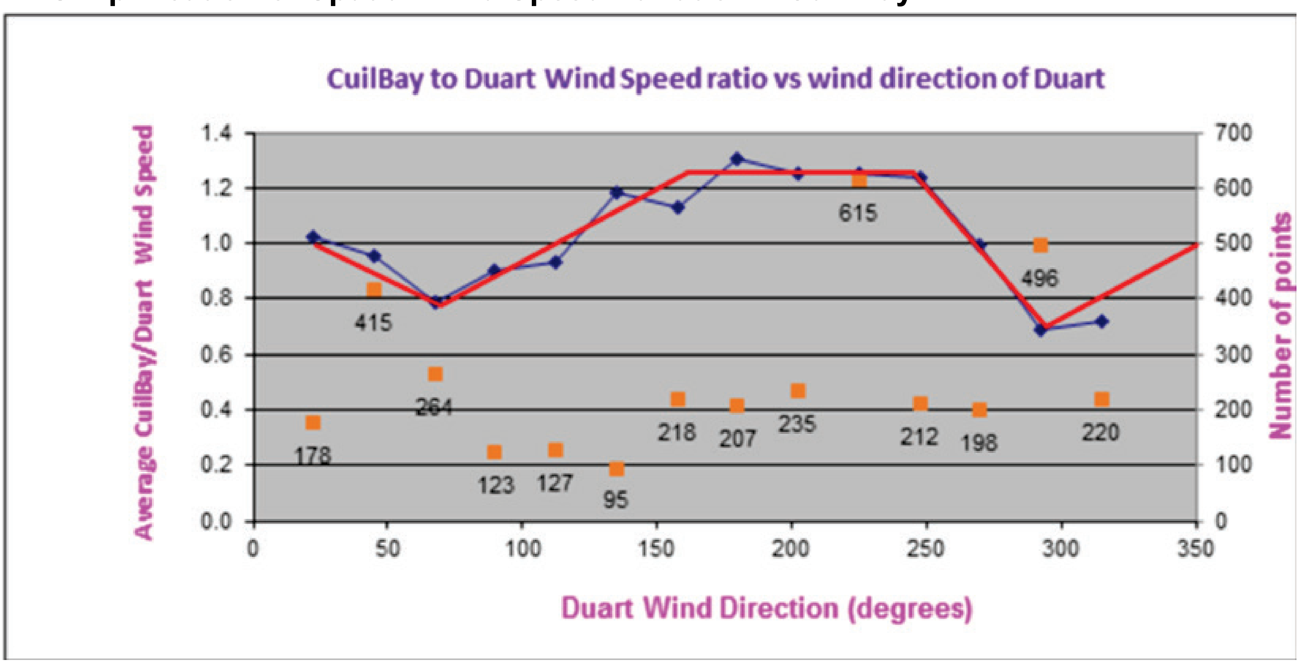
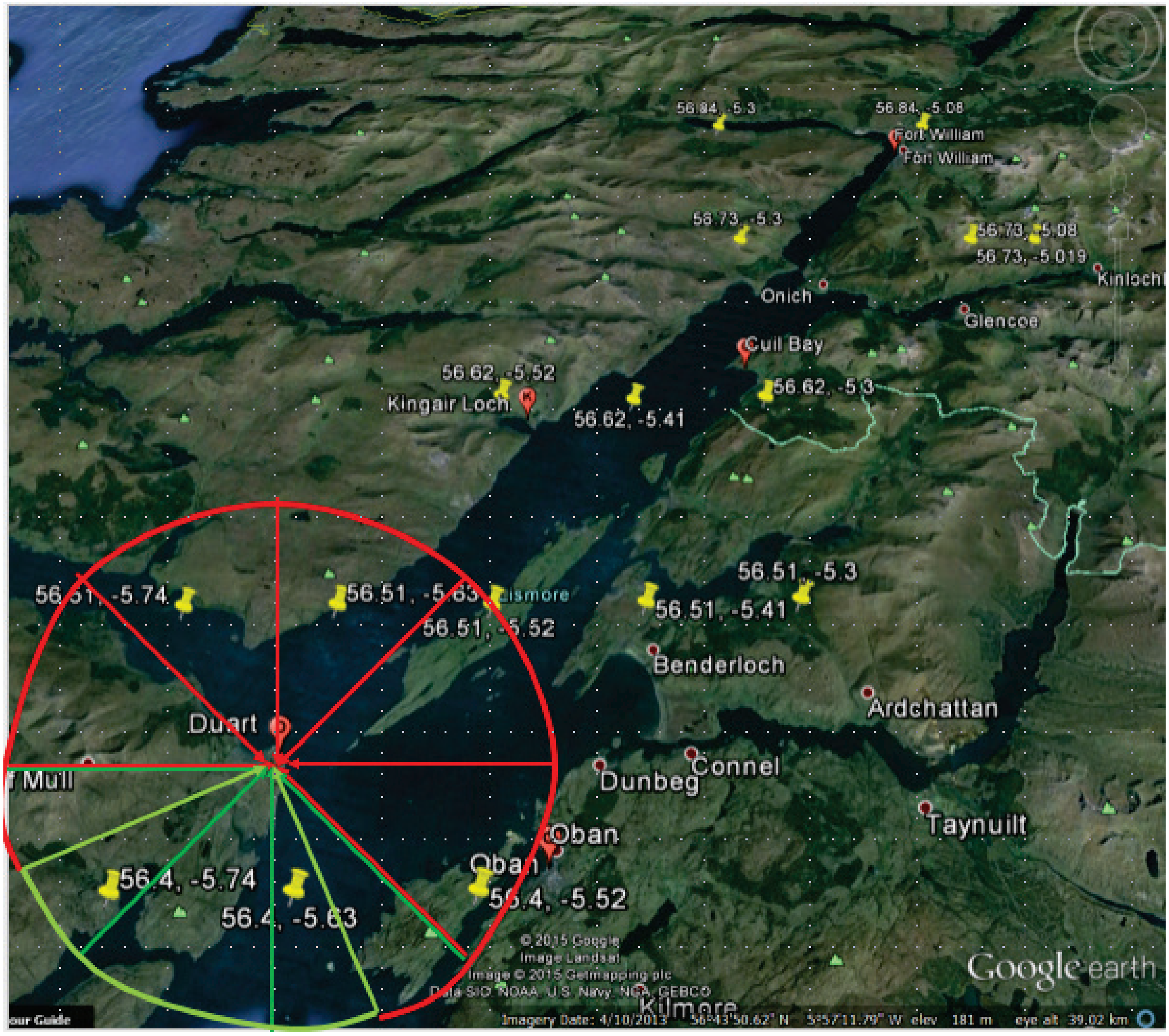


FIGURE 15

- **Comparison of wind speed inside Loch Linnhe and the speed at Duart for different directional sectors.**



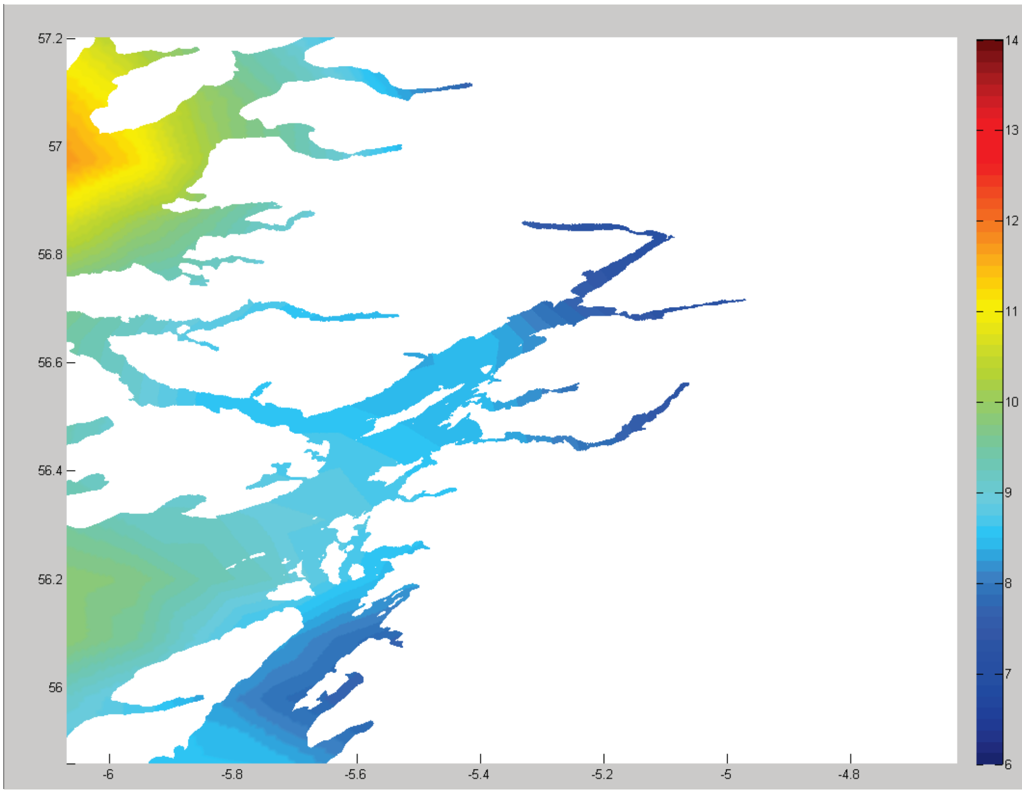

## 10. Interpolation of wind data over Loch Linnhe in the met data file

The wind speed and direction values inside Loch Linnhe were linearly interpolated using the distance of each point from the baseline through Duart (reference station), and the wind speed ratios (and direction differences) at Cuil bay and Fort William

Examples of the wind values in the met file before and after the interpolation are shown in Figures 16 and 17.

FIGURE 16

- **Wind Speed in the met file before (above) and after (below) the interpolation (values for 18th of May 2011).**



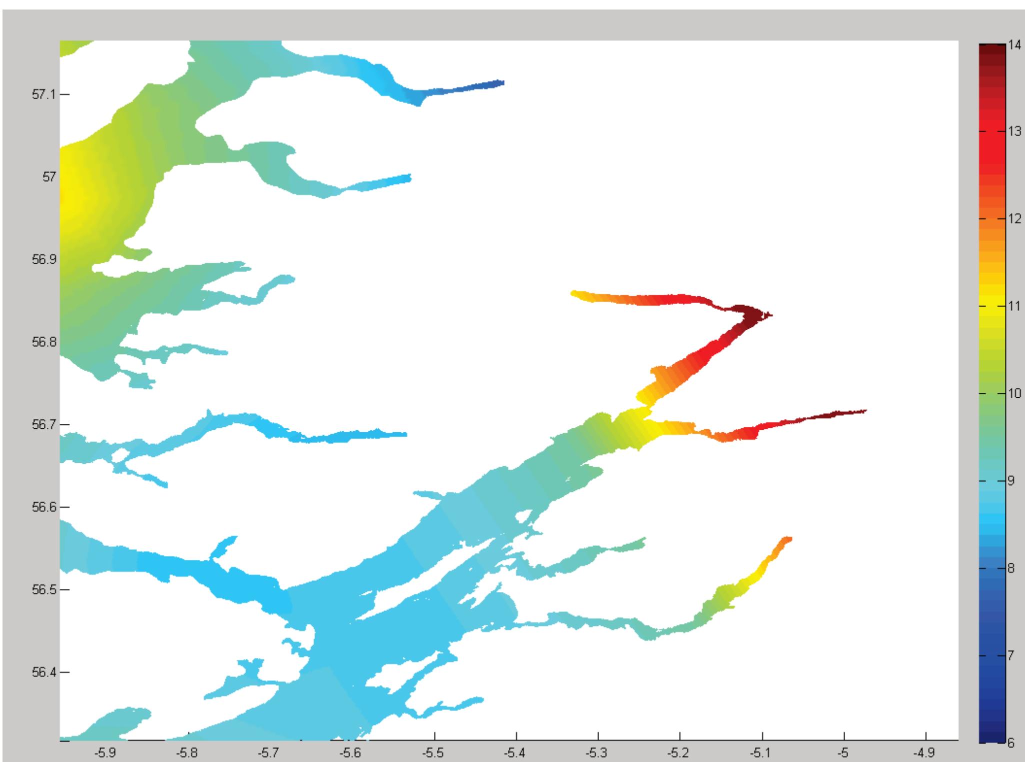
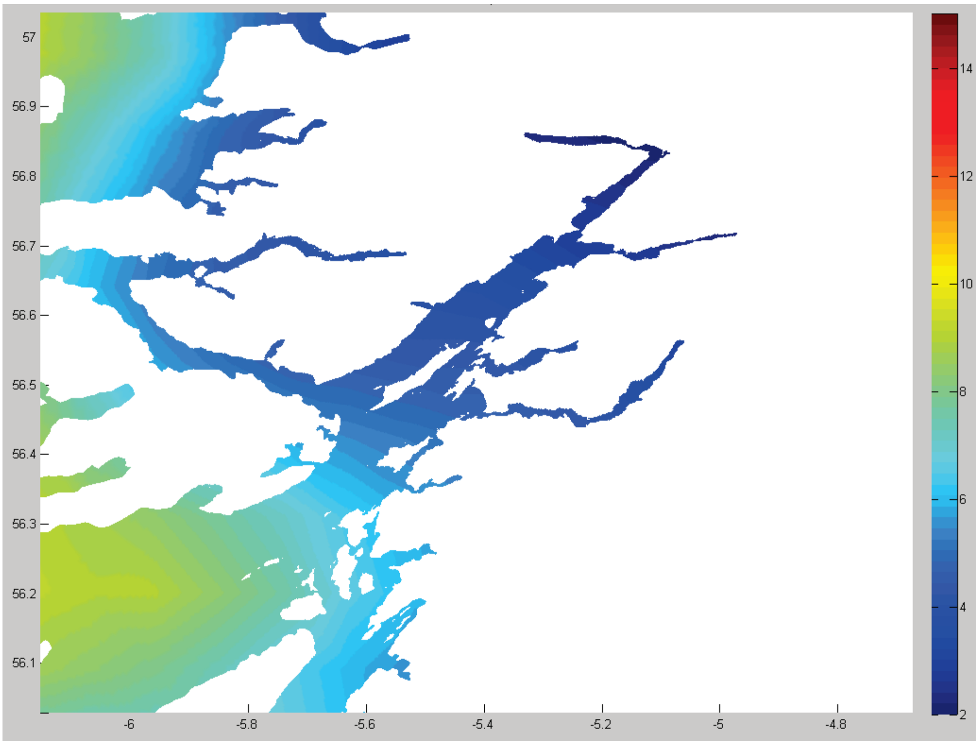
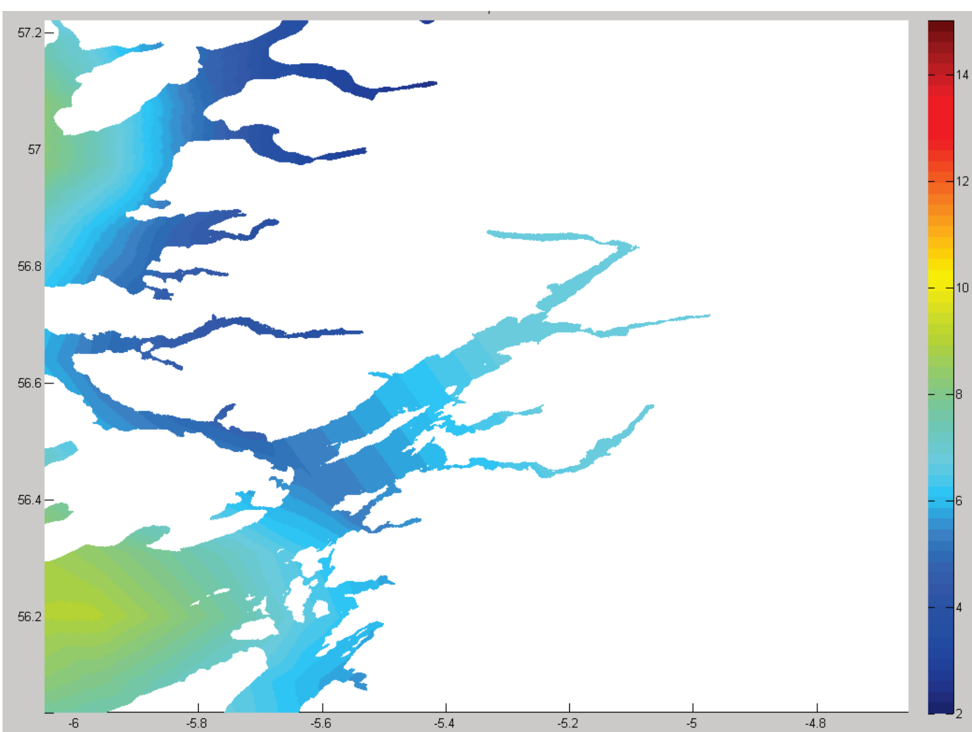



FIGURE 17

- **Wind Speed in the met file before (above) and after (below) the interpolation (values for 27th of May 2011).**



## Conclusions and Recommendations

From the wind analysis for WLLS the following conclusions can be drawn:

- The wind station at Duart was found to give lower prediction error than Oban station when used as the reference station for determining wind speed ratios and wind direction differences inside Loch Linnhe.
- Analysis of the observed wind data at a number of stations in Loch Linnhe, show that for wind directions from the SSE to WSW, the wind speed increases with distance from Duart towards Fort William (i.e. towards the upper sections of the loch). The maximum increase occurs when the wind is blowing from the sea along the alignment of the loch (SW). On the other hand, when the wind is blowing from W to SSE (clockwise), the wind speed generally increases from Fort William towards Duart (at the entrance of the loch). It is concluded that this spatial variation in wind over the loch is partly due to the presence of hills at the sides of the loch, which funnels the airflow within the loch for wind direction from SW.
- The calculated wind speed ratios and wind direction differences at two stations (Cuil bay and Fort William) were used to determine the spatial variation of wind over Loch Linnhe. Although this result show a sensible spatial variation of wind speed in the loch, it is felt that the use of two stations is rather limited. It is therefore recommended that more wind stations should be established within the loch (at least 2 or 3 more stations spread within the loch), as this will give better resolution of the spatial variation within the loch.

# Part 2: Loch Sunart

## 11. Introduction

CH2MHILL were asked to consider the influence of topographic funnelling of wind with in Loch Sunart as was carried out for Loch Linnhe above. However these findings are for reference and have not been included in the manipulation of the wind fields at this time. Wind data at four points within Loch Sunart are available for a 4 month period in 2013 and these along with overlapping data at Duart form the basis of the analysis.

## 12. Data Overview

MARLAB data at the locations shown in Figure 18 was available for the periods shown in Table 7. All data is an average of the previous 2 hours speed and direction. Direction is given as cardinal directions and was converted to degrees as shown in Table 2. The wind speeds were also converted to $U_{10}$ wind speeds using Equation 1 and the elevations given in Table 7.

FIGURE 18

- **Available wind data locations**

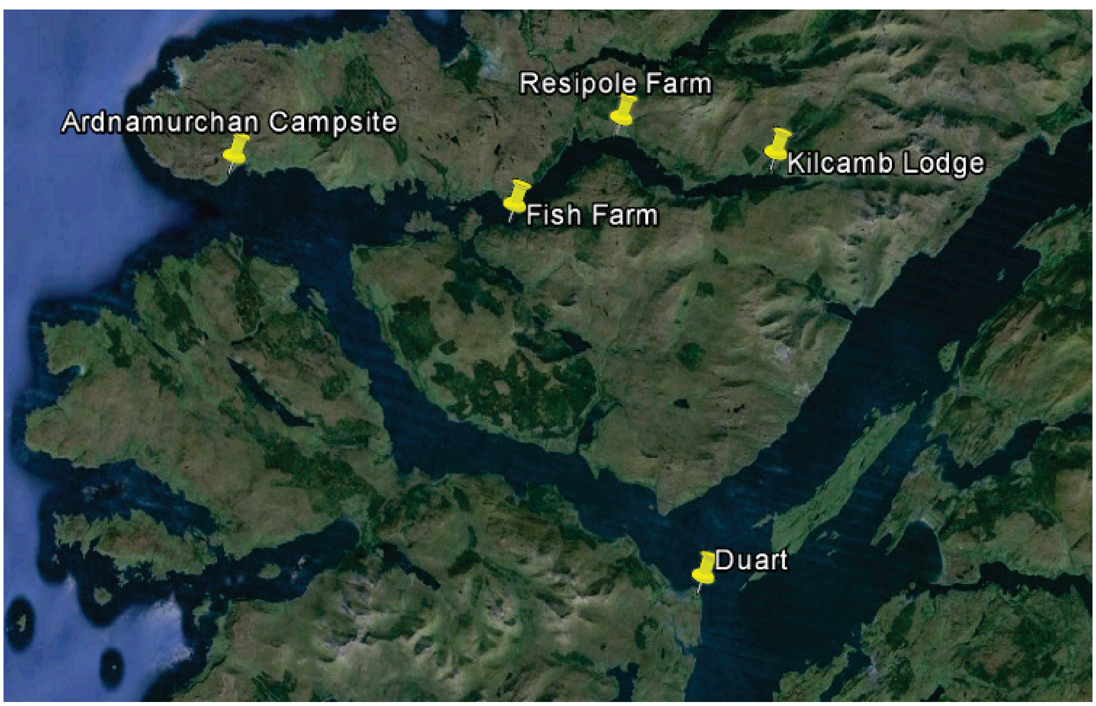


TABLE 7

- **Available wind data locations and start and end dates**

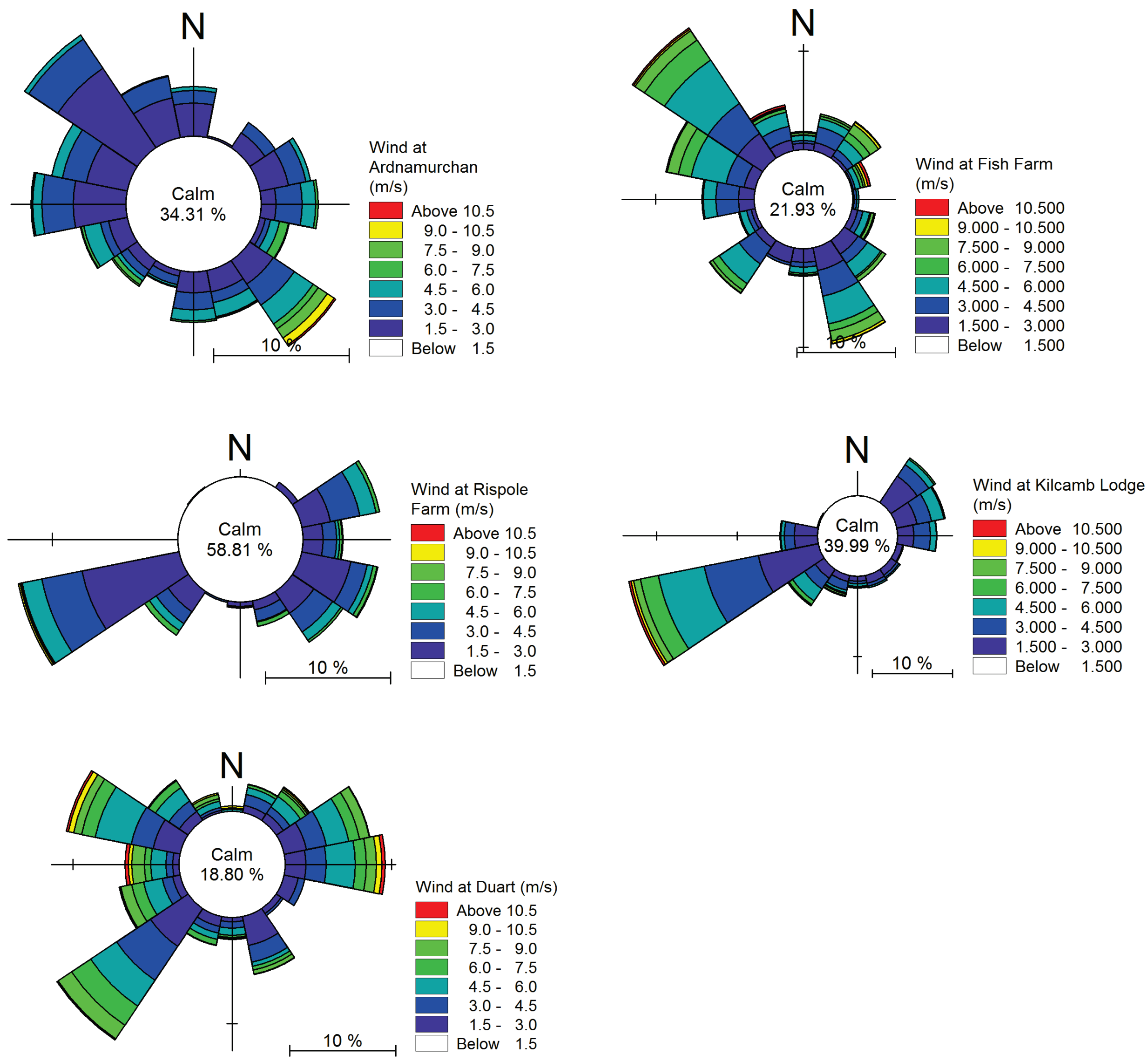
| Location | Coordinates | Start date | End date | Elevation |
|---|---|---|---|---|
| **Kilcamb Lodge** | 56.691, -5.576 | 13/03/2013 16:00 | 16/07/2013 10:00 | 8m |
| **Fish Farm** | 56.662, -5.844 | 12/03/2013 12:00 | 16/07/2013 12:00 | 7m |
| **Resipole Farm** | 56.711, -5.734 | 13/03/2013 11:00 | 16/07/2013 10:00 | 6m |
| **Ardnamurchan Campsite** | 56.689, -6.132 | 12/03/2013 17:00 | 15/07/2013 10:00 | 8m |
| **Castle Duart** | 56.453, -5.651 | 11/03/2013 18:00 | 05/11/2013 08:00 | 41m |

## 13. Wind Roses

Wind roses were plotted at the five locations shown in Figure 18 for the overlapping period between 13/03/2013 16:00 and 15/07/2013 10:00. These wind roses are presented in Figure 19. Initially it was thought that Ardnamurchan campsite could be used as the reference location as it is at the seaward end of Loch Sunart. However on inspection of the wind roses it was clear that this would not be appropriate as the Ardnamurchan campsite is subject to topographic channeling of wind. The prevailing wind direction in the UK is the southwest, at Ardnamurchan the dominant wind directions are northwest and southeast, with the strongest wind coming from the southeast. This suggests there is some channeling of the wind through the Sound of Mull. Ideally a reference location in the open sea close to the entrance of Loch Sunart would be used, unfortunately such data is not available. The best available data for the reference location has been identified as Duart. Comparison of the 2012 Met Office data with the measured data at Duart shown in Figure 11 and 12 show that the wind at Duart is relatively unaffected by the topographic influences, this is likely to be due to the elevation of the weather station (41m above sea level) and its relatively exposed location. The wind roses at the other locations within Loch Sunart do show evidence of topographic funnelling of wind. It is most obvious at Resipole Farm and Kilcamb Lodge.

FIGURE 19

**Wind roses at a) Ardnamurchan Campsite, b) Fish Farm, c) Resipole Farm, d) Kilcamb Lodge and e) Duart**

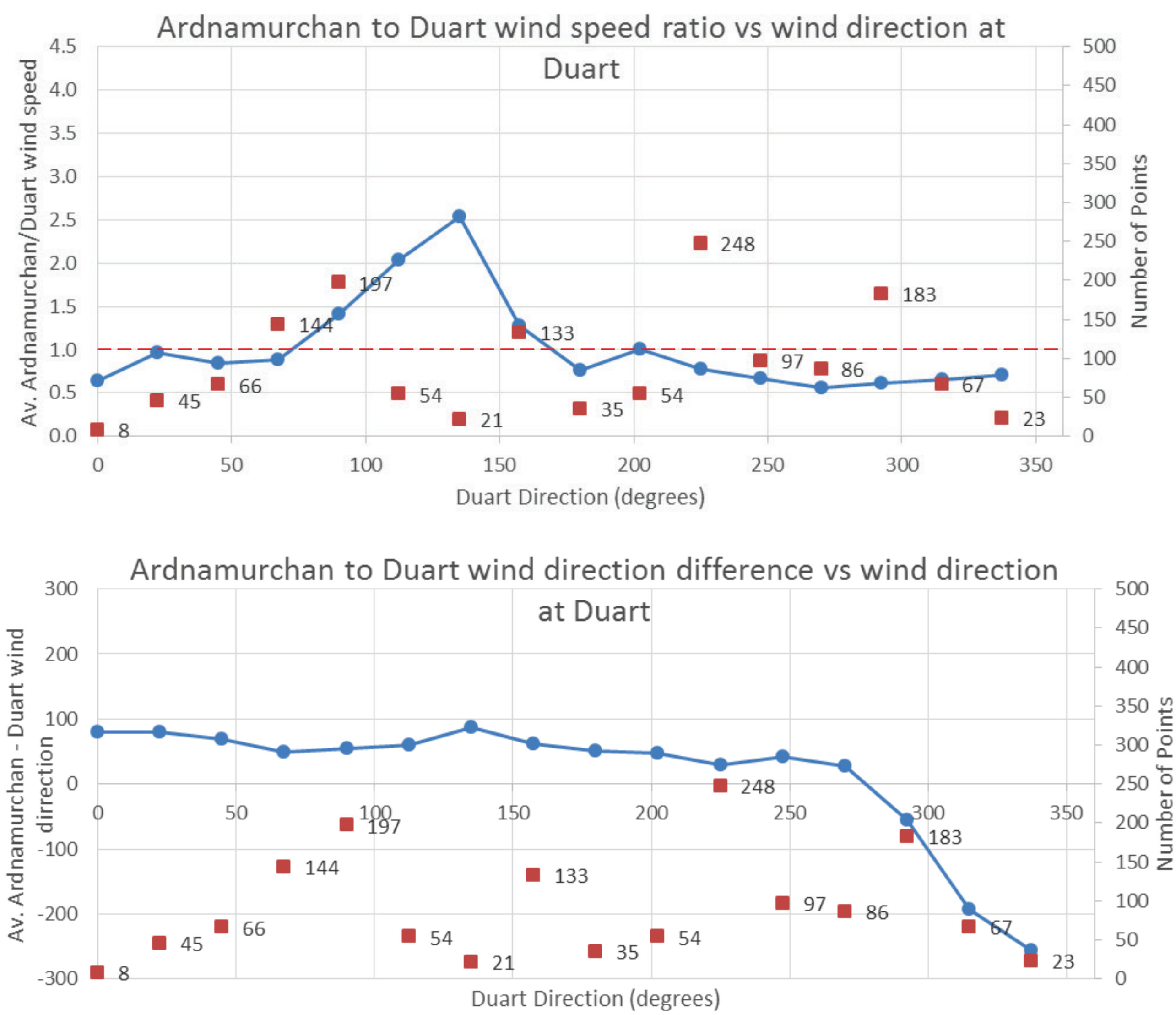



## 14. Correlation Plots

The wind speed ratios and wind direction differences for the 16 directional sectors at each of the stations in Loch Sunart to Duart were calculated using the methods outline in Part 1. The results are shown in Figure 20 to 23 and in Table 8.

FIGURE 20

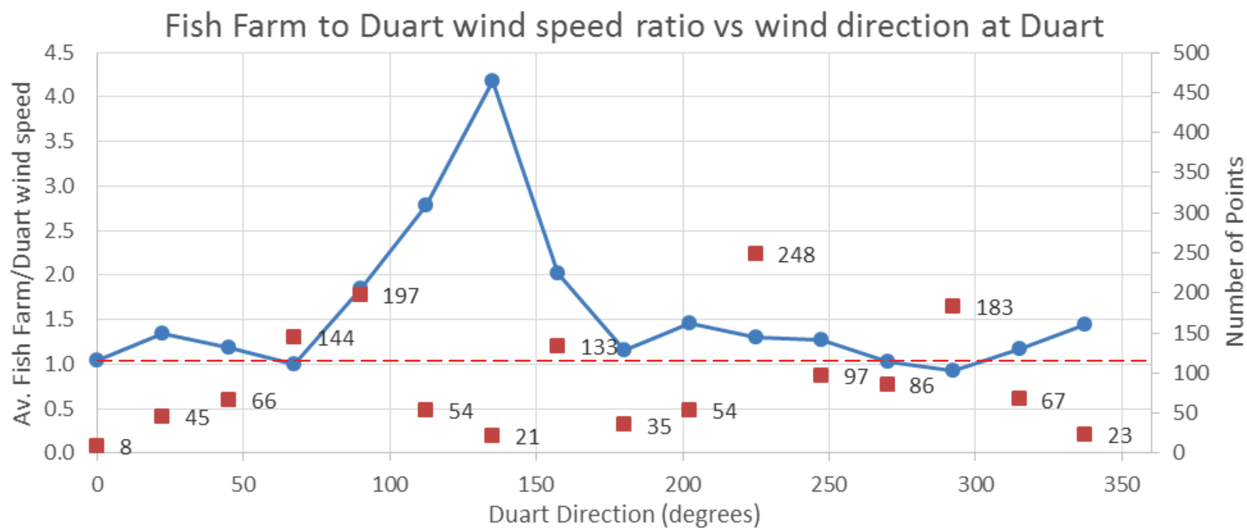
**Wind speed ratios and direction differences between Ardnamurchan Campsite and Castle Duart. Red Squares represent the number of points used to determine the correlation ratio**

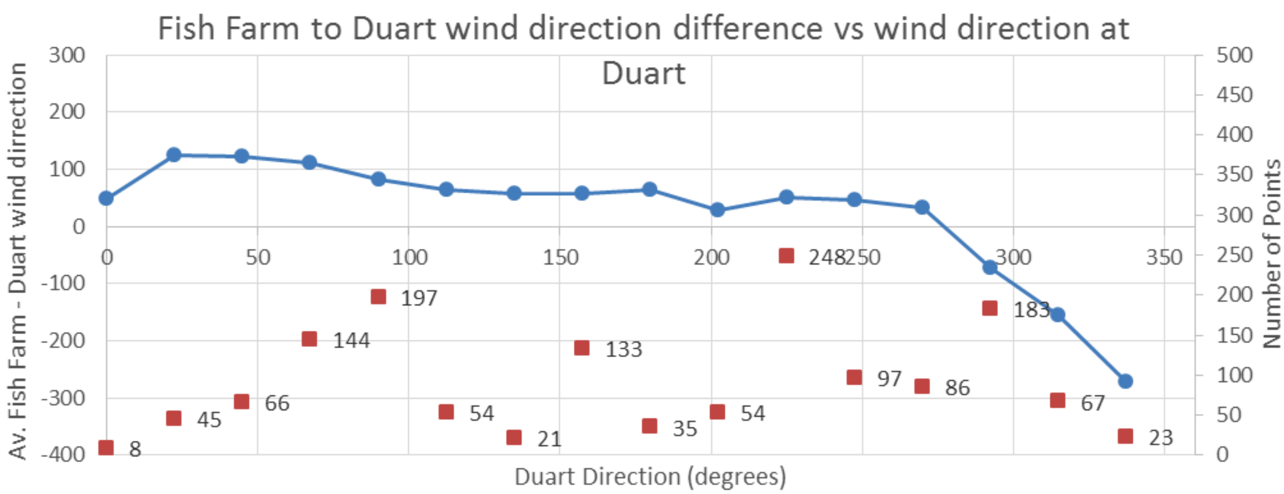



At Ardnamurchan campsite the wind speed is lower than that at Castle Duart between 180° and 67.5° degrees, with a ratio of between 0.64 and 1. The wind speed is higher at Ardnamurchan for winds from 90° to 157.5° with a peak at 135° (SE).

FIGURE 21

**Wind speed ratios and direction differences between the Fish Farm and Castle Duart. Red Squares represent the number of points used to determine the correlation ratio**

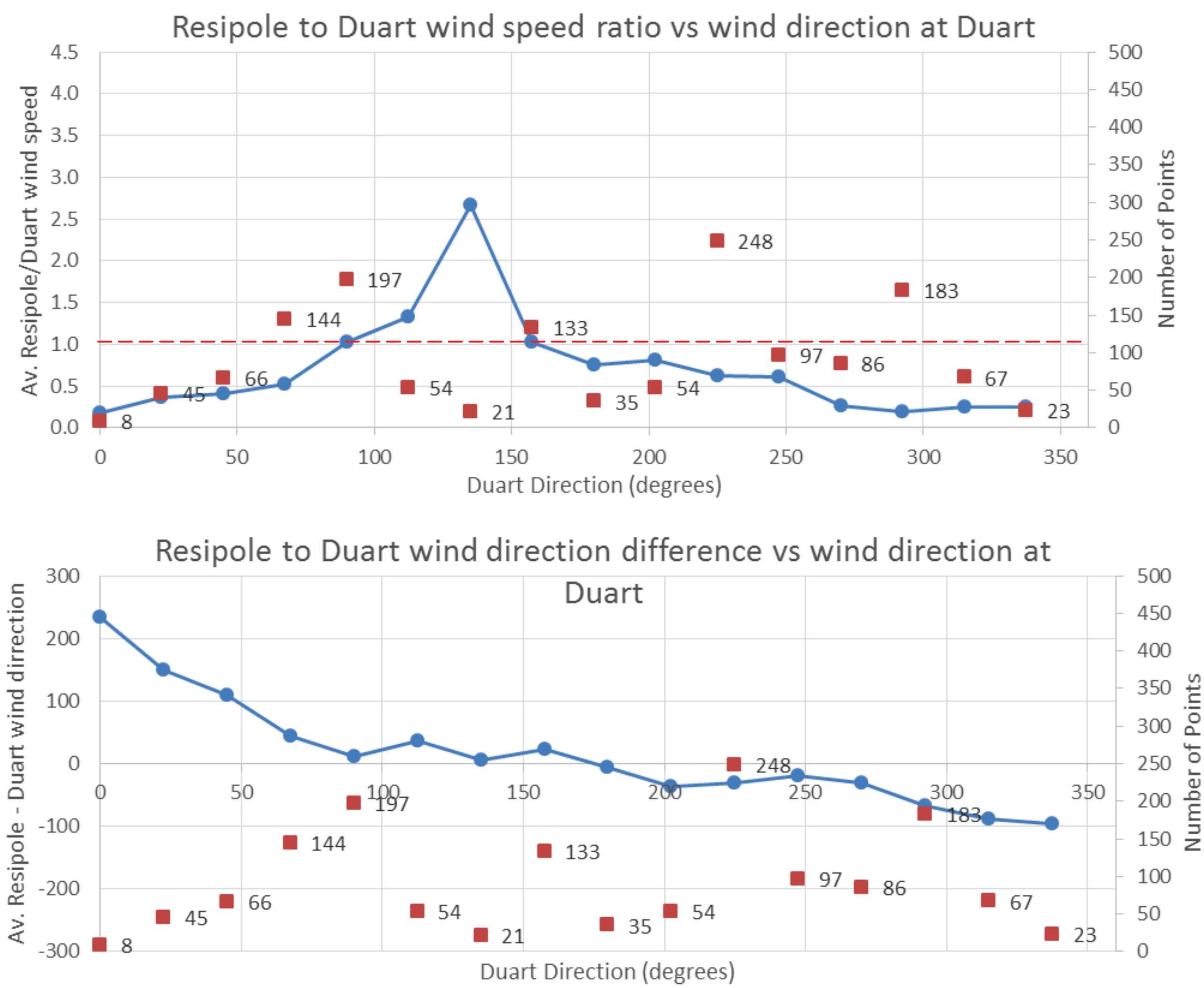



At the Fish Farm location wind speeds are generally higher than at Duart, with the ratio of wind speed only dropping below 1 for two directions (67.5° – ENE and 292.5° WNW). For the majority of directions the wind speed ration is between 1 and 1.5 (180° – 67.5°). As seen at Ardnamurchan there is a peak in the wind speed ratio around wind from the SE, this time the winds are over four times greater at the Fish Farm than Duart.

FIGURE 22

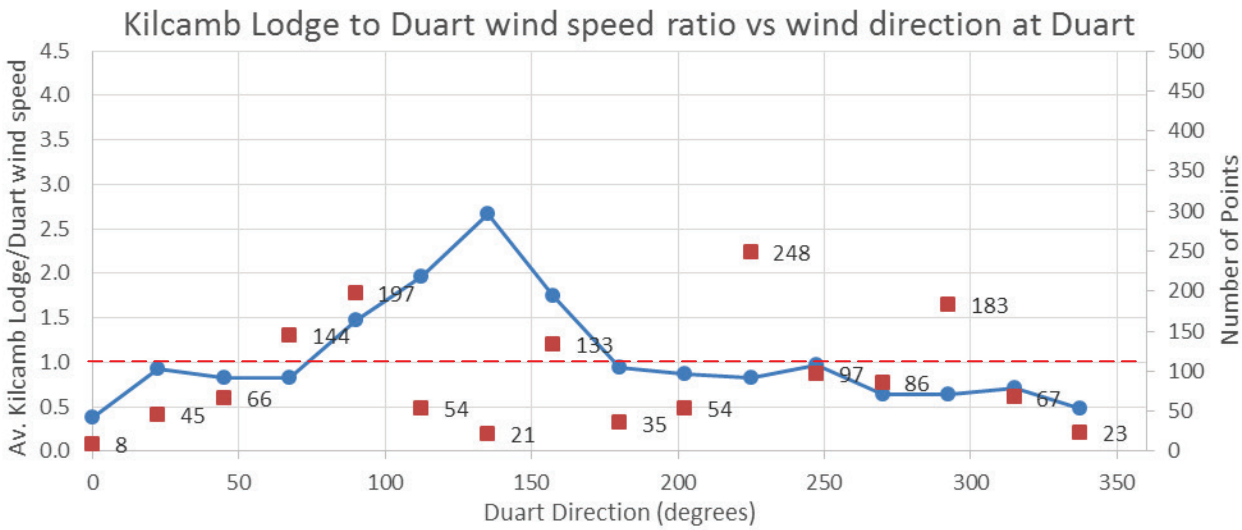
**Wind speed ratios and direction differences between Resipole Farm and Castle Duart. Red Squares represent the number of points used to determine the correlation ratio**

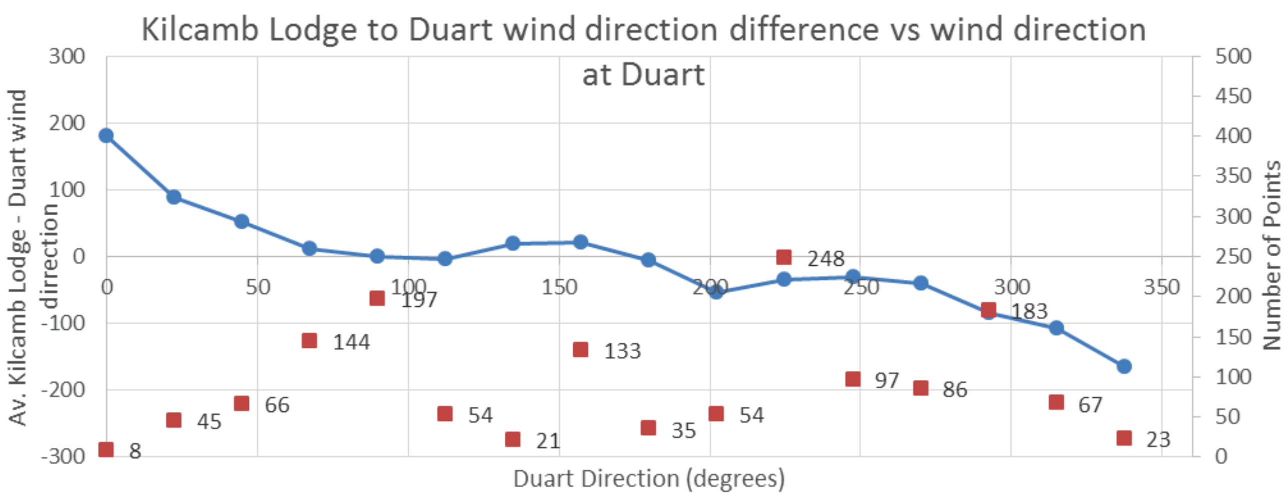



The wind speed ratios for Resipole Farm are the lowest of all the stations, ranging from 0.17 to 0.81 between 202.5° and 67.5°. The peak in the wind speed ratio for winds from the SE is still seen.

FIGURE 23

**Wind speed ratios and direction differences between Kilcamb Lodge and Castle Duart. Red Squares represent the number of points used to determine the correlation ratio**




The wind speed ratios between Kilcamb Lodge and Castle Duart are between 0.5 and 1 from 180° to 67.5°. Again the peak in the wind speed ratio for winds from the SE is seen. It is worth noting that these peaks in ratio seen at all the locations within Loch Sunart is based on only 21 samples at 135°, 54 samples at 117.5°. The results in the correlation plots are summarised in Table 9.

TABLE 8 **Wind speed ratios and direction differences for the weather stations in Loch Sunart with wind at Duart**

| | Directional sectors | Av. wind speed ratio Ardnamurchan / Duart | Av. wind direction difference Ardnamurchan - Duart | Av. wind speed ratio Fish Farm/ Duart | Av. wind direction difference Fish Farm - Duart | Av. wind speed ratio Resipole / Duart | Av. wind direction difference Resipole - Duart | Av. wind speed ratio Kilcamb / Duart | Av. wind direction difference Kilcamb - Duart |
|---|---|---|---|---|---|---|---|---|---|
| **N** | 348.75-11.25 | 0.64 | 80.2 | 1.04 | 47.8 | 0.17 | 234.8 | 0.38 | 180.0 |
| **NNE** | 11.25-33.75 | 0.96 | 79.0 | 1.35 | 125.5 | 0.37 | 149.5 | 0.92 | 88.5 |
| **NE** | 33.75-56.25 | 0.84 | 69.5 | 1.19 | 122.4 | 0.41 | 109.4 | 0.83 | 52.5 |
| **ENE** | 56.25-78.75 | 0.88 | 48.8 | 0.99 | 110.3 | 0.52 | 43.4 | 0.83 | 10.8 |
| **E** | 78.75-101.25 | 1.42 | 54.4 | 1.85 | 82.0 | 1.03 | 11.7 | 1.47 | -0.1 |
| **ESE** | 101.25-123.75 | 2.04 | 59.2 | 2.79 | 65.0 | 1.32 | 36.3 | 1.96 | -4.2 |
| **SE** | 123.75-146.25 | 2.54 | 86.8 | 4.18 | 56.8 | 2.67 | 5.9 | 2.67 | 18.2 |
| **SSE** | 146.25-168.75 | 1.28 | 61.4 | 2.01 | 58.2 | 1.03 | 23.8 | 1.75 | 21.0 |
| **S** | 168.75-191.25 | 0.77 | 51.8 | 1.15 | 64.3 | 0.75 | -6.8 | 0.95 | -6.4 |
| **SSW** | 191.25-213.75 | 1.00 | 47.9 | 1.46 | 28.3 | 0.81 | -37.3 | 0.86 | -53.3 |
| **SW** | 213.75-236.25 | 0.78 | 29.5 | 1.30 | 50.7 | 0.62 | -29.9 | 0.82 | -33.8 |
| **WSW** | 236.25-258.75 | 0.66 | 41.0 | 1.27 | 46.6 | 0.62 | -20.1 | 0.97 | -31.0 |
| **W** | 258.75-281.25 | 0.56 | 27.3 | 1.03 | 32.2 | 0.26 | -29.8 | 0.64 | -39.5 |
| **WNW** | 281.25-303.75 | 0.62 | -55.9 | 0.93 | -71.8 | 0.19 | -67.3 | 0.64 | -85.3 |
| **NW** | 303.75-326.25 | 0.66 | -193.6 | 1.17 | -155.8 | 0.25 | -89.0 | 0.71 | -107.1 |
| **NNW** | 326.25-348.75 | 0.71 | -255.8 | 1.45 | -272.0 | 0.25 | -95.4 | 0.48 | -165.3 |

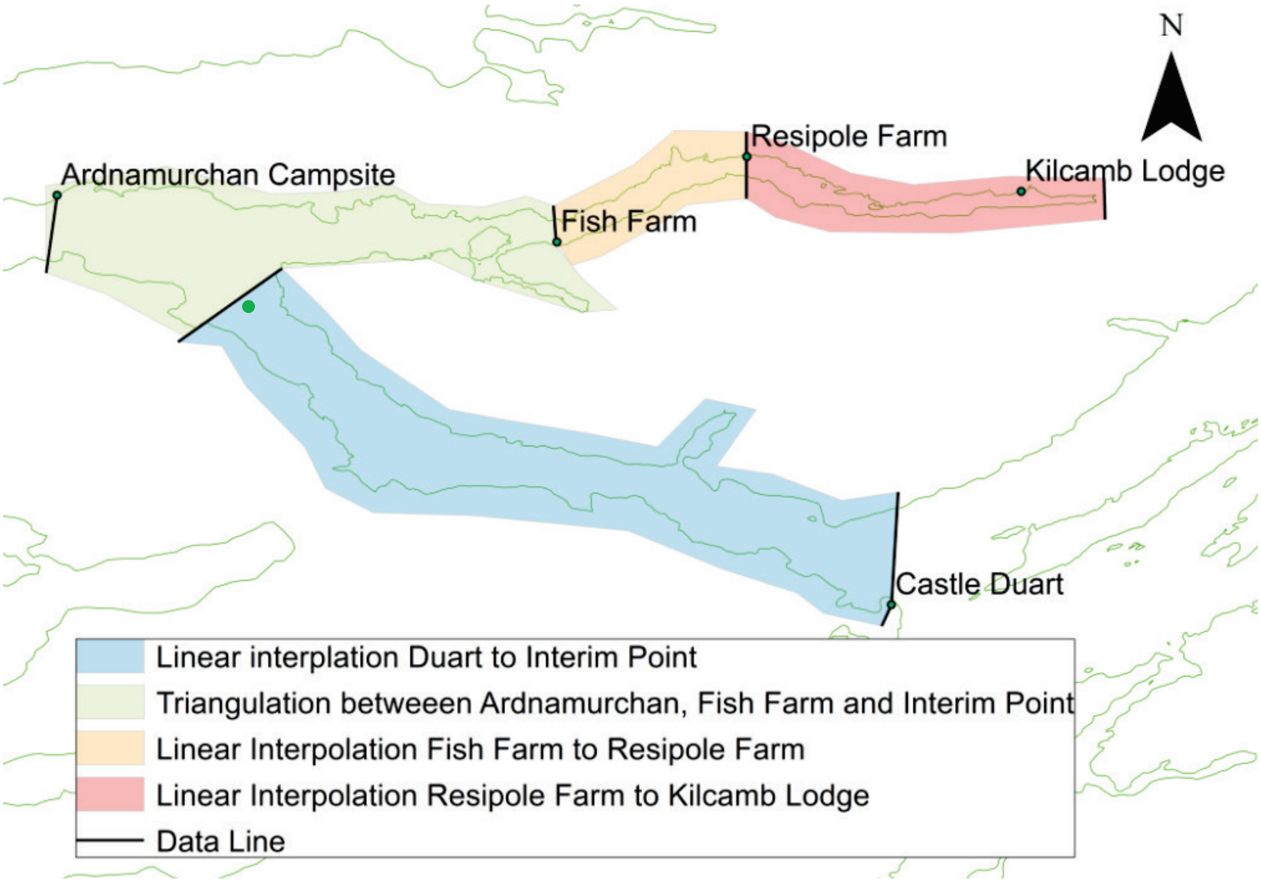
**TABLE 9**
**Variation in observed wind data at stations within Loch Sunart**

| Direction Sector | Ardnamurchan | Fish Farm | Resipole Farm | Kilcamb Lodge |
|---|---|---|---|---|
| **180 – 67.5°N** | Wind speed at Ardnamurchan is lower than at Duart. Minimum ratio of 0.56 for wind from 270 +/- 11.25 °N. | Wind speed at the Fish Farm is slightly higher or the same as at Duart, between 0.93 and 1.45 | Wind speed at Resipole Farm is lower than at Duart. Minimum ratio of 0.17 for wind from 0 +/- 11.25 °N. | Wind speed at Kilcamb Lodge is lower than at Duart. Minimum ratio of 0.38 for wind from 0 +/- 11.25 °N. |
| **67.5 - 180°N** | Wind speed at Ardnamurchan is higher than at Duart. Maximum ratio of 2.54 for wind from 135°N. | Wind speed at Fish Farm is higher than at Duart. Maximum ratio of 4.18 for wind from 135°N. | Wind speed at Resipole Farm is higher than at Duart. Maximum ratio of 2.67 for wind from 135°N. | Wind speed at Kilcamb Lodge is higher than at Duart. Maximum ratio of 2.67 for wind from 135°N. |

## 15. Recommendations

Although the results of this analysis have not been implemented in the wind corrections used in the model guidance on how they could be implemented is given here. The first step would be to determine a time series of wind speed and direction at each location within Loch Sunart based on a time series at Castle Duart and the wind speed ratios and direction differences presented above. Due to the potential for overlapping interpolation around Ardnamurchan campsite it is necessary to add an interim point. The time series at this point will be determined by linear interpolation from Duart to Ardnamurchan. Once these time series have been established the next step would be to interpolate between the points as shown in Figure 24, i.e. linearly from Castle Duart to the interim point, triangulation between Ardnamurchan Campsite, the Interim Point and the Fish Farm, linearly from the Fish Farm to Resipole Farm and finally linearly from Resipole Farm to Kilcamb Lodge. The solid black lines in Figure 24 indicate the lines along which the values from each location will be defined.

FIGURE 24
**Recommended method for interpolation of corrected winds**



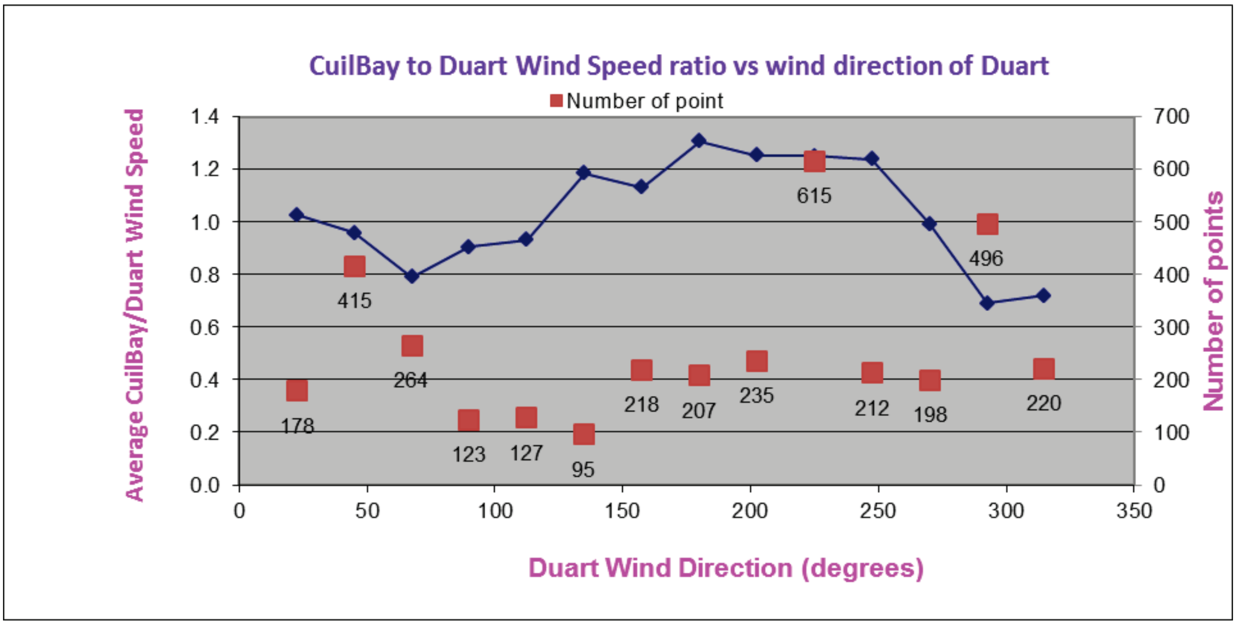

## 16. Limitation

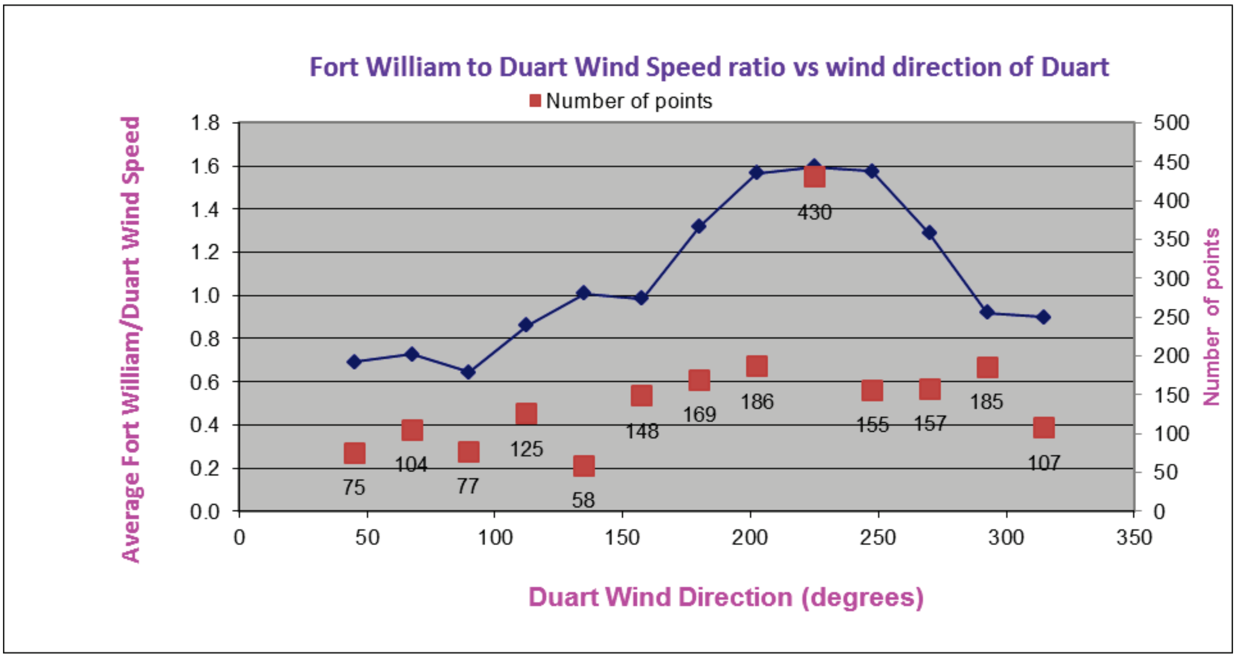
The proposed methodology outlined above for wind interpolation in Loch Sunart has a number of limitations, not least the data available for the analysis. The length of the time series and the number and locations of the stations is not ideal. Four months is not sufficient to develop a robust relationship between the winds at these locations. It would be preferable if the location of the reference station (Duart) was closer to the mouth of Loch Sunart and in an exposed location, ideally in open water. Also the wind stations are located at points where the orientation of the Loch changes, ideally data would be available along the straight sections of the loch to better capture the effect of the wind channelling.

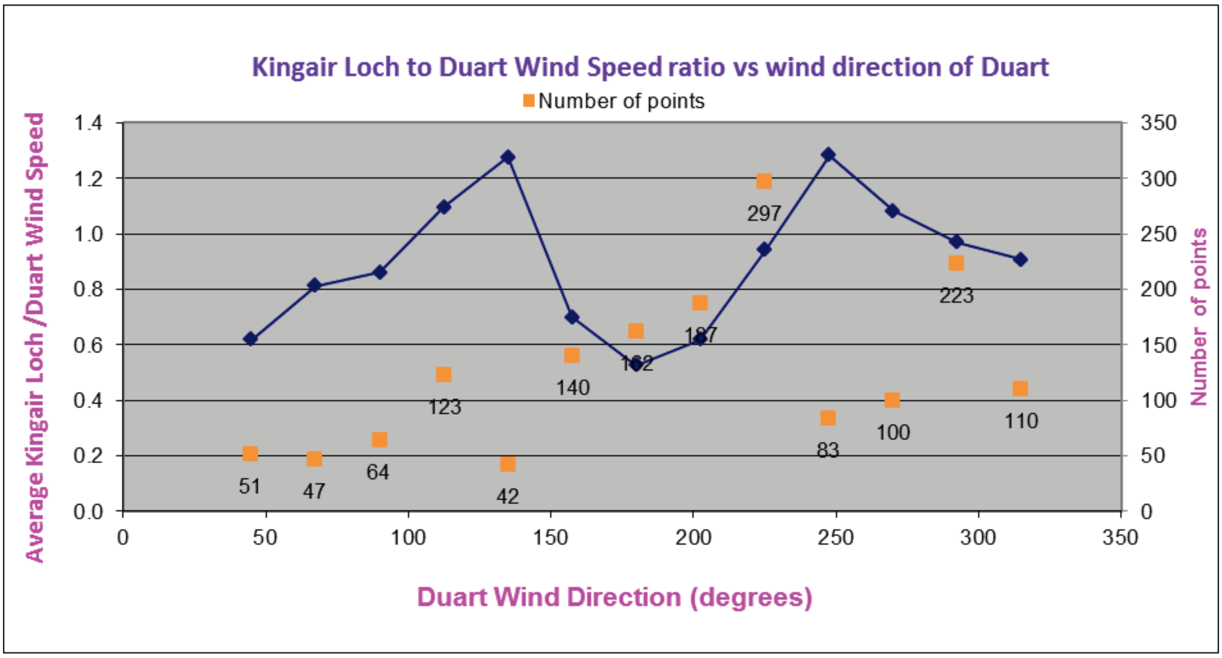
# Appendix A: Correlation Plots

**Reference Point: Duart** **Datasets: 1 and 2**

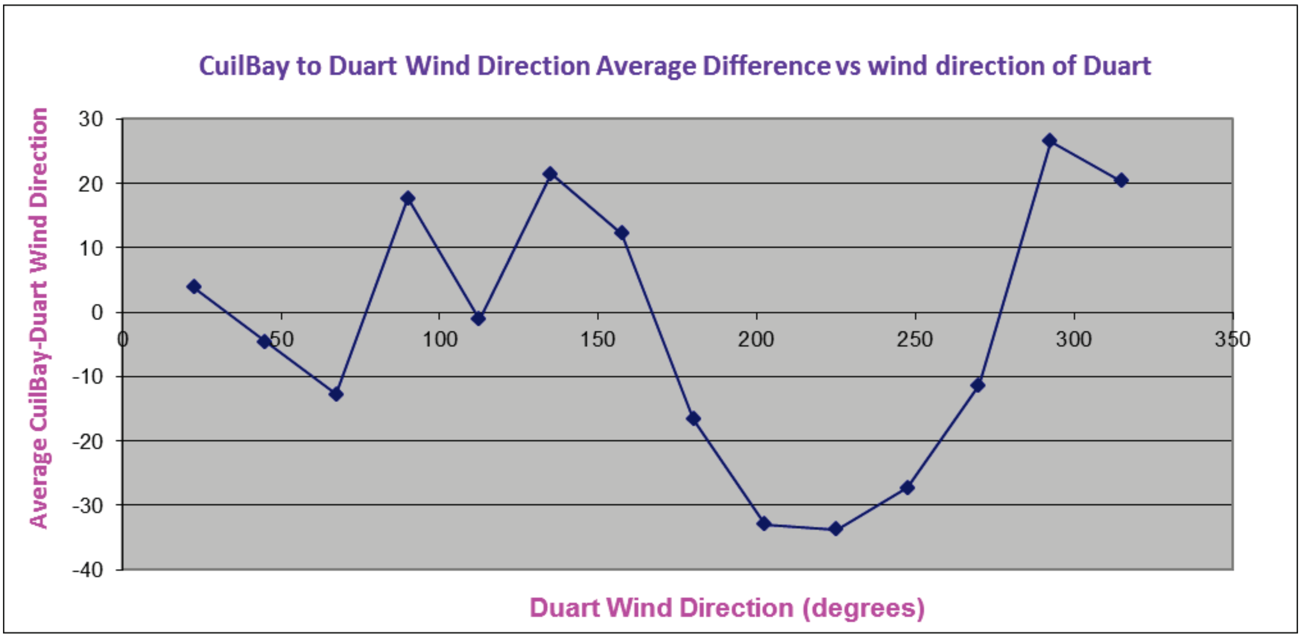
**Wind Speed (removed directions with less than 30 points)**

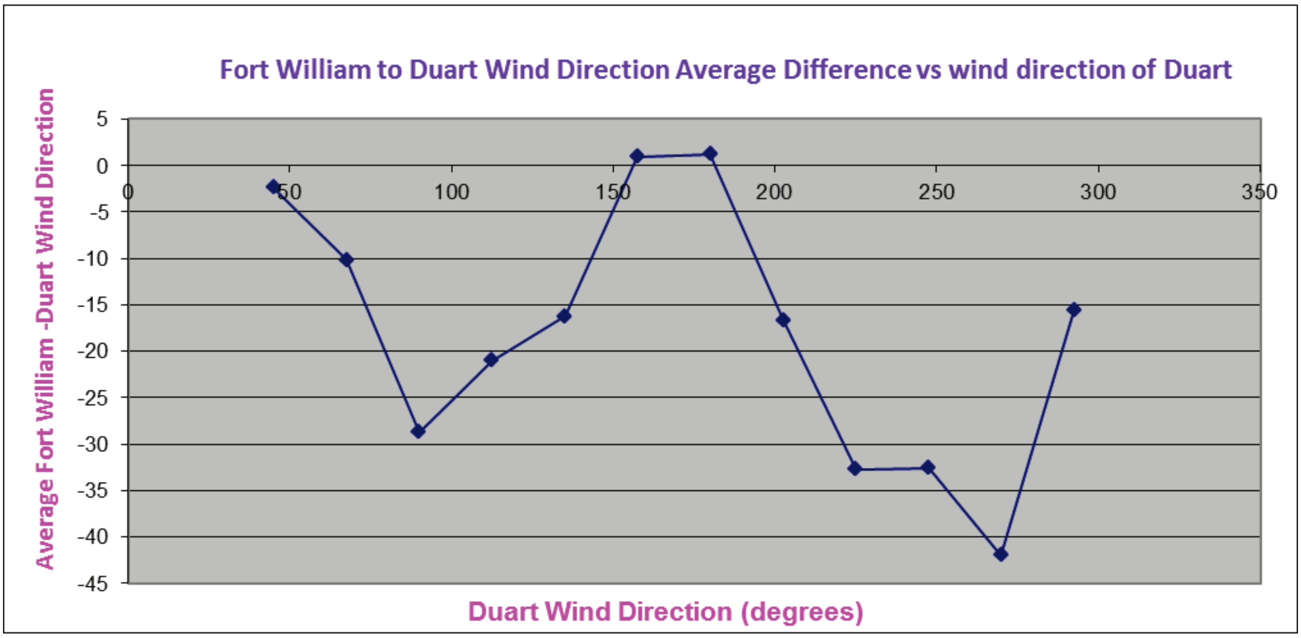


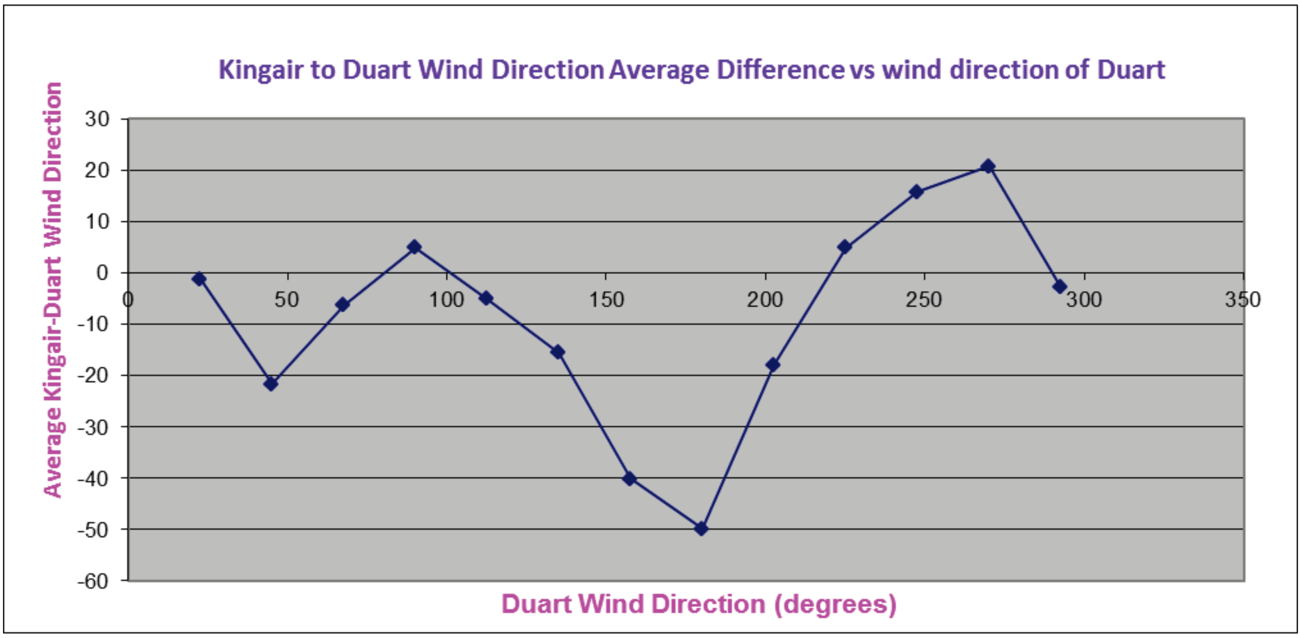






## Wind Direction (removed directions with less than 30 points)

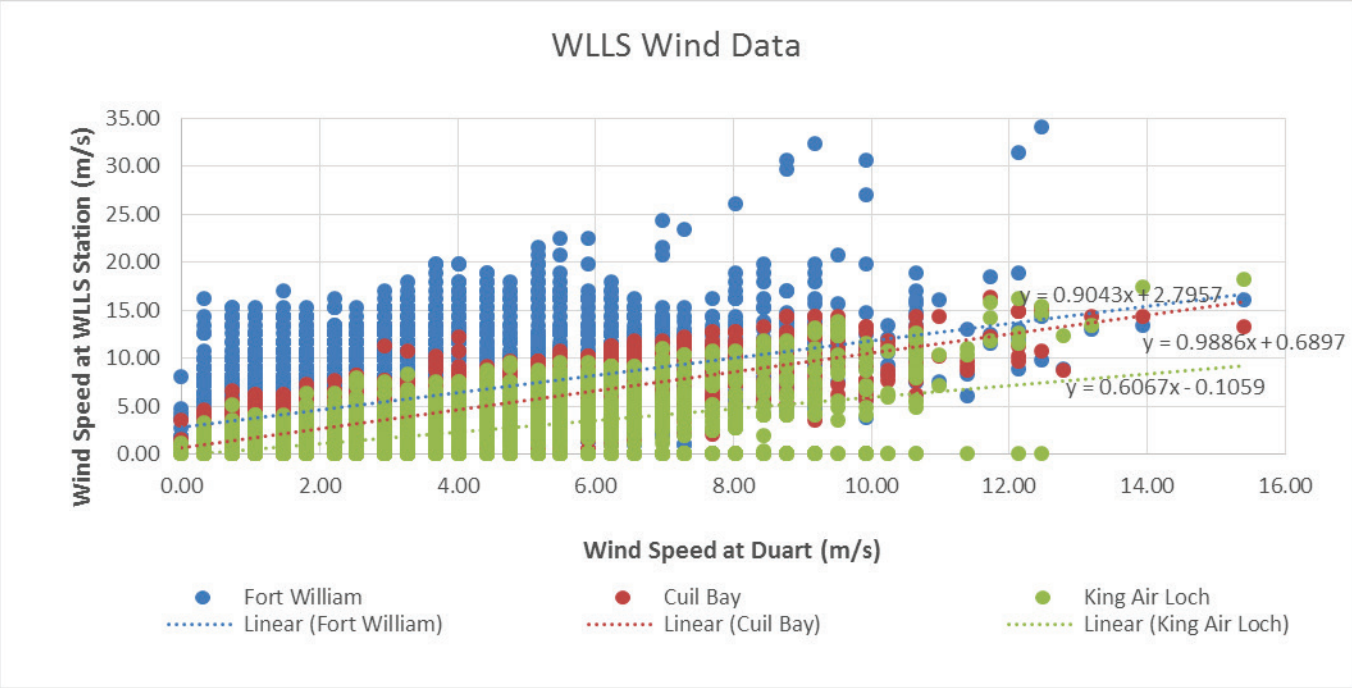


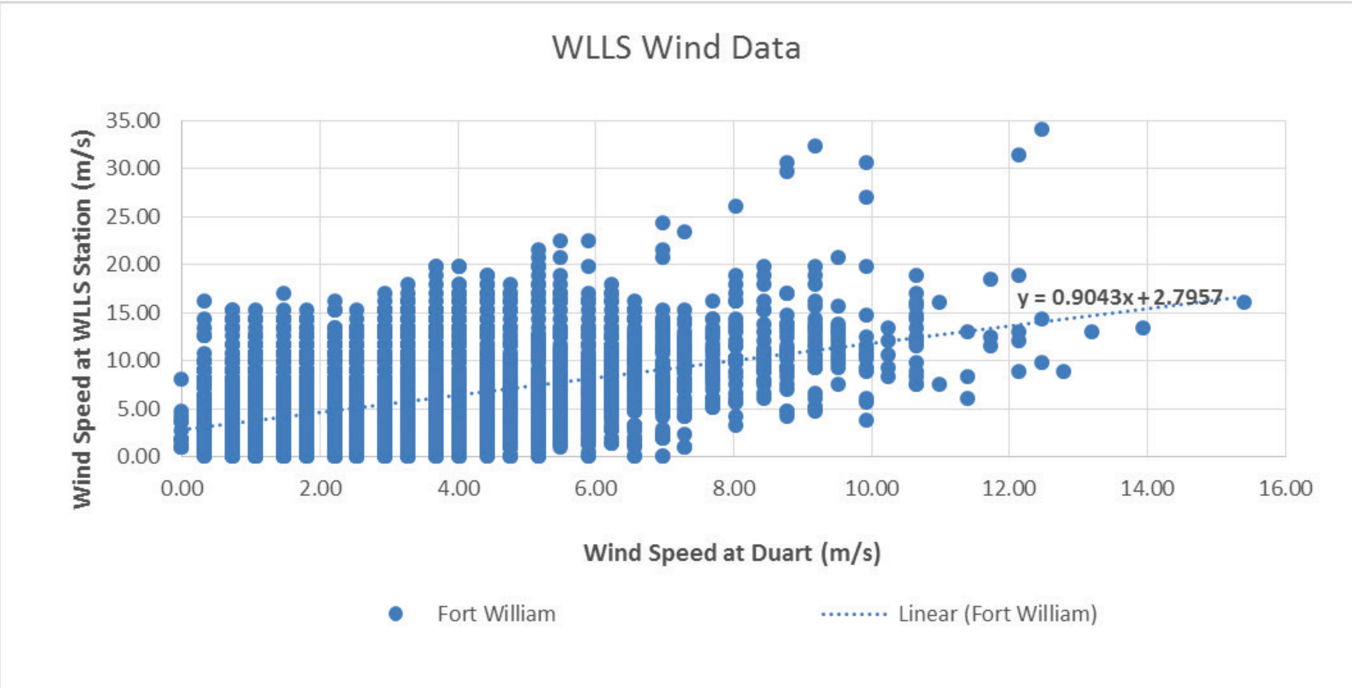

Fort William to Duart Wind Direction Average Difference vs wind direction of Duart
Average Fort William -Duart Wind Direction
Duart Wind Direction (degrees)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
0
50
100
150
200
250
300
350

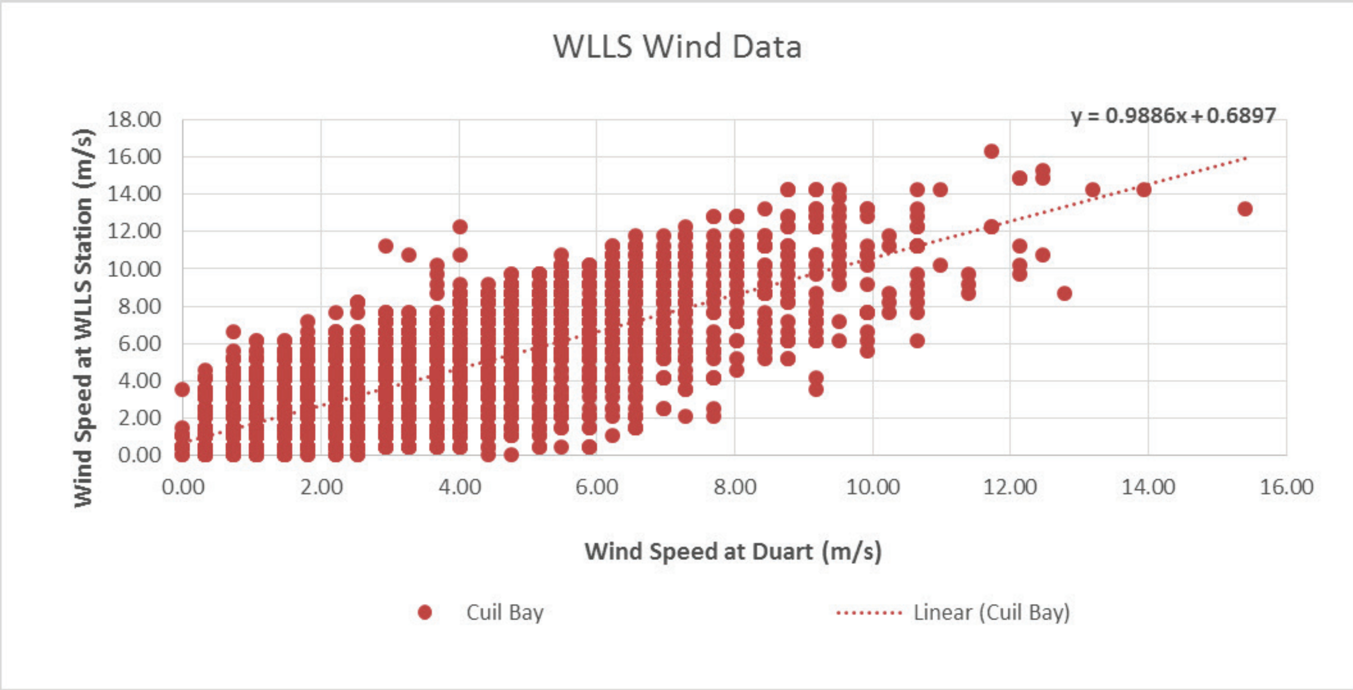

Kingair to Duart Wind Direction Average Difference vs wind direction of Duart
Average Kingair-Duart Wind Direction
Duart Wind Direction (degrees)
30
20
10
0
-10
-20
-30
-40
-50
-60
0
50
100
150
200
250
300
350

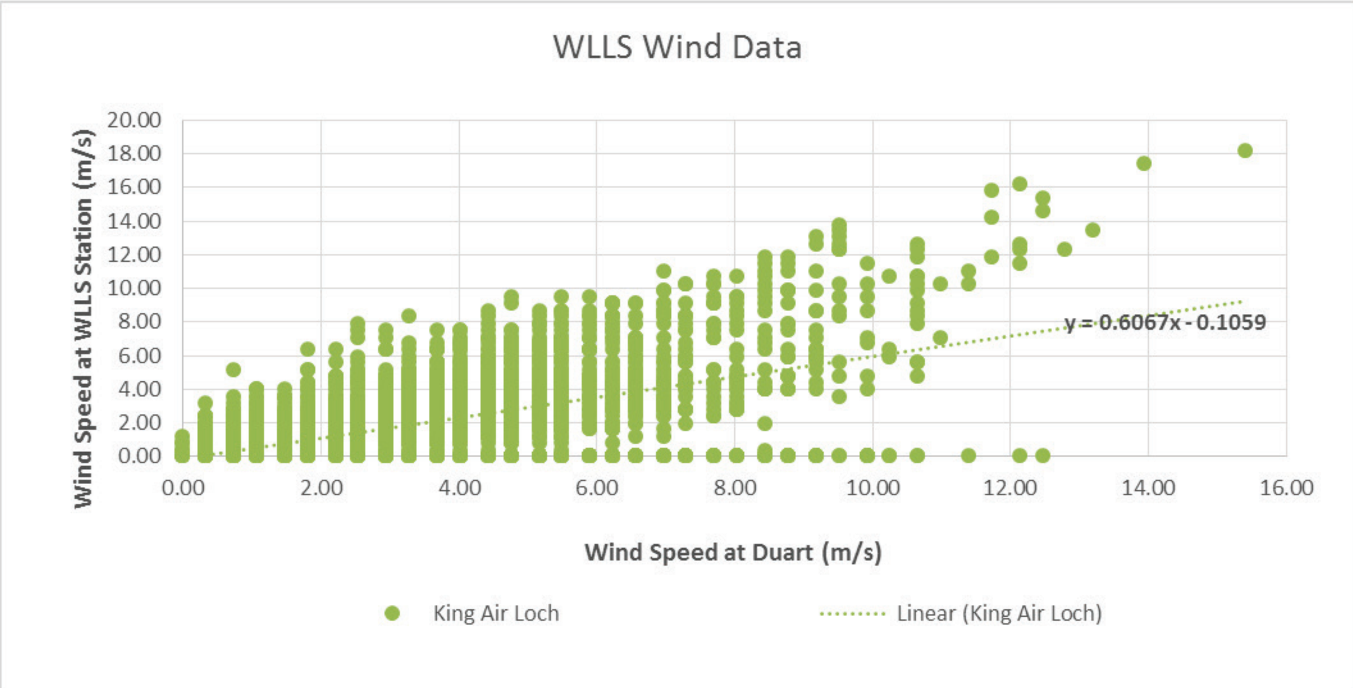
# Appendix B: X-Y Plots

## X-Y Plots Wind Speed (Datasets 1 and 2)

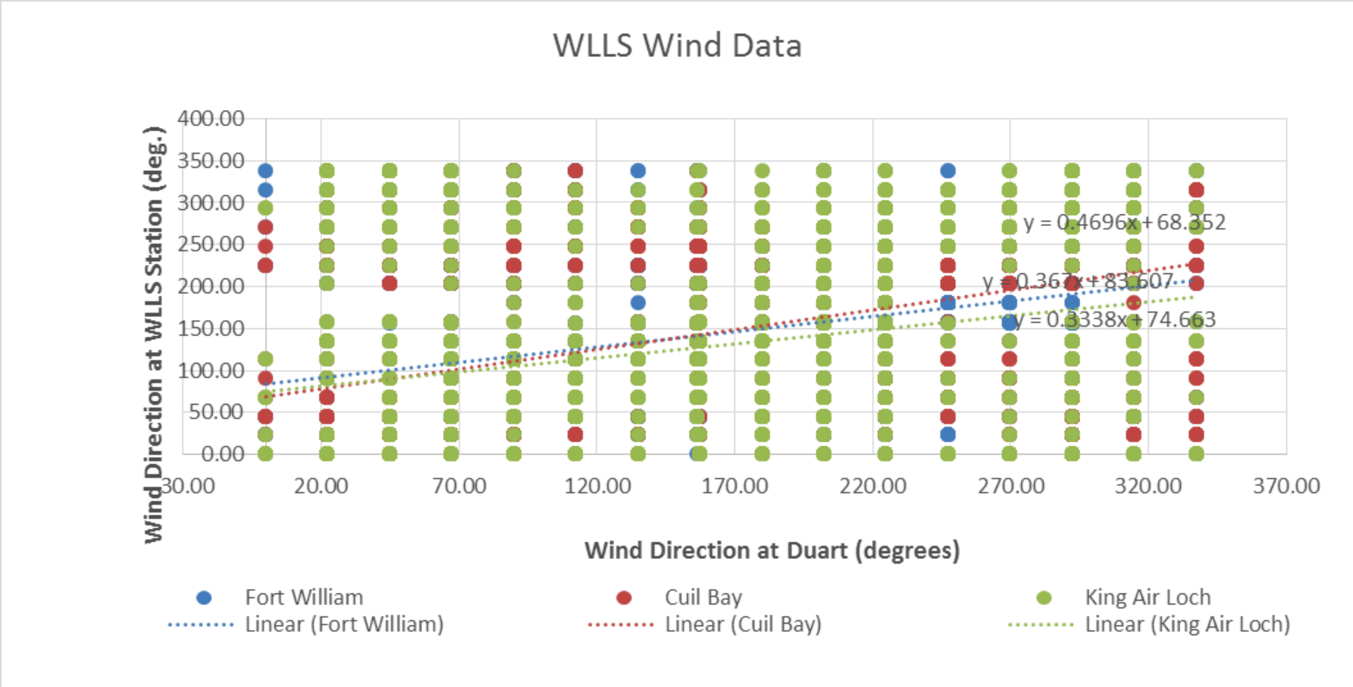


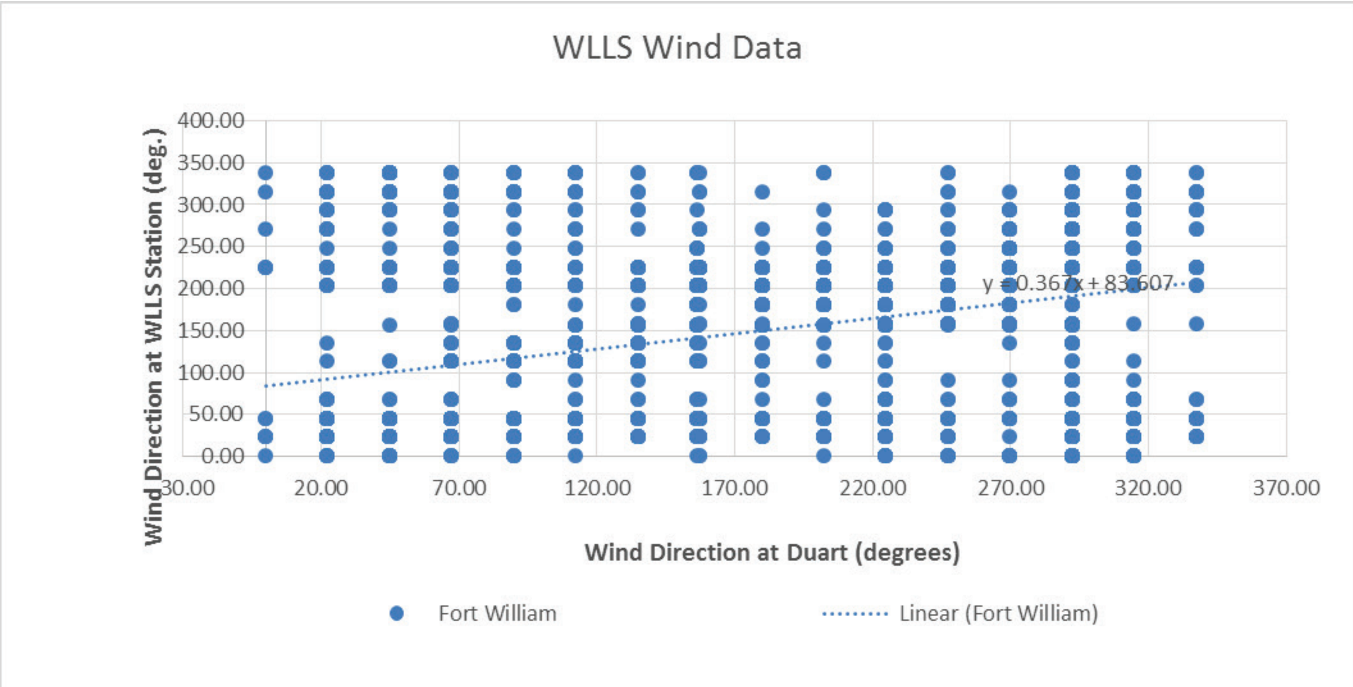



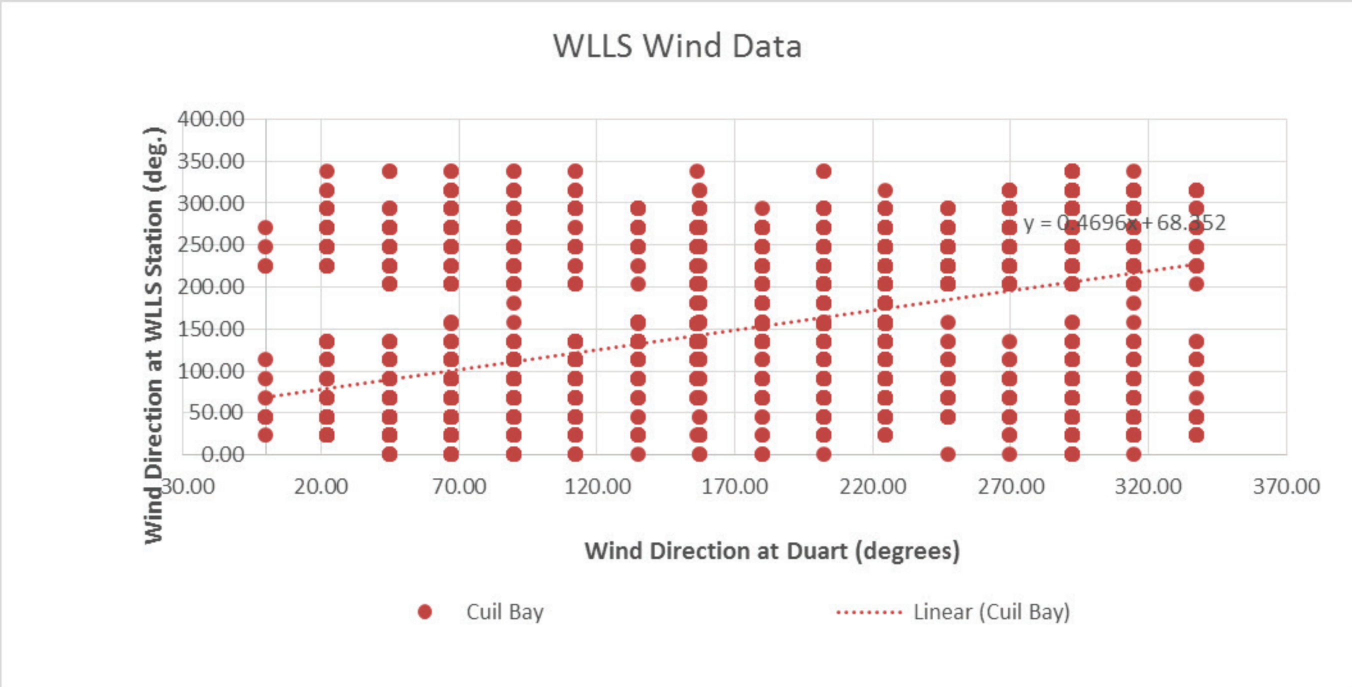

WLLS Wind Data
y = 0.9886x + 0.6897
Wind Speed at WLLS Station (m/s)
Wind Speed at Duart (m/s)
Cuil Bay
Linear (Cuil Bay)

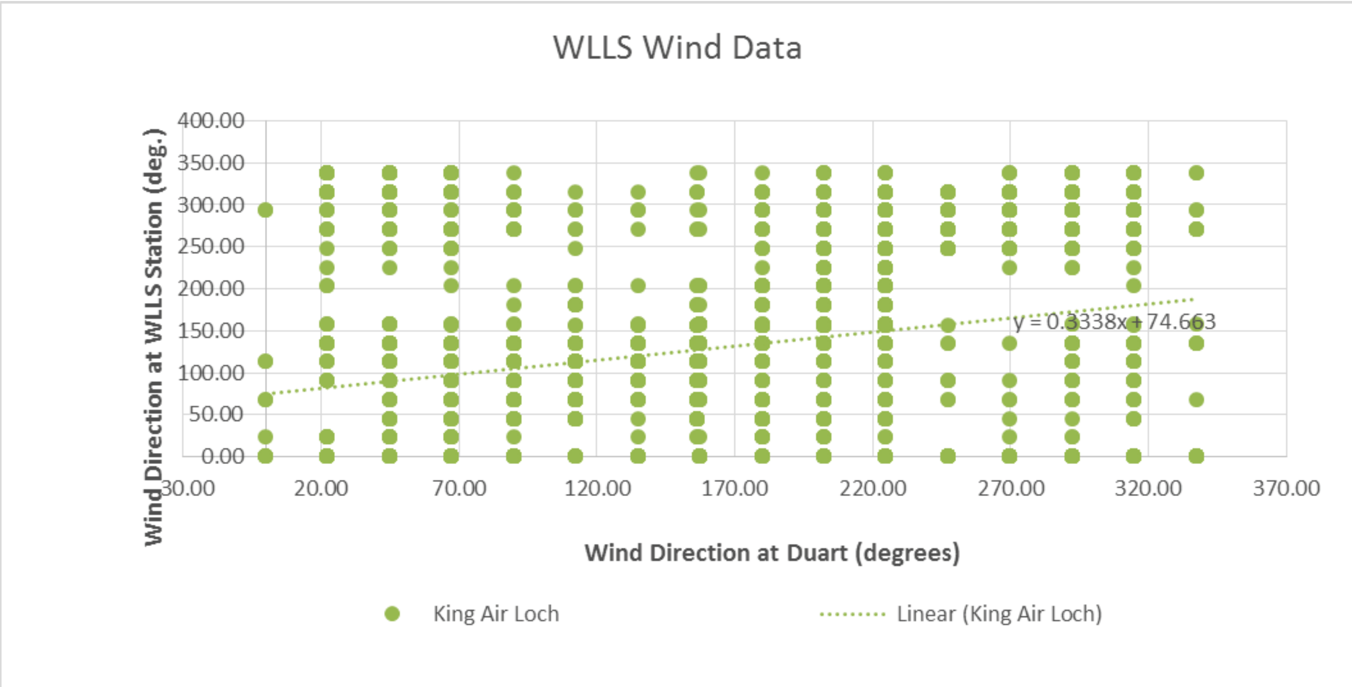

WLLS Wind Data
y = 0.6067x - 0.1059
Wind Speed at WLLS Station (m/s)
Wind Speed at Duart (m/s)
King Air Loch
Linear (King Air Loch)

## X-Y Plots Wind Direction (Datasets 1 and 2)




WLLS Wind Data
Wind Direction at WLLS Station (deg.)
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-30.00
20.00
70.00
120.00
170.00
220.00
270.00
320.00
370.00
y = 0.4696x + 68.352
Wind Direction at Duart (degrees)
Cuil Bay
Linear (Cuil Bay)

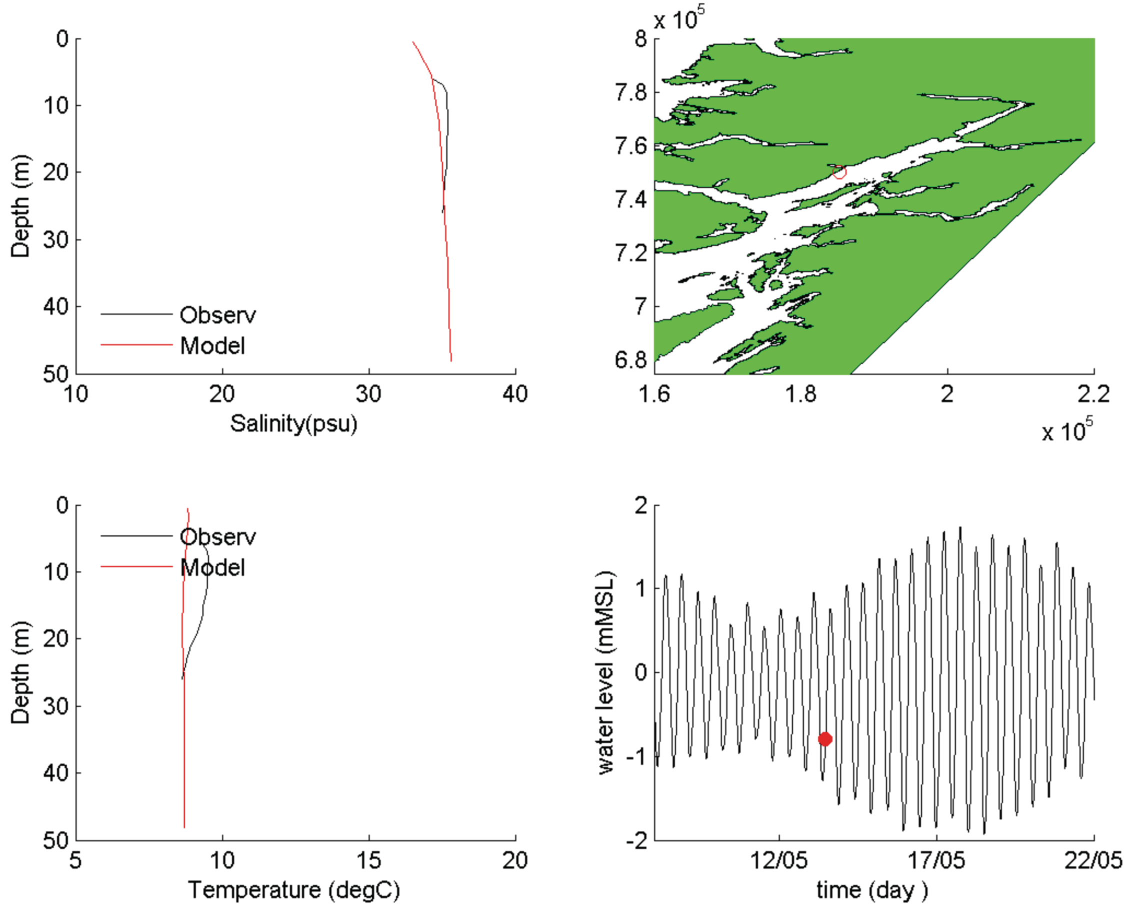

WLLS Wind Data
Wind Direction at WLLS Station (deg.)
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-30.00
20.00
70.00
120.00
170.00
220.00
270.00
320.00
370.00
y = 0.3338x + 74.663
Wind Direction at Duart (degrees)
King Air Loch
Linear (King Air Loch)

# Appendix B

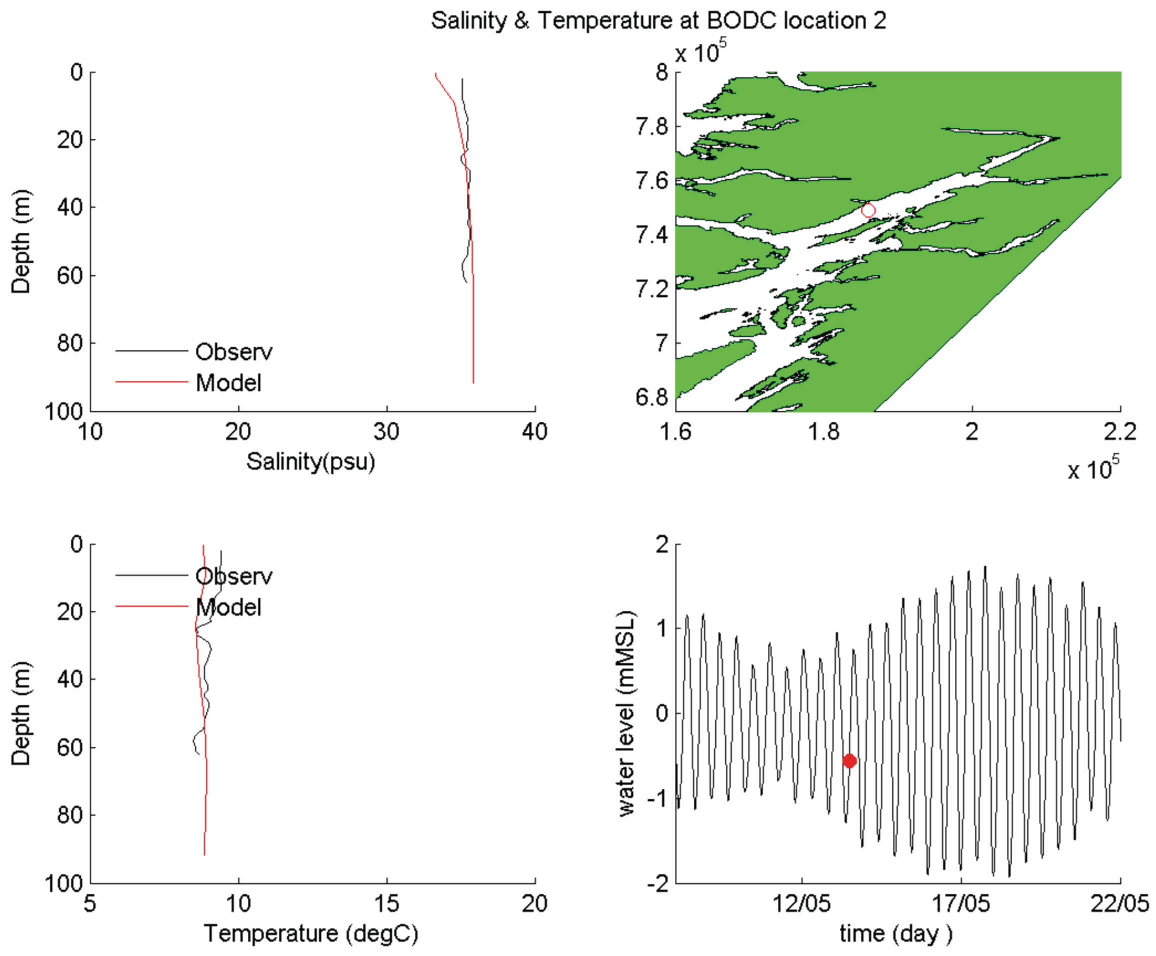
Additional results from May 2011 comparisons

May 2011

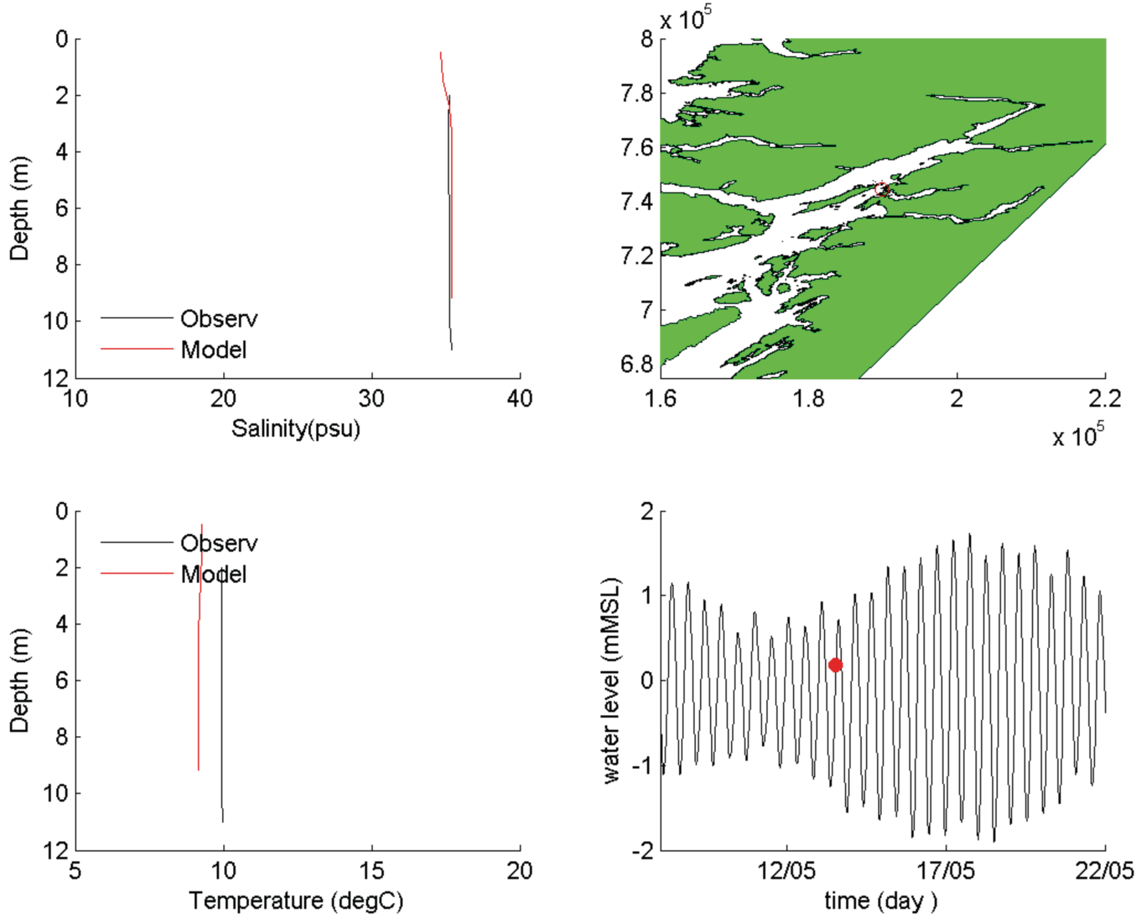
| Client | Consulting Engineer | Project: | Figure Title: | Figure B | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Cross section through the Corran Narrows | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



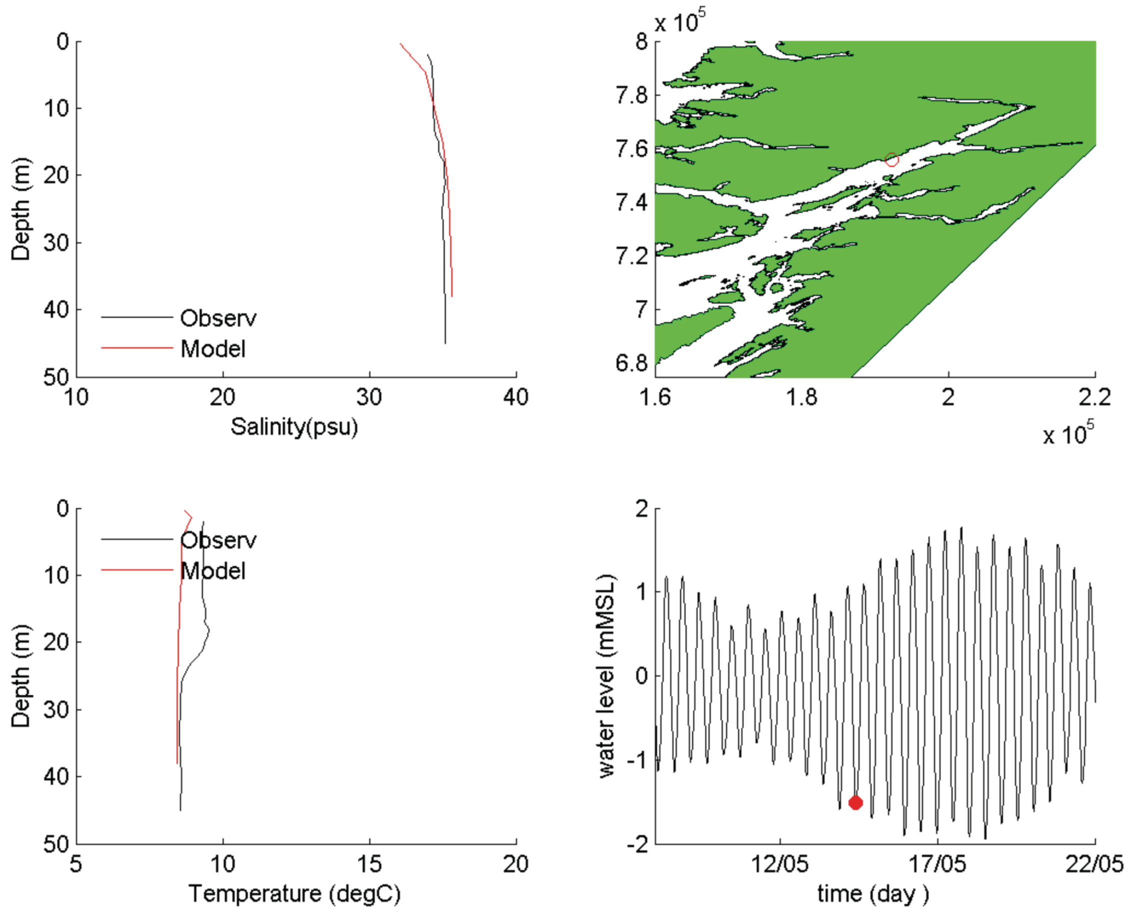

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-1 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Cross section through the Corran Narrows | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



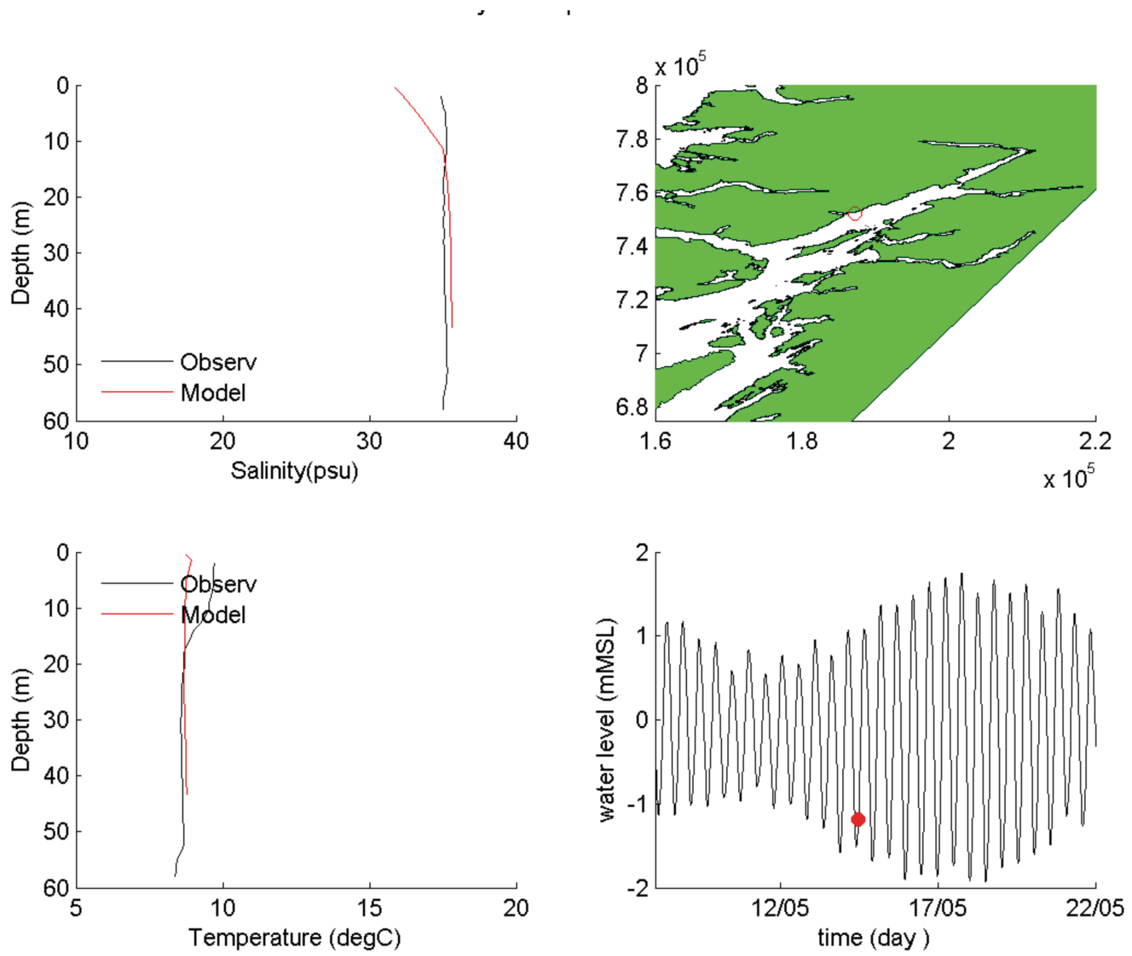

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-2 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Cross section through the Corran Narrows | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



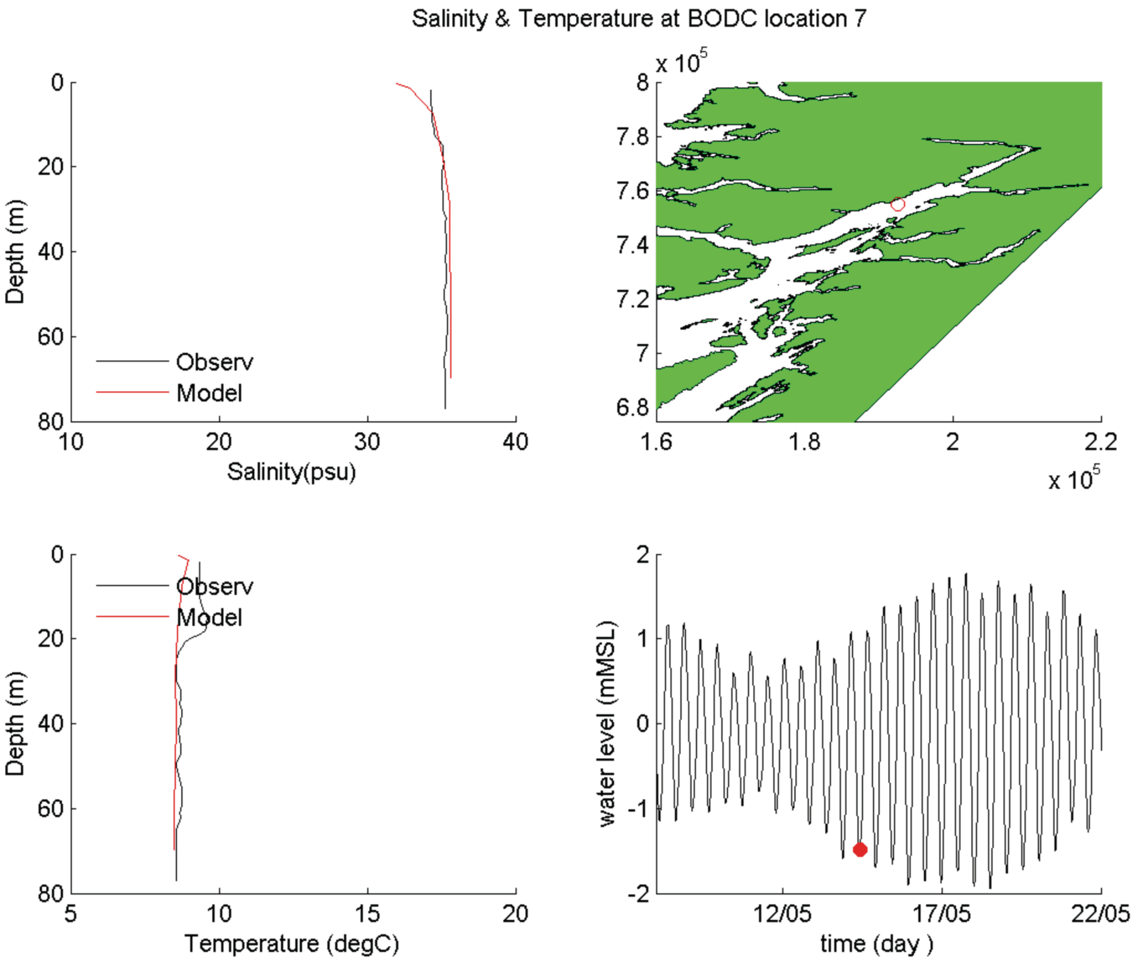

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-3 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Cross section through the Corran Narrows | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



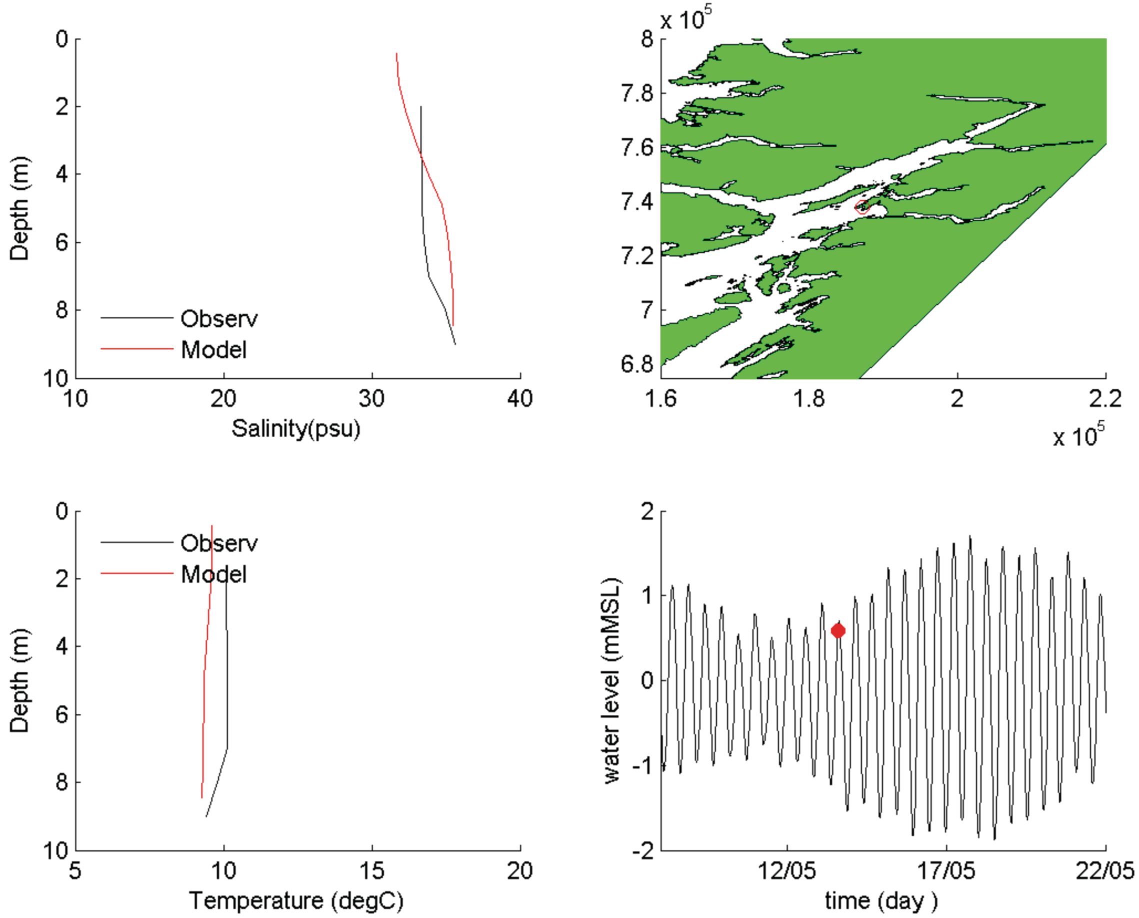

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-4 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B-5 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

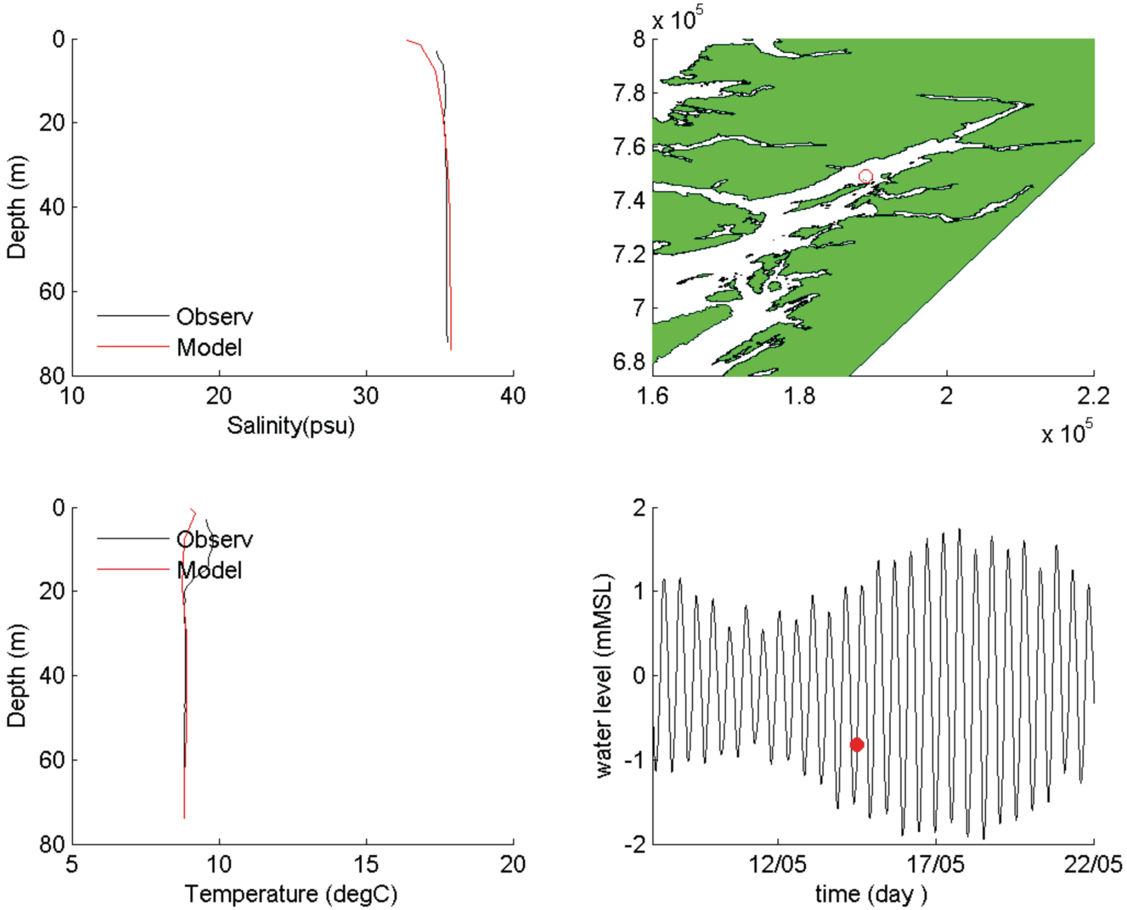



| Client | Consulting Engineer | Project: | Figure Title: | Figure B-6 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

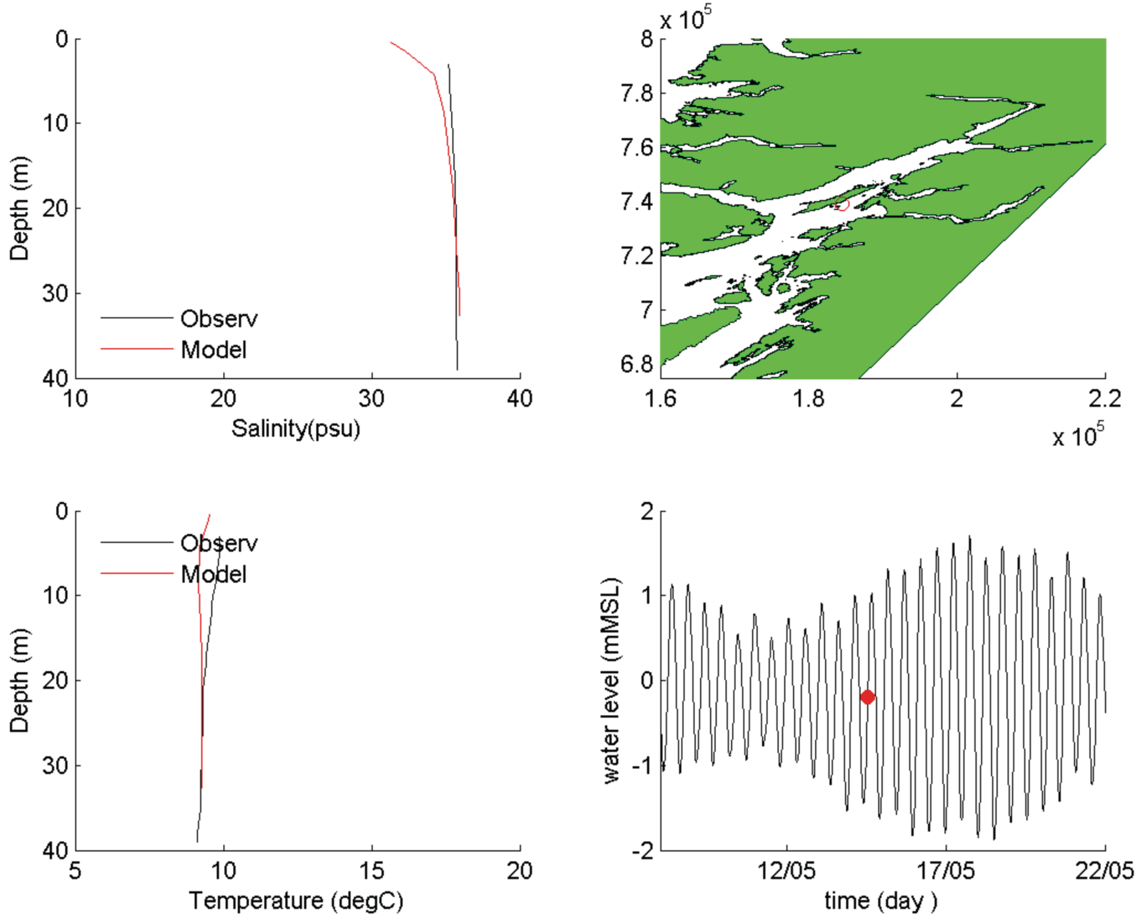



| Client | Consulting Engineer | Project: | Figure Title: | Figure B-7 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

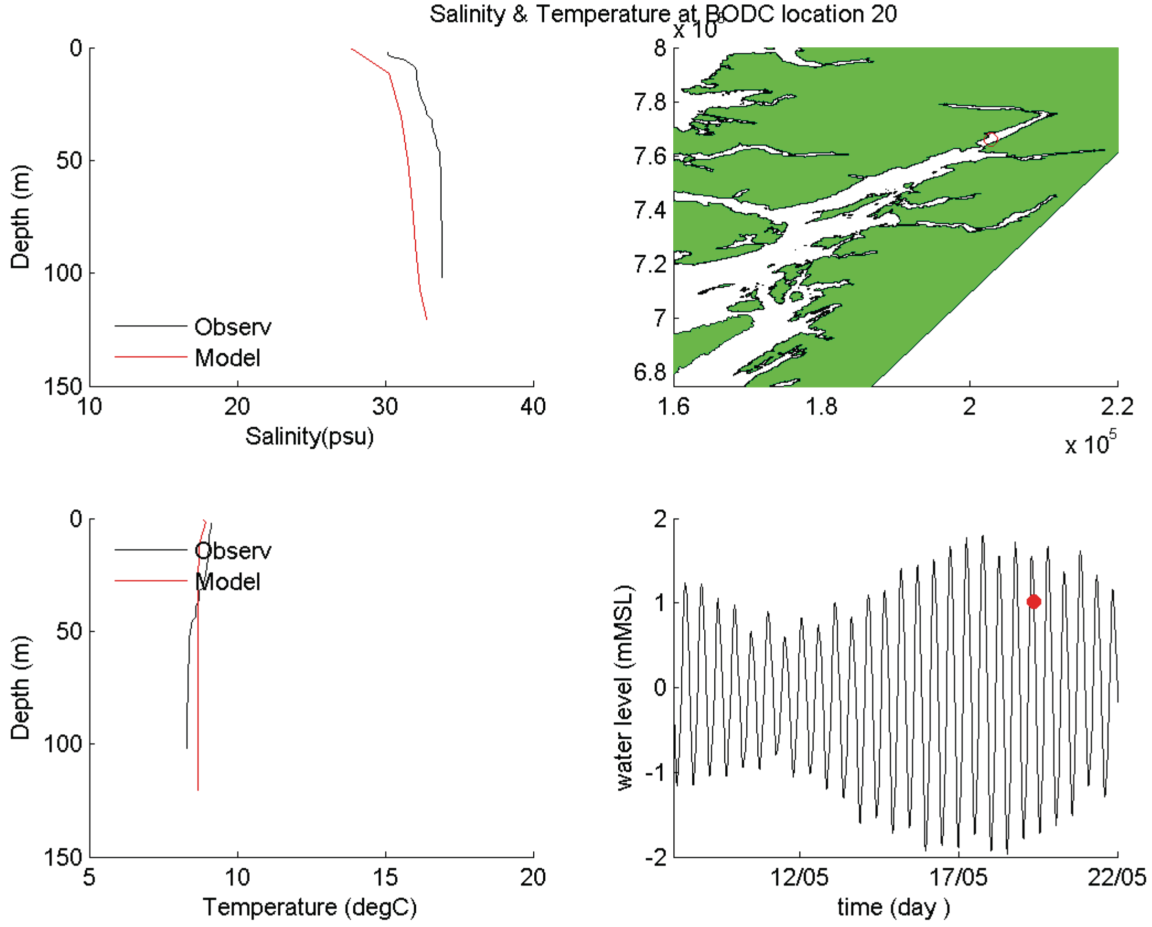
Salinity & Temperature at BODC location 14



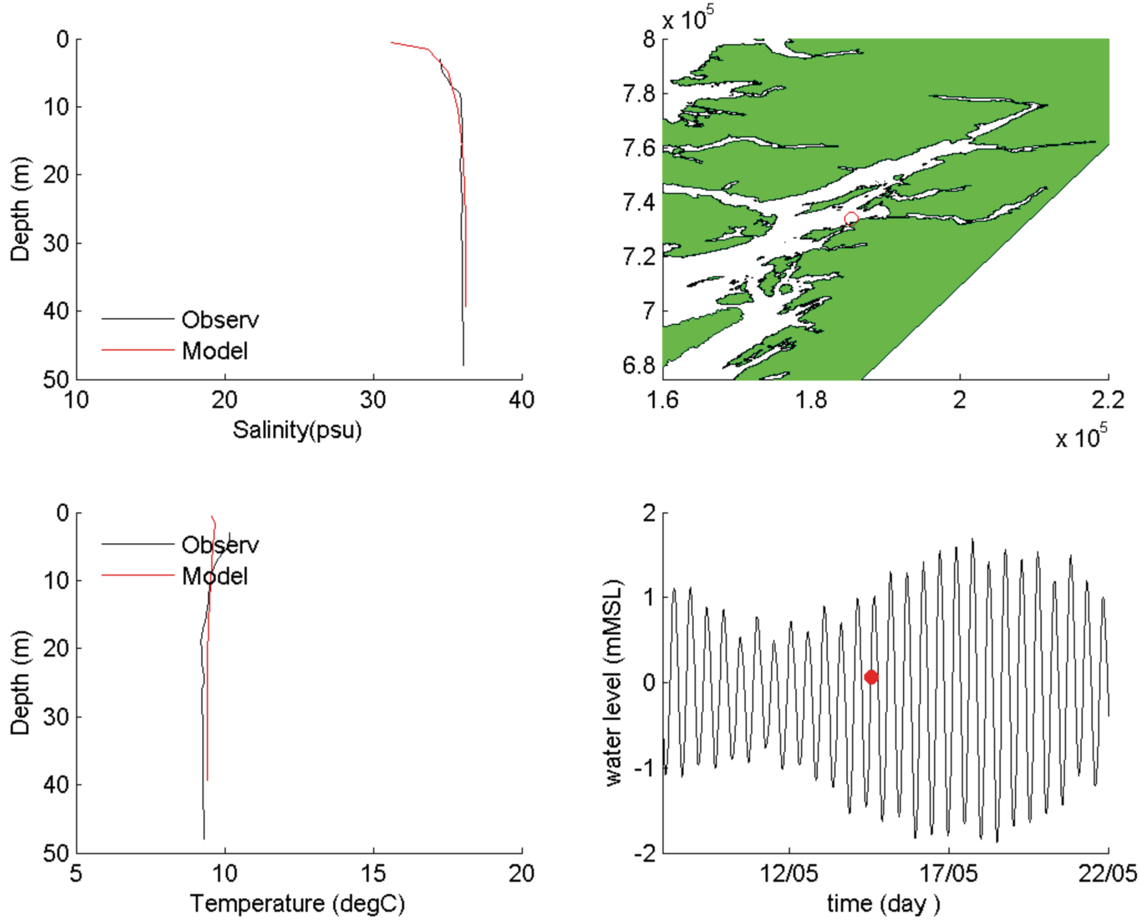

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-8 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B-9 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



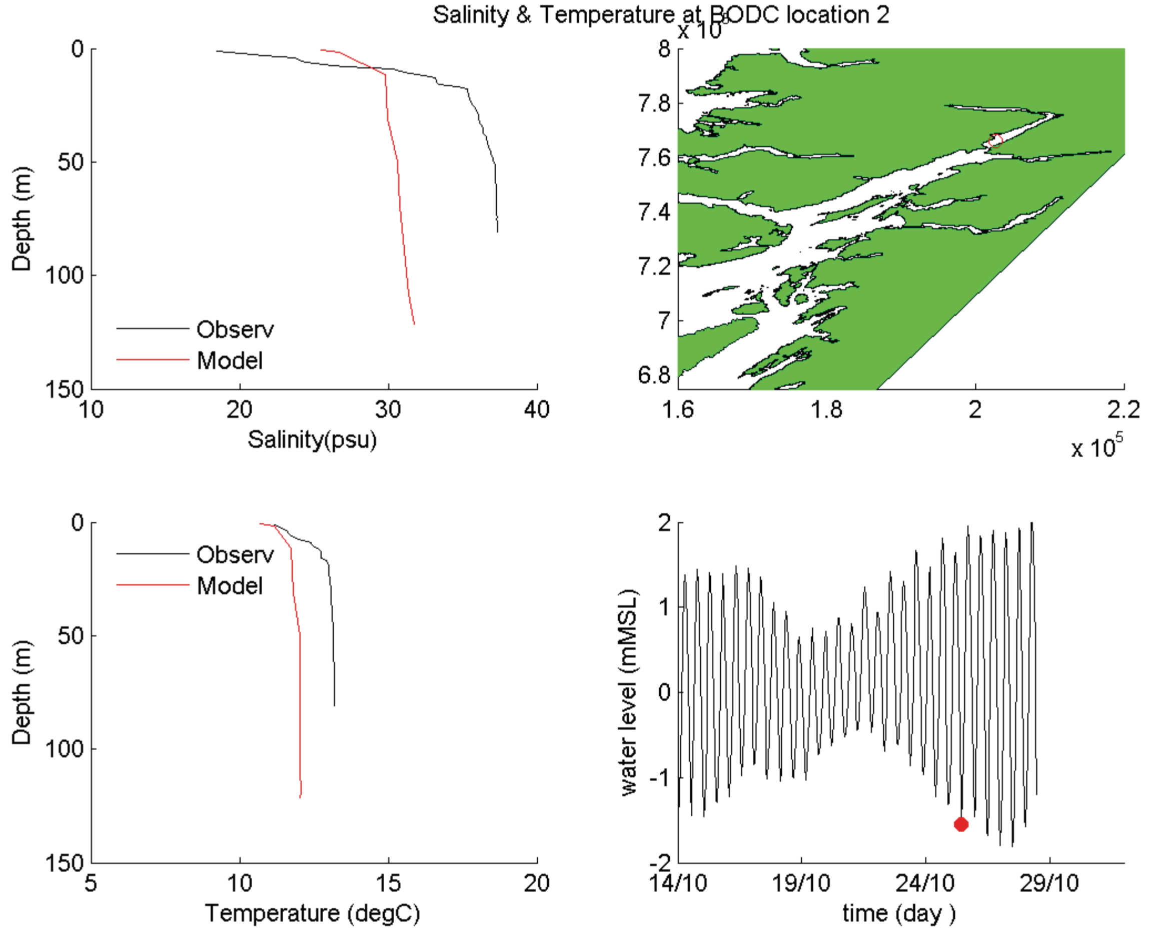

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-10 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



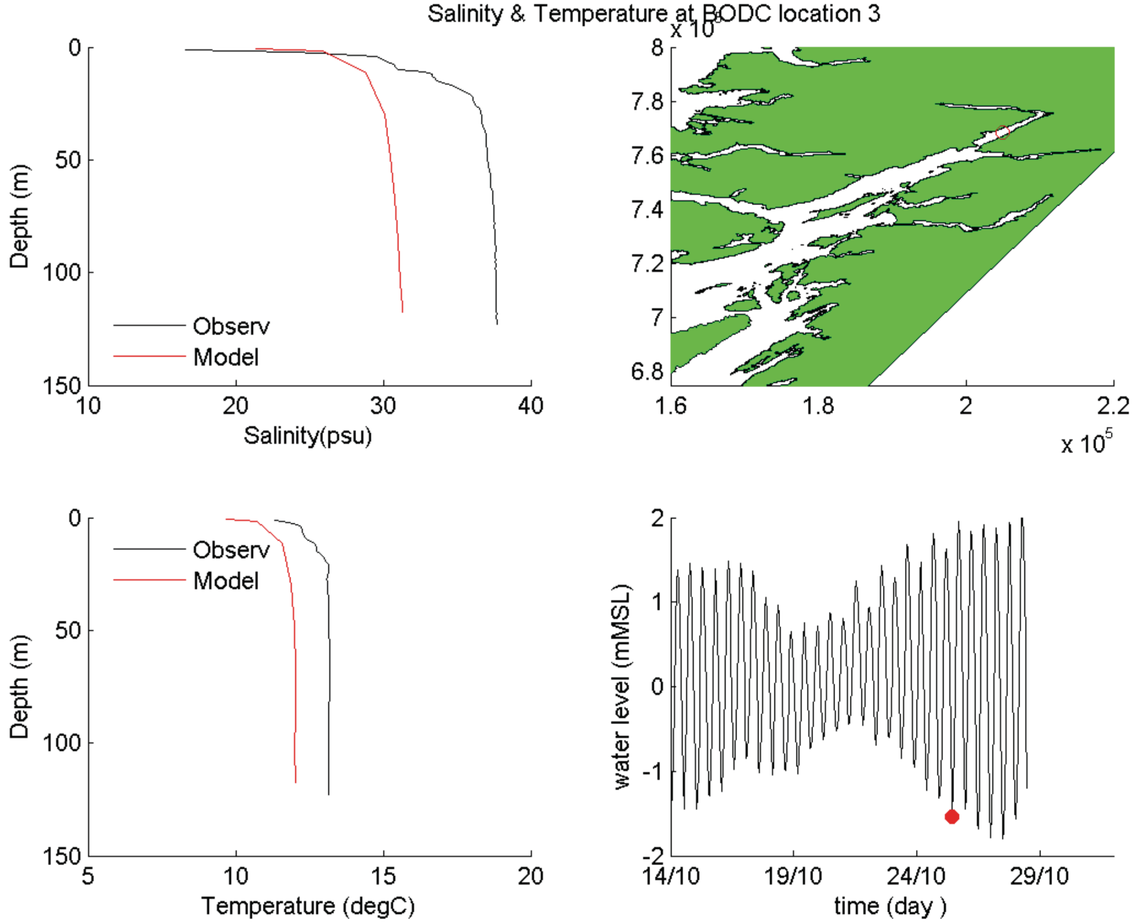

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-11 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

Oct 2011

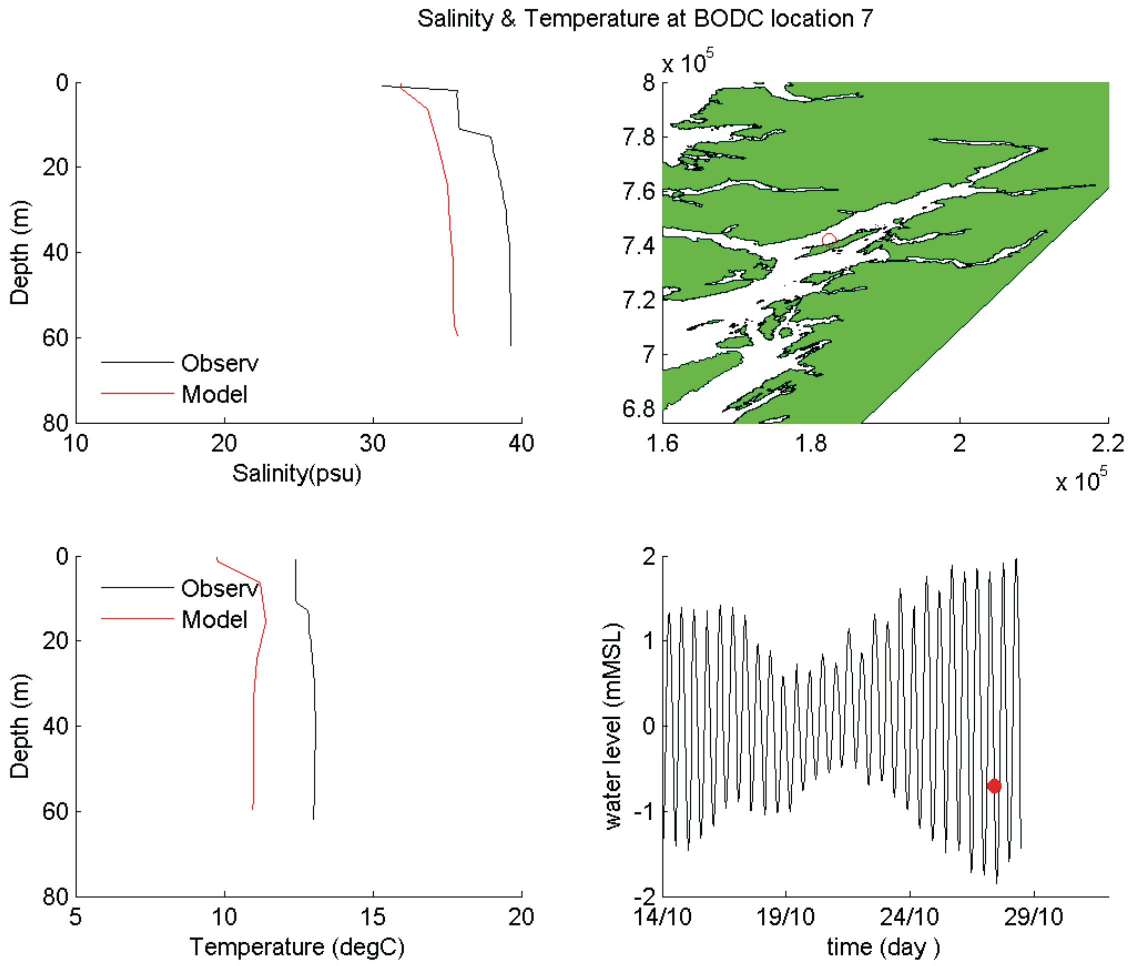
| Client | Consulting Engineer | Project: | Figure Title: | Figure | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Cross section through the Corran Narrows | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B-12 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

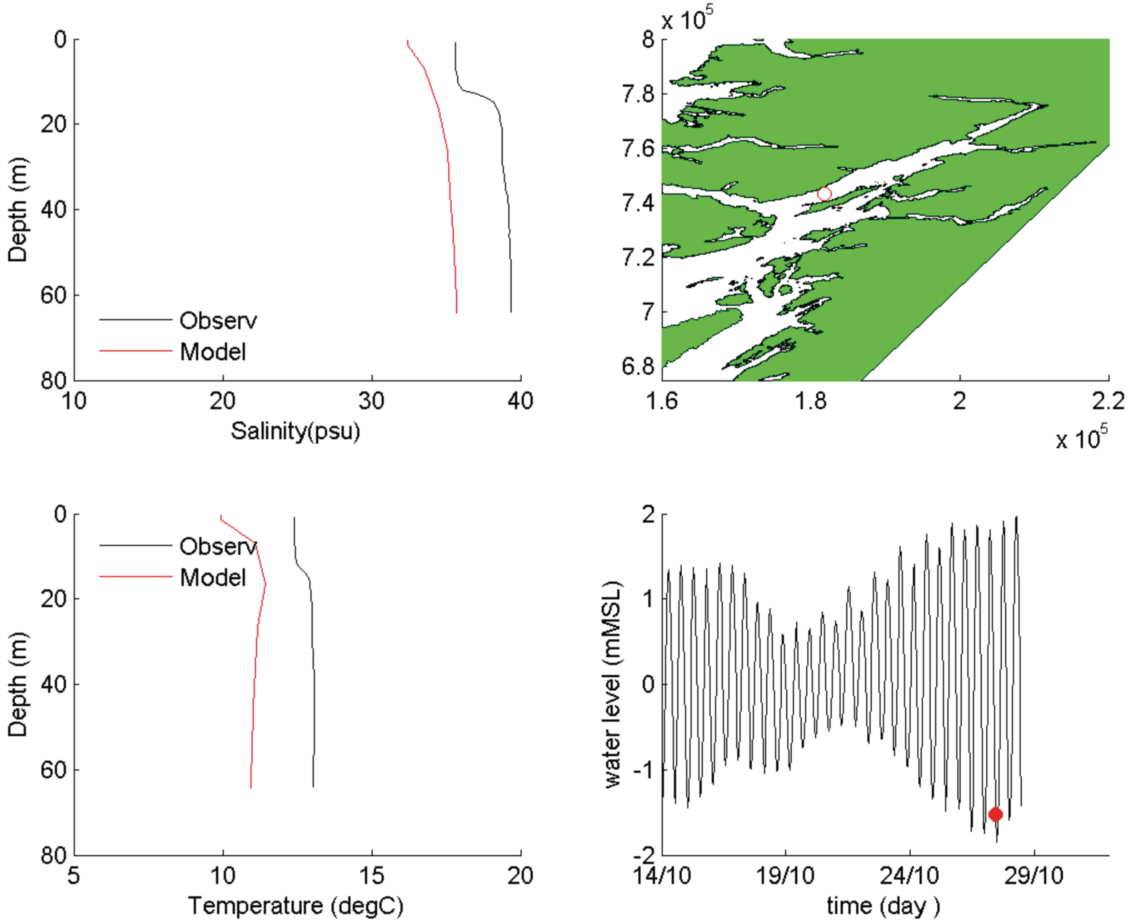



| Client | Consulting Engineer | Project: | Figure Title: | Figure B-13 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

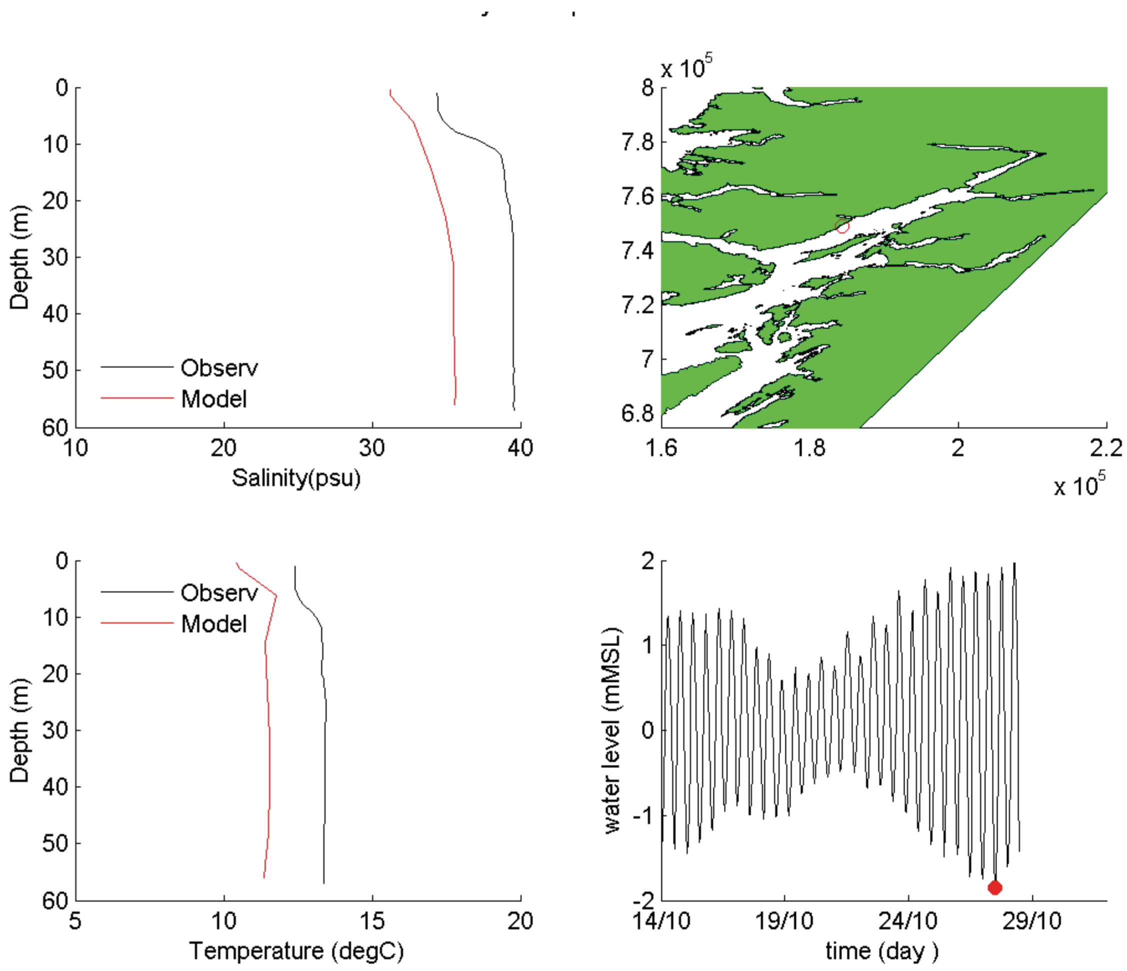



| Client | Consulting Engineer | Project: | Figure Title: | Figure B-14 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

Salinity & Temperature at BODC location 9

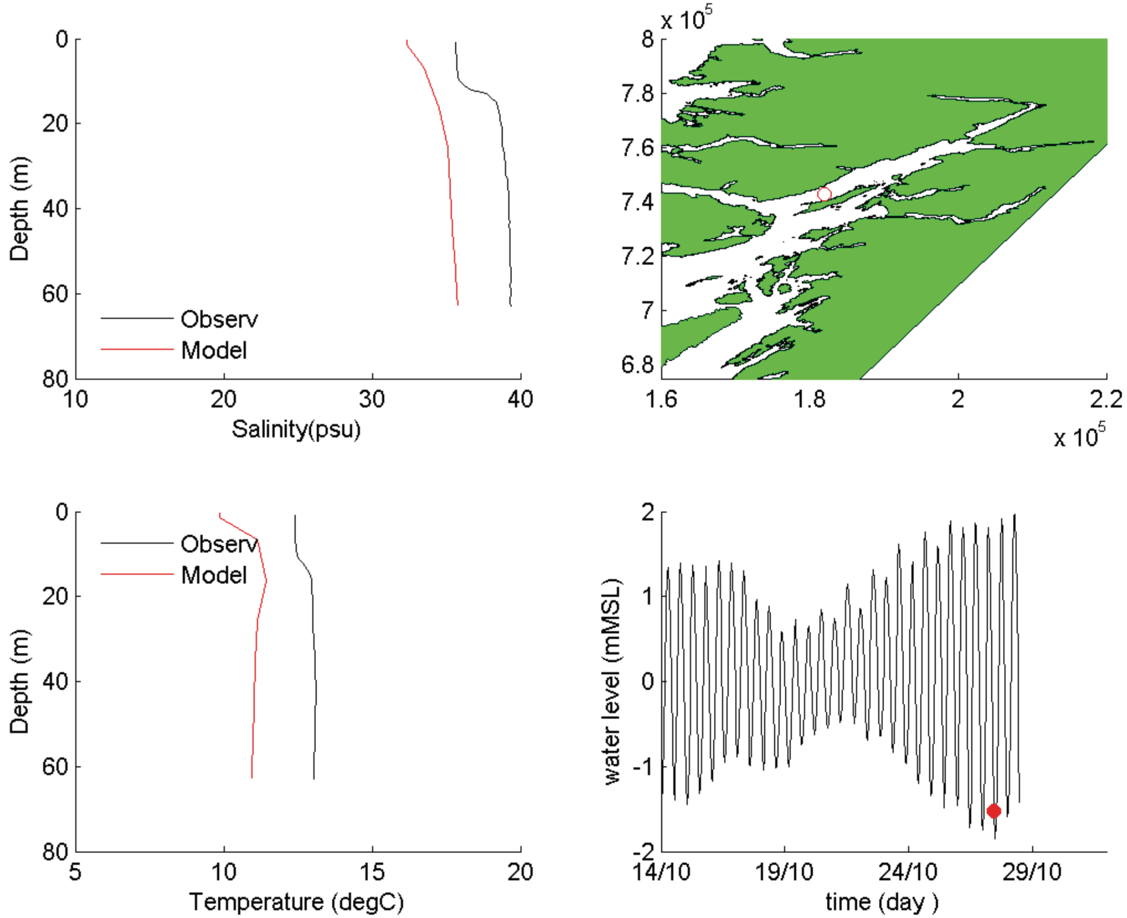



| Client | Consulting Engineer | Project: | Figure Title: | Figure B-15 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

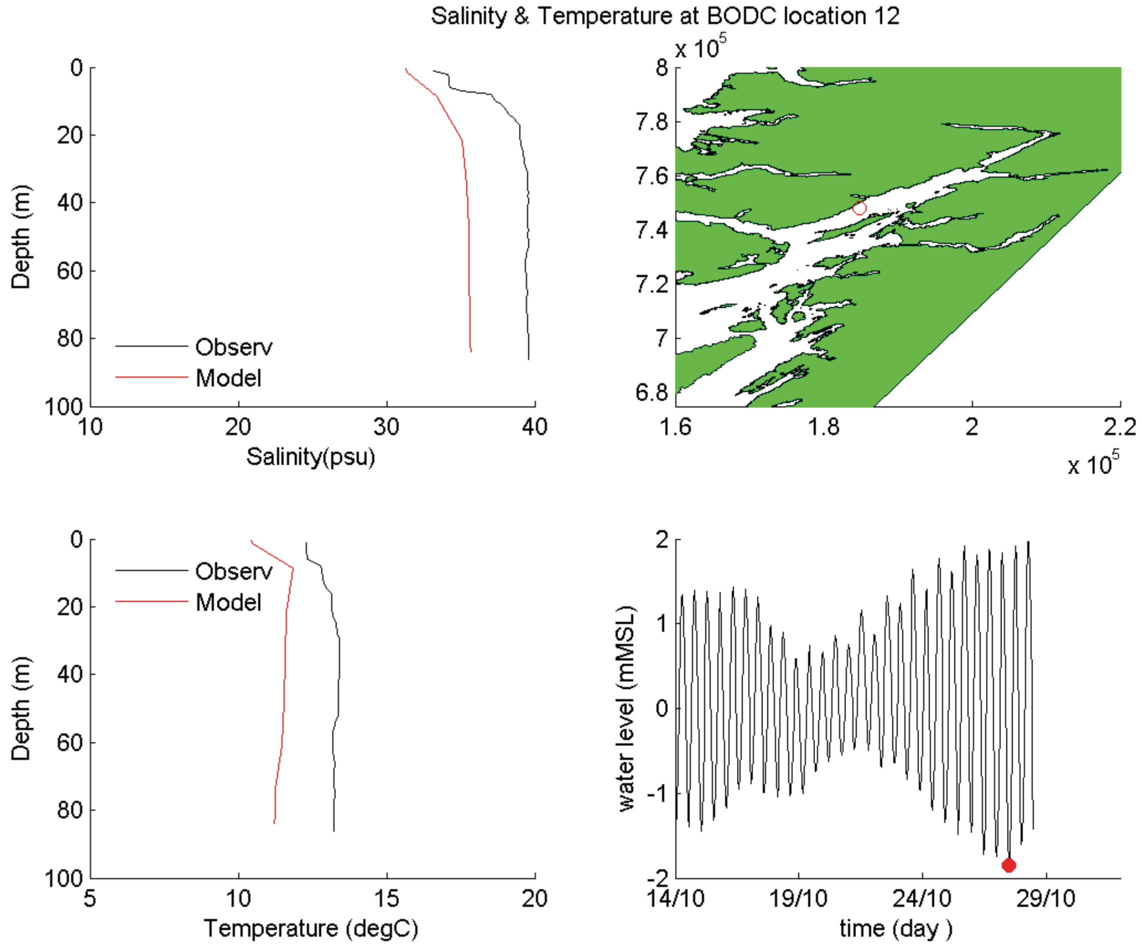



| Client | Consulting Engineer | Project: | Figure Title: | Figure B-16 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

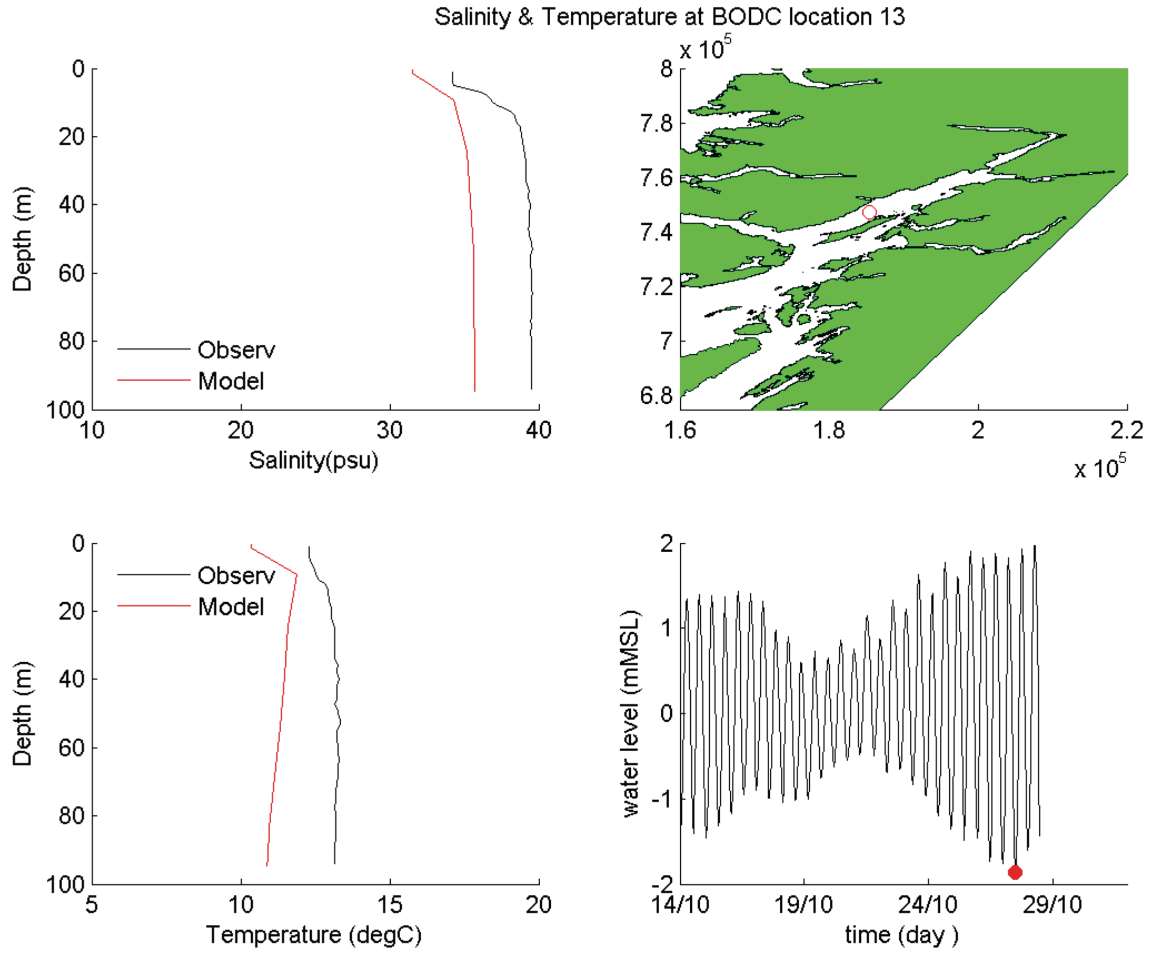
Salinity & Temperature at BODC location 8



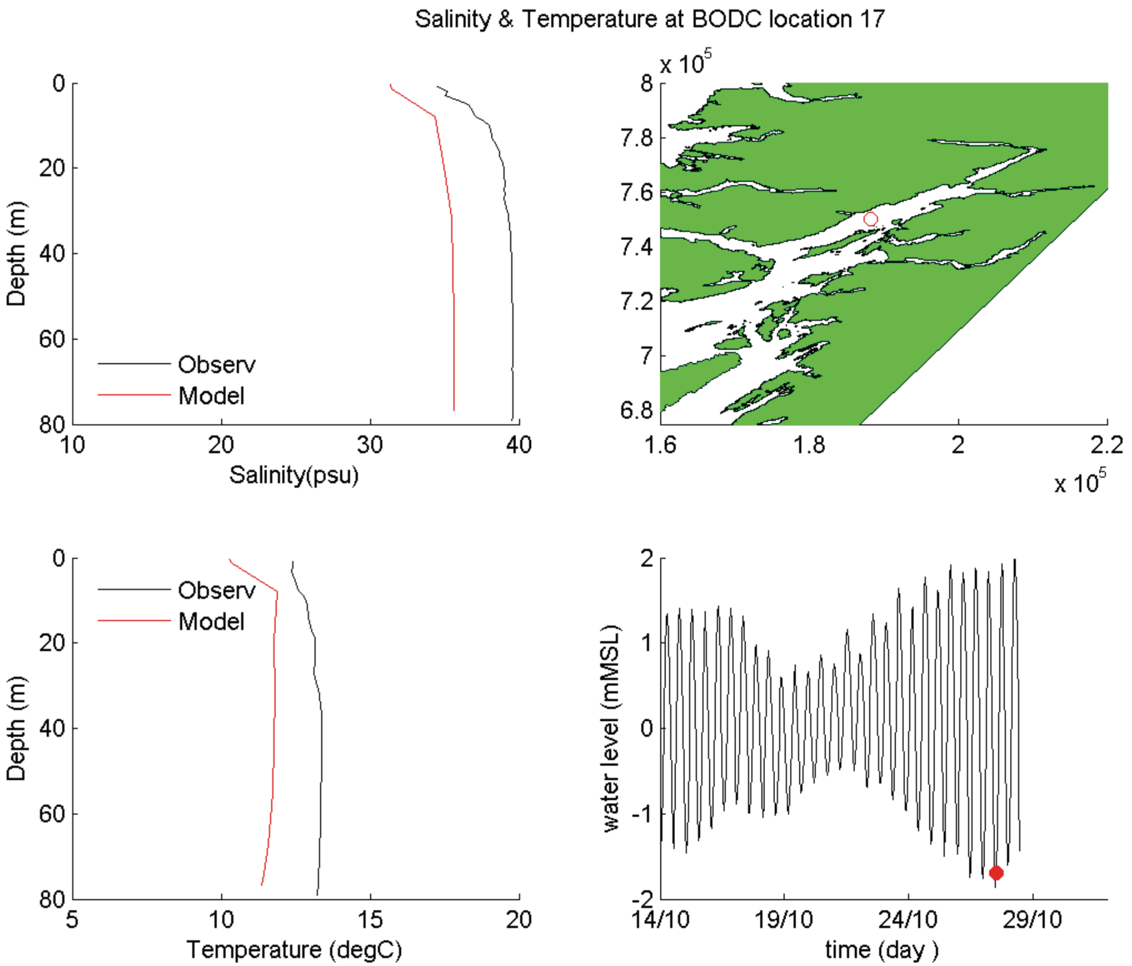

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-17 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



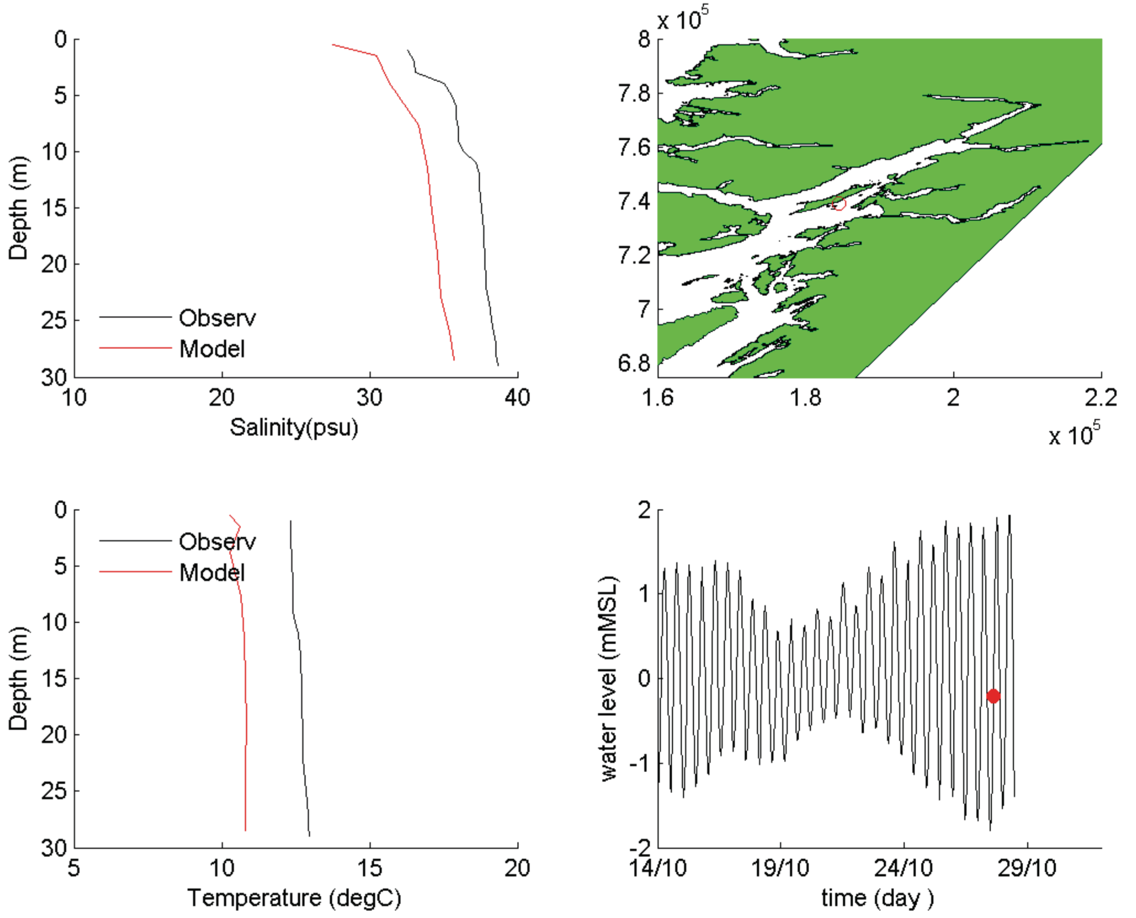

| Client | Consulting Engineer | Project: | Figure Title: | Figure B -18 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



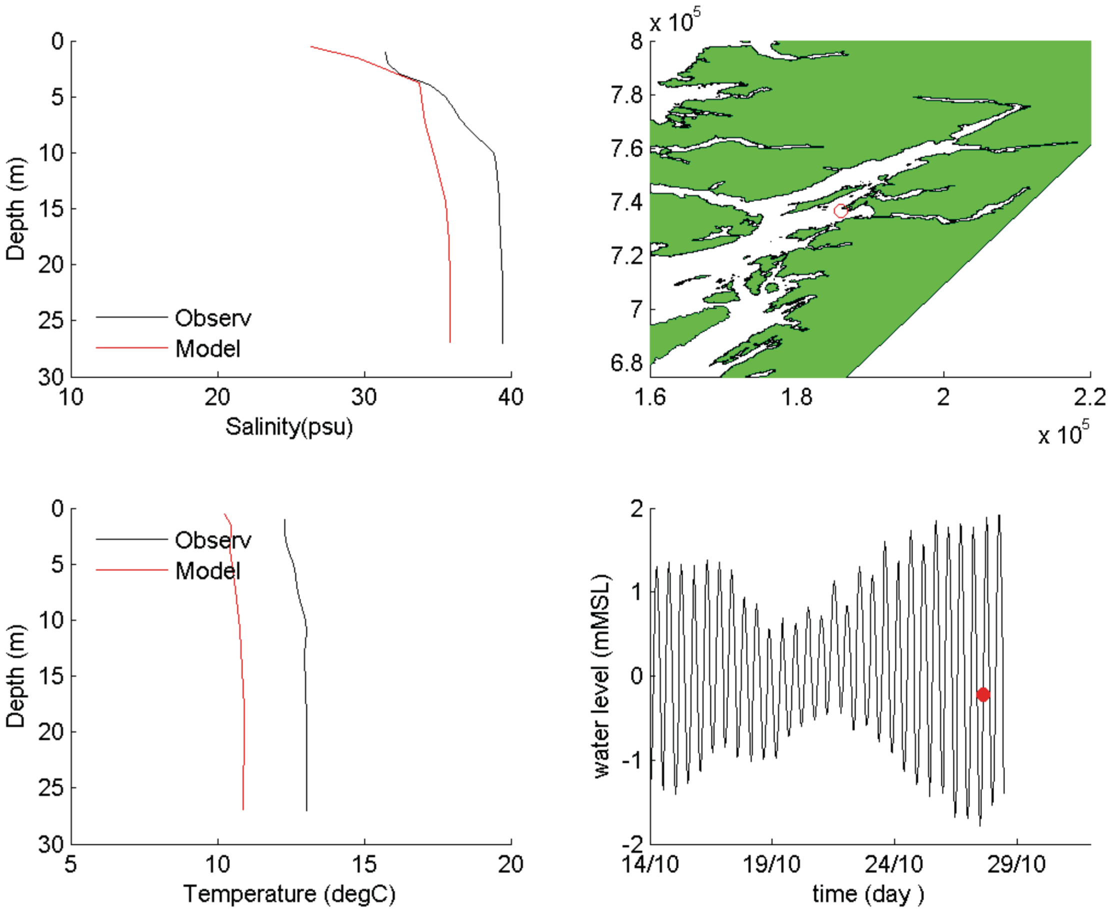

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-19 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure B-20 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



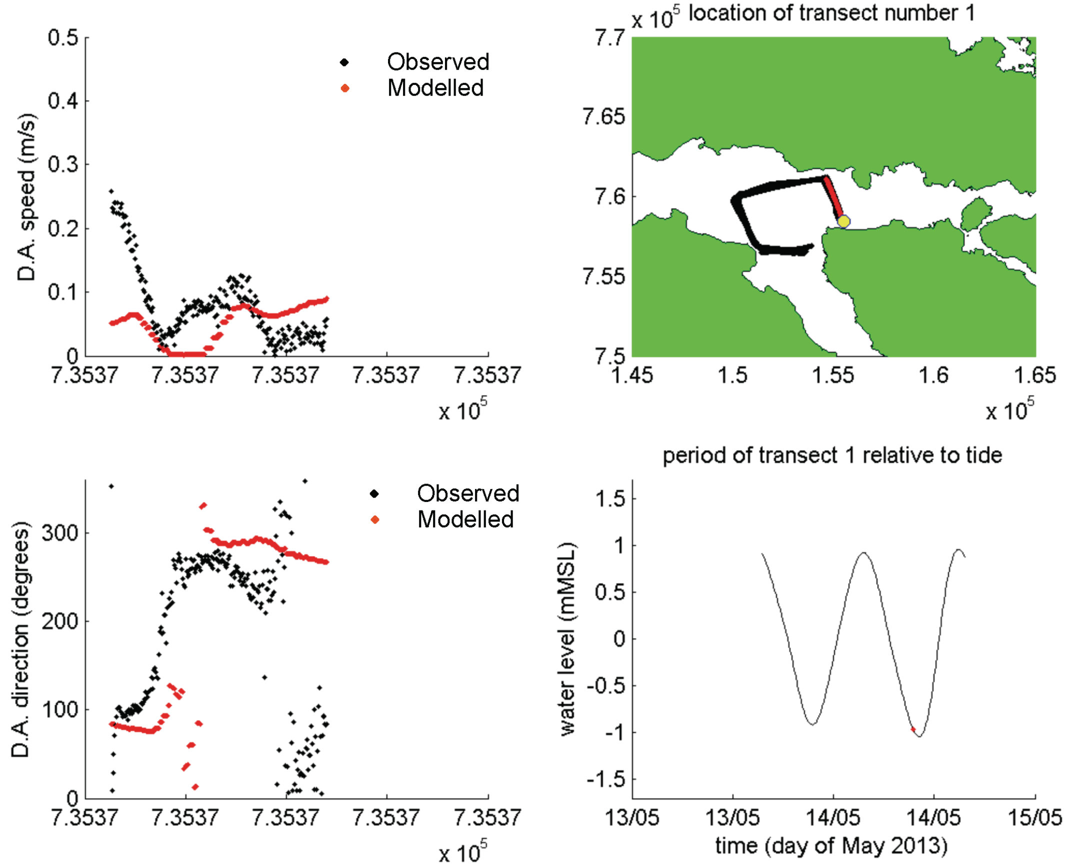

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-21 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



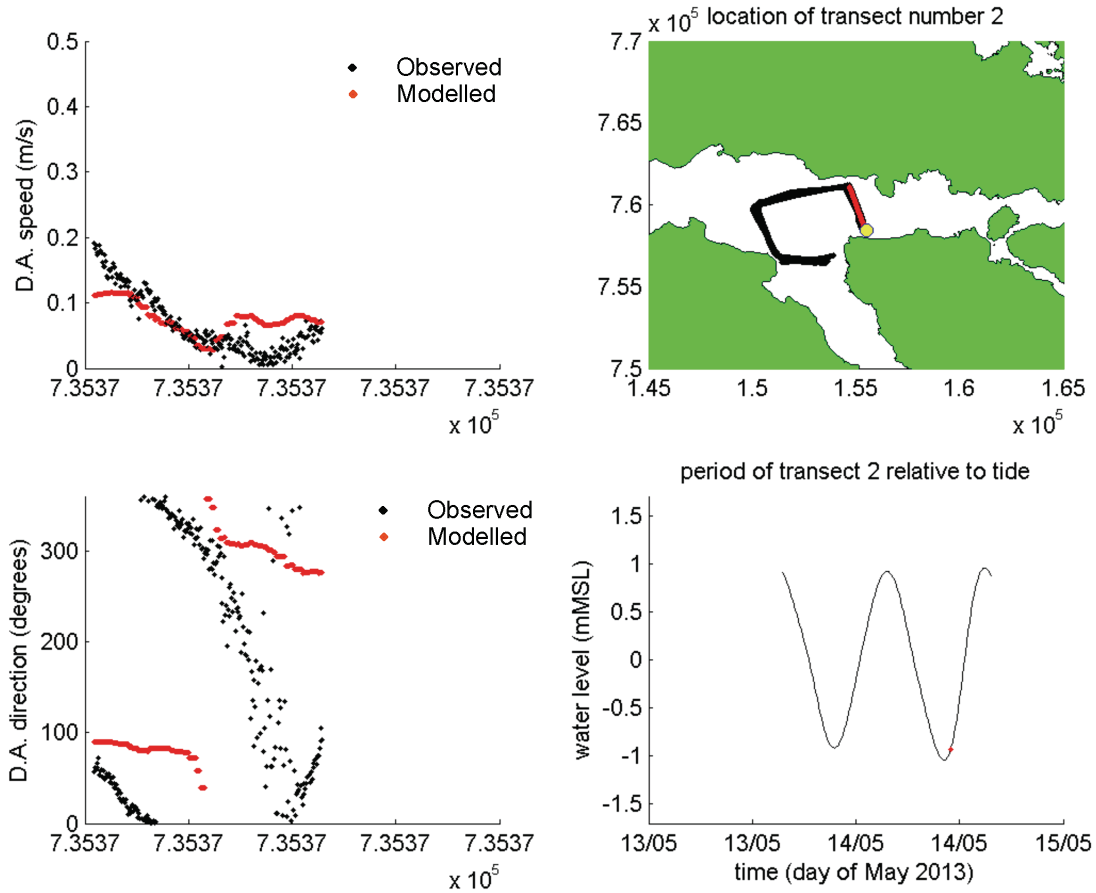

| Client | Consulting Engineer | Project: | Figure Title: | Figure B-22 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparisons with vertical profile CTD measurements | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

# Appendix C

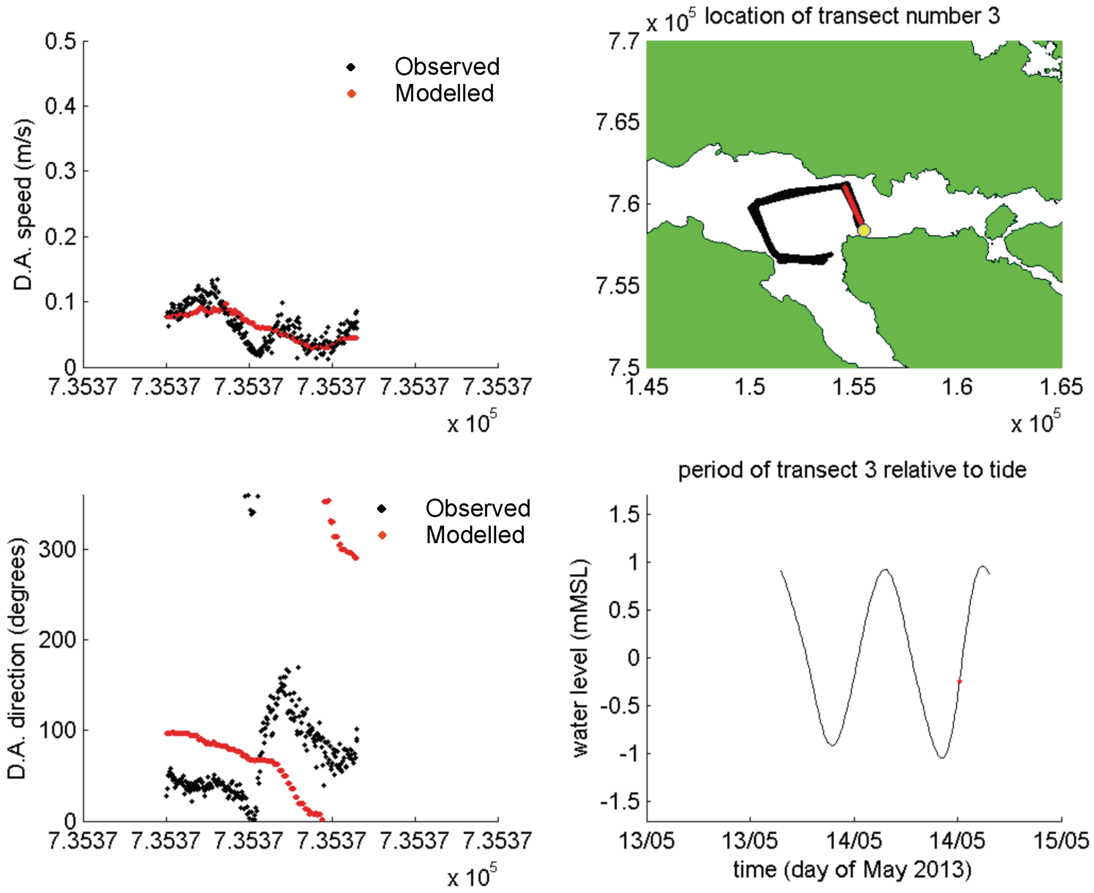
## Additional results from October 2011 comparisons



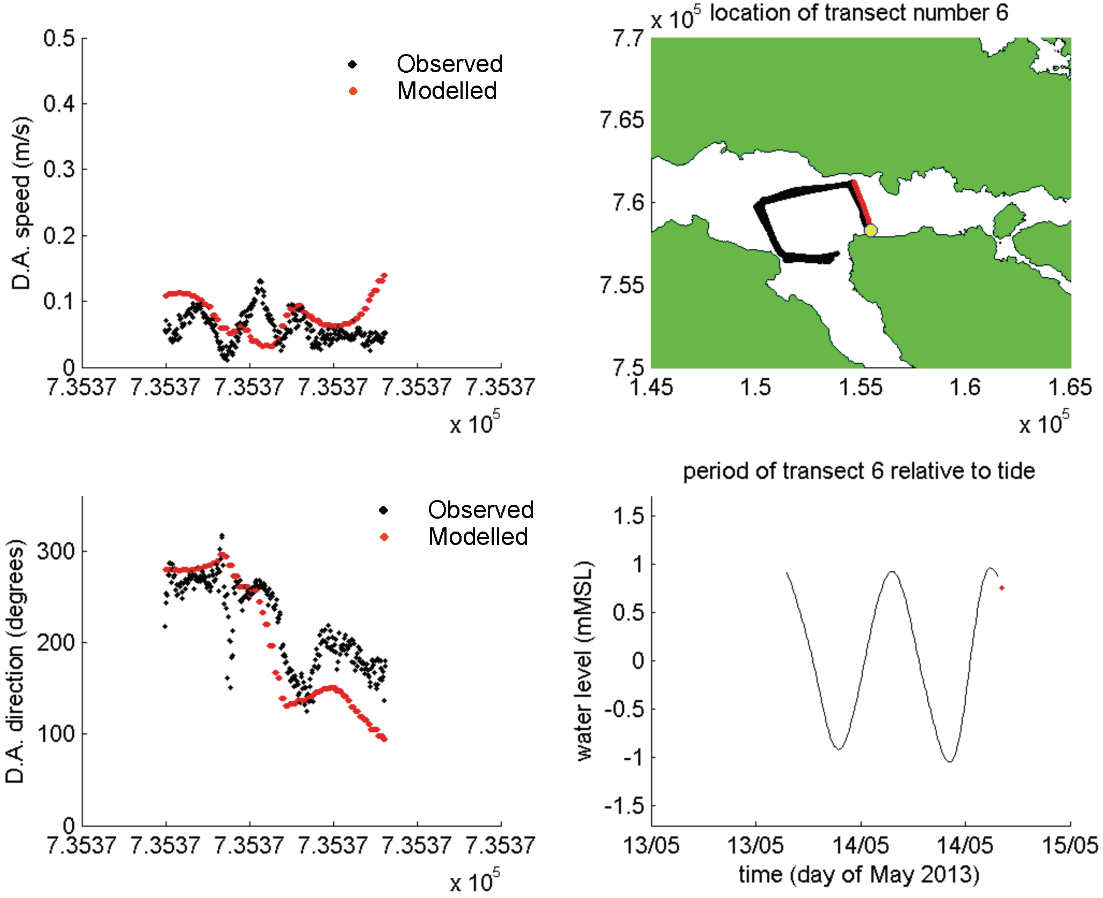

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-1 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



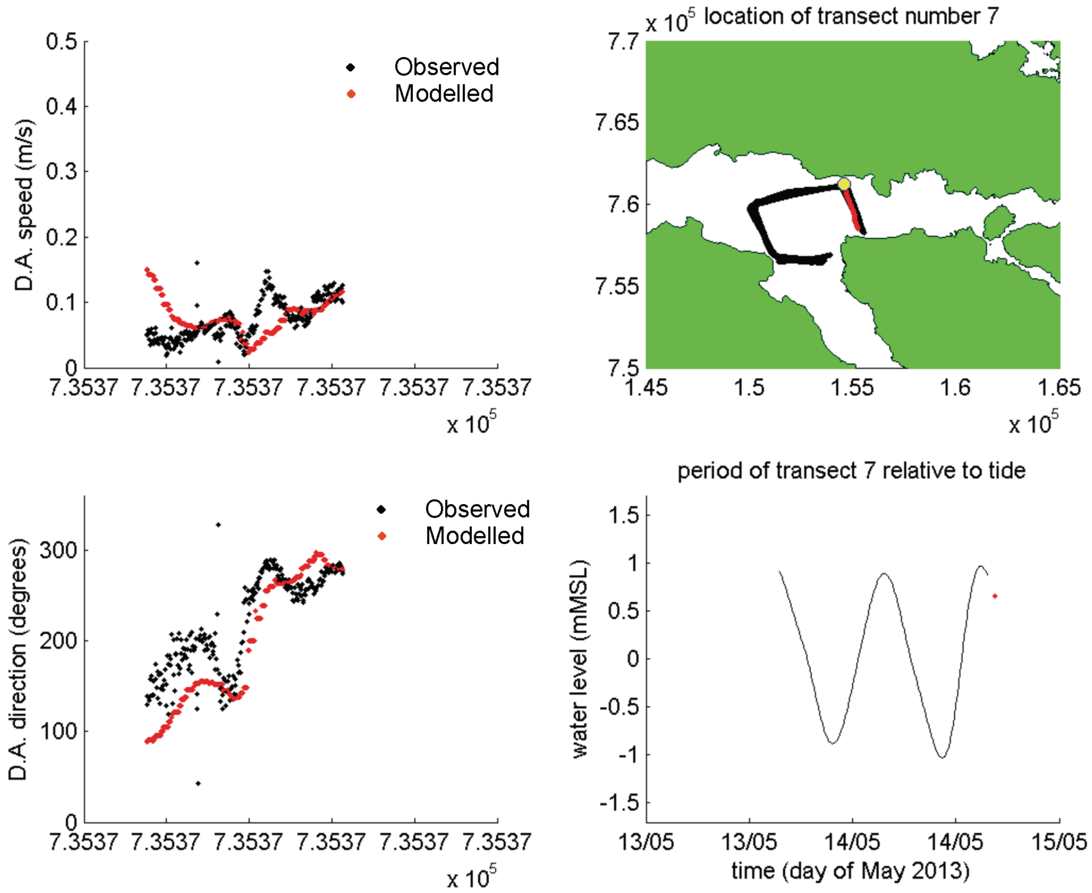

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-2 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



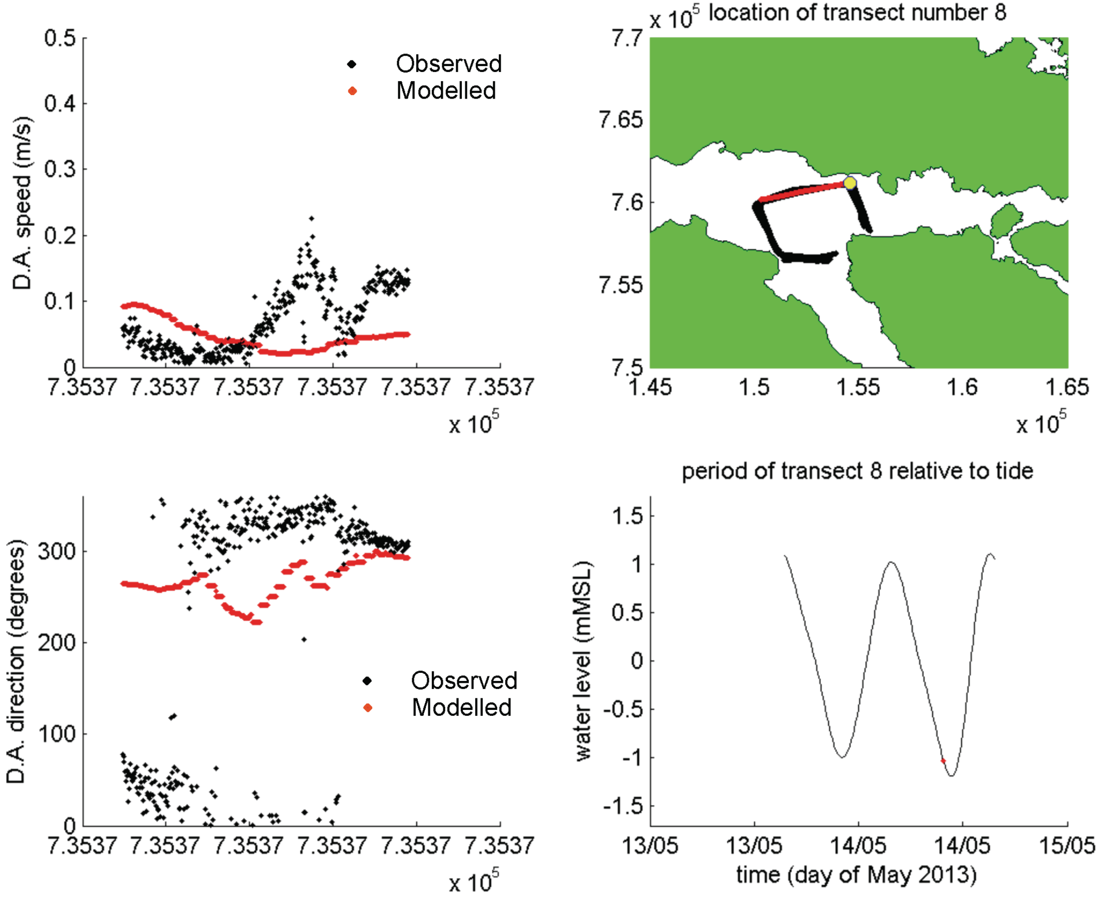

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-3 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



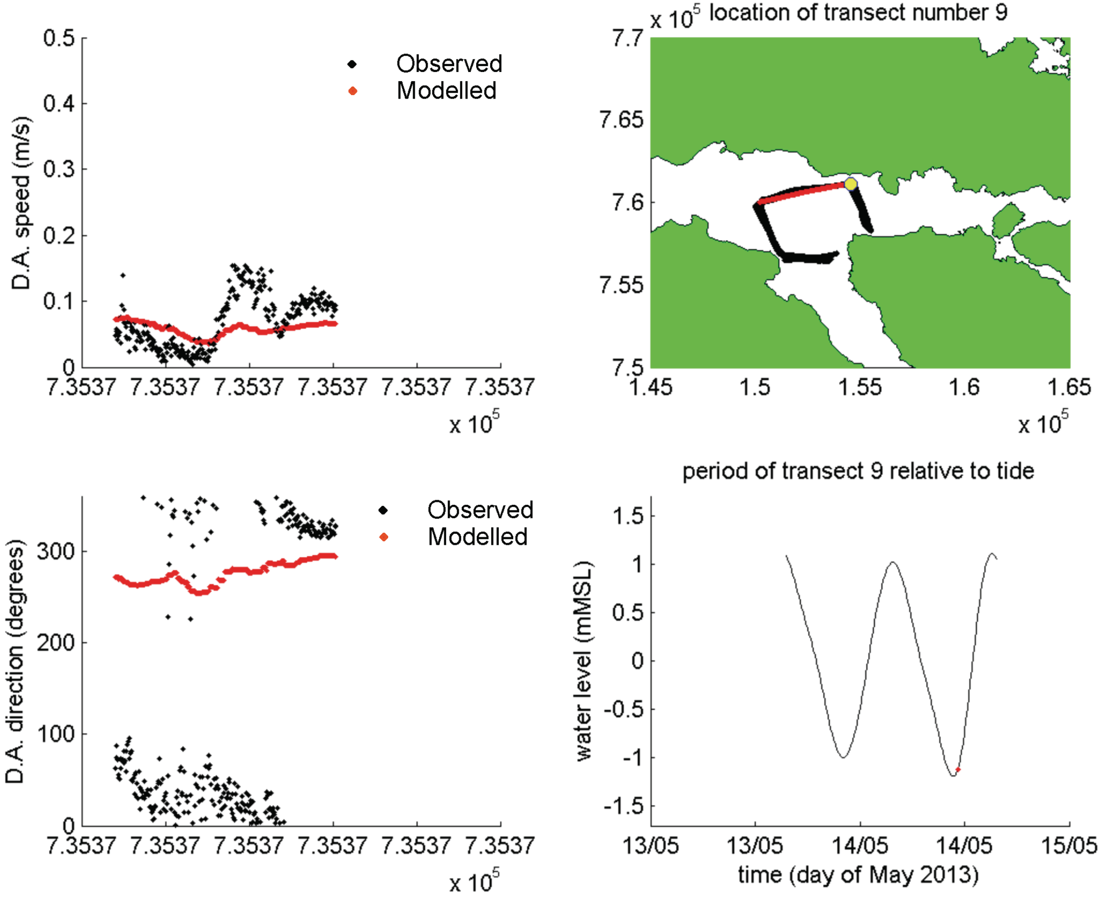

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-4 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



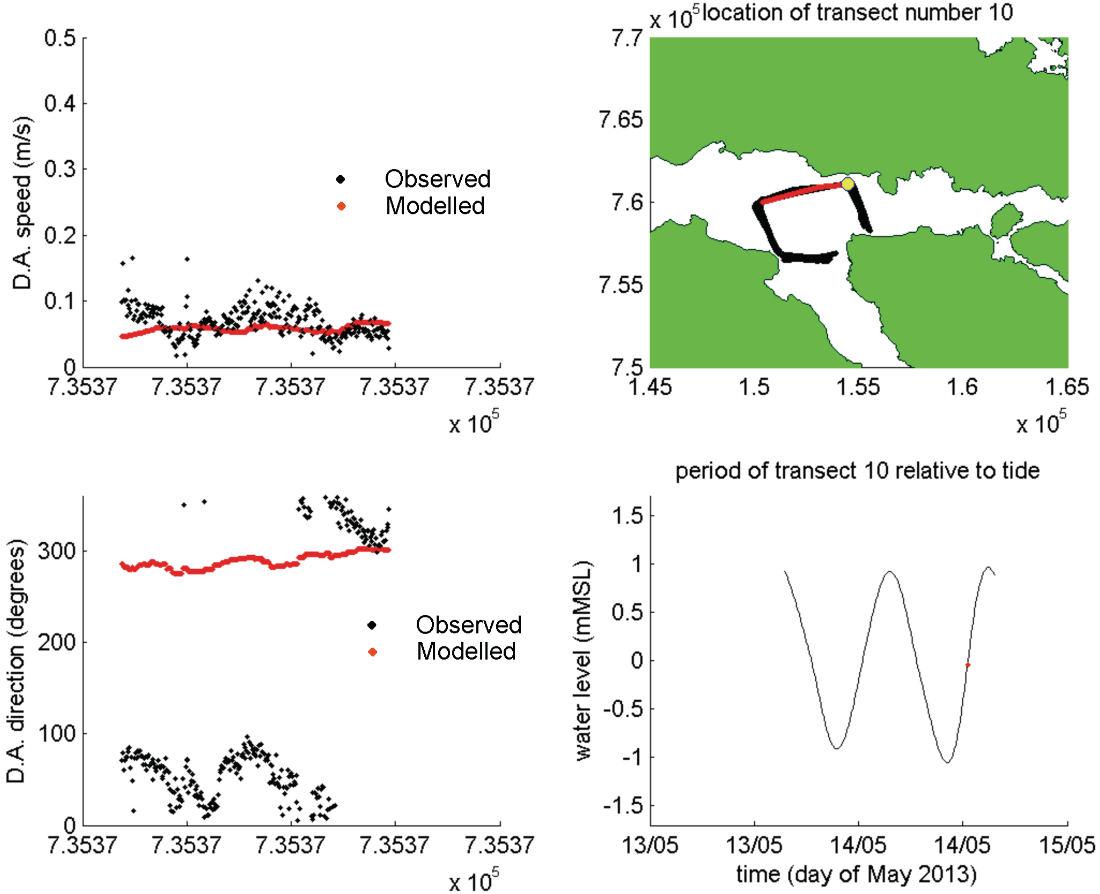

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-5 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



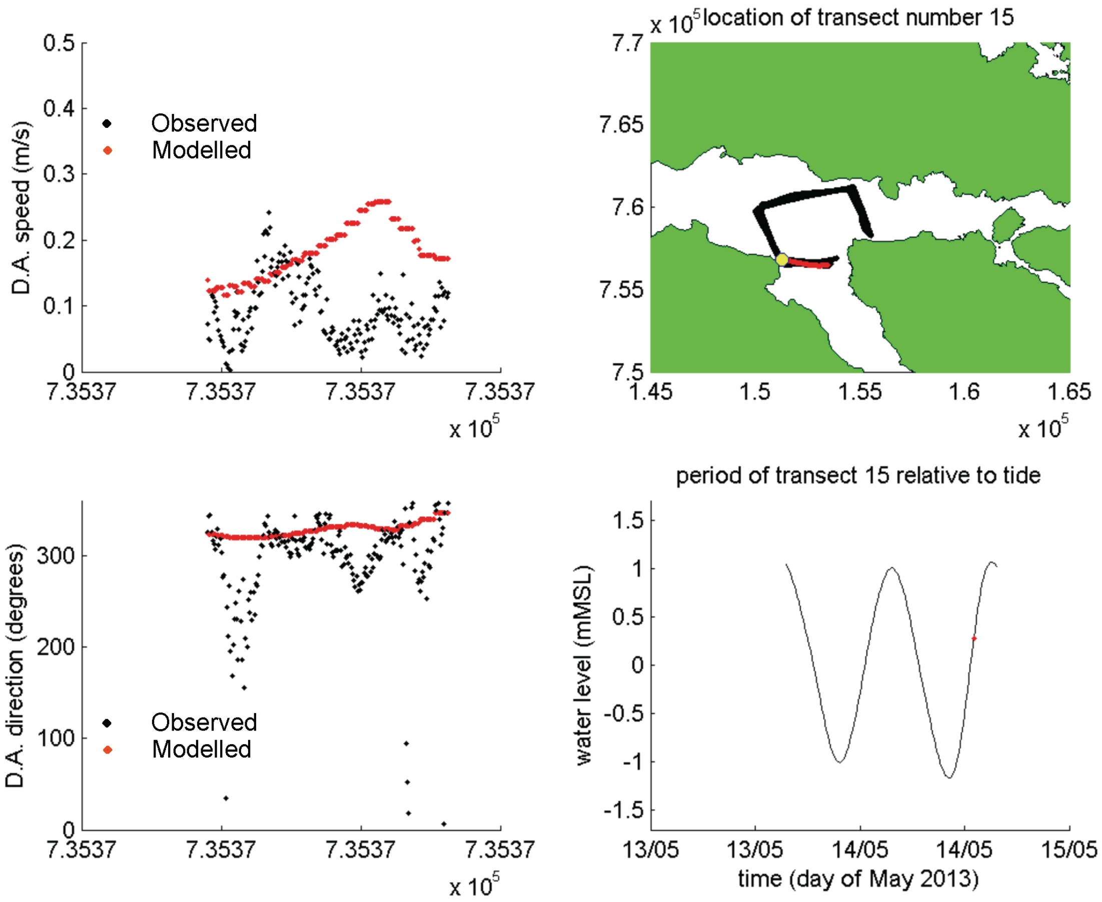

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-6 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



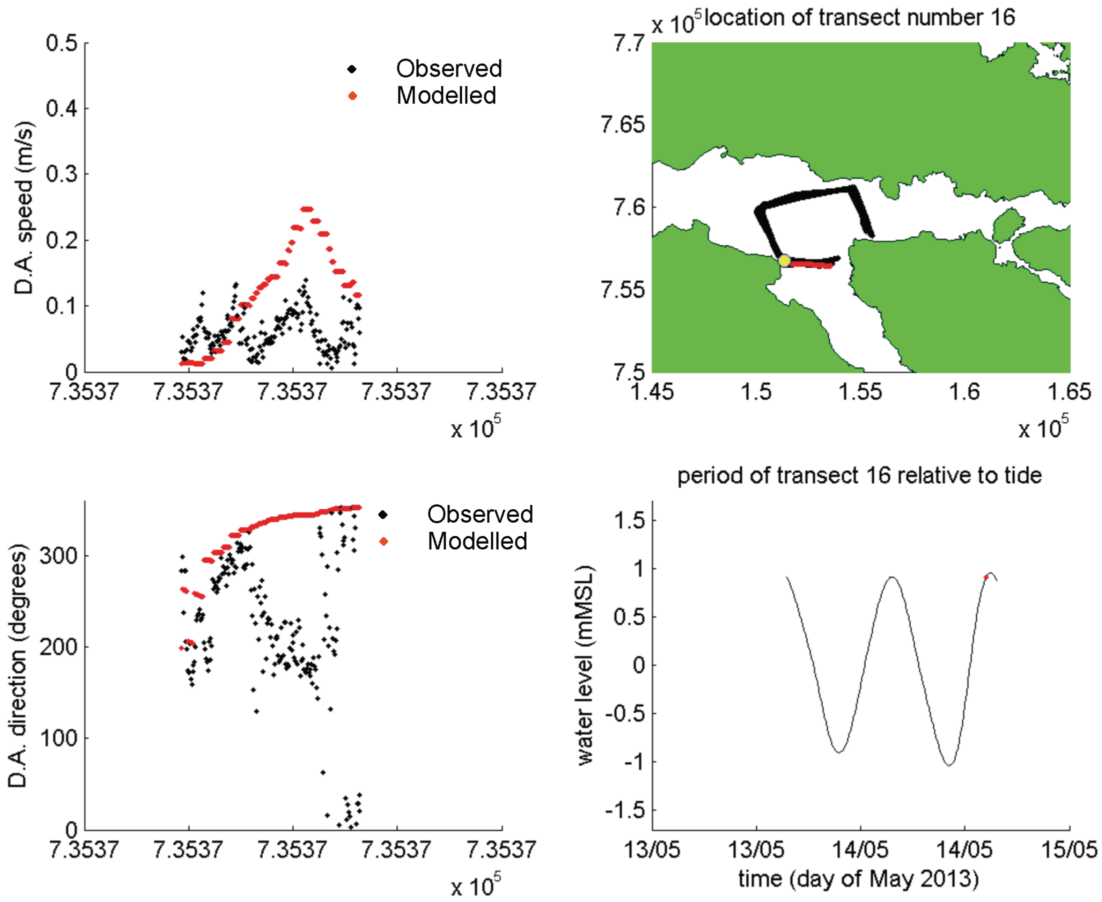

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-7 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



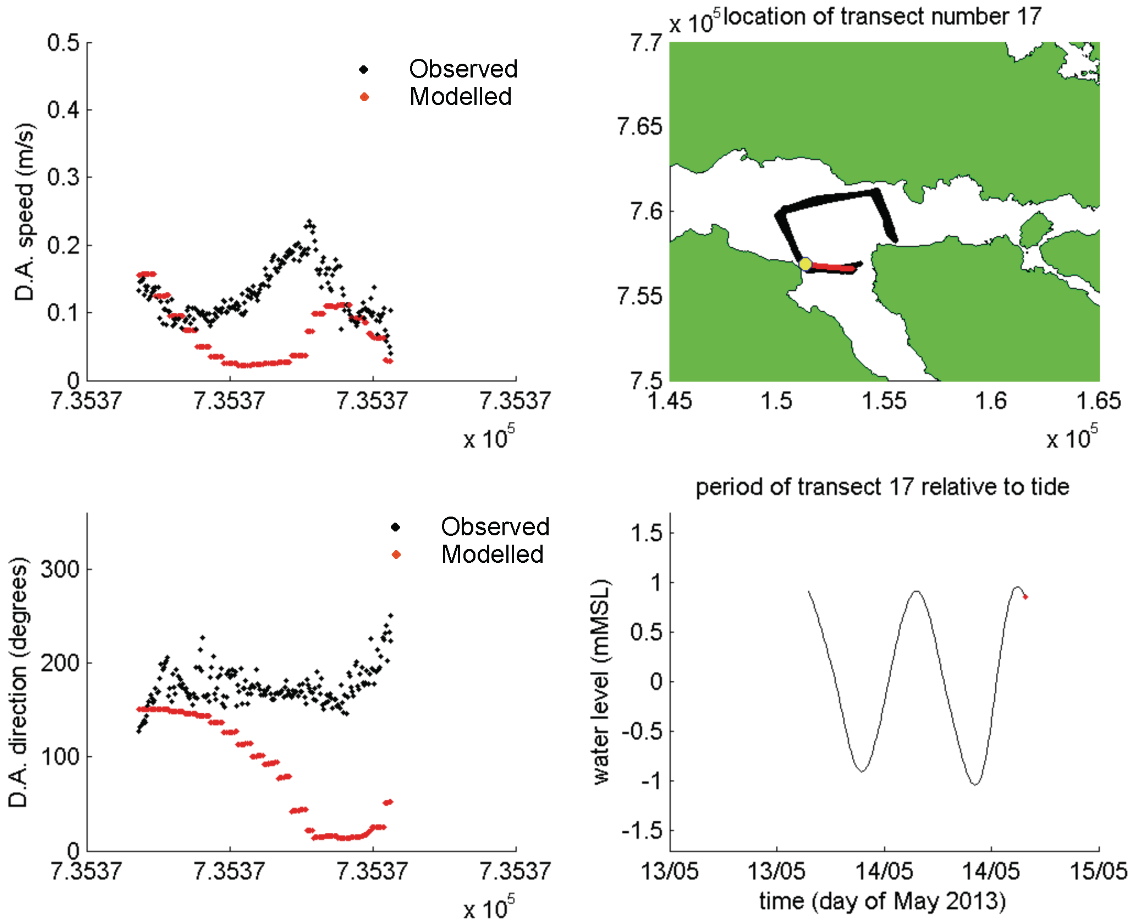

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-8 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



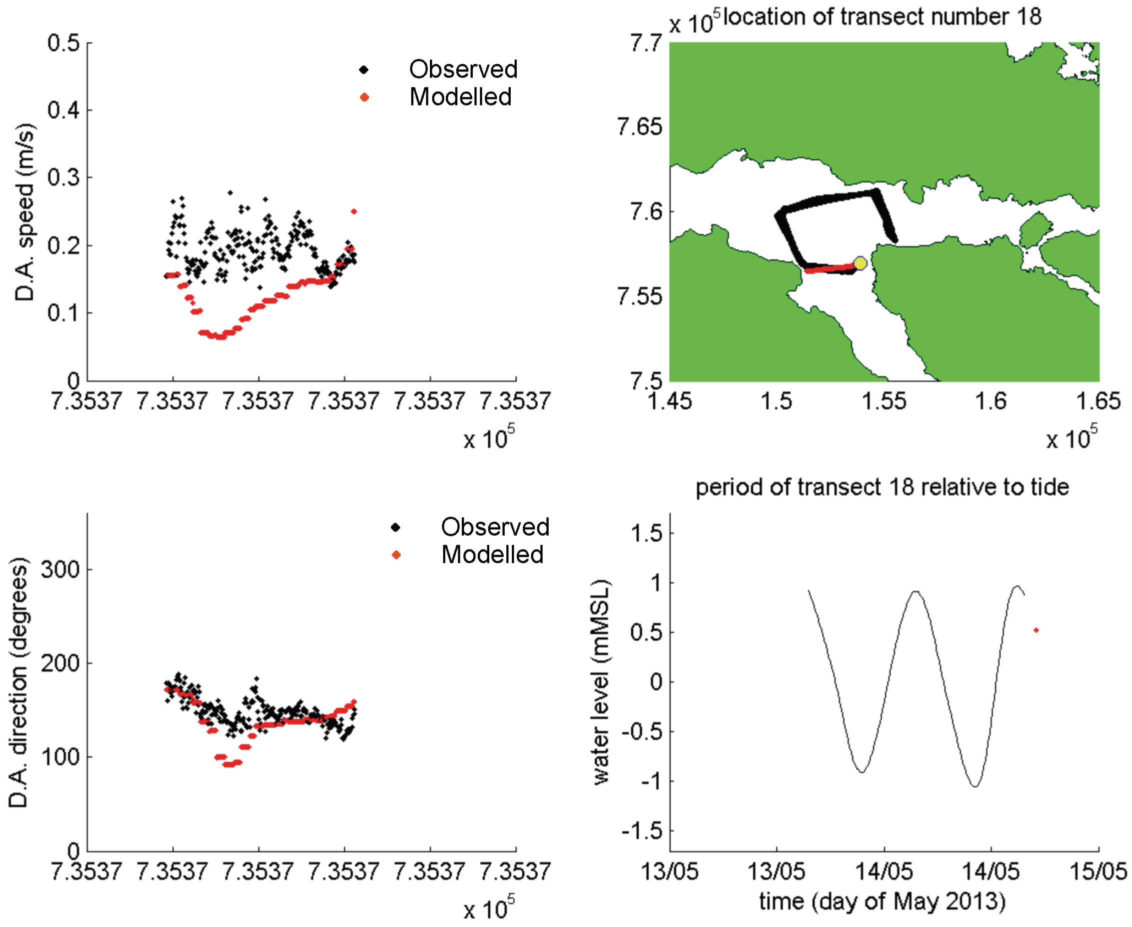

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-9 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



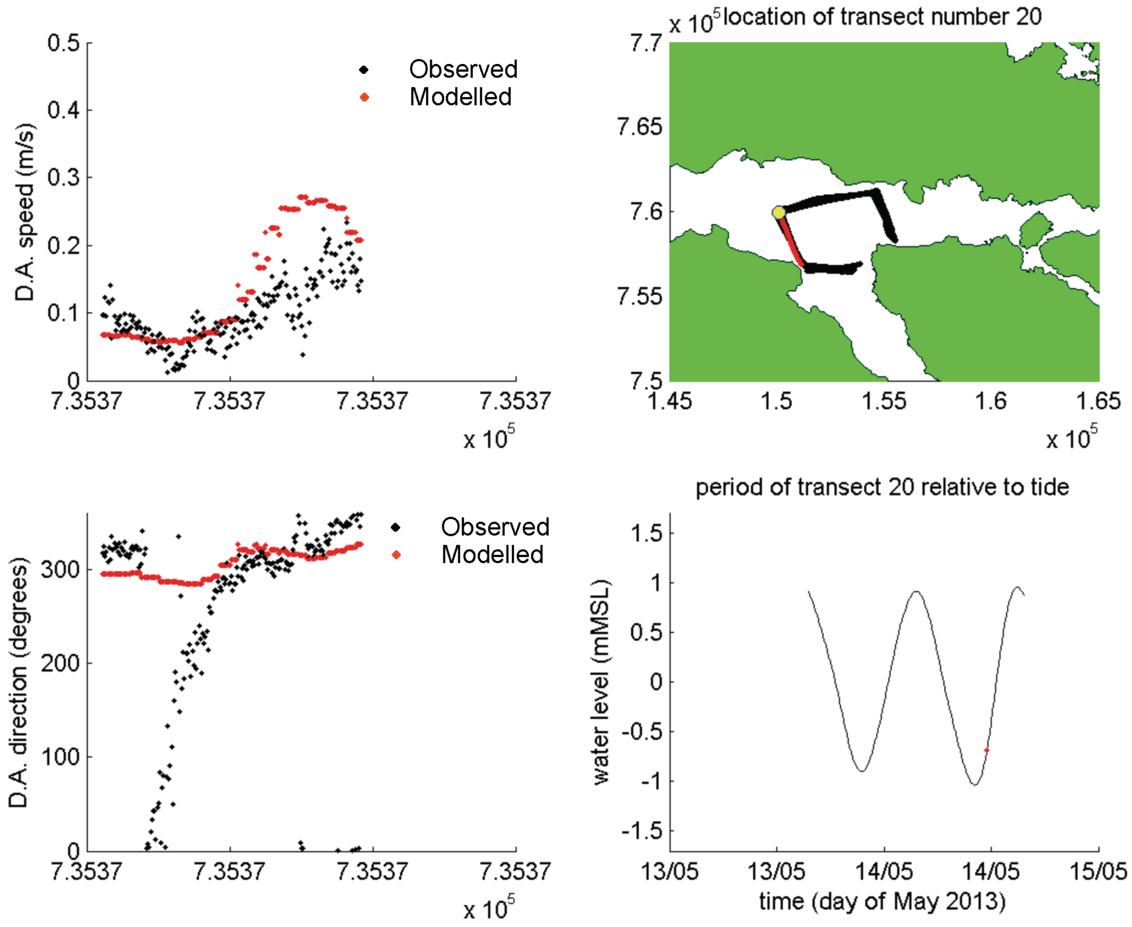

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-10 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



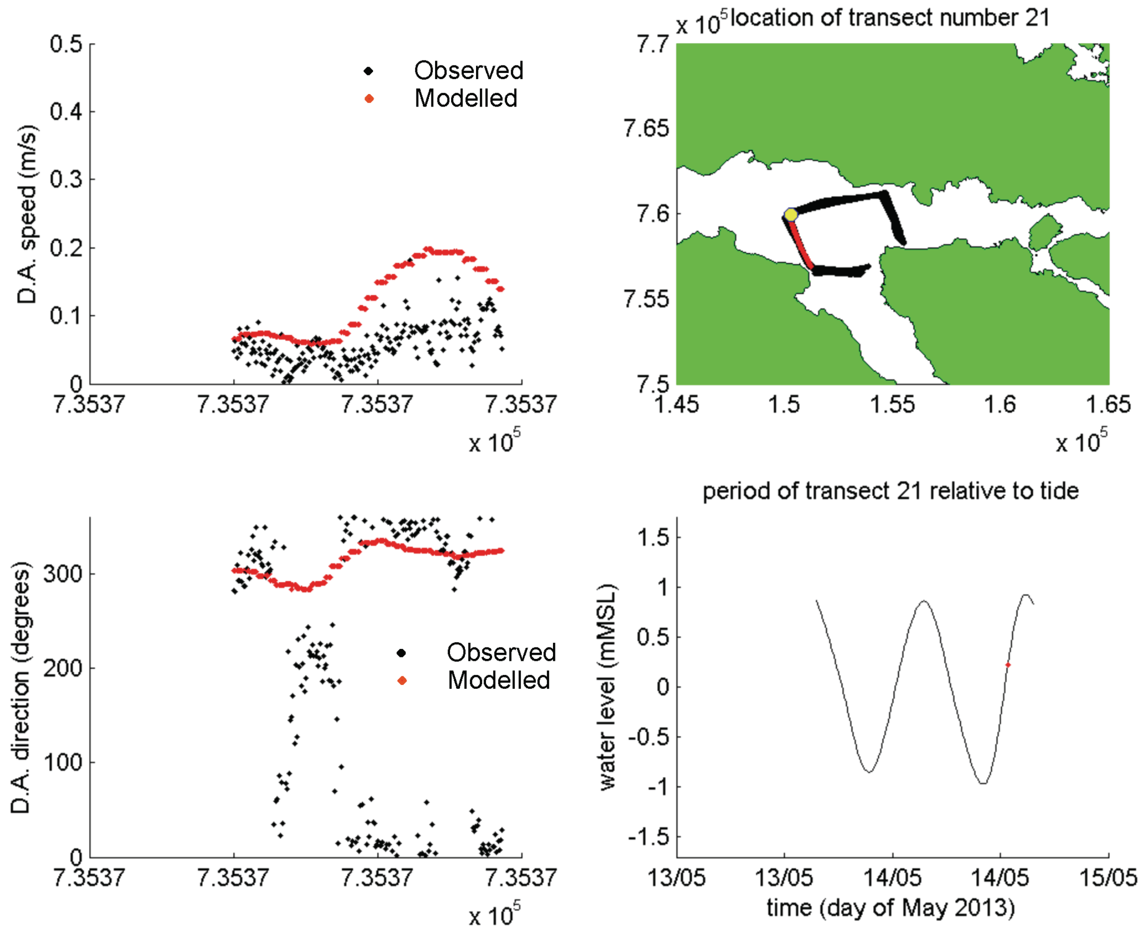

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-11 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m: | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |



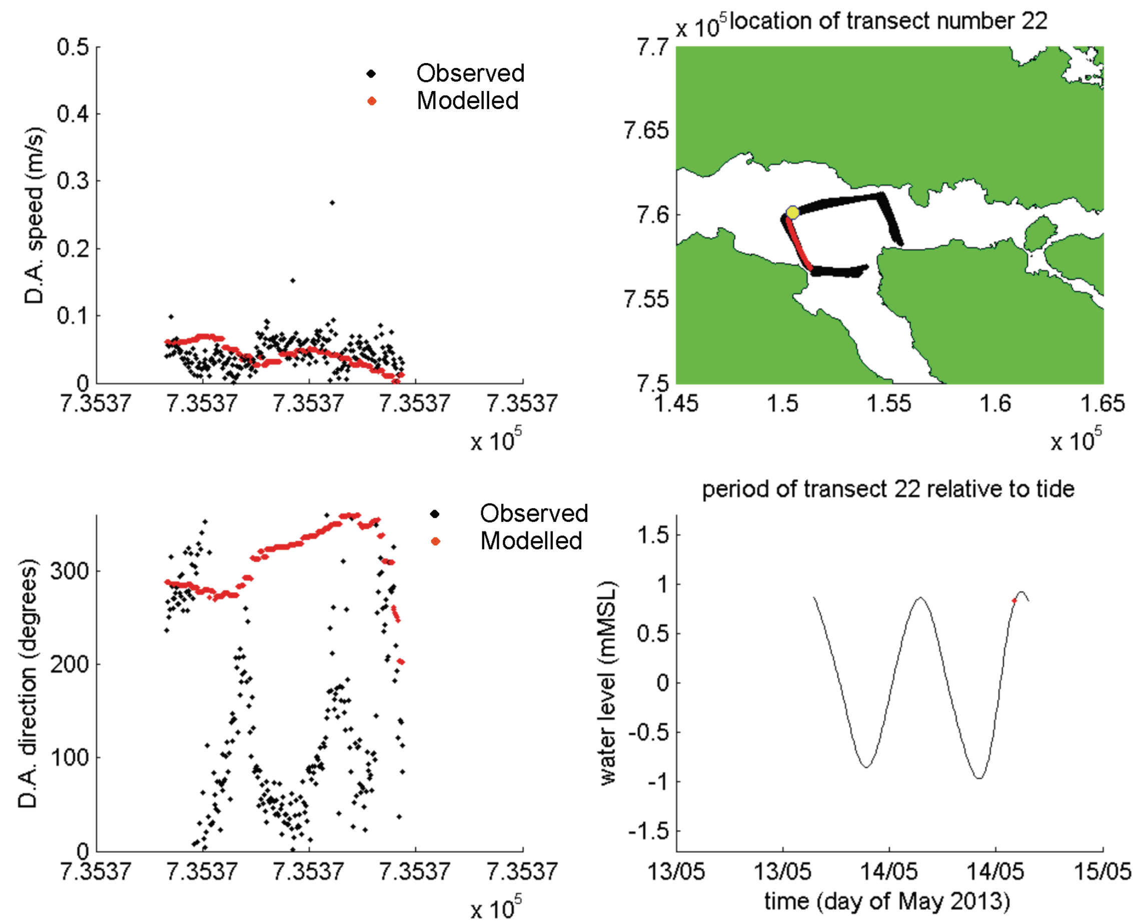

| Client | Consulting Engineer | Project: | Figure Title: | Figure C-12 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and repredicition undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure C-13 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure C-14 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |




| Client | Consulting Engineer | Project: | Figure Title: | Figure C-15 | | |
|---|---|---|---|---|---|---|
| Marine Scotland | ch2m | Wider Loch Linnhe System Model | Comparison between model and observed depth-averaged current transect data in Loch Sunart entrance/Mull Sound. Harmonic analysis and reprediction undertaken with both datasets | Checked DMP | Scale Not to scale | Rev. 0 |
| | | | | Designed FML | Drawn | Date 14/112012 |

This publication is available at **www.gov.scot**

Any enquiries regarding this publication should be sent to us at
The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-78544-987-1 (web only)

Published by The Scottish Government, February 2016

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS63340 (02/16)