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Gladstone Harbour Numerical Modelling Calibration and Validation

R.B17382.001.01.Model_Validation.doc

October 2009

Gladstone Harbour Numerical Modelling Calibration and Validation

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DOCUMENT CONTROL SHEET

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Title :	Gladstone Harbour Numerical Modelling Calibration and Validation
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Synopsis :	This report documents the ongoing development, calibration and validation of numerical models of Gladstone Harbour (Port Curtis).

REVISION/CHECKING HISTORY

REVISION NUMBER	DATE OF ISSUE	CHECKED BY		ISSUED BY	
Draft					
0	30/09/2009	IAT		CLW	
1	2/10/2009	IAT		CLW	

DISTRIBUTION

DESTINATION	REVISION			
	0	1	2	3
GPC/GHD	PDF	PDF		
BMT WBM File	PDF	PDF		
BMT WBM Library	1	1		

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1 INTRODUCTION

1.1 Background

The Port of Gladstone has been established in the naturally sheltered waters of Port Curtis behind Facing and Curtis Islands to the east and north. Port Curtis is connected to the ocean via a major opening to the south of Facing Island (South Channel), a smaller opening between Facing and Curtis Islands (North Channel) and “The Narrows” which extend some 40 km to the north behind Curtis Island. See Figure 1-1 for locality plan.

The Calliope and Boyne Rivers as well as Auckland and South Trees Inlets discharge into the central section of the Port. Further to the south are the connected waterways of Colosseum Inlet, Seven Mile Creek and Rodds Harbour while Grahams Creek and a number of smaller tributaries connect to The Narrows.

These extensive waterway areas and a large tidal range result in significant current velocities in some areas. The high tidal velocities generally assist in maintaining Gladstone harbour as a natural, deep-water port. However a navigation channel has been established and is maintained to provide access for larger draft vessels.

The Port area also contains a number of smaller islands and has extensive areas of inter-tidal flats, which become exposed at low water. For very low tides, some areas reduce to several narrow meandering channels. There are also very large intertidal mangrove and saltpan areas in Port Curtis, which are inundated at higher tide levels.

The Port has had a long history of development and expansion including various dredging and reclamation works. There are plans for further works to accommodate the needs of existing and potential future Port users through the provision additional facilities and to provide safe and efficient access to those facilities.

Development of new port facilities requires a thorough understanding and assessment of the hydrodynamic and coastal processes of Port Curtis. This information is essential for design purposes as well as the assessment of potential impacts. Detailed numerical models of Port Curtis have been established and used for these purposes over many years to assess:

- Tidal hydraulics;
- Flushing characteristics and plume dispersion;
- Wave climate; and
- Sediment dynamics.

The models are used for a range of purposes including:

- Providing information on existing tidal current patterns, water levels and wave conditions for consideration of the location and configuration of port facilities;
- Assessing the impacts of dredging and reclamation works on hydrodynamic, flushing and coastal processes;

- Determination of post construction conditions for design purposes;
- Assessing the potential advection and dispersion of discharges to Port Curtis and impacts on water quality;
- Determining the likely transport, dispersion and settling of turbid plumes generated by dredging works;
- Assessing the potential siltation of dredged areas; and
- Providing data for ship simulation purposes and consideration of navigation constraints.

The models have been based on and calibrated against measured data collected specifically for those purposes. This report provides details of the numerical models used and documents the establishment and calibration/validation of the models with that data.

1.2 Overview of Numerical Models

BMT WBM Pty Ltd (previously WBM Pty Ltd) has progressively developed and updated hydrodynamic based numerical models of Port Curtis over many years using various modelling software. These models have been used by BMT WBM on a range of studies commissioned directly by the Gladstone Ports Corporation (GPC) as well as for other projects and parties undertaking associated works or activities within Port waters.

As part of these previous investigations, BMT WBM has established and calibrated a number of different hydrodynamic and dispersion models of the region. This has included collation of available hydrographic survey data (generally from QT and CQPA) and generation of digital elevation models (DEMs) as well as collection of specific data on tide levels, currents and dispersion characteristics for the purposes of the modelling. As numerical modelling capabilities and tools have evolved, the models have been progressively updated to reflect the latest technology and specific study requirements.

Historically, the models include an original 1 dimensional (ESTRY) hydrodynamic model of Port Curtis and connected waterways including the Calliope River. This model was used for the original IAS for the proposed reclamations west of the Calliope River leading to subsequent approval. Flooding of the lower Calliope River was included in this model.

A 2 dimensional (TUFLOW) hydrodynamic model was then established for the region extending from the Calliope River to Friend Point. This model was dynamically linked to the overall 1D ESTRY model so that overall processes were simulated. It has been used for a range of studies associated with dredging and reclamation at Fisherman’s Landing and also as a base for separate plume dispersion modelling associated with a number of potential trade waste disposals to Port Curtis.

Following this, a detailed 2 dimensional finite element (RMA) model was established which extended from South Trees Island to Friend Point. This model was established to assess the proposed extension to the RG Tanna Wharf and provide detailed data for input to ship simulations. The RMA finite element package was chosen because of its ability to provide a high degree of resolution in the area of interest and accurately represent the proposed works. Specific measurements of currents were also carried out to calibrate the model. This model utilised boundaries from the broader ESTRY / TUFLOW model previously established.

For the Wiggins Island Coal Terminal project (WICT), the decision was made to extensively upgrade and extend the RMA finite element to cover the whole tidal network of Port Curtis from south of Facing Island through to the northern end of the Narrows including all the connected rivers and creeks. The variable mesh finite element approach allowed the detail of the channels and proposed works to be incorporated while still dynamically simulating the whole tidal network for the assessment of impacts. Extensive co-incident data collection was carried out as part of this project as well to provide a comprehensive set of measured water levels at the model boundaries and internal measurements of water levels, currents and flows to calibrate the model.

The overall RMA model was continually upgraded in detail and validated with new data for use on a number of projects. Due to some limitations with RMA and further software development which addresses these and provides additional benefits, the decision was made to convert the model over to run on the finite volume software package TUFLOW-FV. This allowed the benefits of the flexible mesh to be retained as well as providing additional capabilities as outlined below including the ability to extend the model, as well as incorporate more detail and carry out longer simulations in a computationally efficient manner.

The RMA and TUFLOW–FV models were run in parallel for a period with calibration and validation of the TUFLOW-FV model being carried out with all previous data sets. The TUFLOW-FV model has been used for assessments since early 2009 with additional validation as part of the Fisherman's Landing 153Ha Reclamation and the Gladstone Western Basin EIS studies.

The TUFLOW-FV package contains hydrodynamic, advection-dispersion and sedimentation modules. Further details are provided below. The SWAN wave modelling package has been used for the wave assessments in Port Curtis and linked to TUFLOW-FV as needed.

1.3 TUFLOW-FV Description

The TUFLOW-FV numerical scheme solves the conservative integral form of the NLSWE (i.e. assuming that pressure varies hydrostatically with depth), including viscous flux terms and source terms for Coriolis force, bottom-friction and various surface and volume stresses. The scheme is also capable of simulating the advection and dispersion of multiple scalar constituents within the model domain.

The 2D NLSWE in conservative integral form solved by TUFLOW-FV are reproduced below,

$$\frac{\partial}{\partial t}\int_{\Omega}\mathbf{U}\,\mathrm{d}\Omega+\oint_{\partial\Omega}(\mathbf{E}\cdot\mathbf{n})\,\mathrm{ds}=\int_{\Omega}\mathbf{S}\,\mathrm{d}\Omega$$

- $\mathbf{U}$ is the vector of conserved variables : $\mathbf{U}=(h,hu,hv)^T$ (mass, x- and y-momentum terms) ;
- $\mathbf{n}$ is the cell-edge (face) unit normal vector;
- $\mathbf{E}=(\mathbf{F},\mathbf{G})^T$ i represents face fluxes where;
- $\mathbf{F}$ is the x-direction flux vector: $\mathbf{F}=\left(hu,hu^2+\frac{gh^2}{2},huv\right)^T$;

- $\mathbf{G}$ is the y-direction flux vector : $\mathbf{G} = \left(hv, huv, hv^2 + \frac{gh^2}{2} \right)^T$;
- $\mathbf{S}$ is the standard source term vector: $\mathbf{S} = \left(0, gh\left(\frac{\partial z_b}{\partial x} + S_{fx} \right), gh\left(\frac{\partial z_b}{\partial y} + S_{fy} \right) \right)^T$;
- h is the water depth;
- g is acceleration due to gravity;
- u,v are the depth averaged components of the velocity vector ;
- z_b is the bed elevation,
- S_{fx},S_{fy} are the friction slope components
- $\int_{\Omega} d\Omega$ is the cell volume integral and
- $\oint_{\partial\Omega} ds$ is the cell surface integral.

The spatial domain is discretised using contiguous, non-overlapping but irregular triangular and quadrilateral “cells”. Advantages of an irregular flexible mesh include:

- The ability to smoothly resolve bathymetric features of varying spatial scales (e.g. dredged channels adjacent to broad shoaled areas);
- The ability to smoothly and flexibly resolve boundaries such as coastlines;
- The ability to adjust model resolution to suit the requirements of particular parts of the model domain without resorting to a “nesting” approach.

The flexible mesh approach has significant benefits when applied to study areas involving complex coastlines and embayments, varying bathymetries and sharply varying flow and scalar concentration gradients.

A cell-centred spatial discretisation is currently employed in TUFLOW-FV, and requires the calculation of numerical fluxes across cell boundaries. As with many finite volume schemes non-viscous boundary fluxes are calculated using Roe’s approximate Riemann solver (e.g. Glaister, 1988). The source terms due to bed elevation changes between adjacent cells are “up-winded” as part of the Roe flux solver, in order to maintain numerical consistency with the pressure gradient momentum flux terms (Hubbard & Garcia-Navarro, 2000).

Viscous flux terms are calculated using the traditional gradient-diffusion model with a variety of options available for the calculation of eddy-viscosity and scalar diffusivity. The Smagorinksy eddy-viscosity model and the non-isotropic Elder diffusivity model are the options most commonly adopted by BMT WBM modellers.

Both first-order and second-order spatial discretisation schemes are available in TUFLOW-FV. The first-order scheme assumes a piecewise constant value of each conservative constituent in a model cell. The second-order scheme assumes a 2D linear polynomial reconstruction of the conservative constituents within the cell (i.e. a MUSCL scheme). The Total Variation Diminishing (TVD) property (and hence stability) of the solution is ensured using a choice of gradient limiter schemes.

The second-order spatial reconstruction scheme allows for much sharper resolution of gradients in the conserved constituents for a given level of spatial resolution. This is important for resolving relatively short waves (e.g. tsunamis) without excessive numerical diffusion or without over-refining the spatial mesh discretisation. The numerical resolution of sharply varying current distributions and sharp scalar concentration fronts are also much improved with the second-order scheme.

Spatial integration is performed using a midpoint quadrature rule. Temporal integration is performed with an explicit Euler scheme and must therefore maintain a stable time step bounded by the Courant-Friedrich-Levy (CFL) criterion. A variable time step scheme is implemented to ensure that the CFL criterion is satisfied with the largest possible time step. Outputs providing information relating to performance of the model with respect to the CFL criterion are provided to enable informed refinement of the model mesh in accordance with the constraints of computational time.

In very shallow regions (~<0.05m depth), the momentum terms are dropped, in order to maintain stability as the NLSWE approach the zero-depth singularity. Mass conservation is maintained both locally and globally to the limit of numerical precision across the entire numerical domain, including wetting and drying fronts. A conservative mass re-distribution scheme is used to ensure that negative depths are avoided at numerically challenging wetting and drying fronts without recourse to adjusting the time step. Regions of the model domain that are effectively dry are readily dropped from the computations. Mixed sub/super-critical flow regimes are well handled by the FV scheme which intrinsically accounts for flow discontinuities such as hydraulic jumps or bores that may occur in trans-critical flows.

Transport of scalar constituents is solved in a fully-coupled fashion with the NLWSE solution. Simple linear decay and settling are optionally accommodated as source/sink terms in the scalar transport equations.

TUFLOW-FV accommodates a wide variety of boundary conditions, including those necessary for modelling the processes of importance to the present study:

- Water level timeseries;
- In/out flow timeseries;
- Mean Sea Level Pressure gradients;
- Wind stress; and
- Wave radiation stress.

Bed friction is modelled using a Manning’s roughness formulation and Coriolis force is also included in the model formulation.

1.4 2D Depth-Averaged Approximation

Port Curtis experiences a macro-tidal regime with spring tidal ranges commonly exceeding 3m. This large tidal range and associated tidal prism induces high tidal current speeds in the channels as well as wetting/drying of extensive inter-tidal areas. These processes are responsible for ensuring that the waters of Port Curtis are generally both vertically and horizontally well-mixed.

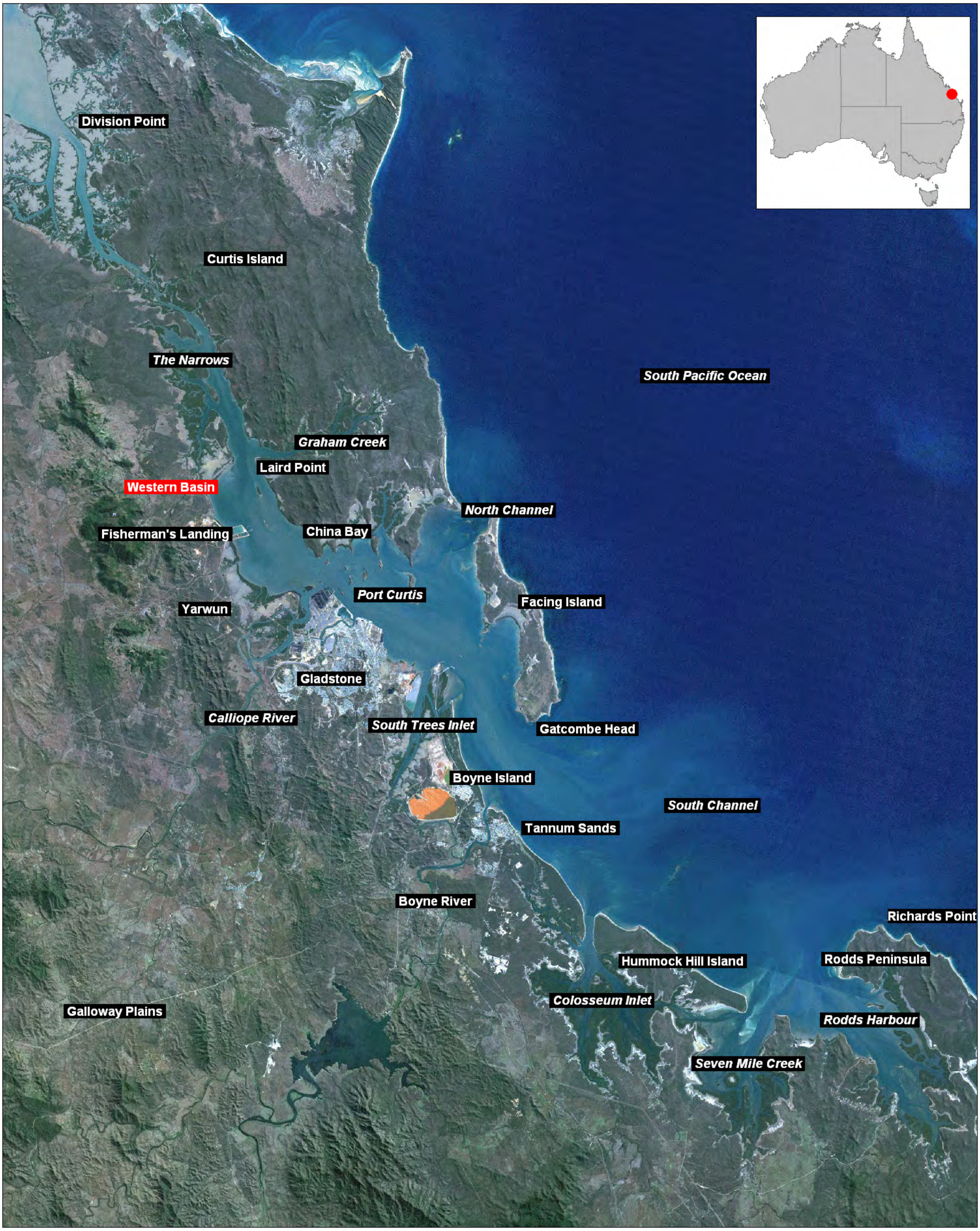
Temperature and salinity profiles collected across 3 separate transects during the late June 2009 spring tides (provided in Appendix A) are generally vertically uniform and indicate an absence of stratification. Profiles collected at the same 3 transects during neap tides in late April also generally show only small variations of temperature and salinity with depth.

Continuous velocity profile datasets obtained by 3 bottom-mounted Acoustic Doppler Current Profiler’s deployed by GHD during May/June 2009 were inspected in order to assess 3-dimensionality of the flow in the main channels (refer Figure 2-34 for instrument locations). The velocity magnitude and direction profiles were plotted at 3-hourly intervals for a spring tide cycle, neap tide cycle and a tidal cycle during strong south-easterly winds, and are provided in Appendix B. The current magnitude measurements are indicative of the logarithmic current profile that would be expected in a fully-mixed boundary layer. Current directions are generally uniform across the full-depth, with some greater variation seen around the turn of the tide. These measurements support the use of a 2D-depth-averaged model for representing the hydrodynamics of Port Curtis under typical tidal and wind-driven conditions.

It is possible that infrequent large freshwater inflow events could cause some stratification of the Port Curtis estuarine system for a period of time following the event. This stratification would eventually be broken down by the energetic tidal mixing induced during spring tidal periods.

The 2D-depth-averaged approximation would fail to represent localised 3D flow features in the vicinity of sharply varying bathymetry. Resolution of such features would be problematic even with a 3D model due to the difficulty of adequately resolving these localised flow variations in a broad-scale model. Furthermore, such local flow features would not be expected to materially impact the broad-scale hydrodynamic response of the system.

In conclusion, an adequately calibrated and validated 2D model would be capable of accurately reproducing the broad-scale flow patterns within a macro-tidal, well-mixed estuarine system such as Port Curtis.



Title:

Locality Plan

Figure: **1-1**

Rev: **A**

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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Approx. Scale

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2 HYDRODYNAMIC MODEL

2.1 Model Details

BMT WBM has developed and repeatedly refined and improved the calibration of hydrodynamic models of the Gladstone region over a number of years. The models cover the whole tidal waterway network of Port Curtis from south of Facing Island through the Narrows to Keppel Bay including all connected rivers and creeks.

The hydrodynamic model being used for this study is based on flexible mesh finite volume (TUFLOW-FV) modelling software which allows fine detail to be included in areas of interest with a lower, but sufficient resolution elsewhere. The variable spatial resolution capability is particularly appropriate for the Port of Gladstone model given the large area of coverage where the resolution of far field areas may be reduced while still allowing the necessary detail to represent channels and berth pockets in areas of interest.

The TUFLOW-FV includes standard 2 dimensional (2D) depth averaged hydrodynamic (HD) and advection-dispersion (AD) modules and also has the capacity to include meteorological forcing, wave related stresses and cohesive sediment transport modules as outlined in subsequent sections. Wetting and drying is accurately incorporated which is important in simulating the inter-tidal flats in Port Curtis and particularly in the vicinity of the proposed reclamation.

The TUFLOW-FV solves the non-linear shallow water equations including solute transport by advection-dispersion in 2D on a flexible mesh comprised of quadrilateral and triangular elements, using a finite-volume numerical scheme. A second-order spatial integration scheme has been used and time integration has been performed using an explicit euler time integration. Advantages of this scheme include;

- flexible mesh resolution;
- local and global conservation of mass (to floating point precision) even in regions of wetting and drying;
- robust and accurate solutions for mixed sub-critical/super-critical flows;
- ability to parallel-process in order to reduce model run-times.

As discussed in Section 1.4 a 2D hydrodynamic model is appropriate for Port Curtis due to the high-energy macro-tidal regime, and low volume of freshwater inflows relative to the tidal prism under normal day to day conditions, which lead to a predominantly well-mixed water-column without significant temperature/salinity stratification.

2.2 Model Extent

The model network extends over an area of some 635 km^2, incorporating Port Gladstone and the main inter-tidal areas between Curtis Island, Facing Island and the mainland. The modelled area represents a reach length of approximately 80km extending from Richards Point at the southeastern extent to Division Point at the northwestern extent.

The model extent includes all the predominant tidal flows into the Port, being the main ocean entrance at the eastern model boundary, the North Channel between Curtis and Facing Islands and through the Narrows.

There are a number of tidal tributaries of the Port including the Calliope River, Auckland Inlet, South Trees Inlet and the Boyne River, which are incorporated into the model. The non-flood fluvial component of flows within these river systems is insignificant in relation to the tidal flux. Thus the modelling of the tributaries focuses on representation of the tidal storage and exchange within the system.

2.3 Model Bathymetry

The model bathymetry is based on a Digital Elevation Model (DEM) of the Port which has been derived from various survey components. This includes:

- detailed pre and post-dredge hydrographic survey data (in digital spot-height format) of the dredged channels, swing basins and berths as provided by the Hydrographic Services section of Maritime Safety Queensland (MSQ) and GPC;
- detailed hydrographic survey data (in digital spot-height format) of broad areas of the Port as provided by the Hydrographic Services section of MSQ and GPC; and
- hydrographic survey data (in digital spot-height and contour format) and outlines of the edges of the shoreline, mangroves and saltpans used in producing Boating Safety Charts of the area as provided by the GIS and Cartography Section of MSQ.

Typical levels have been adopted for the edges of the mangroves and saltpan areas for interpolation in those upper inter-tidal zones where no specific survey level data is available. The various data components have been combined and prioritised with respect to date and detail where there is overlap in producing a base DEM.

As part of recent studies, the previously developed DEM has been updated with additional hydrographic survey data collected by MSQ in the Western Basin area. This includes:

- Clinton Swing Basin to South Passage Island Compiled Hydrographic Survey, June 2008 (MSQ Plan No: F500-014)
- South Passage Island Hydrographic Survey, 18-19 June 2008 (MSQ Plan No: F500-015)
- South Passage Island to Grahams Creek Hydrographic Investigation, October 2008 – December 2008 (MSQ Plan No: F500-016)

Most survey data has been provided relative to LAT or Chart Datum which varies throughout the Port. For modelling purposes, all data has been adjusted to a constant datum (AHD) using information provided by MSQ at various sites. The DEM on which the model has been based is illustrated in Figure 2-1.

2.4 Model Mesh

The model mesh showing the extent of the model coverage is illustrated in Figure 2-2. The mesh demonstrates the advantages of the finite volume approach with accurate boundary fitting and the ability to vary the spatial resolution.

In developing the hydrodynamic model, consideration has been given to the underlying bathymetry in defining the mesh configuration. For example, model resolution was enhanced at locations of rapidly varying bathymetry or expected high flow regions based on channel definition, as well as to represent the dredged channels, swing basins and berth pockets.

Particular focus and enhanced resolution has been incorporated in the study areas to ensure a suitable model representation of bathymetric and flow conditions. The base model mesh has been adjusted to allow appropriate representation of the reclamation area and dredged channel / swing basins by changing the depths only and not the mesh configuration for the developed case scenarios. This eliminates any potential impacts which may be generated by changes in the mesh.

In developing the model mesh, particular focus has been given to a number of key areas to ensure a suitable model representation of flow conditions. Where appropriate the resolution of the model mesh has been increased to provide a more accurate representation of local hydraulic conditions. Some key areas are discussed below.

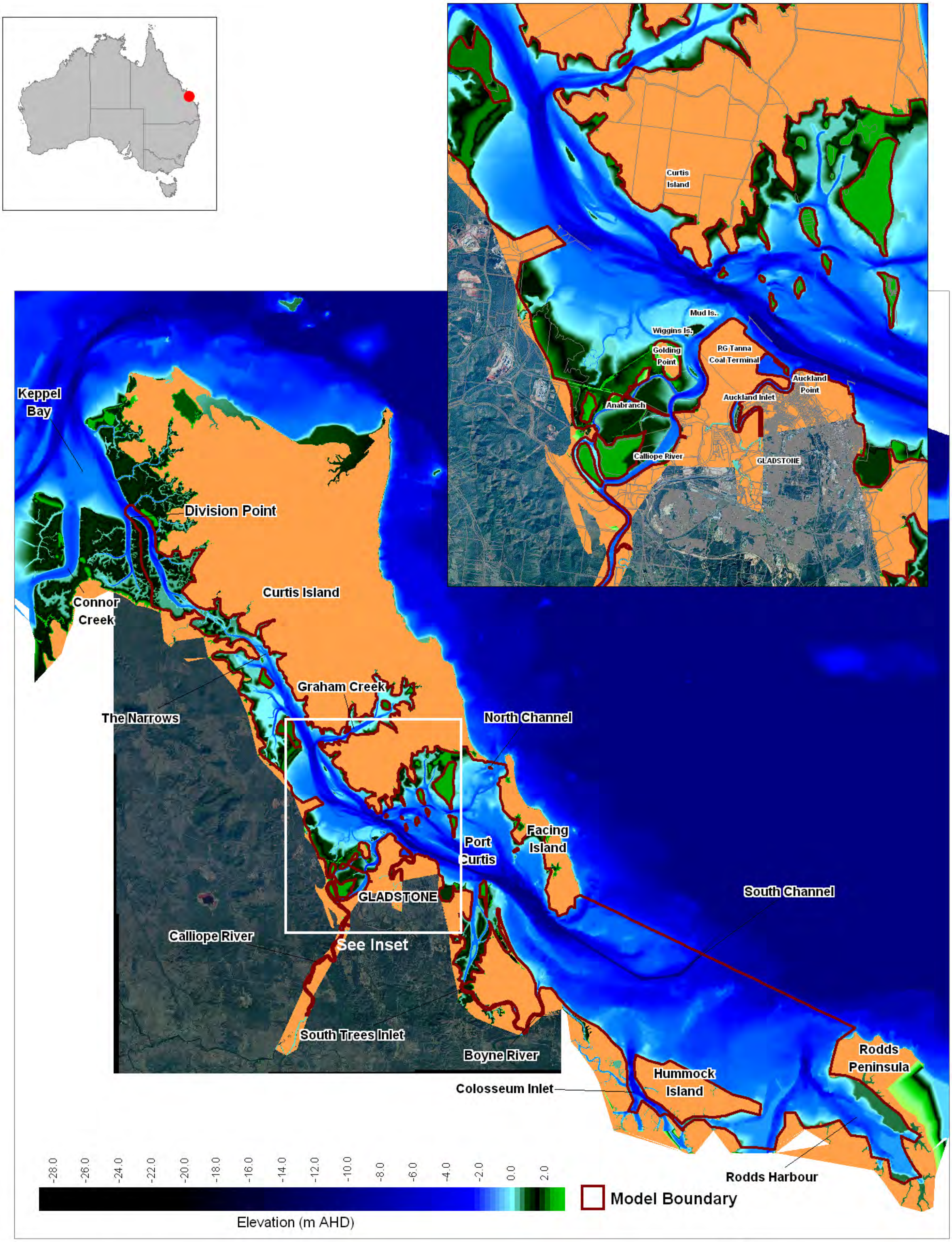
- The flow through the Port is dominated by the main ocean boundary, however the smaller channels of the North Entrance and the Narrows have an impact on the flow distribution within the modelled area. The model resolution has been adapted to define the main channel alignment and bathymetry to adequately define the flow contribution from these channels, particularly at low tides when the flows are restricted to narrow channels.
- Within the modelled area there are a number of dredged areas for shipping channels, turning areas and berth pockets. The DEM developed from the bathymetric survey clearly identifies the extents of these features. The model mesh has been developed accordingly to achieve a good representation of hydraulic conditions within the channels.
- There are numerous islands within the central Port area of interest, some of which have a significant influence on flow distribution. Local adjustment of the mesh resolution has been made to define the land boundaries, and the adjacent flow channels around the islands typically characterised by rapid changes in bathymetry.
- A significant proportion of the model area covers the mangrove and salt pan areas on the tidal fringes. Whilst generally not in critical areas requiring detailed hydraulic analysis, their influence on the tidal hydraulics within the system is important. The major objective in defining these intertidal areas is to represent the contribution to bulk tidal storage volume, which has an impact on the tidal exchange in the system. Thus a relatively coarse resolution has been adopted, sufficient to define the temporary volumetric storage and release over a tidal cycle.
- The Calliope River is a major tributary of the Port of Gladstone. The model has been extended for approximately 25 km upstream of the confluence with the main port channel. This provides the opportunity to adequately define the tidal storage within the river system and simulate the tidal flux. The model mesh has been developed with sufficient detail to enable the flow distribution within the main channel and anabranch to be simulated.

A point inspection of the DEM has been used to define the bed level at the mesh vertices, which are then used by the model to derive cell elevations.

Bed-roughness Manning's coefficients in Table 2-1 were specified for the mesh cells as shown in Figure 2-3. The values of the Manning's coefficients were established as part of the model calibration detailed in Section 2.6.3 and 2.6.4, with subsequent validation undertaken as detailed in Section 2.6.5 and 2.6.6.

Table 2-1 Port Curtis Model Manning's Coefficient.

Region	Manning's "n" coefficient
Channels	0.022
Shallows/Inter-Tidal Flats	0.026
Mangroves	0.100



Title:

Bathymetry of the Port Curtis Area

Figure: **2-1**

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N

0 3 6km
Scale - Inset

0 10 20km
Scale - Main Map

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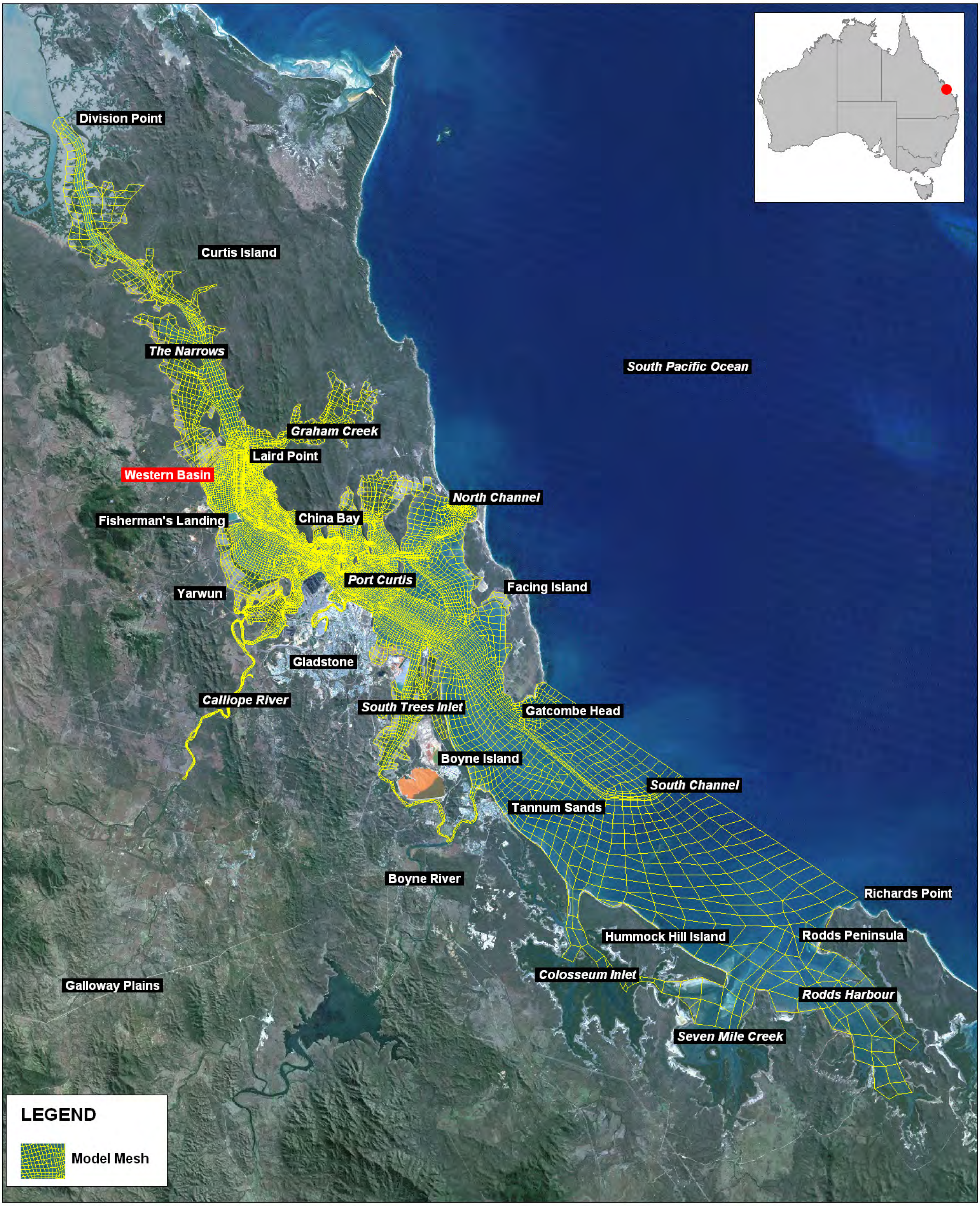

Title:

Finite Volume Model Mesh

Figure:

2-2

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N 0 10 20km

Approx. Scale

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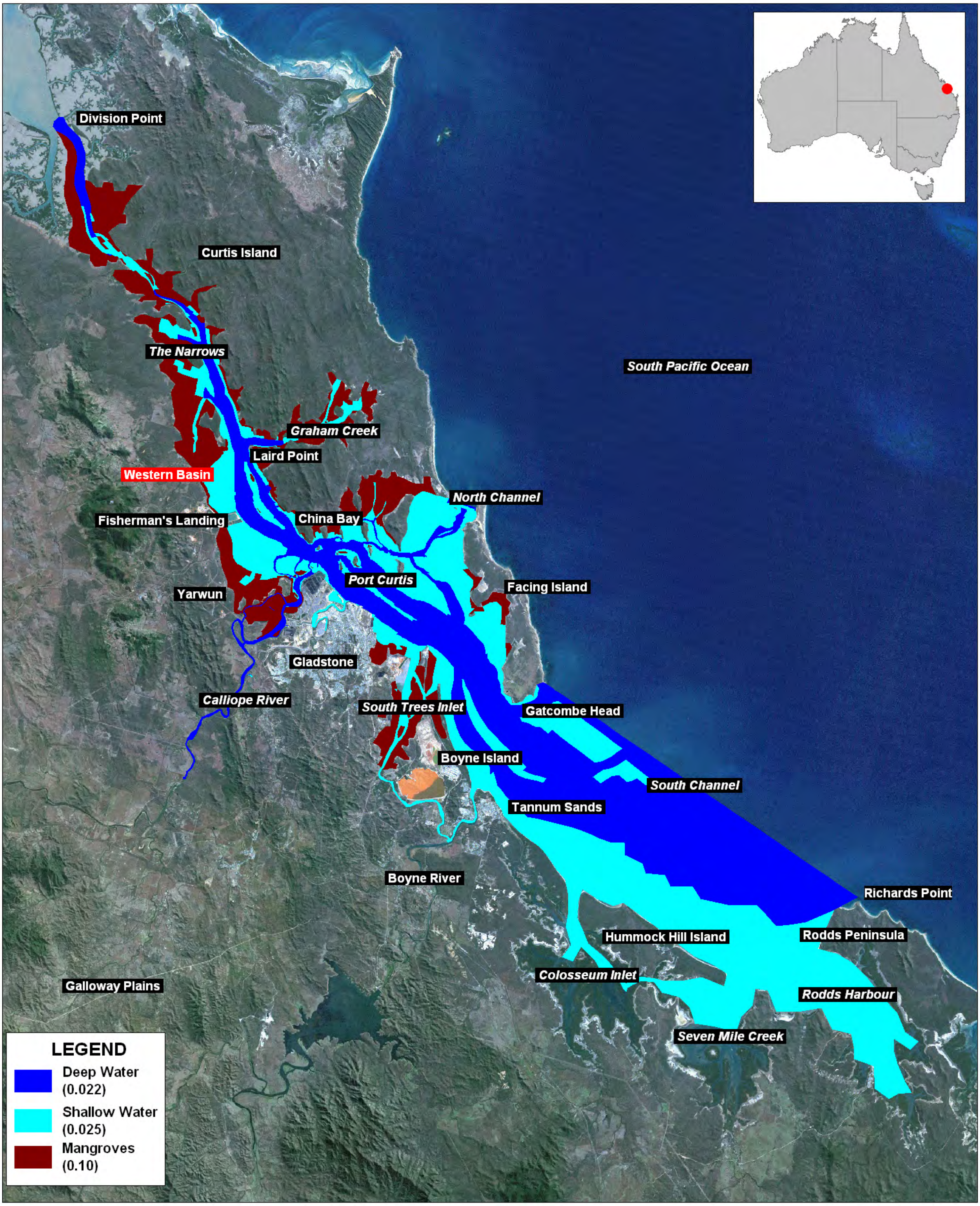

Title:

Port Curtis Model Manning's "n" Coefficients

Figure: 2-3

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N 0 10 20km

Approx. Scale

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2.5 Boundary Conditions

The model extent includes a number of open boundaries requiring the definition of boundary conditions. These boundary conditions define the forcing functions to drive flow in and out of the modelled area. Flow within the model area is dominated by tidal conditions and the main tidal fluxes across the model boundaries are located at:

1 Main Ocean Boundary – extending from Richards Point on Rodds Peninsula to East Point on Facing Island.

2 North Entrance – located across the North Channel entrance between Facing Island and Curtis Island.

3 Division Point – located across the entrance to The Narrows providing a tidal connection between the Port of Gladstone and the Fitzroy River Estuary.

As part of some field data-collection investigations, concurrent recordings of tidal elevations at the boundary locations have been carried out. This water level time series data has been applied at each open boundary as the model forcing condition. Relationships between the open boundaries and permanent Port tide gauges have also been established from these data sets and used to synthesise model boundary conditions when measured data is not available.

Model calibration and validation has been carried out for various locations over a range of periods and conditions as described in Section 2.6. The nature of the open boundary conditions (measured or synthesised) is indicated below for each of the calibration and validation simulation periods.

The main ocean boundary is approximately 26km in length between Richards Point and Facing Island. Over this length, the tidal elevations show variations both in magnitude and timing. In this instance a common water level time series for each model point across the entire length of the boundary is not appropriate. A better representation of this boundary, which has been applied in the model, utilises linear variations in tidal elevation across the boundary, specifically between Richards Point, Beacon S3 and East Channel as shown in Figure 2-4.

The North Entrance and Division Point boundaries, being much shorter than the Main Ocean boundary, apply a common water level across the length of each boundary line, representative of the tidal elevation at each location.

Wind forcing of the model has been included in some simulations based on recorded data from the Bureau of Meteorology (BoM). Again, the status of wind forcing for each simulation period is indicated below. Simulations with and without wind forcing have shown that the overall hydrodynamic and flushing characteristics of the main channel areas are dominated by the macro-tidal water level variations with wind having only a small influence.

The wave climate in the inner harbour area is dominated by locally generated wind waves, with there being negligible ocean swell penetration (Connell Hatch, 2006). Wave conditions are generally mild with significant wave heights being less than 0.5m for about 96% of the time and less than 0.3m for about 80% of time (BMT WBM, 2009). Even during extreme wave conditions, wave periods are typically less than 5s. Such short period waves would not be expected to significantly contribute to the forcing of currents within the inner harbour. Accordingly, coupling of the wave and hydrodynamic models has not been undertaken.

There are number of tidal tributaries incorporated in the model including the Calliope and Boyne Rivers. The normal day to day fluvial component of flow within these river systems is insignificant in relation to the tidal fluxes through Port Curtis. Accordingly, freshwater inflows have not been included in the tide model simulations, as these have no significant influence on water levels and flows in the main body of Port Curtis except under flood conditions.

2.6 Model Calibration and Validation

2.6.1 Overview

As part of previous studies, various water level and velocity/flow data have been collected to initially calibrate and subsequently validate the hydrodynamic model. This data has typically targeted specific study areas within Port Curtis. Comprehensive data collection was undertaken in April-May 2006 for calibration of the overall RMA finite element model as part of the WICT EIS project. Subsequent to that, data has been collected on a number of other occasions and in specific areas for further calibration and validation of that model as part of other projects. The model mesh and bathymetry has typically been refined and updated as well as part of this process.

With the conversion of the model to TUFLOW-FV and further refinement of the mesh for the purposes of the Gladstone Western Basin EIS project, the opportunity has been taken to re-run the latest model configuration with all key data sets from 2006 onwards to illustrate and confirm the model calibration and validation.

The data sets used are summarised below in Section 2.6.2. Some data sets include measured boundary data while others use synthesised boundaries based on relationships derived from the measurements as described in Section 2.5. For each data set, a summary is provided below of:

- Tide boundary source and other forcing data;
- Calibration/validation data details including type and location; and
- Illustration and discussion of comparison between measured data and model results.

It should be noted that each simulation has been carried out using the latest model mesh and bathymetry as prepared for the Gladstone Western Basin EIS (August 2009). As such there will be some slight variations from the original simulations in terms of updated bathymetry including any dredging and any model mesh refinements since that time. These are not expected to introduce major variations but should be noted with respect to the simulations using older data sets.

2.6.2 Data Sets

The following data sets have been used as part of the calibration and validation of the of the inner harbour area of the TUFLOW-FV model:

- 26th April – 8th May 2006 - WICT EIS (initial calibration)
- 2nd November – 9th November 2006 – Boatshed Point/China Bay Investigations (further calibration)
- 10th August – 25th August 2008 – Fisherman’s Landing 153Ha Reclamation EIS (initial validation)
- 15th April – 30th June 2009 – Gladstone Western Basin EIS (further validation)

2.6.3 WICT EIS Data

2.6.3.1 Data Set and Simulation Summary

This data set was collected as part of the WICT project and focused on calibration of the inner harbour area of the model in the vicinity of the entrance to the Calliope River. As the project included aspects of potential influence on the Calliope River, data was collected also in the Calliope River itself. Not all Calliope River data has been presented here.

The data collected included continuous time series data of water elevations using fixed point tide gauges and flow / velocity distribution for defined transects using boat mounted Acoustic Doppler Current Profiler’s (ADCP’s). The location of the tide gauges and ADCP transects used for calibration are presented in Figure 2-4 with a summary of the simulation and data sets as per Table 2-2 below.

Table 2-2 WICT EIS Simulation Summary

Project	Wiggins Island Coal Terminal EIS
Period	26th April – 8th May 2006
Focus Area	Main channel area near entrance to Calliope River
Boundary Data	Main Ocean Sth of Facing Island – Measured water levels (3 locations) (WBM & MSQ) North Entrance between Curtis & Facing Islands – Measured water levels (WBM) Division Point Nth end of The Narrows – Measured water levels (WBM) Wind Forcing – Recorded wind data (BOM)
Calibration Data	Continuous Water Levels - South Trees (MSQ) - Auckland Point (MSQ) - Fisherman’s Landing (MSQ) - Black Swan Island (WBM) Spring Tide ADCP Transects - Tide Island to Mud Island - Tide Island to Curtis Island (Hamilton Point)

	- Wiggins Island to RG Tanna Coal Terminal - Wiggins Island Side Channel (to Golding Point) - Mud Island to Wiggins Island Neap Tide ADCP Transects - Tide Island to Mud Island - Tide Island to Curtis Island (Hamilton Point) Bottom-Mounted S4 Current Meter

2.6.3.2 Water Level Comparisons

Calibration plots of observed and simulated water levels for the April/May 2006 data set are presented in Figure 2-5 to Figure 2-8. The figures show a good calibration of water levels both in timing and magnitude of the flood and ebb tide peaks. The good calibration is achieved for both the representative spring and neap tide conditions.

2.6.3.3 Total Flow Comparisons

ADCPs measure 3D velocities in a profile of discrete bins at an instant in time (called an ensemble). Boat-mounted ADCPs have been used to measure velocity profiles while the boat traverses a transect. Total flow through the transect has been calculated by integrating the ADCP velocity profile data vertically from the bottom-most to the top-most bin and horizontally/temporally across each transect using the Winriver II software. Additionally estimates of water column top and bottom flow components not directly measured by the ADCP have been estimated using the default "power" function extrapolation of this software. Total flows (including top and bottom estimates) calculated by Winriver II have been used for comparing with the modelled flows.

Modelled flows have been output for specified transects that approximately represent the repeated boat tracks. Flow is calculated as the depth-averaged velocity x depth and integrated across the specified transect. It is important to recognise that the ADCP transects as indicated are representative of locations and extents. In terms of field observations, access may be limited across the entire cross section width, at a particular location, due to the presence of shallow areas on the tidal fringes and/or the presence of mangroves. In these instances the total flow may be slightly underestimated by field observations.

Simulated flows for the time of the ADCP transects shown in Figure 2-4 have been extracted from the model results. Plots showing the simulated flows with the observed flows (as determined from the ADCP measurements) for the April 2006 spring tide data set are presented in Figure 2-9 to Figure 2-13. The transect from Tide Island to Mud Island represents the main flow through the Port area. This transect has a peak flood tide flow of approximately 15,000m^3/s and a peak ebb tide flow of approximately 20,000m^3/s for the April/May 2006 calibration period. The bulk of this flow enters the Port through main ocean boundary. A good calibration has been achieved for these flows (see Figure 2-9). The remaining April/May 2006 transects also show reasonably good calibration.

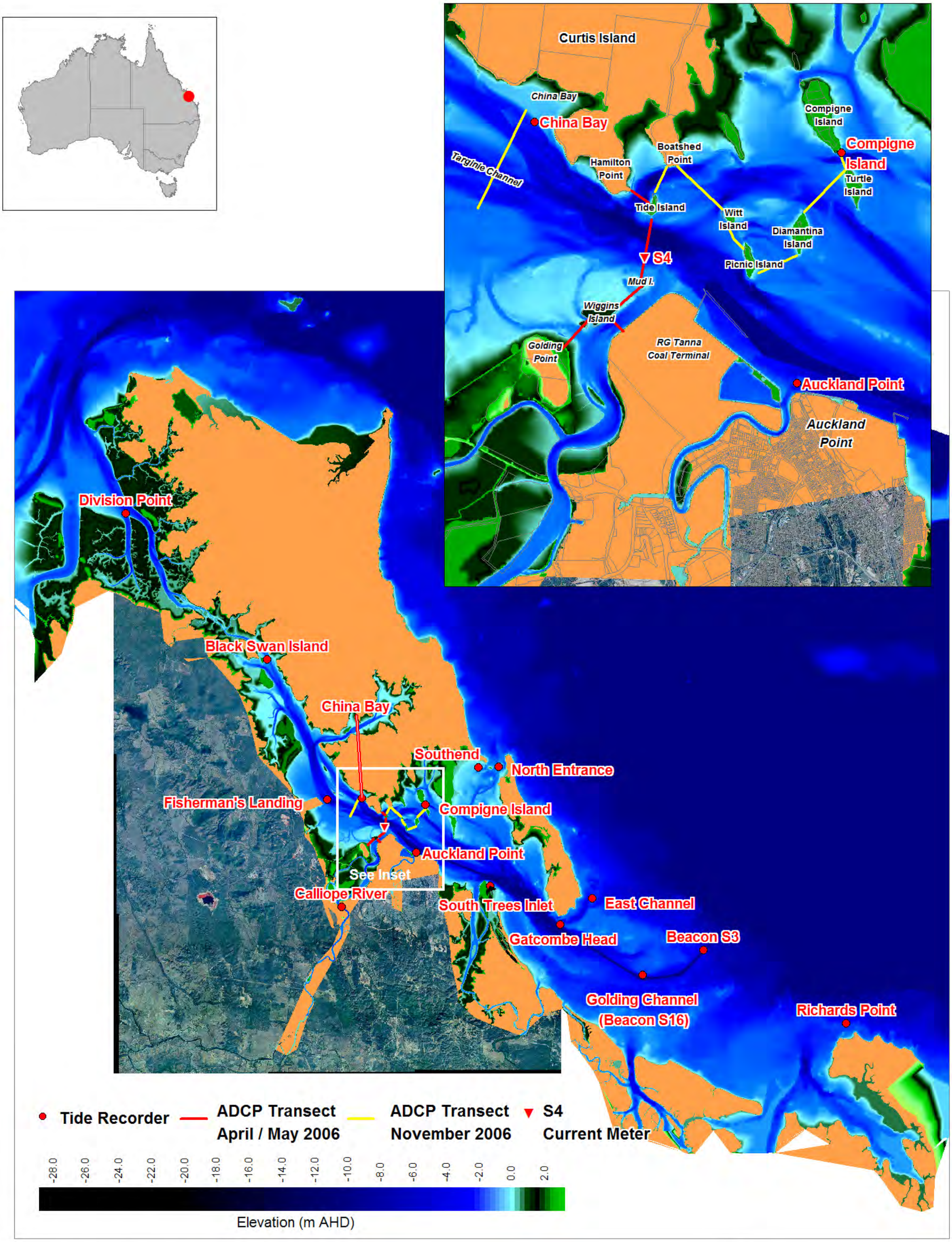
The simulated flows from Tide Island to Curtis Island are lower than the observed for the peak of the flood tide and slightly higher for the ebb tide flows. The flow through this narrow channel is characterised by high velocities with complex current patterns and eddies. Local deepening of the channel or changes in the bathymetry could provide for differences in flow capacity which are not reflected in the model. Boating charts indicate a shallow bar approximately 800m to the east of Tide Island that may have an influence on the peak flood tide flows. Nevertheless, the proportion of the total flow through the system conveyed through this section of the transect is approximately 15%, such that a minor discrepancy in simulated peak flows will not have a major influence on the total flow distribution across the greater extent of the model.

The neap tide transects are presented in Figure 2-14 and Figure 2-15. The Tide Island to Mud Island (the main channel) transect again shows a good calibration of both timing and magnitude. The model is again slightly over predicting the ebb tide flow and under predicting the peak flood tide flow for the Tide Island to Curtis Island on the neap tide.

2.6.3.4 Velocity Magnitude and Direction Comparisons

The model velocity magnitude and direction predictions were compared to the fixed S4 current meter data and is presented in Figure 2-16 and Figure 2-17. For the most part the modelled velocity magnitude is a reasonable representation of the measured data. Flood tide current speeds are over-estimated by the model during the spring tides, while ebb tide and neap tide current speeds are generally well represented. The observed current direction is generally well reproduced by the model, though the measured directional variation ebbing and flooding spring tides is not completely replicated by the model. The S4 was deployed in the general vicinity of the Calliope River ebb-delta, where bathymetric variations and curvature of the main channel are expected to induce complex flow patterns with large spatial gradients in currents. Vertical shearing of the currents under spring tide flow conditions may be such that the S4 current meter is not measuring a current speed that is representative of the depth-average. It is likely that more detailed velocity profile measurements, for instance using an ADCP would be required to resolve the current patterns at the Calliope River mouth.

Instantaneous velocity transects for the section from Tide Island to Mud Island have also been extracted from the model results at about the times of peak spring flood and ebb tidal currents and compared with the ADCP transect data. The modelled versus observed data for both velocity speed and direction are presented in Appendix C. The observed ADCP data has been presented as depth averaged values at each location across the transect. It should be noted that the ADCP data reflects a period of time for the transect to be completed, while the model results are at an instant in time within that period. The ADCP directions are also subject to variation by +/- 8 degrees due to limitations of the instruments at the time. This does not affect the flow calculations as presented above. Generally the plots show good correlation between the modelled current speed and direction distributions across the channel and the ADCP measurements.



Title:

Calibration Data - 2006

Figure: 2-4

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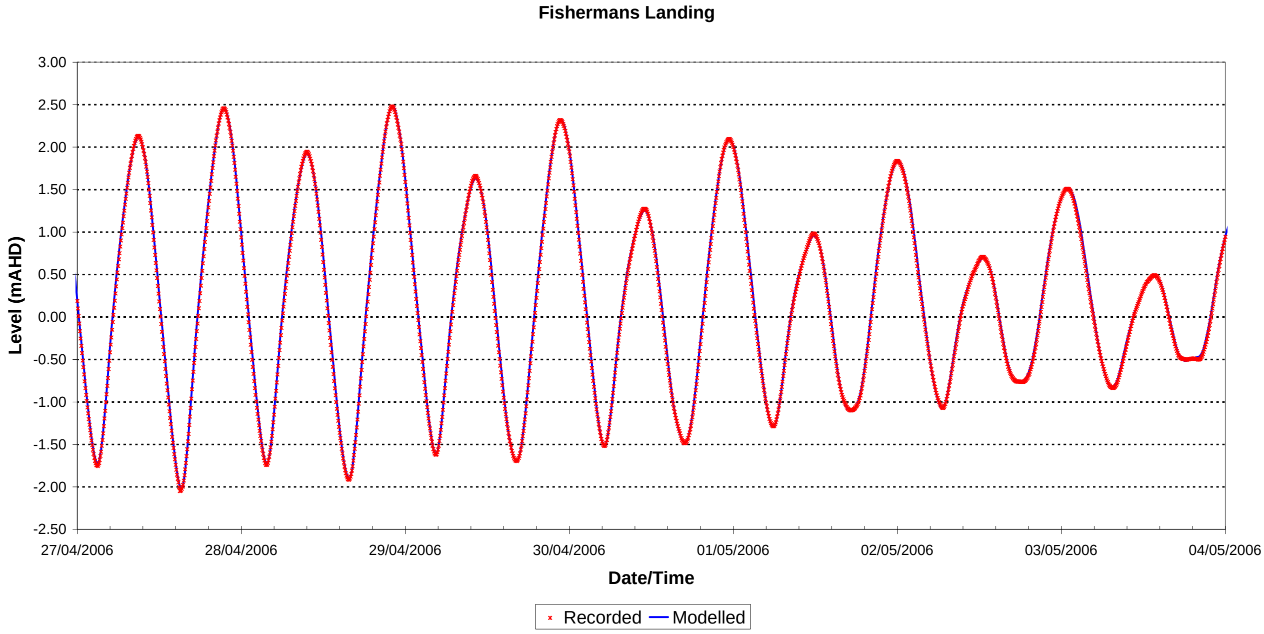


Figure 2-5 Water Level Calibration - Fisherman's Landing, April 2006

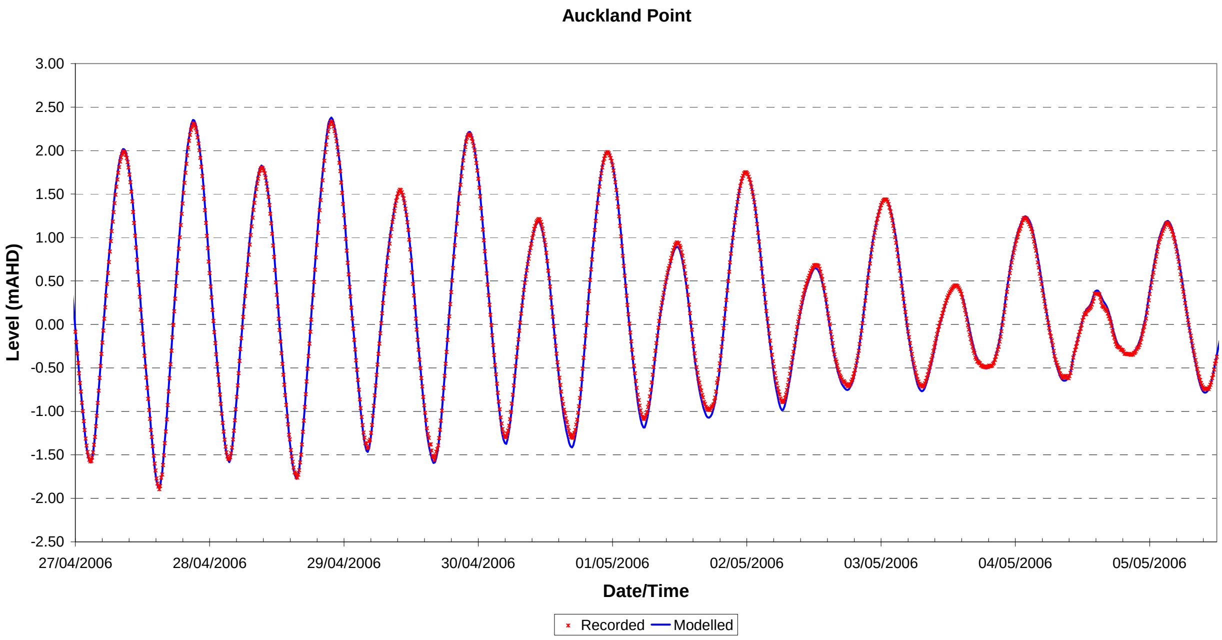


Figure 2-6 Water Level Calibration – Auckland Point, April 2006

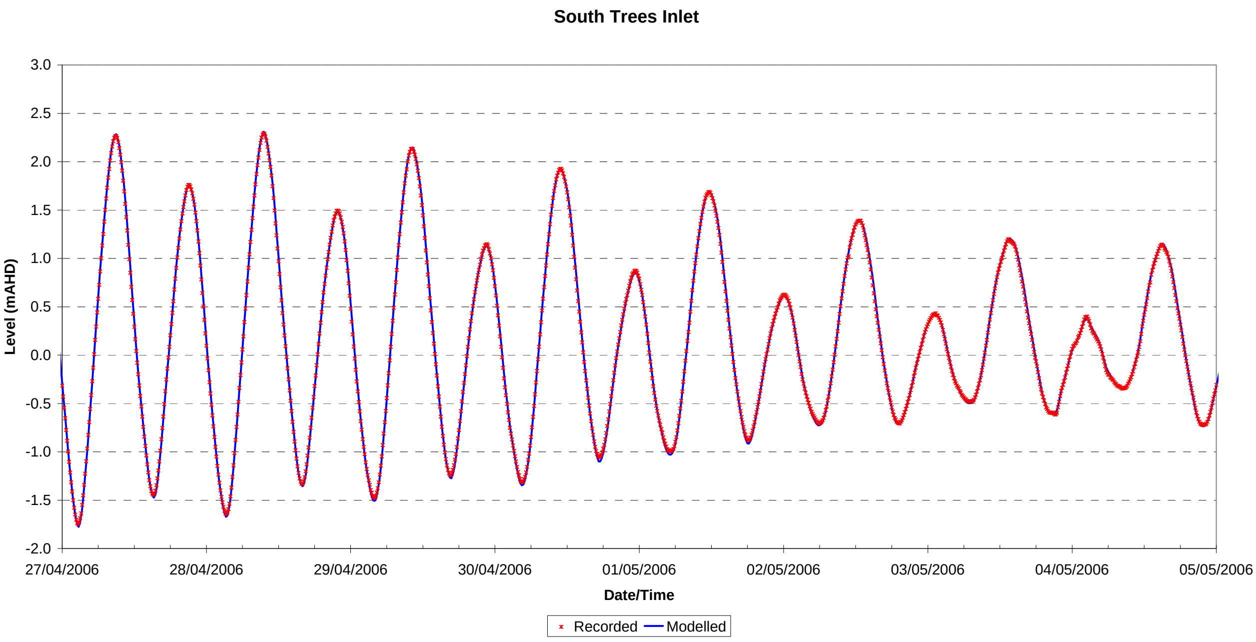


Figure 2-7 Water Level Calibration – South Trees, April 2006

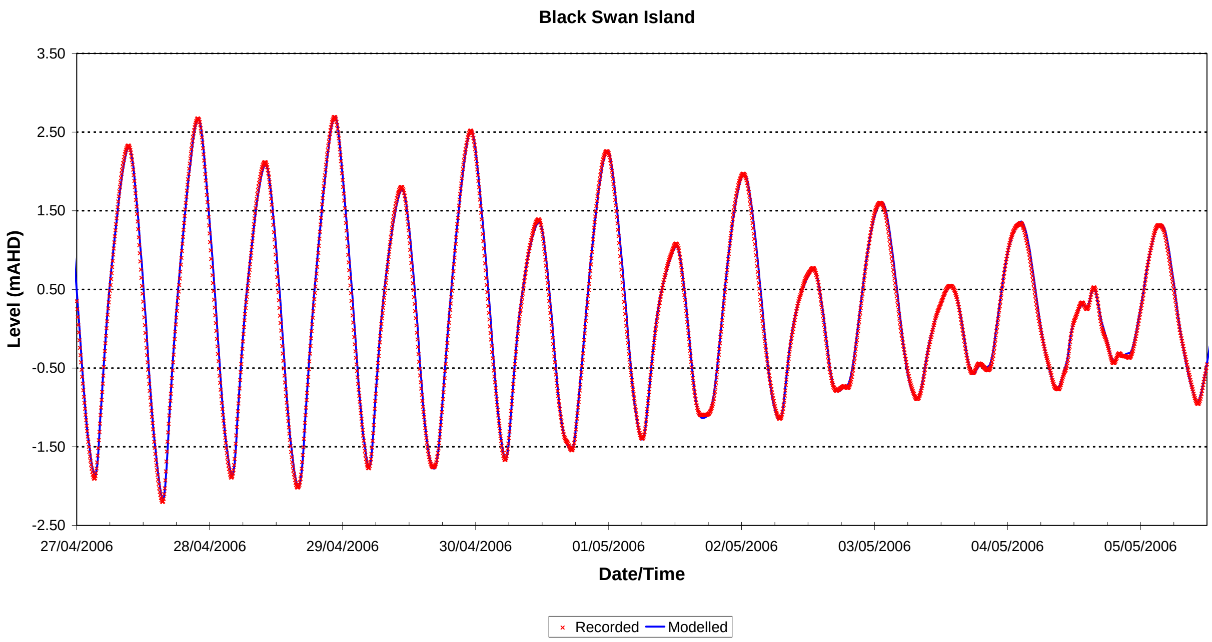


Figure 2-8 Water Level Calibration – Black Swan, April 2006

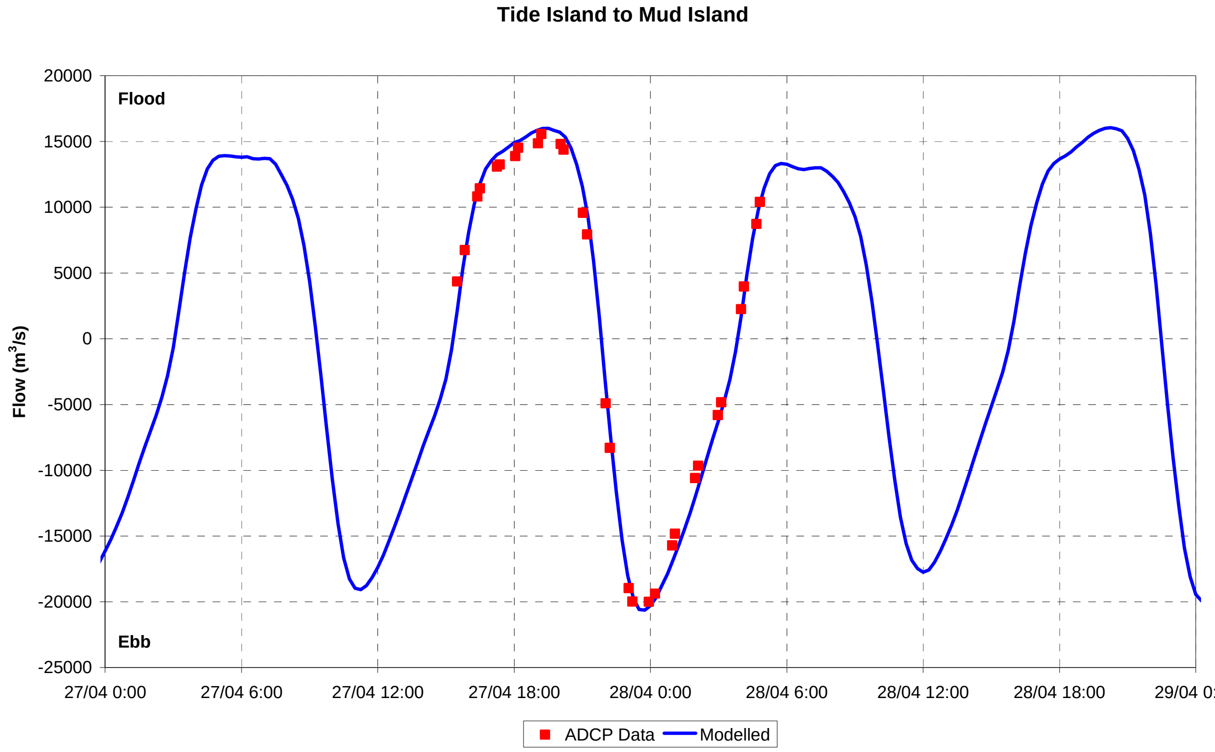


Figure 2-9 Flow Calibration – Tide island to Mud Island, April 2006

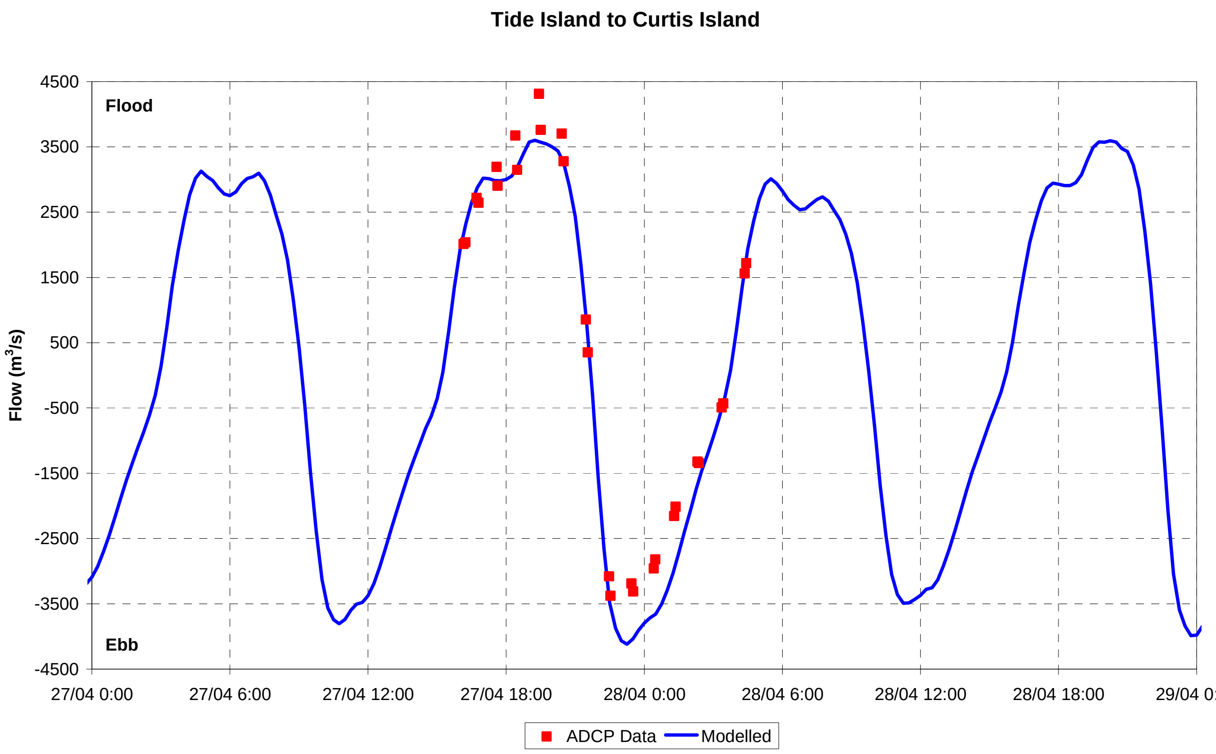


Figure 2-10 Flow Calibration – Tide Island to Curtis Island, April 2006

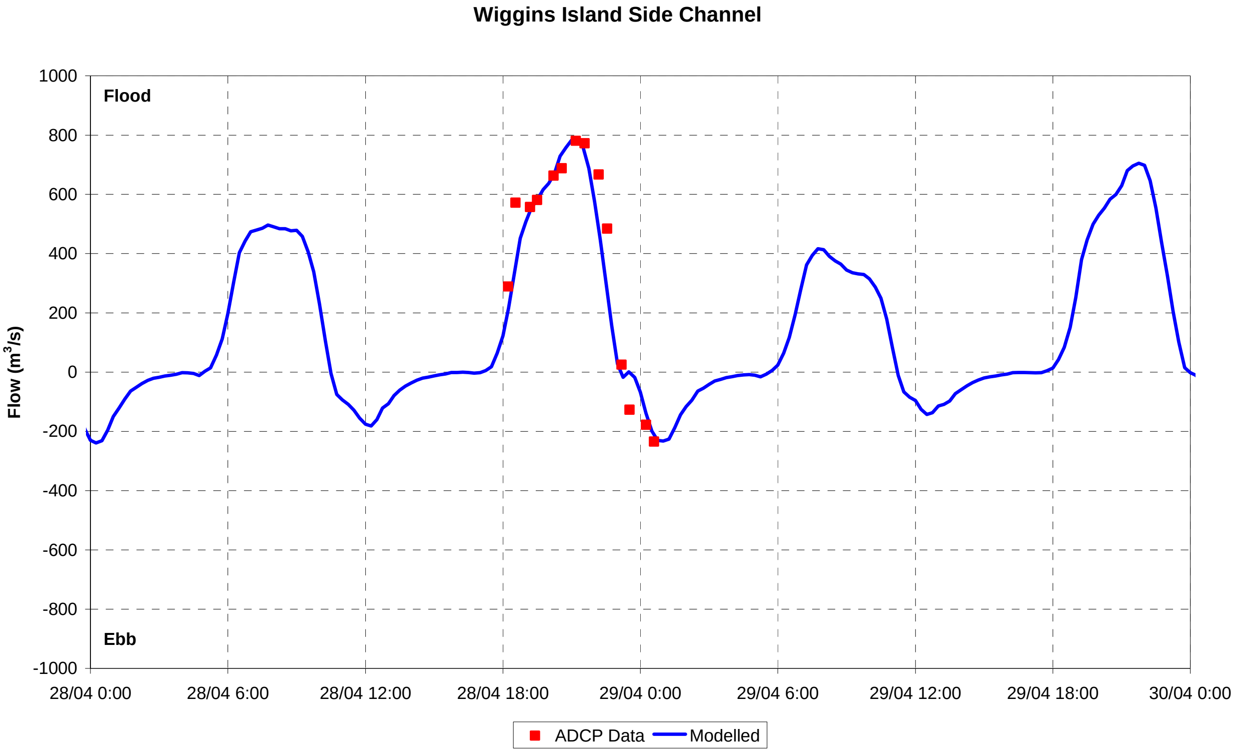


Figure 2-11 Flow Calibration – Wiggins Island Side Channel, April 2006

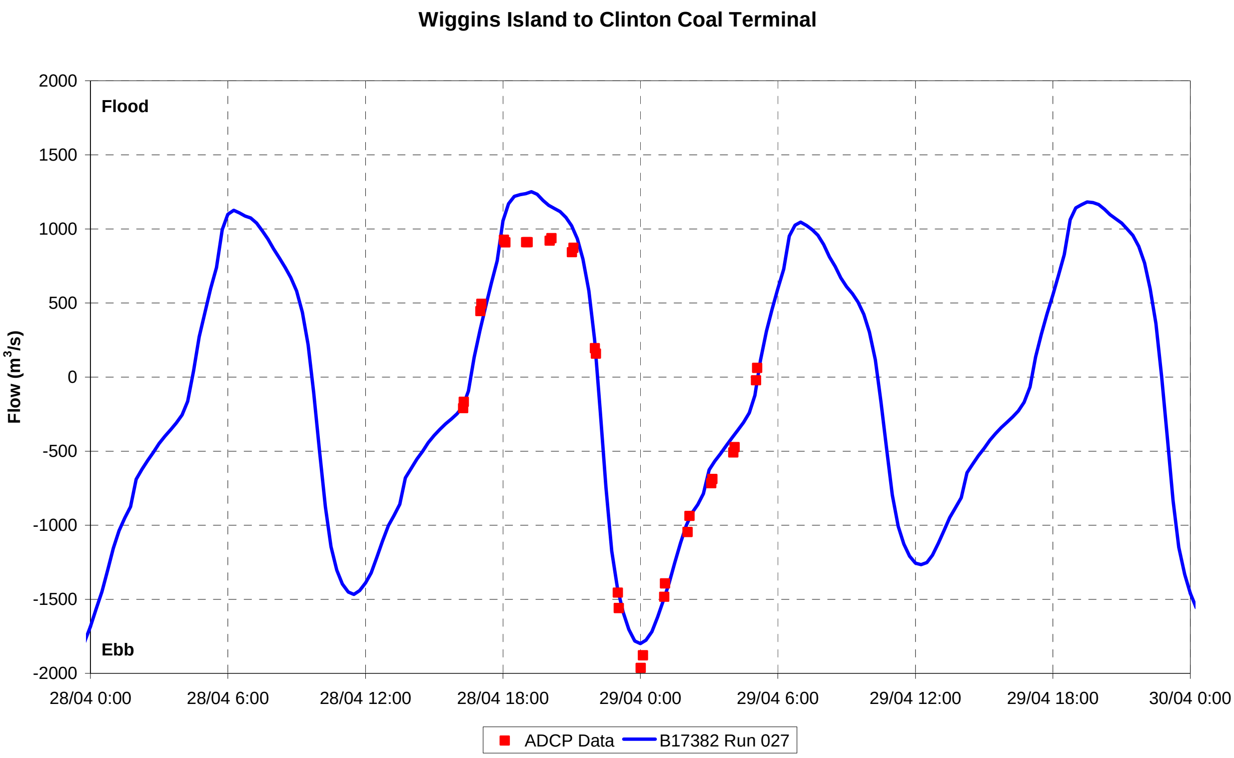


Figure 2-12 Flow Calibration – Wiggins Island to RG Tanna Coal Terminal, April 2006

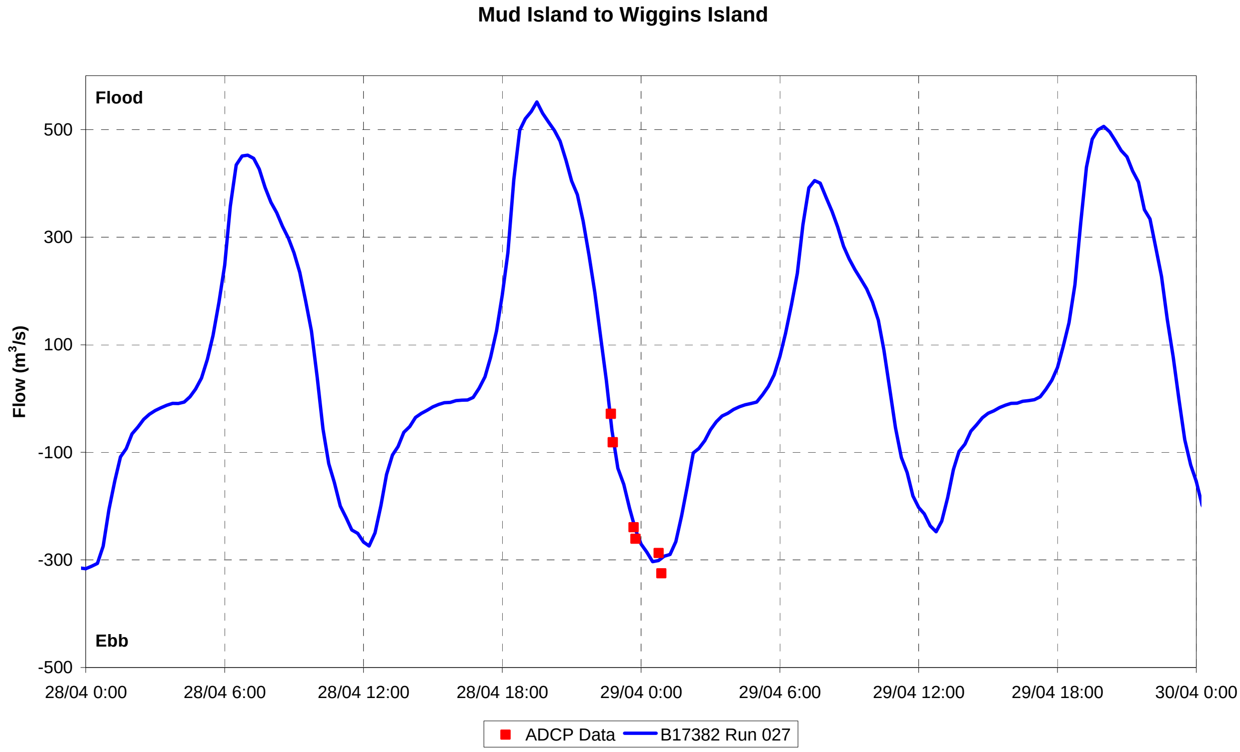


Figure 2-13 Flow Calibration – Mud Island to Wiggins Island, April 2006

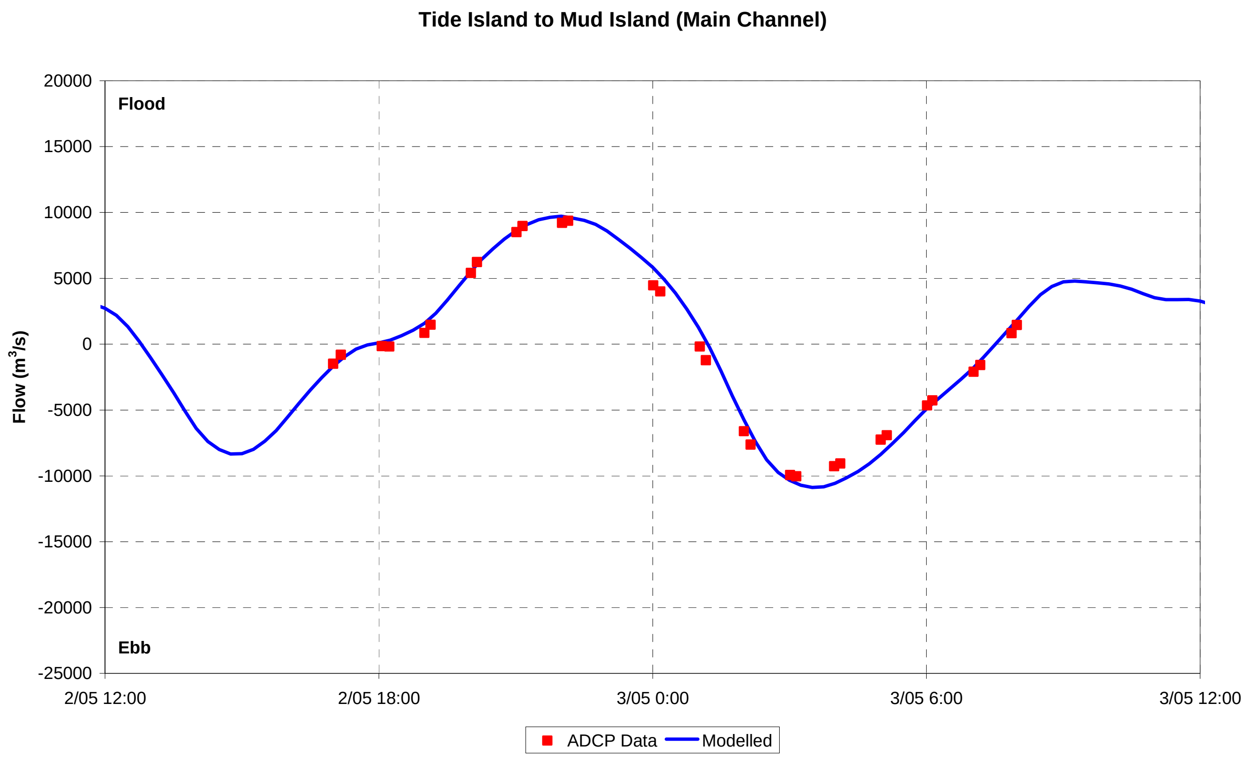


Figure 2-14 Flow Calibration – Tide Island to Mud Island, May 2006 (Neap Tide)

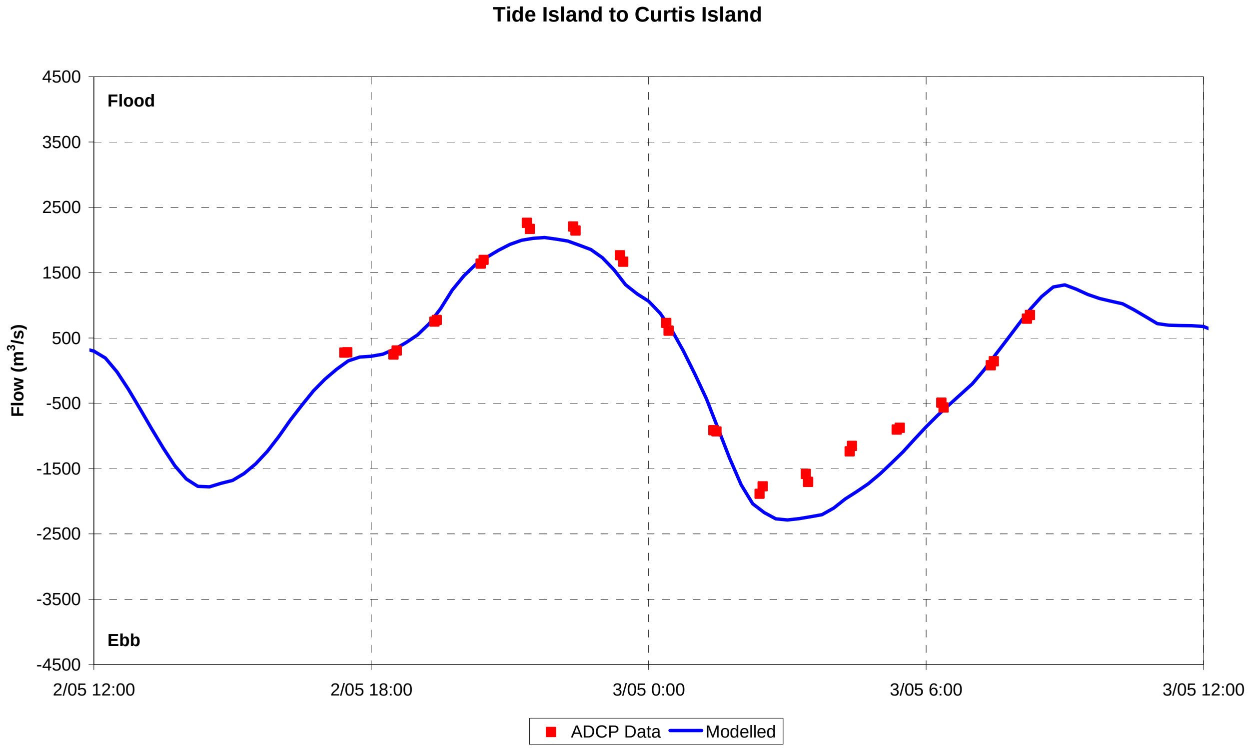


Figure 2-15 Flow Calibration – Tide Island to Curtis Island, May 2006 (Neap Tide)

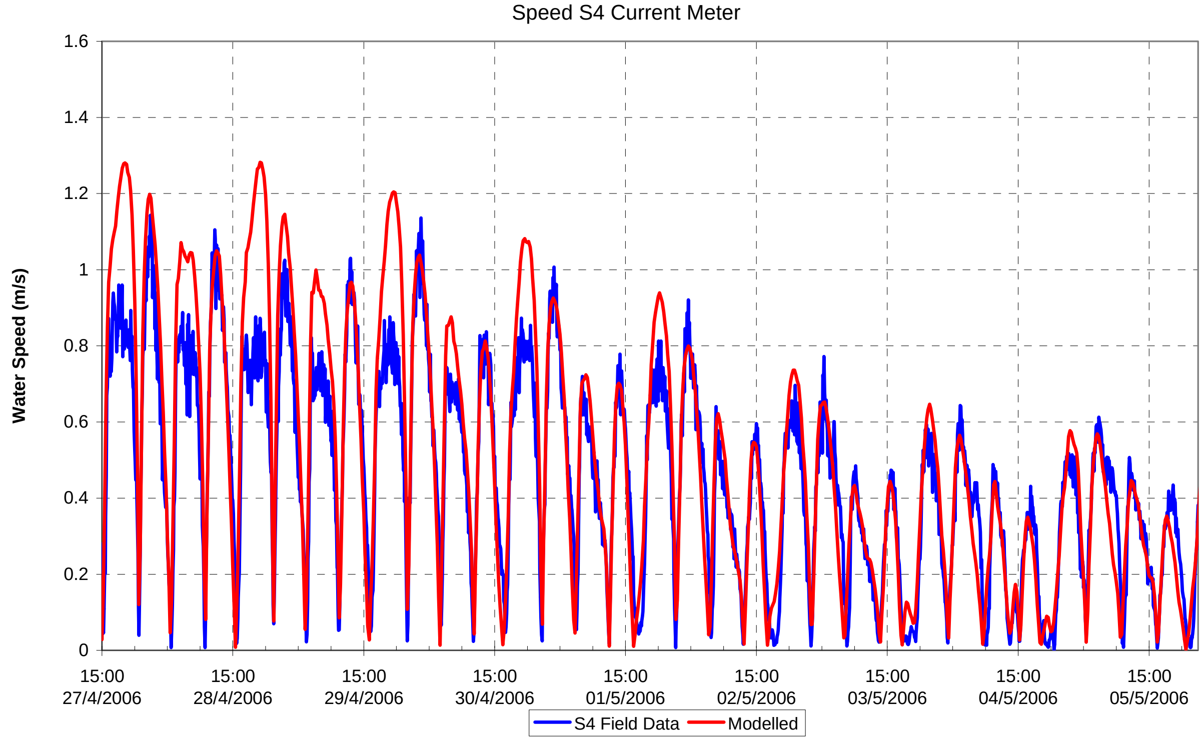


Figure 2-16 Current Speed – S4 Current Meter, April 2006

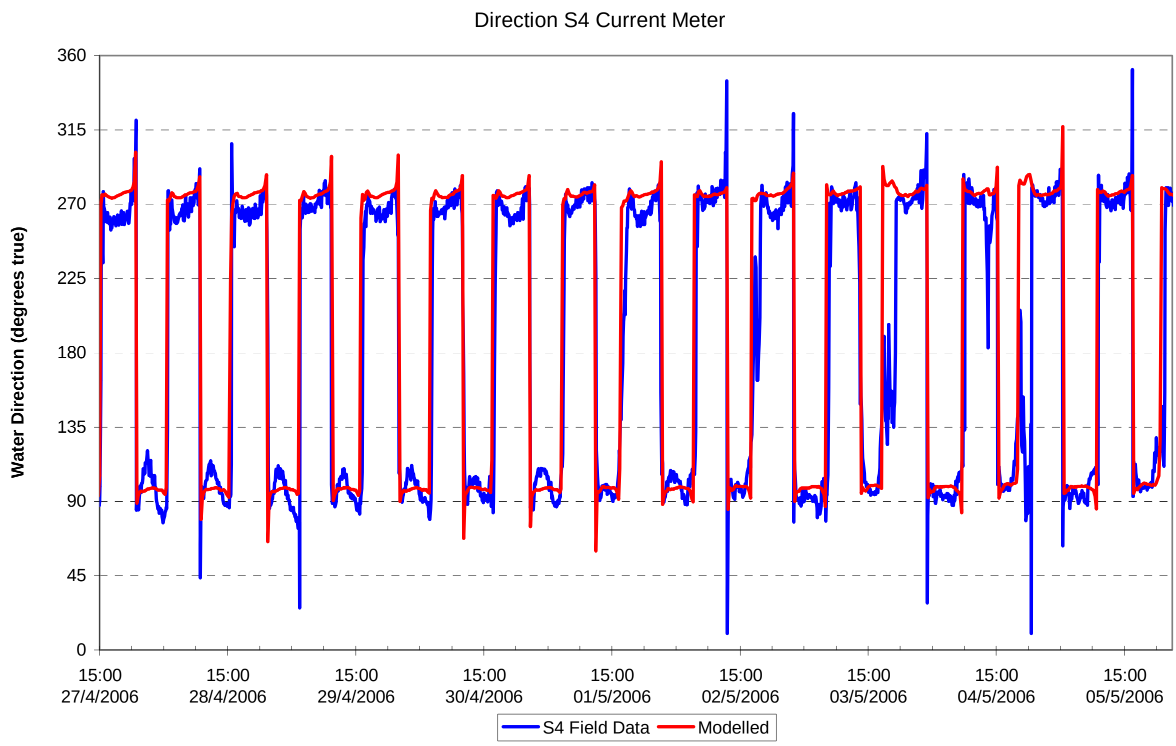


Figure 2-17 Current Direction – S4 Current Meter, April 2006

2.6.4 Boatshed Point/China Bay Data

2.6.4.1 Data Set and Simulation Summary

This data set was collected as part of hydraulic investigations of alternate channel and swing basin options. The focus areas for this investigation were on the south-western end of Curtis Island in the vicinity of Boatshed Point (to the east of Hamilton Point) and North China Bay (north of Hamilton Point).

The data collected included continuous time series of water elevations using fixed point tide gauges and flow / velocity distribution for defined transects using boat mounted Acoustic Doppler Current Profilers (ADCPs). The location of the tide gauges and ADCP transects used for calibration are presented in Figure 2-4 with a summary of the simulation and data sets as per Table 2-3 below.

Table 2-3 Boatshed Point/China Bay Simulation Summary

Project	Boatshed Point / China Bay Investigations
Period	2nd November – 9th November 2006
Focus Area	Boatshed Point and North China Bay (south-western end of Curtis Island)
Boundary Data	Main Ocean Sth of Facing Island – Synthesised from MSQ gauge data North Entrance between Curtis & Facing Islands – Synthesised from MSQ gauge data Division Point Nth end of The Narrows – Synthesised from MSQ gauge data Wind Forcing –Recorded wind data (BOM)
Calibration Data	Continuous Water Levels - South Trees (MSQ) - Auckland Point (MSQ) - Fisherman's Landing (MSQ) - Black Swan Island (WBM) - China Bay (WBM) - Golding Channel (MSQ) - Gatcombe Head (MSQ) - South End Jetty / North Entrance (MSQ) - Beacon S3 (MSQ) Spring Tide ADCP Transects - China Bay to Targinie Channel - Tide Island to Curtis Island (Boatshed Point) - Curtis Island (Boatshed Point) to Witt Island - Picnic Island to Witt Island - Picnic island to Diamantina Island - Turtle Island to Compigne Island - Turtle Island to Diamantina Island

2.6.4.2 Water Level Comparisons

The modelled and recorded water levels for the November 2006 data set are presented in Figure 2-18 to Figure 2-26.

The calibration plots indicate a generally good calibration to water levels. There are some slight datum shifts throughout the data set which could be related to some of the boundary conditions being derived from previous relationships rather than directly measured. There is also a slight timing shift apparent at the Fisherman's Landing gauge, this is unexplained as the model fits the measured data well at the nearby China Bay site.

2.6.4.3 Total Flow Comparisons

The flow calibration for the November 2006 data set is presented in Figure 2-27 to Figure 2-33. These illustrate comparison of simulated flows with observed flows determined from the ADCP transect measurements. The China Bay to Targinie section represents the main flow through the Port area and good calibration has been achieved for this area. The model also demonstrates good calibration for the remaining November 2006 flow transects although it slightly under predicts the flow between Curtis and Witt Islands. The model also slightly under-predicts flows between Turtle Island and Compigne Island, particularly on a flood tide. ADCP transects highlight that there are complex flow patterns in this area.

2.6.4.4 Velocity Magnitude and Direction Comparisons

Instantaneous velocity transects from the November 2006 data set have been extracted from the model results and compared to the observed ADCP measurements. Velocity magnitude and direction are compared at about the time of peak flood and ebb tides for the various transects in Appendix D. The observed ADCP data has been presented as depth averaged values at each location across the transect. It should be noted that the ADCP data reflects a period of time for the transect to be completed, while the model results are at an instant in time within that period. The ADCP directions are also subject to variation by +/- 8 degrees due to set up limitations at the time. This does not affect the flow calculations as presented above.

The model shows a good correlation for the China Bay to Targinie transect, which represent the main flow through the Port area. The current speeds and direction across the Curtis Island to Witt Island transect are generally well represented by the model, as are Turtle Island to Diamantina Island. The steep velocity gradients at the near-shore extents of these are not always replicated by the model for its current level of resolution.

The Tide Island to Curtis Island transects were taken at an oblique angle to the flow and the model is shown to not represent the complex circulations forming in the lee of Hamilton Point and Tide Island. This is most noticeable on the ebb tide, where the ADCP directions indicate a "swirling" current not reflected in the model. This may indicate that there is insufficient model resolution to represent the flow "separation" and perhaps inaccurate model bathymetry in the vicinity of these transects. As the model is adequately replicating the total flow across this section this is not expected to impact the ability of the model to reproduce the behaviour elsewhere in the model.

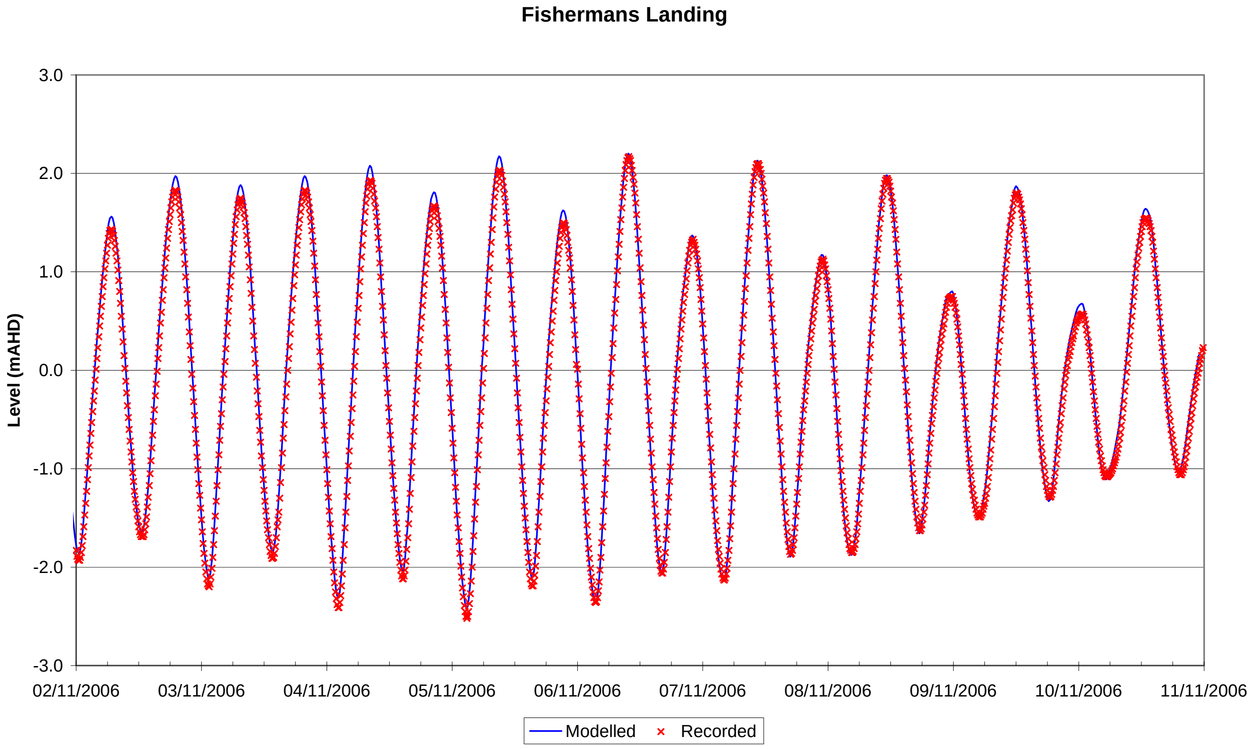


Figure 2-18 Water Level Calibration – Fisherman's Landing, November 2006

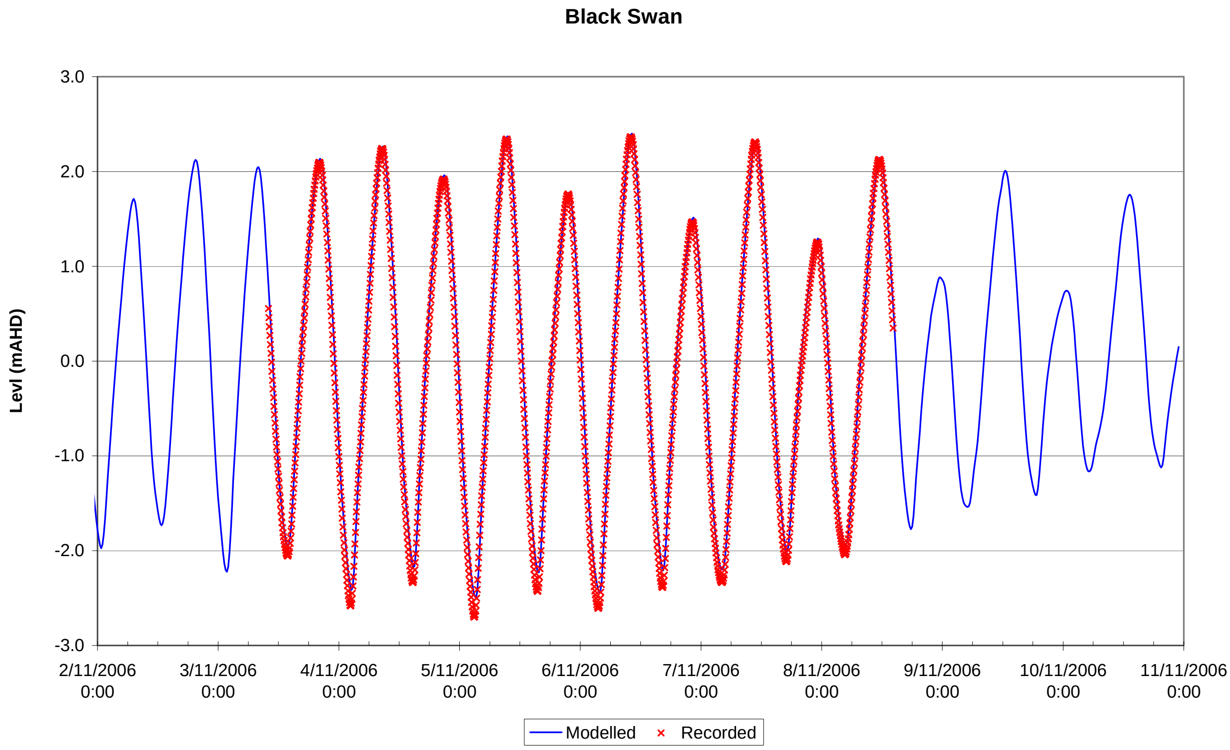


Figure 2-19 Water Level Calibration – Black Swan Inlet, November 2006

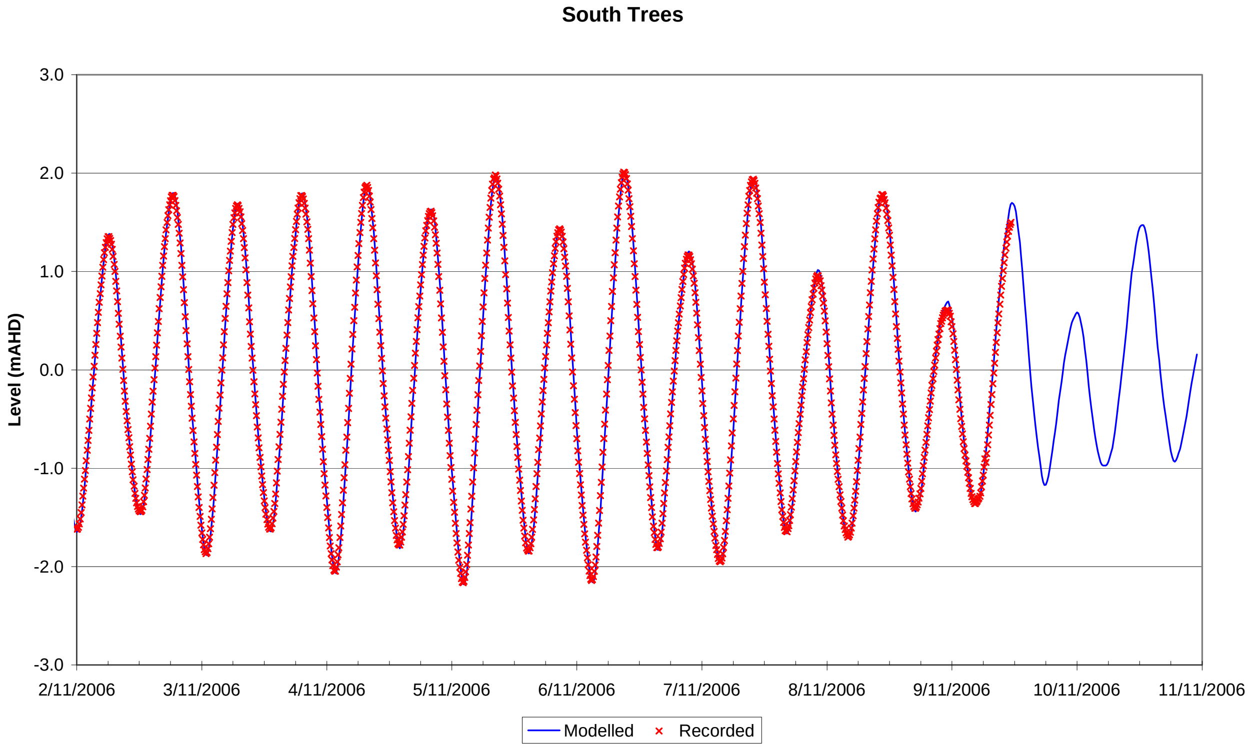


Figure 2-20 Water Level calibration – South Trees, November 2006

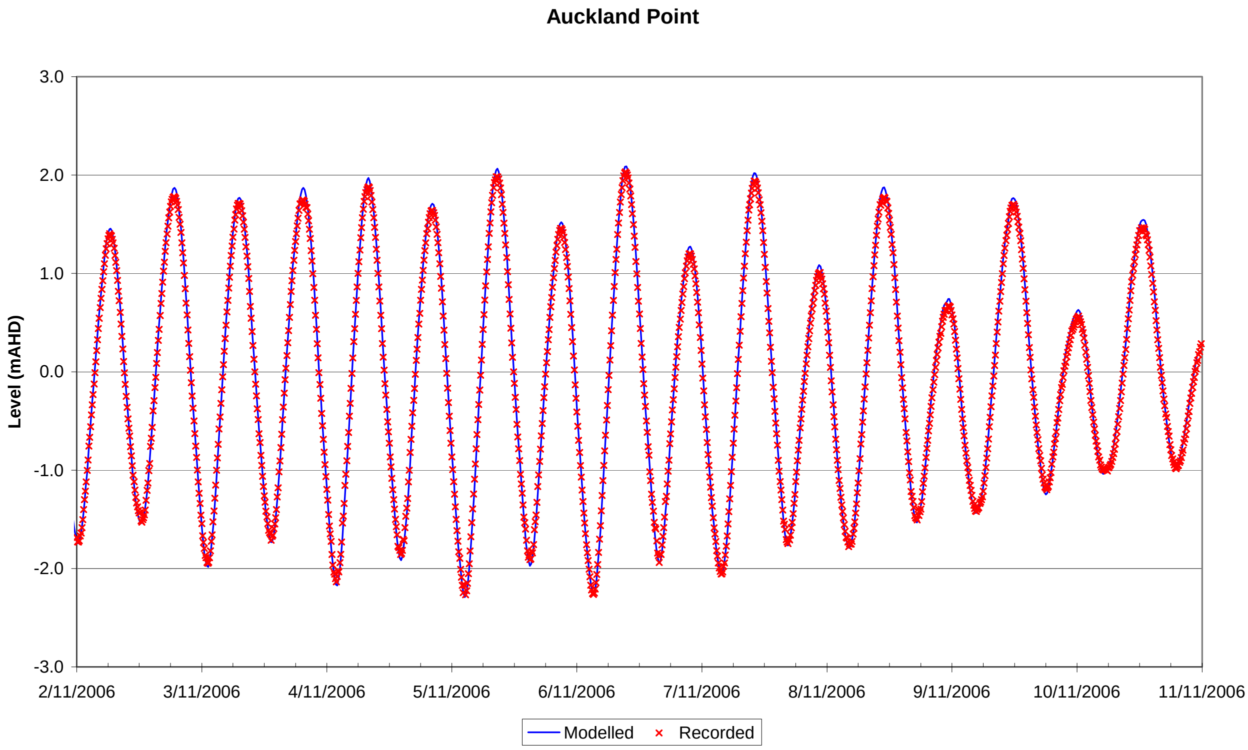


Figure 2-21 Water Level calibration – Auckland Point, November 2006

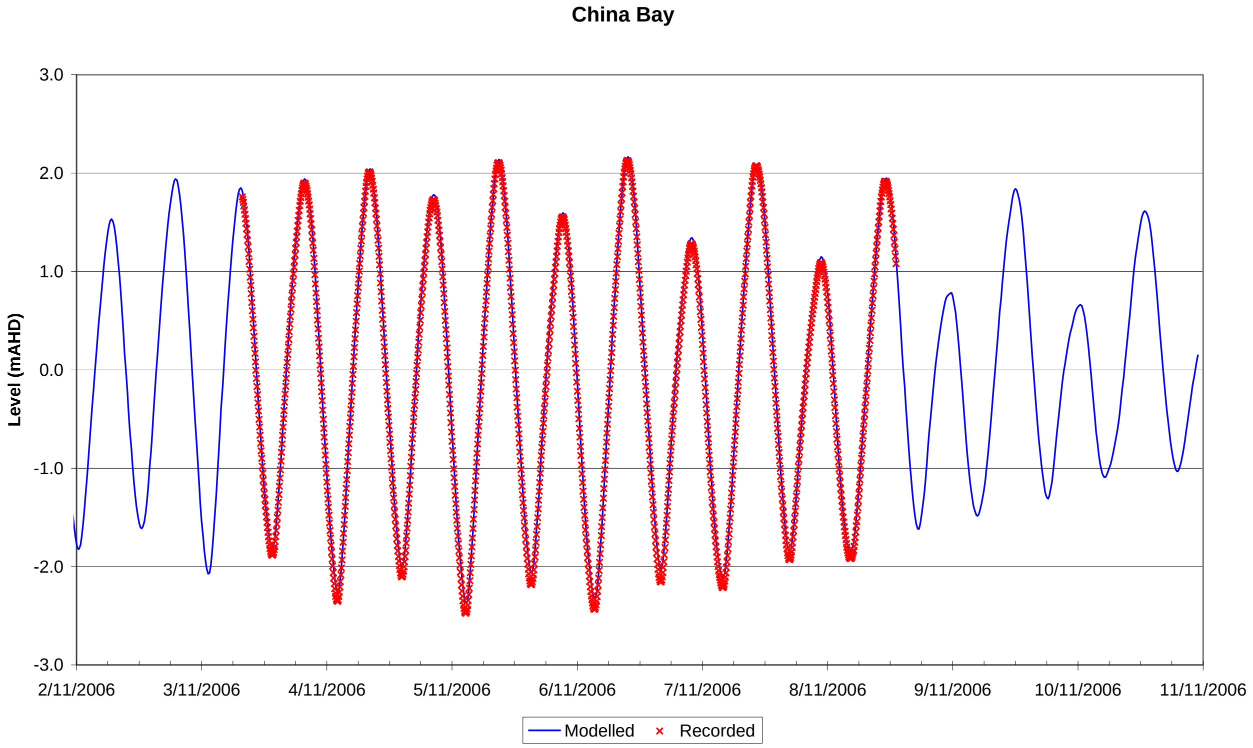


Figure 2-22 Water Level Calibration – China Bay, November 2006

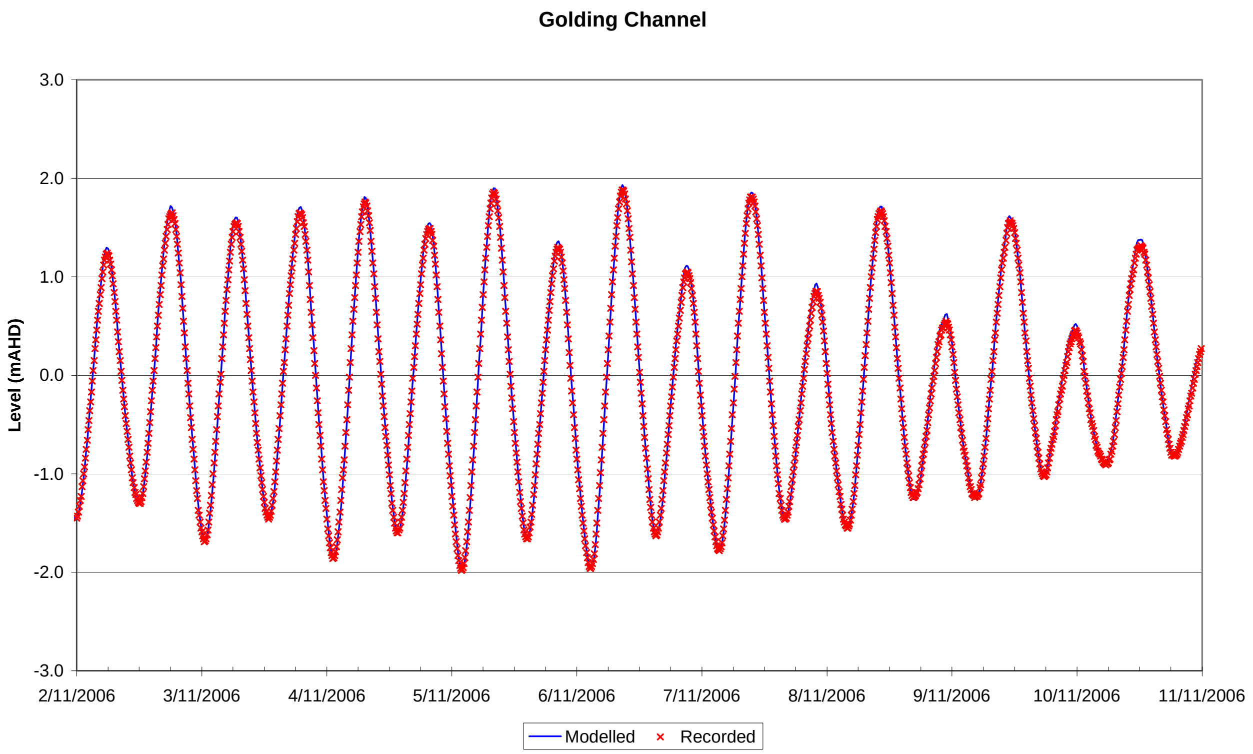


Figure 2-23 Water Level Calibration – Golding Channel, November 2006

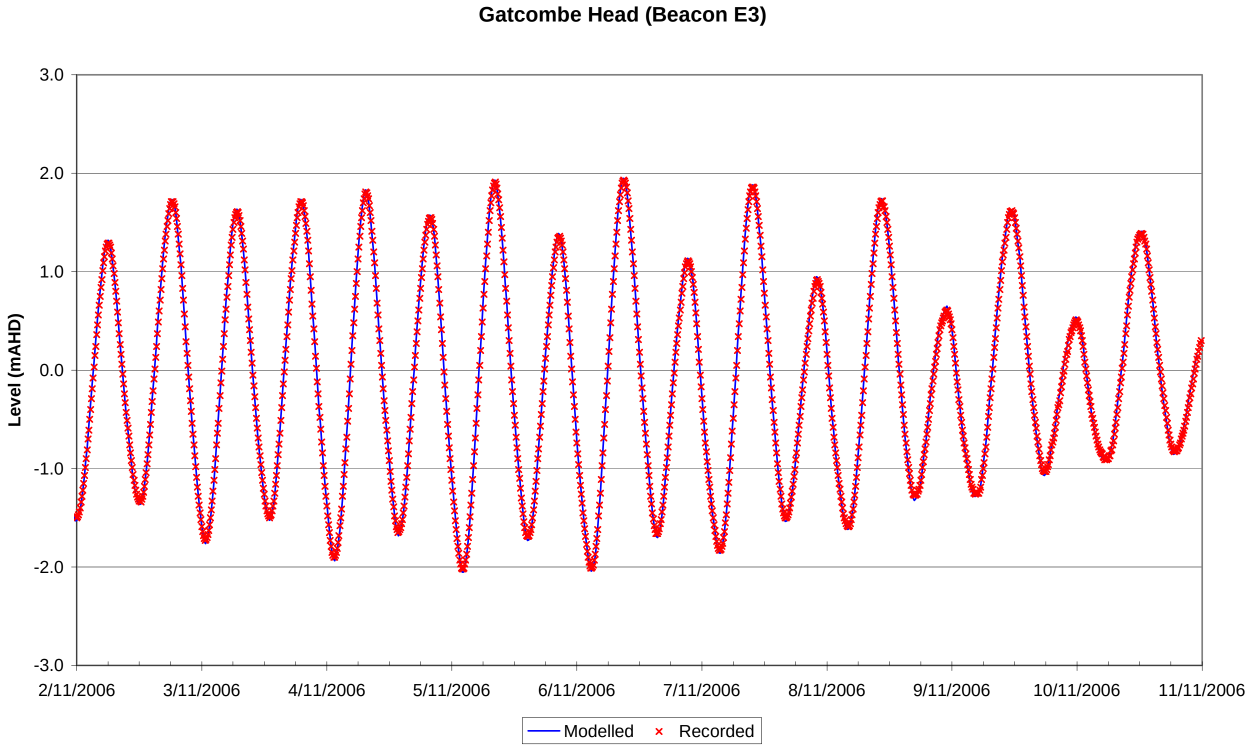


Figure 2-24 Water Level calibration – Gatcombe Head, November 2006

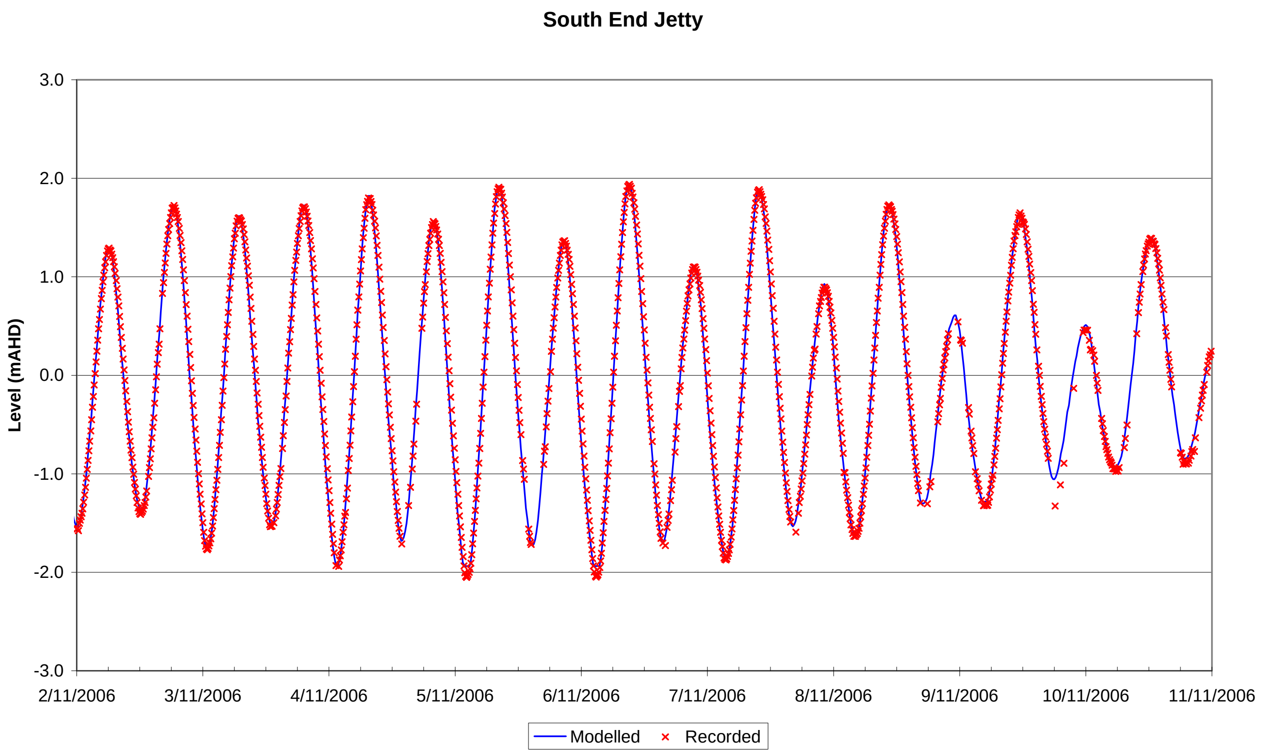


Figure 2-25 Water Level Calibration – South End Jetty, November 2006

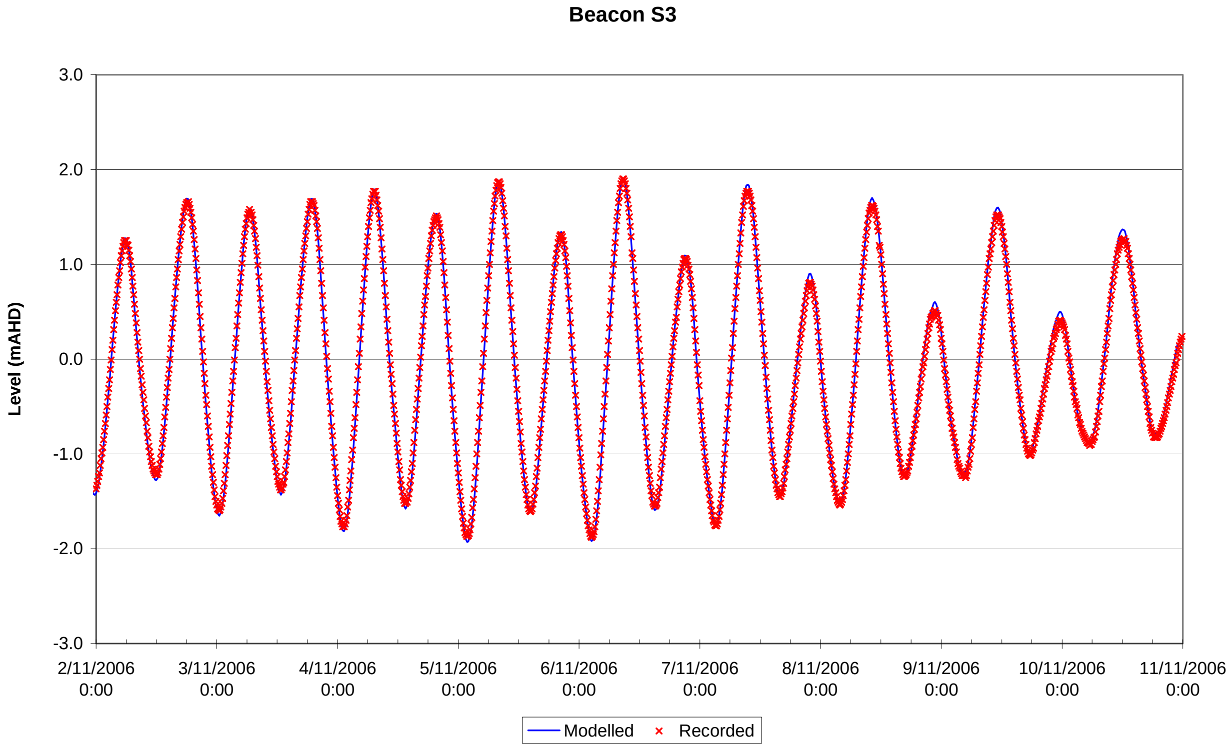


Figure 2-26 Water Level Calibration – Beacon S3, November 2006

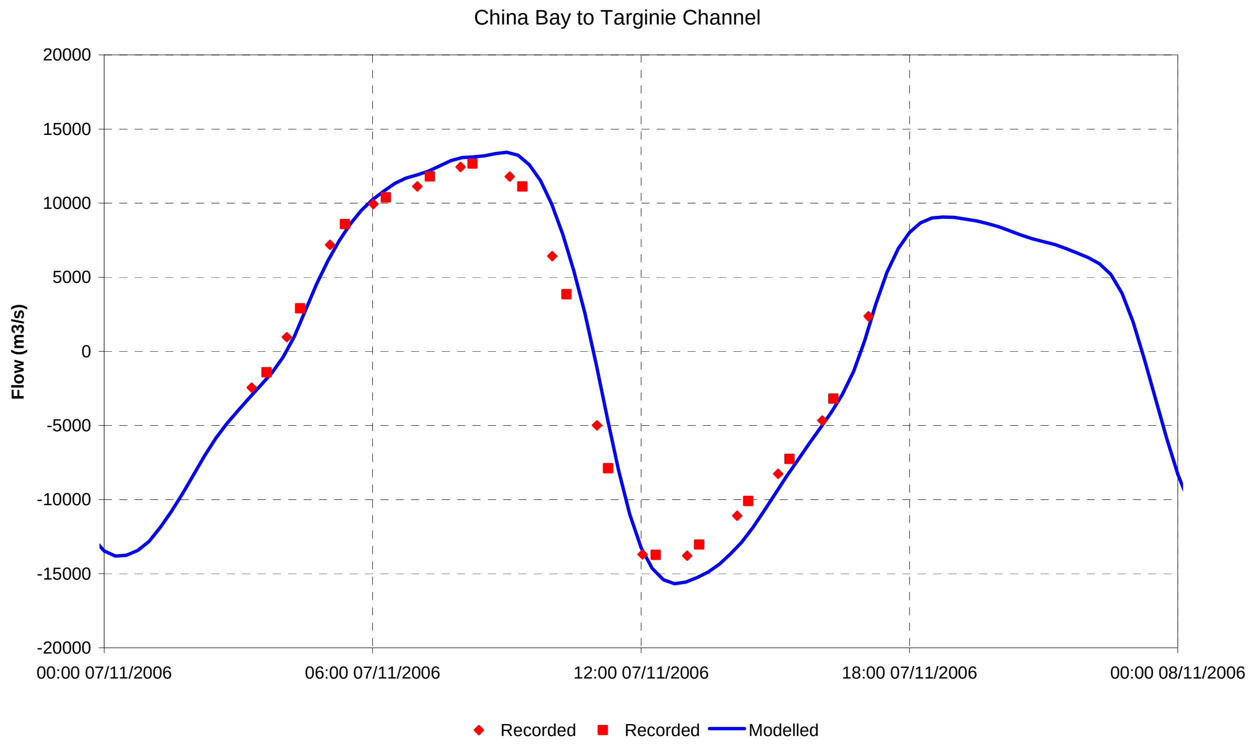


Figure 2-27 Flow Calibration – China Bay to Targinie Channel, November 2006

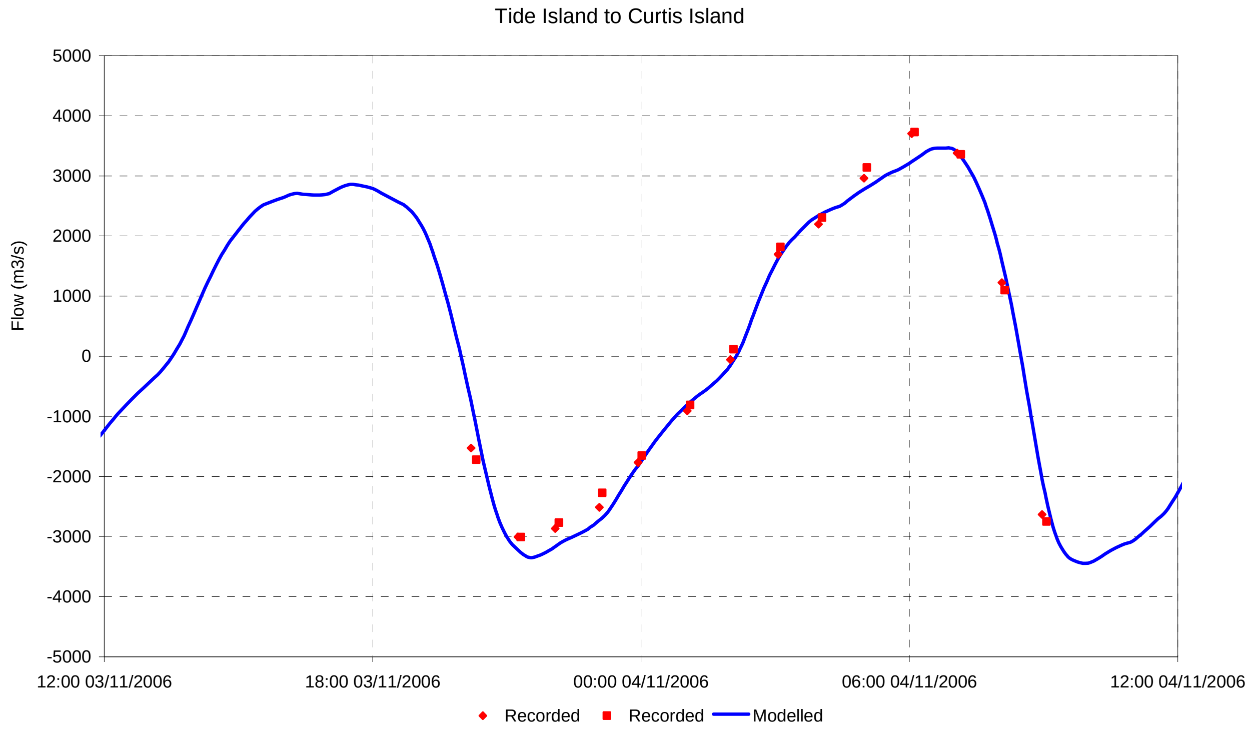


Figure 2-28 Flow Calibration – Tide Island to Curtis Island, November 2006

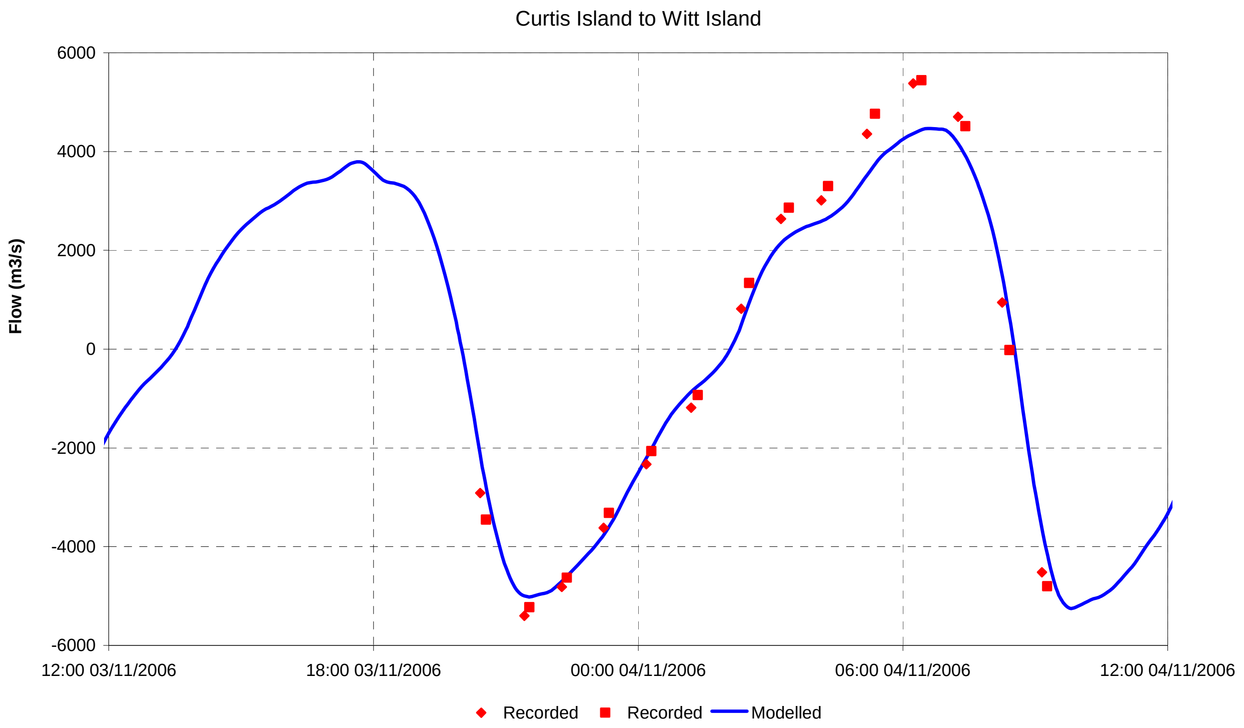


Figure 2-29 Flow Calibration – Curtis Island to Witt Island, November 2006

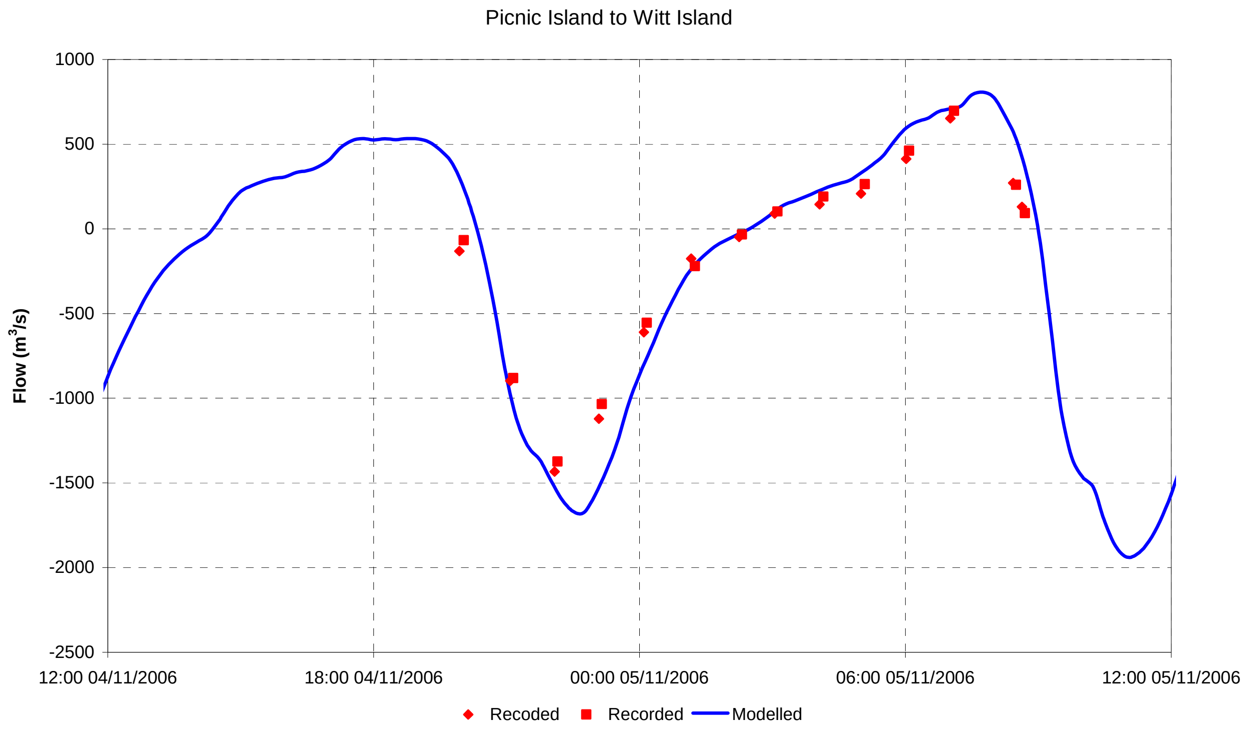


Figure 2-30 Flow Calibration – Picnic Island to Witt Island, November 2006

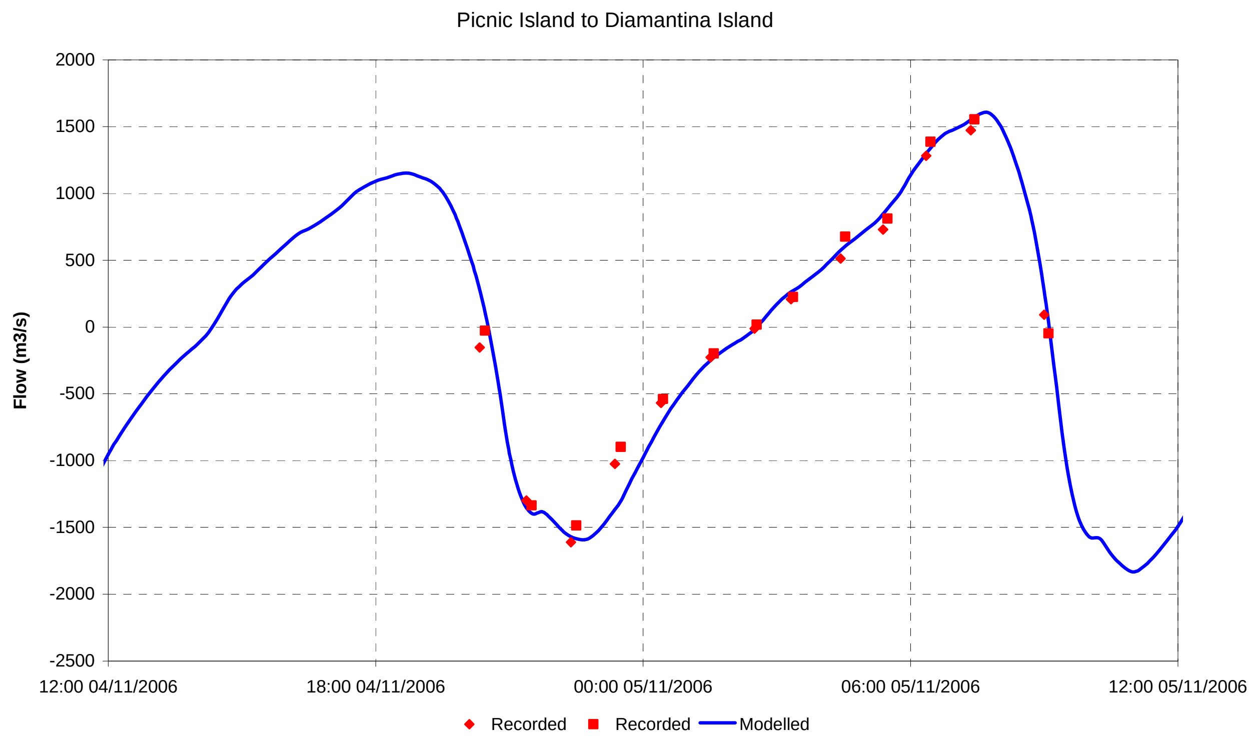


Figure 2-31 Flow Calibration – Picnic Island to Diamantina Island, November 2006

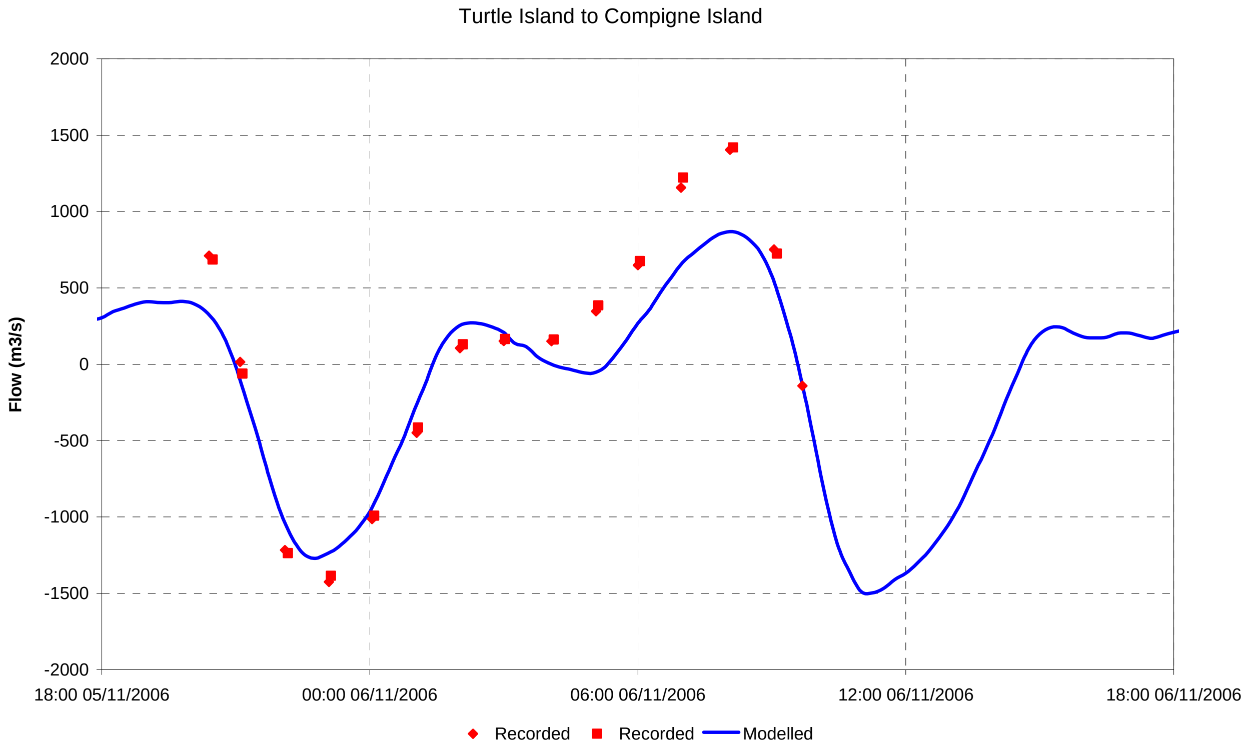


Figure 2-32 Flow Calibration – Turtle Island to Compigne Island, November 2006

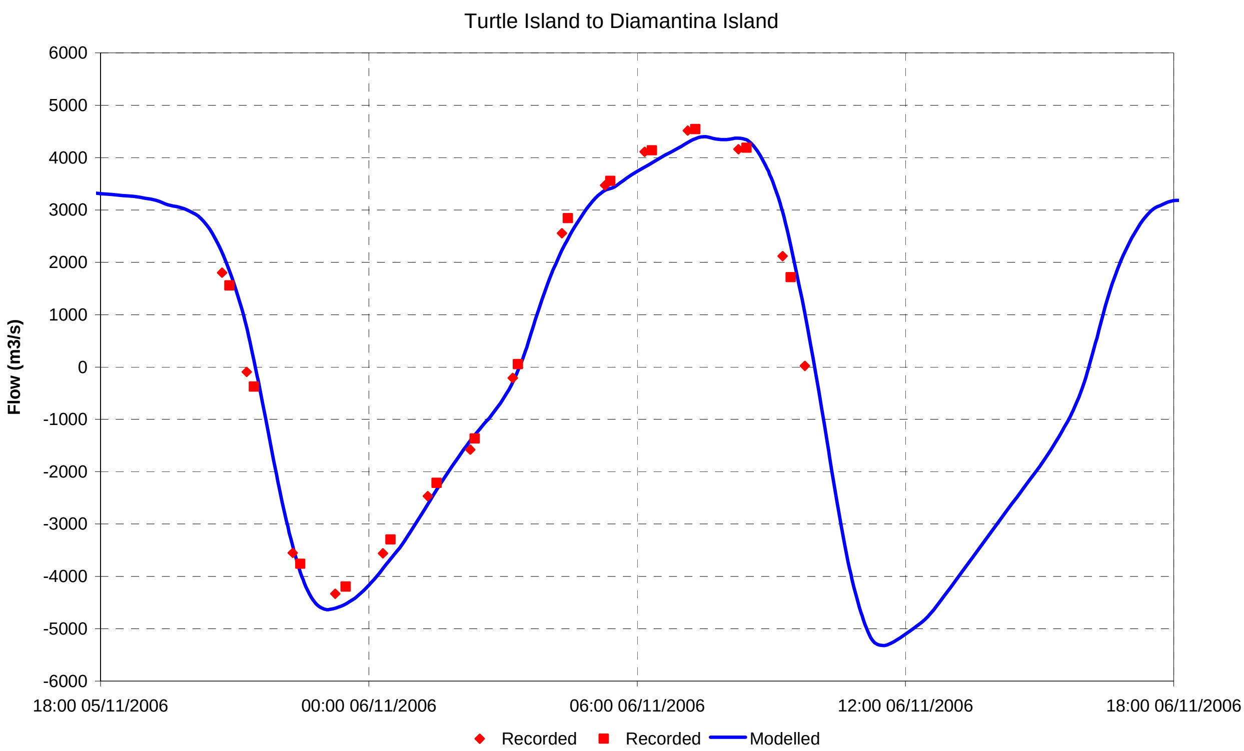


Figure 2-33 Flow Calibration – Turtle Island to Diamantina Island, November 2006

2.6.5 Fisherman's Landing 153Ha Reclamation EIS Data

2.6.5.1 Data Set and Simulation Summary

This data set was collected as part of the Fisherman's Landing 153 Hectare Reclamation EIS. The focus of the measurements was the main and side channels in the vicinity of Fisherman's Landing and the Passage Islands.

The data collected included continuous time series of water elevations using fixed point tide gauges and flow / velocity distribution for defined transects using boat mounted Acoustic Doppler Current Profilers (ADCPs). The location of the tide gauges and ADCP transects used for calibration are presented in Figure 2-34 with a summary of the simulation and data sets as per Table 2-4 below.

The simulation was undertaken without any further adjustment of model parameters and therefore represents validation of the model with an independent data set.

Table 2-4 Fisherman's Landing Simulation Summary

Project	Fisherman's Landing 153Ha Reclamation EIS
Period	10th August – 25th August 2008
Focus Area	Fisherman's Landing area of Port Curtis
Boundary Data	Main Ocean Sth of Facing Island – Synthesised from MSQ gauge data North Entrance between Curtis & Facing Islands – Synthesised from MSQ gauge data Division Point Nth end of The Narrows – Synthesised from MSQ gauge data Wind Forcing –recorded wind data (BOM)
Validation Data	Continuous Water Levels - South Trees (MSQ) - Auckland Point (MSQ) - Fisherman's Landing (MSQ) Spring Tide ADCP Transects - Fisherman's Landing – Main Channel Only - Fisherman's Landing – Main and Side ("Curtis") Channels

2.6.5.2 Water Level Comparisons

Modelled and recorded water levels are presented in Figure 2-35 to Figure 2-37. The model shows a good replication of the recorded water levels.

2.6.5.3 Total Flow Comparisons

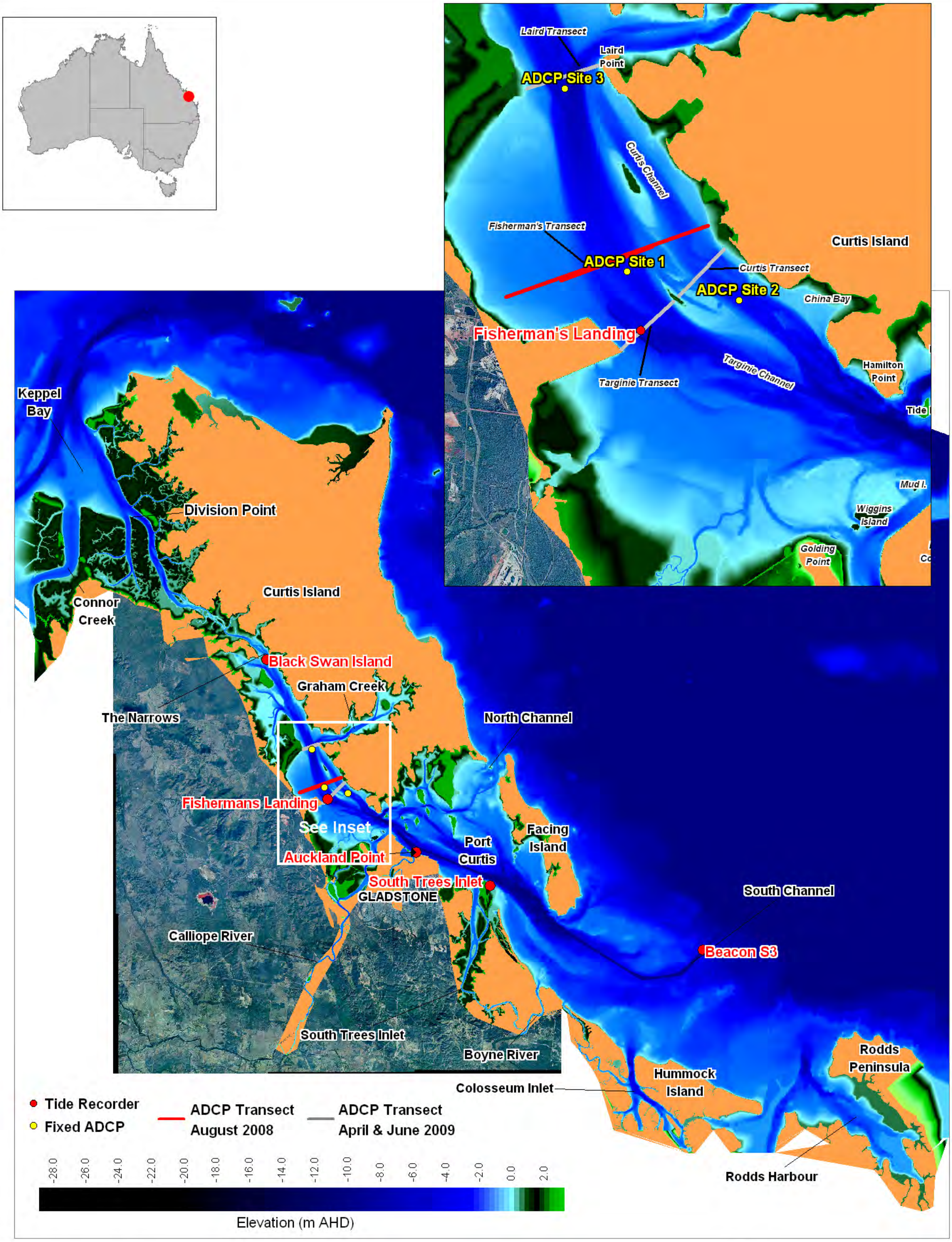
Simulated flows for the ADCP transects shown in Figure 2-34 have been extracted from the model results and compared with observed flows as determined from the ADCP transect measurements.

The August 2008 ADCP transects were taken at Fisherman's Landing (see Figure 2-34). As discussed in Section 2.6.3.4 the length of the observed transects depends on the water level, as shallow areas can prevent access by the boat. For the purposes of flow validation the Fisherman's

Landing, transects have been split into 2 transects: those that include the main channel only (Targinie Channel) and those that also include “Curtis” Channel (“Main and side channel”). The flow validation for these transects is presented in Figure 2-38. This figure shows the model is good at replicating the observed flows.

2.6.5.4 Velocity Magnitude and Direction Comparisons

Plan figures of velocity magnitude and direction (modelled and observed) for individual transects are shown in Appendix E. These illustrate the depth averaged ADCP velocity and direction across each transect (represented as white stick plots) and interpolated modelled velocity (represented as red velocity vectors) at about the mid-point time of the measured transect. These figures show that the model replicates the velocity distribution well across this transect.



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Validation Data - 2008/2009

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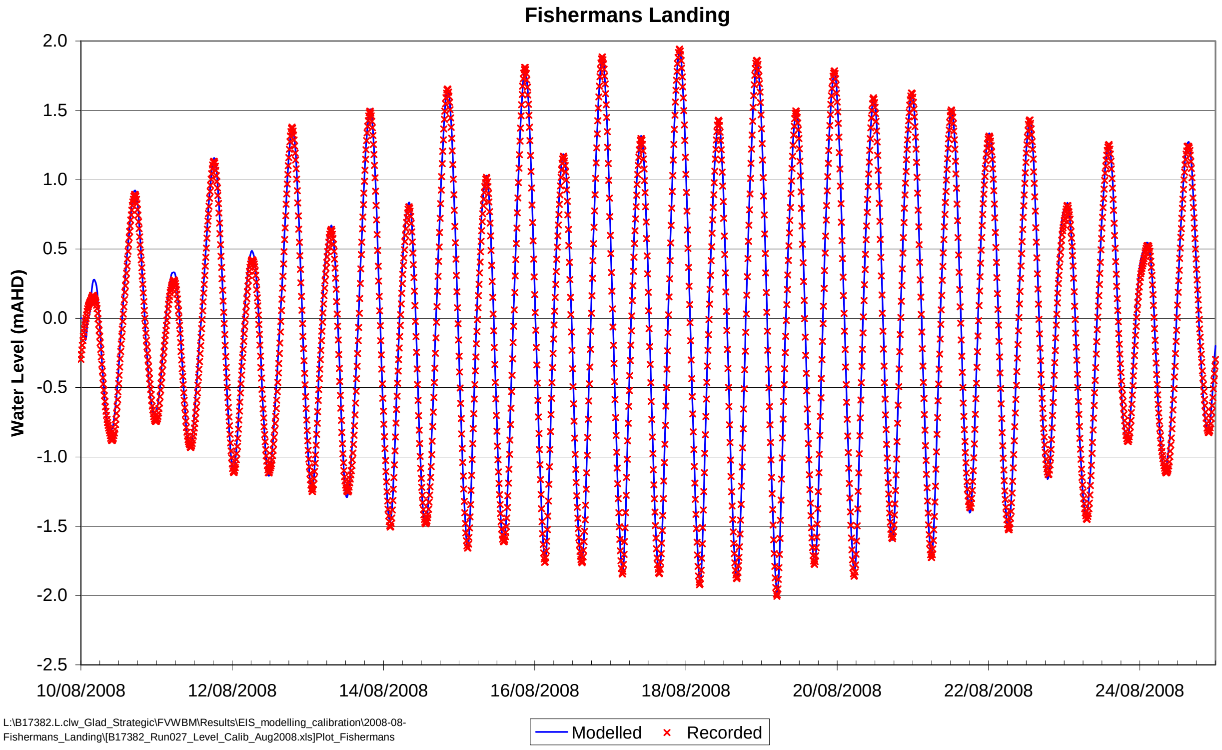

Figure 2-35 Water Level Validation – Fisherman's Landing, August 2008

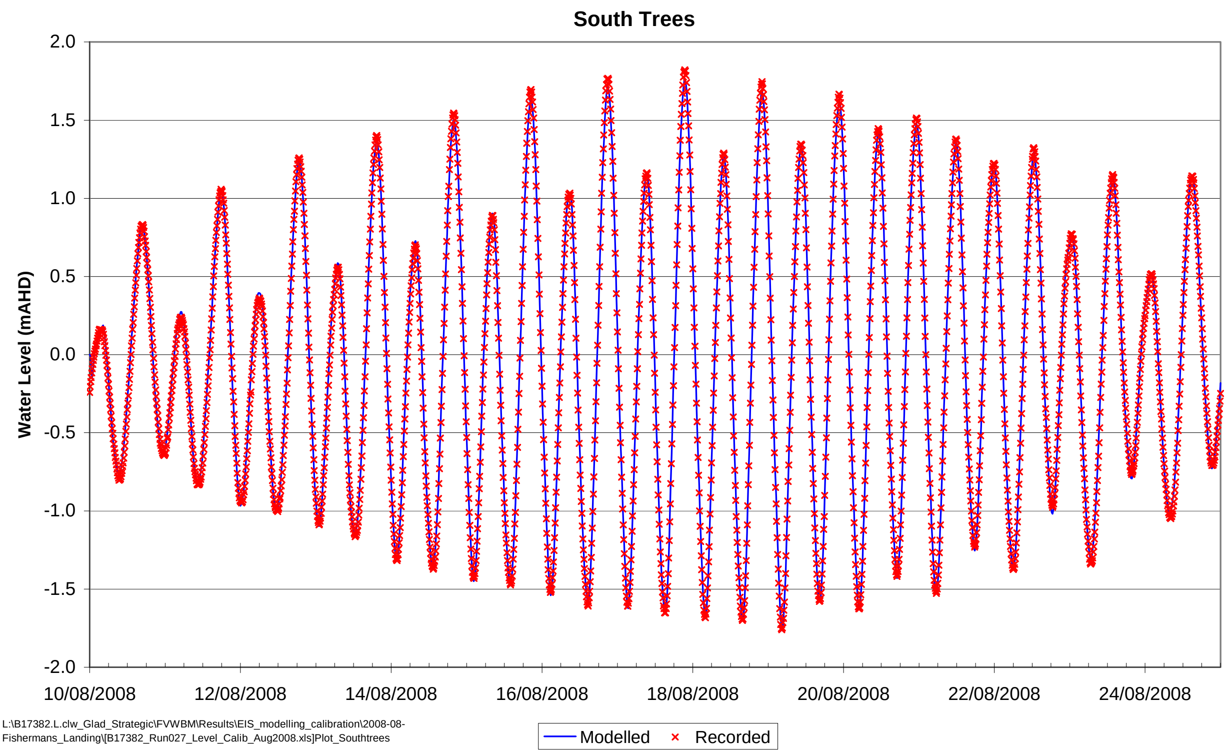

Figure 2-36 Water Level Validation – South Trees, August 2008

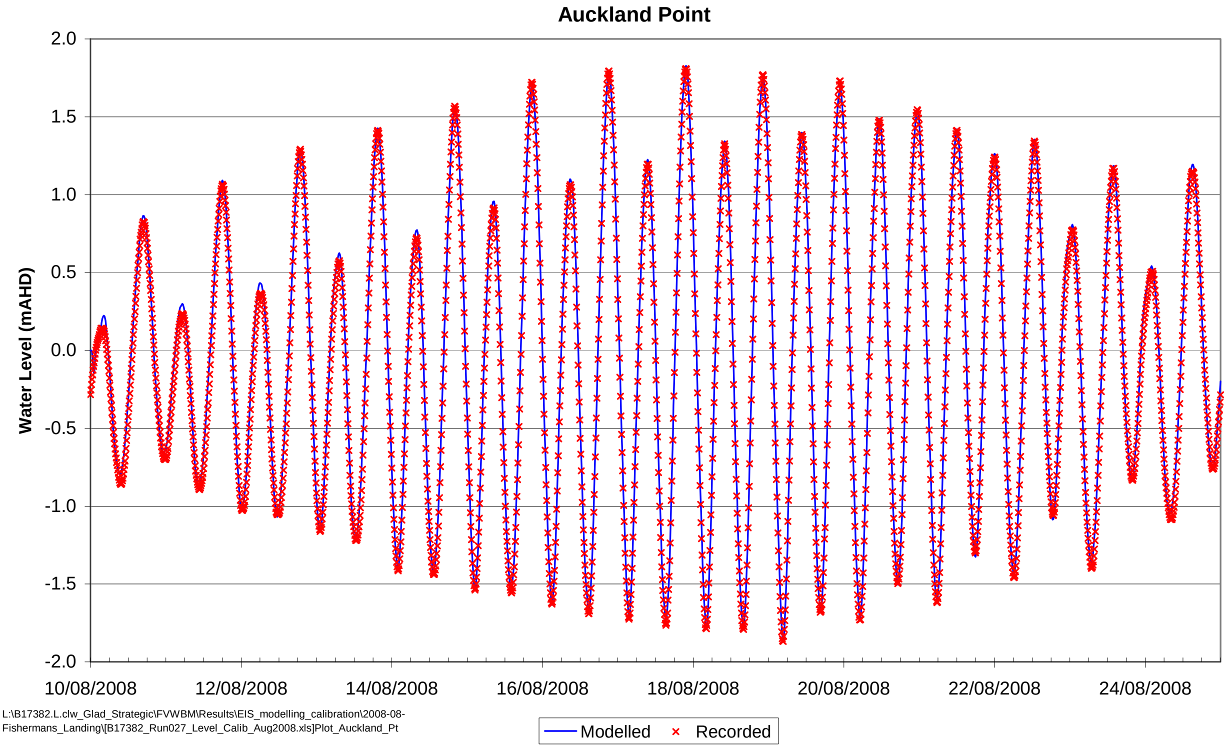

Figure 2-37 Water Level Validation – Auckland Point, August 2008

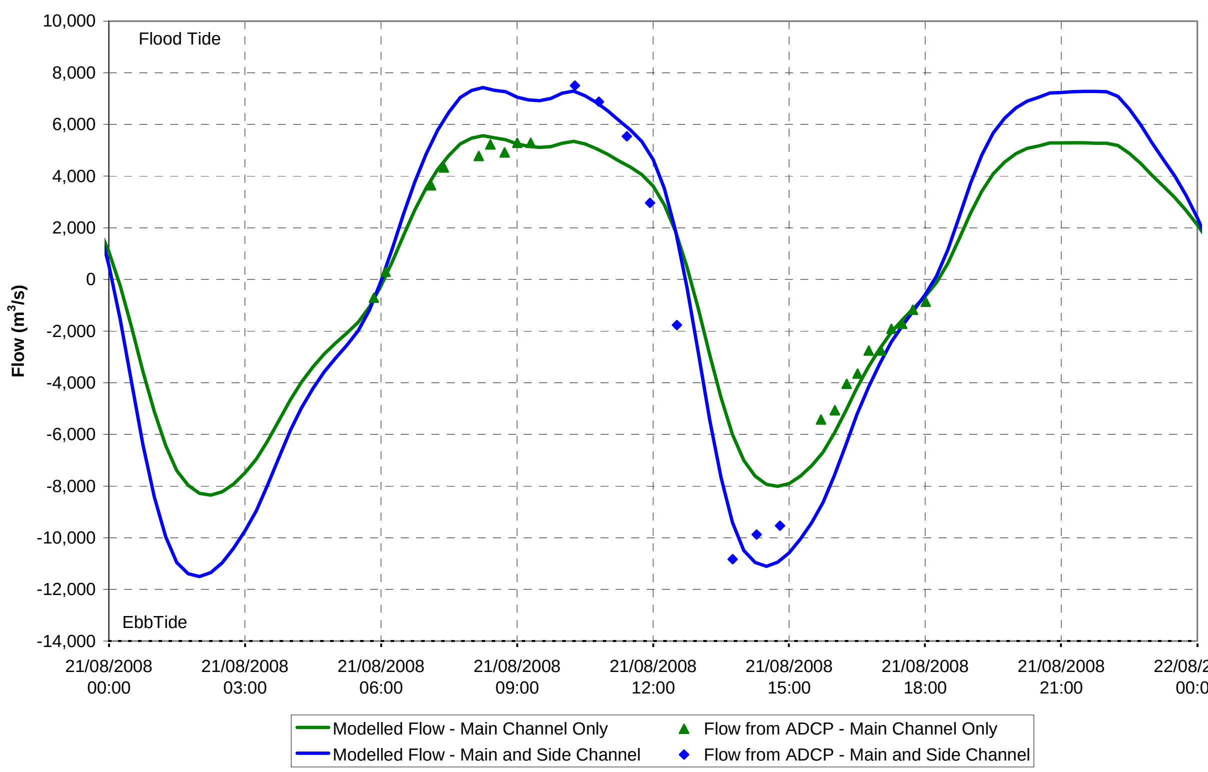

Figure 2-38 Flow Validation – Fisherman's Landing, August 2008

2.6.6 Gladstone Western Basin EIS Data

2.6.6.1 Data Set and Simulation Summary

This data set was collected as part of the Gladstone Western Basin Strategic Dredging and Reclamation EIS with the focus on the area of Port Curtis from the Calliope River mouth to the entrance of The Narrows at Laird Point.

The data collected included continuous time series data of water elevations using fixed point tide gauges and flow / velocity distribution for defined transects using boat mounted Acoustic Doppler Current Profilers (ADCPs) under spring and neap tide conditions. Continuous time series of velocity magnitude and direction was also measured with fixed bottom mounted ADCP units. The locations of the tide gauges, fixed ADCP units and ADCP transects used for validation are presented in Figure 2-34 with a summary of the simulation and data sets as per Table 2-5 below.

The simulation was undertaken without any further adjustment of model parameters and therefore represents validation of the model with an independent data set. The main model boundaries also utilised measured water levels for the period.

Table 2-5 Western Basin EIS Simulation

Project	Gladstone Western Basin EIS
Periods	15th April – 23rd April 2009 (Neap) 17th May – 30th June 2009 (continuous ADCP measurements) 24th June – 28th June 2009 (Spring)
Focus Area	Western Basin area of Port Curtis (The Narrows to the Calliope River)
Boundary Data	Main Ocean Sth of Facing Island – Recorded data at Richards Point, Seal Rocks and Gatcombe Head North Entrance between Curtis & Facing Islands – Recorded Data 16/04 to 30/04 and 23/06 to 30/06 remaining values synthesised from MSQ gauge data Division Point Nth end of The Narrows – Synthesised from MSQ gauge data Wind Forcing –Recorded wind data (BOM)
Validation Data	Continuous Water Levels - South Trees (MSQ) - Auckland Point (MSQ) - Fisherman’s Landing (MSQ) - Black Swan Island (WBM) Spring Tide ADCP Transects - Laird Point - Targinie Channel - “Curtis” Channel Neap Tide ADCP Transects - Laird Point - Targinie Channel - “Curtis” Channel

	Continuous Velocity, Bottom Mounted ADCP (GHD) - Main Channel near Laird Point - Main Channel in Western Basin - "Curtis" Channel

2.6.6.2 Water Level Comparisons

Modelled and recorded water levels are presented in Figure 2-35 to Figure 2-37. The model shows a good replication of the recorded water levels.

2.6.6.3 Total Flow Comparisons

Simulated flows for the ADCP transects shown in Figure 2-34 have been extracted from the model results and compared with the observed flows as determined from the ADCP measurements. As discussed in Section 2.6.3.3 it is important to recognise that the ADCP transects are indicated are representative locations and extents. In terms of field observations, the boat may not be able to access the full transect due to shallow areas. In these areas the total flow may be underestimated by field observations. This is particularly apparent in the "Curtis" Channel transects, with the longer sections including the flowpath between "Curtis" Channel and the Main Channel. Shorter transects were restricted to the "Curtis" Channel flowpath only.

The April and June 2009 transects are taken at the same three locations; Laird Point, Targinie Channel and "Curtis" Channel (see Figure 2-34). The April 2009 transects are taken throughout a neap tide and the June 2009 transects a spring tide.

The model flow validation for the neap tide transects is presented in Figure 2-50 to Figure 2-52. The spring tide flow validation is presented in Figure 2-53 to Figure 2-55. The model shows a good validation against the neap (April 2009) transects. Due to the changes in the length of the "Curtis" channel transects, two modelled flows are presented, the longer of these includes the flowpath immediately north of South Passage Island.

For the spring (June 2009) transects the model is replicating the "Curtis" Channel flows well. The model has a tendency to slightly over predict flood-tide and more strongly ebb-tide flow magnitudes for the Laird Point and Targinie Channel transects. As discussed below, the spring tide Targinie Channel transect data was influenced by moored ships at Fisherman's Landing casting a shadow effect on the observed velocities.

2.6.6.4 Velocity Magnitude and Direction Comparisons

Fixed bottom mounted ADCP units were operating for the period 25/05/2009 to 19/06/2009 (see Figure 2-34). Comparison of the modelled and observed velocity magnitudes is presented in Figure 2-56 to Figure 2-61. Comparison of the modelled and observed velocity directions is presented in Figure 2-62 to Figure 2-67.

The model is generally replicating the velocity magnitude and direction well for the entire period. Peak ebb velocities are slightly over-estimated at all three sites but most strongly at Laird Point (Site 3).

Plan figures of velocity magnitude and direction (modelled and observed) for individual transects are shown in Appendix F. These illustrate the depth averaged ADCP velocity and direction across each transect (represented as white stick plots) and interpolated modelled velocity (represented as red velocity vectors) at about the mid-point time of the transect. These figures show that the model replicates the velocity distribution well. It is worth noting that the measured transects in the Targinie channel show a shadowing effect of a berthed ship. This can be seen as an area of lower velocity magnitudes on the south western end of the transects. The shadowing effect is more apparent on ebb tides. Berthed ships were not modelled in the simulation.

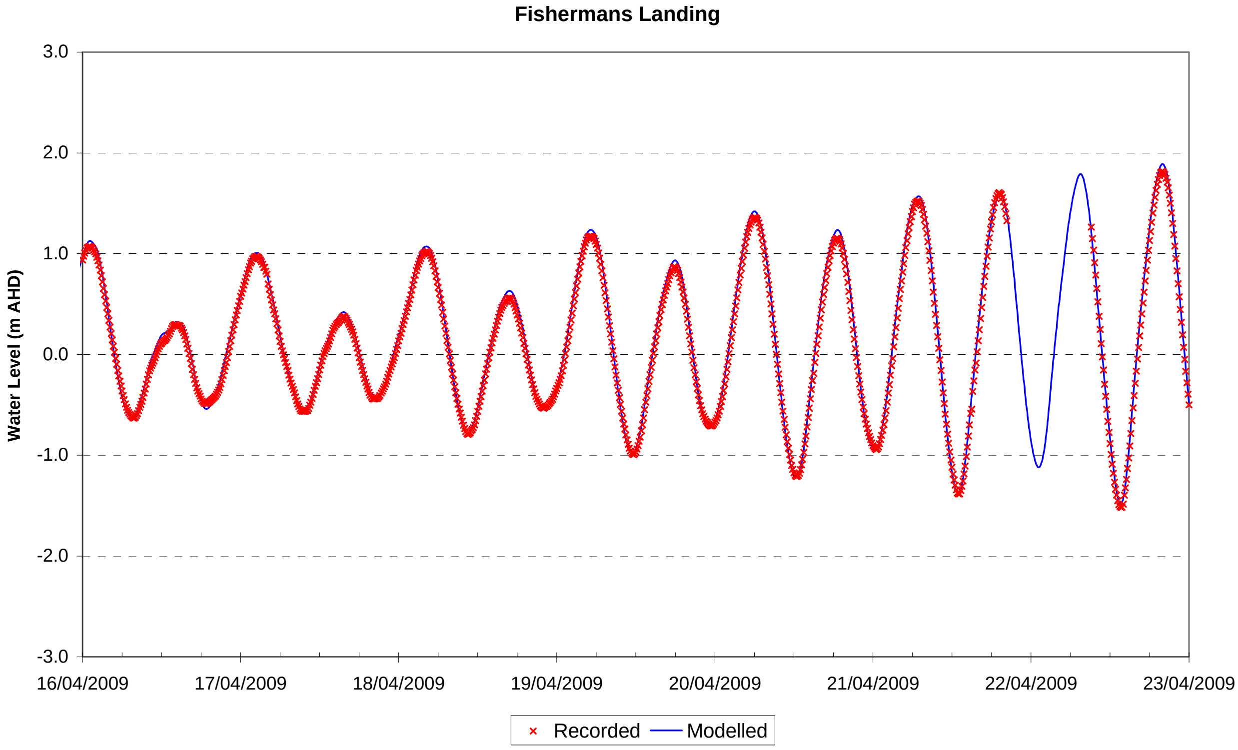

Figure 2-39 Water Level Validation – Fisherman's Landing, April 2009 (Neap Tide)

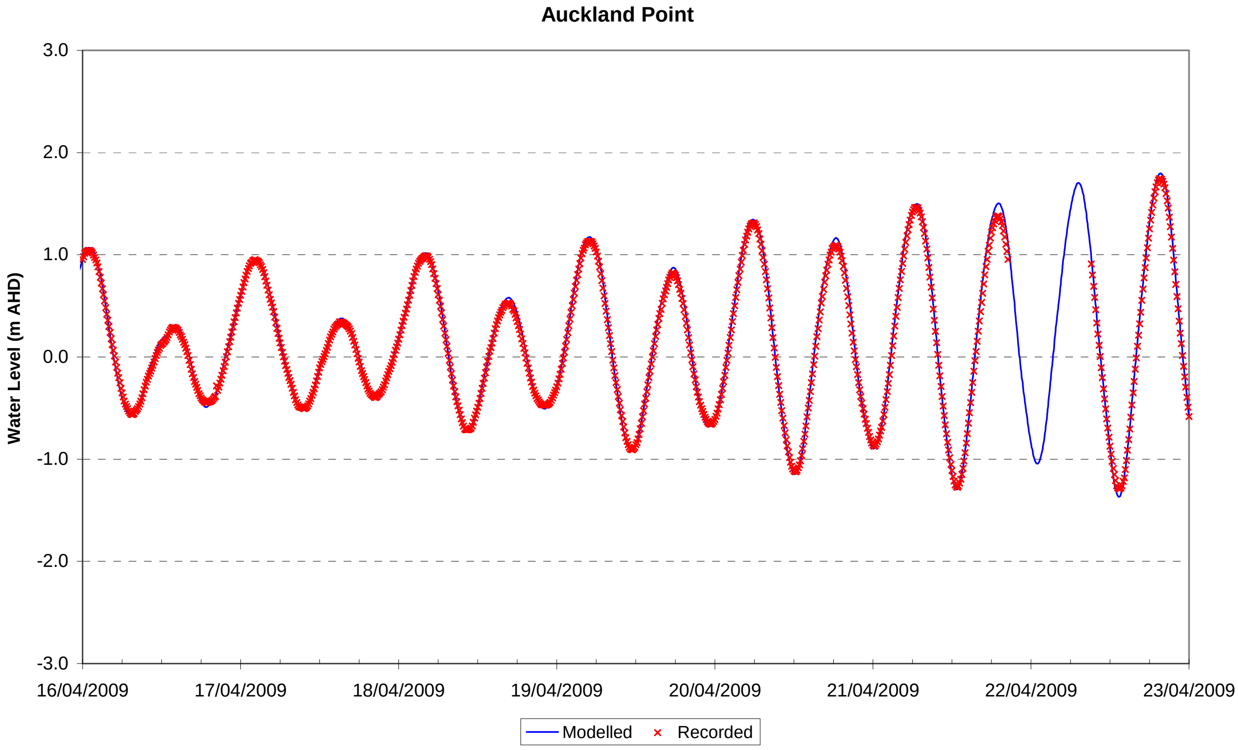

Figure 2-40 Water Level Validation – Auckland Point, April 2009 (Neap Tide)

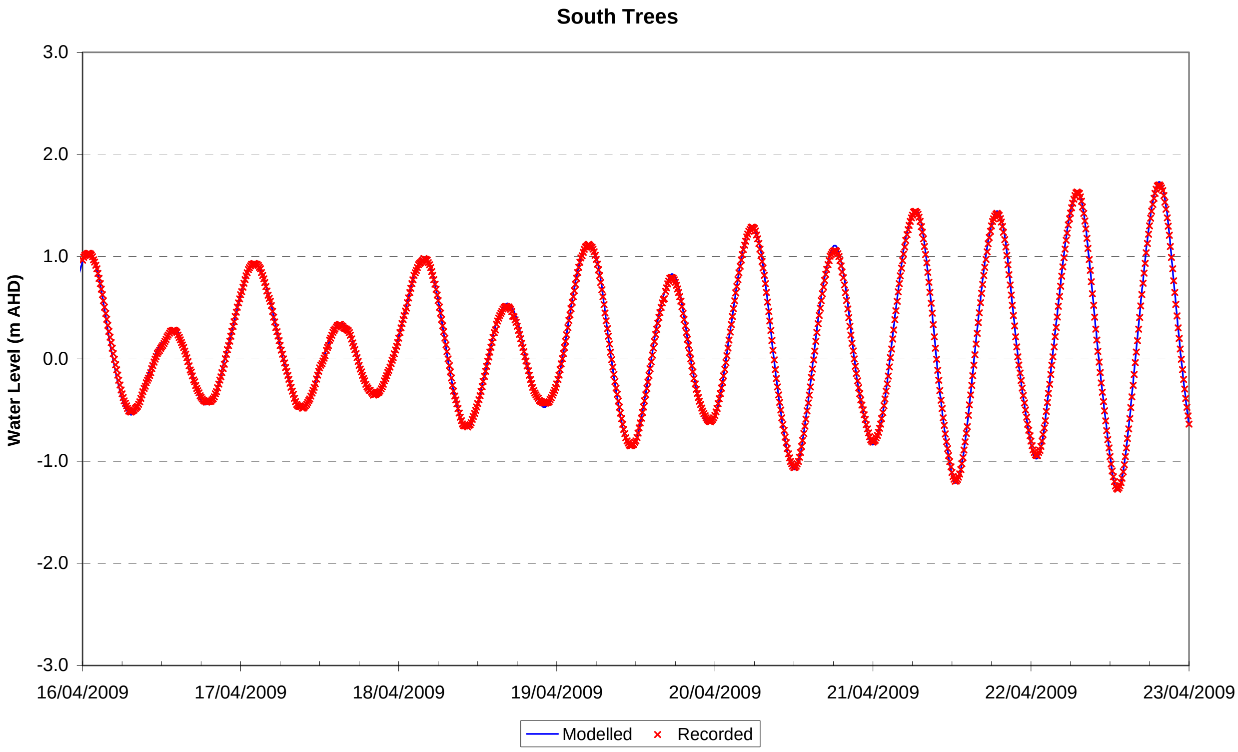

Figure 2-41 Water Level Validation – South Trees, April 2009 (Neap Tide)

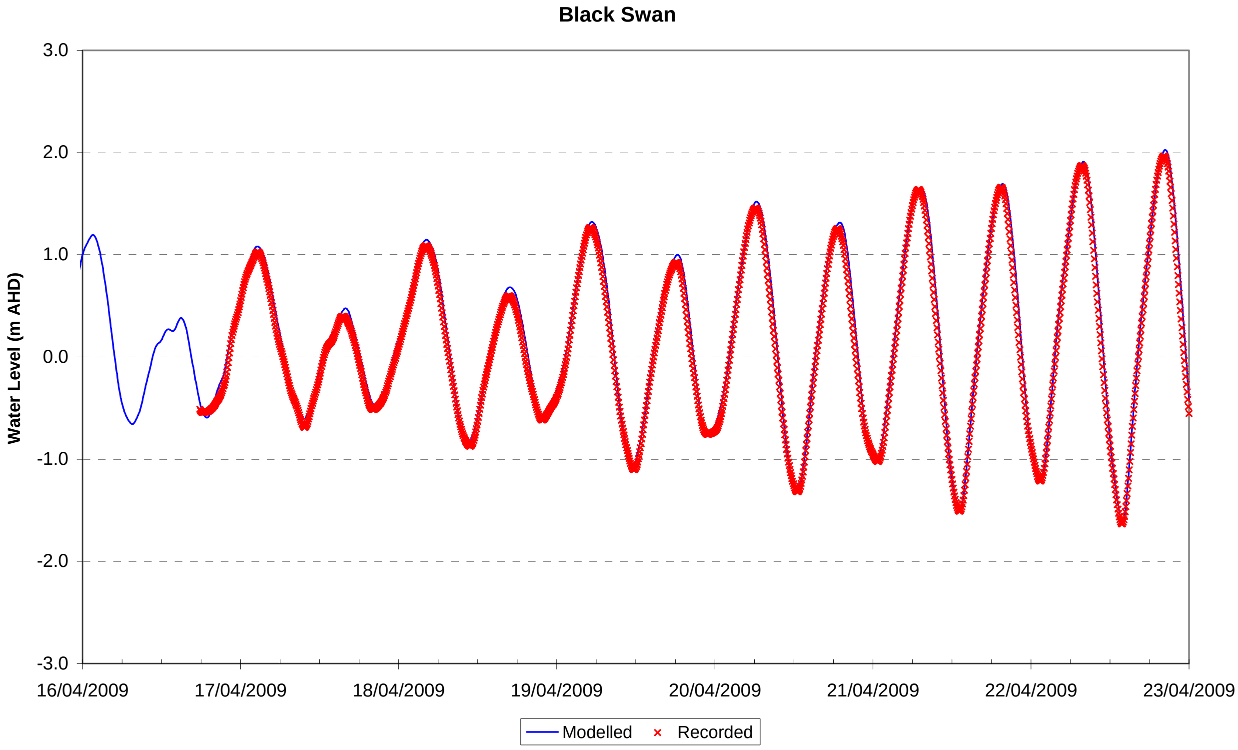

Figure 2-42 Water Level Validation – Black Swan Inlet, April 2009 (Neap Tide)

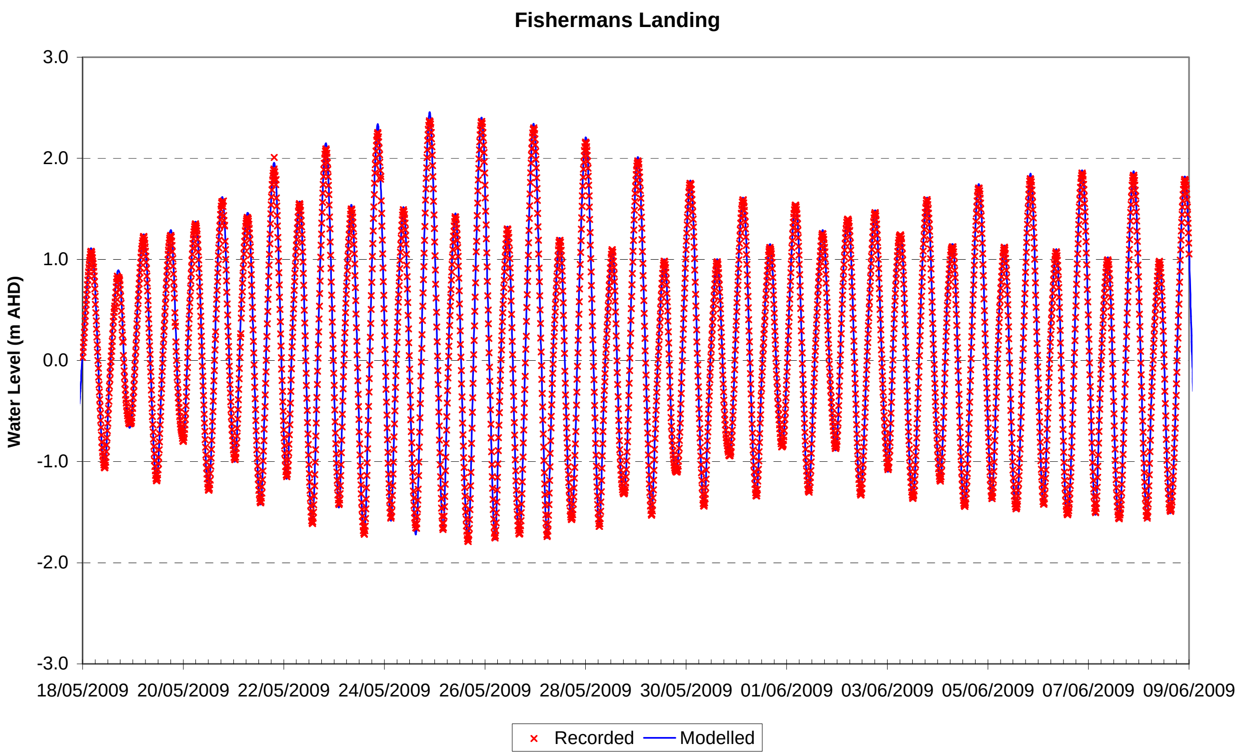

Figure 2-43 Water Level Validation – Fisherman's Landing, May 2009

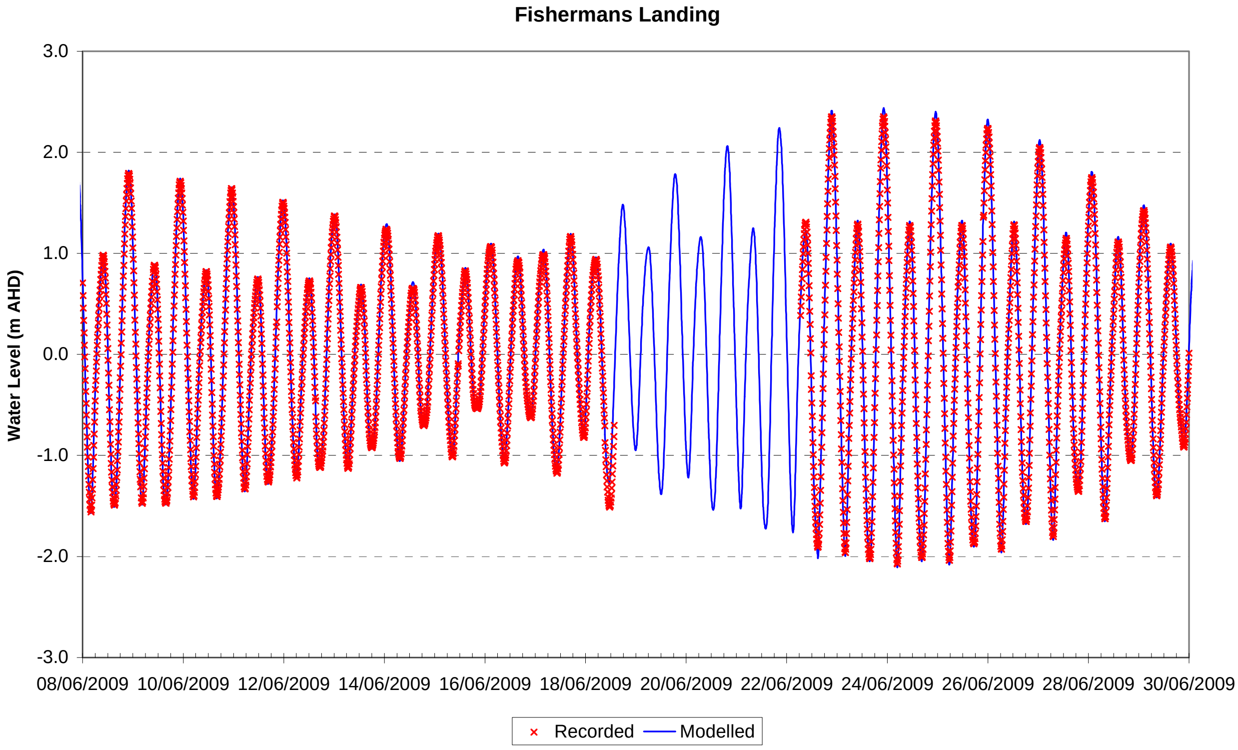

Figure 2-44 Water Level Validation – Fisherman's Landing, June 2009

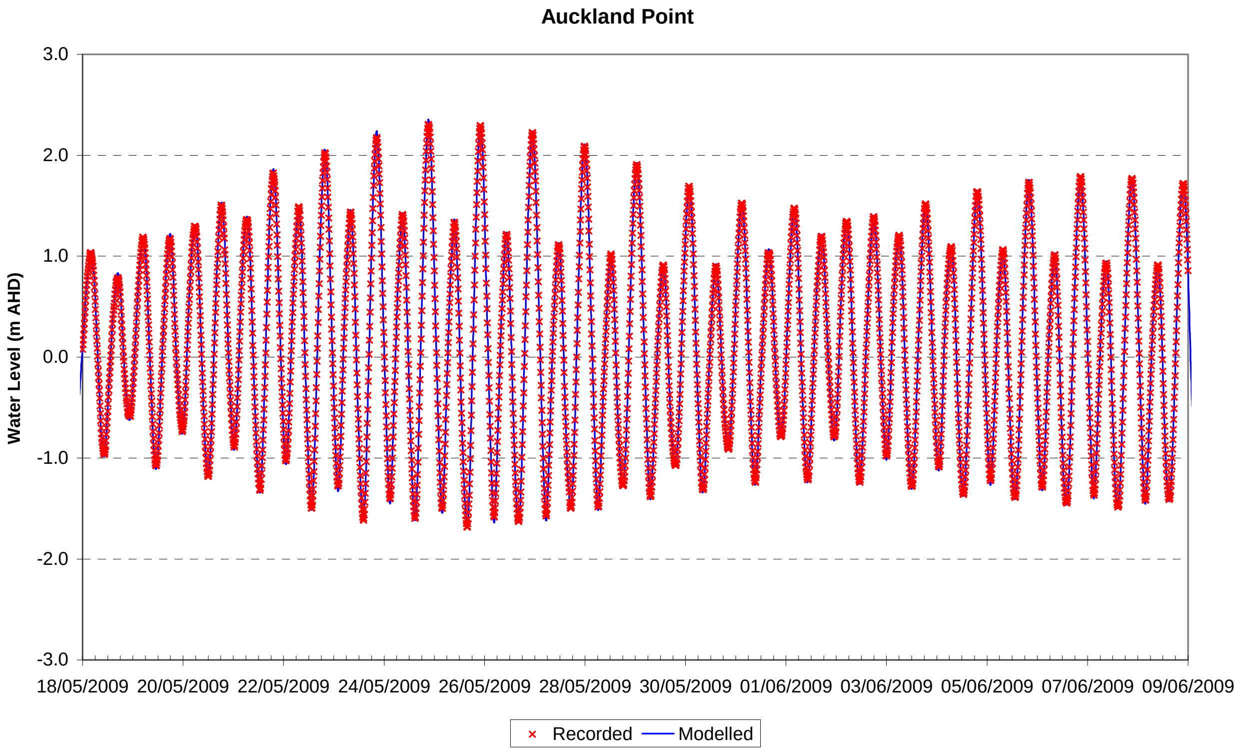

Figure 2-45 Water Level Validation – Auckland Point, May 2009

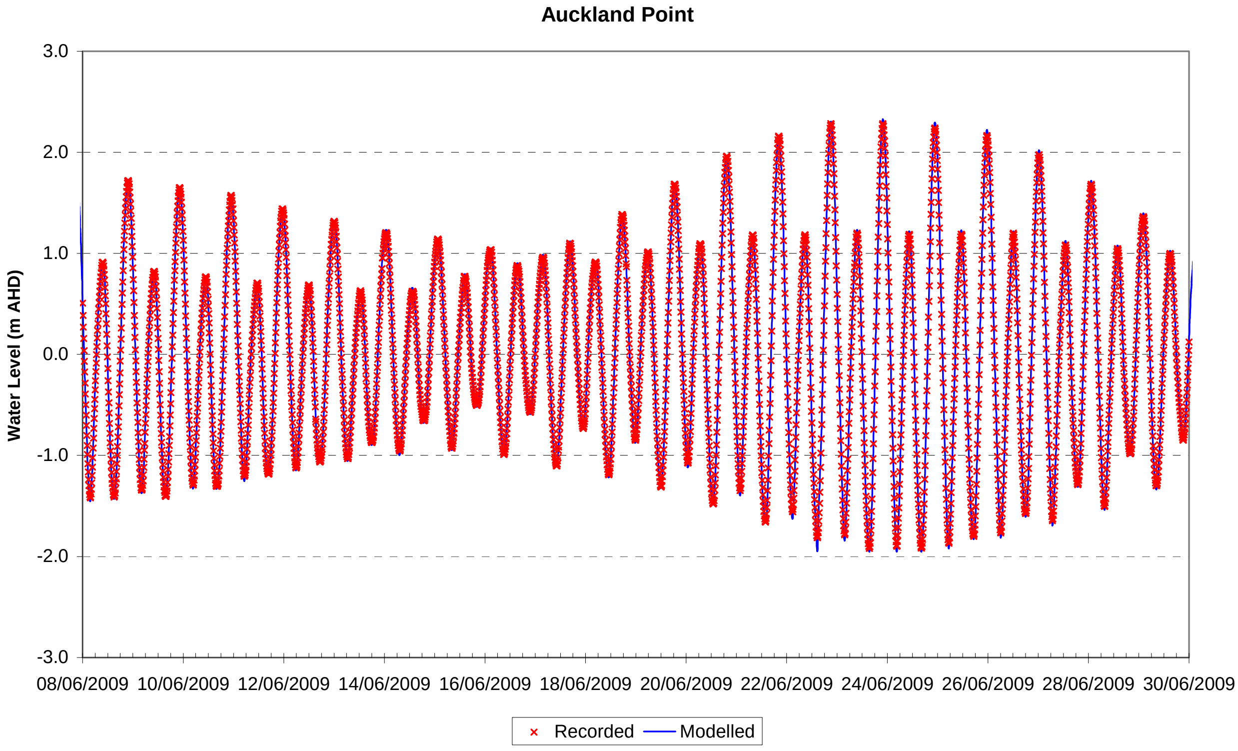

Figure 2-46 Water Level Validation – Auckland Point, June 2009

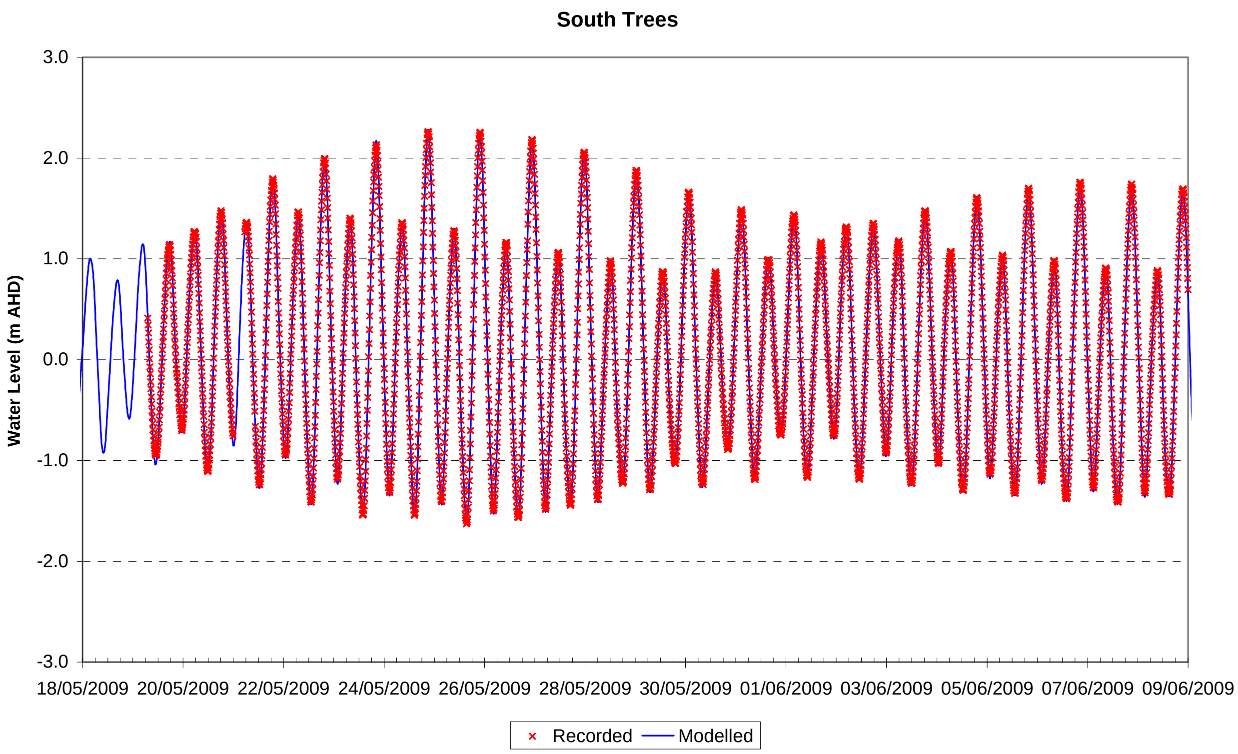

Figure 2-47 Water Level Validation – South Trees, May 2009

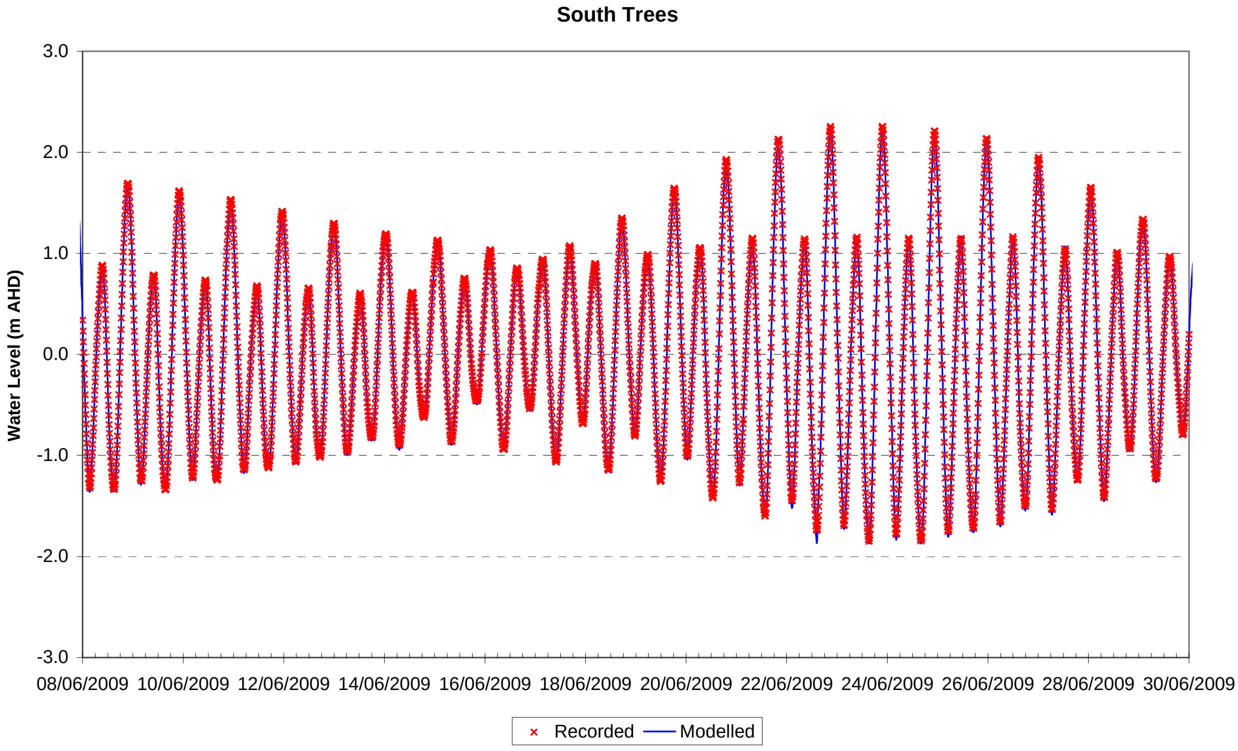

Figure 2-48 Water Level Validation – South Trees, June 2009

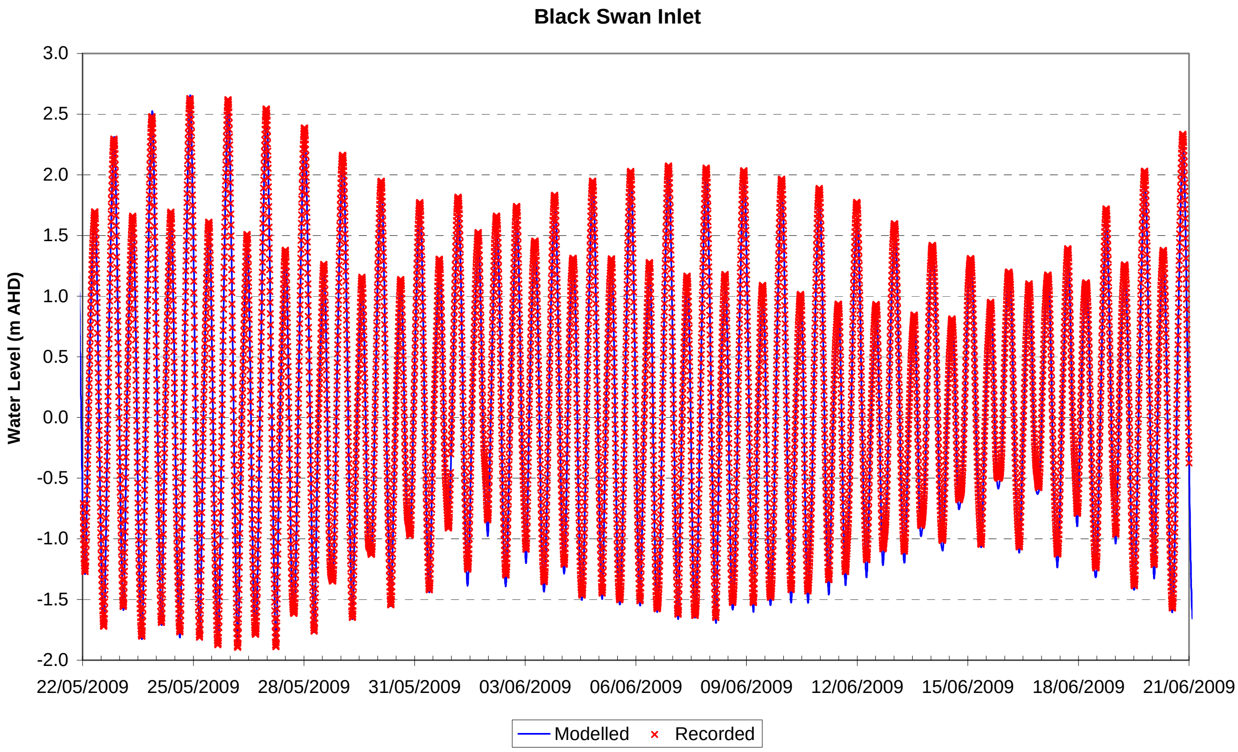

Figure 2-49 Water Level Validation – Black Swan Inlet May/June 2009

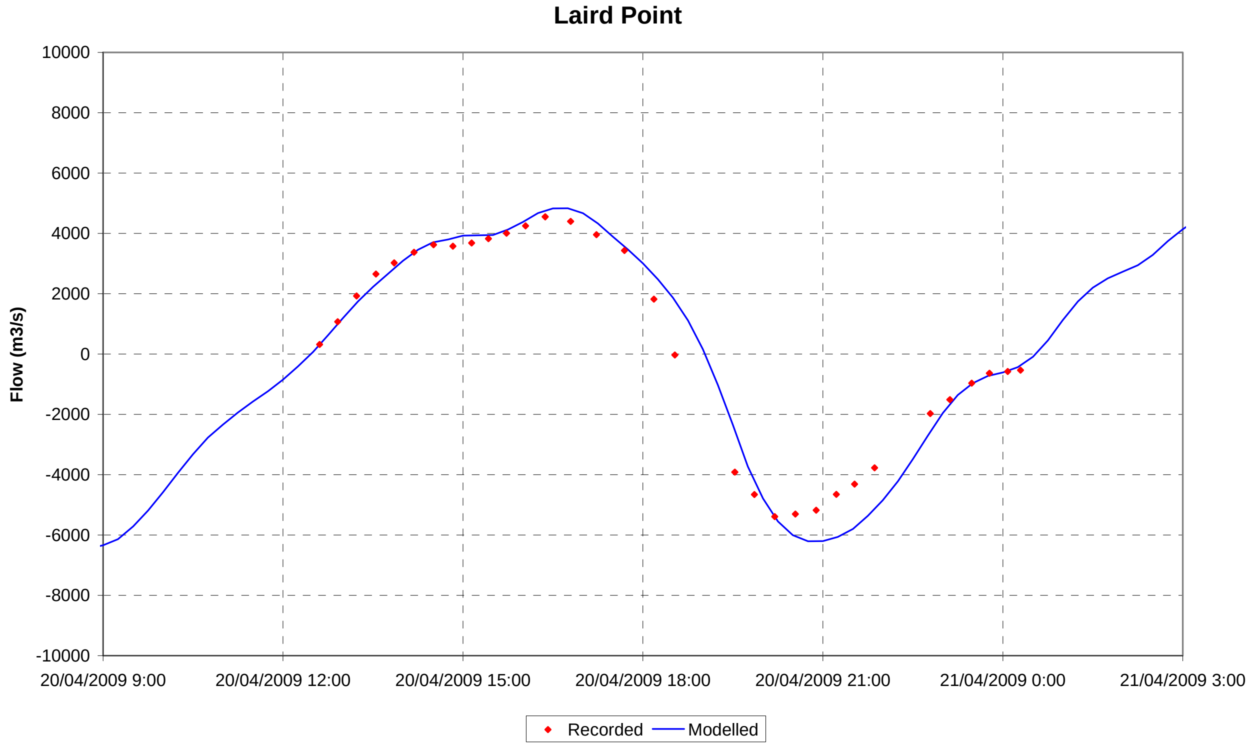

Figure 2-50 Flow Validation – Laird Point, April 2009 (Neap Tide)

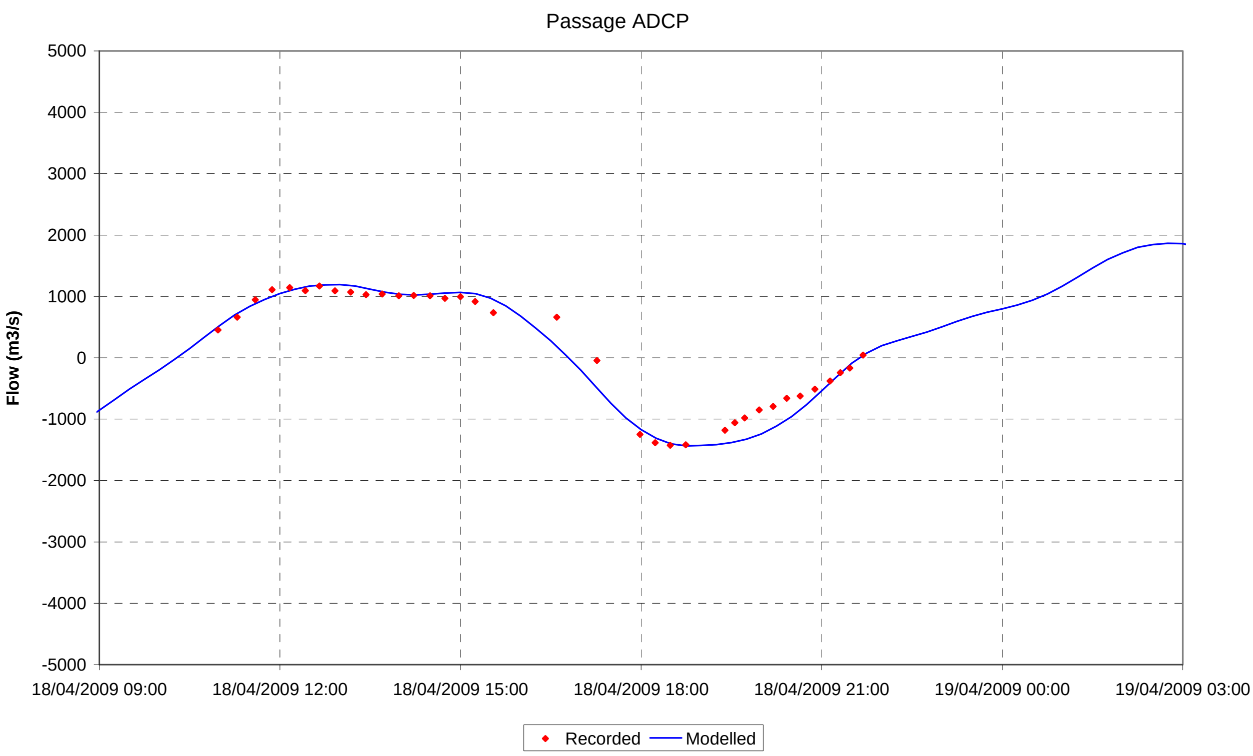

Figure 2-51 Flow Validation – “Curtis” Channel, April 2009 (Neap Tide)

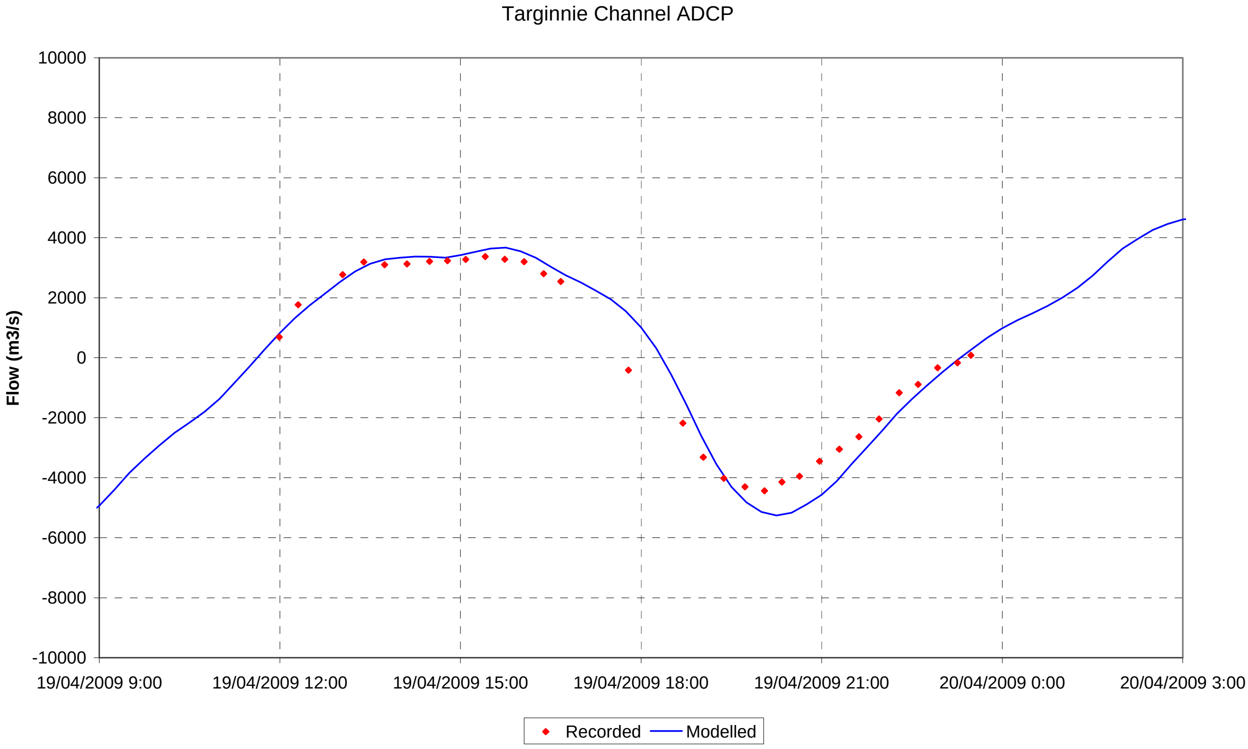

Figure 2-52 Flow Validation – Targinie Channel, April 2009 (Neap Tide)

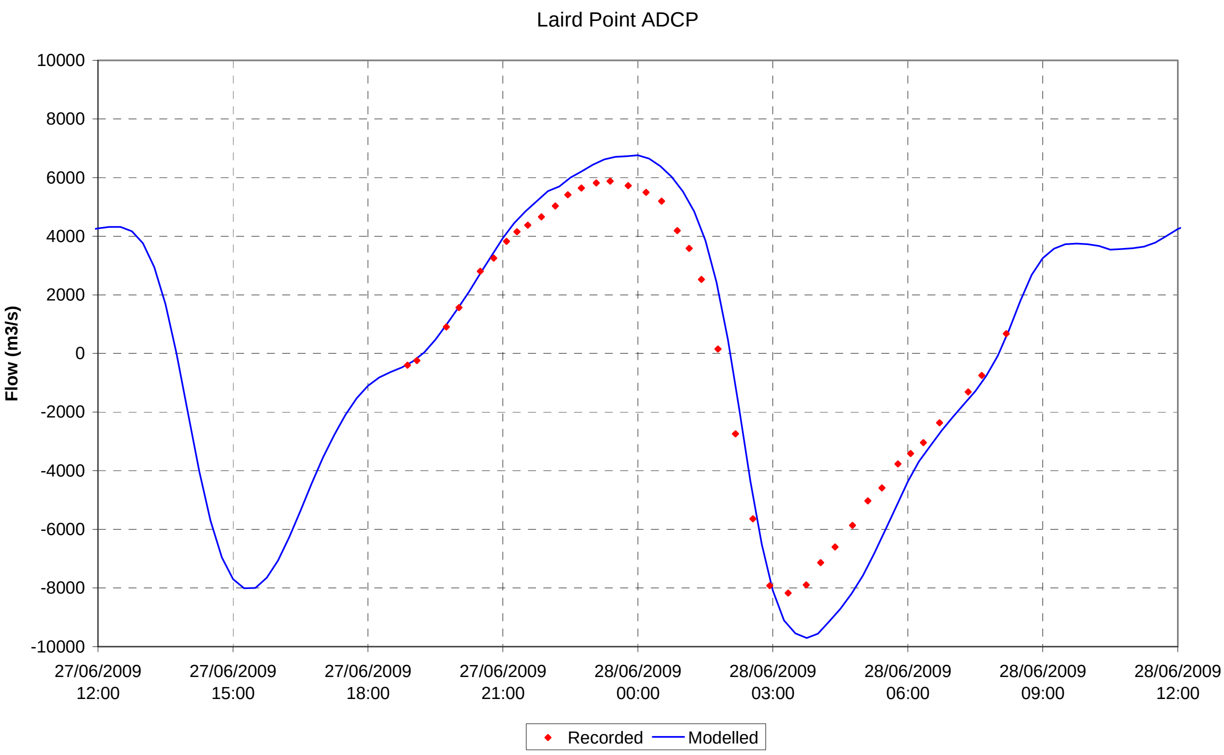

Figure 2-53 Flow Validation – Laird Point, June 2009

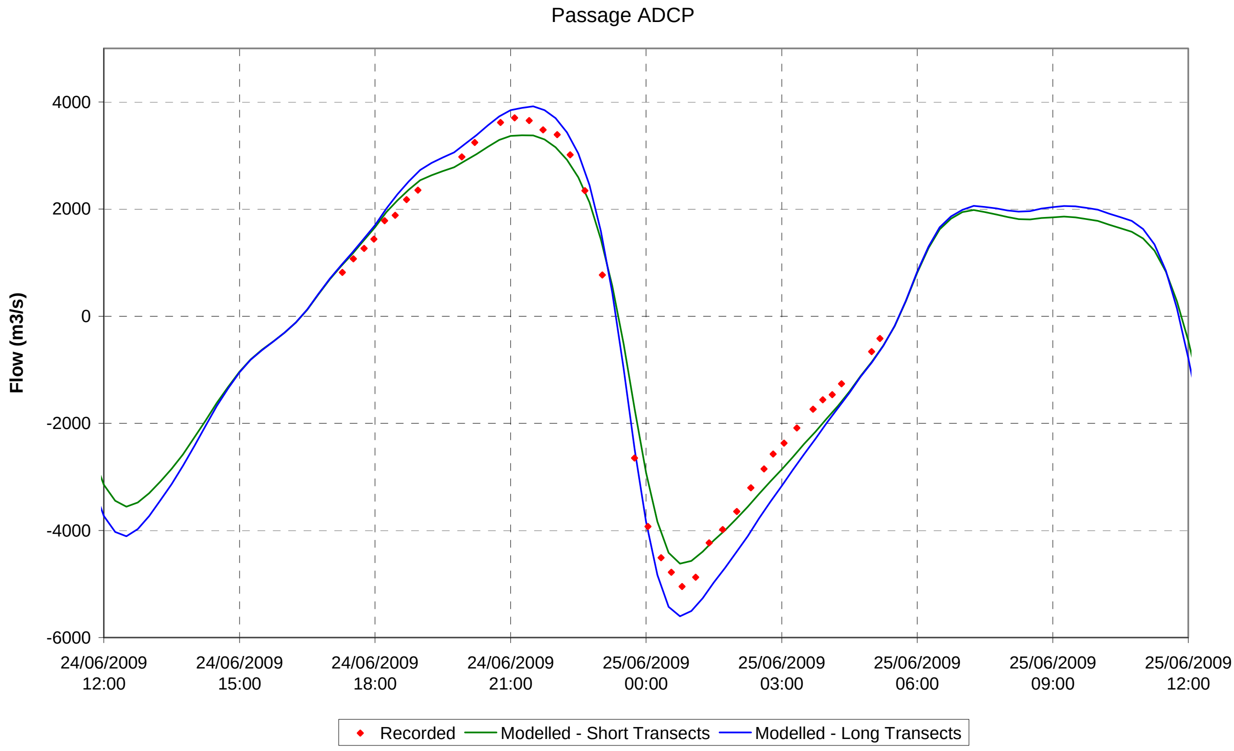

Figure 2-54 Flow Validation – "Curtis" Channel, June 2009

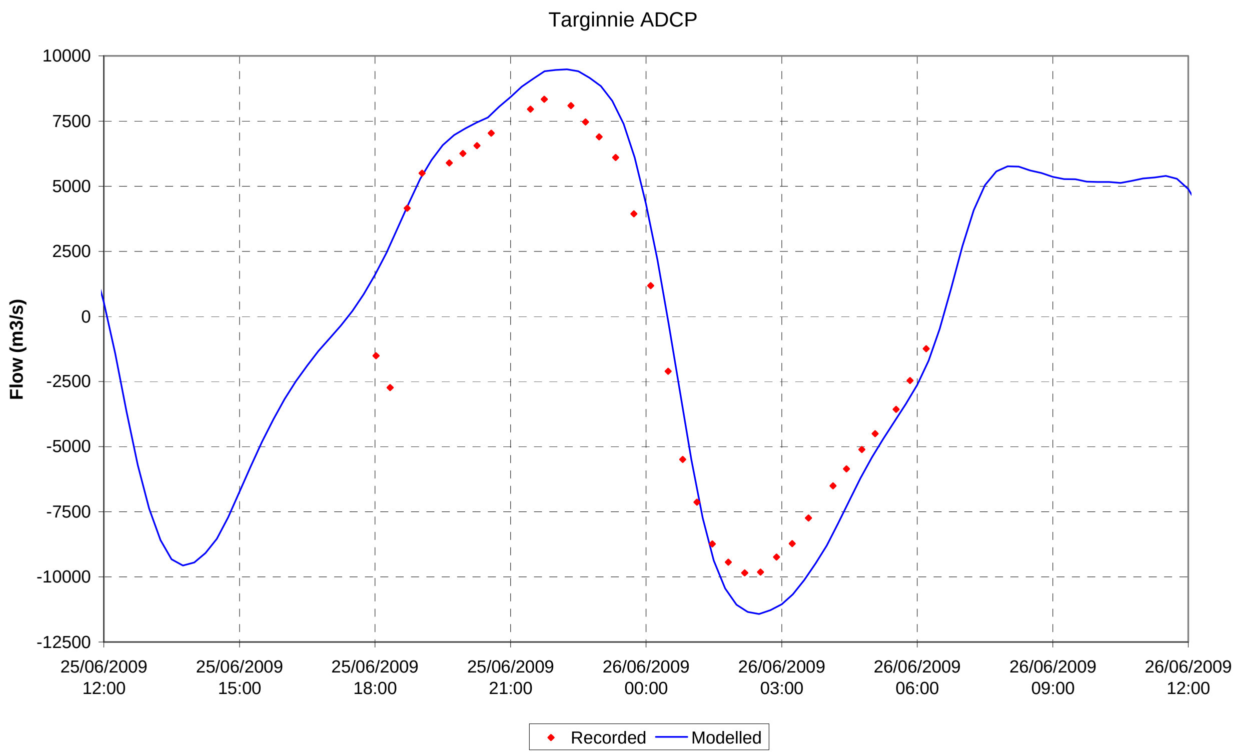

Figure 2-55 Flow Validation – Targinie Channel, June 2009

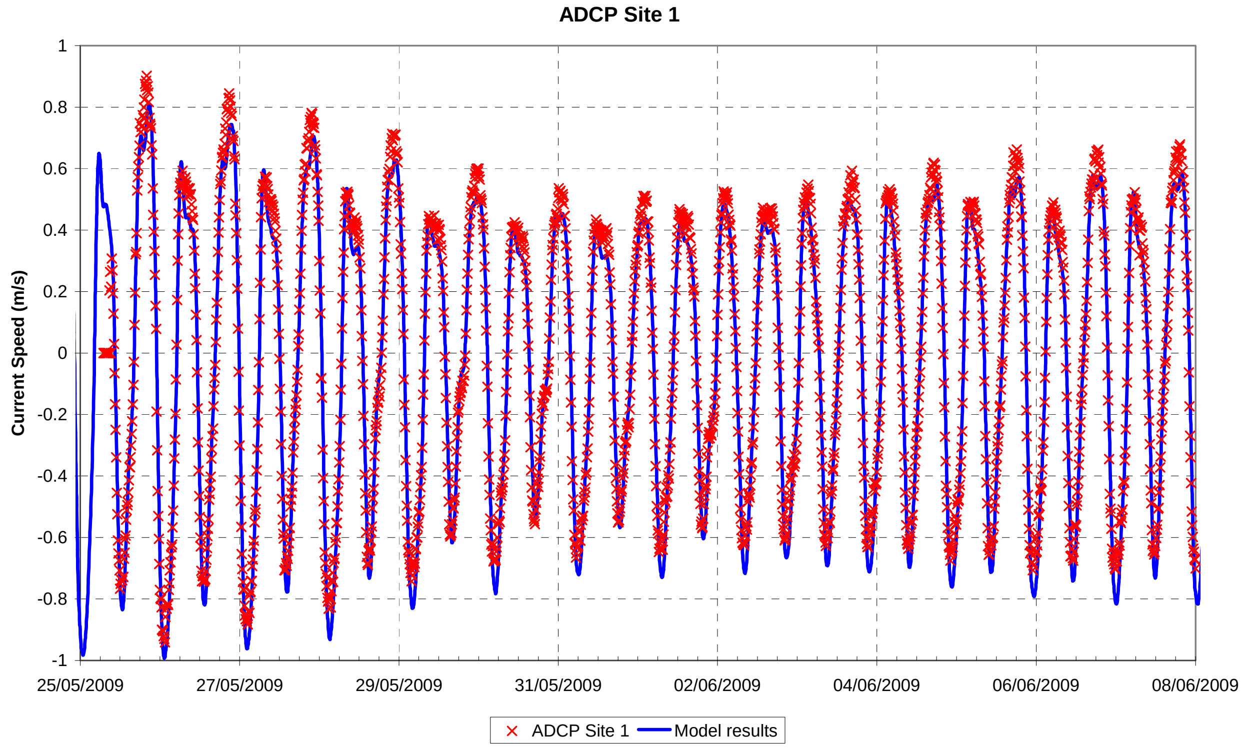

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Figure 2-56 Current Speed – GHD ADCP Site 1, May 2009

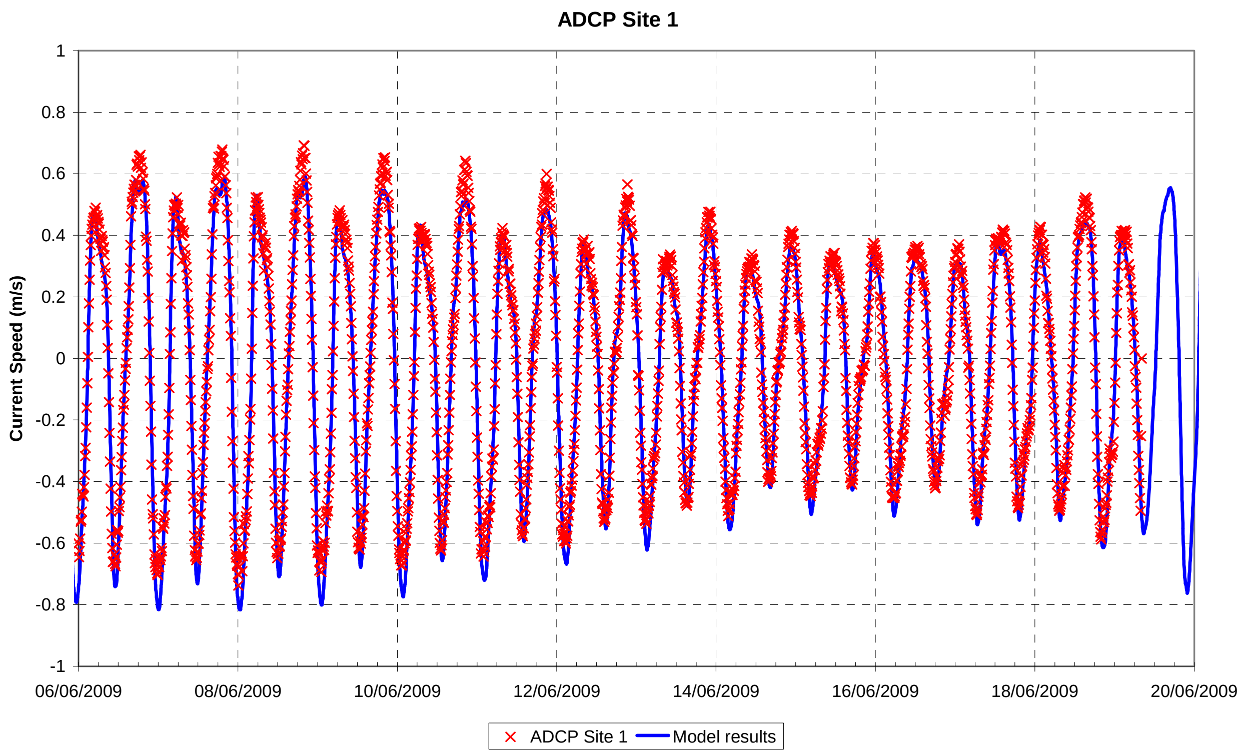


Figure 2-57 Current Speed – GHD ADCP Site 1, June 2009

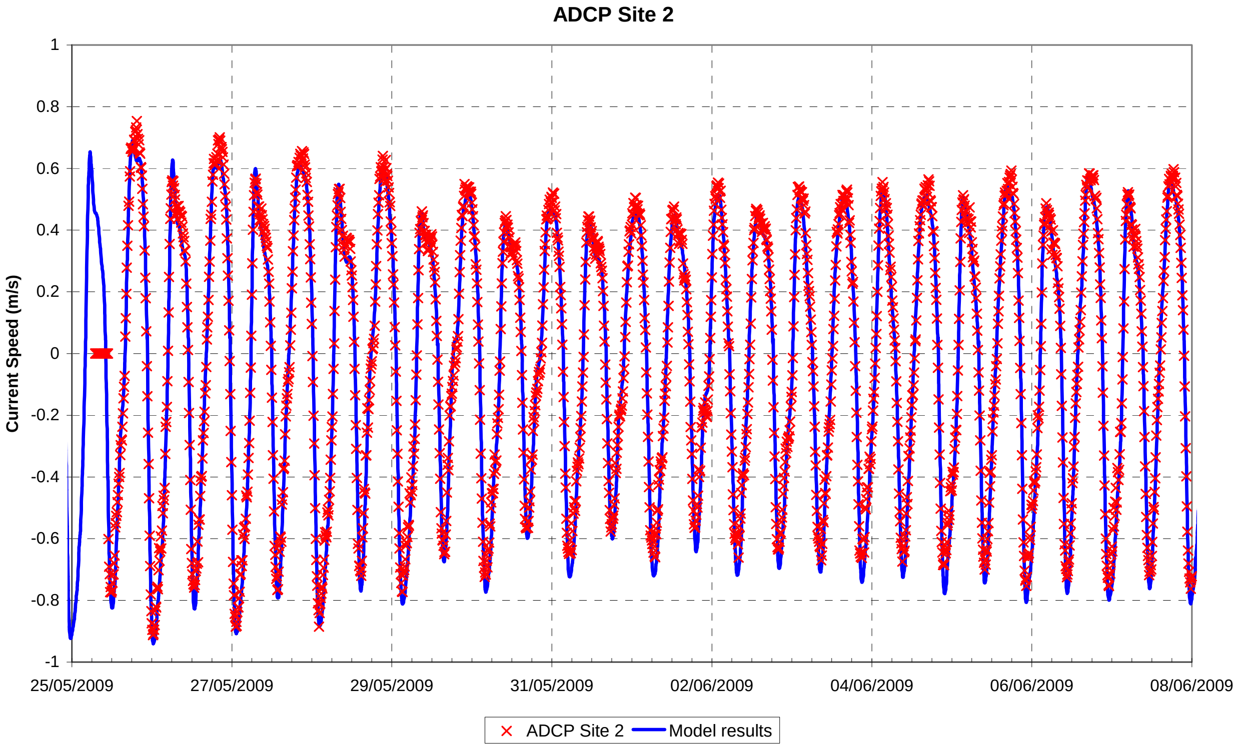


Figure 2-58 Current Speed – GHD ADCP Site 2, May 2009

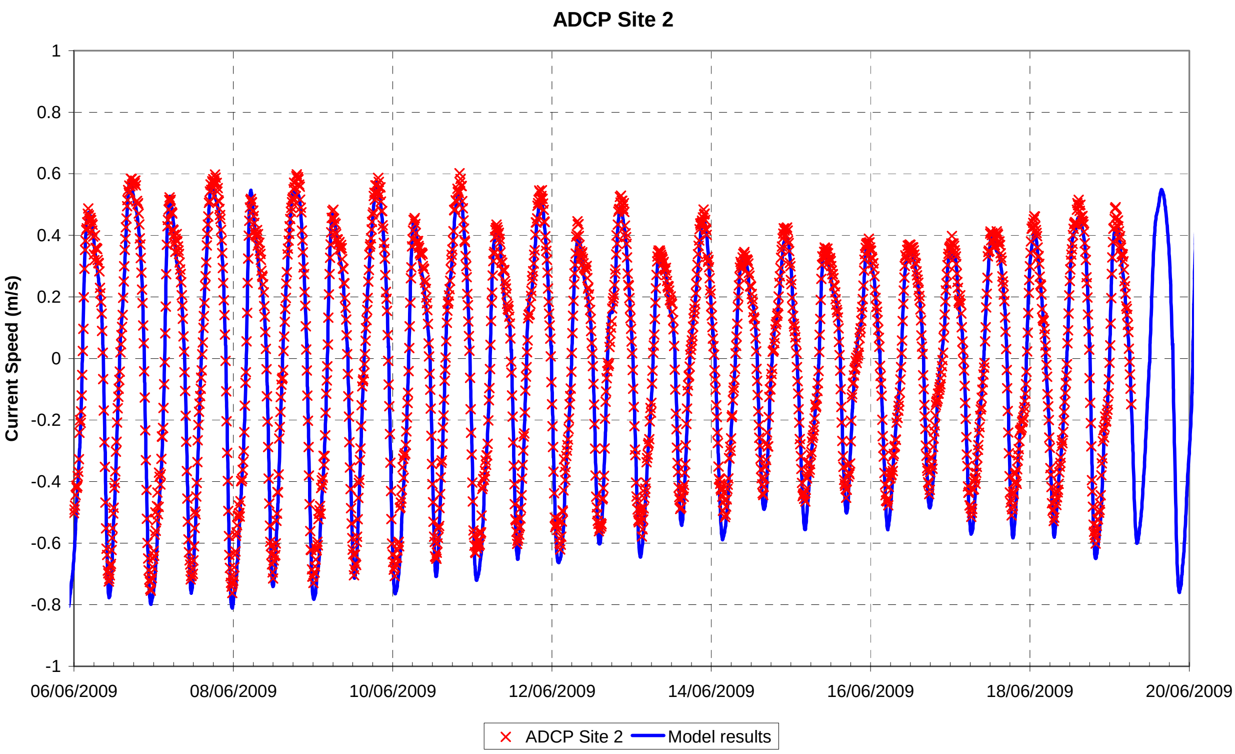


Figure 2-59 Current Speed – GHD ADCP Site 2, June 2009

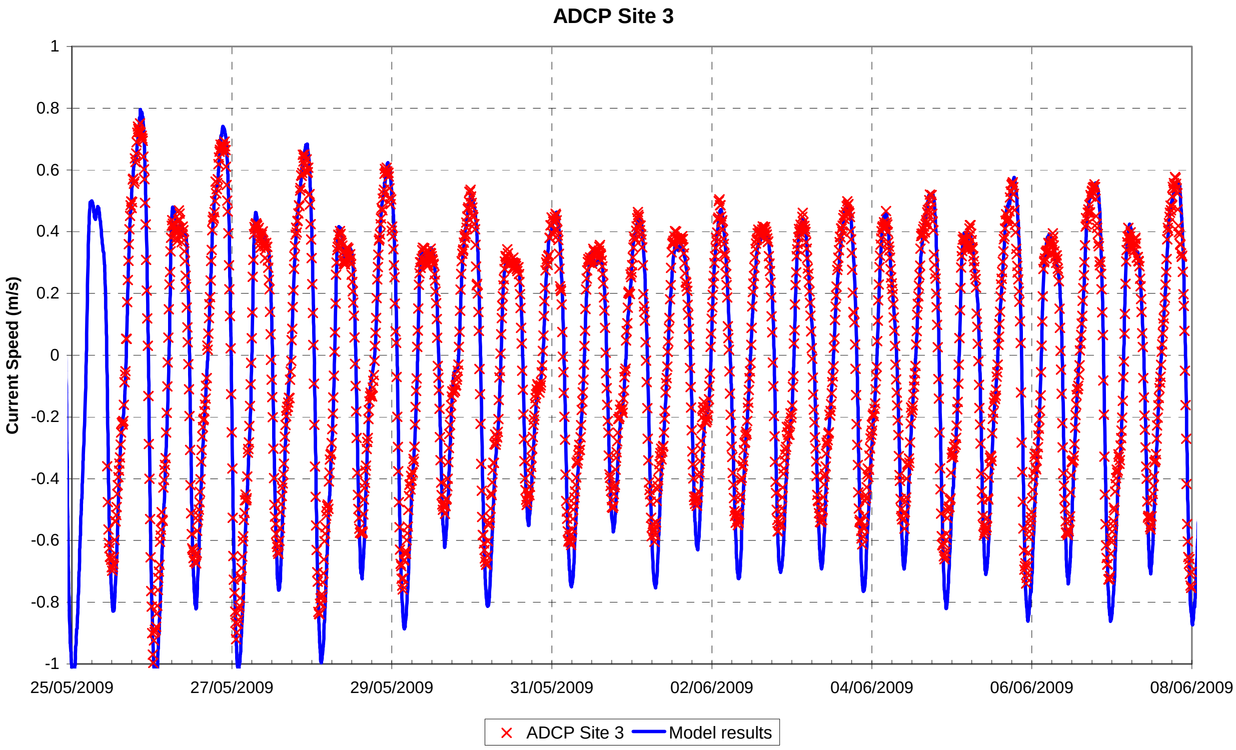


Figure 2-60 Current Speed – GHD ADCP Site 3, May 2009

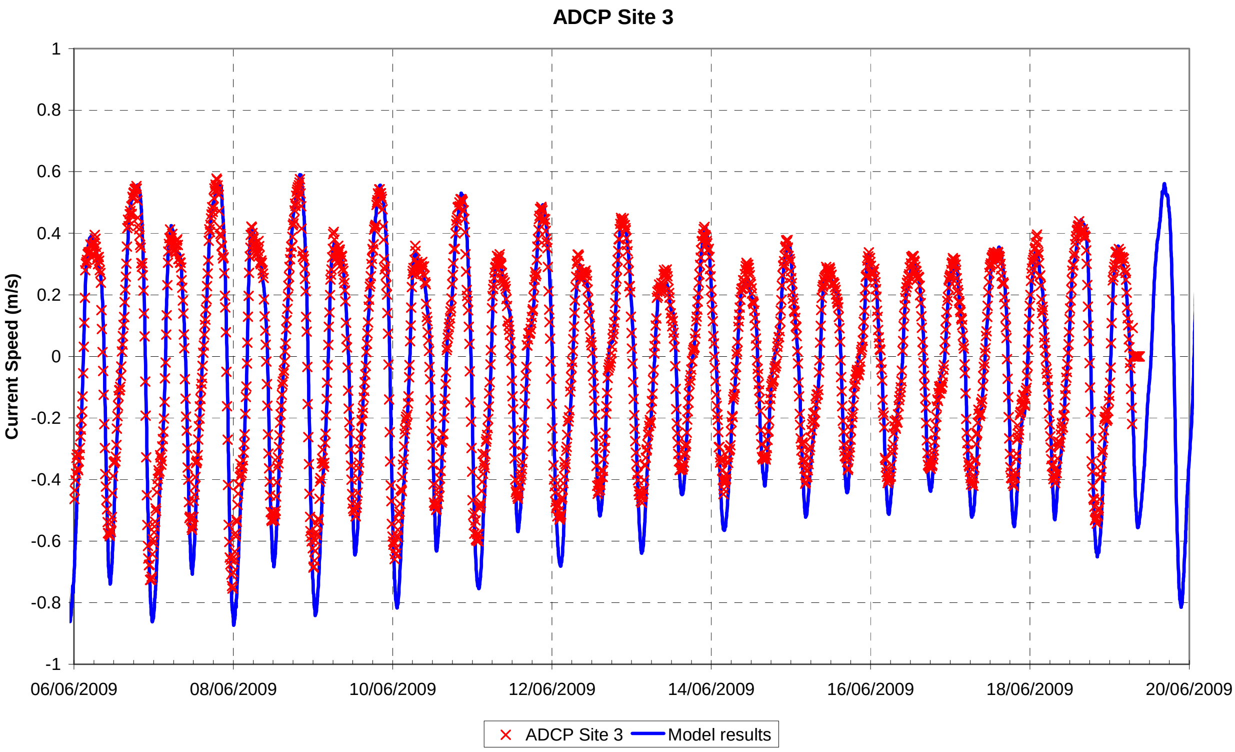


Figure 2-61 Current Speed – GHD ADCP Site 3, June 2009

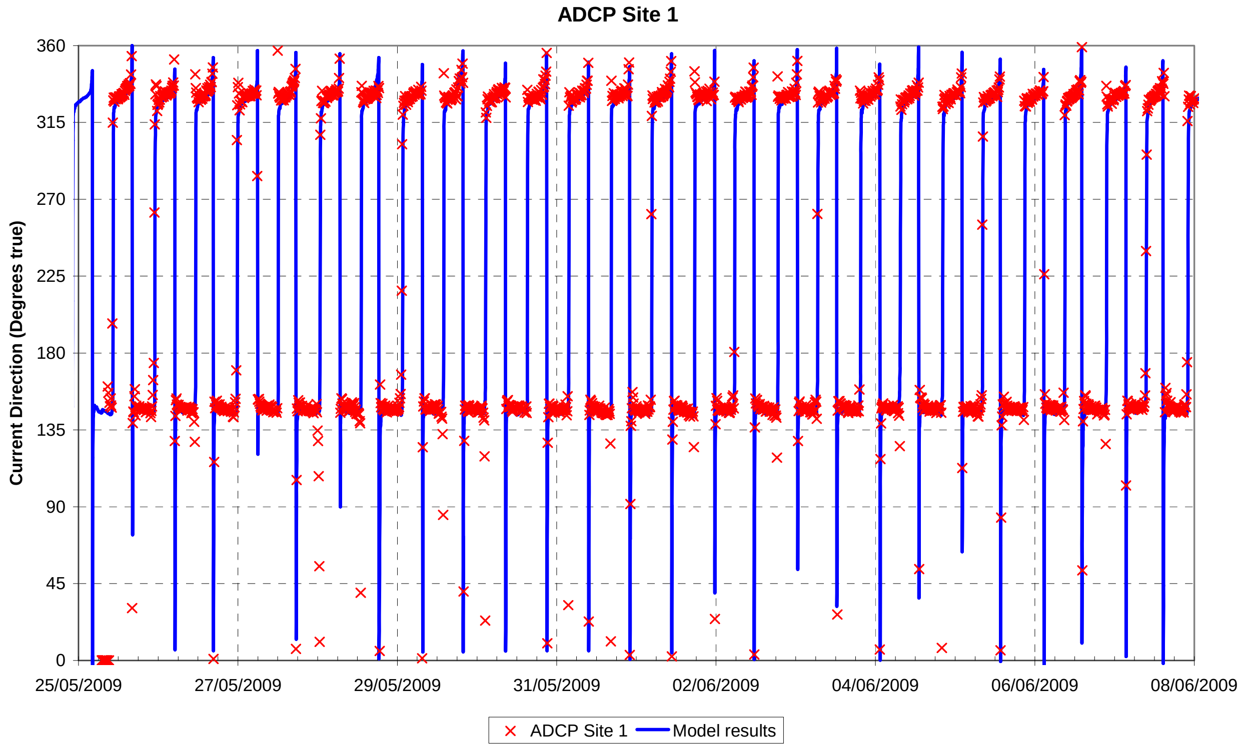


Figure 2-62 Current Direction – GHD ADCP Site 1, May 2009

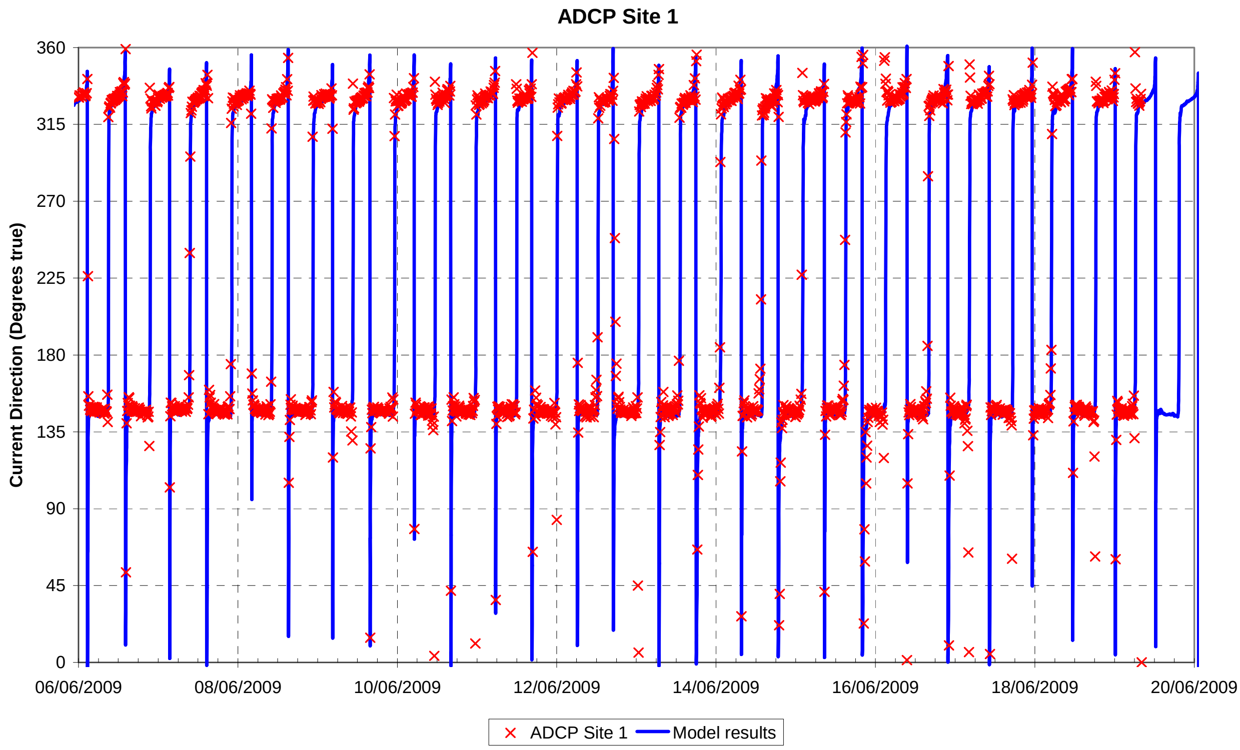


Figure 2-63 Current Direction – GHD ADCP Site 1, June 2009

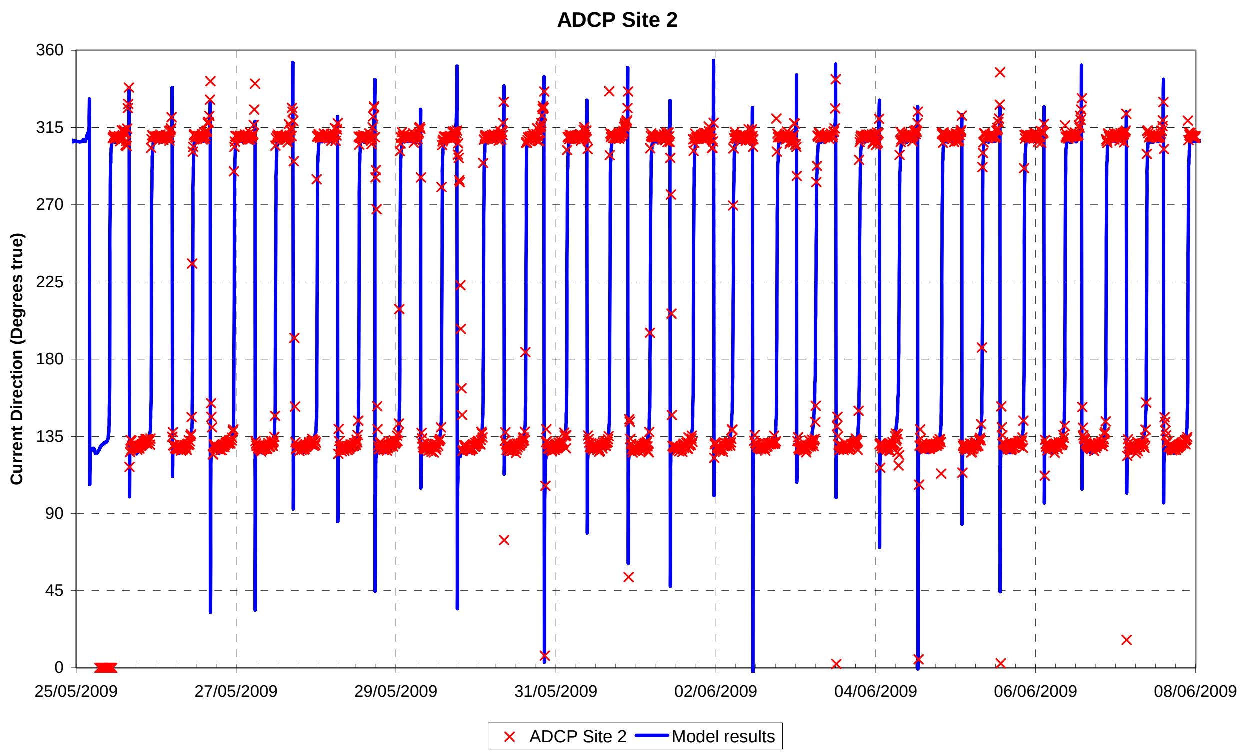


Figure 2-64 Current Direction – GHD ADCP Site 2, May 2009

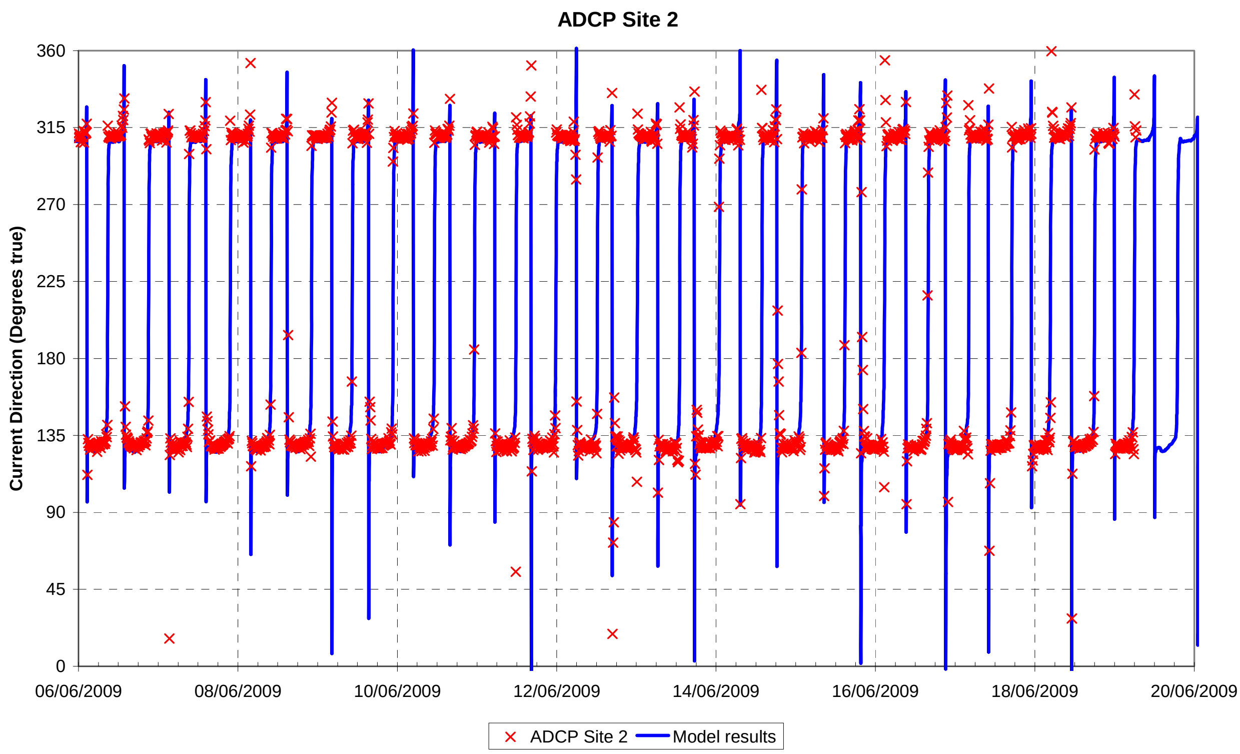


Figure 2-65 Current Direction – GHD ADCP Site 2, June 2009

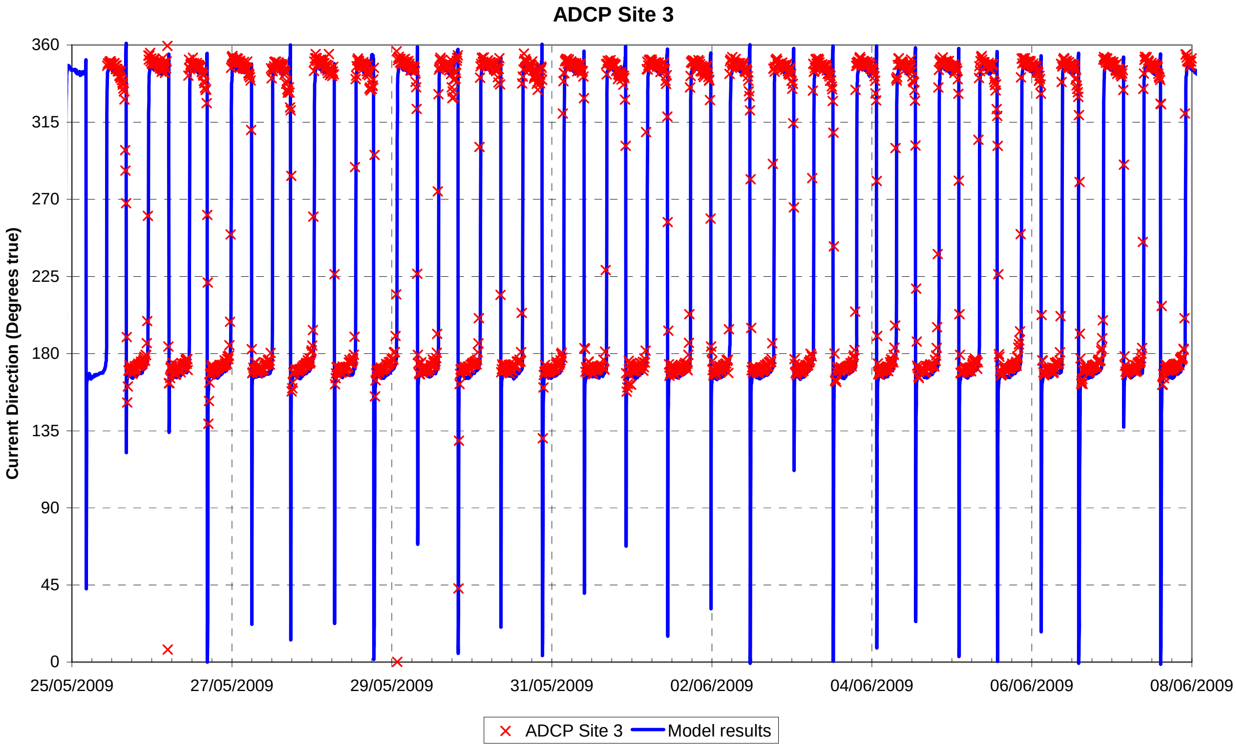


Figure 2-66 Current Direction – GHD ADCP Site 3, May 2009

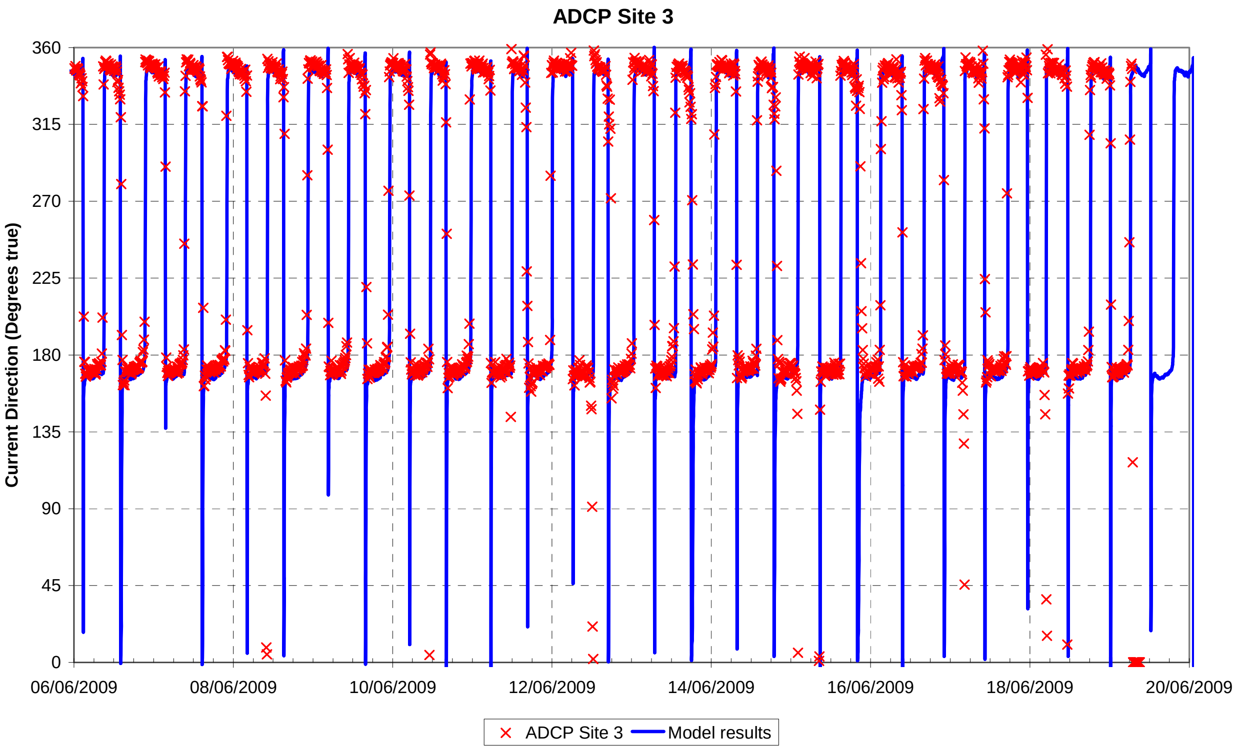


Figure 2-67 Current Direction – GHD ADCP Site 3, June 2009

3 ADVECTION DISPERSION MODEL

3.1 Model Details

The Advection-Dispersion (AD) module of the calibrated and validated TUFLOW-FV model has been used to simulate the mixing and flushing characteristics of Port Curtis and has been used in impact assessments of dredging/reclamation works on flushing efficiency and to simulate the dispersion of sediment plumes generated during dredging works.

The TUFLOW-FV mode can use either first or second-order spatial discretisation schemes, however the second-order scheme has been used exclusively for the Port Curtis modelling to ensure that numerical diffusion is minimised.

3.2 Mixing Parameters

Horizontal mixing due to un-resolved turbulence and velocity dispersion is modelled using a gradient diffusion approach. The an-isotropic diffusion tensor is related to the instantaneous flow characteristics using an Elder type model (Fisher et al., 1979).

$$D_l = K_l u^* h; \; D_t = K_t u^* h$$

where D_l is the dispersion coefficient in the direction of the flow advection, u^* is the friction velocity, h is the depth, D_t is the transverse dispersion coefficient and K_l, K_t are scaling coefficients. Based on a WBM dye release study conducted in Port Curtis several years ago, values of K_l=60 and K_t=6 have been adopted in previous RMA modelling studies (Connell Hatch, 2006) and in the present studies using the TUFLOW-FV model. These dispersion coefficients result in flushing time predictions that are consistent with another hydrodynamic modelling study of Port Curtis undertaken by Hertzfeld et al. (2004).

4 WAVE MODEL

4.1 Model Details

The local day to day and extreme wave generation and propagation characteristics within Port Curtis have been assessed using the SWAN wave modelling software. SWAN is a phase-averaged, spectral wave model developed at Delft University of Technology (2006). Its modelling capabilities include;

- Wave shoaling and refraction;
- Wave/current interaction;
- Wave generation by wind;
- Wave energy dissipation by whitecapping, depth-induced wave breaking and bottom friction;
- Non-linear wave-wave interactions (quadruplets and triads) which cause an internal re-distribution of wave energy between different frequencies.

The model can be run in first, second or third-generation mode. These modes refer to the level of physics incorporated into the model capabilities.

The numerical wave model incorporates swell wave propagation, generation and growth of 'sea' waves due to local winds, dissipation processes of bottom friction and breaking and shoaling and refraction as affected by the shallower areas. In the SWAN model, the waves are described with a 2Dimensional energy density spectrum which gives reliable results in non-linear situations such as wave breaking. Thus, SWAN can reliably represent the physical wave transformation processes occurring within the study area and has been successfully used for many previous wave generation and propagation studies worldwide as well as in Queensland.

4.2 Model Extent

Two wave models have been developed being a regional model and a local model. The regional model extends from the northwest corner of The Narrows to offshore of Facing Island (extent of 64km by 20km) and has a cell size of 200m by 200m. The local nested model covers an area of 7km by 7km in the Western Basin of Port Curtis and has a cell size of 50m by 50m. The bed levels for the models have been extracted from the regional DEM described in Section 2-3.

4.3 Model Configuration

The SWAN model allows for the selection of several parameters that can influence the processes of wave growth and decay. Conventionally used calibration parameter values have been adopted. Most of these parameters have default settings, based on experience in similar situations, and these have been used unless otherwise noted. The following SWAN model configuration has been used for the prediction of wave generation and propagation within Port Curtis:

- Generation 3 Physics;
- Westhuysen whitecapping parameterisation with wind input of Yan;

- Quadruplet non-linear wave interaction enabled;
- Depth-limited wave breaking; and
- Collin's friction model.

5 DREDGE PLUME MODEL

5.1 Natural Process Description

The origin of dredge plumes is intrinsically linked to the natural seabed material and dredge plume impacts can only be understood in the relation to the natural re-suspension mechanisms and resulting turbidity environment.

The Port Curtis Project Area seabed and intertidal areas are made up of mixed sediments comprising varying proportions of gravels, sands and fine silt/clay materials. These materials can become re-suspended by tidal currents and the action of locally-generated wind-waves on shallow areas.

Continuous measurements of turbidity variations over periods in excess of a fortnight indicate that the spring-neap tidal cycle is a dominant signal in the suspended sediment time series as seen in Figure 5-1 for data collected by BMT WBM adjacent to Fisherman's Landing in August/September 2008. Any direct correlation between wave-height and suspended sediment levels are much less clearly discerned from the available measurements, which indicates that tidal-currents are the dominant natural re-suspension mechanism within the Port Curtis Project Area.

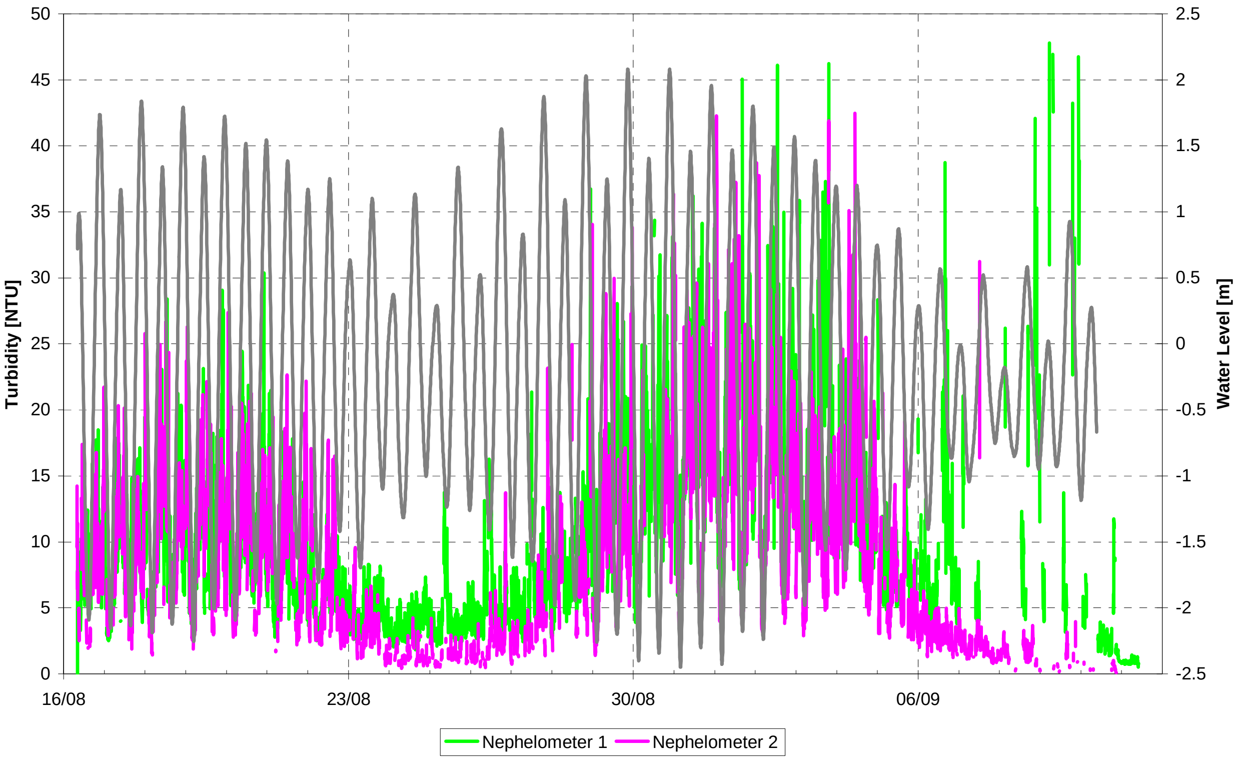


Figure 5-1 Turbidity time series collected by BMT WBM

5.2 Dredge Plume Monitoring

5.2.1 Data Collection

On the 29th and 30th June 2009 BMT-WBM undertook monitoring of the sediment plume produced by the cutter suction dredge "Wombat" operating near Fisherman's Landing in Port Curtis. Current velocities were measured using a vessel-mounted ADCP instrument, and sediment concentrations were inferred from the backscatter intensity of the acoustic signal. Water samples analysed for Total Suspended Solids (TSS) and measurements of turbidity converted to TSS were used to calibrate the TSS/backscatter correlation. These measurements enabled an assessment of the lateral extent of the plume and estimation of the total suspended sediment flux.

The measurements were made during flood tide conditions on both days. On the 29th June the "Wombat" was oriented with the cutter head facing away from the incoming tide and was operating without its booster pump. On the 30th June the "Wombat" was operating with its booster pump and was oriented facing away from the incoming tide until approximately 3pm, when it turned to face the current.

5.2.2 Data Analysis

A total of 38 ADCP transects were measured over the two day monitoring period

- 29th June 10:00-15:00 Transect numbers 000 to 018
- 30th June 10:45-15:45 Transect numbers 019 to 037

Water levels measured at Fisherman's Landing during this period are shown in Figure 5-2.

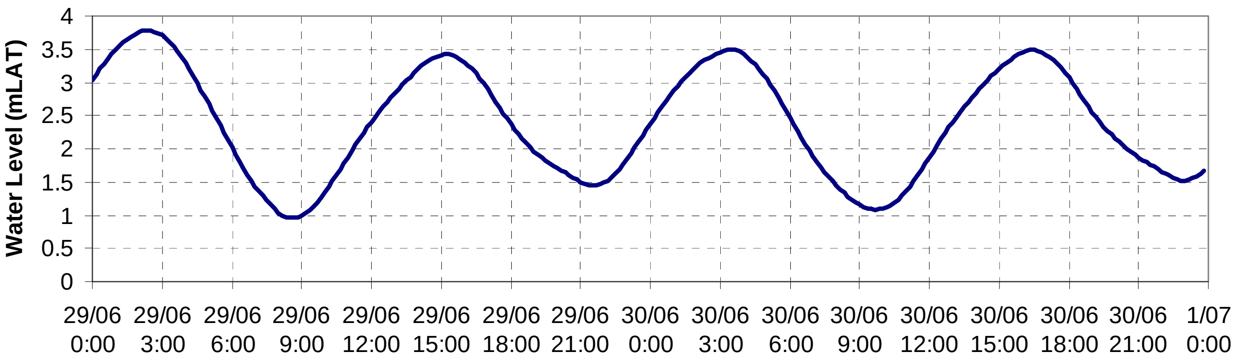


Figure 5-2 Water level at Fisherman's Landing (MSQ)

The ADCP instrument sampled at a frequency of 2Hz and had a working acoustic frequency of 1200kHz. The vertical profile was divided into 0.25m bins, with the uppermost bin at a depth of 0.62m.

Water quality measurements were conducted concurrently using a handheld multi-probe meter and 15 water samples were taken for subsequent laboratory analysis. The measurements of turbidity in Nephelometric Turbidity Units (NTU) were plotted against Total Suspended Solids (TSS) measurements from the laboratory samples to determine the NTU-TSS relationship. Data from another dredge plume monitoring campaign in Port Curtis were also included. The derived relationship is shown in Figure 5-3. A power law relationship was used for TSS values less than 4.7mg/L, and a linear relationship for values above that threshold.

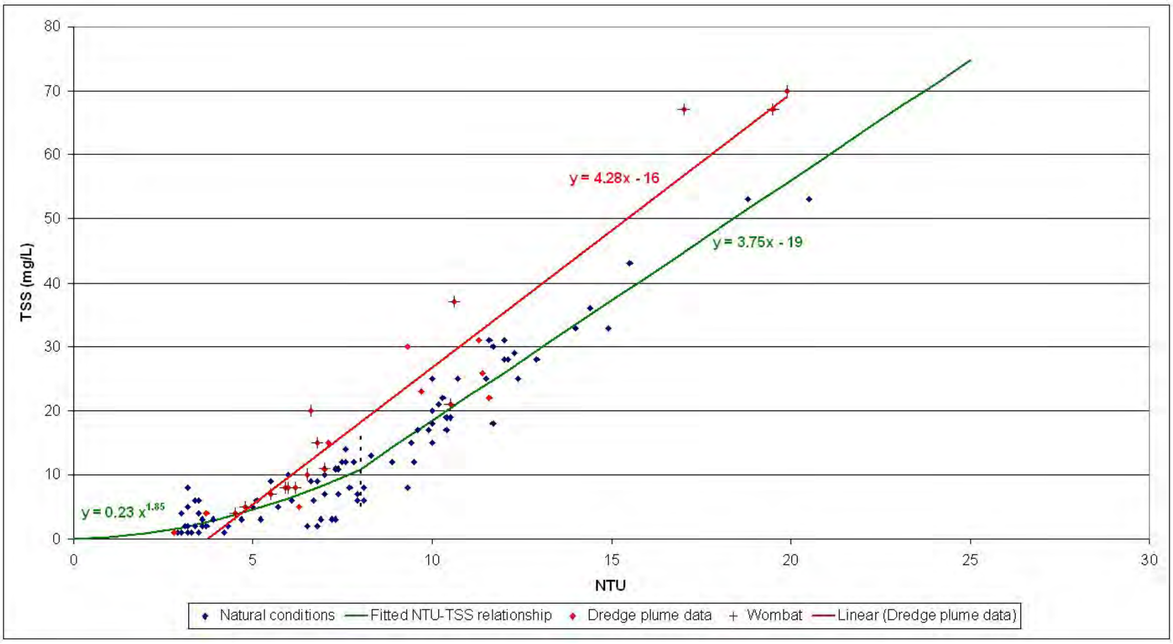


Figure 5-3 NTU-TSS Relationship Derived for Both Natural and Dredge Plume Sampling

Some water samples were analysed for

Some examples of TSS profiles derived from the turbidity profile measurements are shown in Figure G-1. It is noted that the maximum TSS inferred using this technique was around 63mg/L.

The TSS estimates obtained both directly from lab samples and indirectly from turbidity measurements were then used to derive a relationship between the ADCP acoustic signal backscatter intensity and TSS. The software package Sediview includes a built-in calibration module for this purpose which is based on acoustic theory. The calibration process requires information on water temperature and salinity at the site, scaling factors and offsets for each of the four transducers in the ADCP instrument, the sediment attenuation coefficient (a function of the sediment characteristics) and other calibration constants.

The estimates of TSS obtained from the ADCP backscatter signal were then plotted as a function of depth and distance along each transect. An estimate of the background TSS was made for each transect and this background signal was subtracted from the total estimated TSS to obtain the net surplus TSS due to dredging operations. TSS estimates were capped at a maximum value of 200mg/L due to the uncertainty surrounding the accuracy of the calibration procedures above that level and in order to alleviate the problem of erroneous backscatter spikes in the ADCP measurements. It is noted that the maximum TSS measured in any of the water samples was 70mg/L. The sensitivity of the sediment flux estimates to this choice of maximum concentration is discussed below.

ADCP backscatter measurements are prone to occasional spikes/elevated values that are un-related to TSS in the water column. These spikes may arise due to a number of sources of interference, including bubbles generated near the surface by the survey vessel / dredge / 3rd-party vessel and objects “pinged” in the water-column such as fish or seaweed. A clean-up procedure has been carried out to remove most of the obviously erroneous data.

The depth averaged sediment flux vector was estimated by multiplying the above-background TSS concentration at each elevation in each profile by the corresponding water velocity vector and then taking the depth average.

Table 5-1 Particle Size Characteristics of Both Natural and Dredge Plume Suspended Sediments

Description	Depth (m)	TSS (mg/L)	Turbidity (NTU)	d10 ηm	d50 ηm	d90 ηm	% Med Sand >159 ηm	% Fine Sand <159 ηm >71 ηm	% Silt <71 ηm >5 ηm	% Clay <5 ηm
U/S of dredger	5	8	6.2	2.5	7.6	25	0.03	1.65	71.7	26.6
Dredge plume close to dredge head	6	8	6	2.8	8.6	32	0.00	1.55	75.9	22.6
25-30m D/S dredge head	10	67	17	2.4	12.0	60	0.35	8.67	68.2	22.8
Dredge plume	7	11	7	2.3	7.0	25	0.01	2.79	67.4	29.8
Dredge plume	10	70	19.9	2.4	10.0	60	1.04	7.97	66.0	25.0
Dredge plume	10	21	10.5	2.5	8.9	40	0.06	4.19	70.8	25.0
D/S of dredger	10	67	19.5	2.4	12.7	58	0.03	8.20	68.7	23.1
D/S of dredger	5	20	6.6	2.3	10.3	77	1.45	12.52	59.9	26.1
D/S of dredger (outside of plume)	10	5	4.8	2.2	8.1	24	0.00	0.35	71.2	28.5
U/S of dredger	3	8	5.9	2.1	6.1	16.2	0.00	0.00	64.7	35.3
D/S of dredger	10	15	6.8	2.8	10.0	49	0.00	5.72	72.6	21.7
Dredge plume	12.5	37	10.6	2.3	11.0	62	0.49	9.19	65.2	25.1
Pond outlet	-	9	-	1.6	3.5	7.5	0.00	0.00	34.7	65.3
Pond outlet	-	10	-	2.8	8.6	32	0.00	0.00	57.9	42.1
Passage Transect - West	5	53	18.8	2.5	8.5	40	0.78	4.62	69.5	25.1
Passage Transect - East	5	53	20.5	2.4	9.1	53	3.37	5.09	66.7	24.8
Targinnie Transect - Centre. 10 m deep.	5	12	7.5	2.1	6.3	16.4	0.00	0.00	66.0	34.0
Targinnie Transect - Centre. 15 m deep.	10	29	12.3	2.6	8.2	19.7	0.97	4.35	69.6	25.0
Targinnie Transect - East. 6.8 m deep.	5	20	10	2.0	6.6	22	0.00	0.21	67.1	32.7
Targinnie Transect - Centre. 14 m deep.	5	36	14.4	2.2	8.6	38.9	0.48	4.25	68.8	26.5
Targinnie Transect - Centre. 14 m deep.	10	43	15.5	2.5	9.3	60	1.89	6.89	67.0	24.2
Targinnie Transect - Centre.	10	6	6.1	2.1	5.9	14.2	0.00	0.00	64.3	35.7
Laird Transect - East. 6.8 m deep.	3	22	11.6	2.6	8.3	39	0.65	4.23	70.2	25.0
Laird Transect - Centre. 13 m deep.	10	9	6.8	2.2	6.0	19	0.00	0.69	64.1	35.2
Dredge Plume - Mean		35.1	11.5	2.5	10.1	51.4	0.4	6.8	68.3	24.6
Dredge Plume - Stdev		26.0	5.7	0.2	1.8	16.5	0.5	3.5	4.6	2.5
Dredge Plume - Median		21.0	10.5	2.4	10.0	58.0	0.1	8.0	68.2	25.0
Decant - Mean		9.5	-	2.2	6.1	19.8	0.0	0.0	46.3	53.7
Decant - Stdev		9.5	-	2.2	6.1	19.8	0.0	0.0	46.3	53.7
Decant - Median		9.5	-	2.2	6.1	19.8	0.0	0.0	46.3	53.7
Natural - Mean		23.4	10.8	2.3	7.6	29.8	0.6	2.5	67.8	29.1
Natural - Stdev		17.8	5.2	0.2	1.2	14.9	1.0	2.5	2.6	4.7
Natural - Median		20.0	10.0	2.2	8.1	24.0	0.0	1.7	67.1	26.6

5.2.3 Results and Discussion

A contour plot of the maximum depth-averaged TSS measured within 15m x 15m cells is shown in Figure G-2. It is seen that the width of the discernible plume was approximately 100m at its widest point, and that the depth averaged concentration fell away rapidly as a function of distance along the plume. It should be noted that the spatial coverage of the measurements was limited and that the actual maximum depth-average at any given location may not have been measured. Therefore these results should be considered as indicative only.

The depth average of the above-background TSS due to dredging activity is plotted as a function of distance downstream of the dredge in Figure G-3. Note that this graph includes both the maximum plume concentrations at the plume centreline as well as the lower plume concentrations at the plume edges. Depth averaged concentrations of up to 200mg/L were obtained within 100m downstream of the dredge, falling to a maximum of around 60mg/L at 200m downstream of the dredge. The measured depth-averaged concentration dropped to approximately 5mg/L above background levels within about 600m downstream of the dredge along the centreline of the plume. However, at distances greater than 400m downstream of the dredge there are not sufficient measurements to robustly characterise the probability distribution of plume concentrations above background.

The processed TSS estimates for each transect are presented in Figure G-4 to Figure G-41. For each transect, the first plot presented is a contour plot of the estimated TSS as a function of distance along the transect and depth. The second plot presents the depth averaged TSS (without subtraction of the background concentration) as a function of distance along the transect. The third and final plot is a plan view of the transect path with the start of the transect marked and the other transect paths in grey.

The TSS contours illustrate that highest concentrations were typically measured close to the bed where the cutter-head was operating. Both concentrations and vertical gradients generally increase with proximity to the dredging operation. The vertical gradients become less pronounced with increasing distance away from the dredge, demonstrating the presence of significant vertical mixing processes and also that the finer fractions (which are more readily vertically-mixed) remain in suspension.

Where a transect path crossed the dredge plume, the section/s of the ADCP track that crossed the plume have been visually identified. The plume-only sediment flux normal to each plume-crossing transect section was then estimated. The plume-only sediment flux through each of these transect sections is shown on the plots in Appendix C Figure G-4 to Figure G-41, and each section is highlighted in a different colour on both the depth averaged concentration plot and the transect plan plot.

The reliable measurements of plume-only sediment flux are summarised in Table 5-2. It can be seen that a wide range of instantaneous sediment flux measurements were made, which indicates the high temporal variability of sediment entrainment rate generated by the dredge. The minimum measured plume flux was 0.2kg/s and the maximum was 8.4kg/s. The mean plume flux from 24 reliable transects over the two monitoring days was 2.5kg/s with a standard deviation of 2.0kg/s. The median plume flux was 2.2kg/s.

The sensitivity of the plume sediment flux estimates to the choice of maximum concentration was also tested. With a maximum concentration of 500mg/L instead of 200mg/L, the mean plume flux rises to 3.0kg/s, a 20% increase. Only seven of the measured cross-section fluxes (shown in bold in Table 5-2) are affected by this choice of upper limit.

The reliable plume sediment flux estimates have been plotted versus the transect distance from the dredge in Figure G-42. These results indicate the scatter in plume flux and also show the general decreasing trend with distance from the dredge.

Table 5-2 Plume sediment flux measurements

Transect Number	Time	Plume Flux - 200mg/L max (kg/s)	Plume Flux - 500mg/L max (kg/s)	Distance from Dredge (m)
3	29/06/2009 10:27	3.4	**5.0**	75
4	29/06/2009 10:31	3.7	**6.3**	75
7	29/06/2009 11:08	8.4	**10.5**	75
7	29/06/2009 11:08	3.0	3.0	140
8	29/06/2009 11:33	6.5	**8.2**	85
8	29/06/2009 11:33	3.4	3.4	145
11	29/06/2009 12:23	4.0	**5.2**	75
13	29/06/2009 12:40	1.2	1.2	200
14	29/06/2009 14:20	4.4	**5.6**	85
16	29/06/2009 14:36	0.7	0.7	85
16	29/06/2009 14:36	0.5	0.5	135
17	29/06/2009 14:44	0.3	0.3	75
18	29/06/2009 14:51	0.2	0.2	170
21	30/06/2009 11:03	0.8	0.8	35
23	30/06/2009 11:16	4.0	4.0	125
25	30/06/2009 11:35	1.7	1.7	390
26	30/06/2009 11:41	0.9	0.9	620
30	30/06/2009 13:15	3.0	**3.6**	100
32	30/06/2009 13:26	3.2	3.2	200
34	30/06/2009 13:42	2.6	2.6	185
34	30/06/2009 13:42	1.7	1.7	110
36	30/06/2009 14:17	1.3	1.3	100
36	30/06/2009 14:17	0.7	0.7	200
37	30/06/2009 15:30	1.2	1.2	90
	Mean:	2.5	3.0	
	Std Deviation:	2.0	2.7	
	Median:	2.2	2.2	

5.3 Cohesive Sediment Module Description

Dredge plumes have been simulated using the cohesive sediment module of TUFLOW-FV in combination with the hydrodynamic and advection-dispersion modules already described. The cohesive sediment module performs the following tasks;

- Tracking the sediment quantity and composition of (multiple) seabed sediment layers;
- Tracking (multiple) sediment fractions in the water column; and
- Tracking sediment exchange between the water column and the seabed:
  - Erosion; and
  - Deposition.

A range of options for modelling these processes are available within the cohesive sediment module, however only those parameterisations used in the Port Curtis dredge plume modelling assessments are described below.

Dredge plumes have been modelled using 3 suspended sediment classes/fractions; fine sand, silt and clay.

The effective clear water sediment settling velocity, w_{s0}, for each fraction is directly specified and is assumed to have no dependence on either suspended sediment concentration (e.g. flocculation or hindered settling).

The modelled rate of sediment settling is a function of the depth-averaged sediment concentration, the still-water fall velocity (w_{s0}) and the bed shear stress (τ_b), according to the relationship:

$$Q_{sd} = w_{s0}*\max(0,(1-\tau_b/\tau_{cd}))$$

where τ_{cd} is a model parameter defining the critical shear stress for deposition. As such, sediment settling is reduced below its still water value by the action of bed shear stress and associated vertical mixing in the water column.

Re-suspension of already deposited plume material has not been included in the dredge plume assessments for the reason that while there is the potential for re-suspension of the fine suspended load which does settle out, it will generally become mixed with and hence indistinguishable from the re-suspension of the natural bed material.

5.4 Settling Velocity Calibration

The relative composition of the dredge plume source loads in terms of the 3 sediment fractions, the assumed still-water fall velocities and equivalent Stokes diameter are based on the "Wombat" monitoring data and have been summarised in Table 5-3.

A critical shear stress for deposition of 0.5 N/m^2 was adopted following calibration of the settling parameters to the measured reduction in turbidity during the transition from spring-tides to neap-tides, as shown in Figure 5-4. The calibration assessment was undertaken by dosing the model with an initial TSS concentration of 40mg/L (approximately equivalent to 16NTU using the relationship in Figure 5-3), comprising 3% fine-sand, 68% silt and 29% clay based on the natural suspended sediment measurements in Table 5-1. In Figure 5-4 it can be seen that the measured general trend in turbidity decay is reproduced in this assessment, however the strong semi-diurnal variations in turbidity during the spring tides at the beginning are not reproduced. These strong variations in the measurements may be due to a combination of spatial gradients which were advected past the turbidity sensor and/or active re-suspension/deposition over the timescale of a tidal cycle. The former process would not be accurately represented due to the artificial initial condition of this model calibration assessment while erosion processes were not included in the sediment plume modeling for reasons already stated.

Table 5-3 Plume Model Sediment Fractions and Settling Parameters

Particle	Fine Sand	Silt	Clay
Still Water Fall Velocity, w_{s0} (m/s)	1.0E-02	2.0E-04	2.0E-05
Eqivalent Stokes Diameter, d_{s0} (ηm)	110	15	4.8
Critical Shear Stress Deposition, τ_{cd} (N/m^2)	0.5	0.5	0.5
Sediment particle density, ρ_s (kg/m^3)	2650	2650	2650
% Dredge Plume	16	56	28
% Dump Plume	16	56	28
% Decant Plume	0	35	65

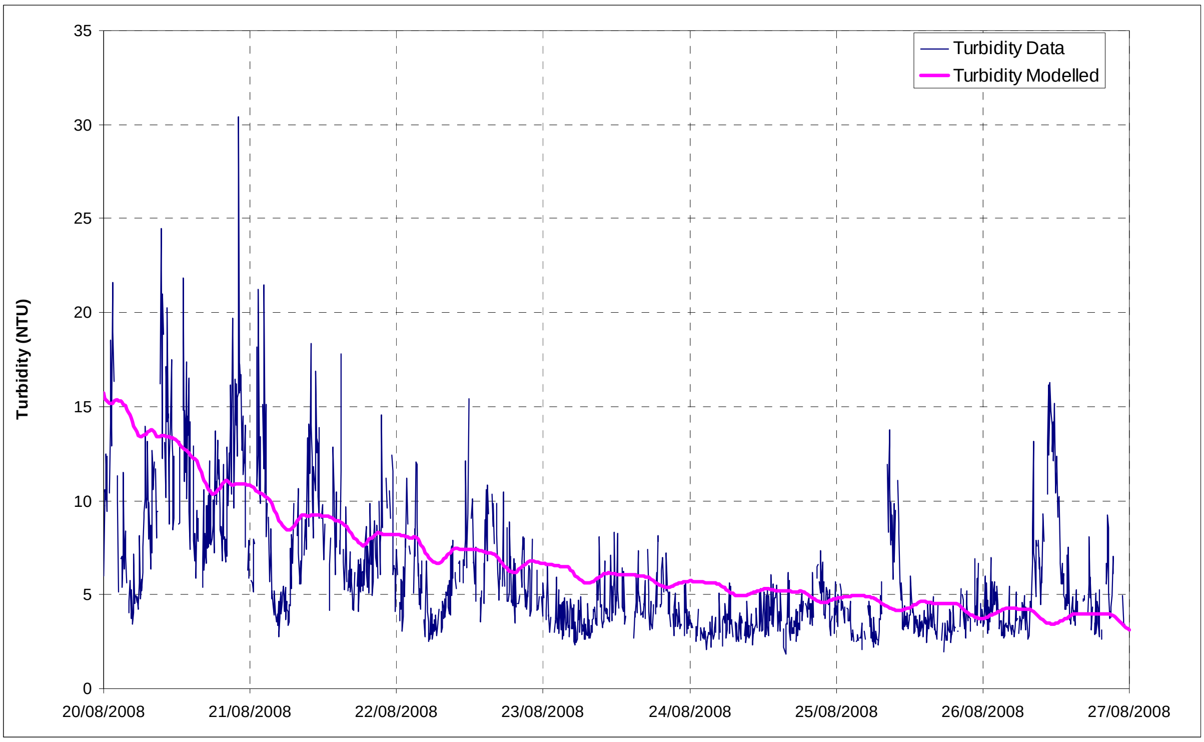
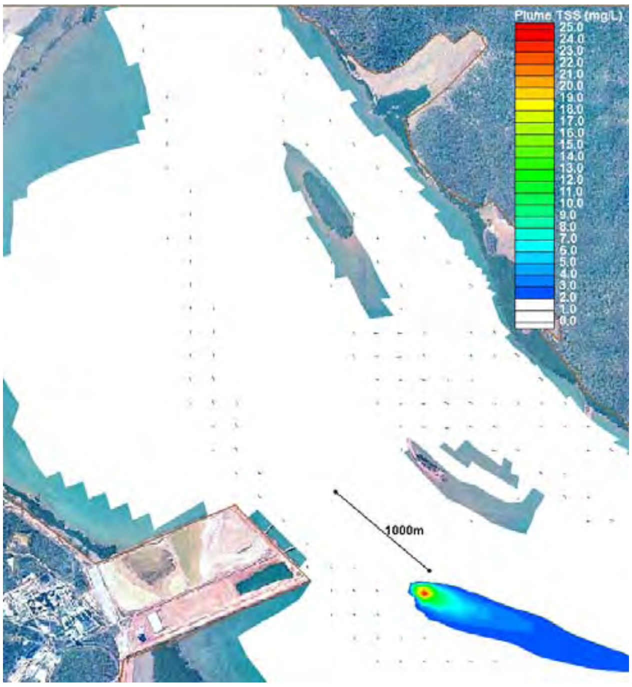


Figure 5-4 Sediment settling velocity calibration comparison

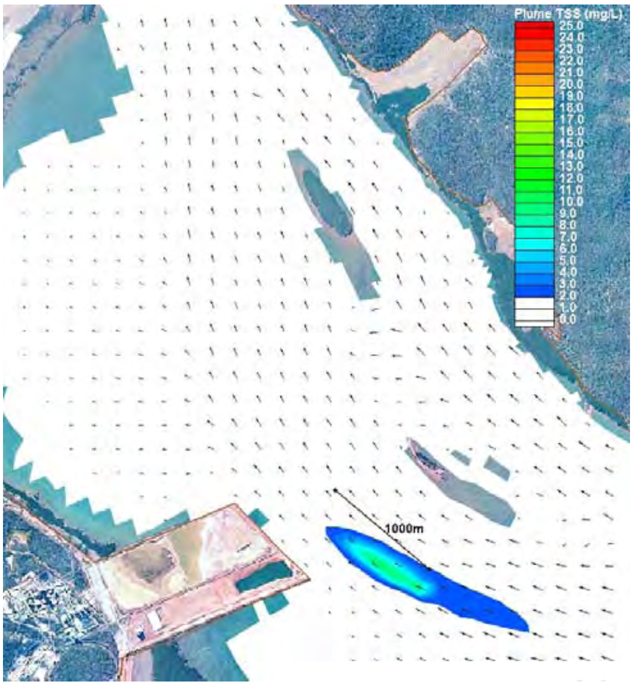
5.5 Dredge Plume Model Validation

Validation of the dredge plume model was undertaken by simulating the period of Wombat dredging when monitoring was undertaken (as described in Section 5.2). A plume TSS source rate of 2.5kg/s was introduced into a single model cell with side dimensions of approximately 50m. The region of the model in the vicinity of Fisherman's landing generally has mesh cells with dimensions between 30-150m, which limits the ability to resolve plume features less than this scale. The model was warmed up for a period of two days prior to extracting results.

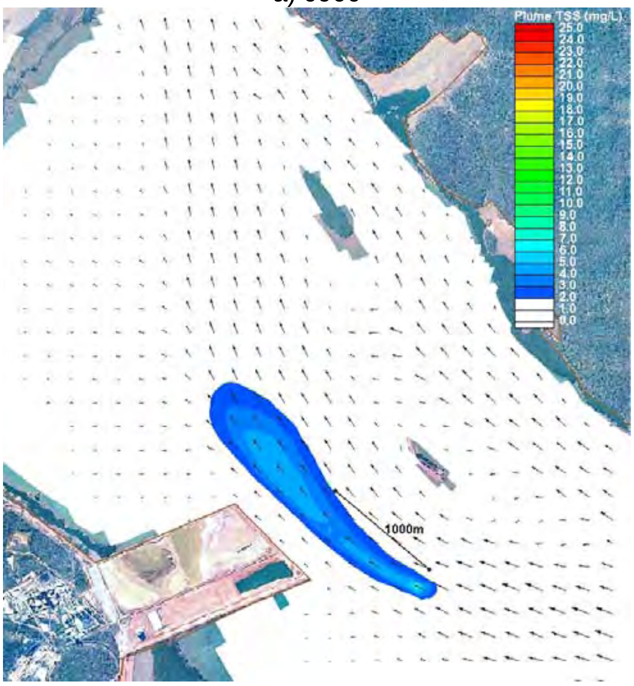
An hourly series of predicted plume TSS snapshots corresponding the period of monitoring undertaken on the 29/06/2009 have been extracted from the model for the purpose of comparison with the dredge plume monitoring data (Section 5.2 and Appendix G). The modelled plume TSS snapshots are provided in Figure 5-5 below. The coloured dredge plume contours range from 2mg/L to 25mg/L.



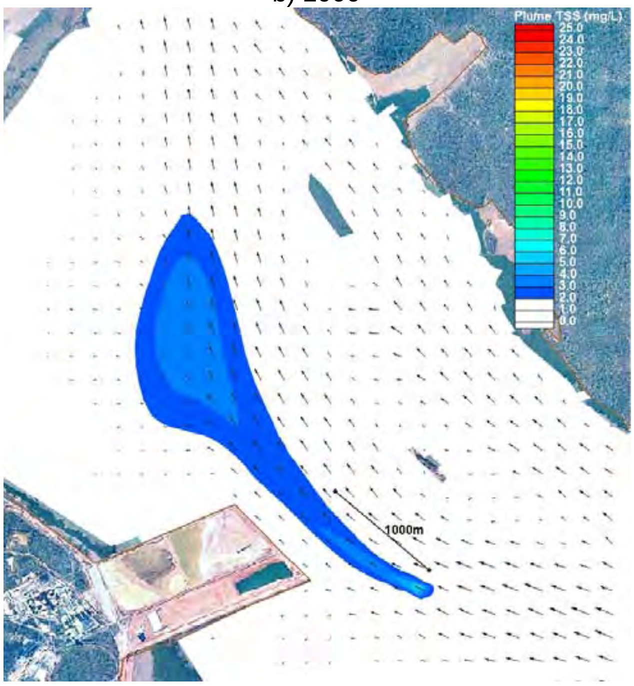
a) 0900



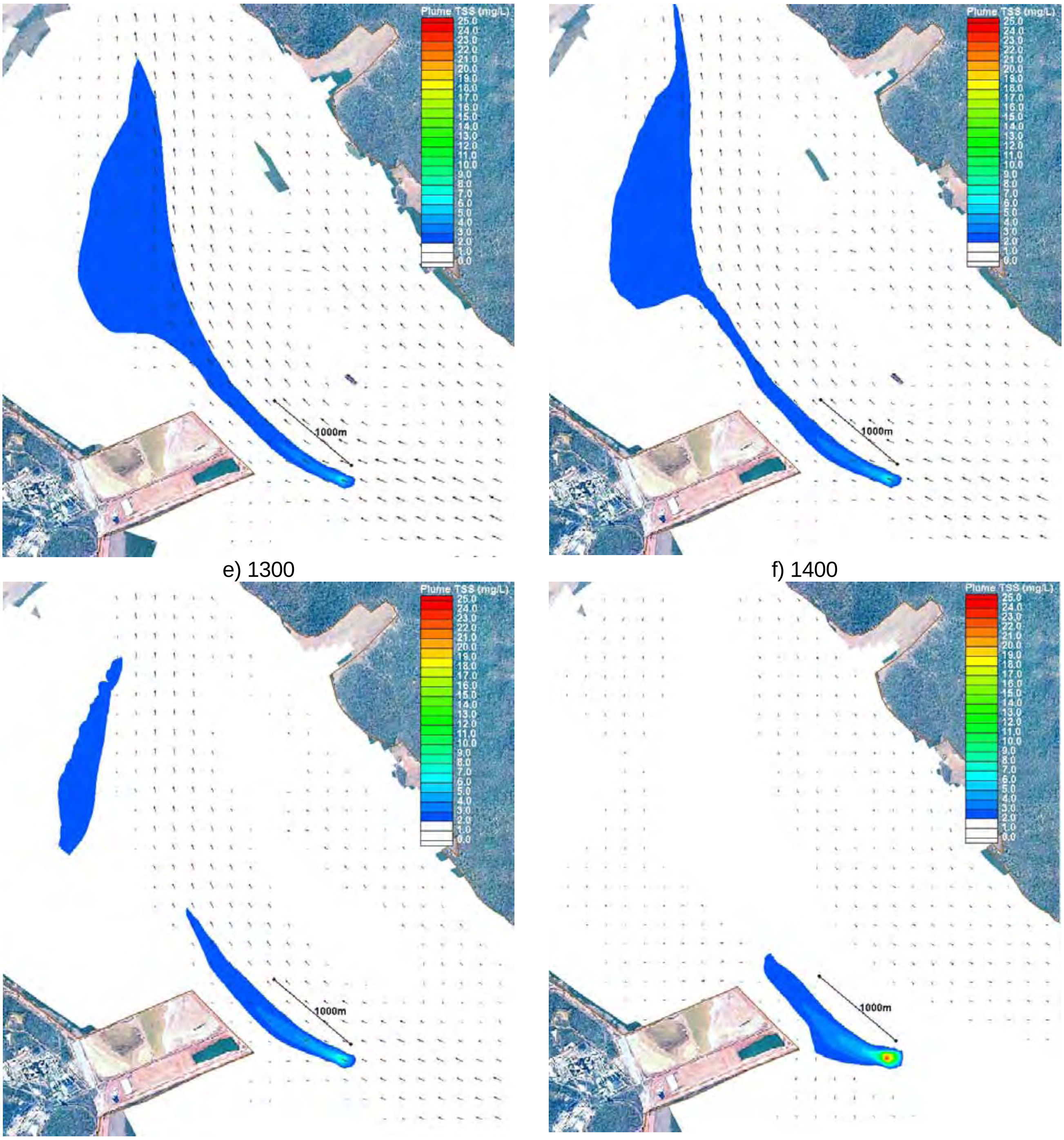
b) 1000



c) 1100



d) 1200



e) 1300 f) 1400

g) 1500 h) 1600

Figure 5-5 Modelled Wombat Dredge Plume Snapshots (29/062009)

In general the following conclusions can be made about the modelled and measured plume comparisons:

- Near-field plume dilution and correspondingly plume width are over-predicted by the model;
- Mid to far-field plume concentrations are comparable to the measured concentrations above background levels;
- Modelled mid to far-field plume width is generally greater than 150-200m, which is larger than the comparable measured plume widths.

Regarding the first point, near-field under-prediction of the peak plume concentrations is expected in a broad-scale model such as described here. Initial model dilution of the plume occurs over an entire model cell, which is significantly larger than the near-source plume size. The model/data comparisons shown here indicate that in the medium to far-field, the model inaccuracies due to finite resolution become less significant due to the natural flow dispersion and turbulent diffusion processes that result in horizontal mixing of the plume.

In the mid to far-field the modelled plume centreline concentrations are consistent with the measured concentrations above background levels and the plume width is slightly over-predicted. These results provide confidence that the dredge plume impacts are conservatively predicted using the model (as described) in combination with a reasonable estimate of plume source loading.

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Connell Hatch (2006) Environmental Impact Statement, Wiggins Island Coal Terminal, Central Queensland Ports Authority and Queensland Rail.

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Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J. and Brooks, N.H. (1979). Mixing in Inland and Coastal Waters. 483 pp, Academic Press, San Diego, California.

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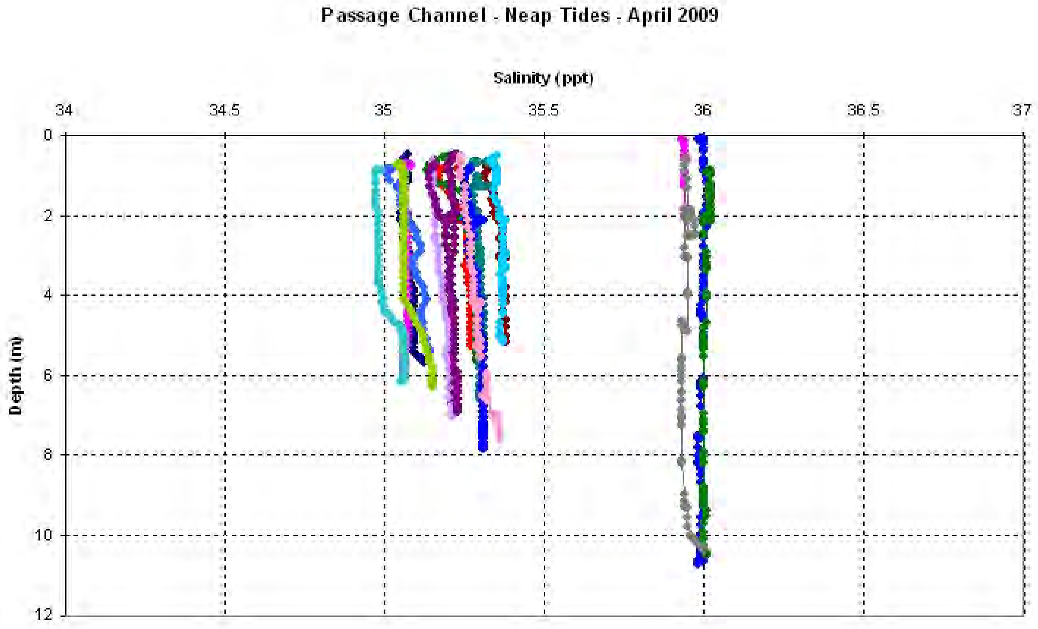
APPENDIX A: SALINITY AND TEMPERATURE PROFILES



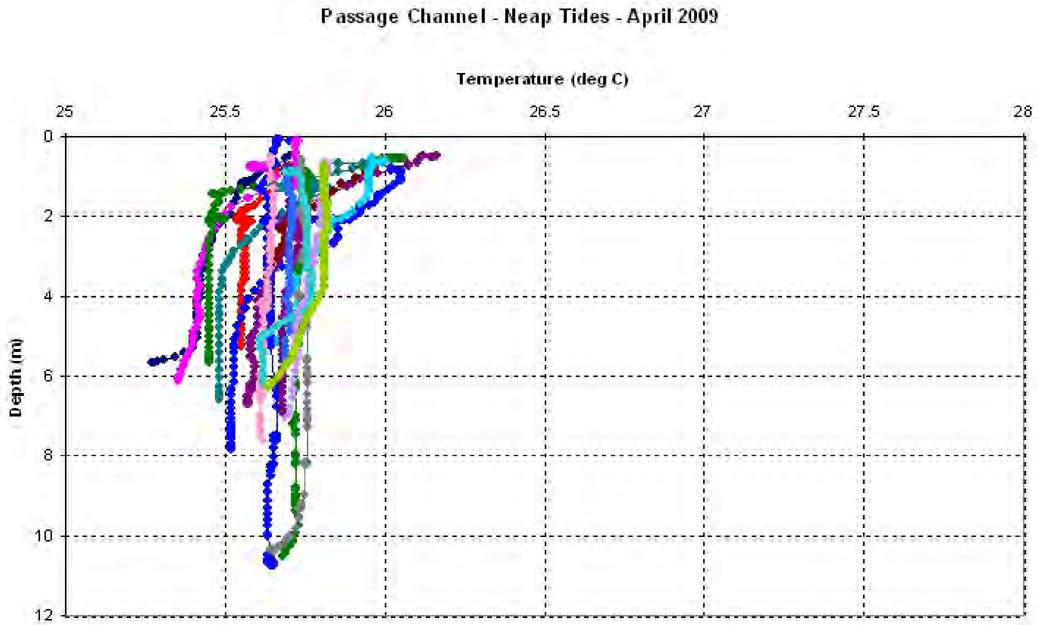
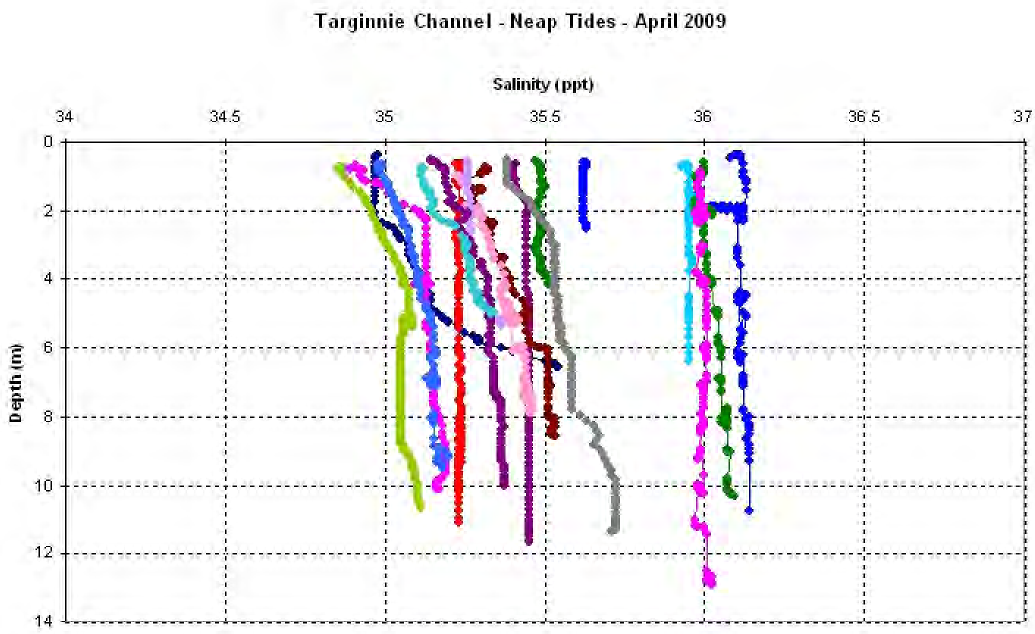


Figure A-1 "Curtis" Channel Salinity and Temperature Profiles (18-19 April 2009)



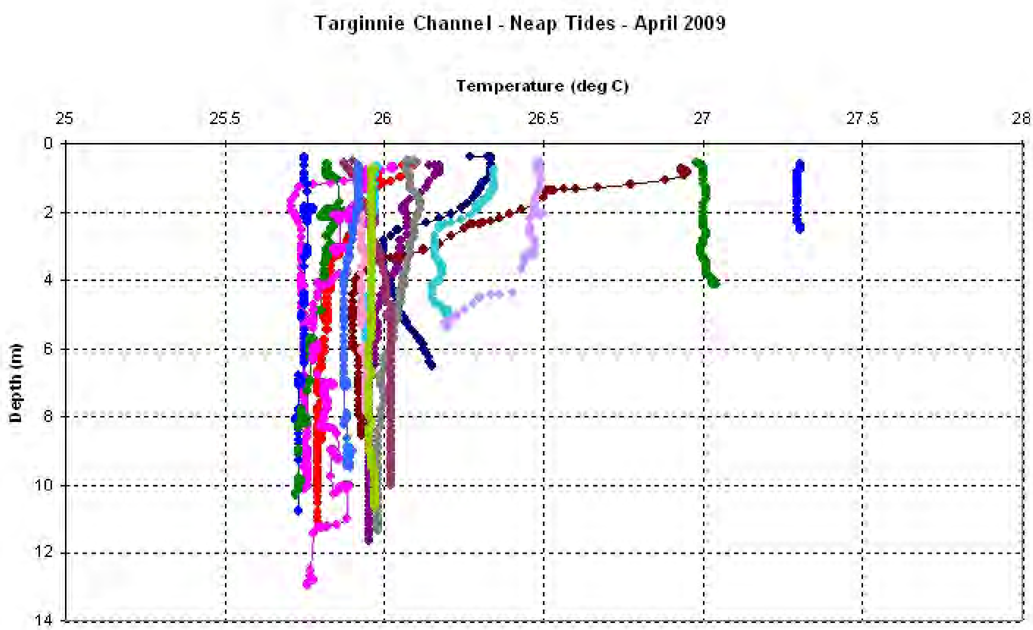
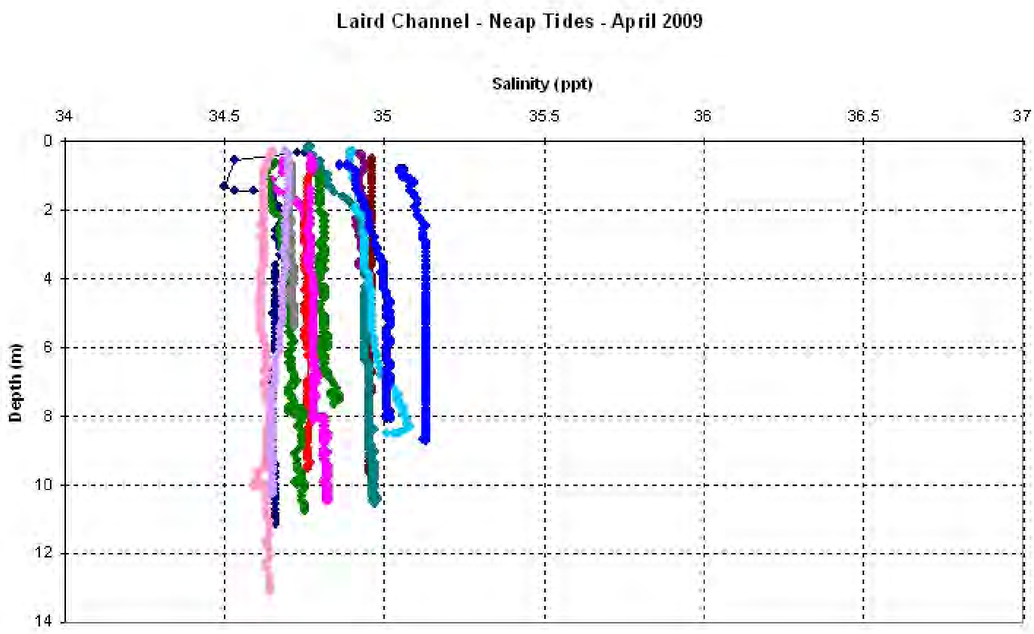


Figure A-2 Targinie Channel Salinity and Temperature Profiles (19-20 April 2009)



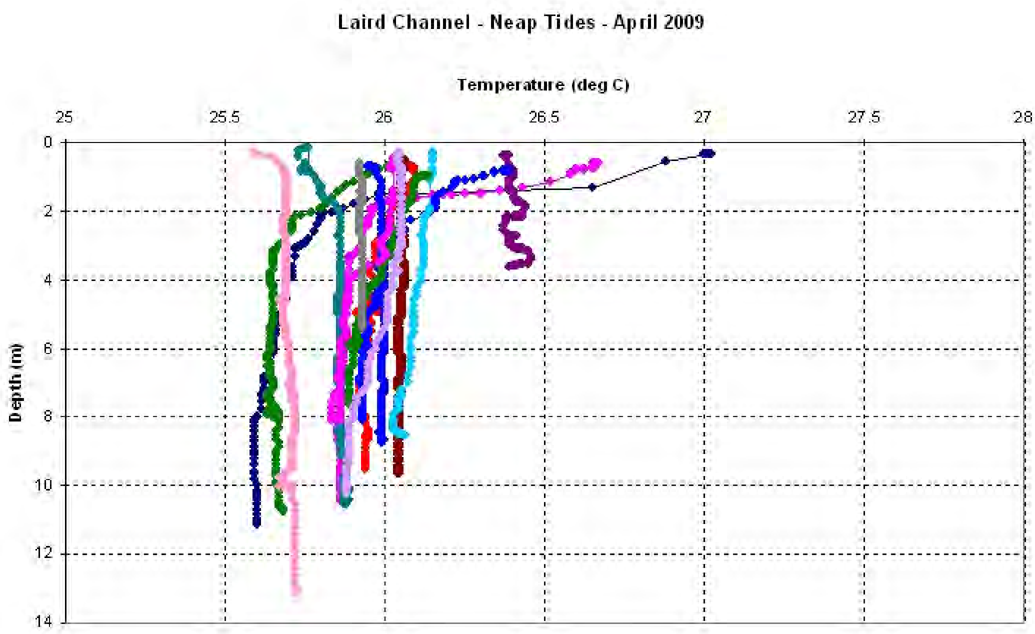
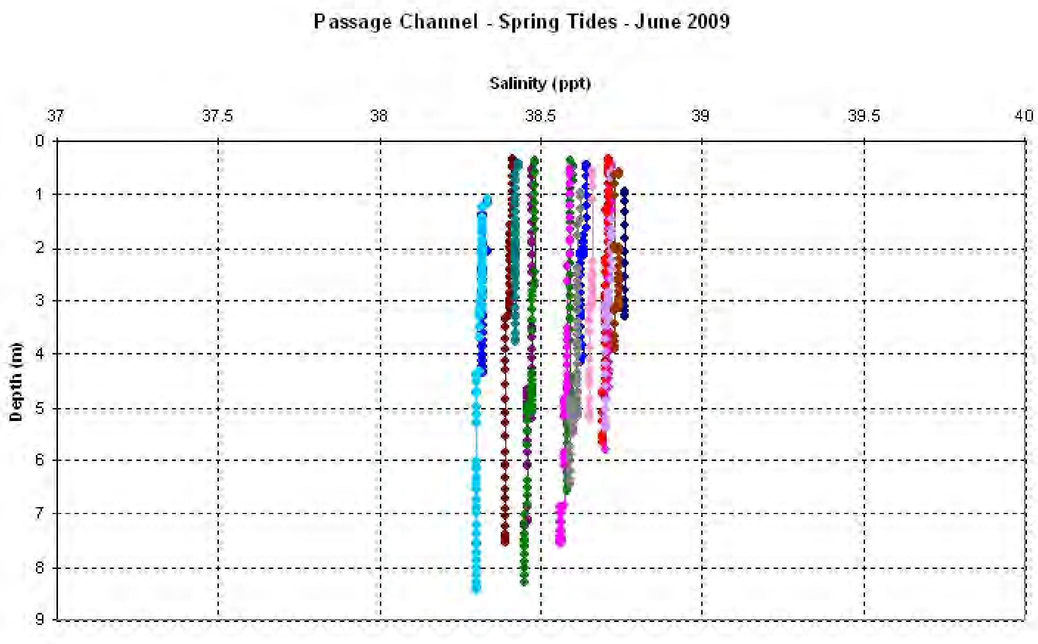


Figure A-3 Laird Point Salinity and Temperature Profiles (20-21 April 2009)



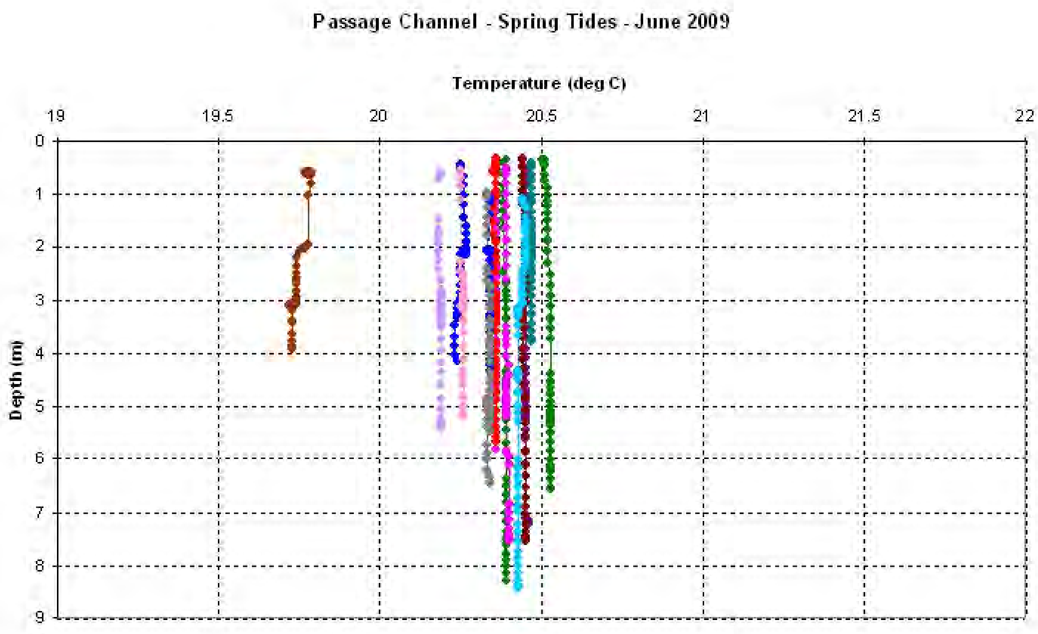
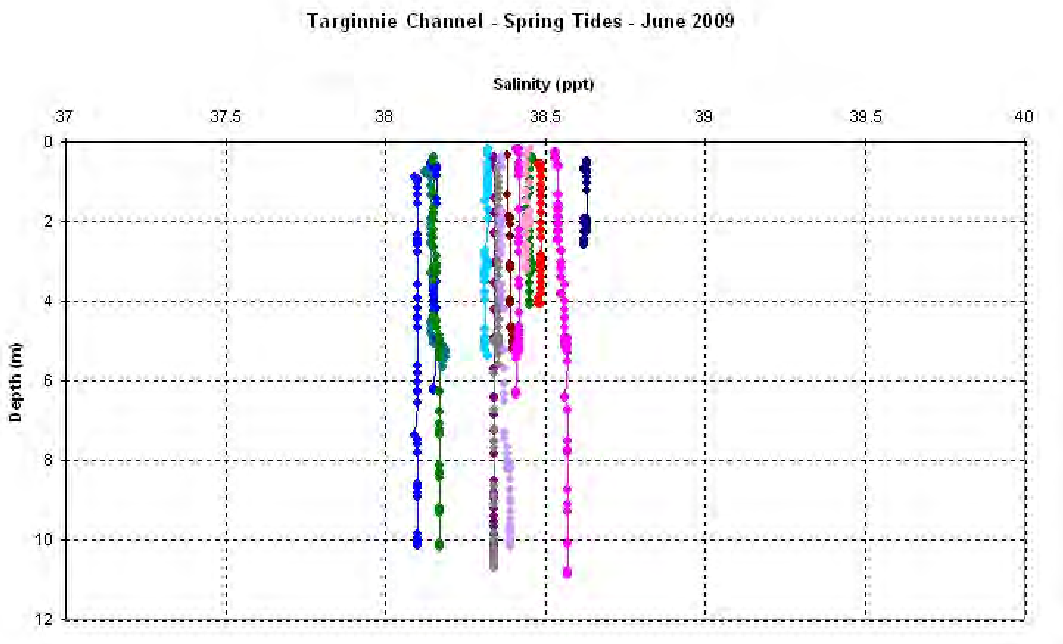


Figure A-4 "Curtis" Channel Salinity and Temperature Profiles (24-25 June 2009)



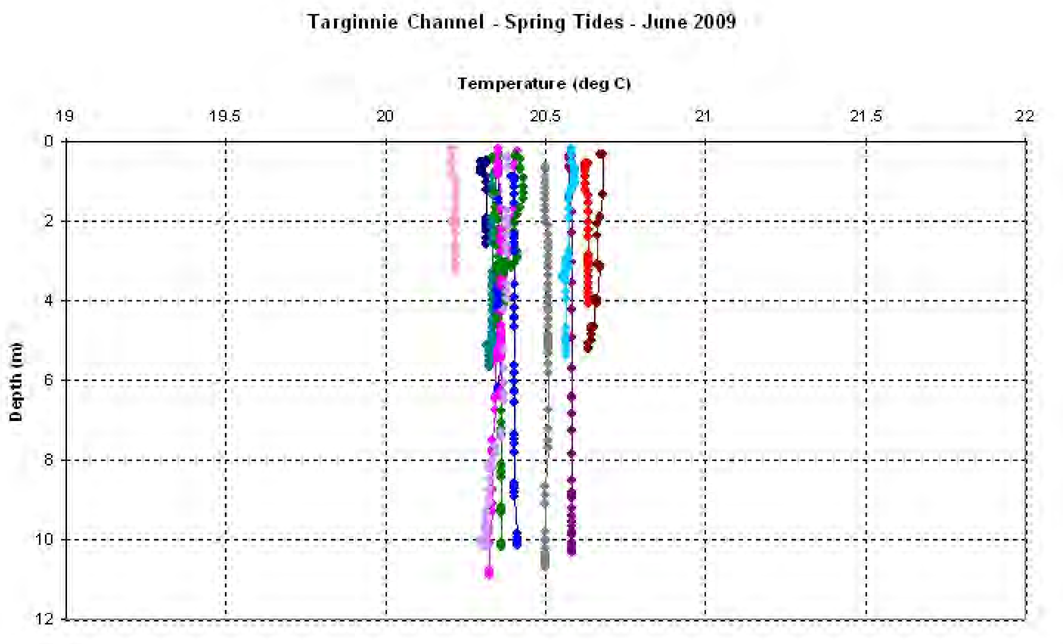
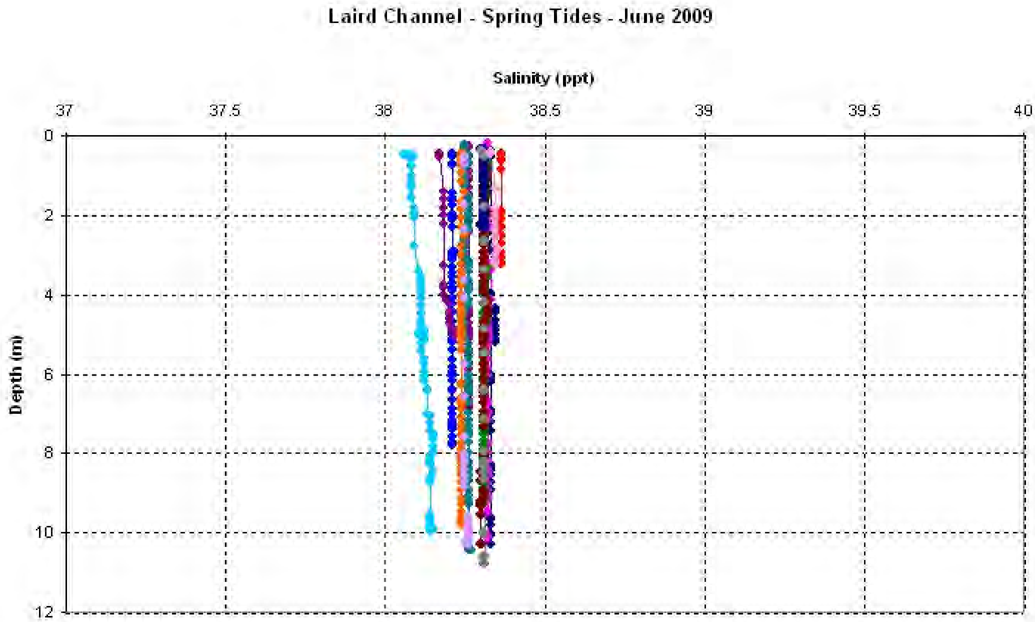


Figure A-5 Targinie Channel Salinity and Temperature Profiles (25-26 June 2009)



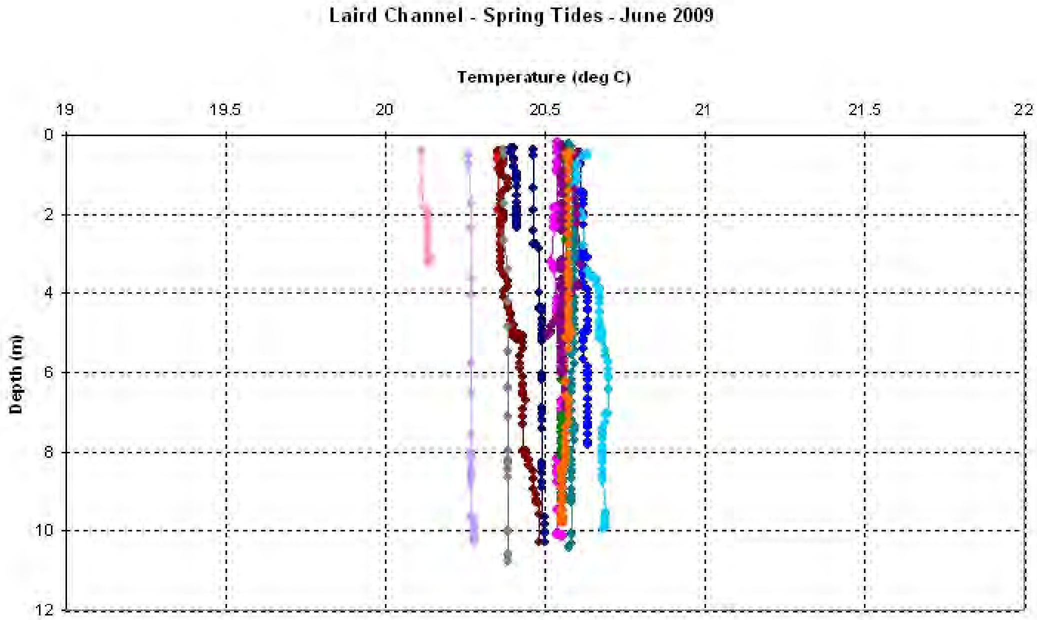


Figure A-6 Laird Point Salinity and Temperature Profiles (26-27 June 2009)

APPENDIX B: VELOCITY PROFILES

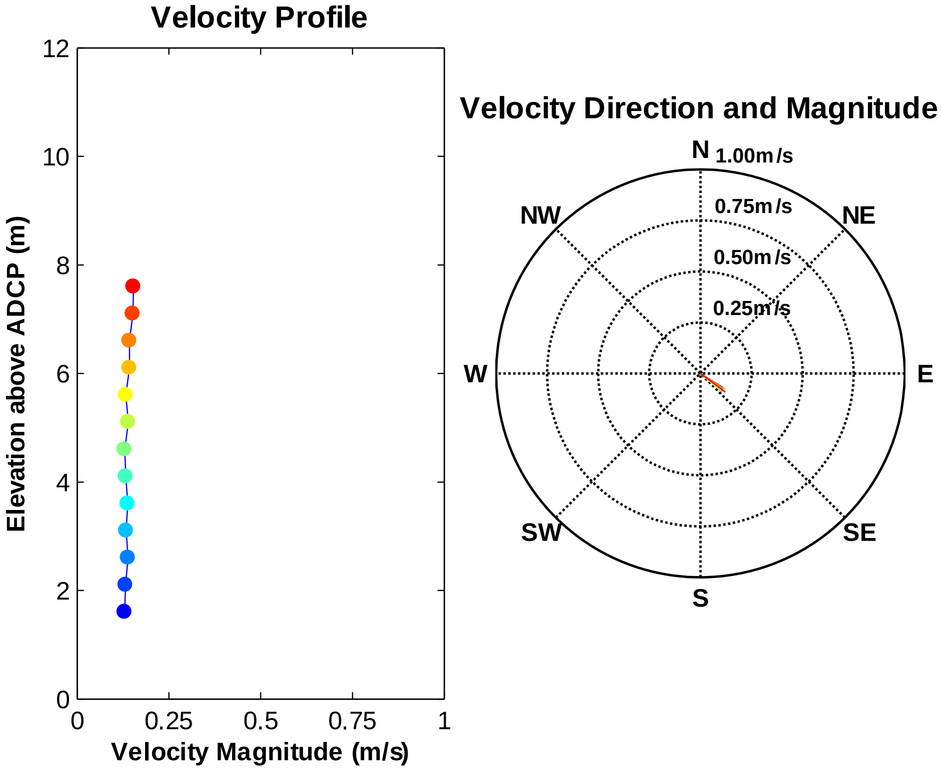


Figure B-1 GHD ADCP Site 1 Spring Tide (25/05/2009 16:00)

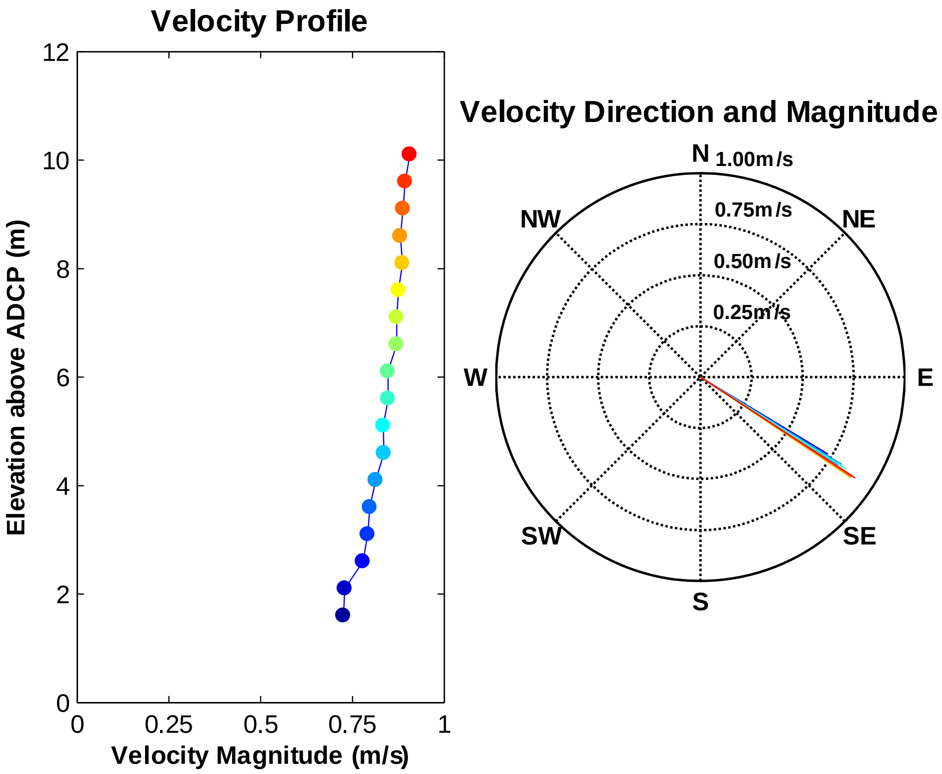


Figure B-2 GHD ADCP Site 1 Spring Tide (25/05/2009 19:00)

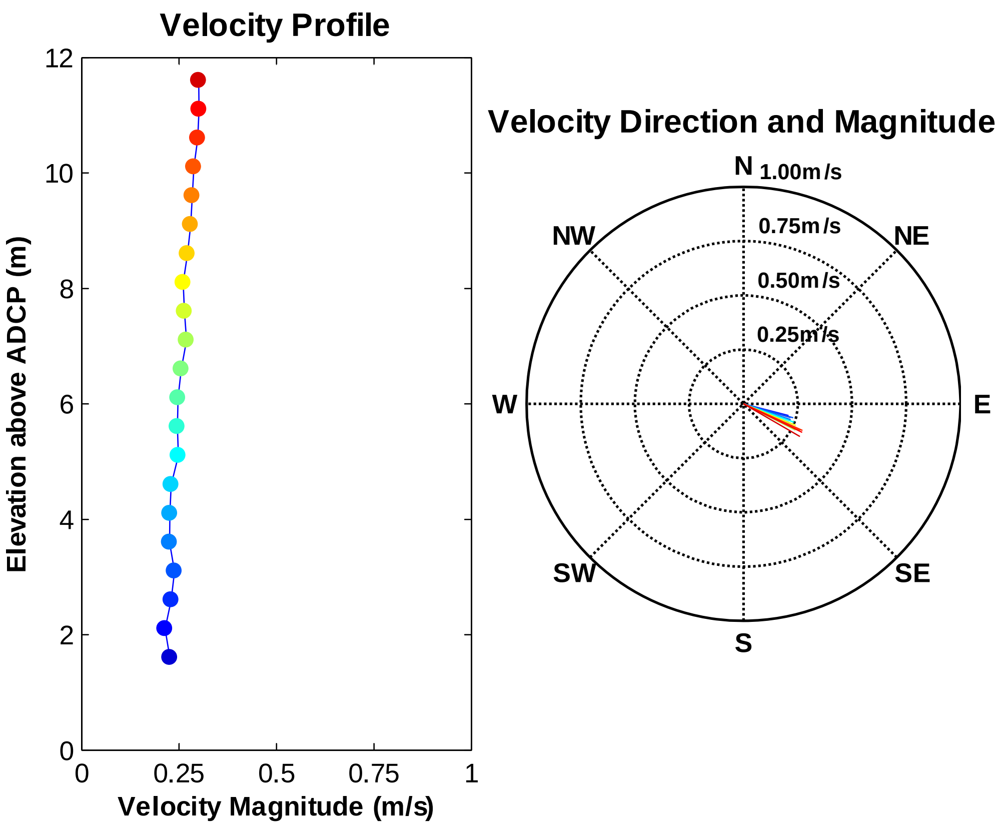


Figure B-3 GHD ADCP Site 1 Spring Tide (25/05/2009 22:00)

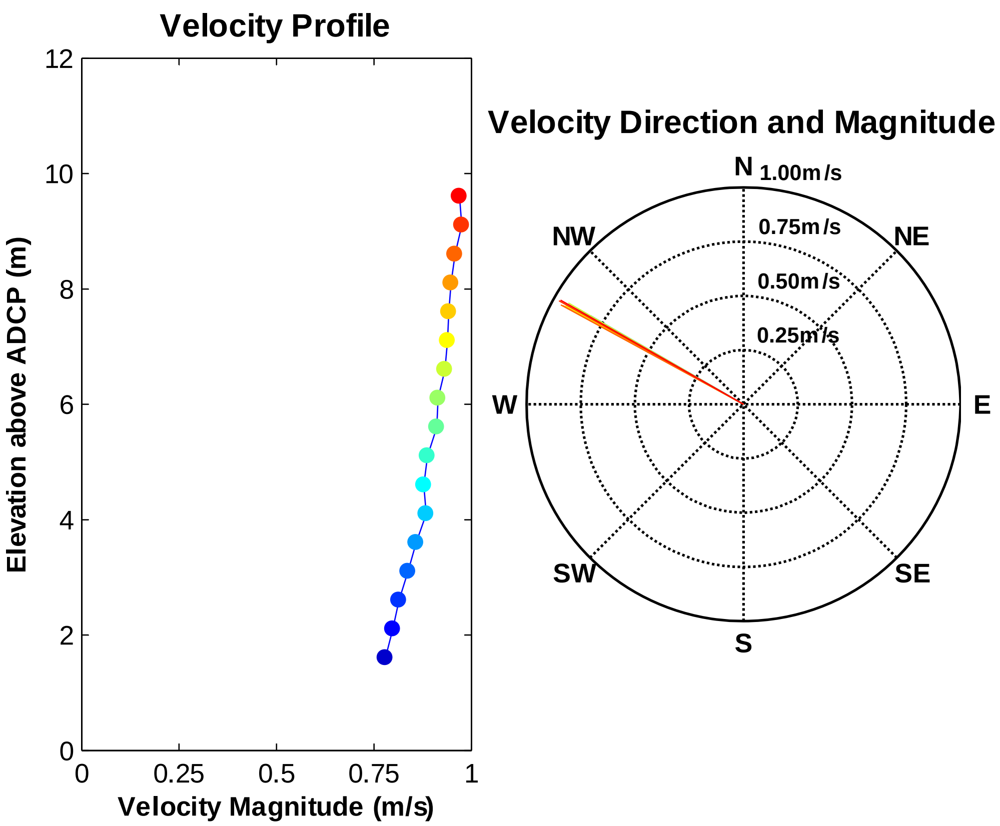


Figure B-4 GHD ADCP Site 1 Spring Tide (26/05/2009 01:00)

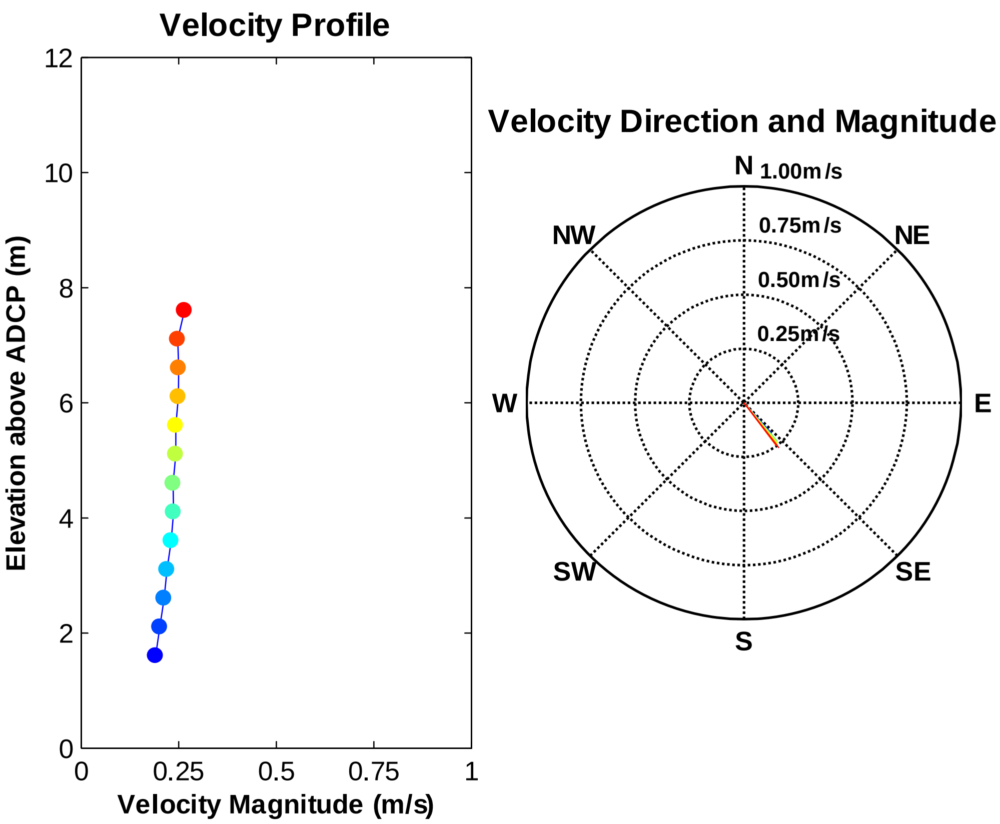


Figure B-5 GHD ADCP Site 2 Spring Tide (25/05/2009 16:00)

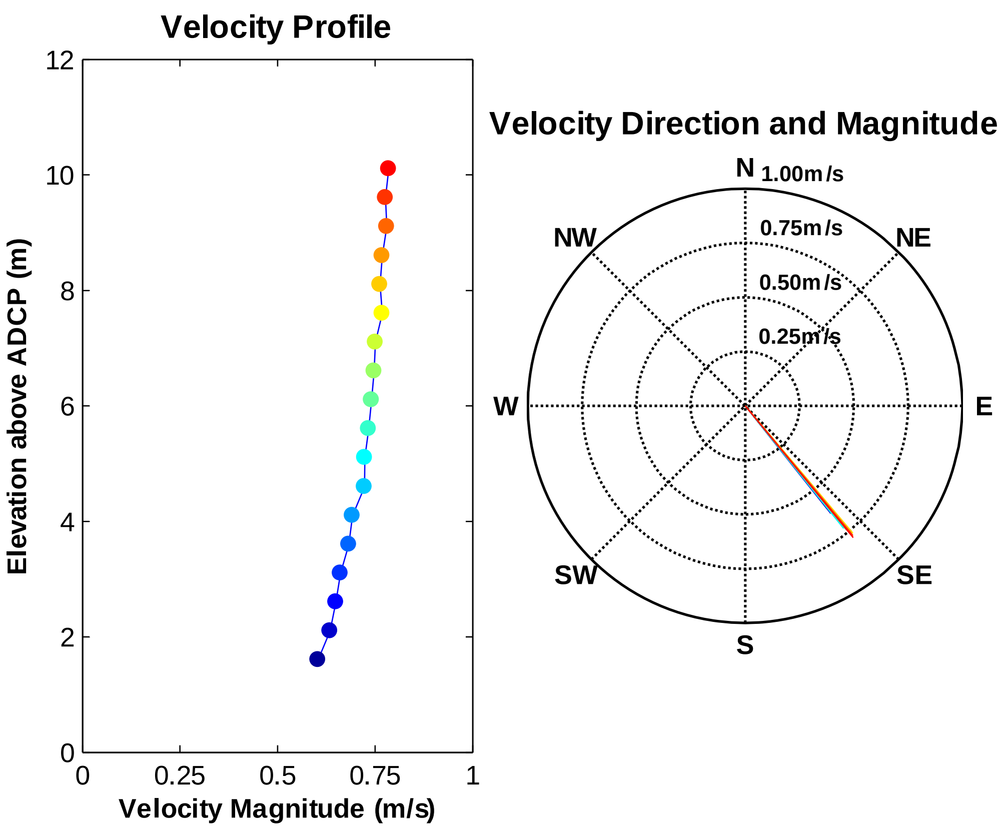


Figure B-6 GHD ADCP Site 2 Spring Tide (25/05/2009 19:00)

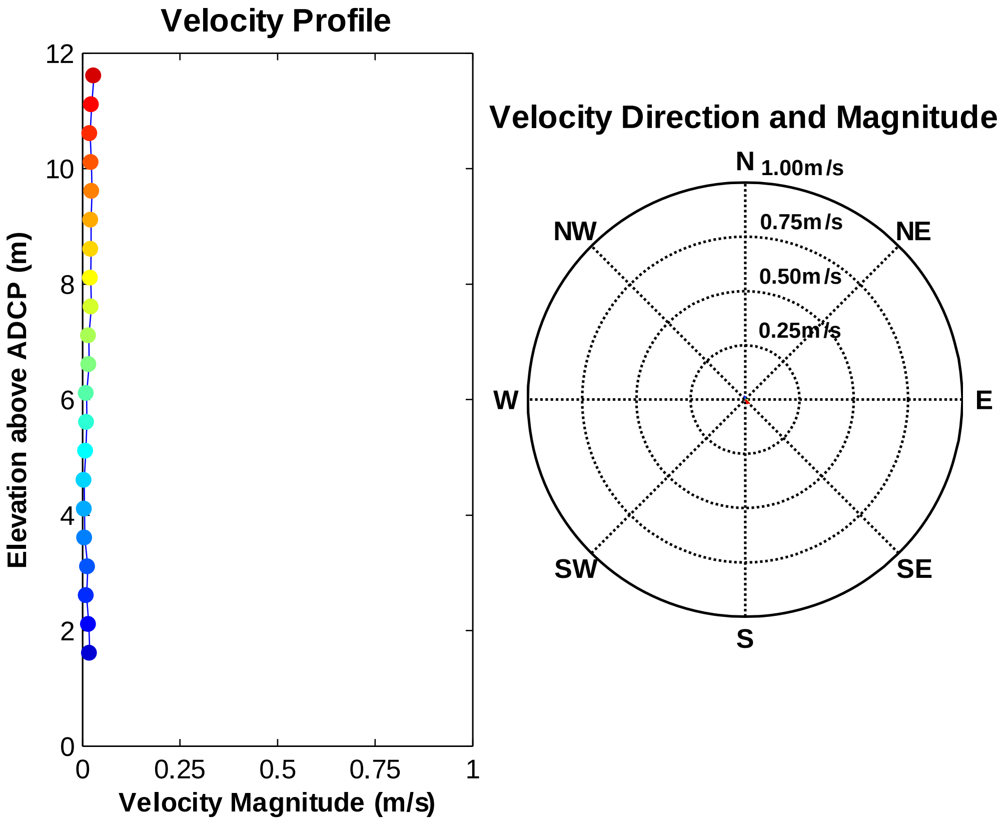


Figure B-7 GHD ADCP Site 2 Spring Tide (25/05/2009 22:00)

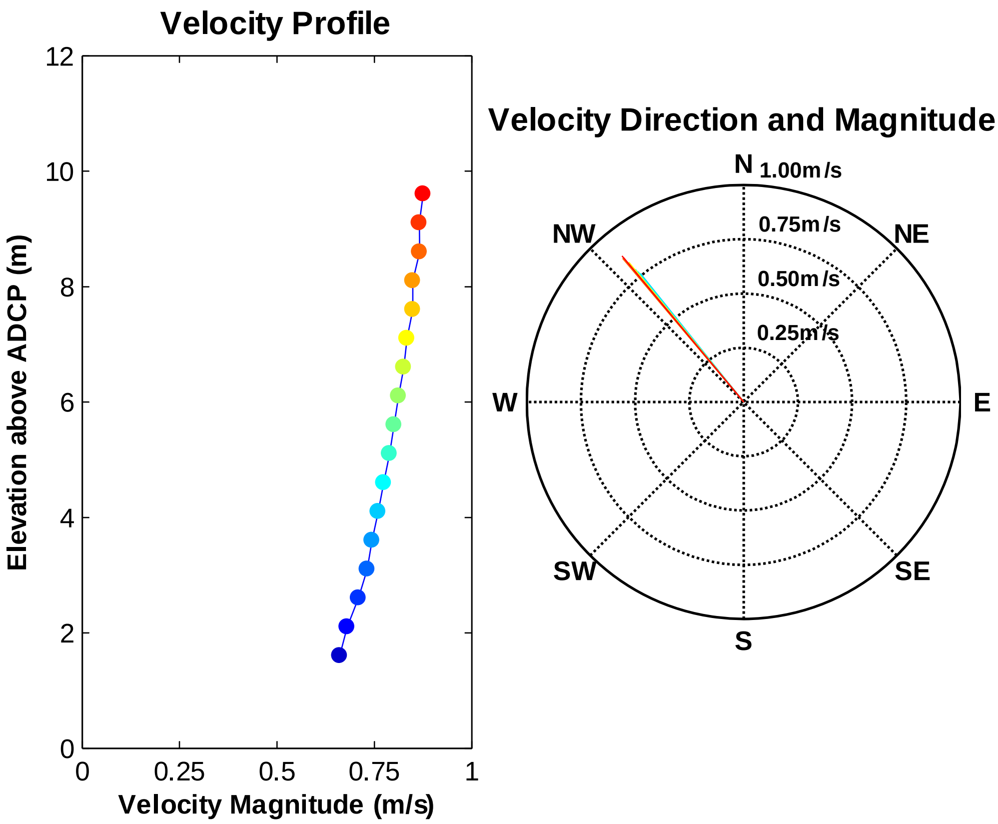


Figure B-8 GHD ADCP Site 2 Spring Tide (26/05/2009 01:00)

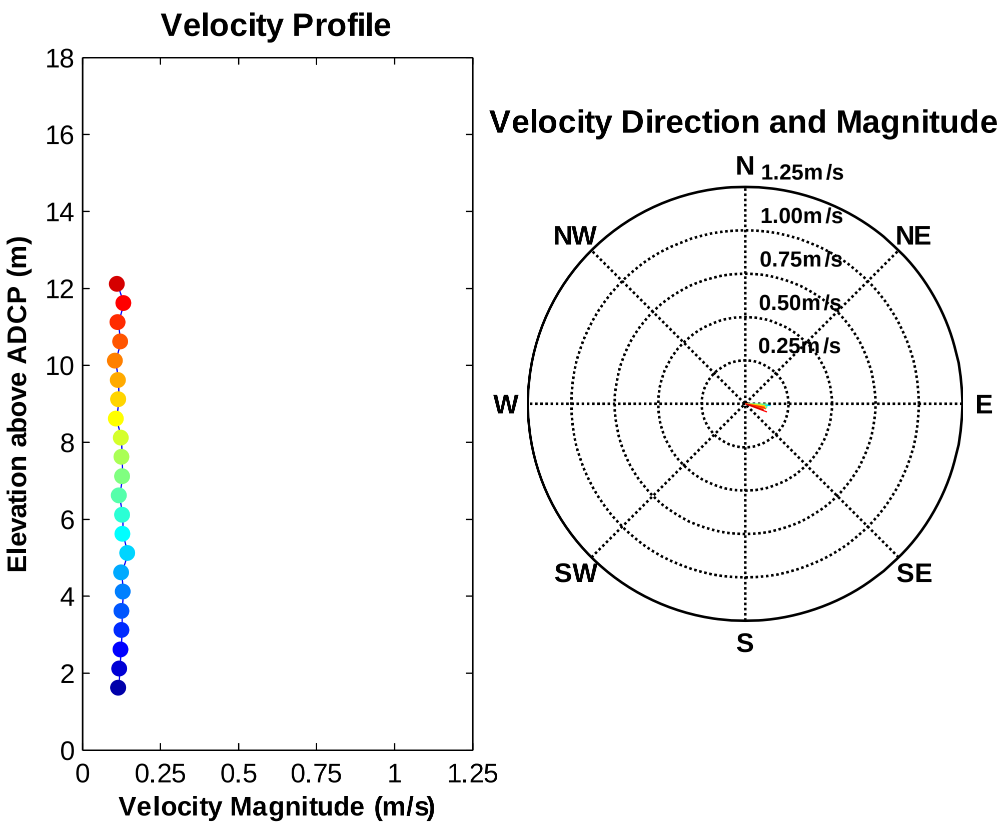


Figure B-9 GHD ADCP Site 3 Spring Tide (25/05/2009 16:00)

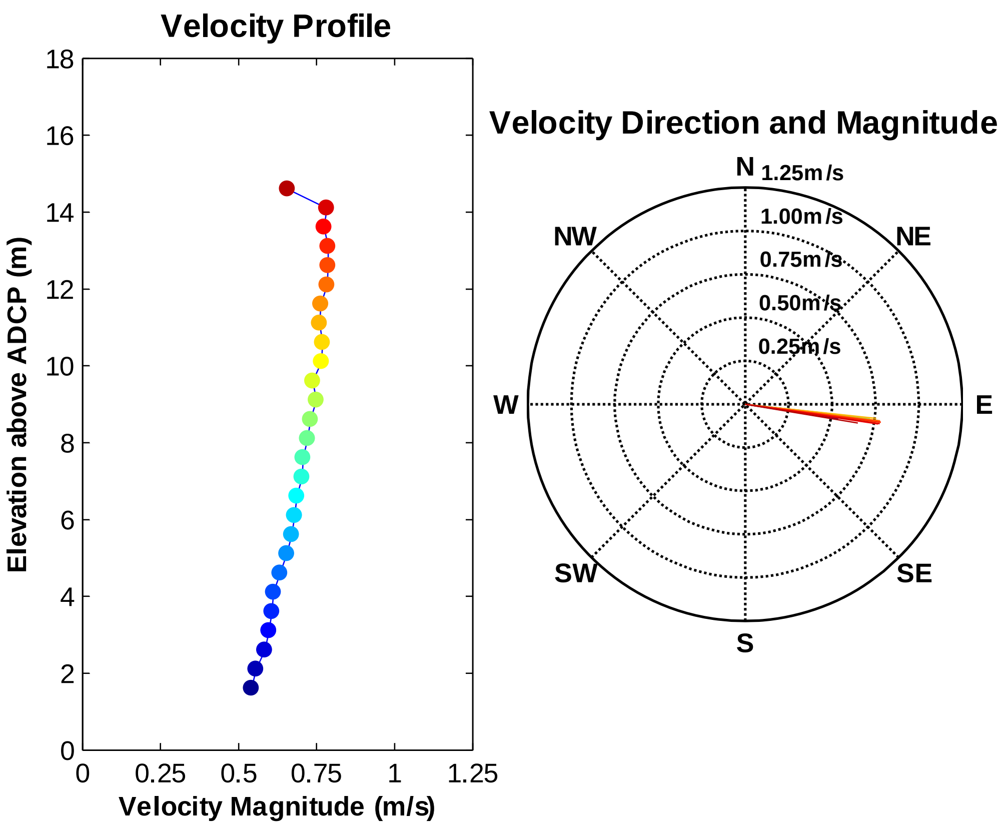


Figure B-10 GHD ADCP Site 3 Spring Tide (25/05/2009 19:00)

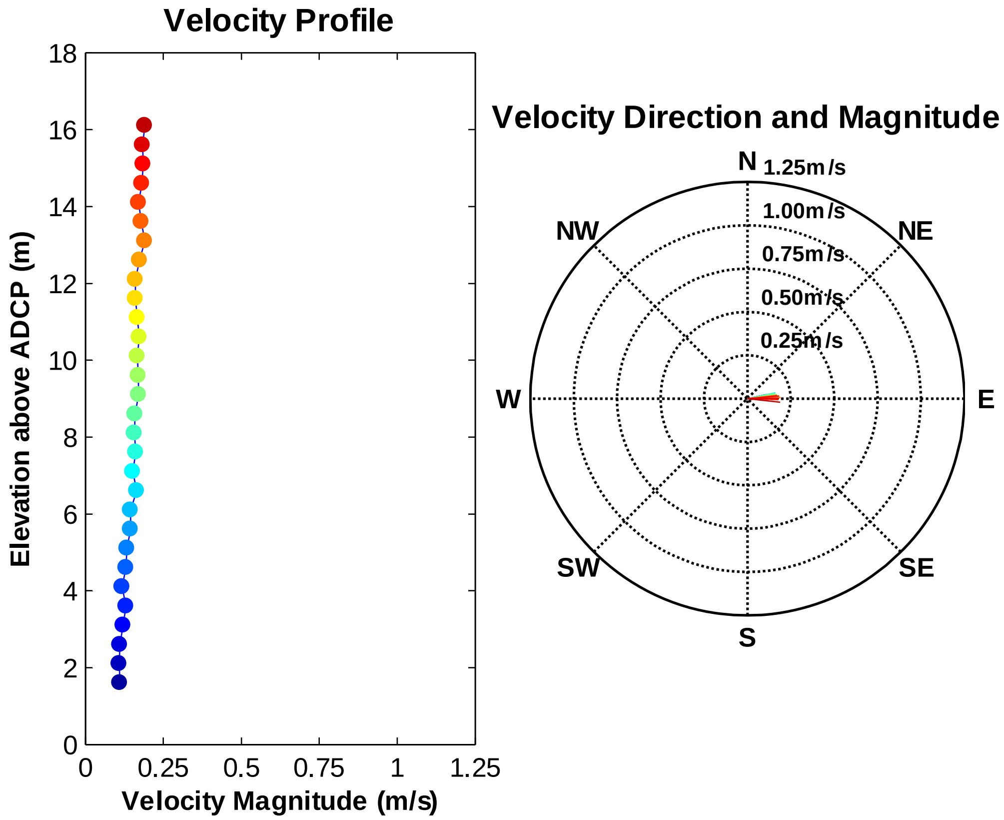


Figure B-11 GHD ADCP Site 3 Spring Tide (25/05/2009 22:00)

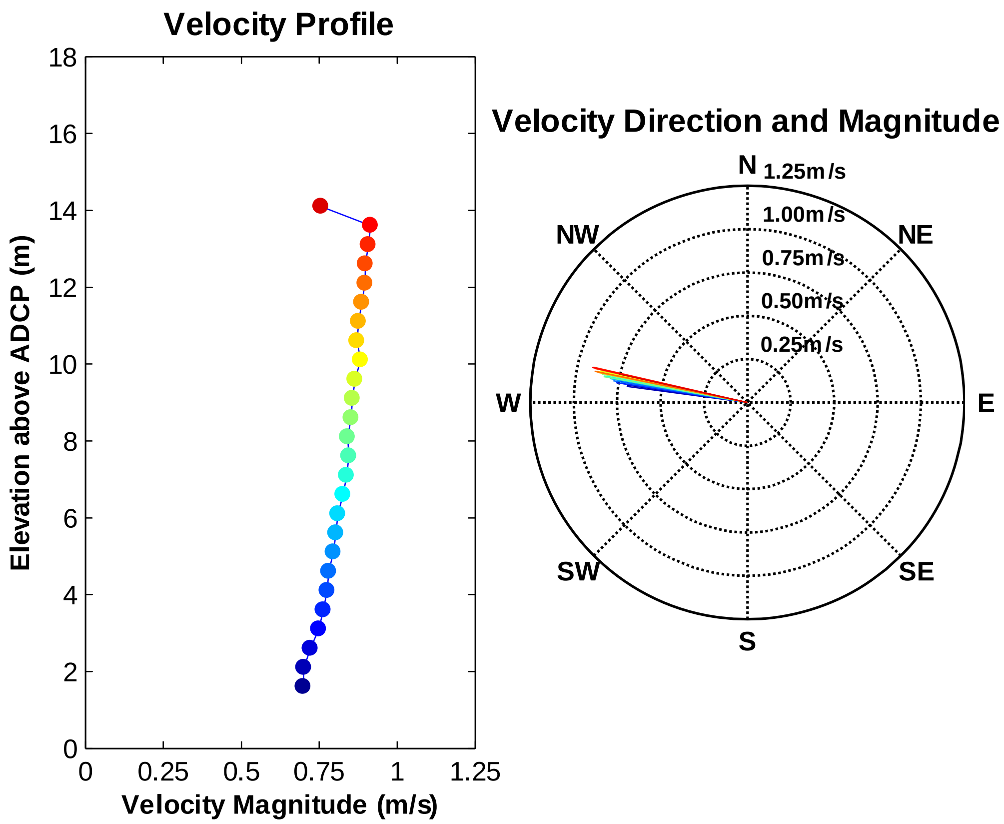


Figure B-12 GHD ADCP Site 3 Spring Tide (26/05/2009 01:00)

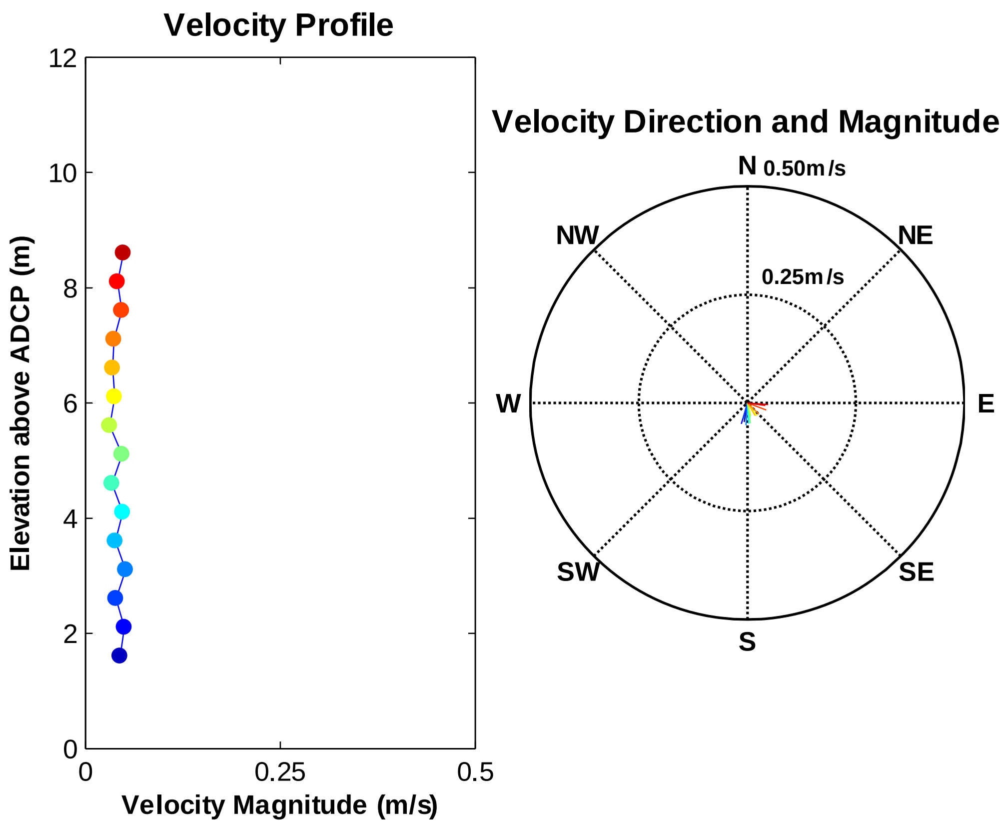


Figure B-13 GHD ADCP Site 1 Neap Tide (15/06/2009 20:30)

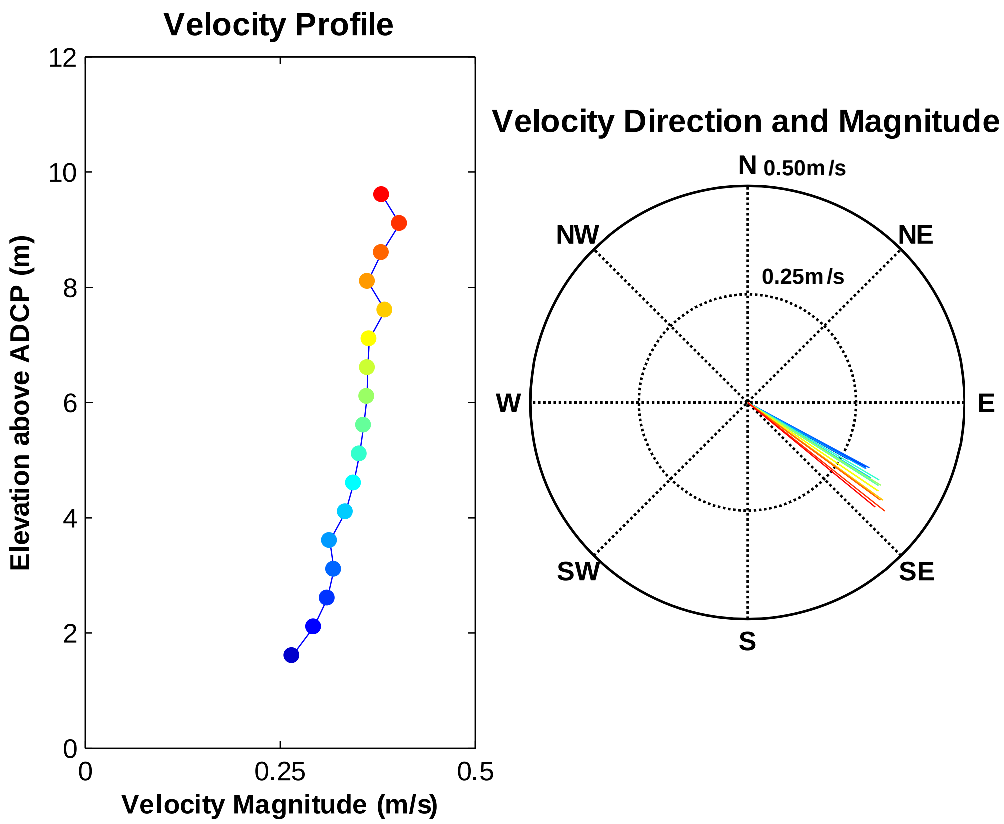


Figure B-14 GHD ADCP Site 1 Neap Tide (15/06/2009 23:30)

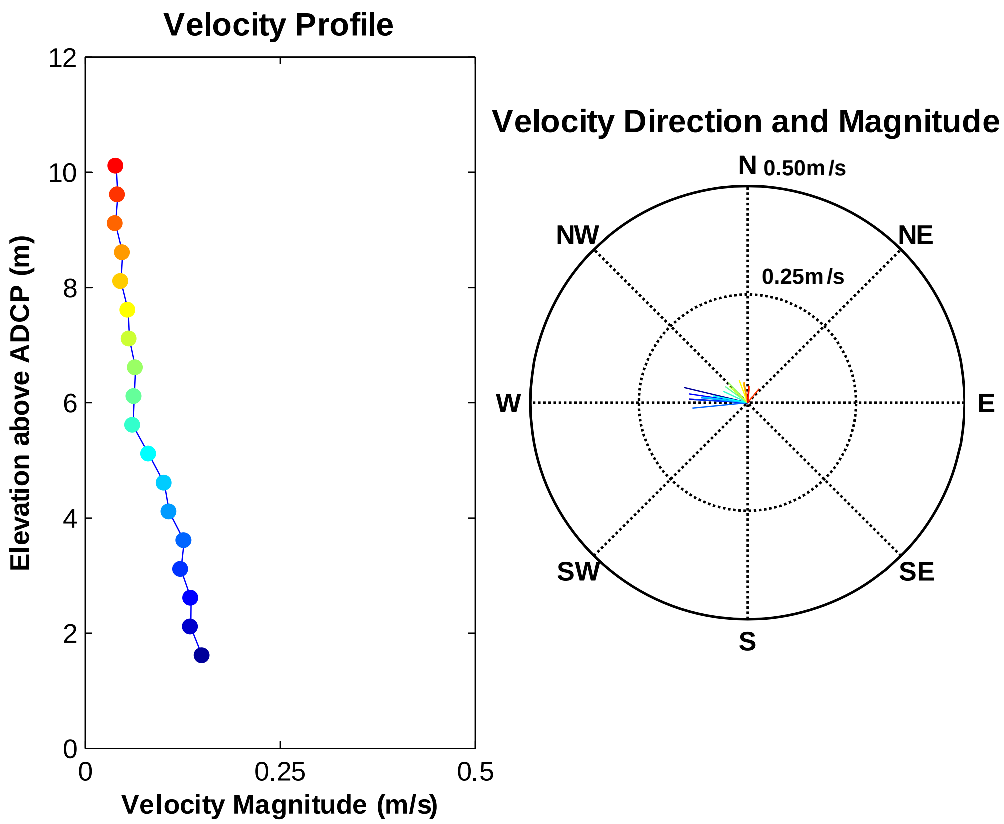


Figure B-15 GHD ADCP Site 1 Neap Tide (16/06/2009 02:30)

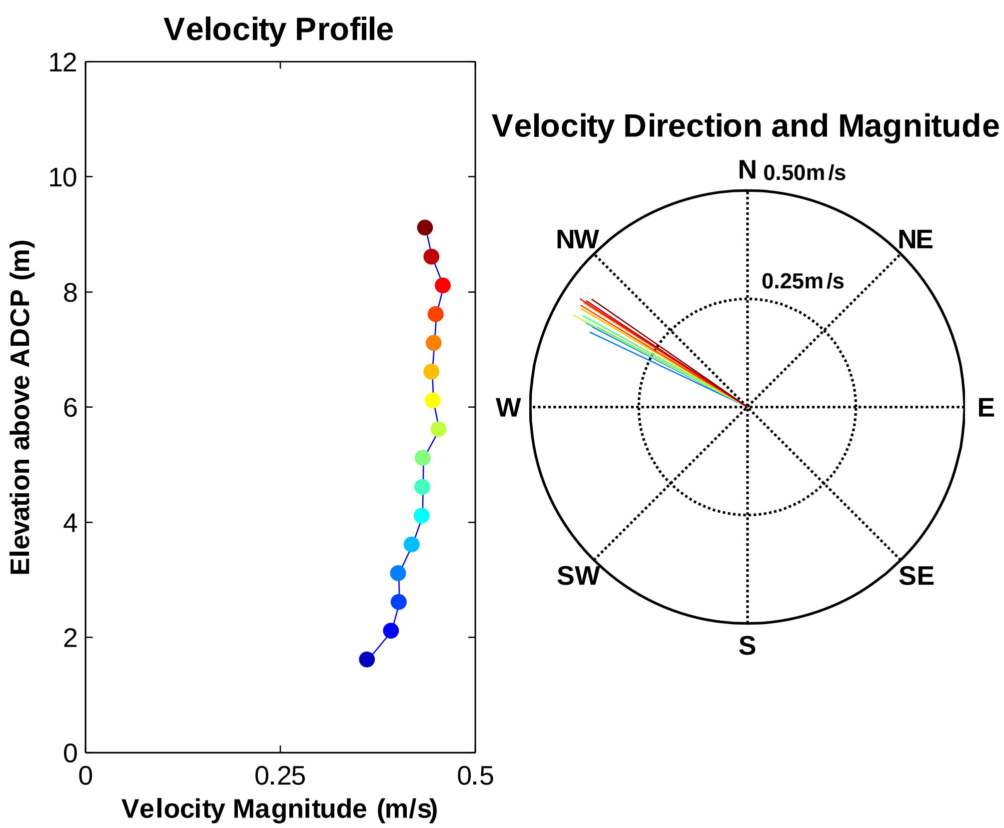


Figure B-16 GHD ADCP Site 1 Neap Tide (16/06/2009 05:30)

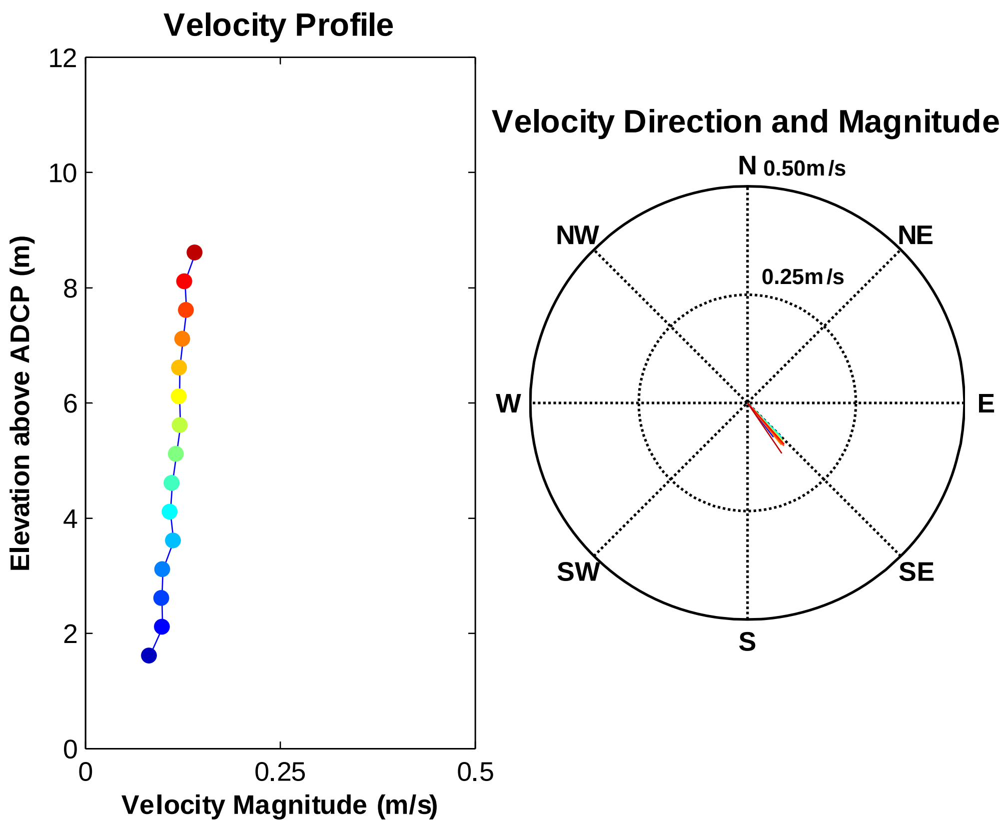


Figure B-17 GHD ADCP Site 2 Neap Tide (15/06/2009 20:30)

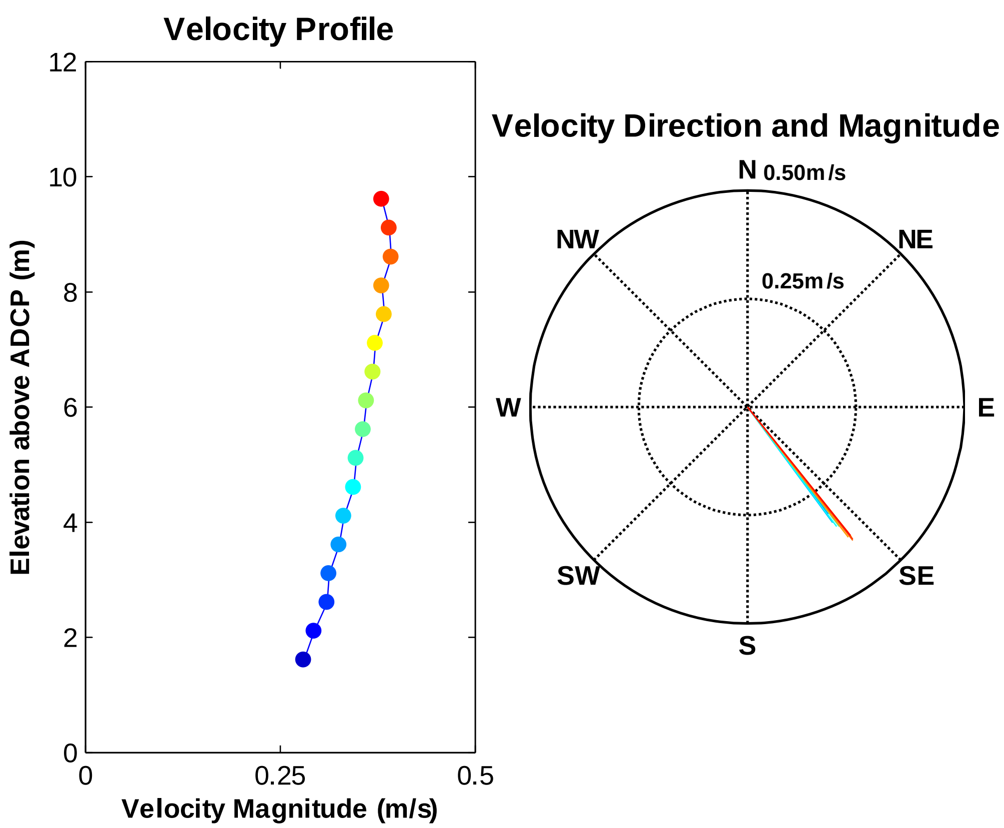


Figure B-18 GHD ADCP Site 2 Neap Tide (15/06/2009 23:30)

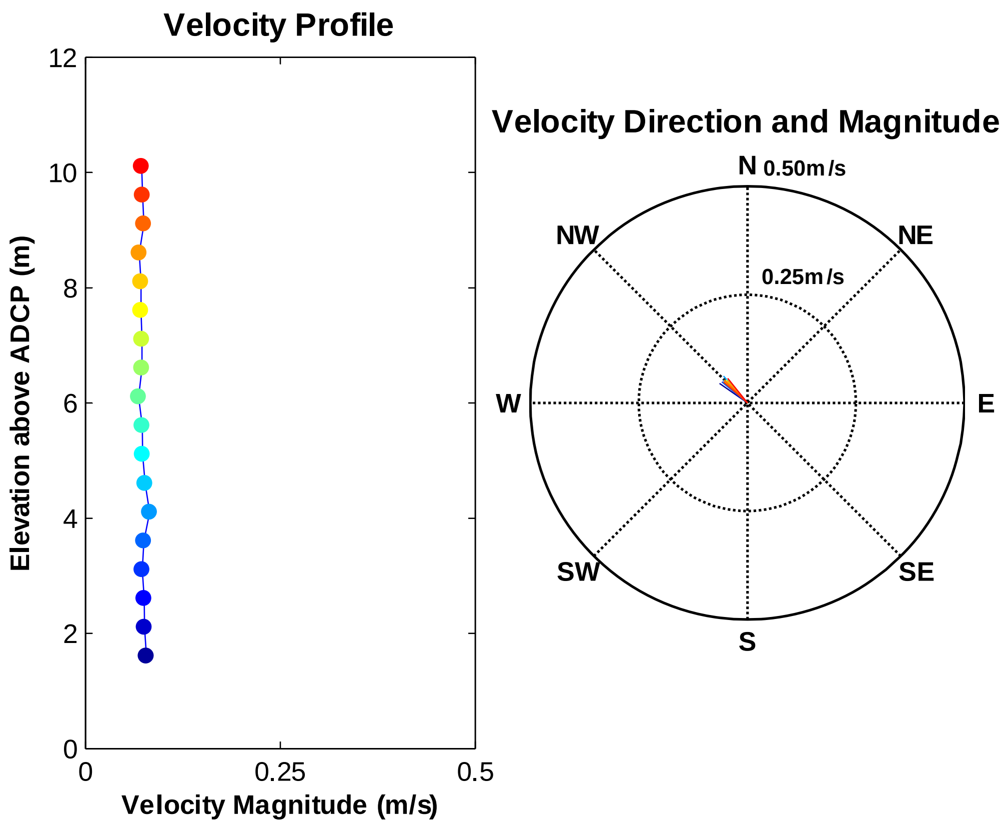


Figure B-19 GHD ADCP Site 2 Neap Tide (16/06/2009 02:30)

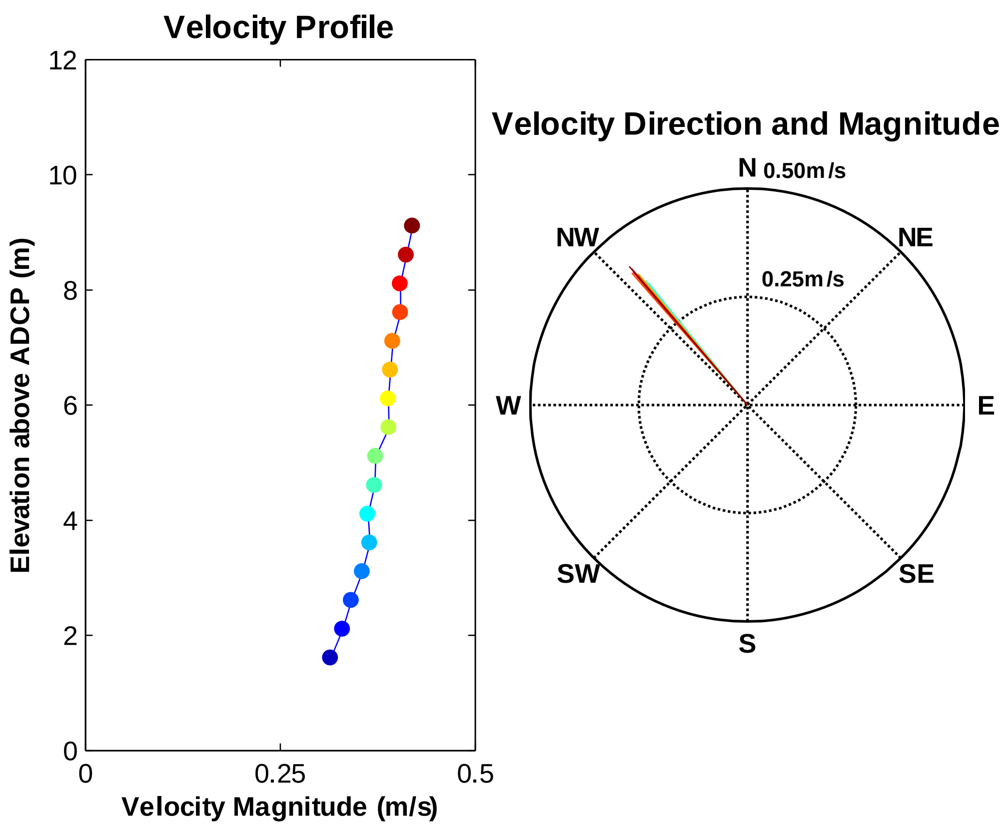


Figure B-20 GHD ADCP Site 2 Neap Tide (16/06/2009 05:30)

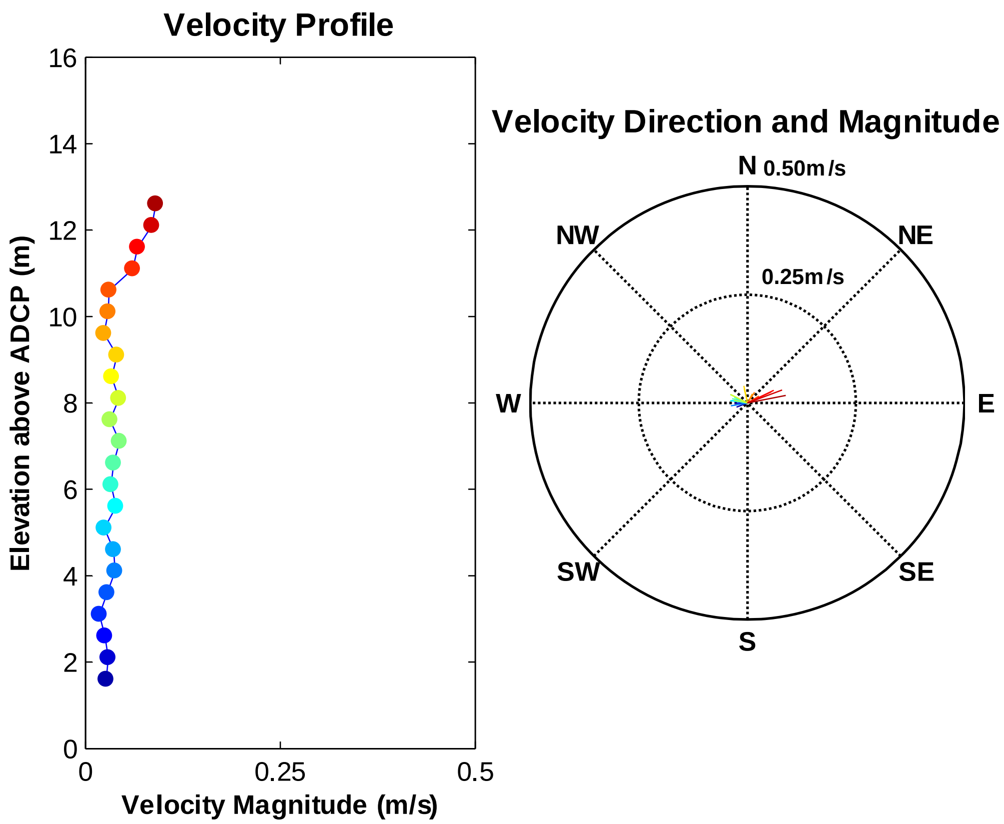


Figure B-21 GHD ADCP Site 3 Neap Tide (15/06/2009 20:30)

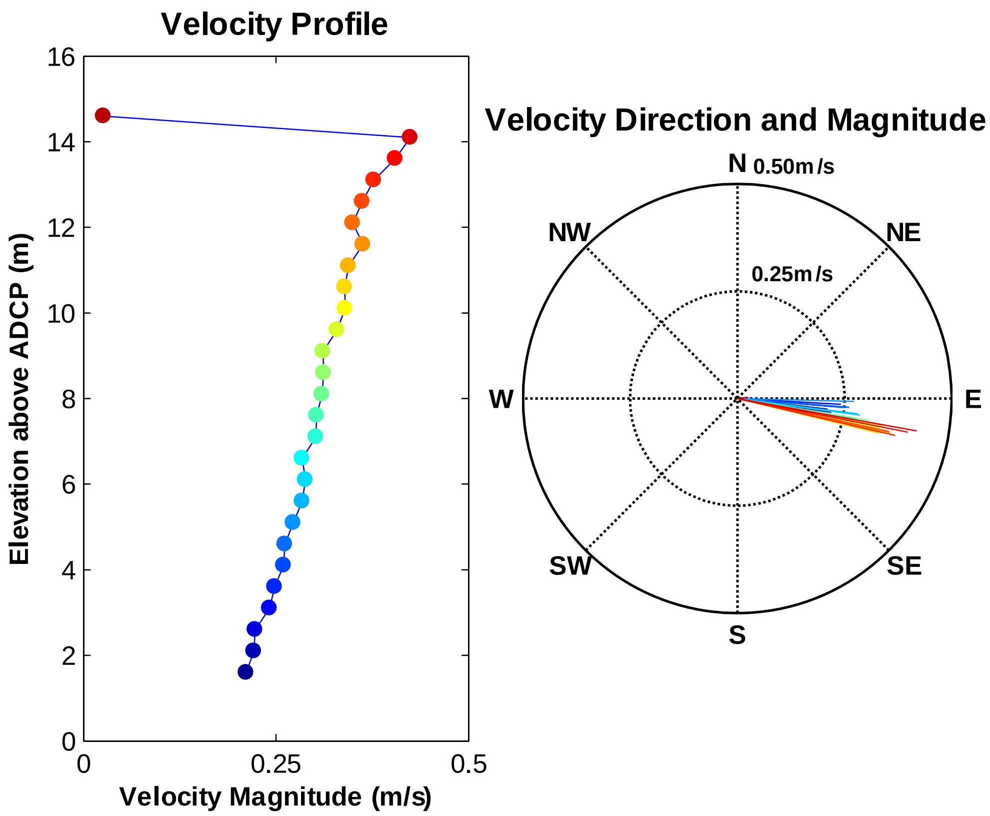


Figure B-22 GHD ADCP Site 3 Neap Tide (15/06/2009 23:30)

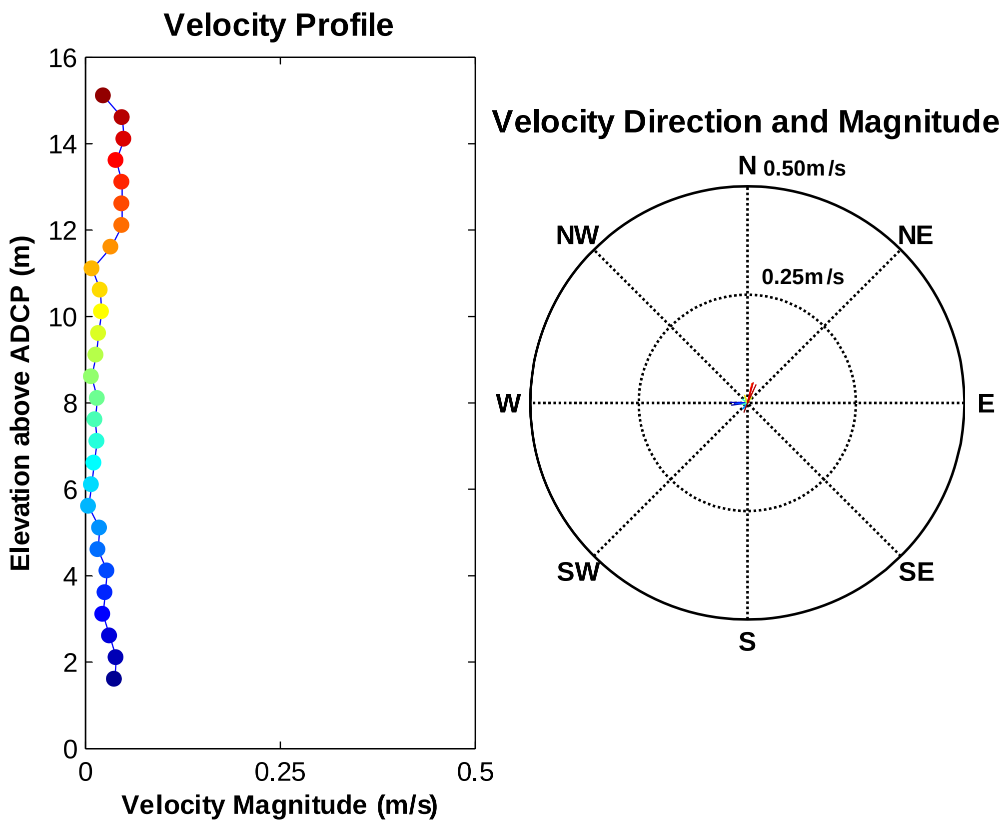


Figure B-23 GHD ADCP Site 3 Neap Tide (16/06/2009 02:30)

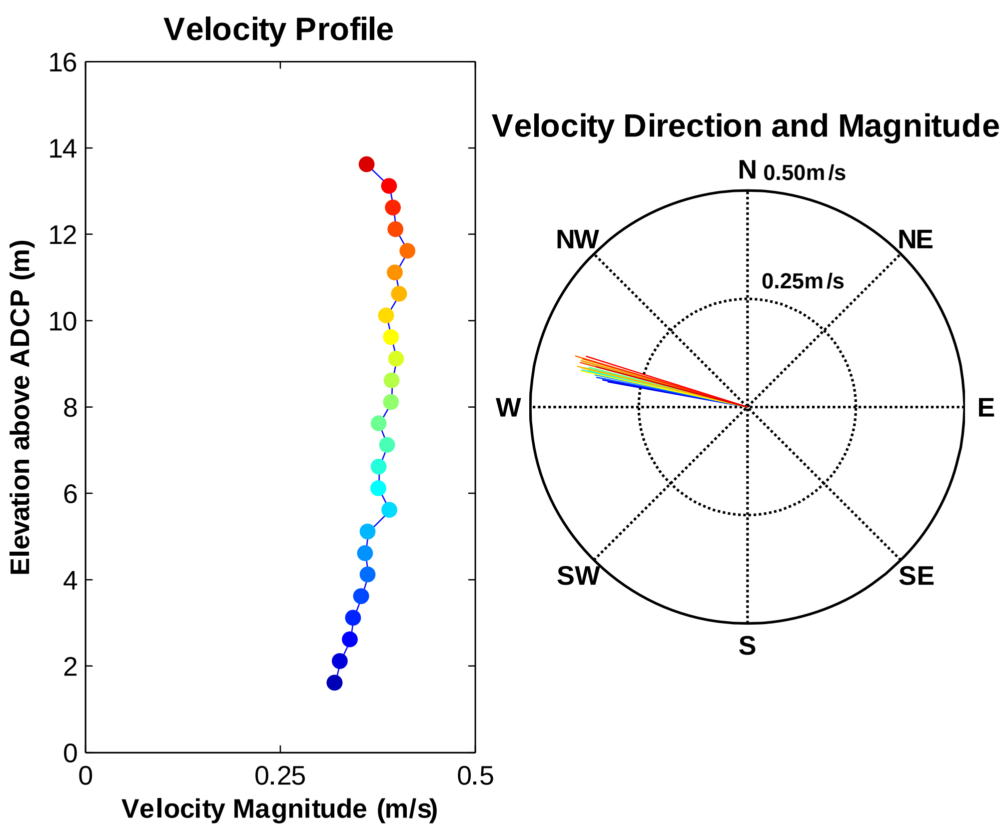


Figure B-24 GHD ADCP Site 3 Neap Tide (16/06/2009 05:30)

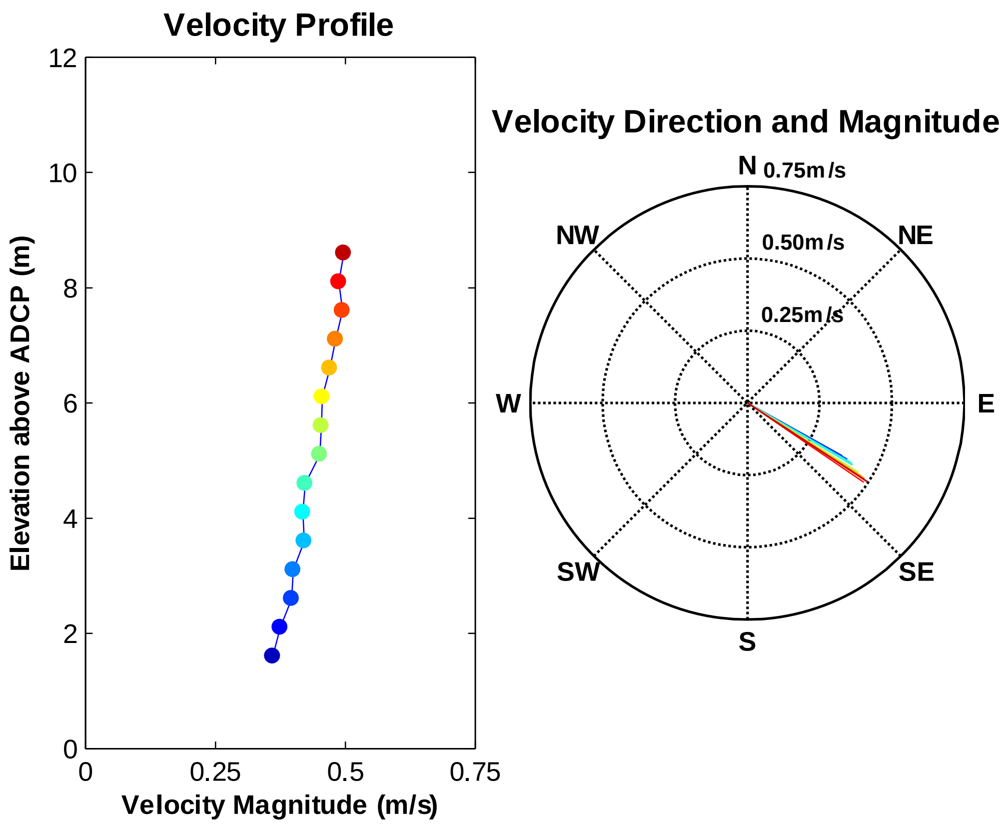


Figure B-25 GHD ADCP Site 1 Windy Period (01/06/2009 12:00)

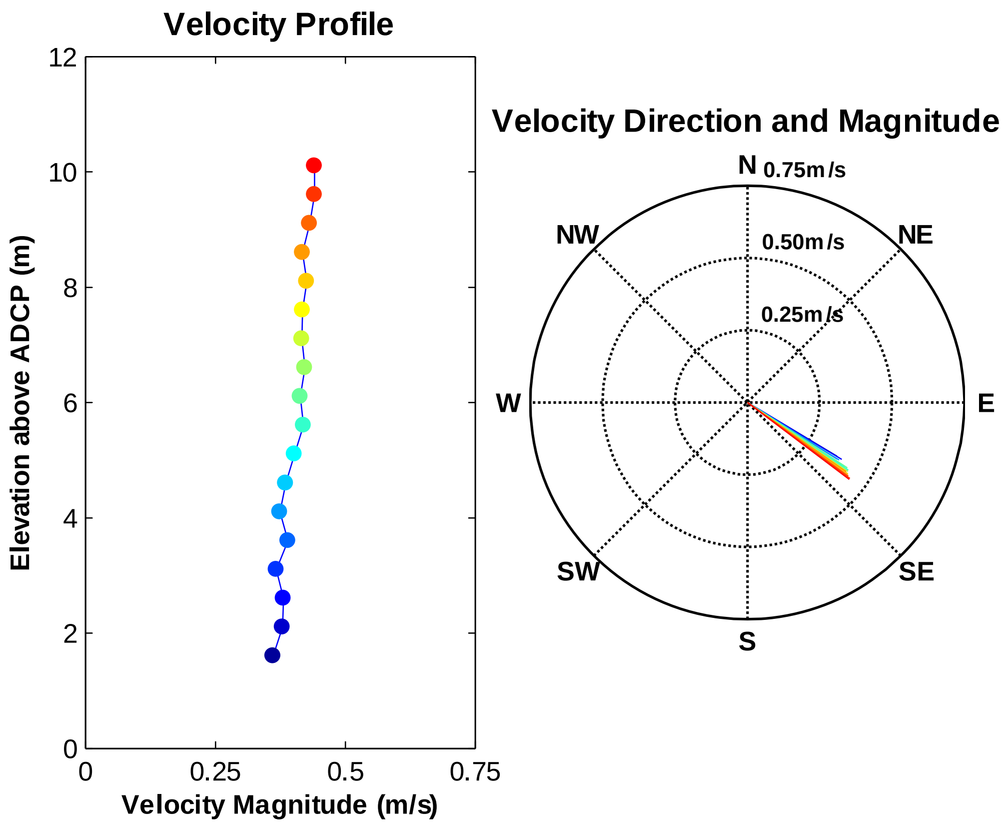


Figure B-26 GHD ADCP Site 1 Windy Period (01/06/2009 15:00)

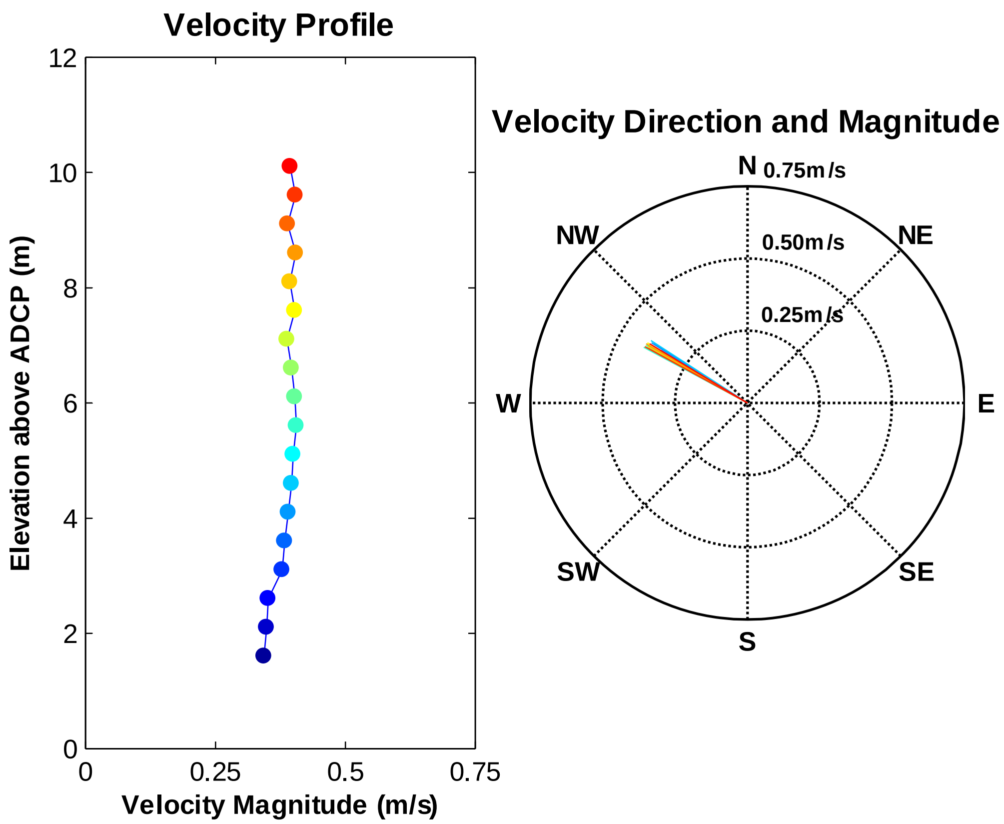


Figure B-27 GHD ADCP Site 1 Windy Period (01/06/2009 18:00)

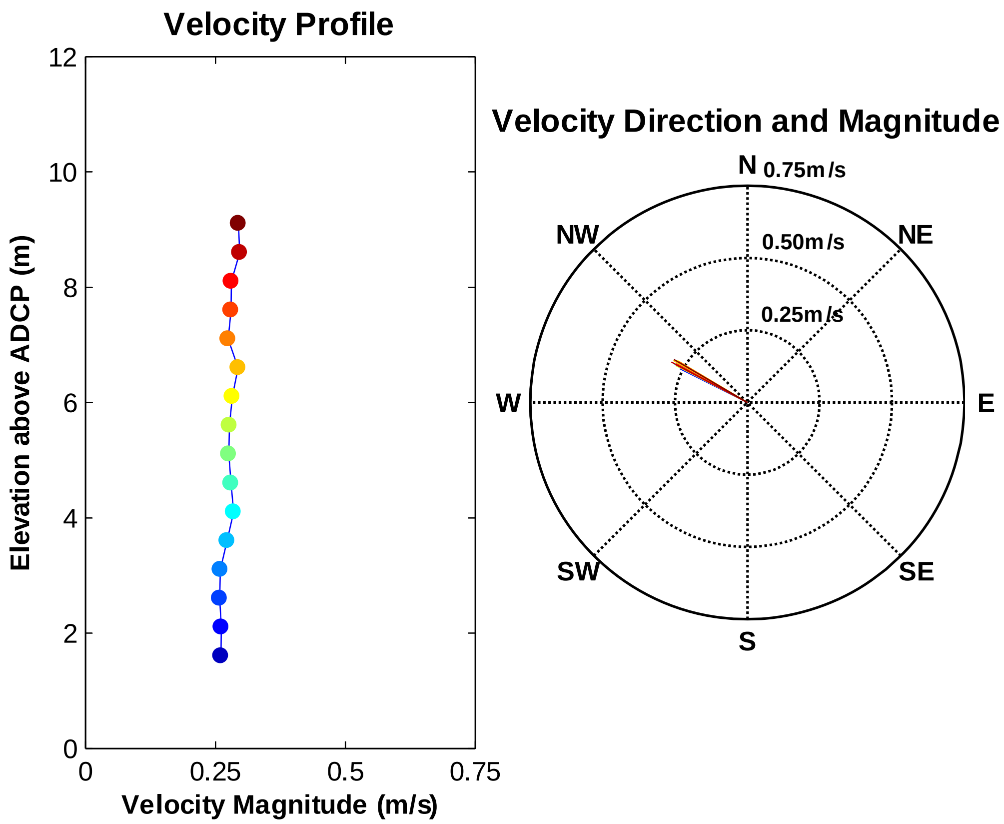


Figure B-28 GHD ADCP Site 1 Windy Period (01/06/2009 21:00)

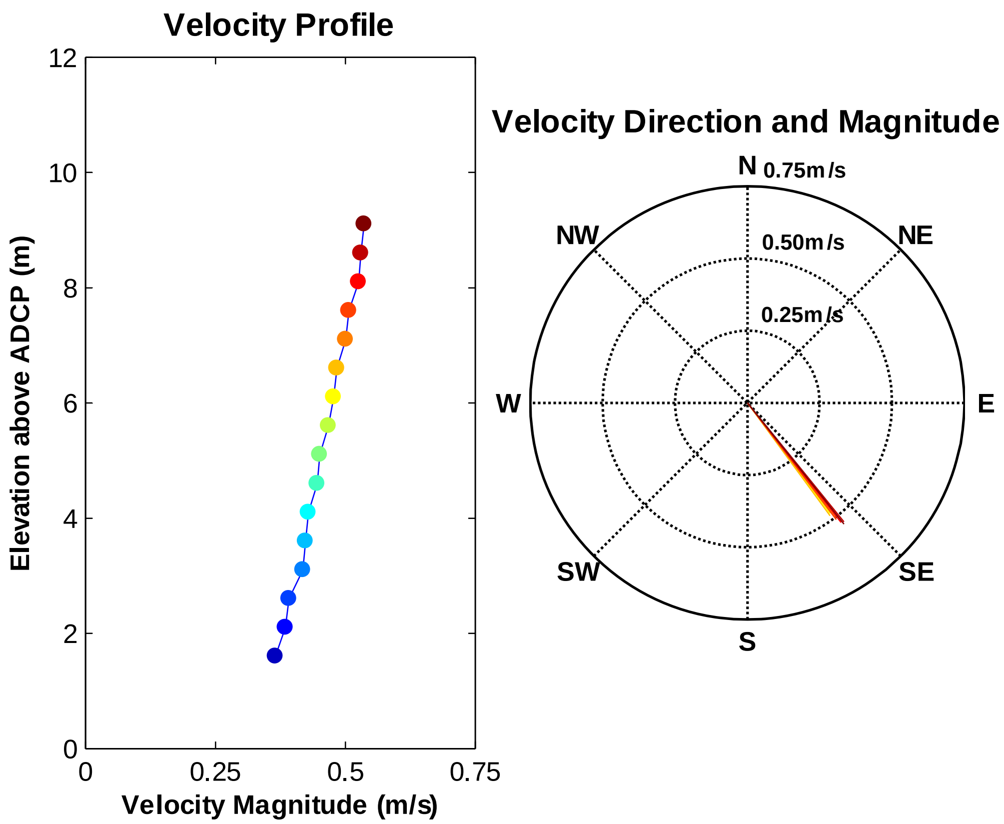


Figure B-29 GHD ADCP Site 2 Windy Period (01/06/2009 12:00)

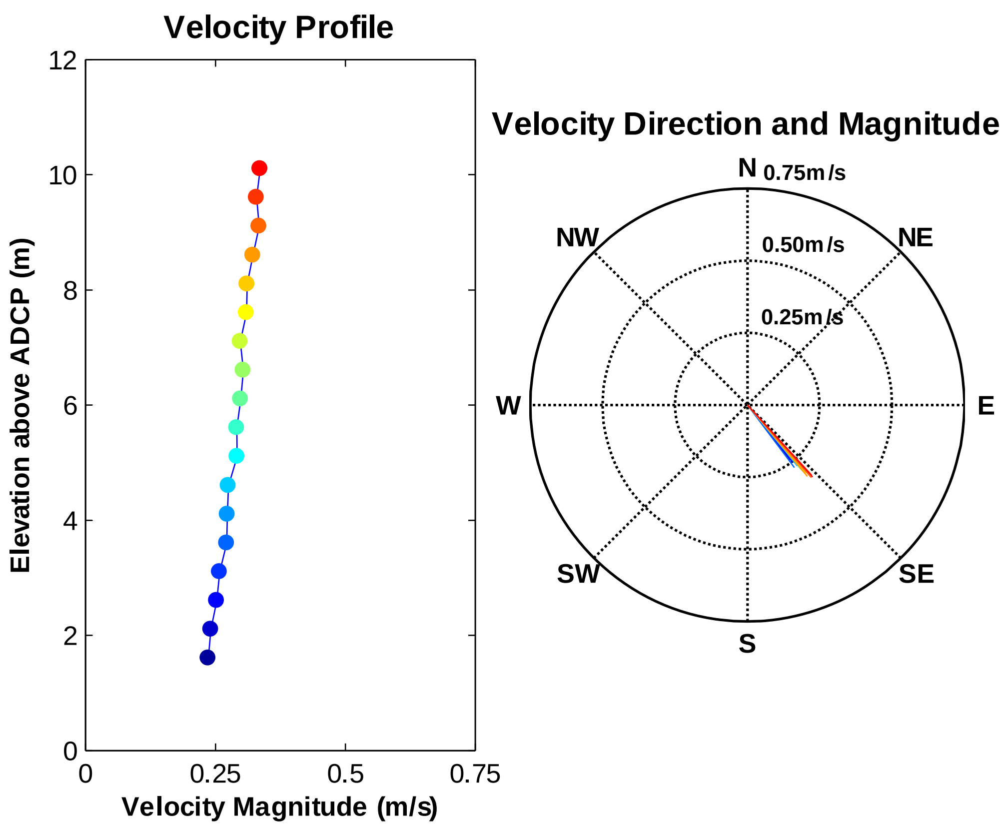


Figure B-30 GHD ADCP Site 2 Windy Period (01/06/2009 15:00)

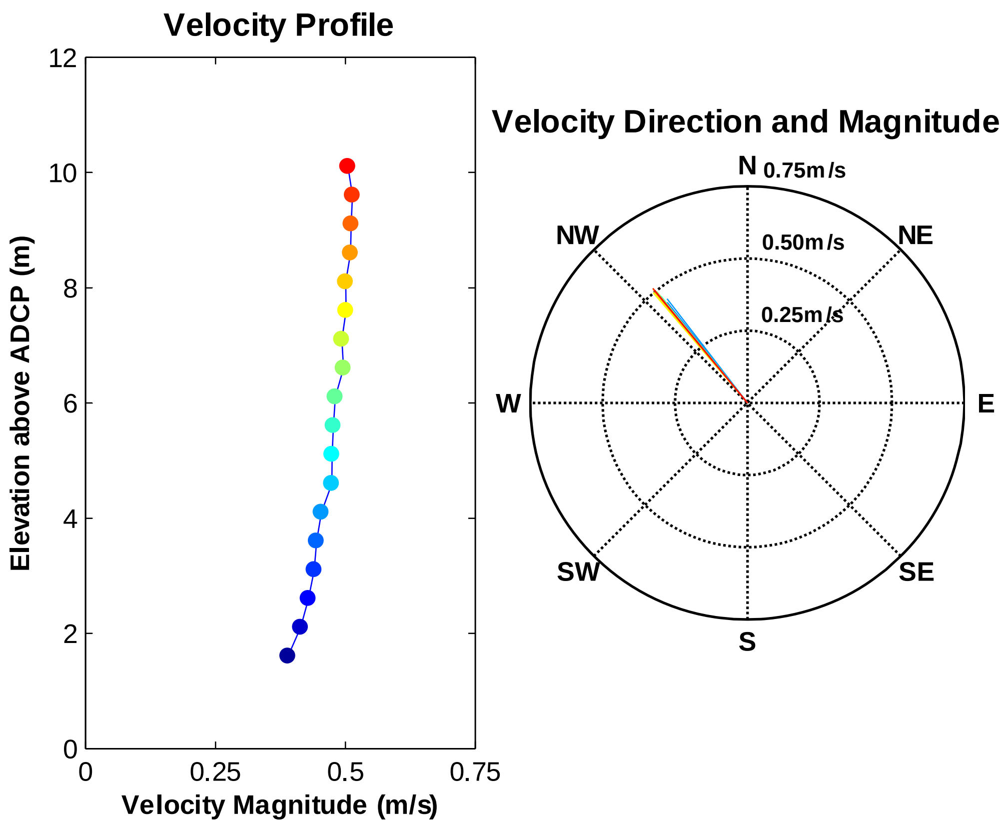


Figure B-31 GHD ADCP Site 2 Windy Period (01/06/2009 18:00)

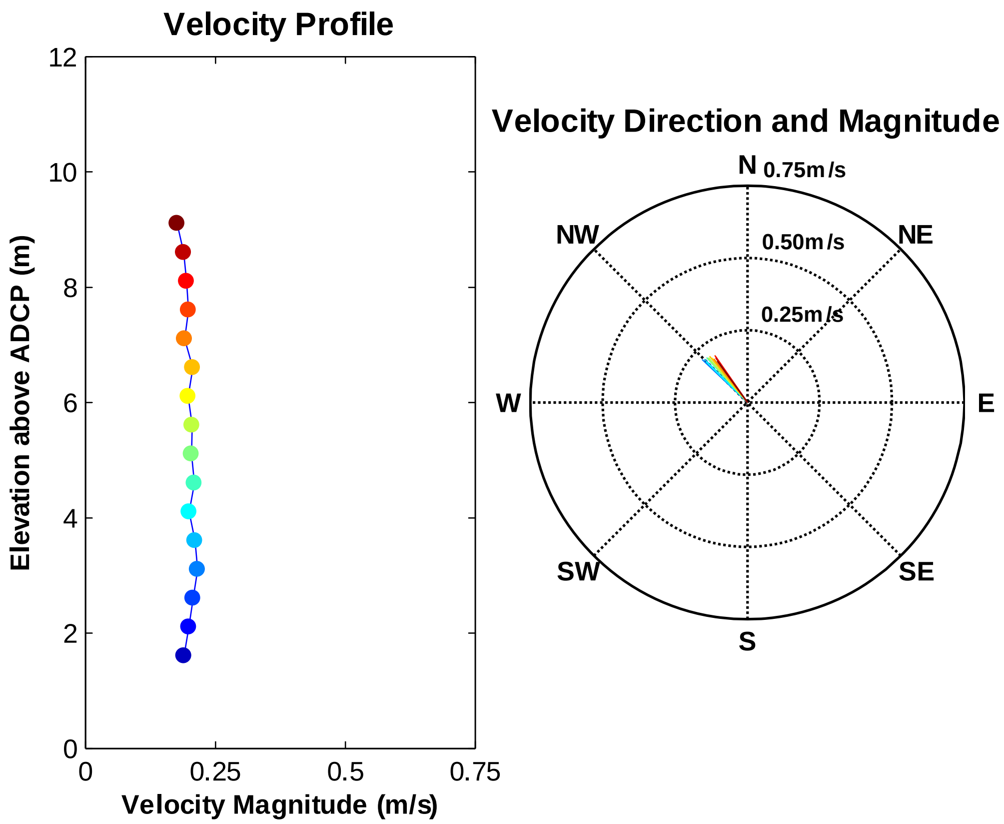


Figure B-32 GHD ADCP Site 2 Windy Period (01/06/2009 21:00)

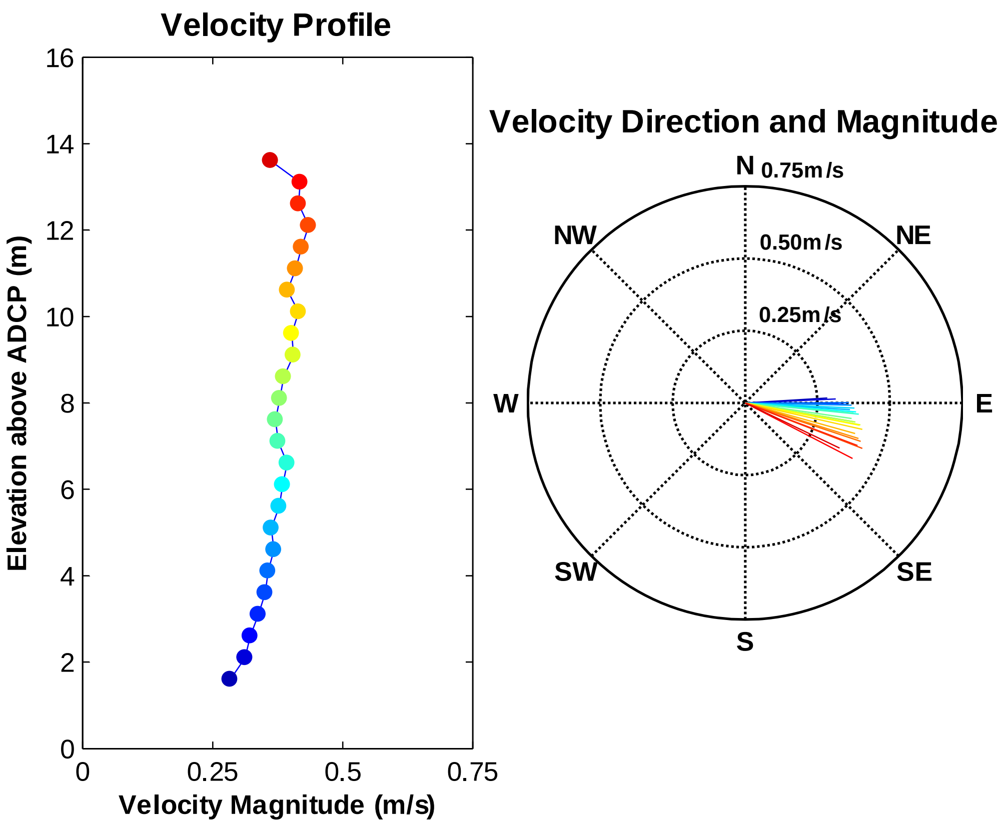


Figure B-33 GHD ADCP Site 3 Windy Period (01/06/2009 12:00)

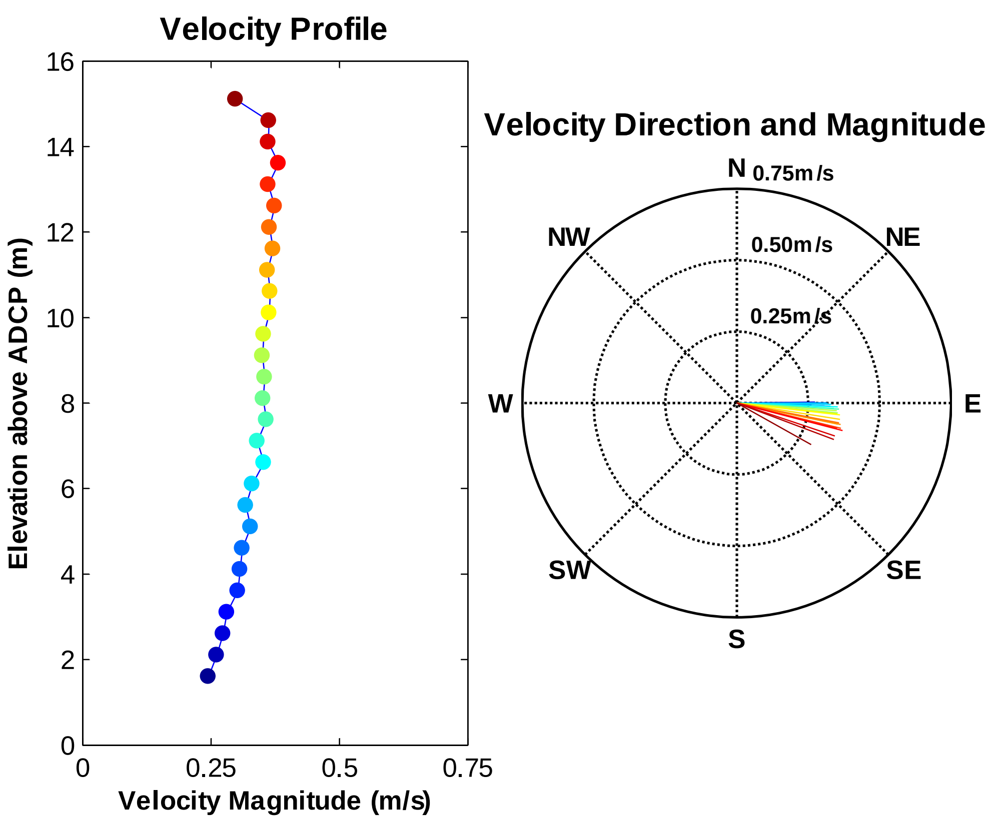


Figure B-34 GHD ADCP Site 3 Windy Period (01/06/2009 15:00)

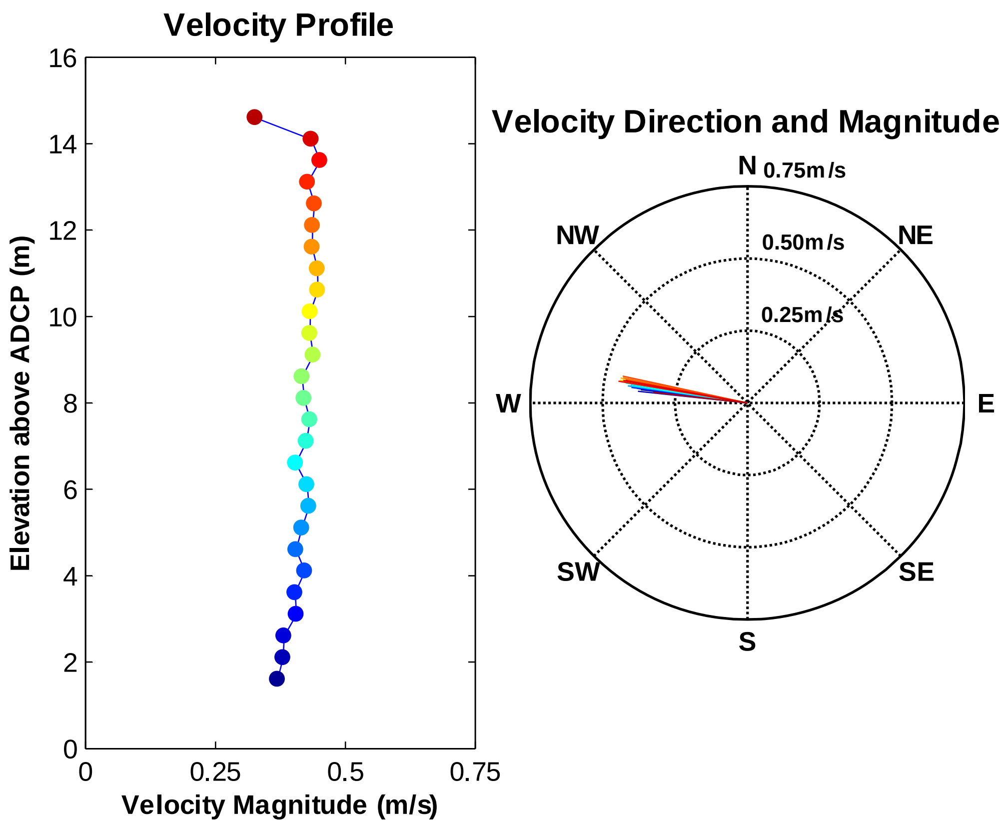


Figure B-35 GHD ADCP Site 3 Windy Period (01/06/2009 18:00)

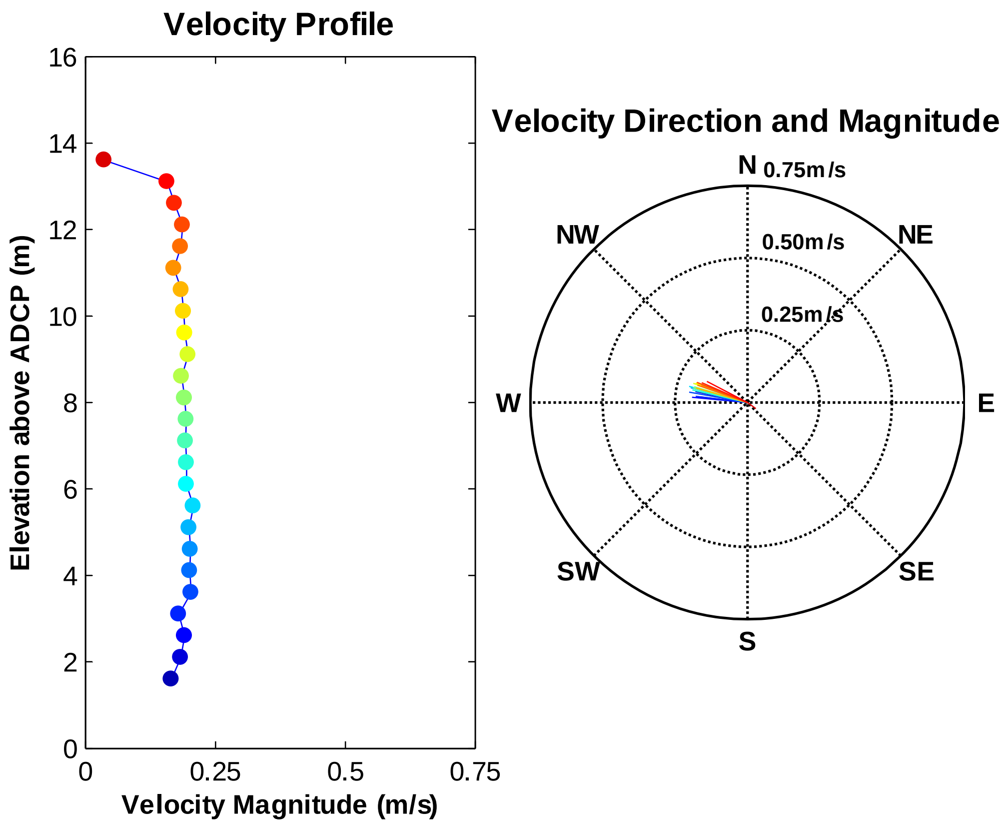


Figure B-36 GHD ADCP Site 3 Windy Period (01/06/2009 21:00)

APPENDIX C: CURRENT VELOCITY PLOTS APRIL 2006

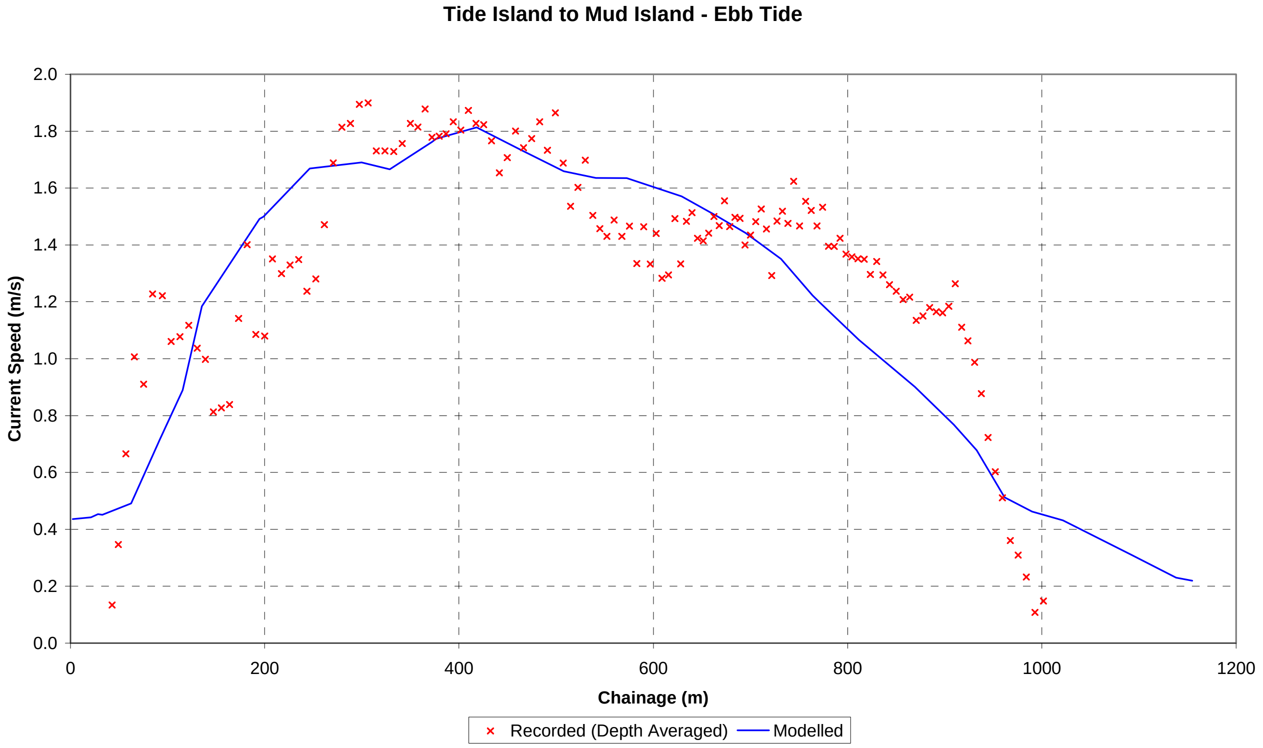


Figure C-1 Current Speed – Tide Island to Mud Island, April 2006: Ebb Tide

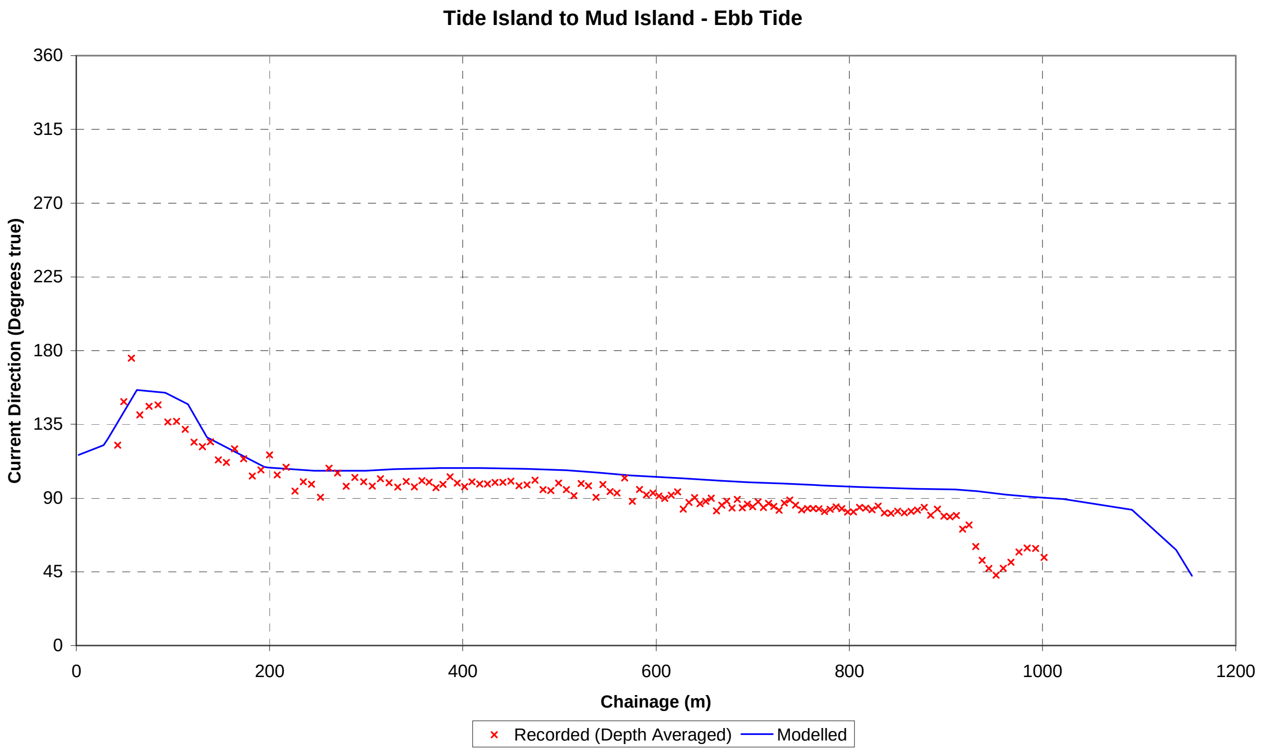


Figure C-2 Current Direction – Tide Island to Mud Island, April 2006: Ebb Tide

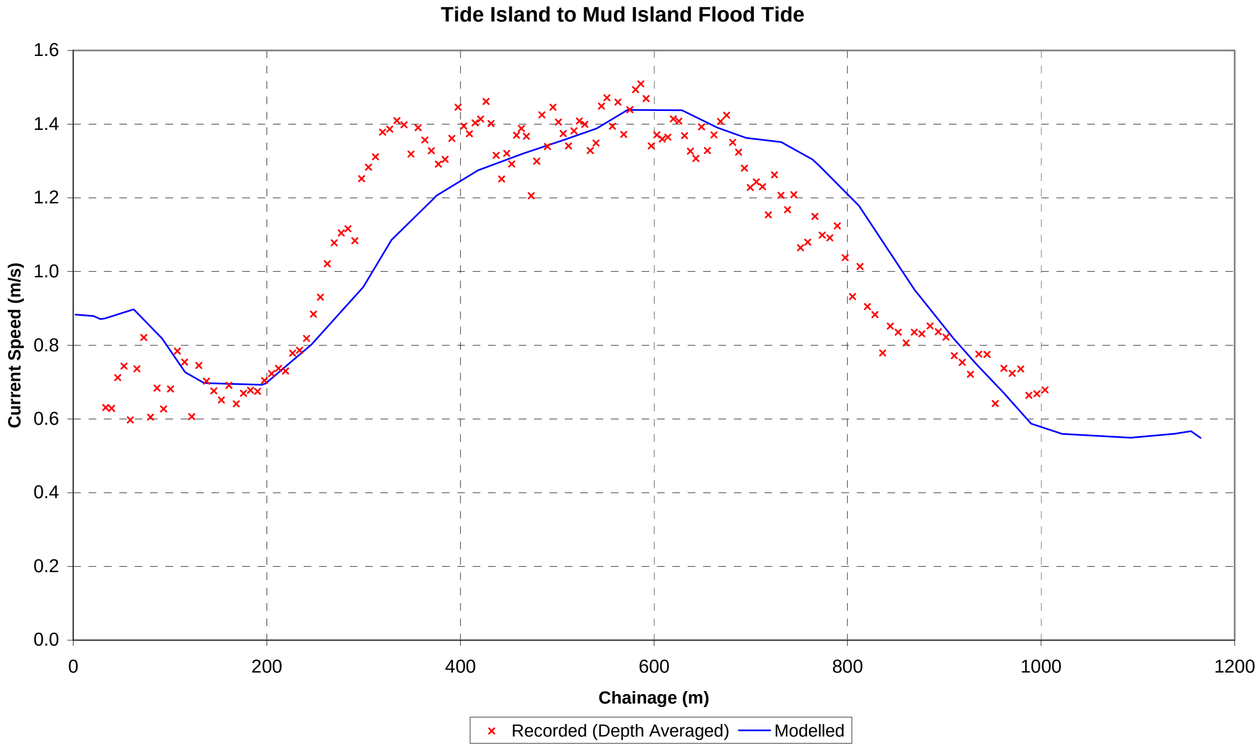


Figure C-3 Current Speed – Tide Island to Mud Island, April 2006: Flood Tide

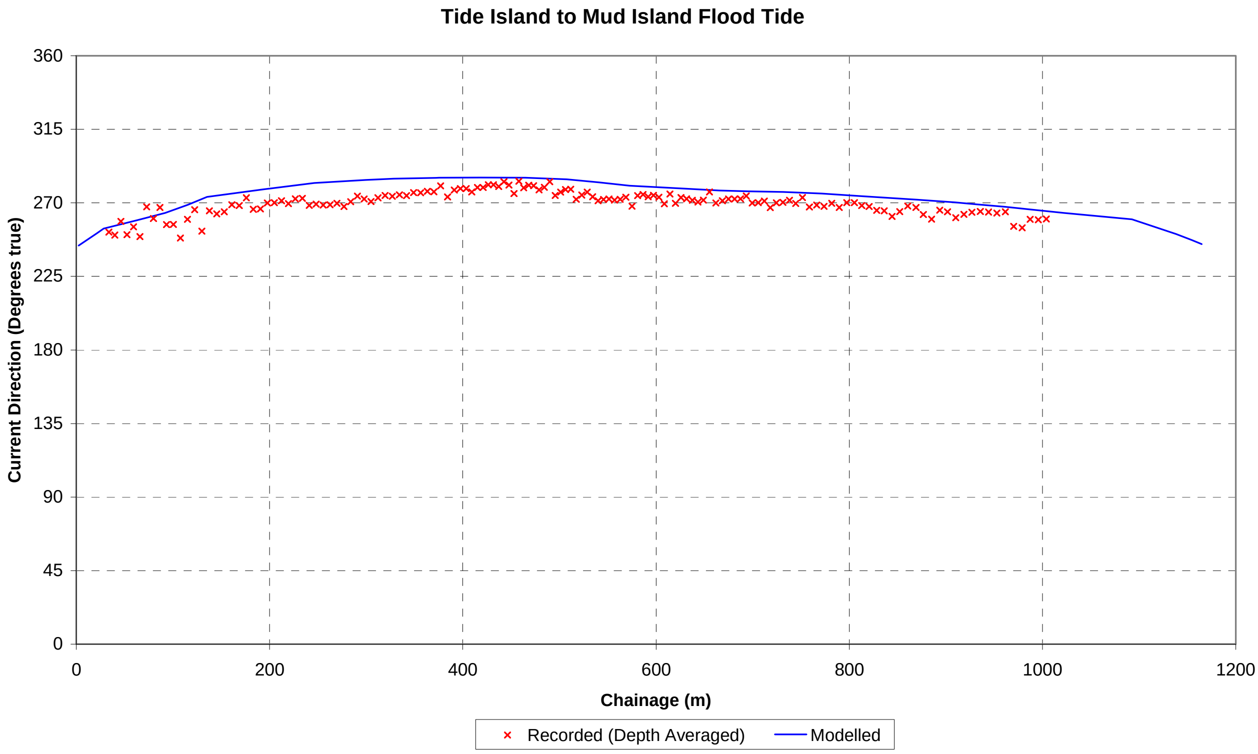


Figure C-4 Current Direction – Tide Island to Mud Island, April 2006: Flood Tide

APPENDIX D: CURRENT VELOCITY PLOTS NOVEMBER 2006

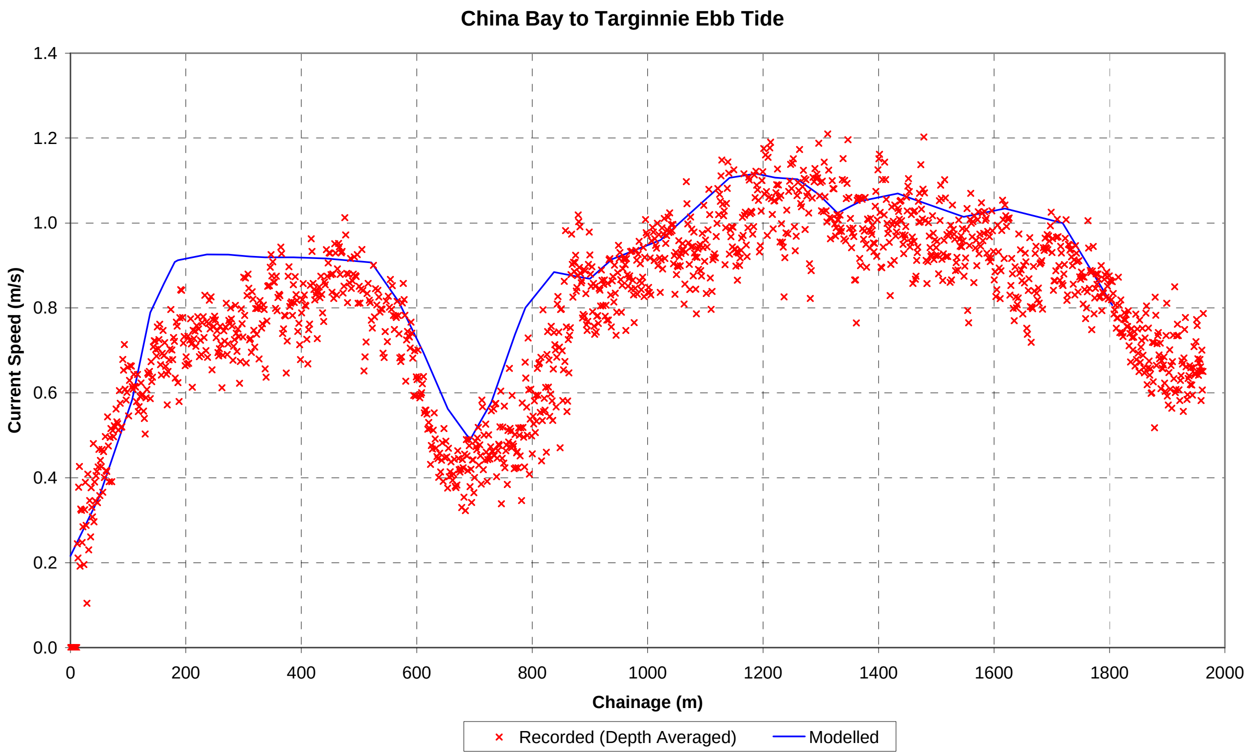


Figure D-1 Current Speed – China Bay to Targinie, November 2006: Ebb Tide

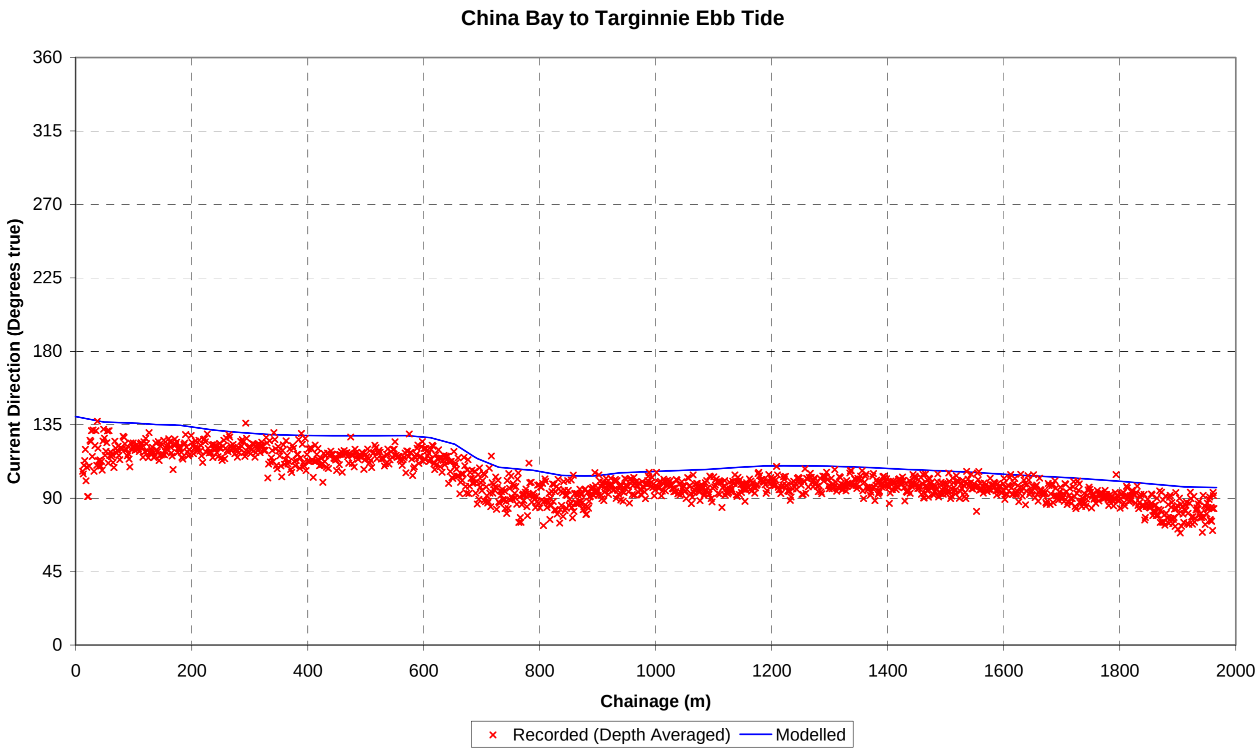


Figure D-2 Current Direction – China Bay to Targinie, November 2006: Ebb Tide

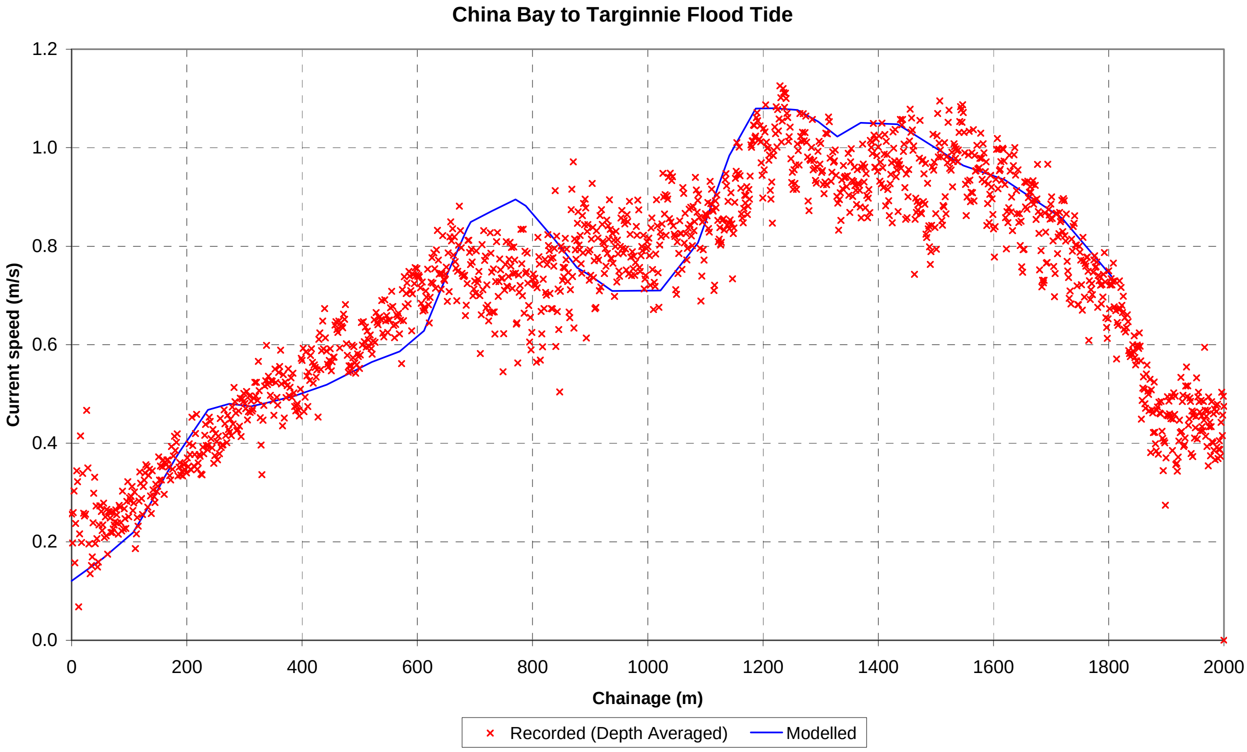


Figure D-3 Current Speed – China Bay to Targinie, November 2006: Flood Tide

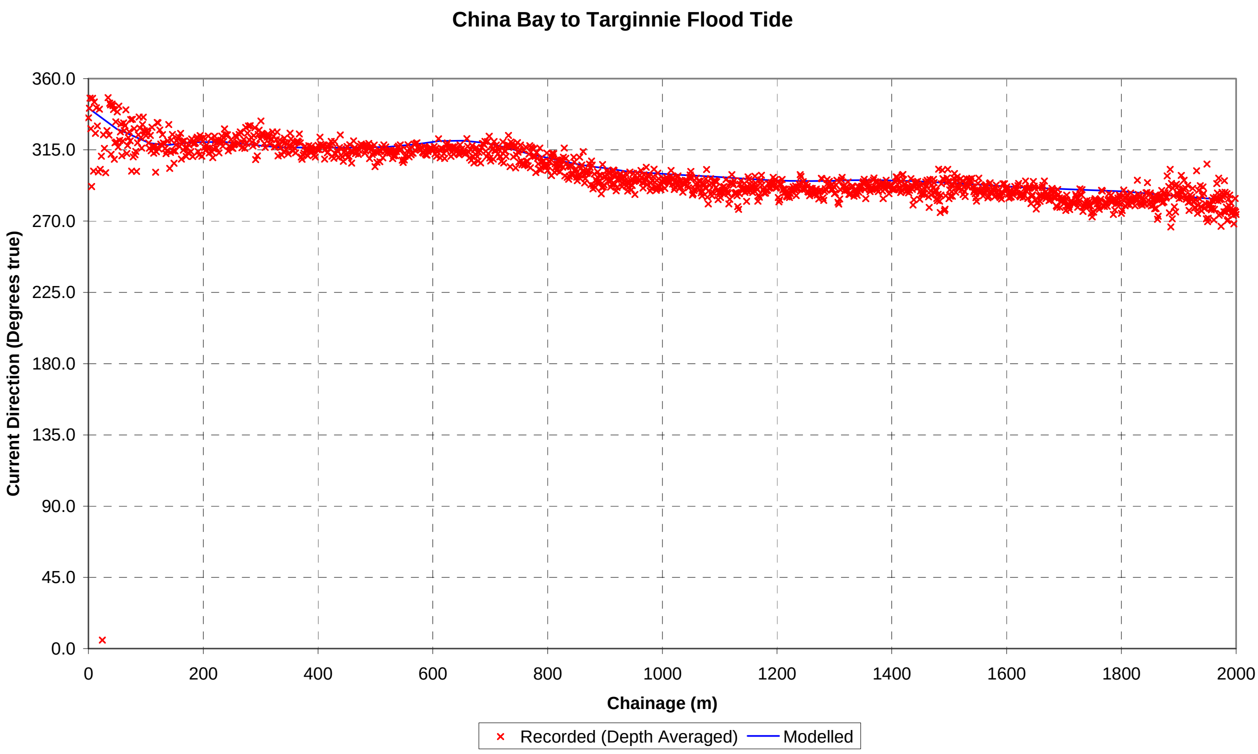


Figure D-4 Current Direction – China Bay to Targinie, November 2006: Flood Tide

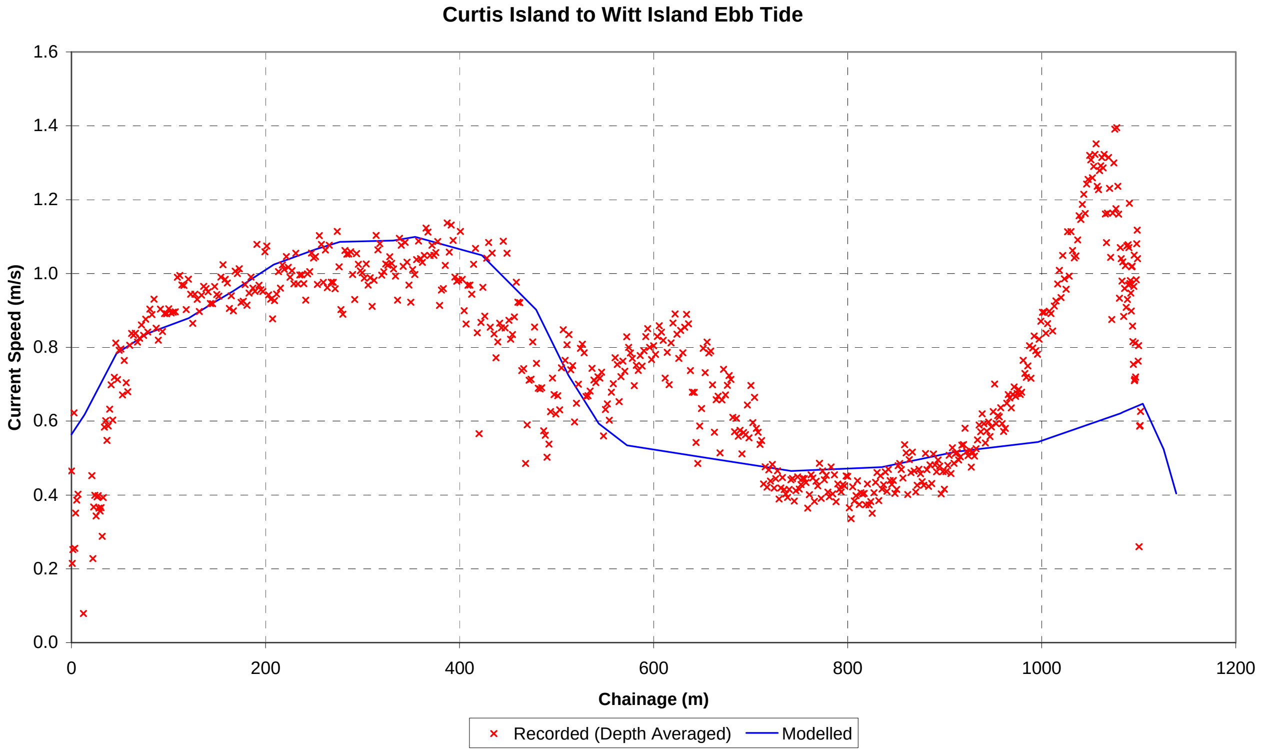


Figure D-5 Current Speed – Curtis Island to Witt Island, November 2006: Ebb Tide

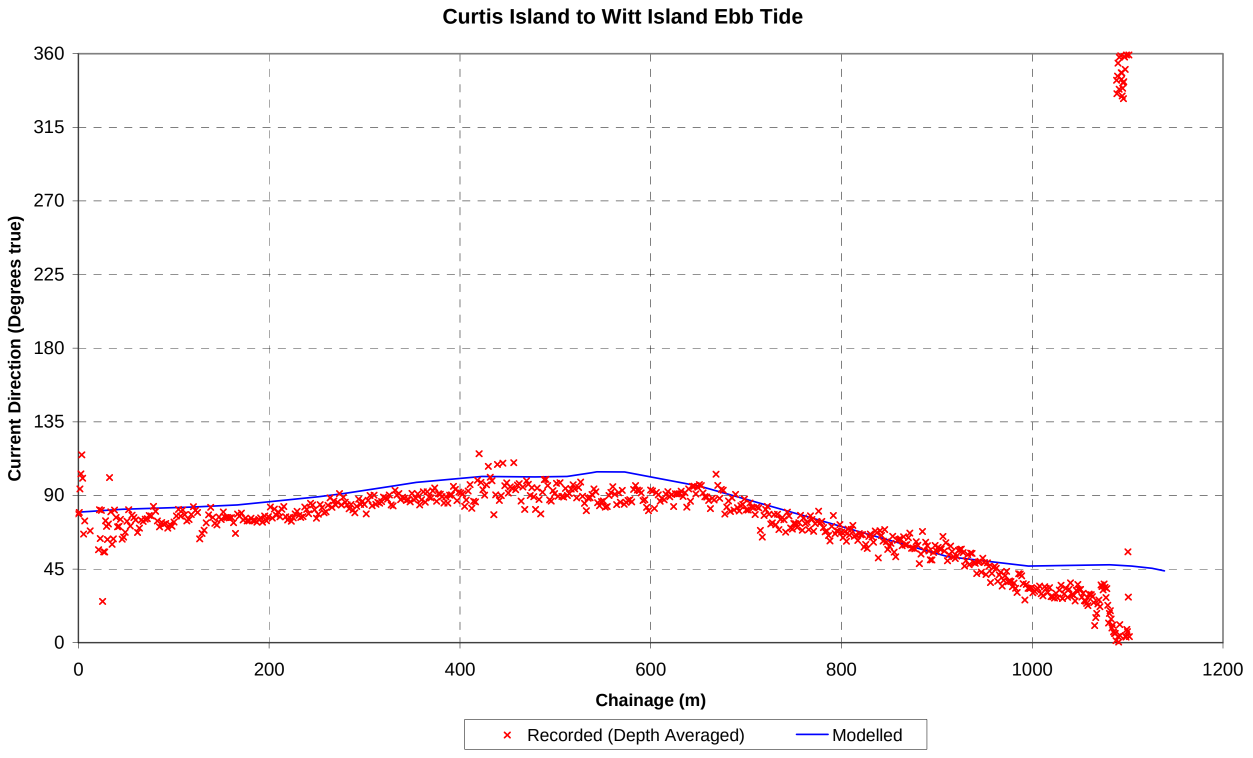


Figure D-6 Current Direction – Curtis Island to Witt Island, November 2006: Ebb Tide

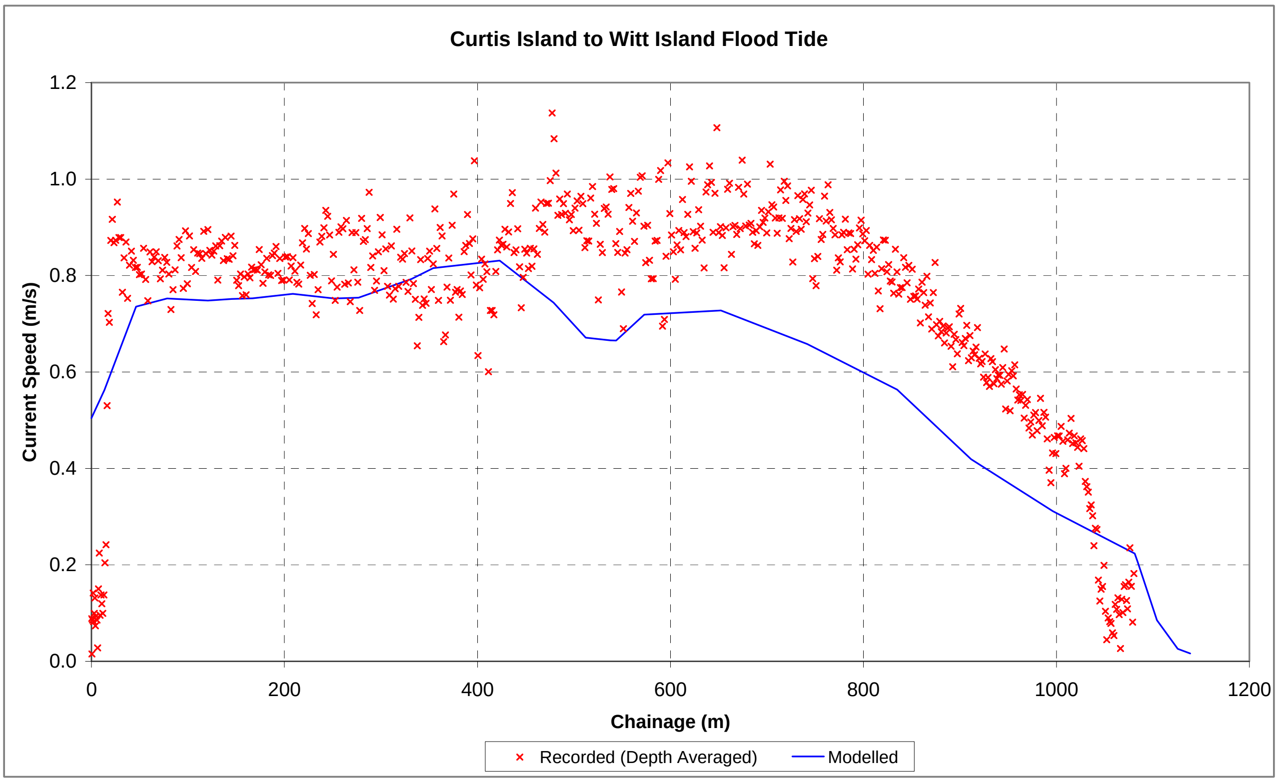


Figure D-7 Current Speed – Curtis Island to Witt Island, November 2006: Flood Tide

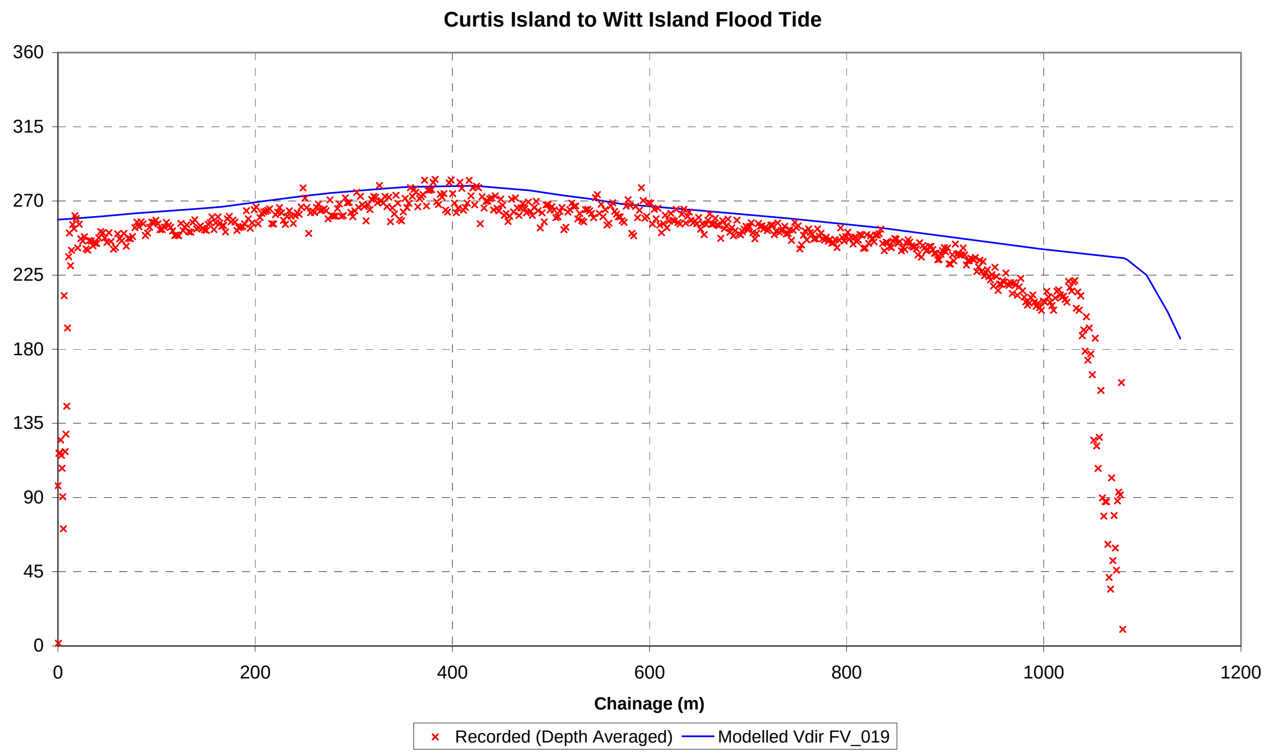


Figure D-8 Current Direction – Curtis to Witt Island, November 2006: Flood Tide

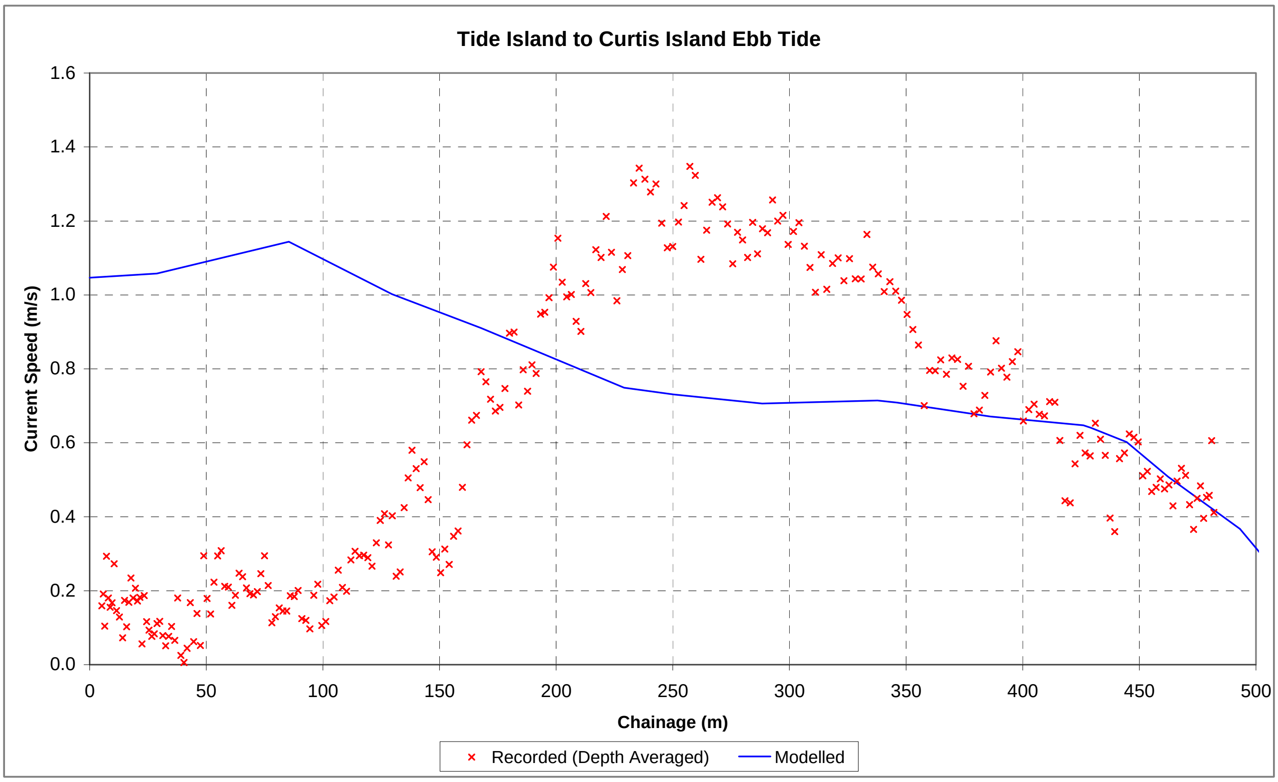


Figure D-9 Current Speed – Tide Island to Curtis Island, November 2006: Ebb Tide

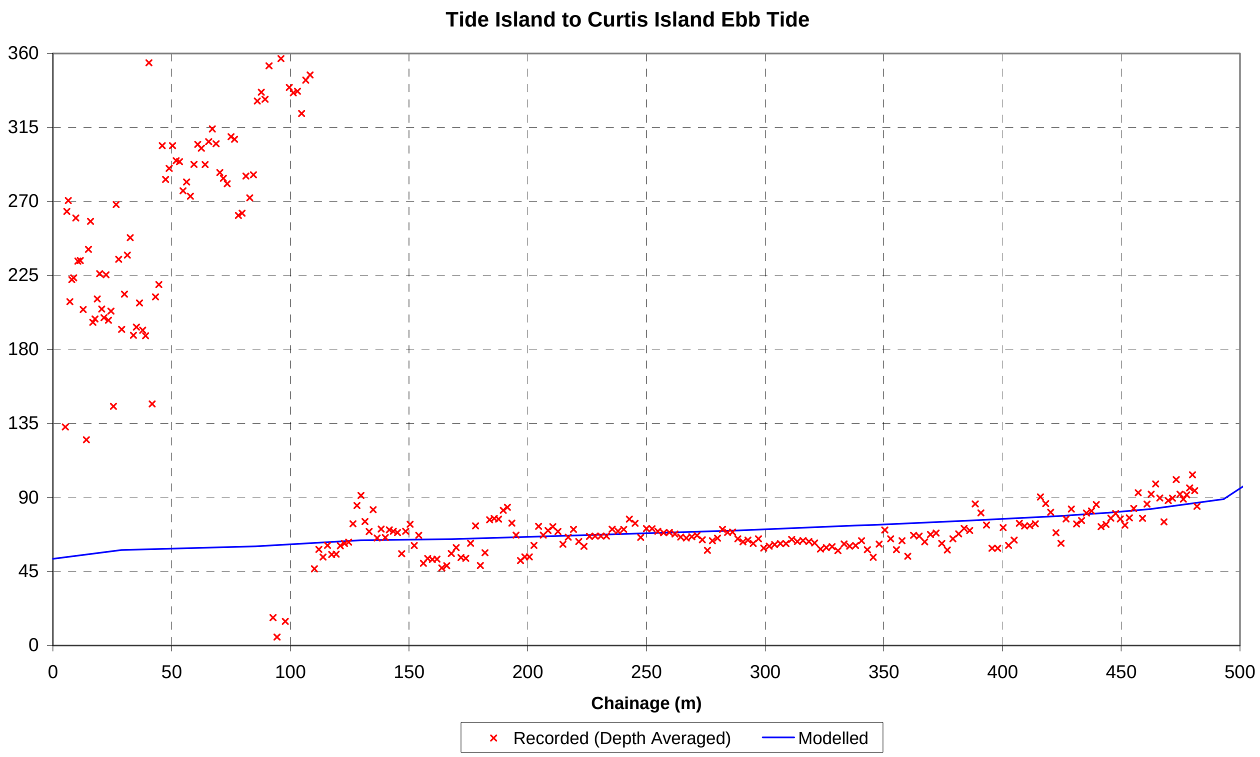


Figure D-10 Current Direction - Tide Island to Curtis Island, November 2006: Ebb Tide

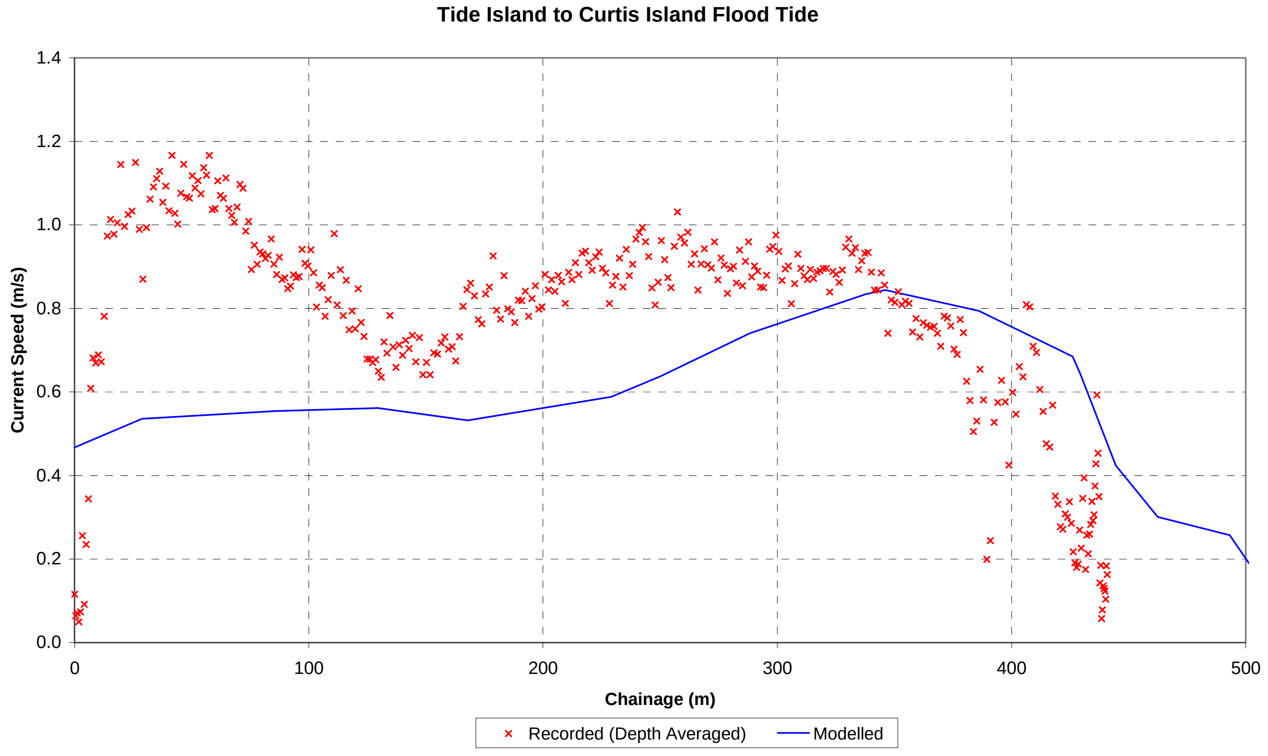


Figure D-11 Current Speed – Tide Island to Curtis Island, November 2006: Flood Tide

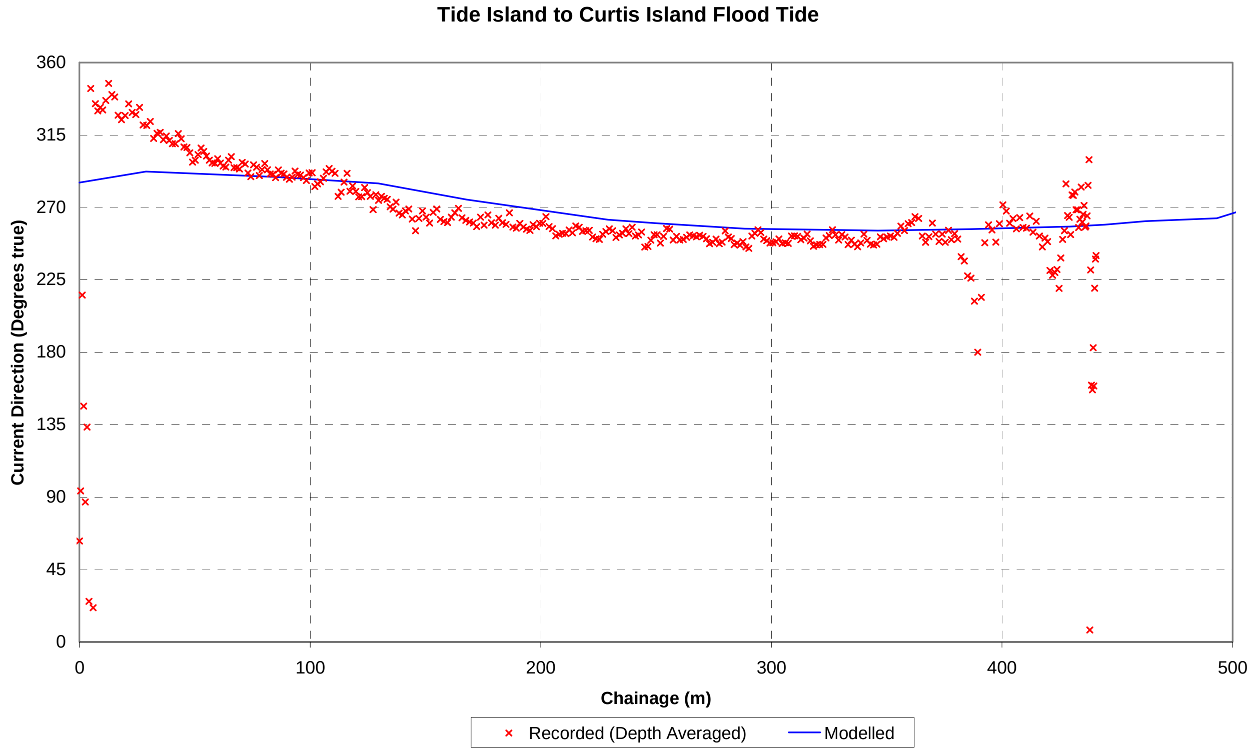


Figure D-12 Current Direction – Tide Island to Curtis Island, November 2006: Flood Tide

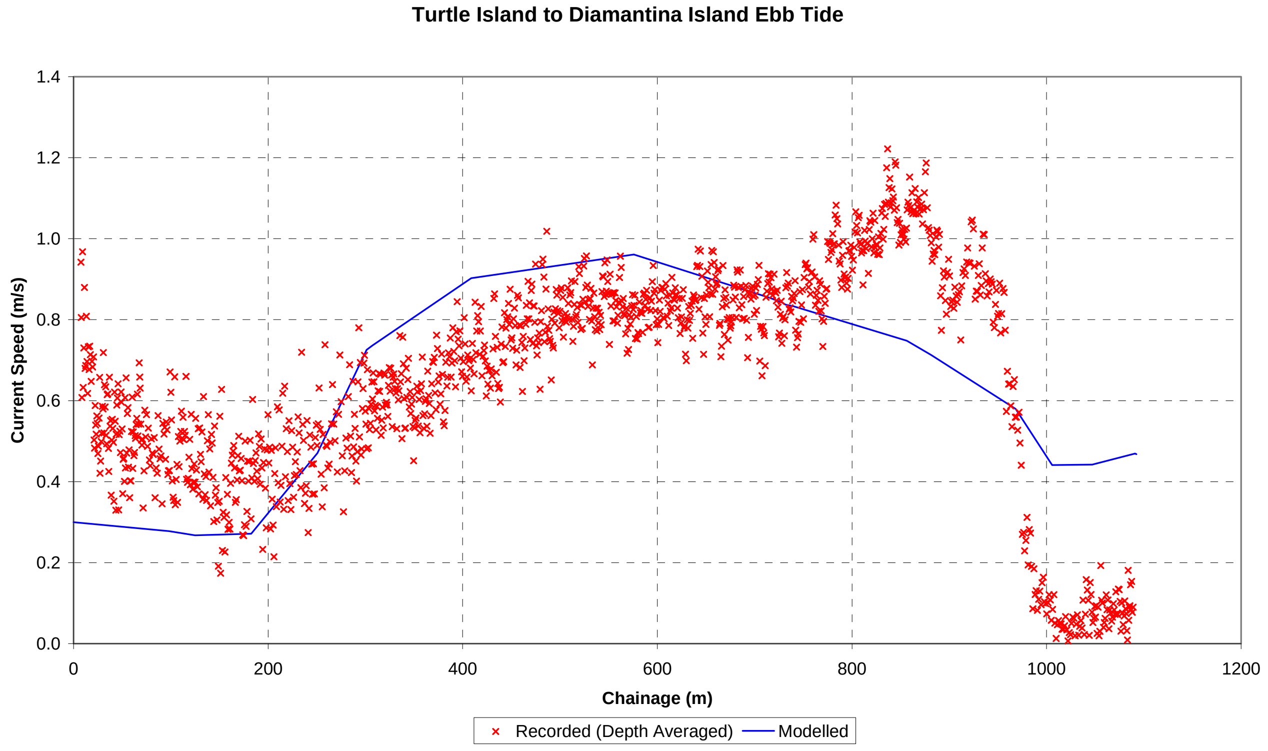


Figure D-13 Current Speed – Turtle Island to Diamantina Island, November 2006: Ebb Tide

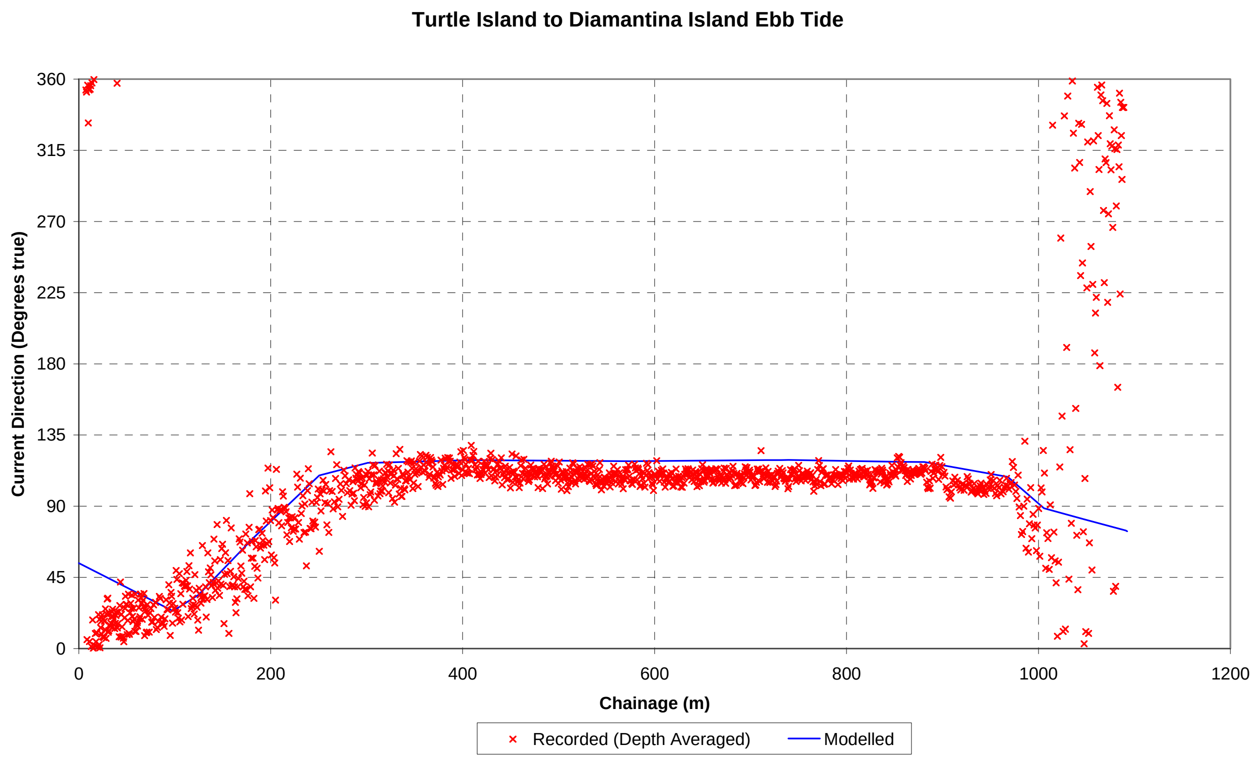


Figure D-14 Current Direction – Turtle to Diamantina, November 2006: Ebb Tide

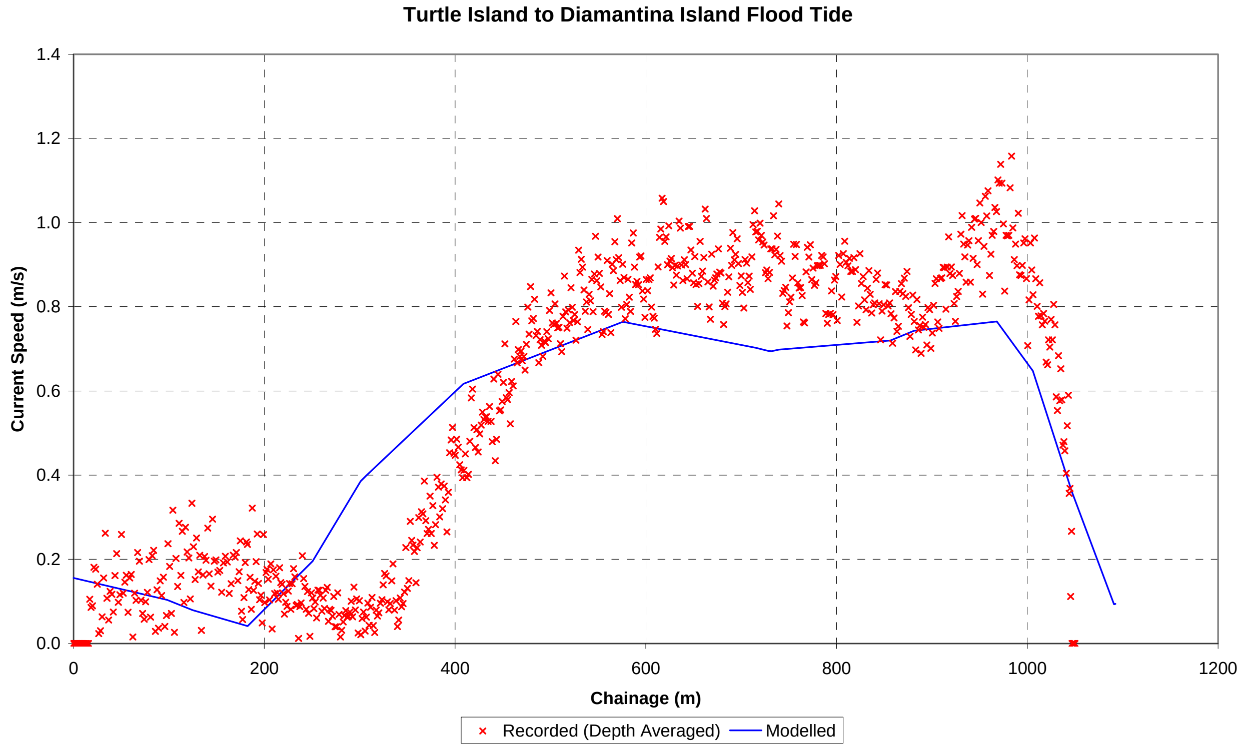


Figure D-15 Current Speed – Turtle Island to Diamantina Island, November 2006: Flood Tide

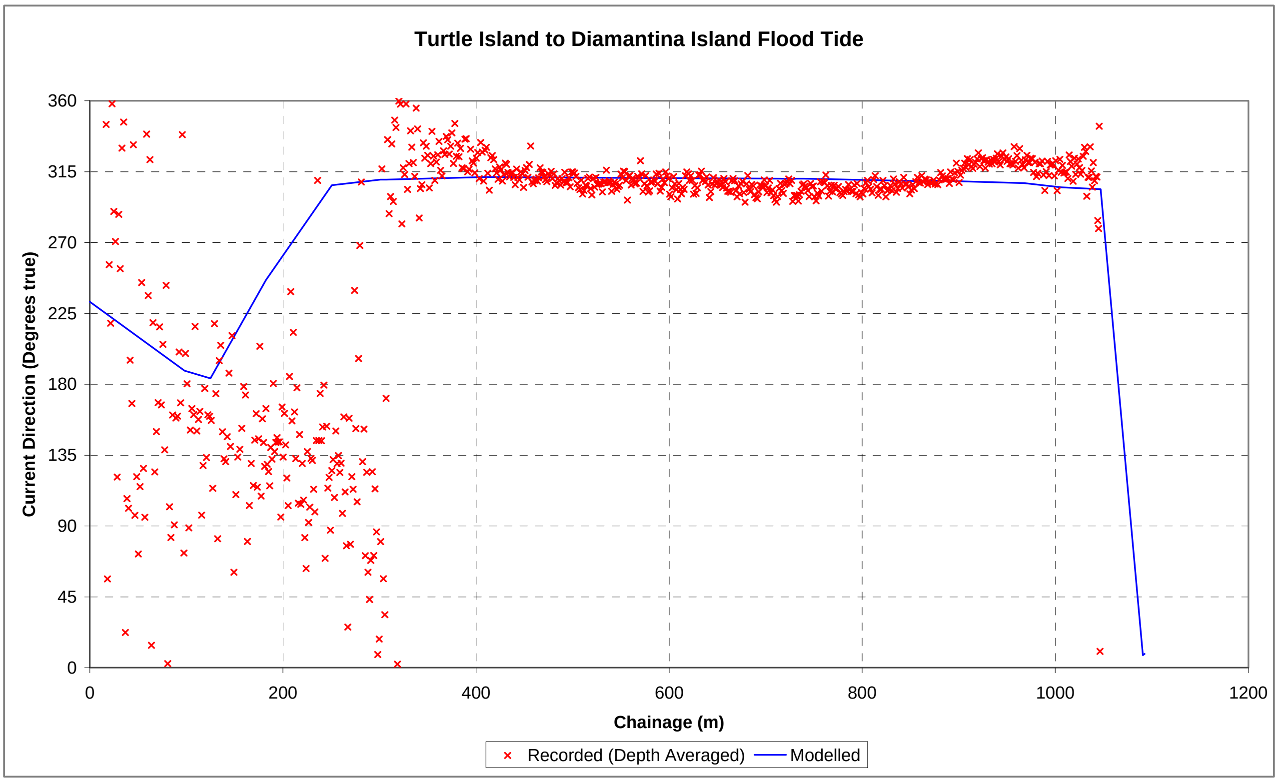
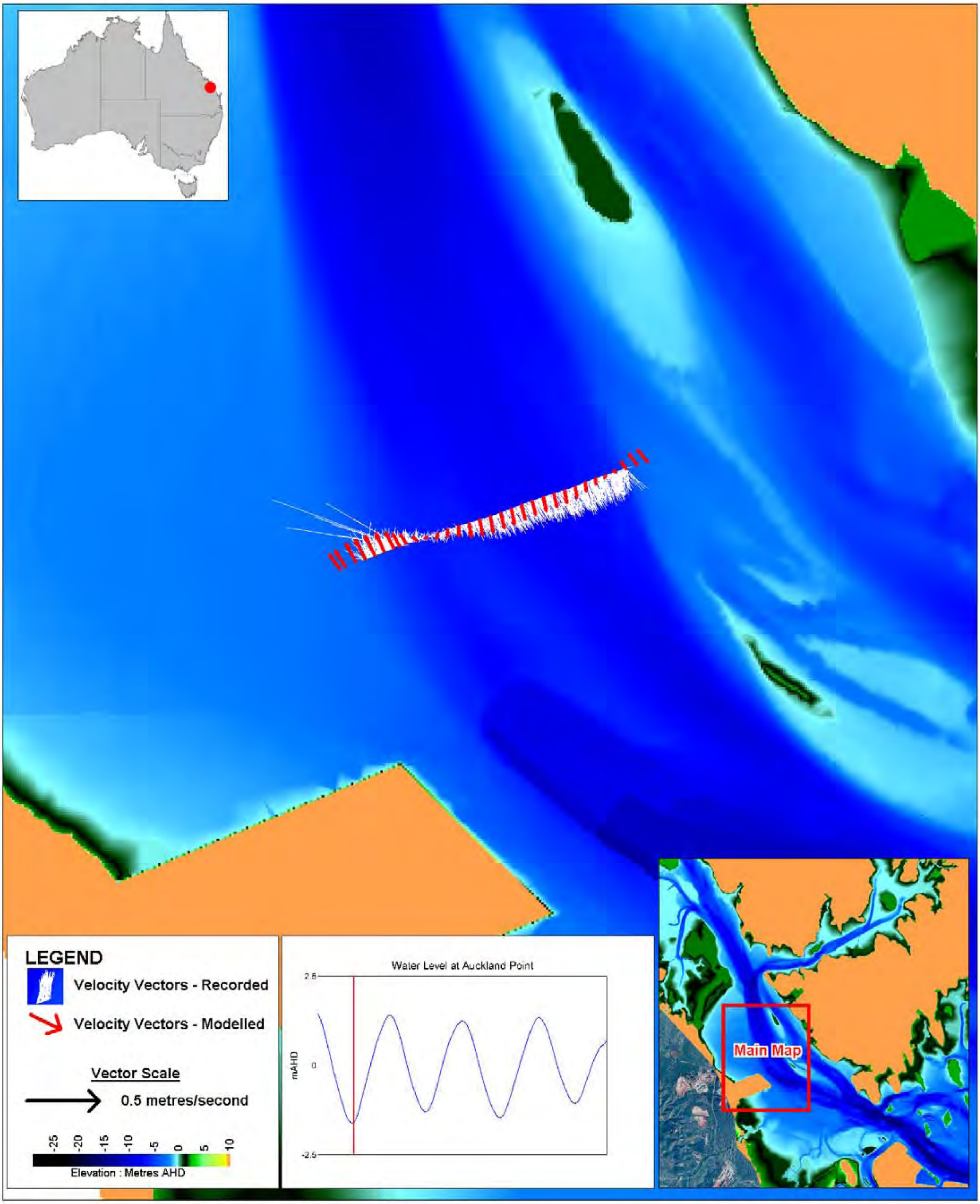


Figure D-16 Current Direction – Turtle Island to Diamantina Island, November 2006: Flood Tide

APPENDIX E: CURRENT VELOCITY PLOTS AUGUST 2008



Title:

ADCP Transect Fishermans Landing 120

Figure: **E-1**

Rev: **A**

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Scale - Main Map

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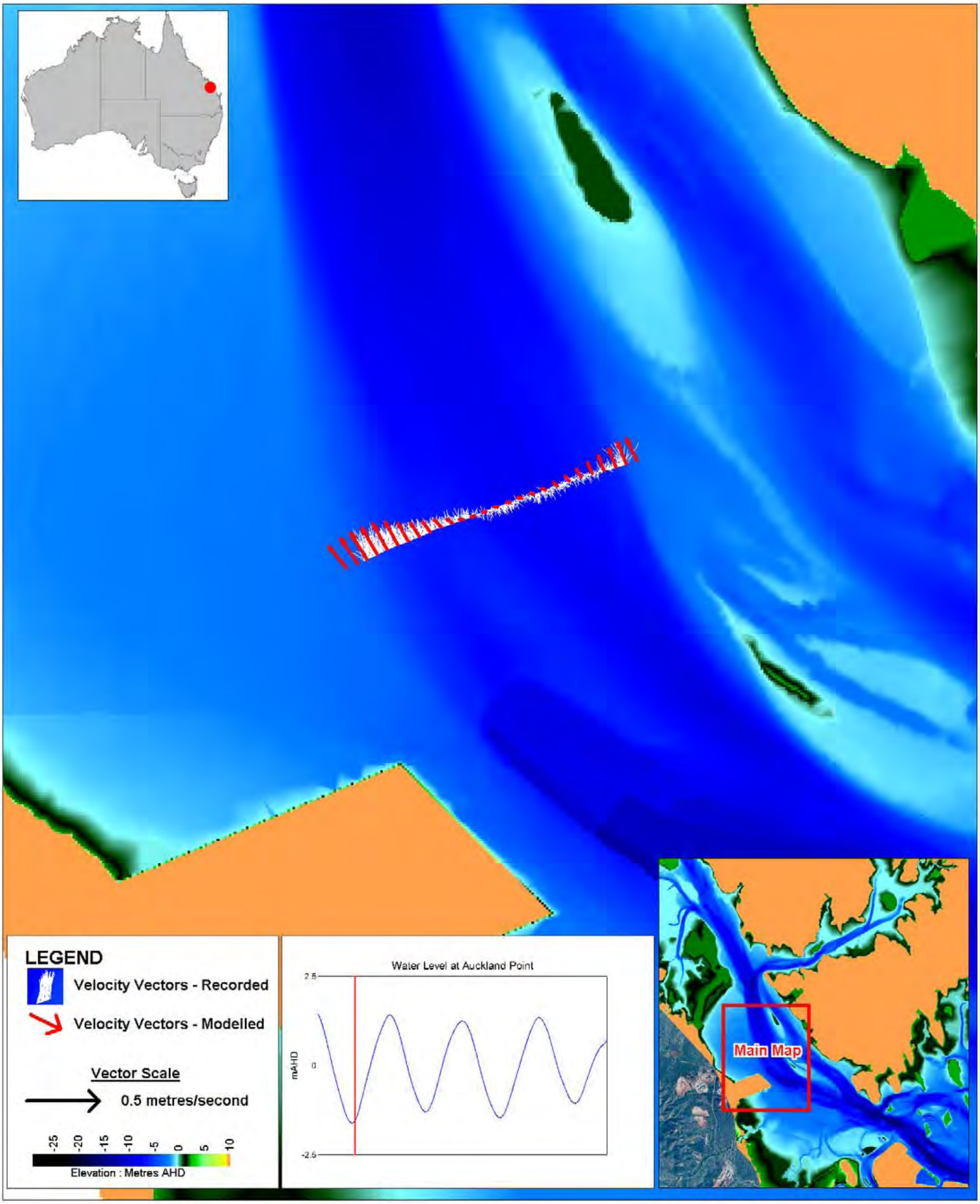

Title:

ADCP Transect Fishermans Landing 121

Figure: E-2

Rev: A

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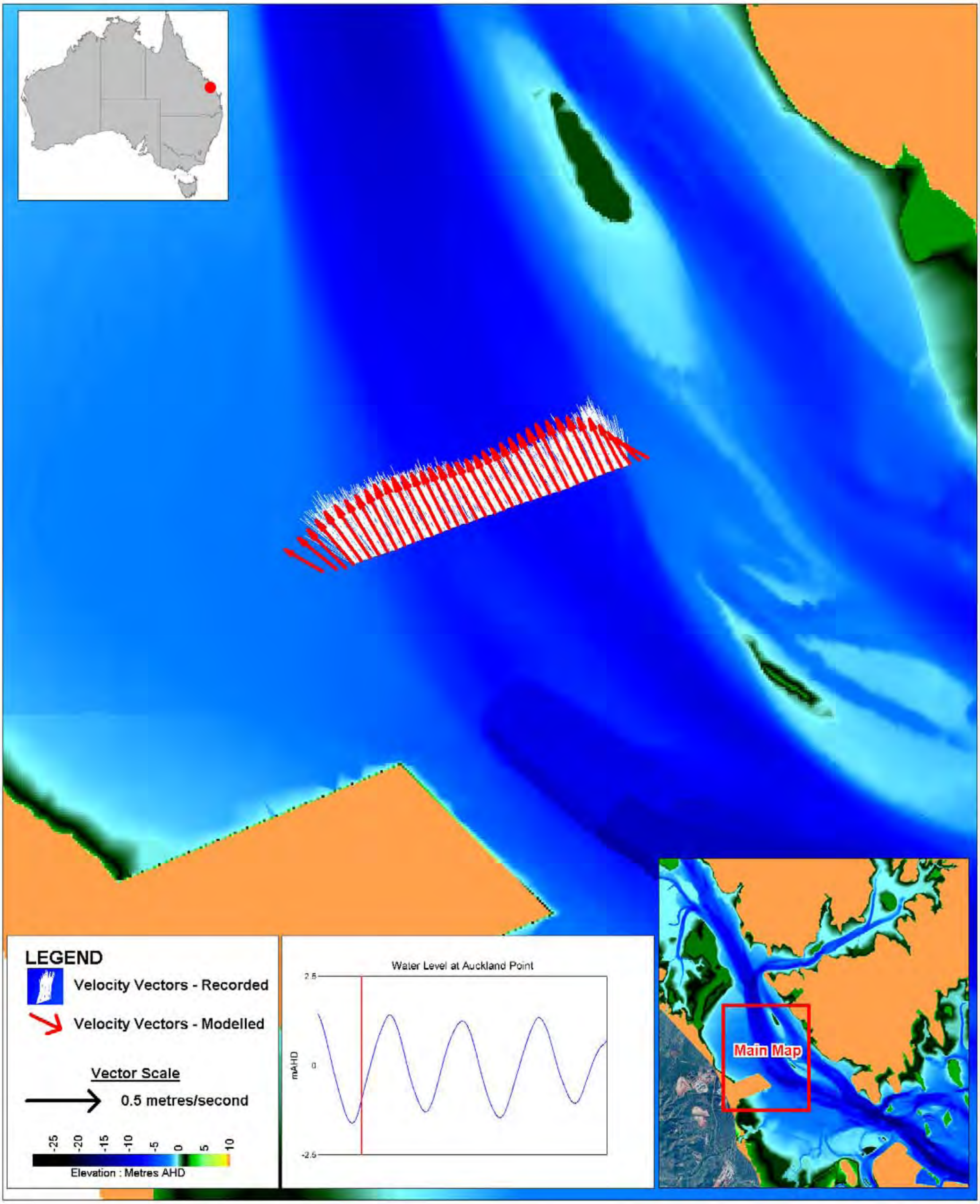

Title:

ADCP Transect Fishermans Landing 122

Figure: **E-3**

Rev: **A**

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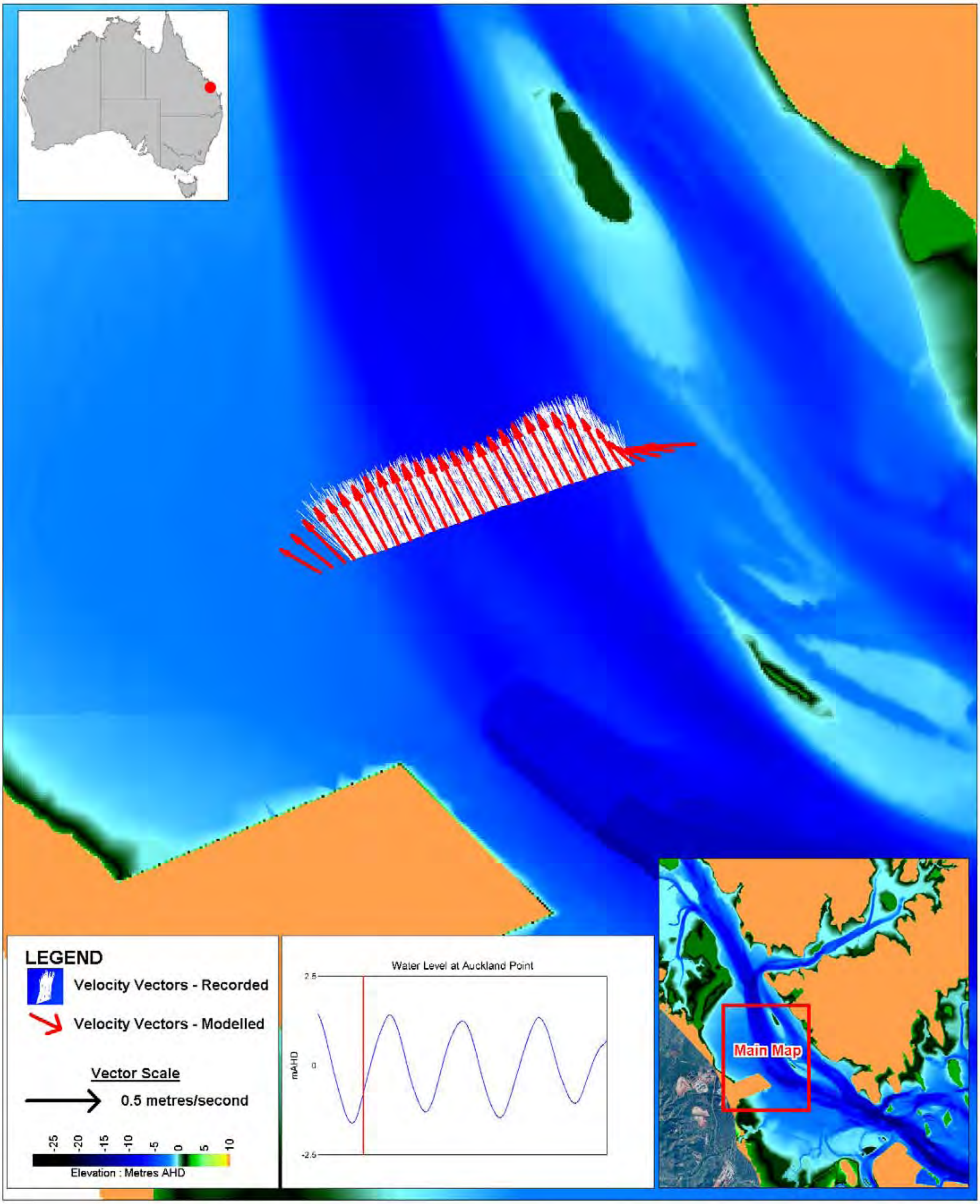

Title:

ADCP Transect Fishermans Landing 123

Figure: E-4

Rev: A

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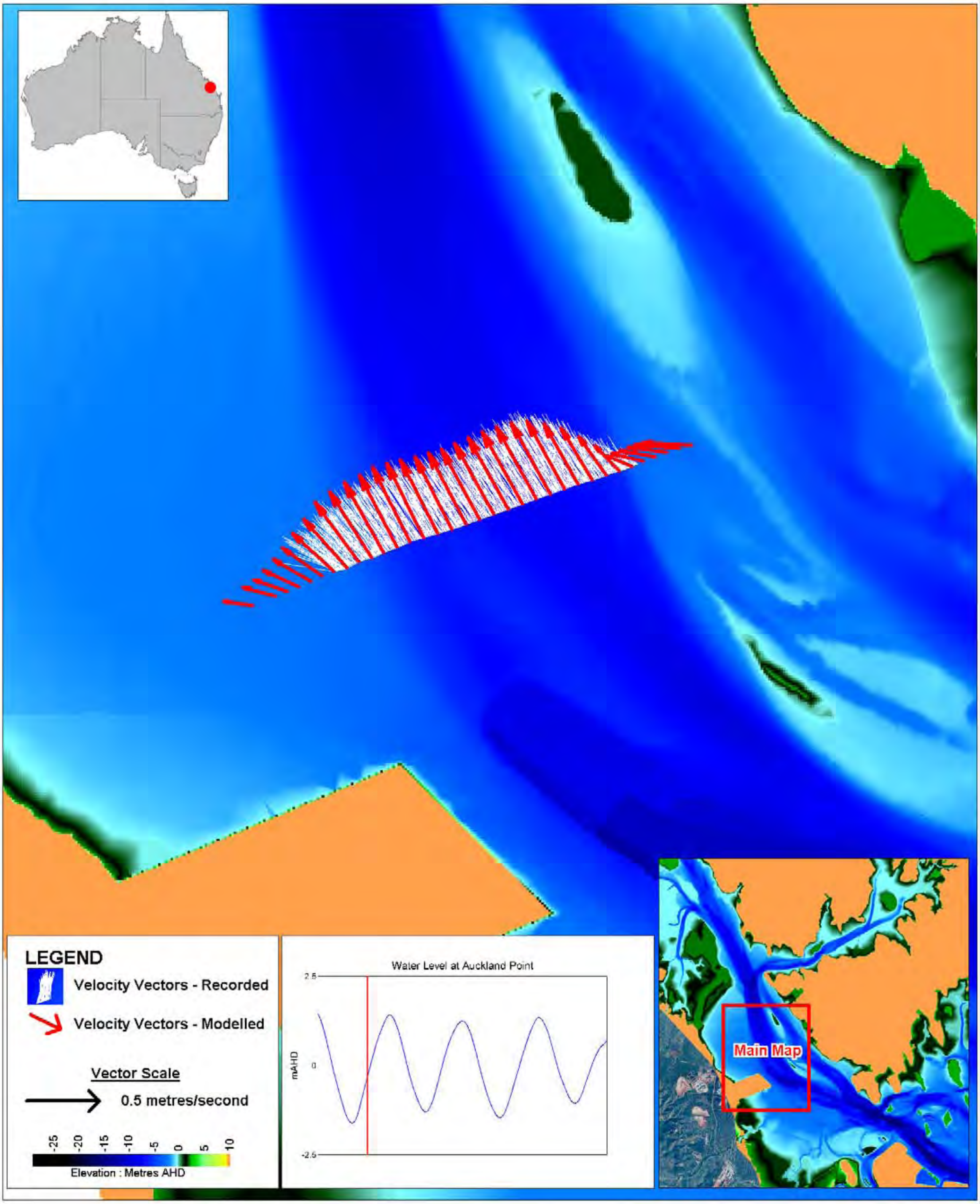

Title:

ADCP Transect Fishermans Landing 124

Figure: **E-5**

Rev: **A**

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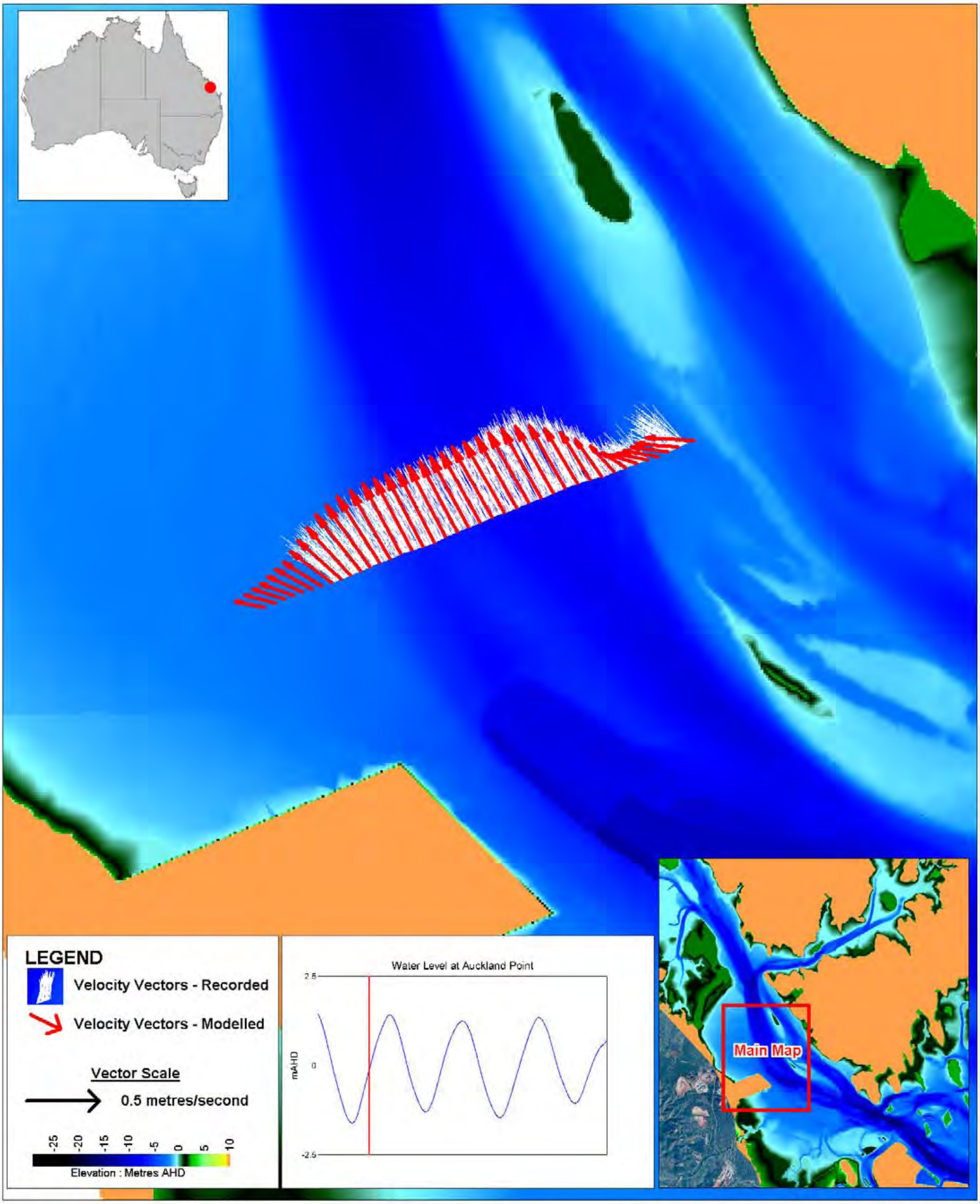

Title:
ADCP Transect Fishermans Landing 125

Figure: E-6

Rev: A

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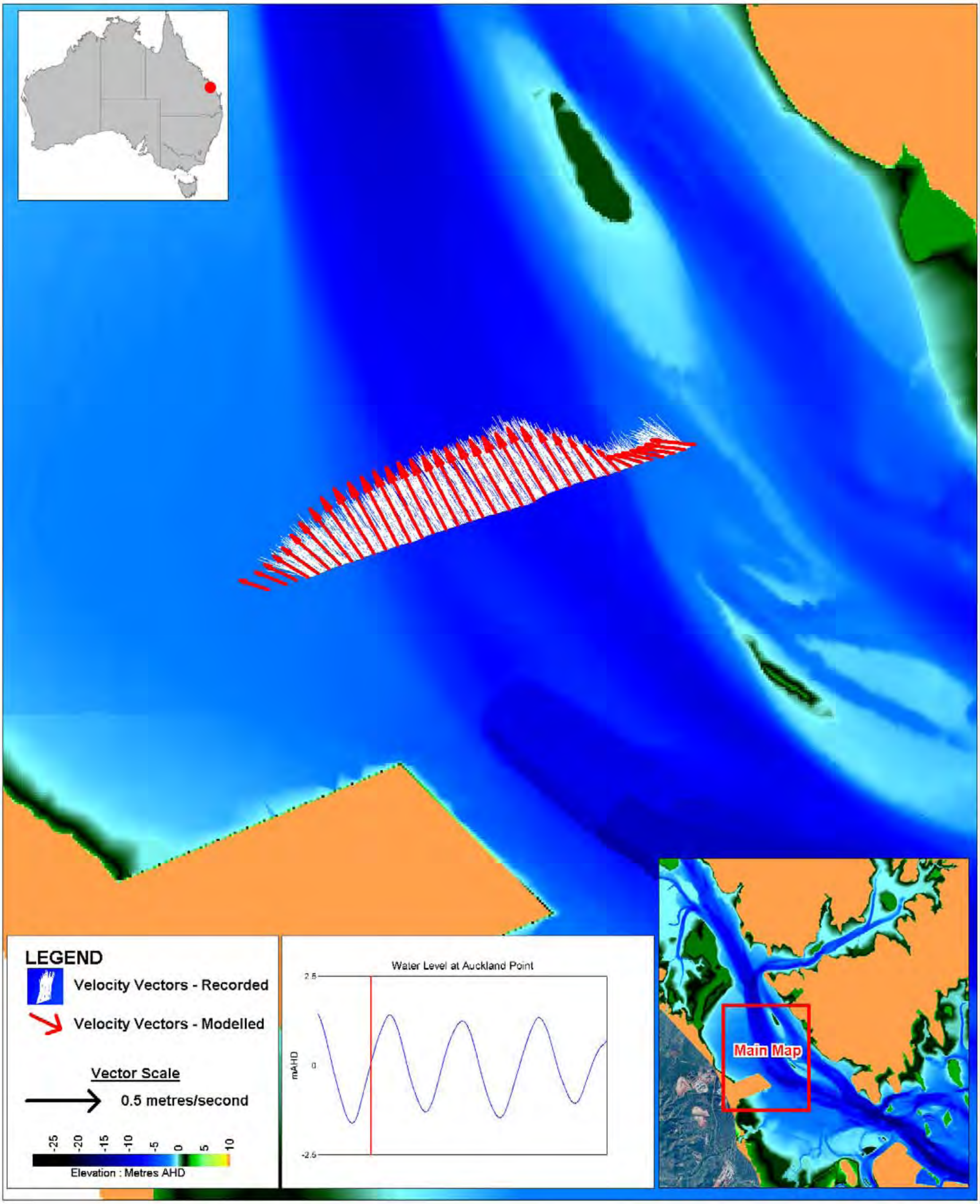

Title:

ADCP Transect Fishermans Landing 126

Figure: E-7

Rev: A

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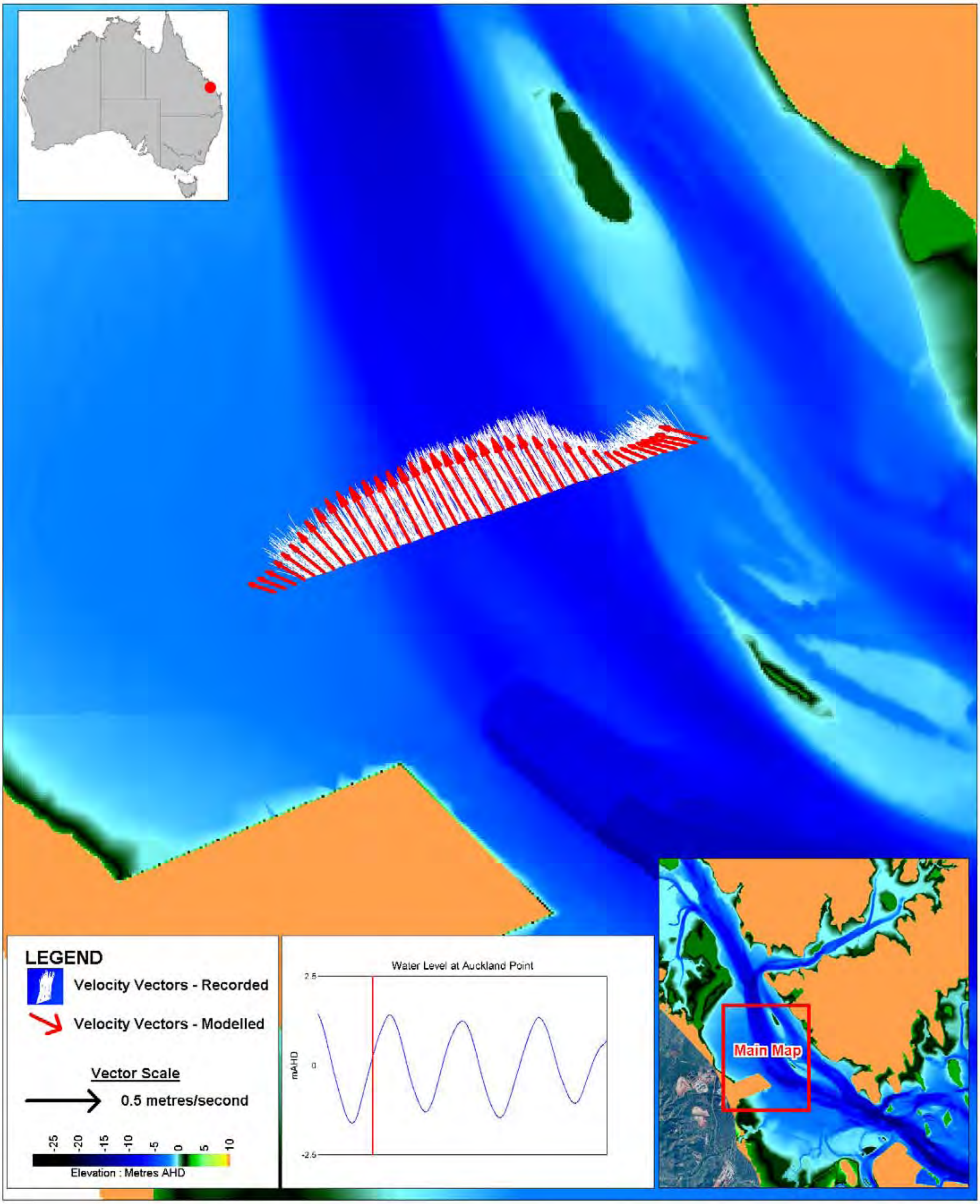

Title:

ADCP Transect Fishermans Landing 127

Figure: **E-8**

Rev: **A**

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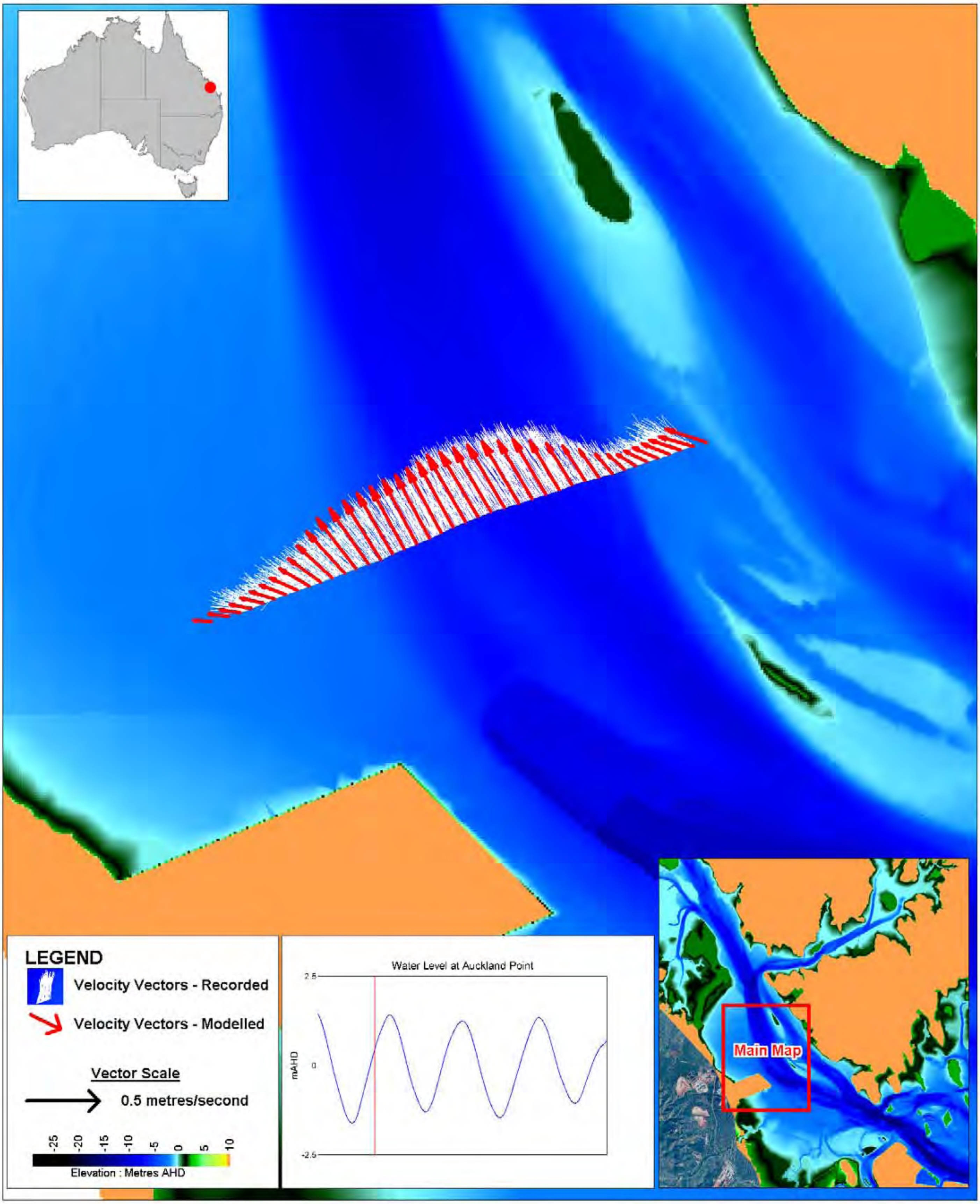

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ADCP Transect Fishermans Landing 128

Figure: E-9

Rev: A

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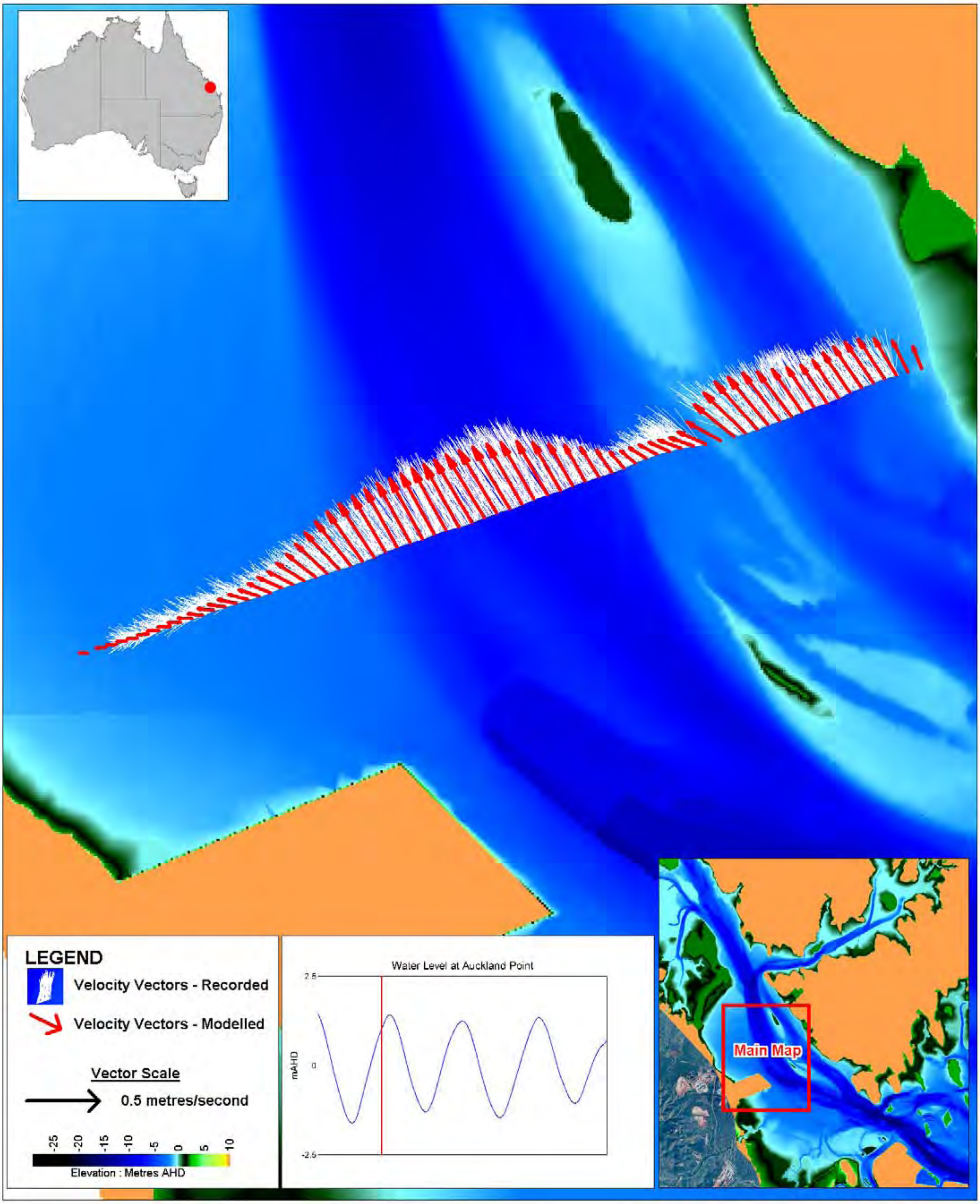

Title:

ADCP Transect Fishermans Landing 129

Figure: **E-10**

Rev: **A**

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Scale - Main Map

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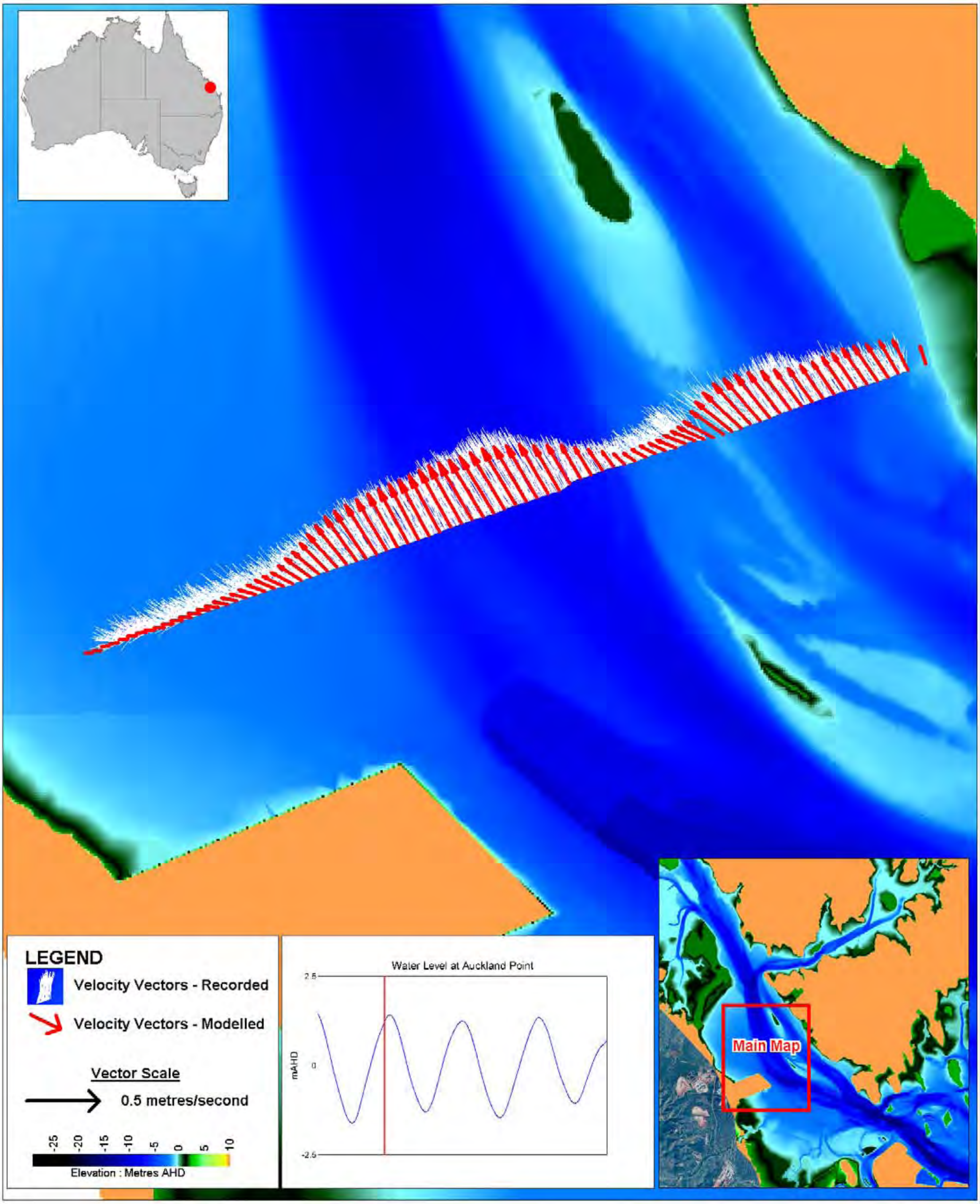

Title:

ADCP Transect Fishermans Landing 130

Figure: **E-11**

Rev: **A**

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Scale - Main Map

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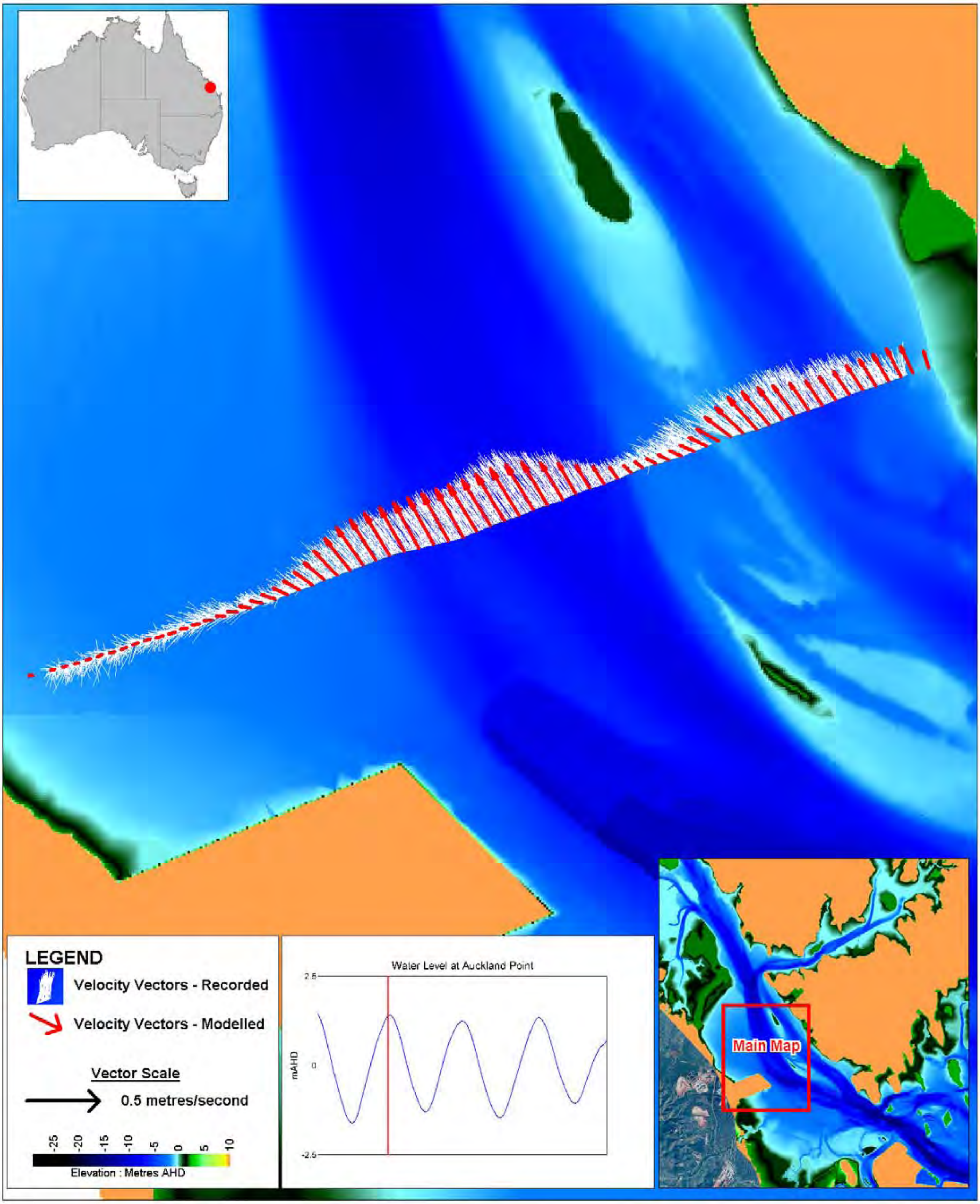

Title:

ADCP Transect Fishermans Landing 131

Figure: **E-12**

Rev: **A**

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Scale - Inset

0 0.5 1km

Scale - Main Map

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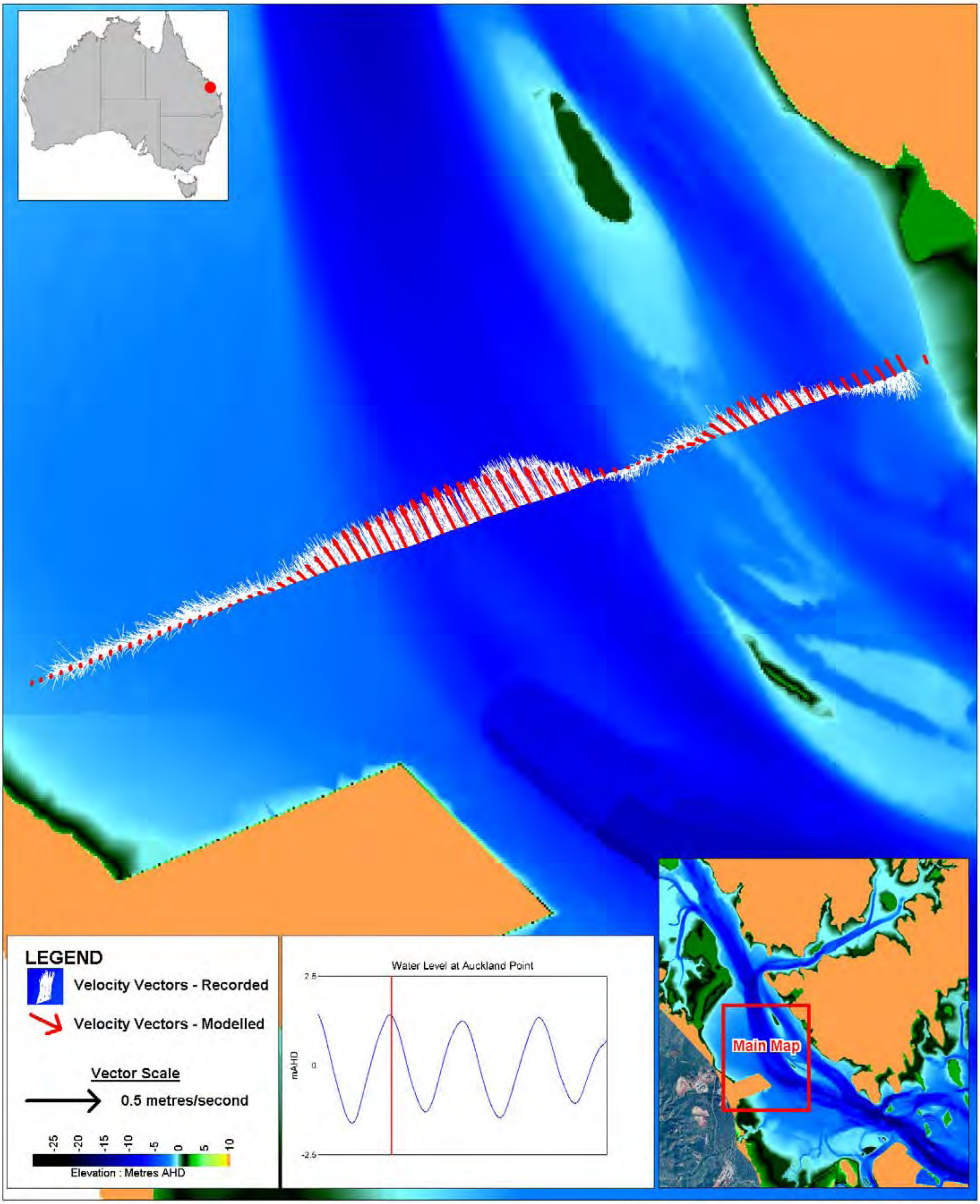

Title:

ADCP Transect Fishermans Landing 132

Figure: E-13

Rev: A

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Scale - Main Map

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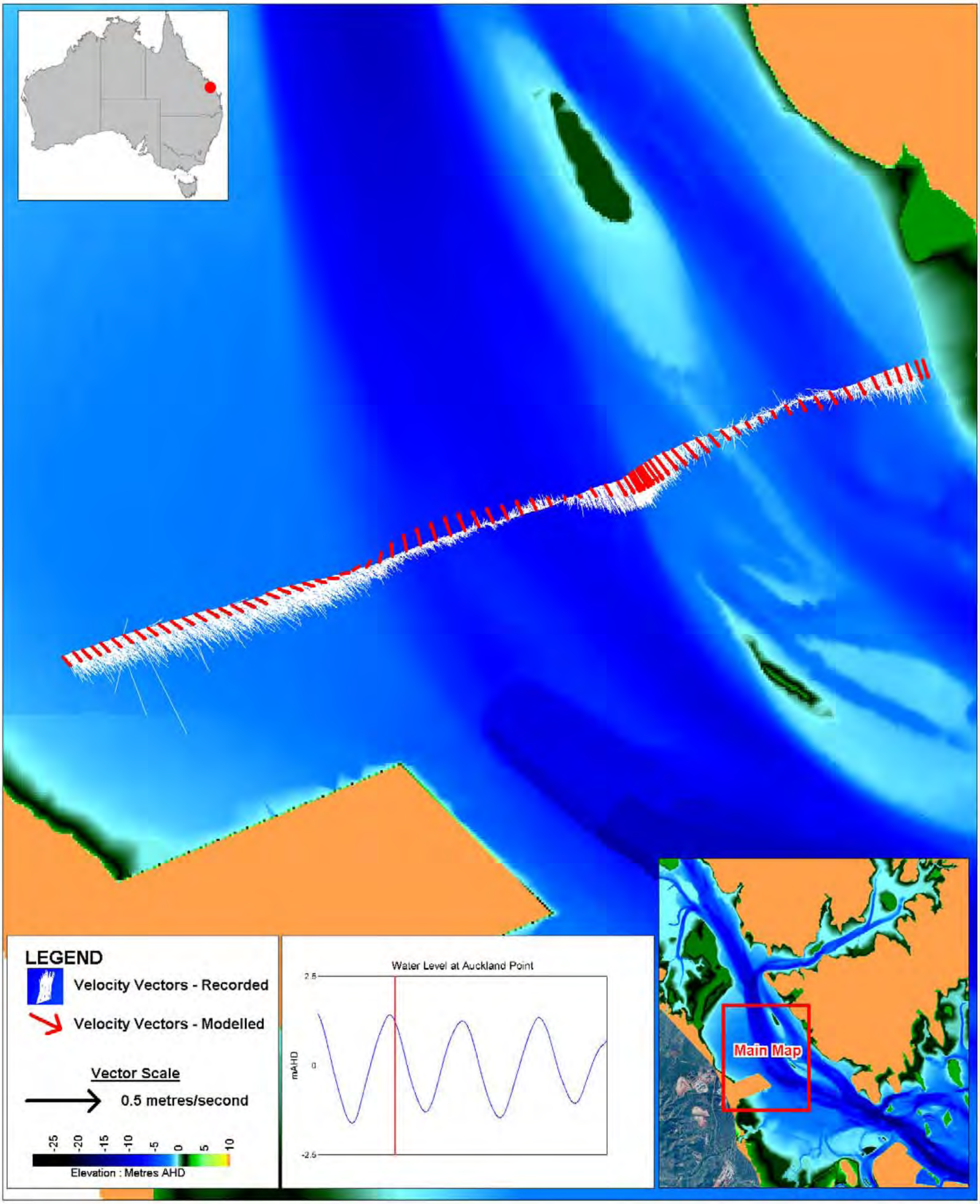

Title:

ADCP Transect Fishermans Landing 133

Figure: **E-14**

Rev: **A**

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Scale - Main Map

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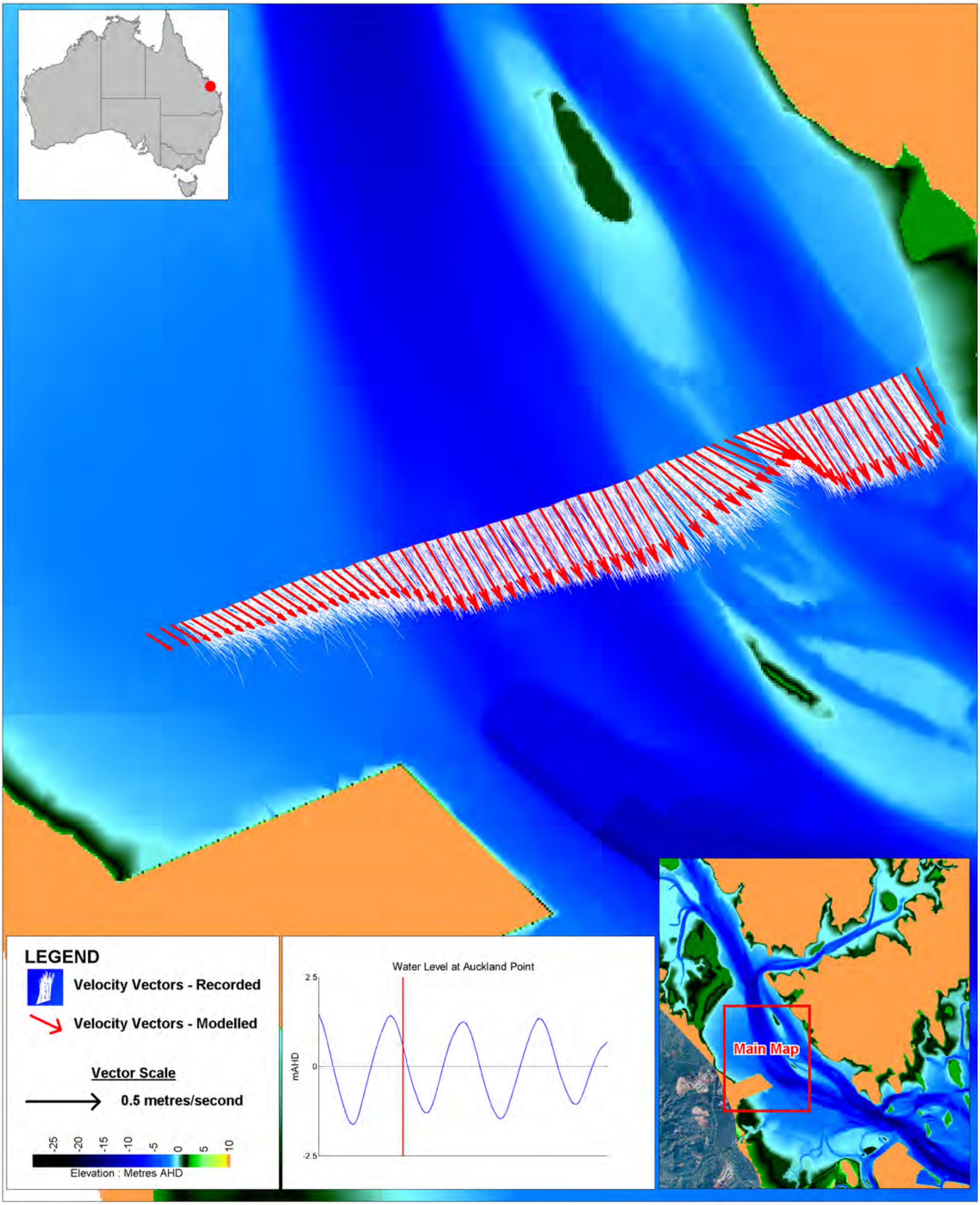

Title:

ADCP Transect Fishermans Landing 134

Figure: **E-15**

Rev: **A**

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Scale - Inset

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Scale - Main Map

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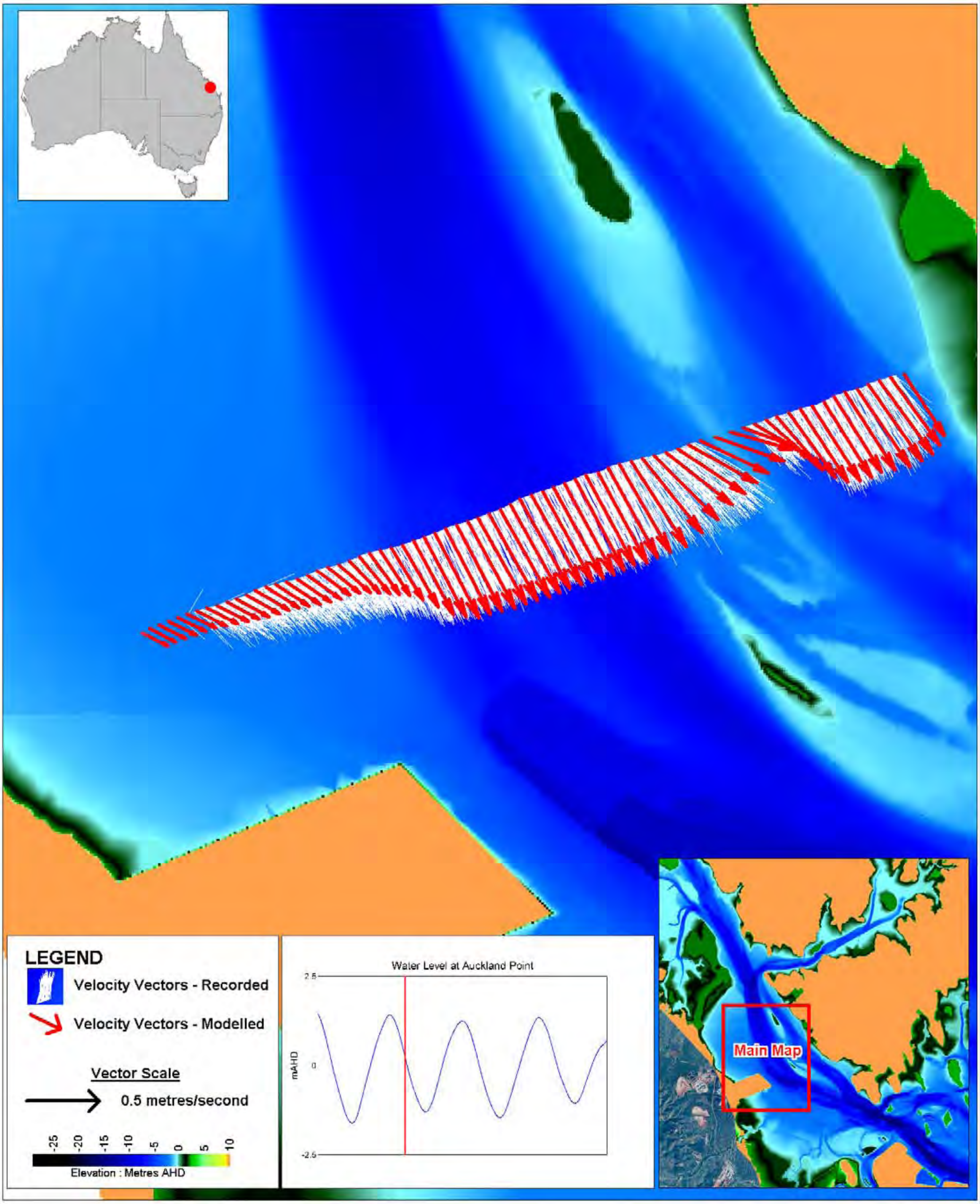

Title:

ADCP Transect Fishermans Landing 135

Figure: **E-16**

Rev: **A**

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Scale - Main Map

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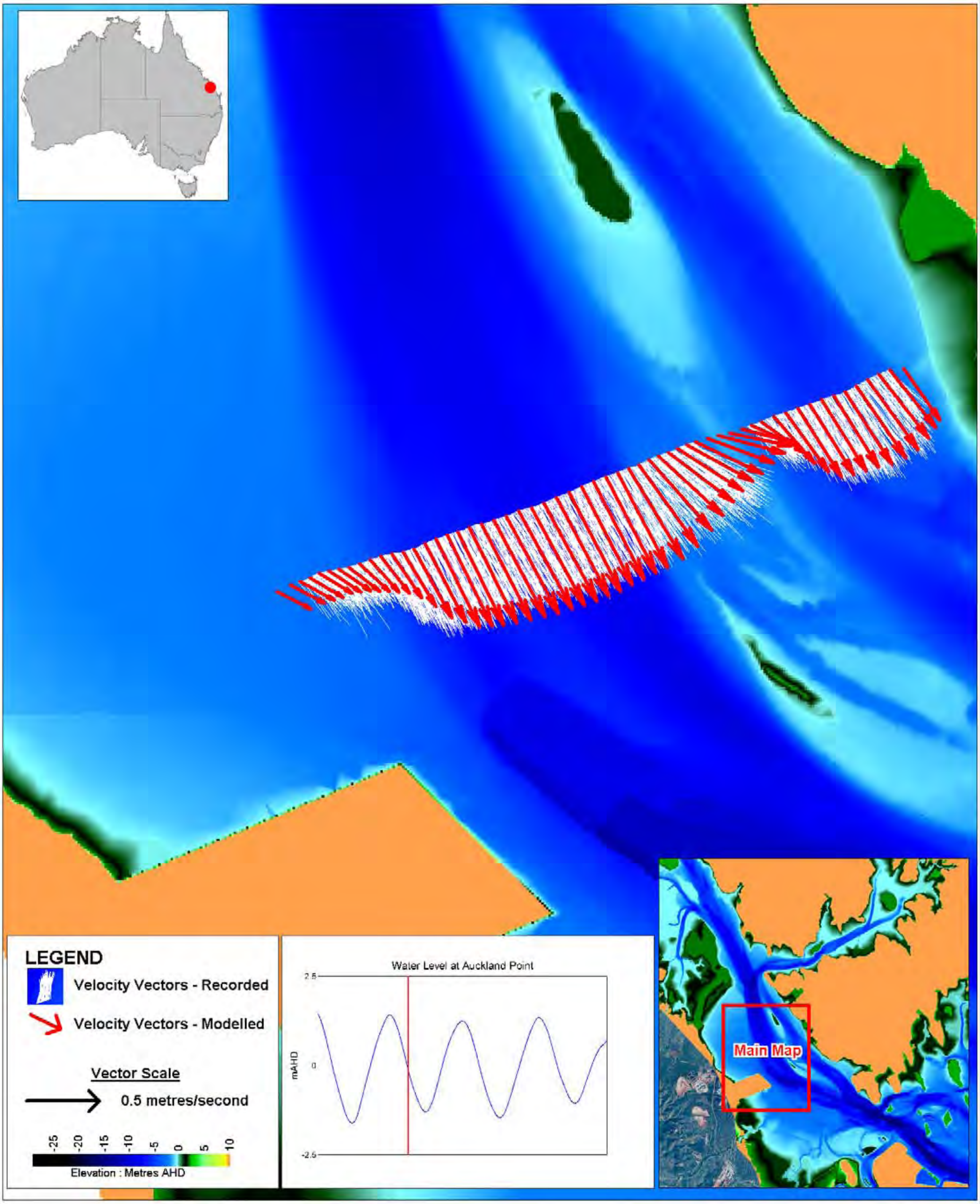

Title:

ADCP Transect Fishermans Landing 136

Figure: E-17

Rev: A

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Scale - Main Map

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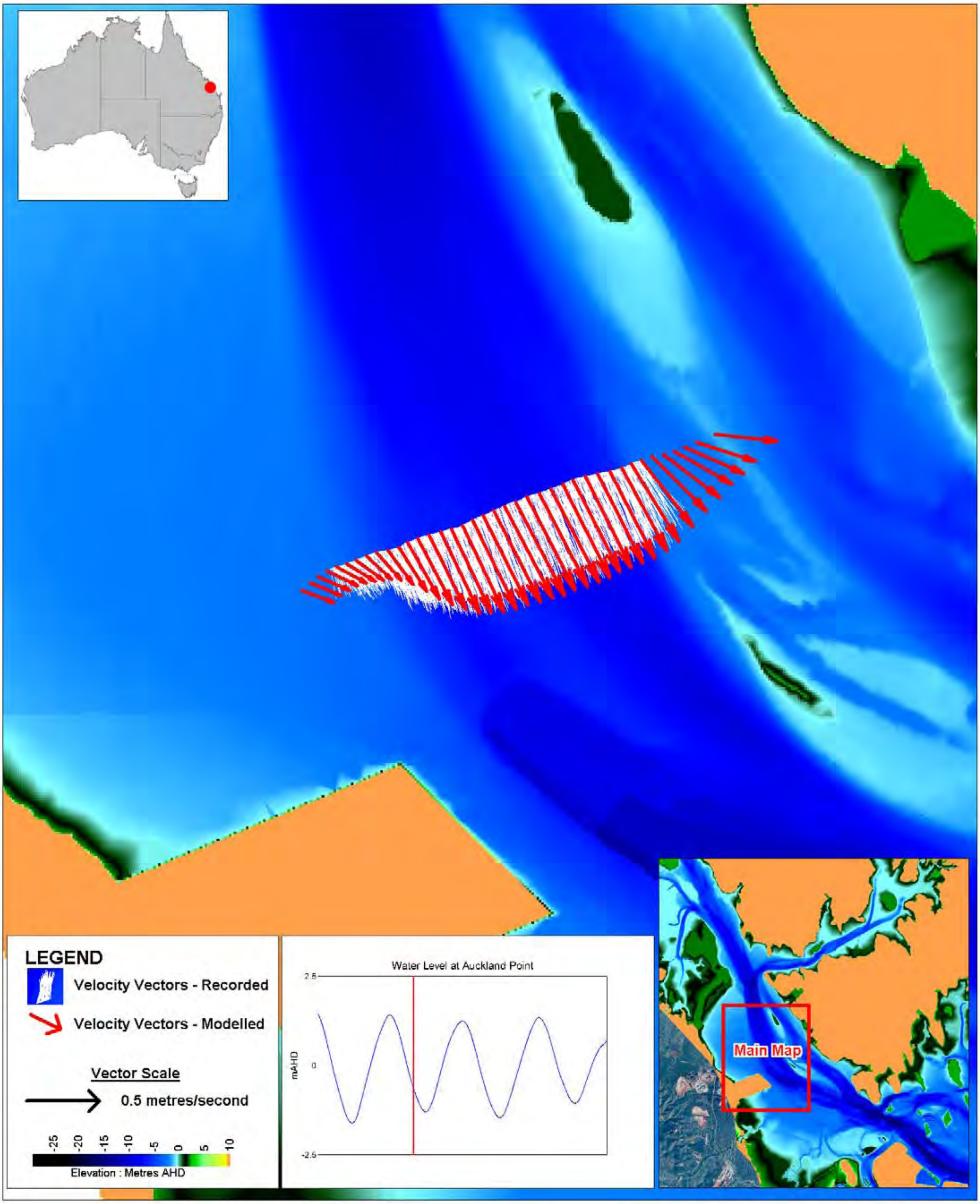

Title:

ADCP Transect Fishermans Landing 137

Figure: **E-18**

Rev: **A**

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Scale - Inset

0 0.5 1km

Scale - Main Map

BMT WBM

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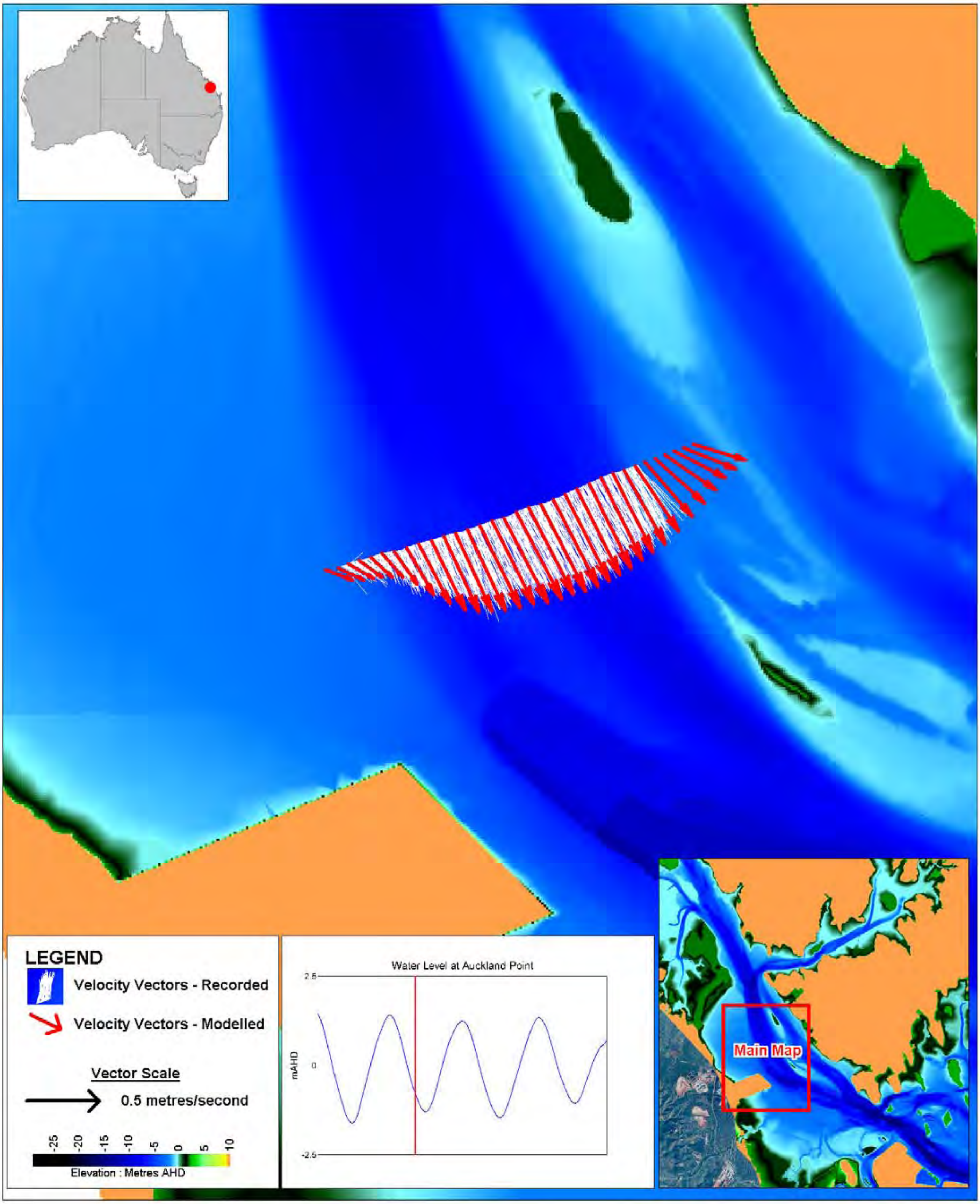
Filepath : \\wbmfs2\drafting\B17382_I_clw_Glad Strategic\DRG\Calib\ADCP\Aug2008\COA_018_090804_FishLand_Trans137.wor



Title:

ADCP Transect Fishermans Landing 138

Figure: **E-19**

Rev: **A**

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Scale - Inset

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Scale - Main Map

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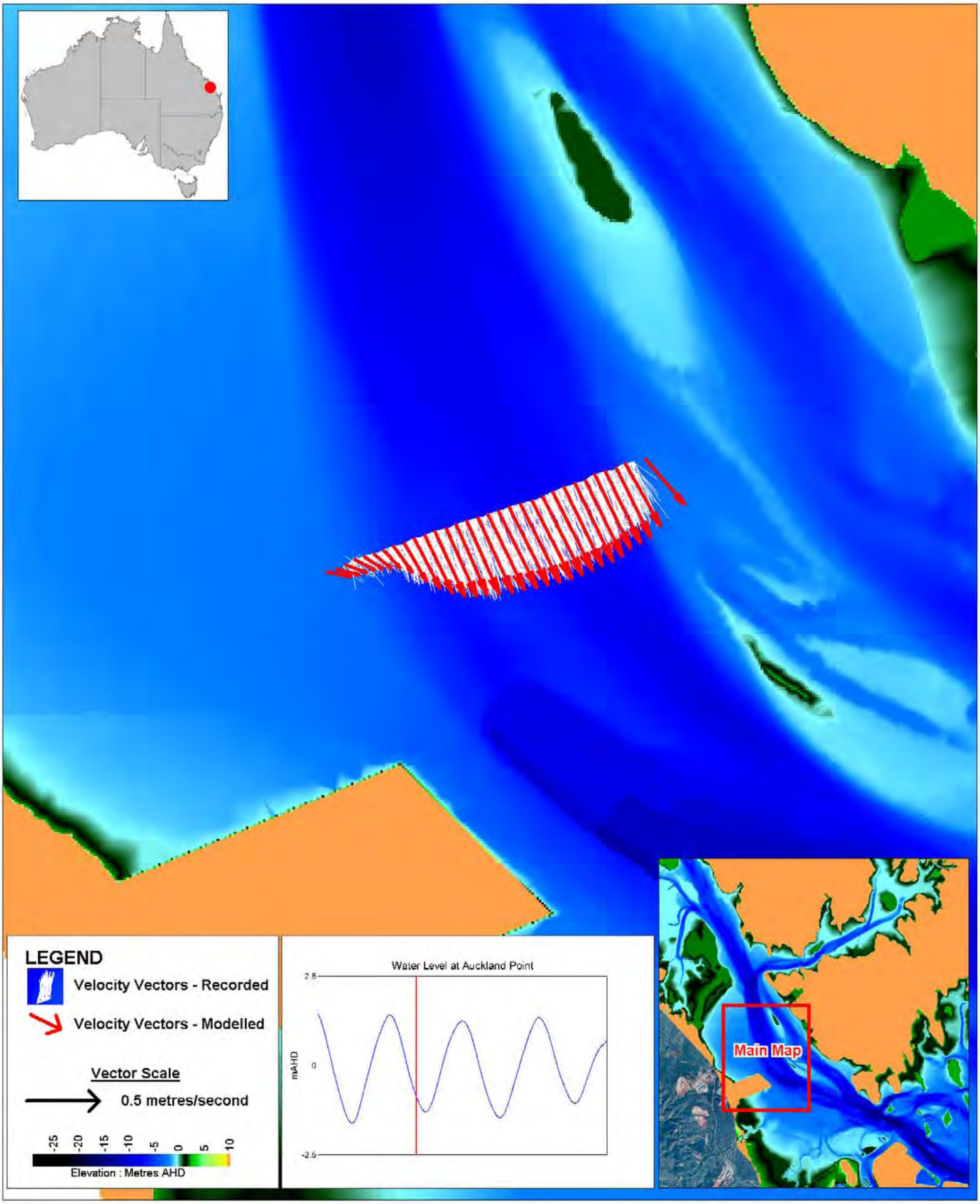

Title:

ADCP Transect Fishermans Landing 139

Figure: E-20

Rev: A

N

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Scale - Inset

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Scale - Main Map

BMT WBM

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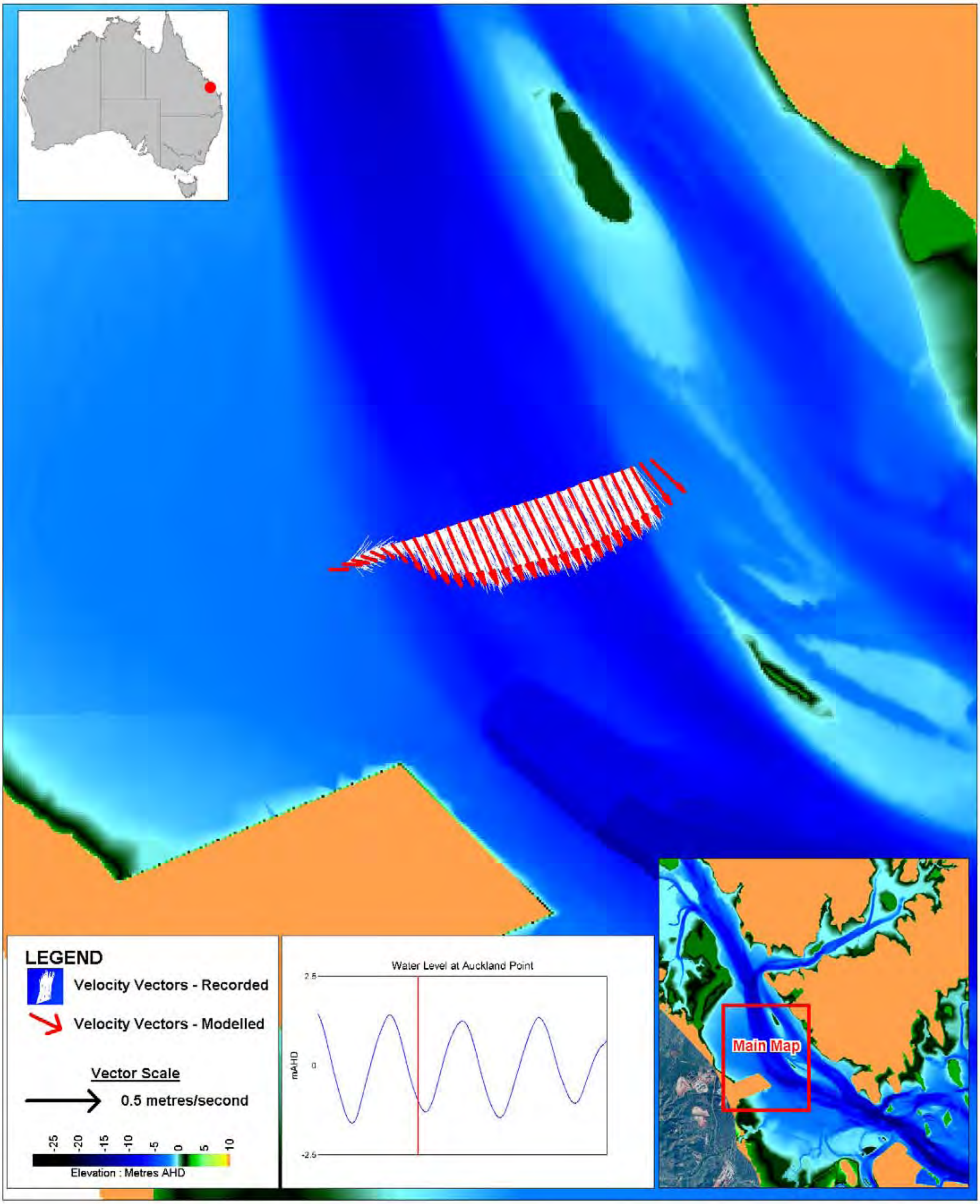

Title:

ADCP Transect Fishermans Landing 140

Figure: E-21

Rev: A

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0 5 10km
Scale - Inset

0 0.5 1km
Scale - Main Map

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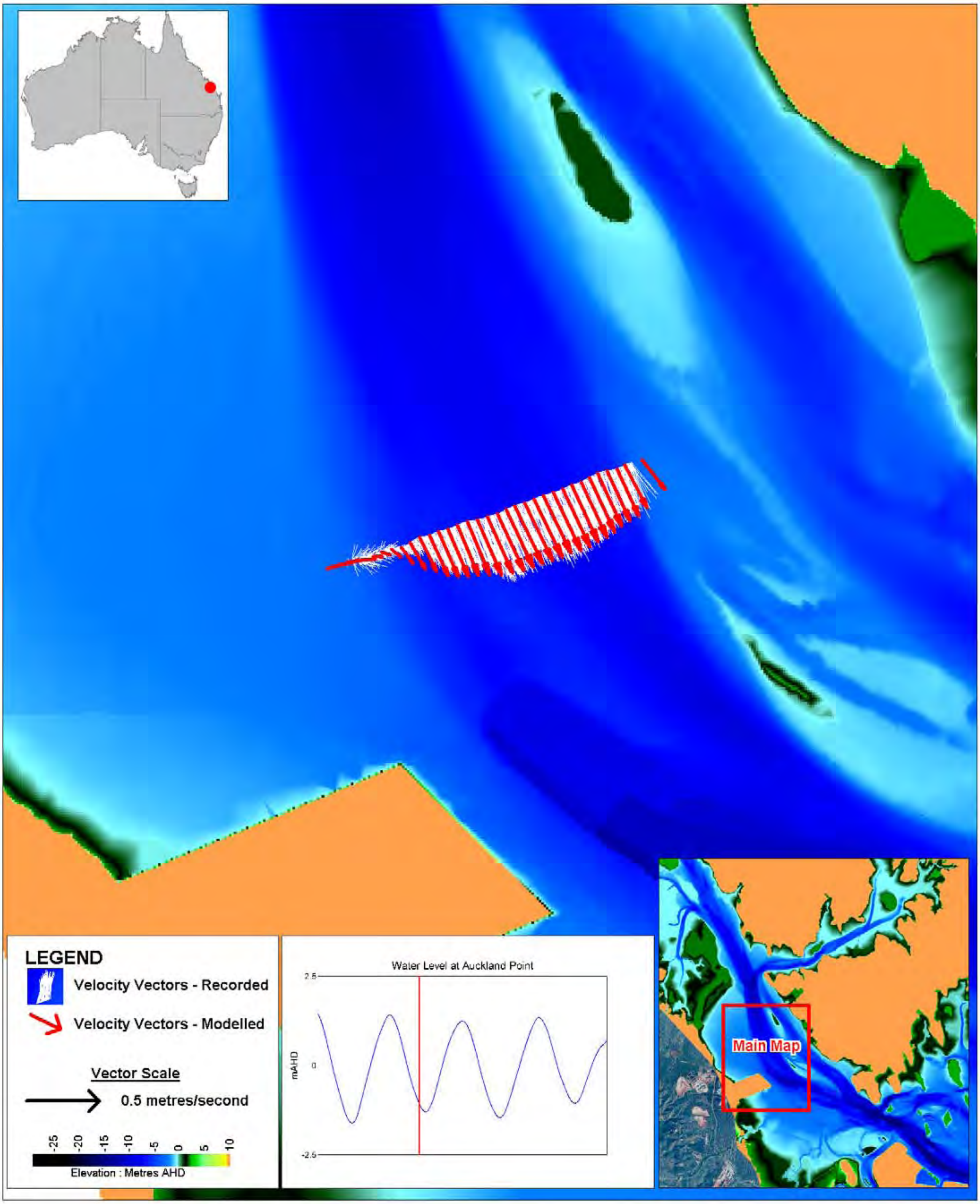

Title:
ADCP Transect Fishermans Landing 141

Figure: E-22

Rev: A

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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Scale - Inset

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Scale - Main Map

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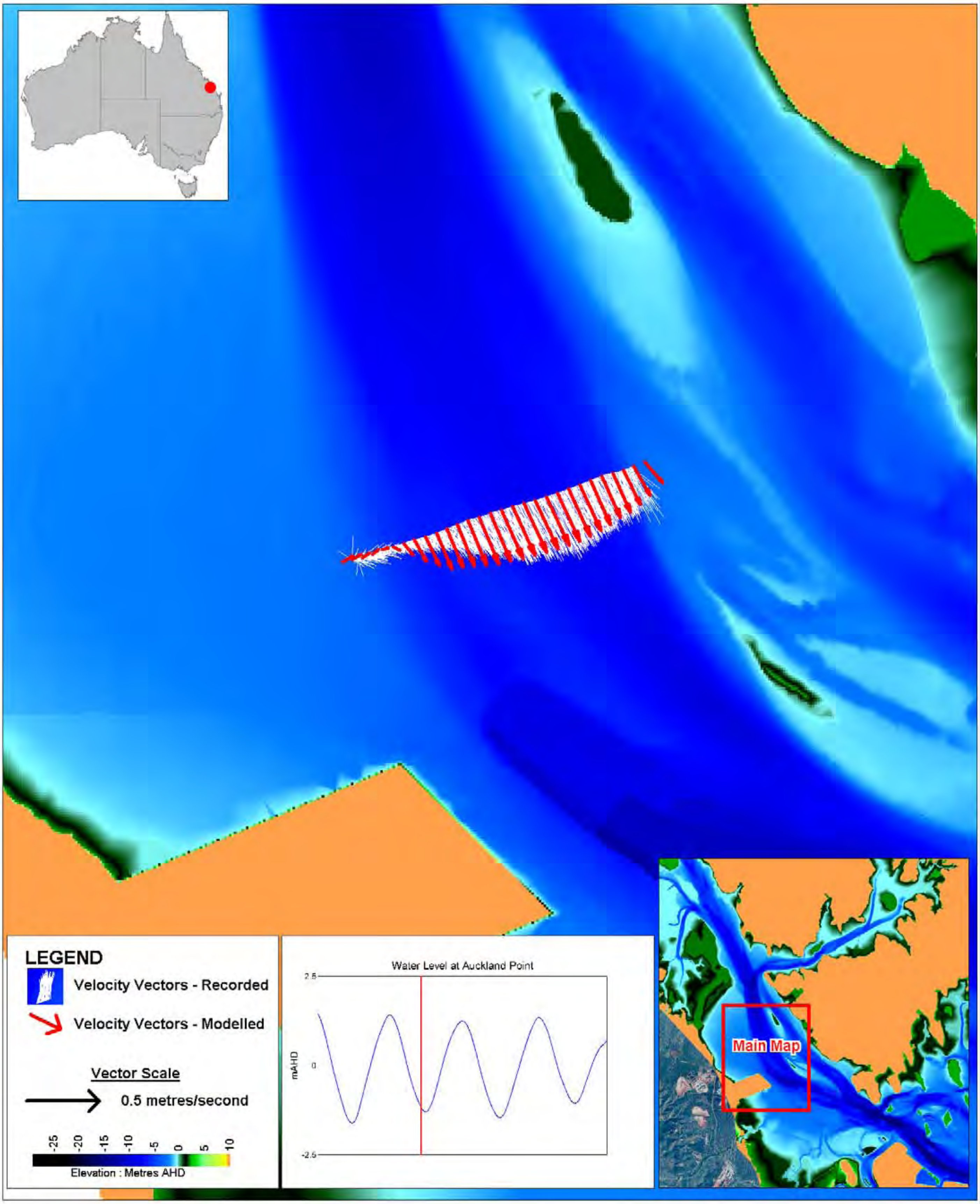

Title:
ADCP Transect Fishermans Landing 142

Figure: **E-23**

Rev: **A**

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Scale - Inset

0 0.5 1km
Scale - Main Map

BMT WBM
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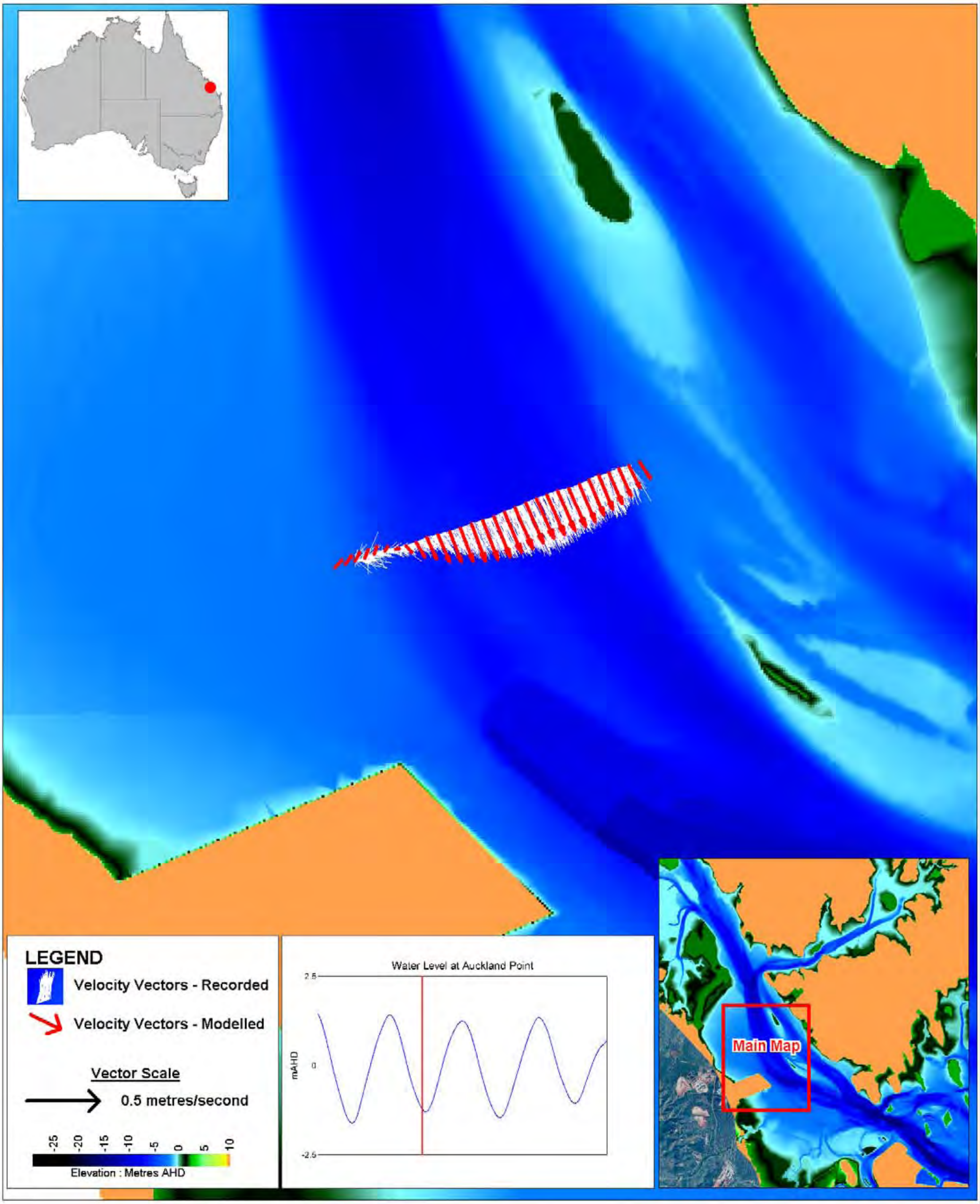

Title:

ADCP Transect Fishermans Landing 143

Figure: **E-24**

Rev: **A**

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Scale - Main Map

BMT WBM
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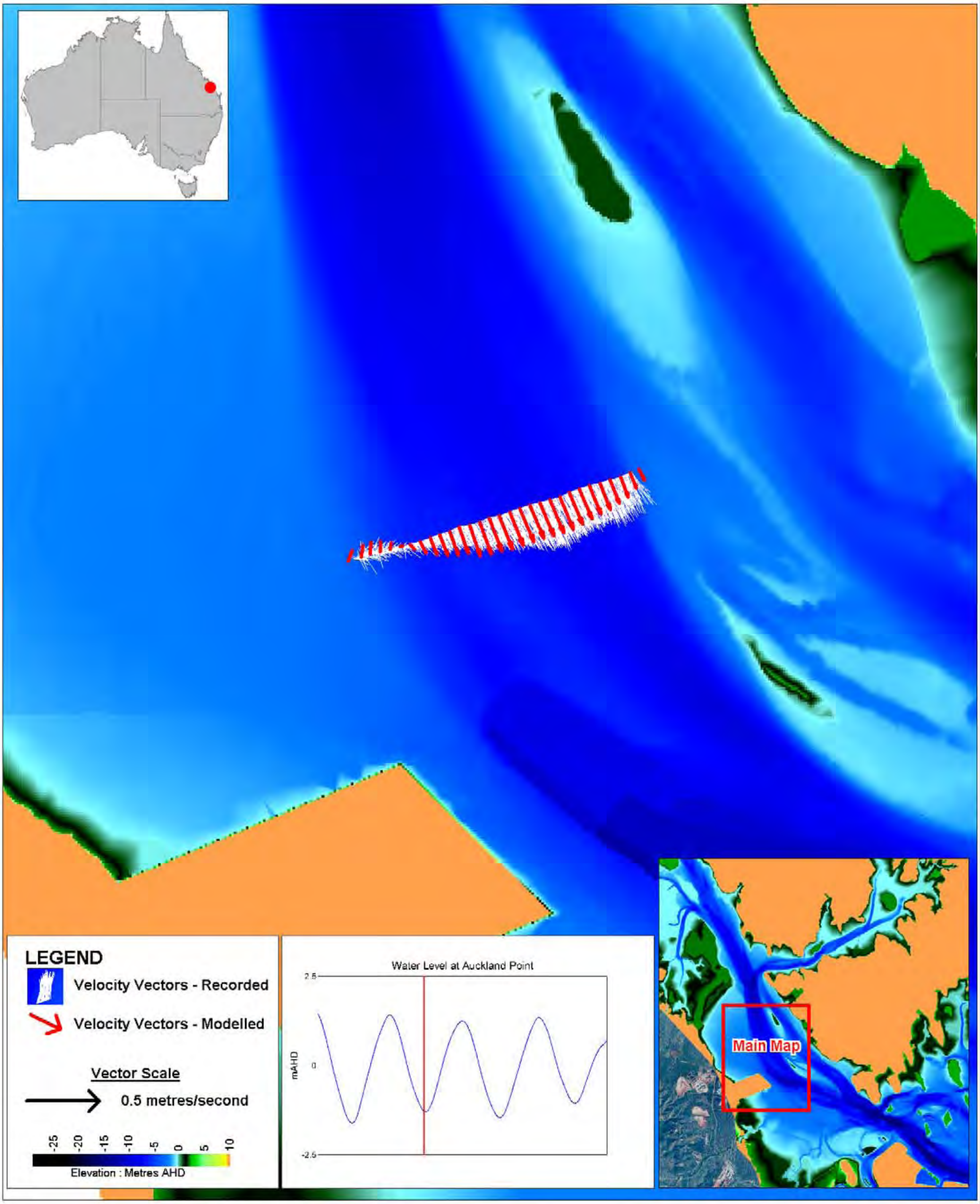

Title:
ADCP Transect Fishermans Landing 144

Figure: **E-25**

Rev: **A**

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Scale - Inset
0 0.5 1km
Scale - Main Map

BMT WBM
www.wbmpl.com.au

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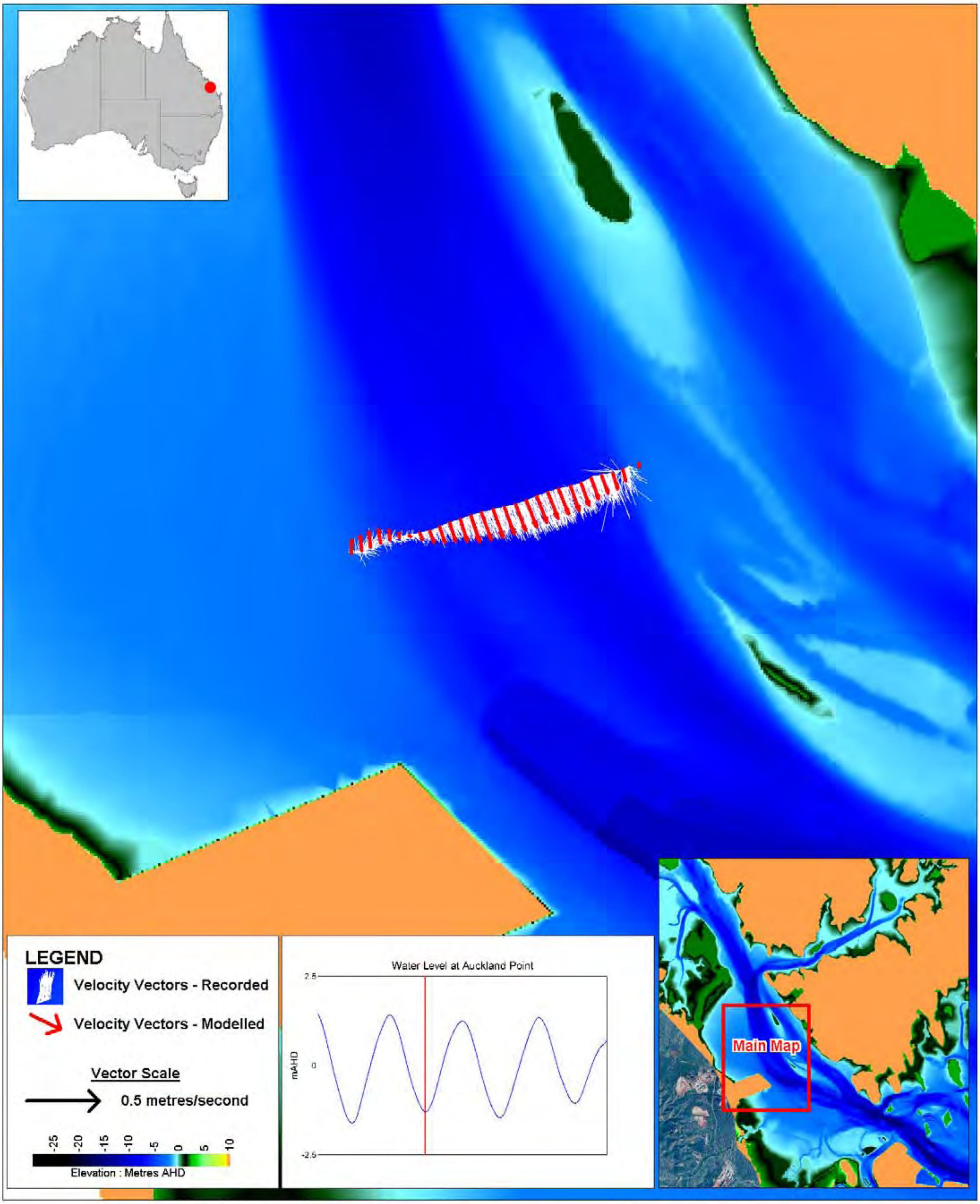

Title:
ADCP Transect Fishermans Landing 145

Figure: **E-26**

Rev: **A**

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Scale - Inset

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Scale - Main Map

BMT WBM
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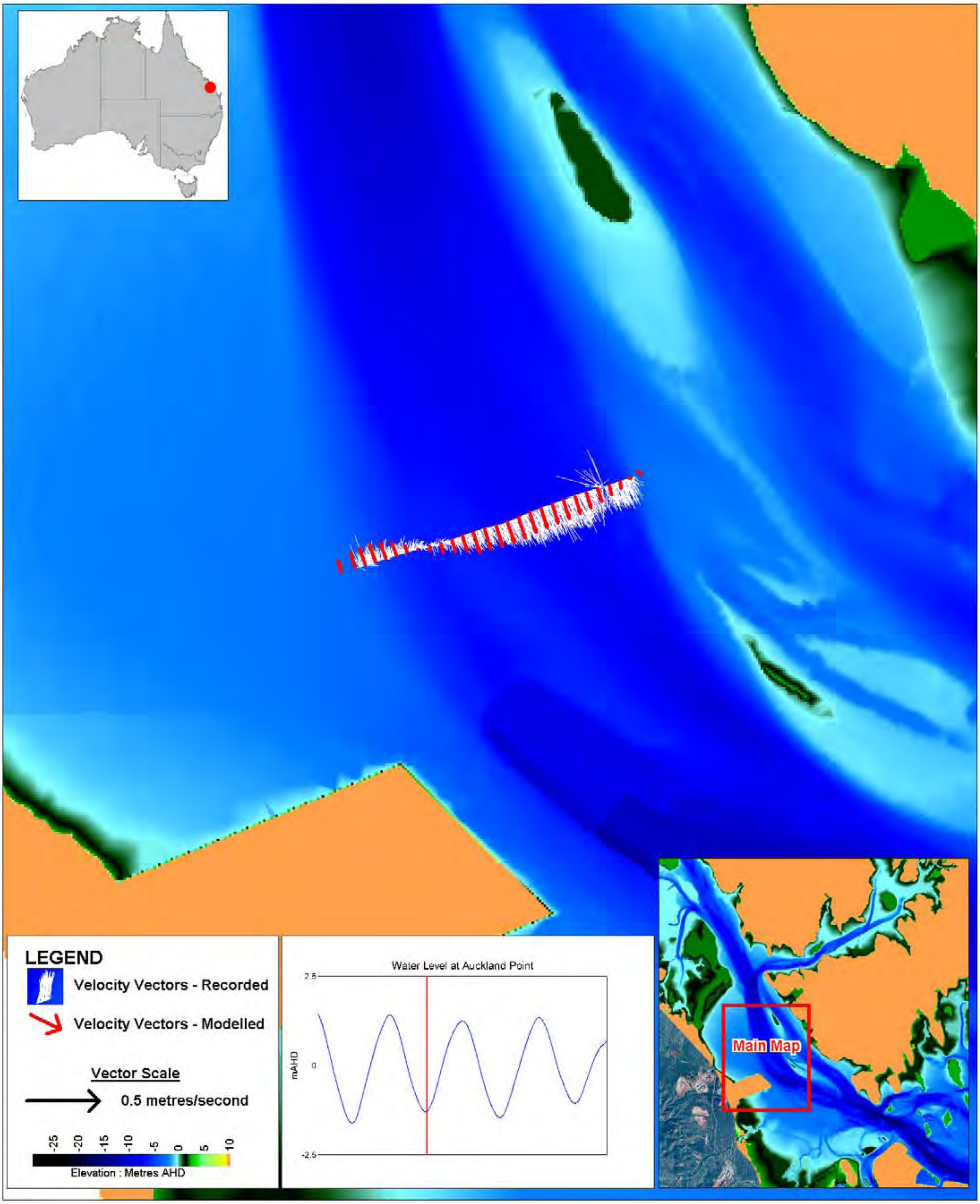

Title:

ADCP Transect Fishermans Landing 146

Figure: **E-27**

Rev: **A**

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Scale - Inset

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Scale - Main Map

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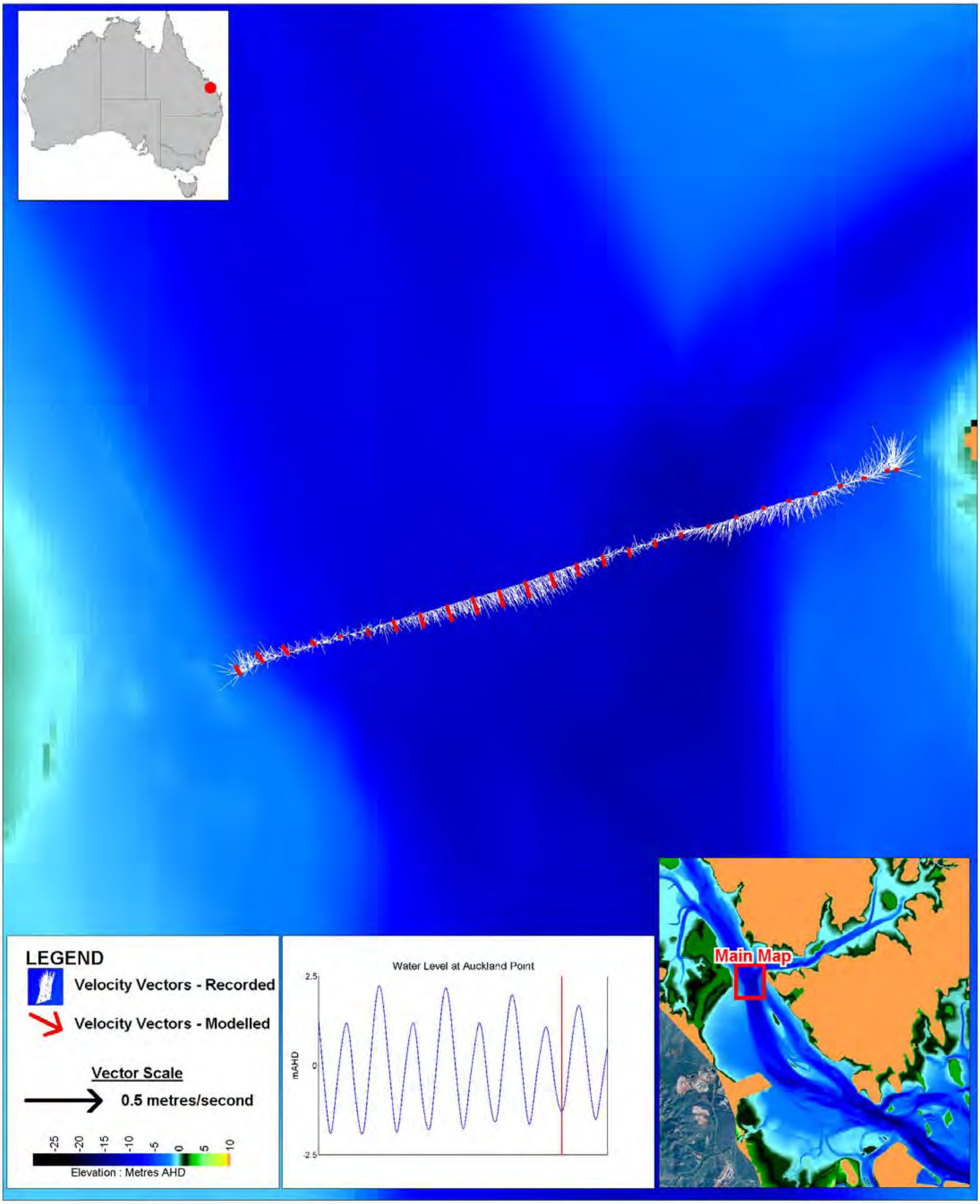
Filepath : \\wbmfs2\drafting\B17382_I_clw_Glad Strategic\DRG\Calib\ADCP\Aug2008\COA_027_090804_FishLand_Trans146.wor

APPENDIX F: CURRENT VELOCITY PLOTS JUNE 2009



Title:

ADCP Transect Laird Point 000

Figure: **F-1**

Rev: **A**

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Scale - Inset

0 150 300m
Scale - Main Map

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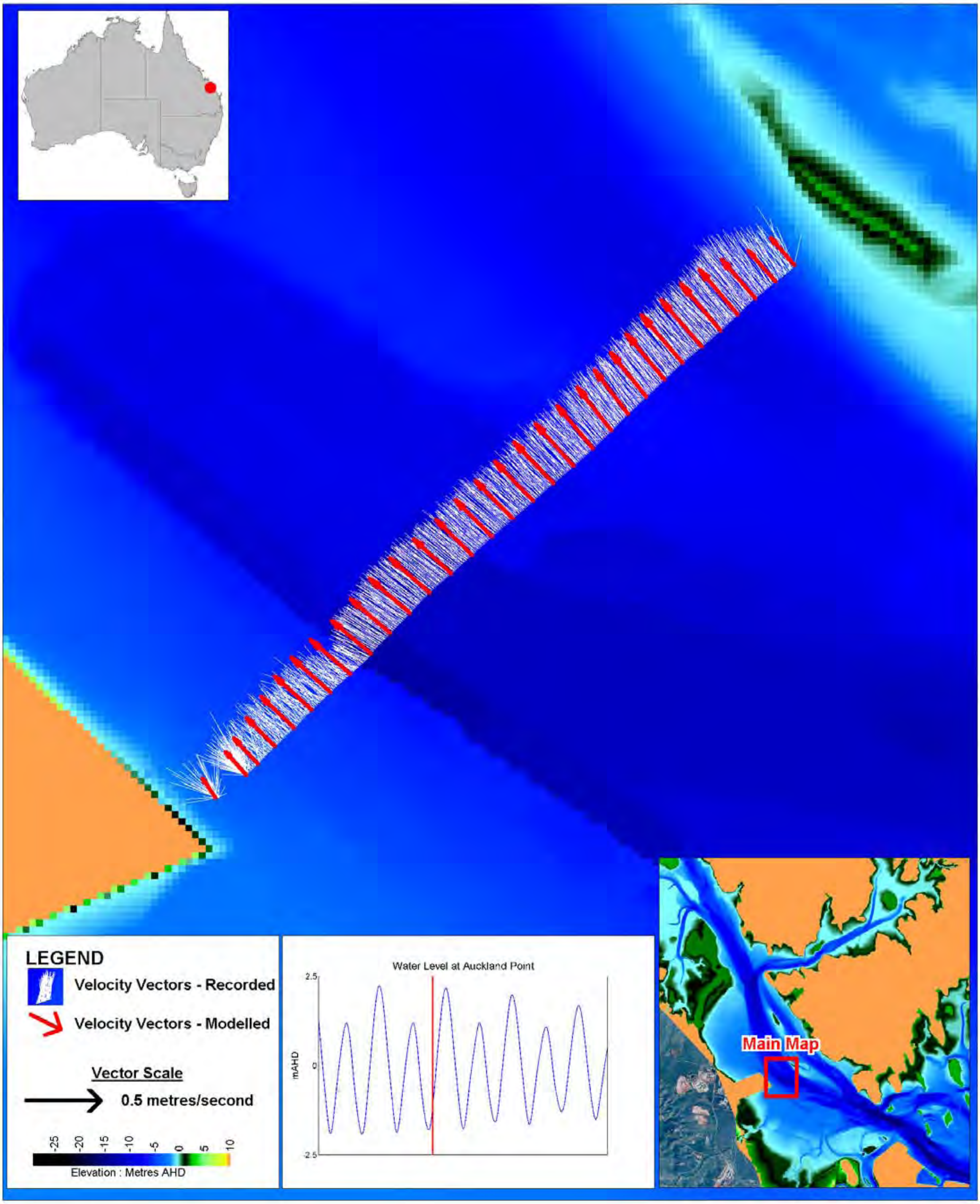

Title:

ADCP Transect Targinnie 002

Figure: **F-28**

Rev: **A**

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Scale - Inset

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Scale - Main Map

BMT WBM

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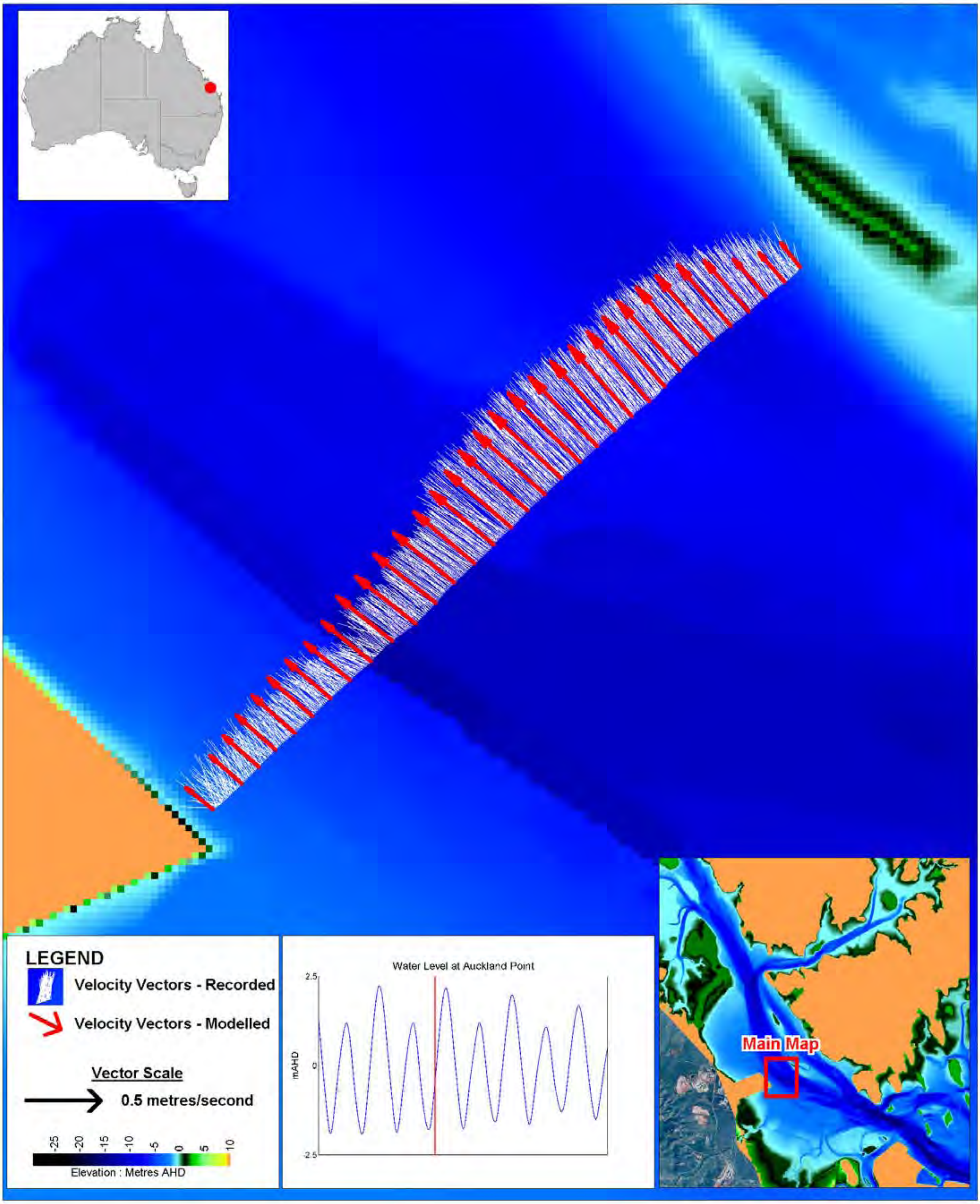

Title:

ADCP Transect Targinnie 006

Figure: **F-29**

Rev: **A**

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Scale - Inset

0 150 300m
Scale - Main Map

BMT WBM
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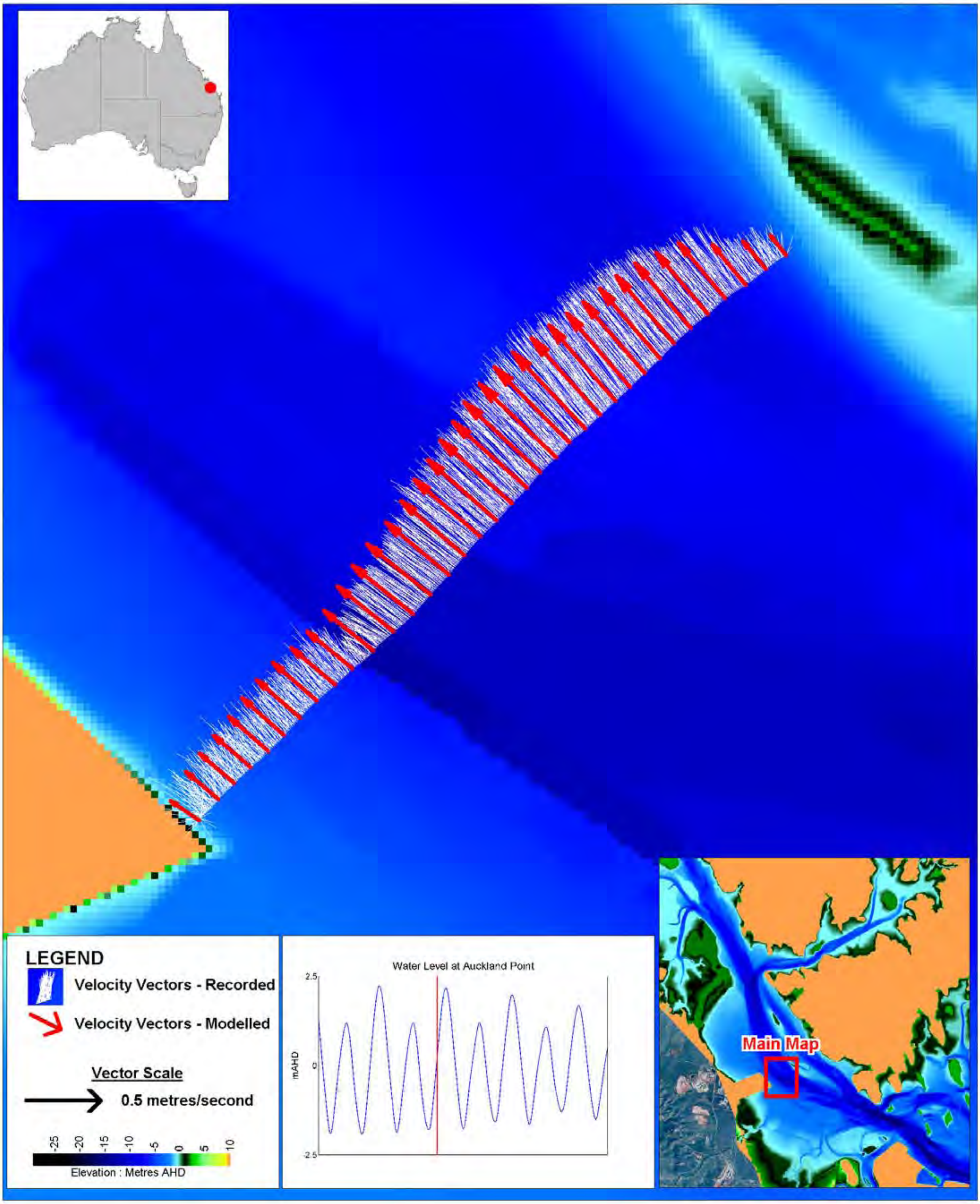

Title:
ADCP Transect Targinnie 008

Figure: **F-30**

Rev: **A**

N

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Scale - Inset

0 150 300m
Scale - Main Map

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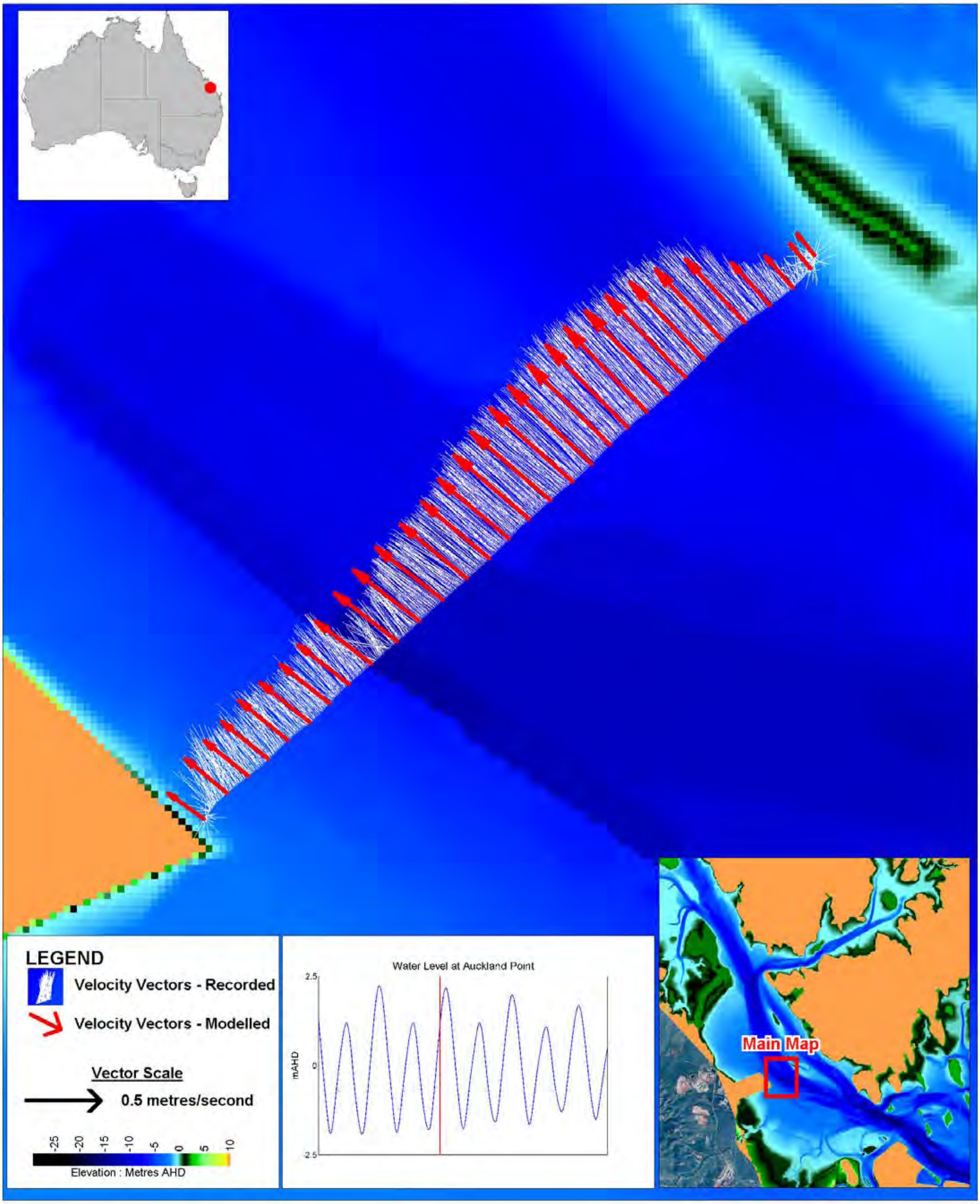

Title:

ADCP Transect Targinnie 010

Figure: **F-31**

Rev: **A**

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N

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Scale - Inset

0 150 300m
Scale - Main Map

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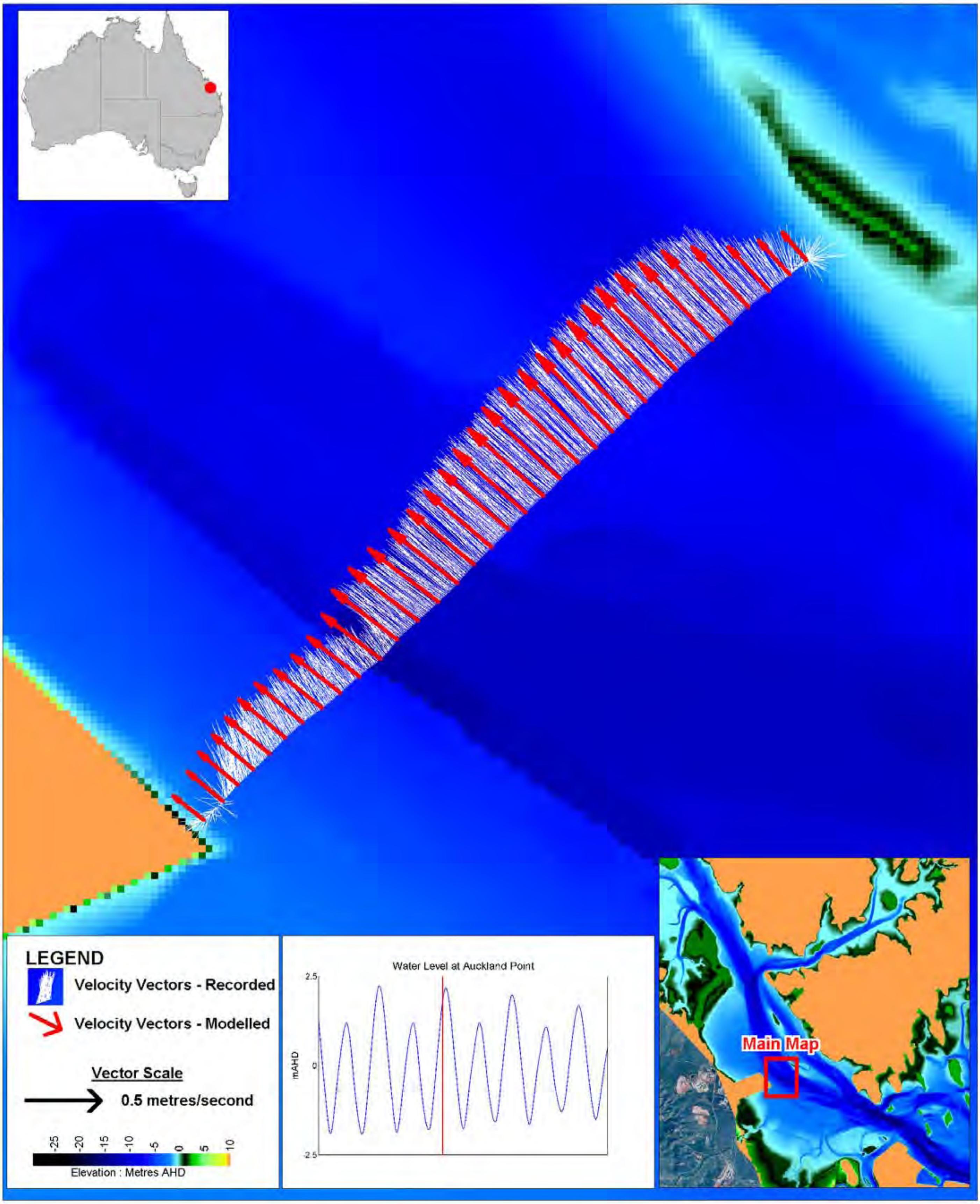

Title:

ADCP Transect Targinnie 013

Figure: **F-32**

Rev: **A**

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N

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Scale - Inset

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Scale - Main Map

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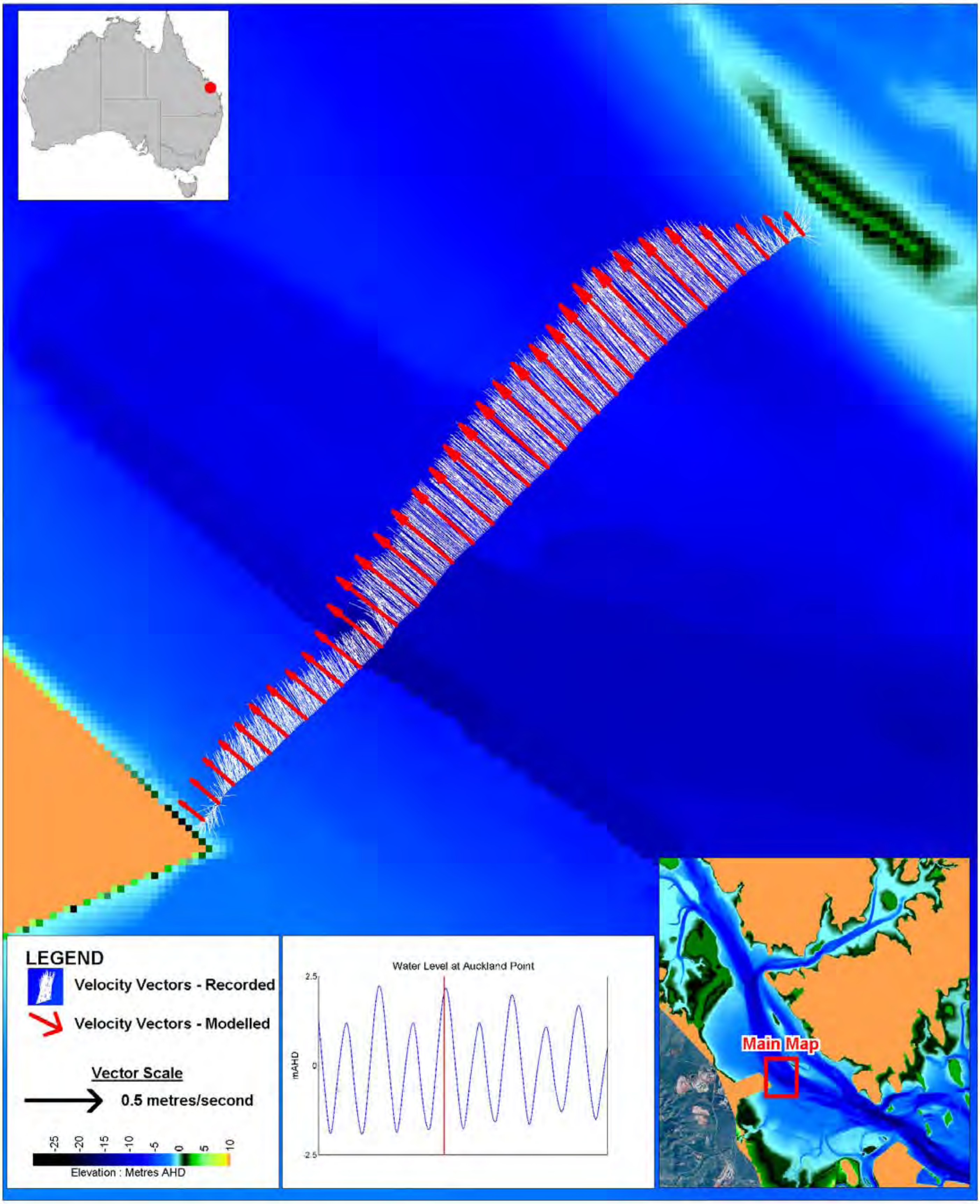

Title:

ADCP Transect Targinnie 015

Figure: F-33

Rev: A

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N

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Scale - Inset

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Scale - Main Map

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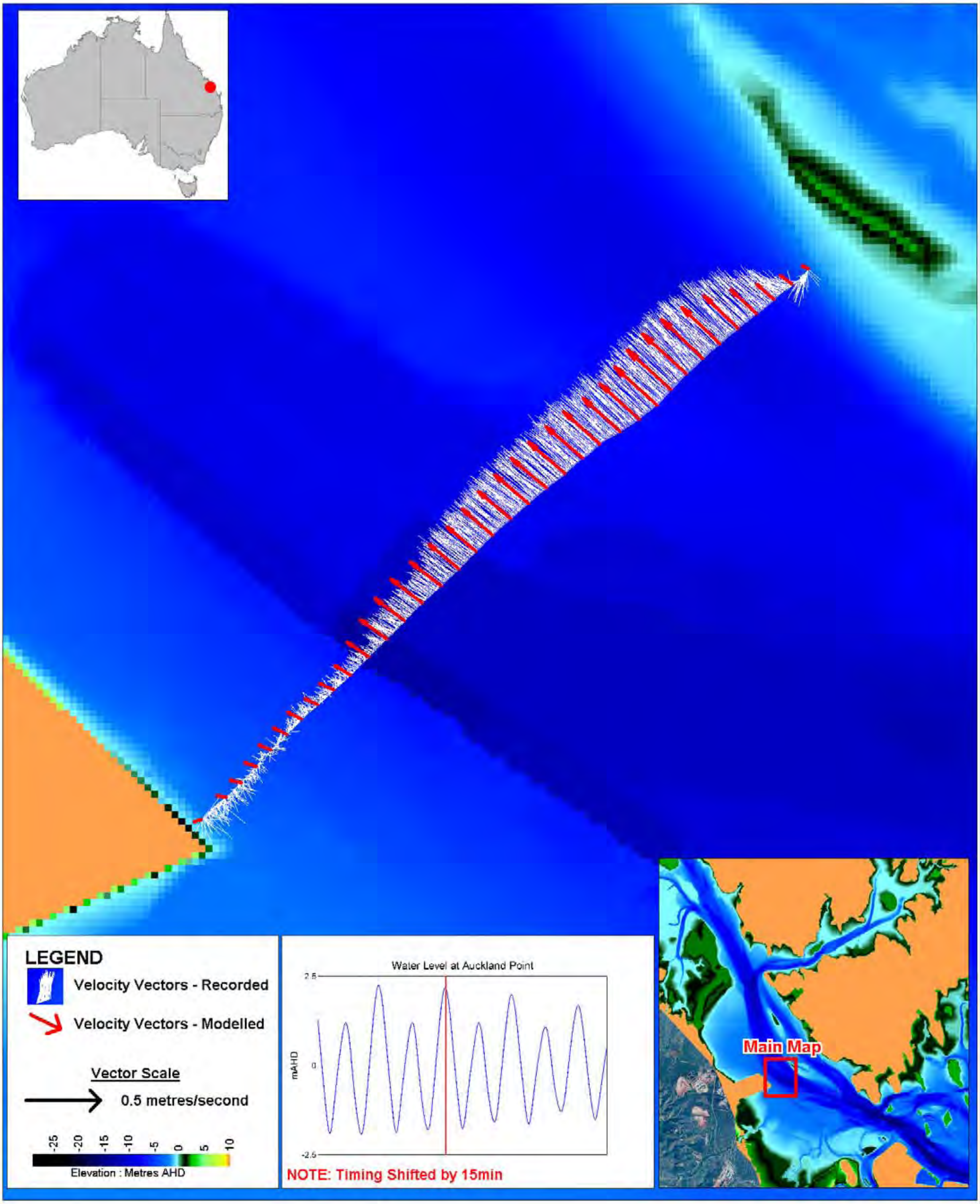

Title:

ADCP Transect Targinnie 017

Figure: **F-34**

Rev: **A**

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Scale - Inset

0 150 300m

Scale - Main Map

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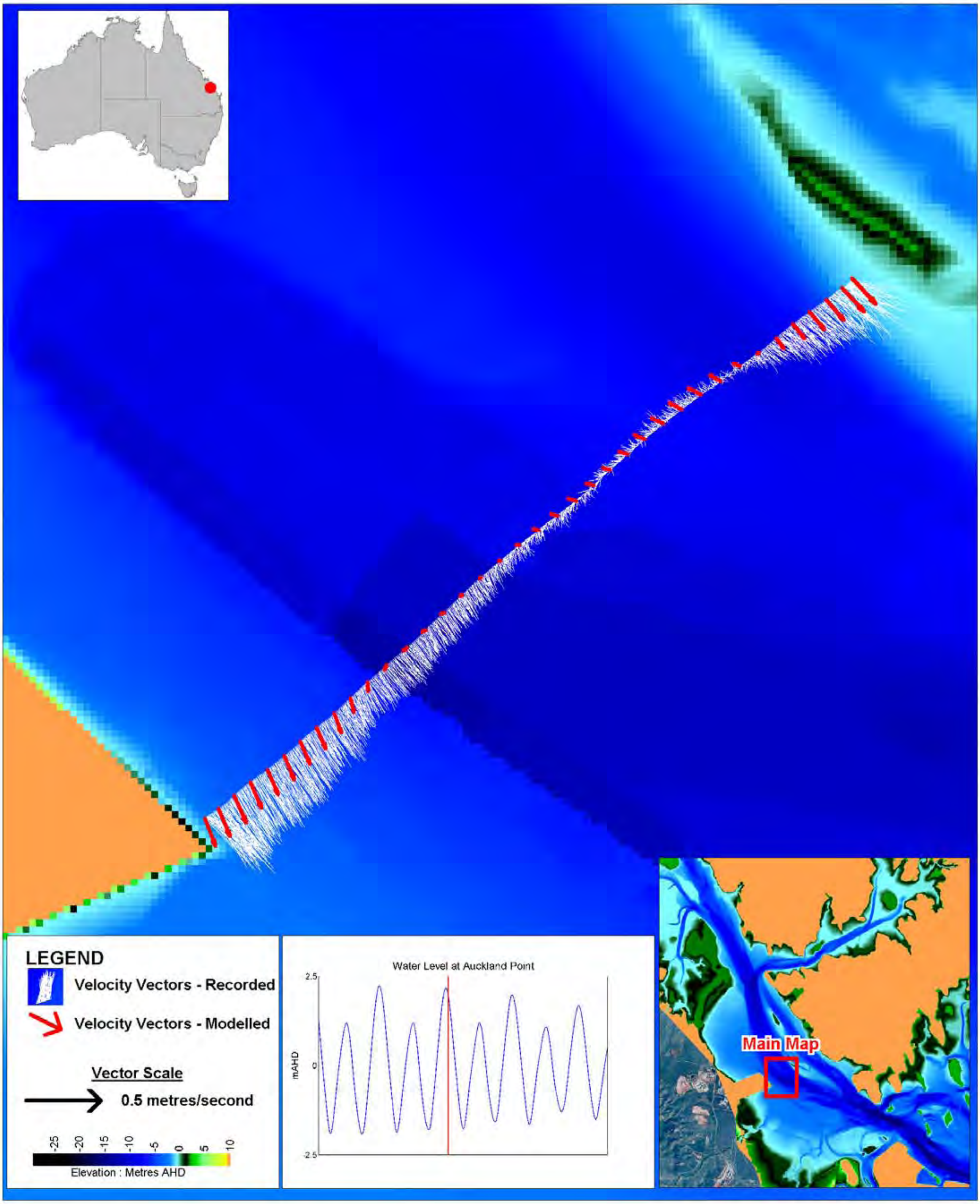

Title:

ADCP Transect Targinnie 019

Figure: **F-35**

Rev: **A**

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N

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Scale - Inset

0 150 300m

Scale - Main Map

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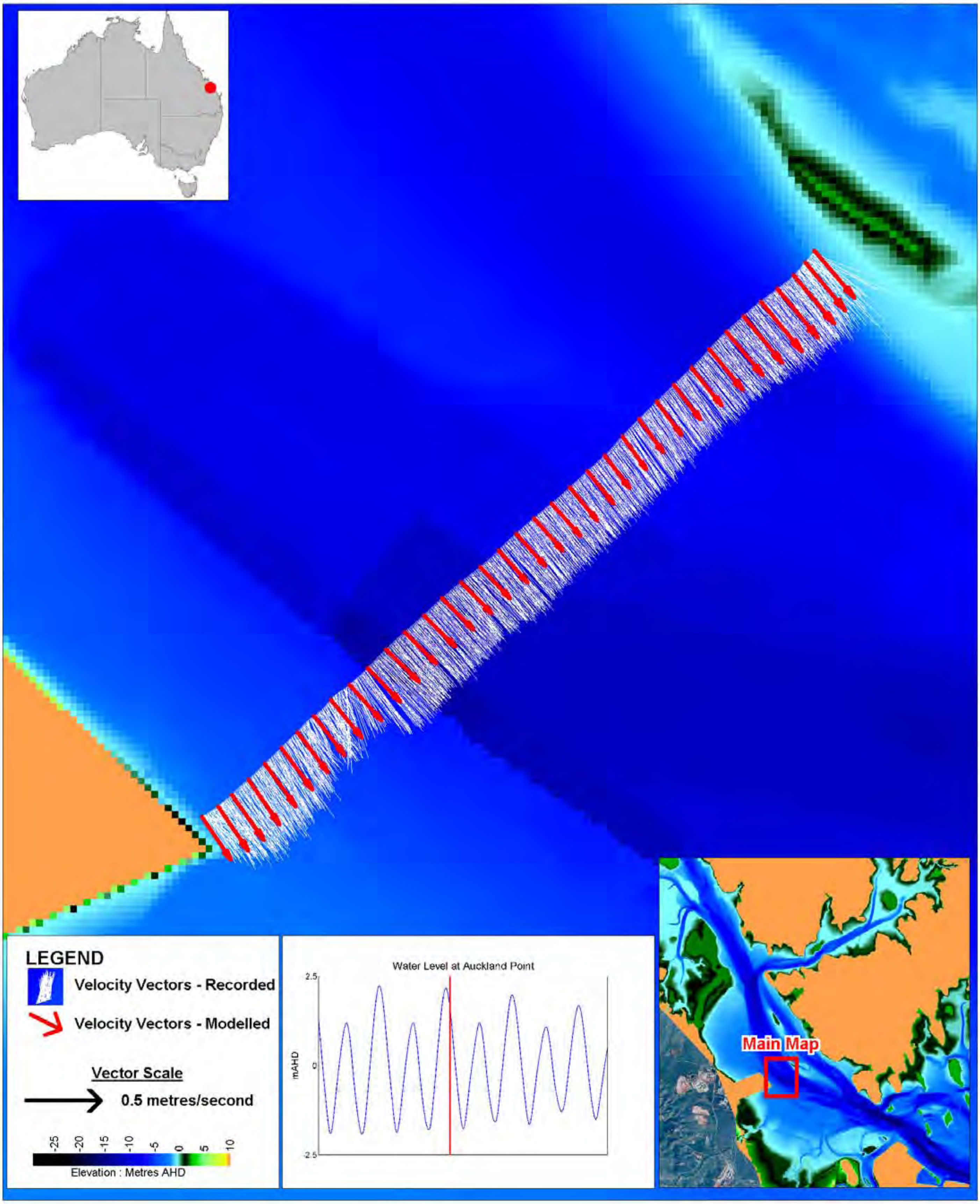

Title:

ADCP Transect Targinnie 021

Figure: **F-36**

Rev: **A**

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Scale - Inset

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Scale - Main Map

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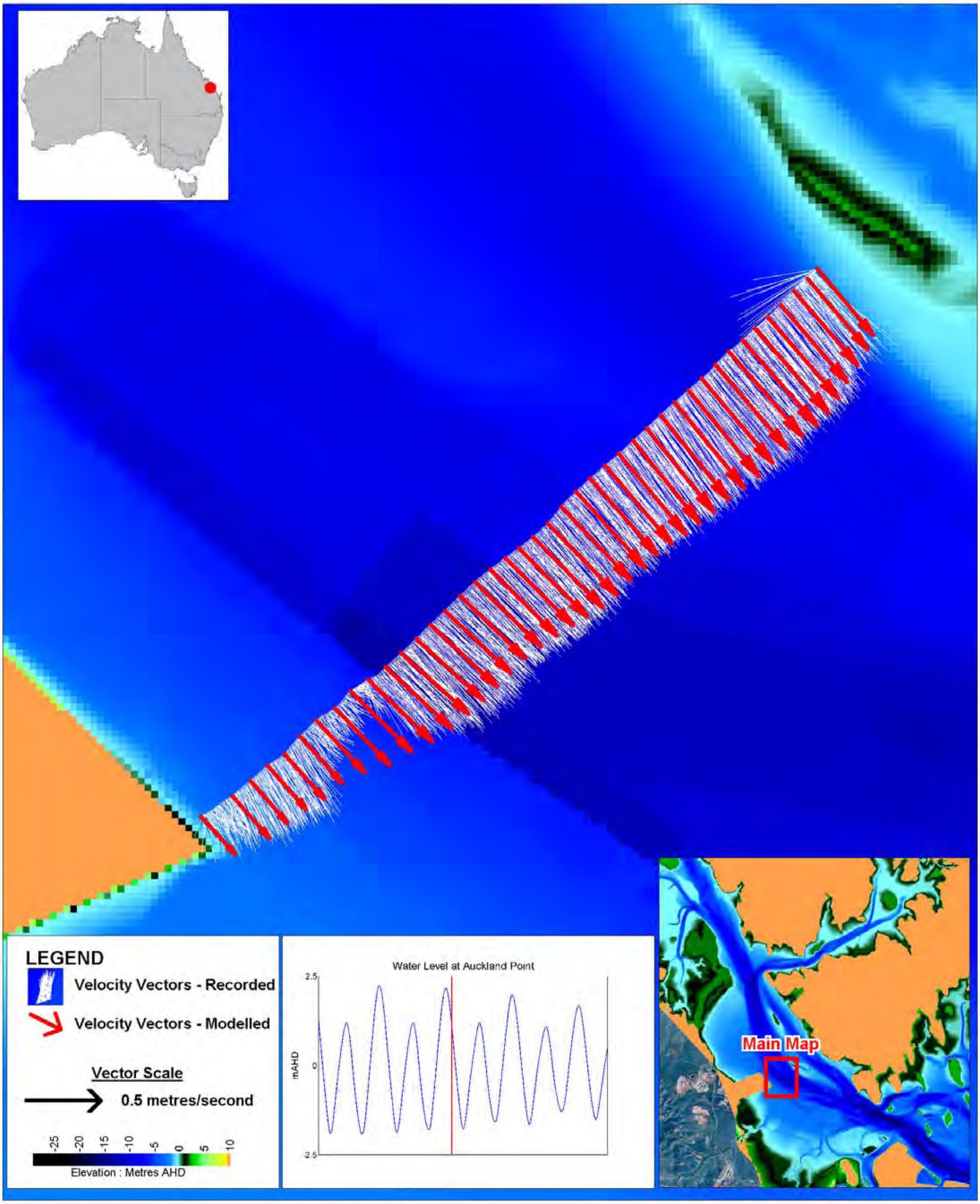

Title:

ADCP Transect Targinnie 023

Figure: **F-37**

Rev: **A**

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N

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Scale - Inset
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Scale - Main Map

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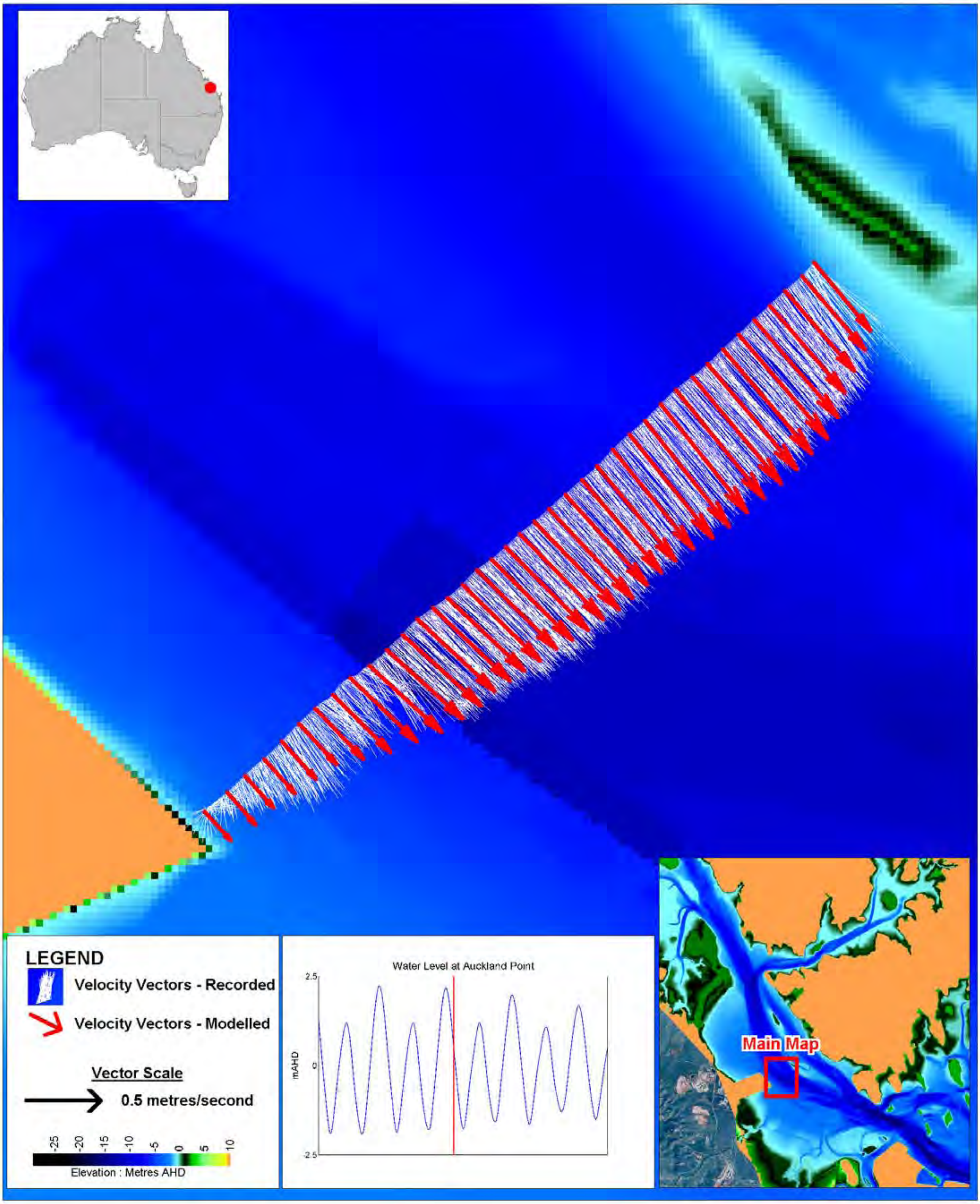

Title:

ADCP Transect Targinnie 025

Figure: **F-38**

Rev: **A**

N

0 5 10km

Scale - Inset

0 150 300m

Scale - Main Map

BMT WBM

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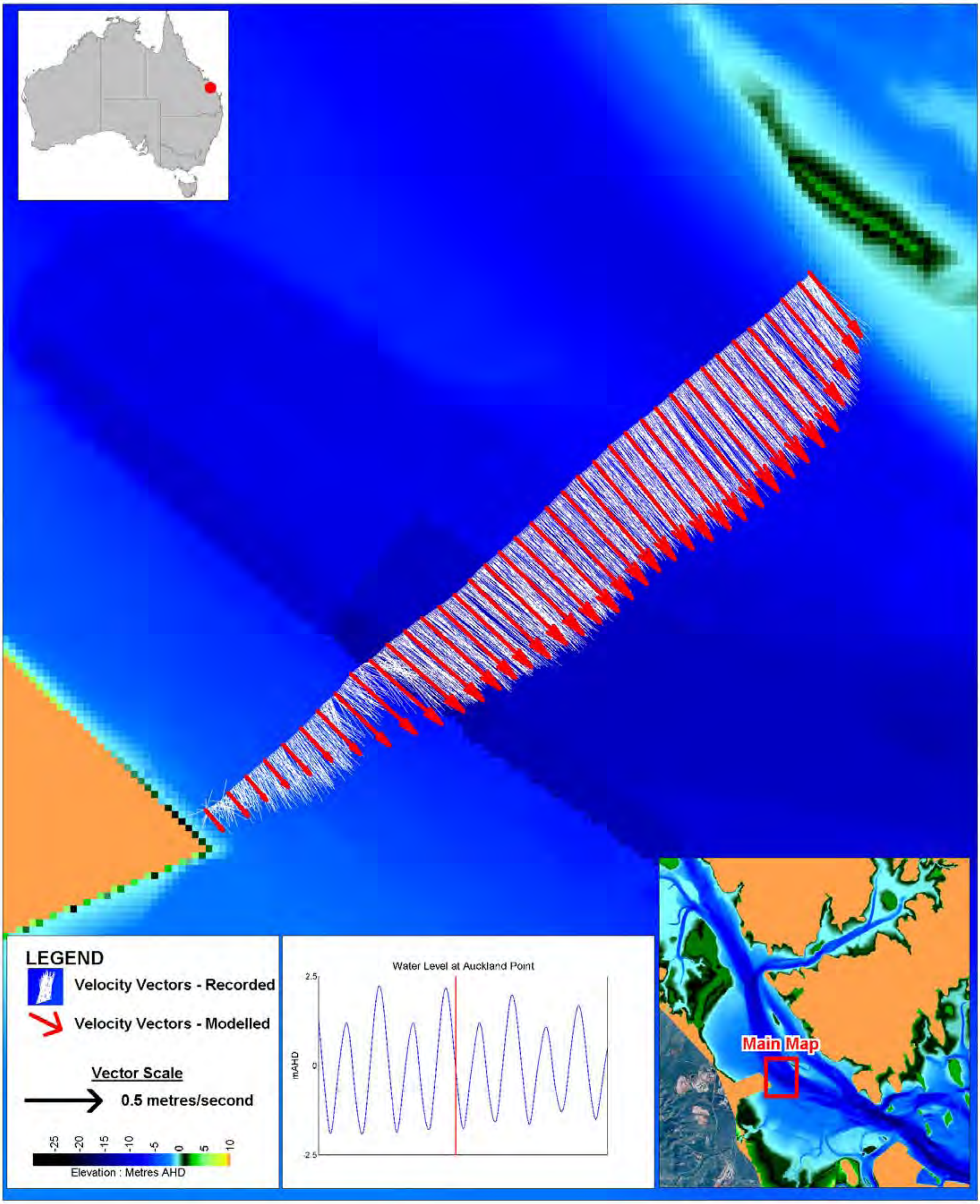

Title:

ADCP Transect Targinnie 027

Figure: **F-39**

Rev: **A**

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N

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Scale - Inset

0 150 300m
Scale - Main Map

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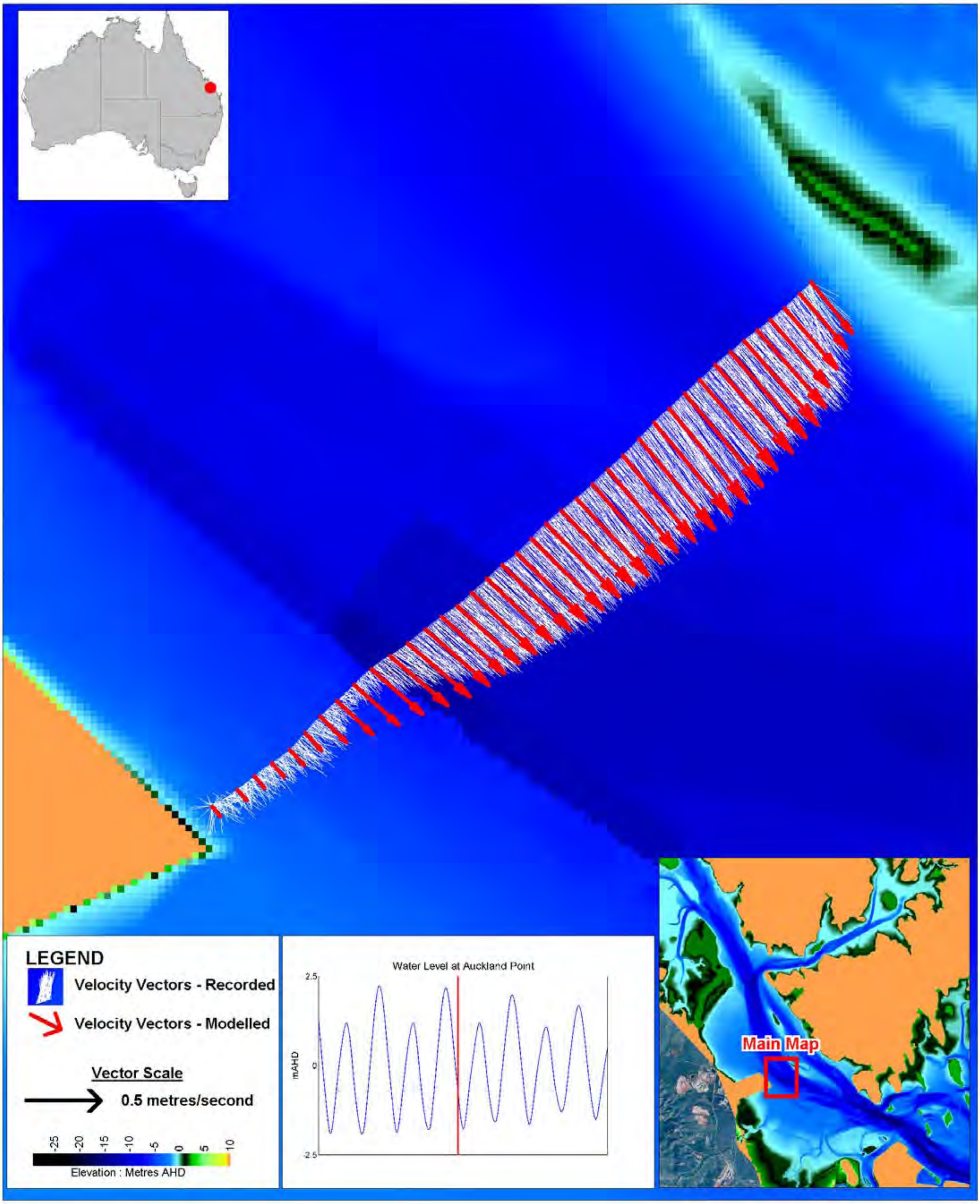

Title:

ADCP Transect Targinnie 029

Figure: **F-40**

Rev: **A**

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N

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Scale - Inset
0 150 300m
Scale - Main Map

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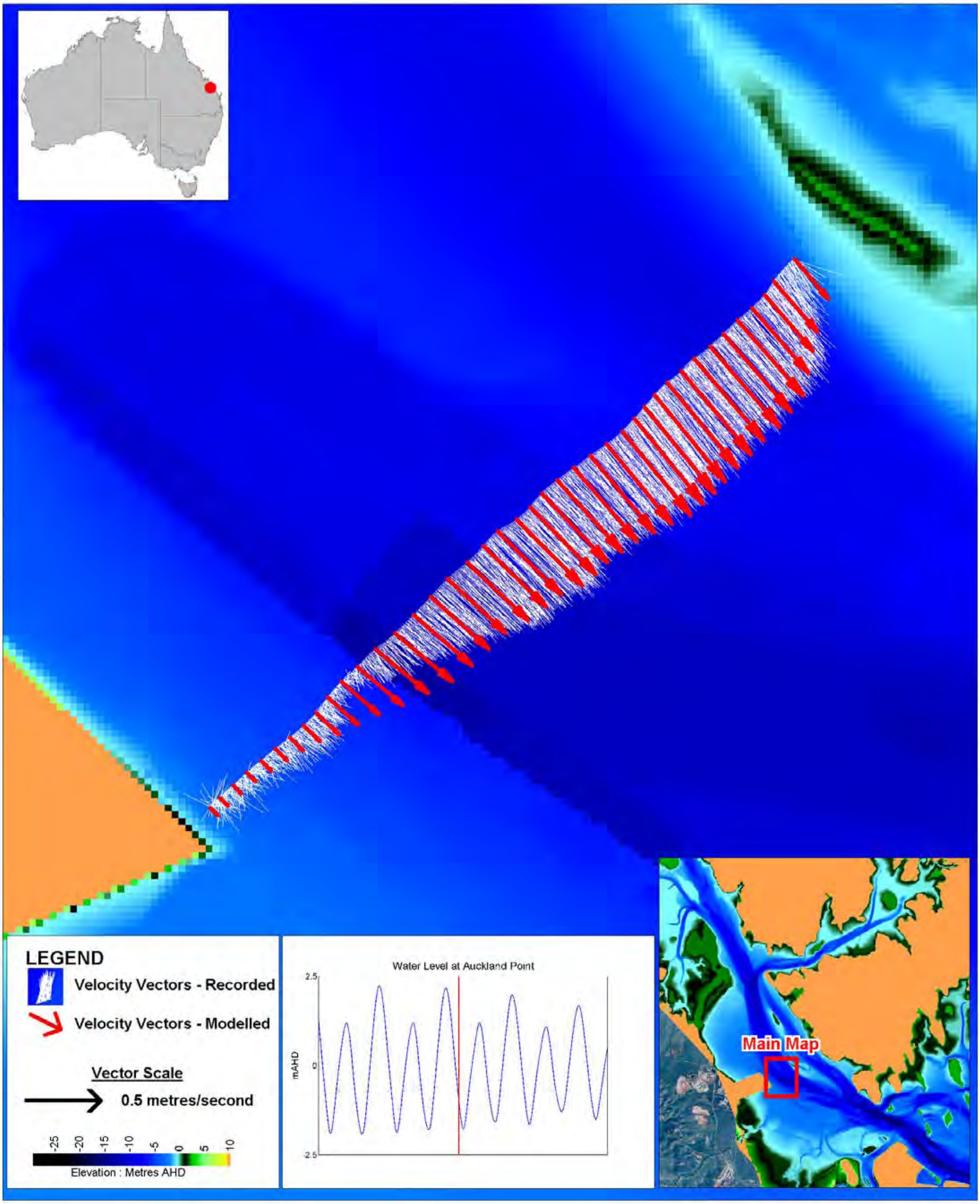

Title:

ADCP Transect Targinnie 030

Figure: **F-41**

Rev: **A**

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0 5 10km
Scale - Inset

0 150 300m
Scale - Main Map

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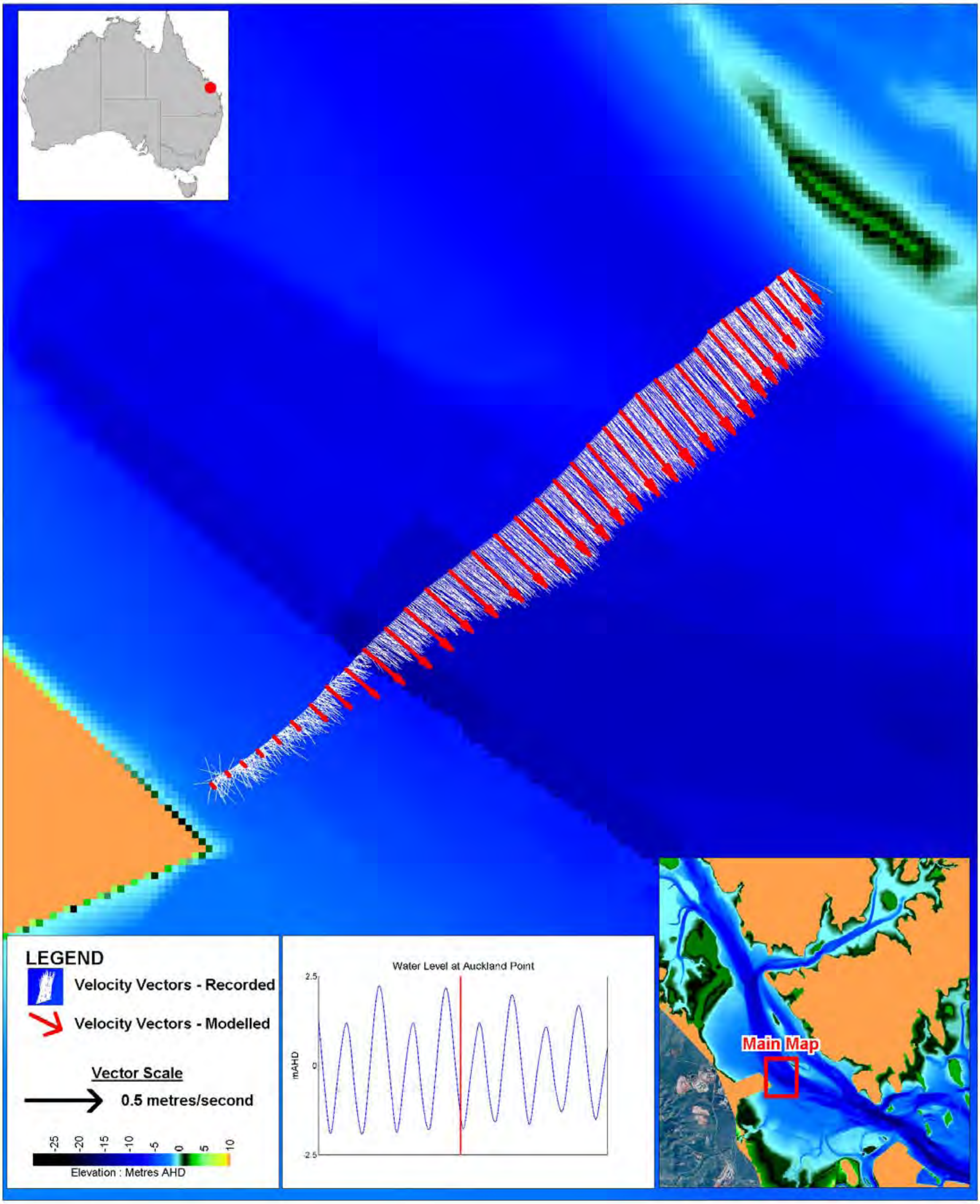

Title:
ADCP Transect Targinnie 032

Figure: **F-42**

Rev: **A**

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N

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Scale - Inset
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Scale - Main Map

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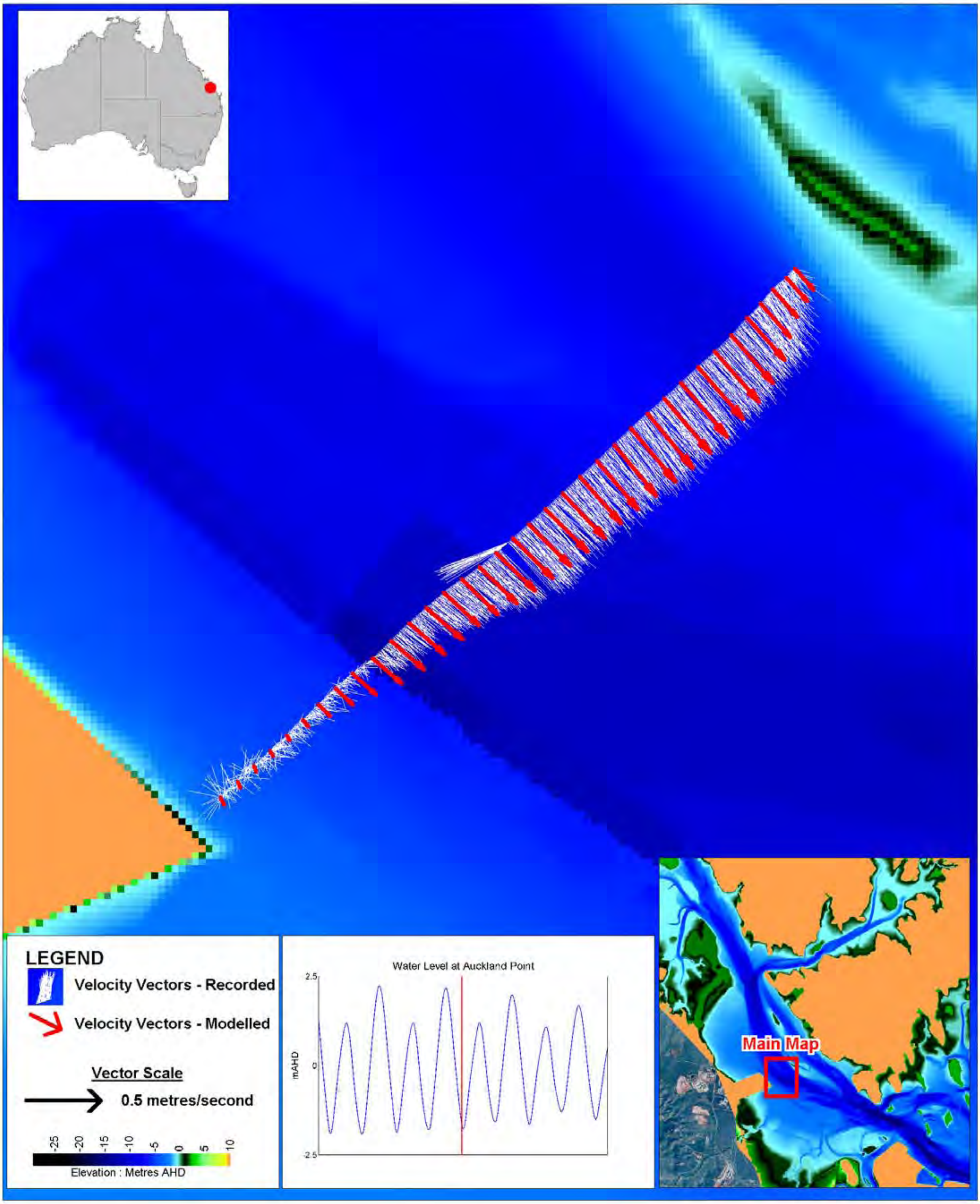

Title:

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Figure: **F-43**

Rev: **A**

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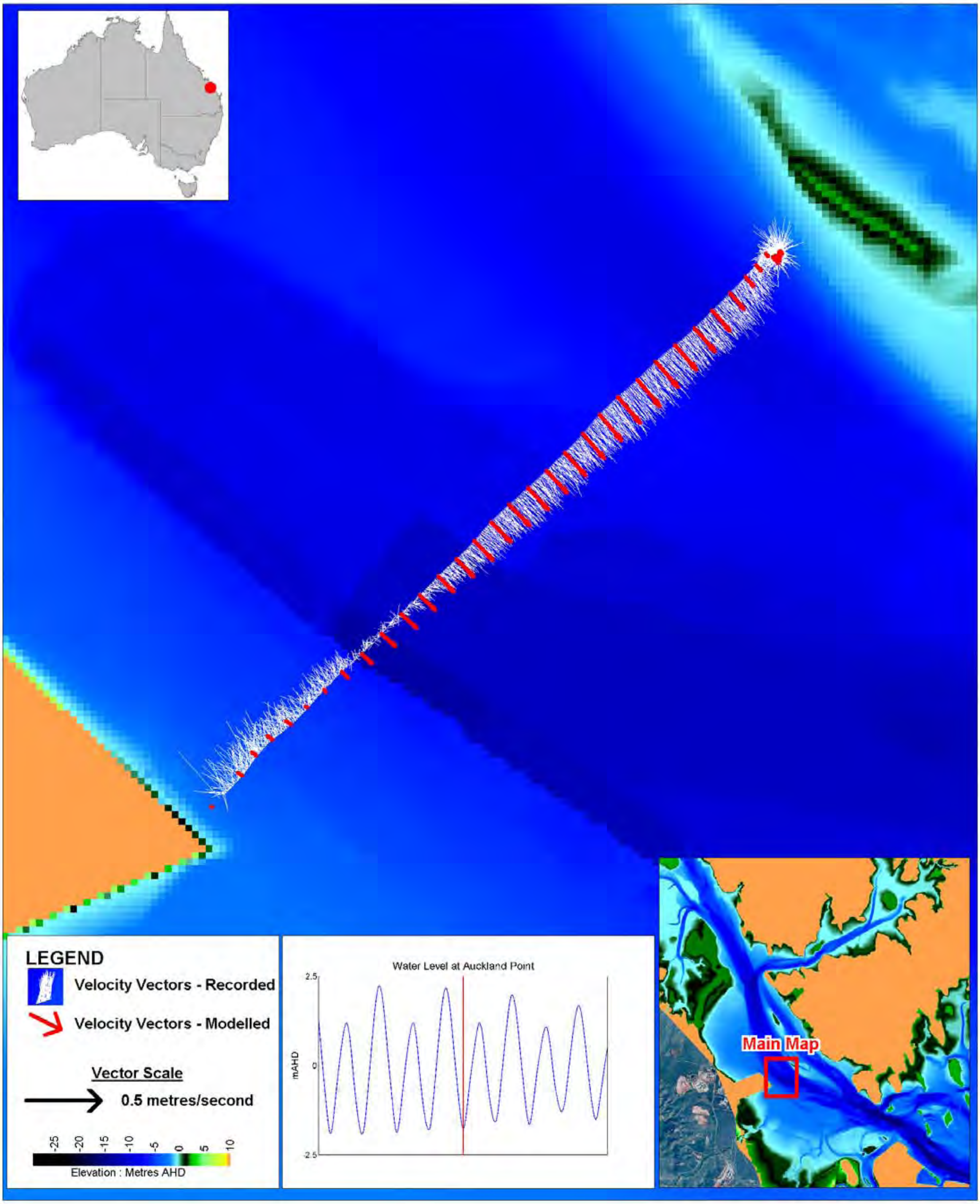

Title:

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Figure: **F-44**

Rev: **A**

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BMT WBM
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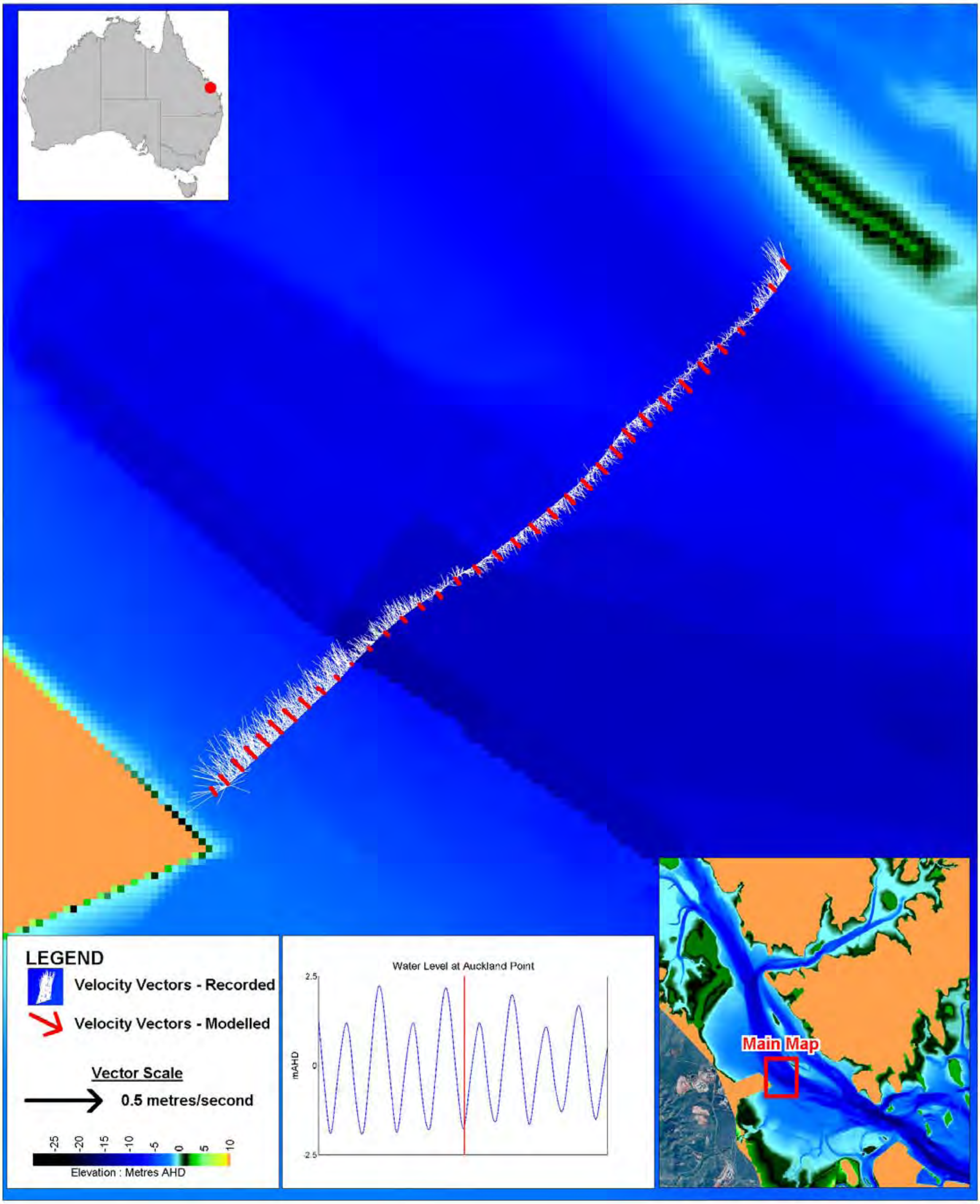

Title:

ADCP Transect Targinnie 036

Figure: F-45

Rev: A

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Scale - Inset
0 150 300m
Scale - Main Map

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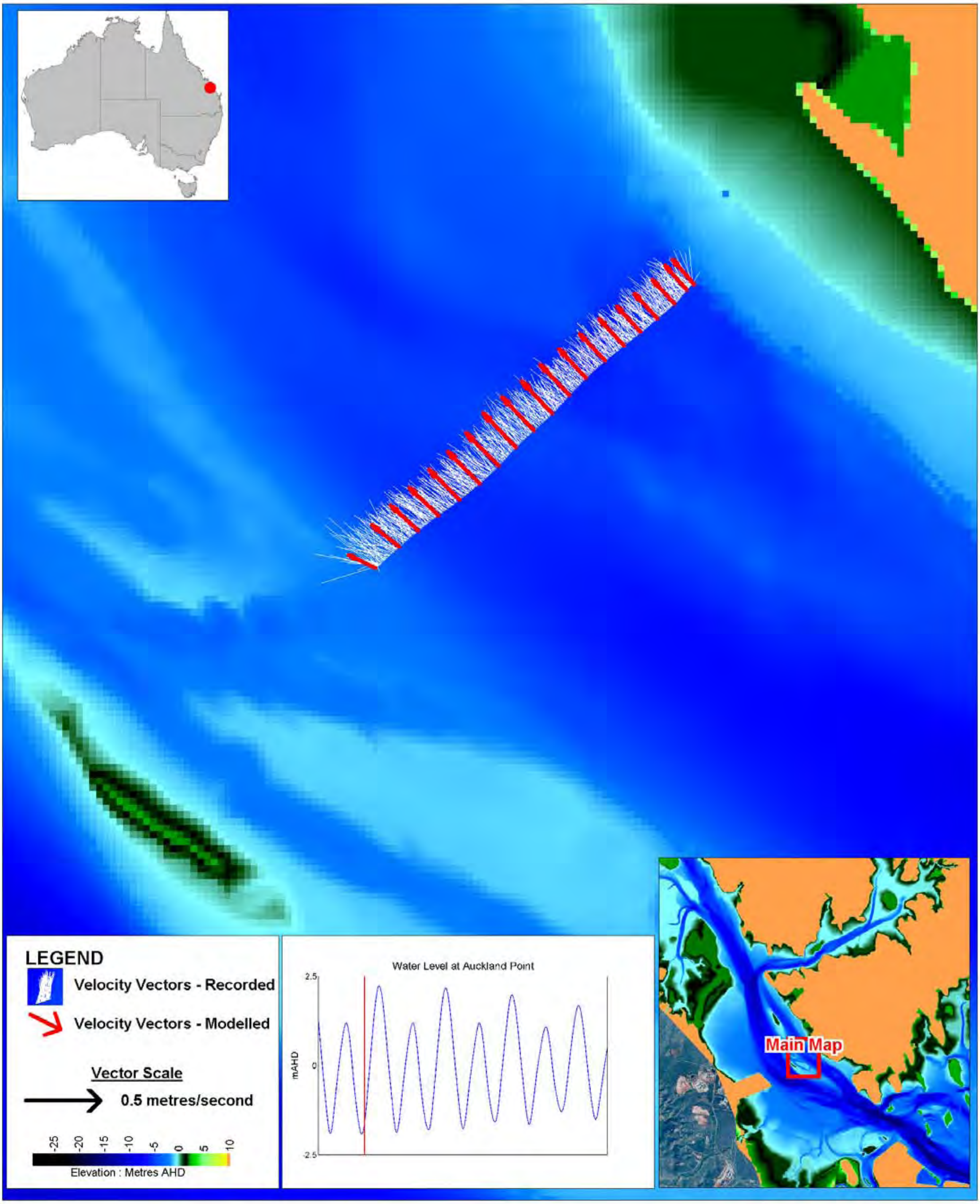

Title:

ADCP Transect Curtis 000

Figure: **F-46**

Rev: **A**

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Scale - Main Map

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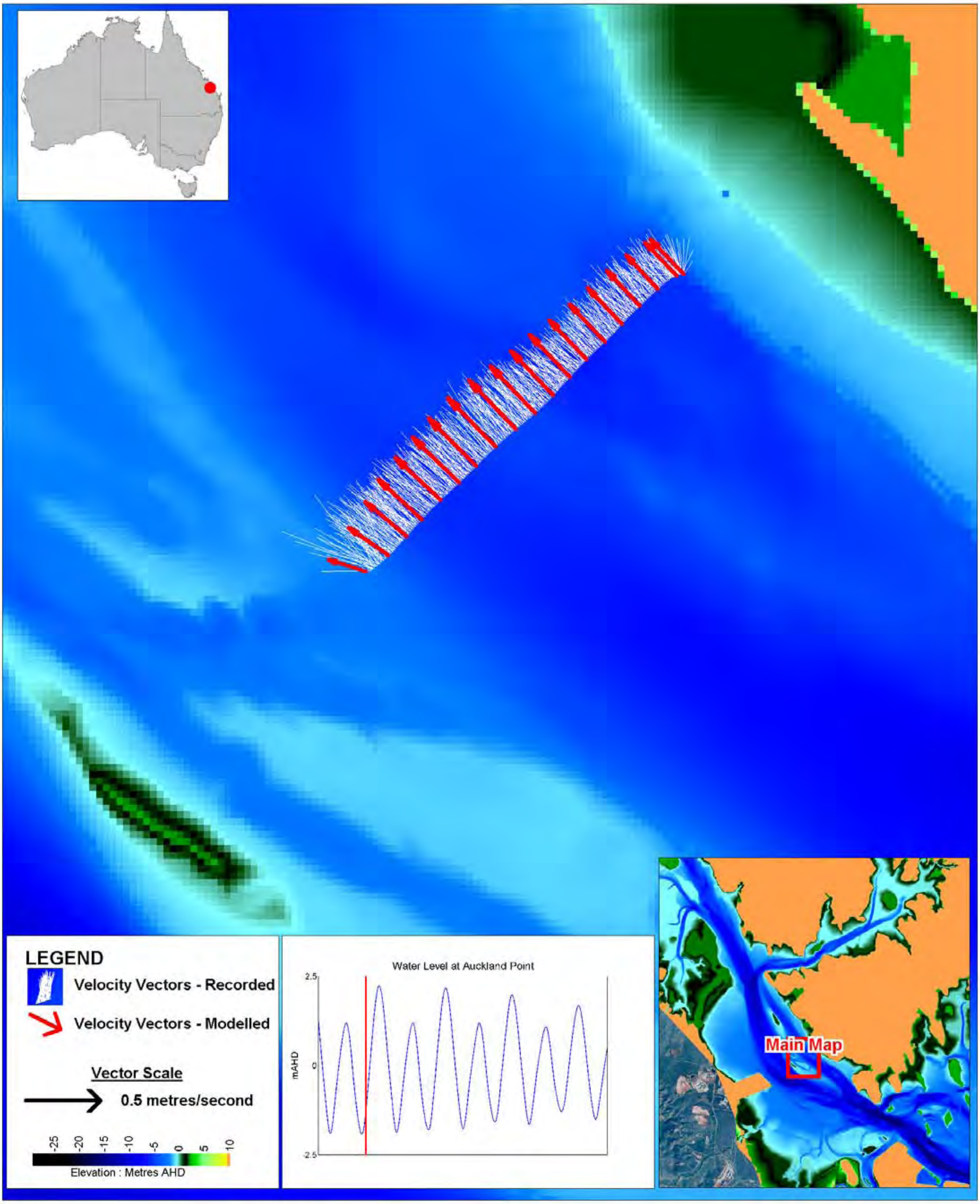

Title:

ADCP Transect Curtis 002

Figure: **F-47**

Rev: **A**

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Scale - Inset

0 150 300m

Scale - Main Map

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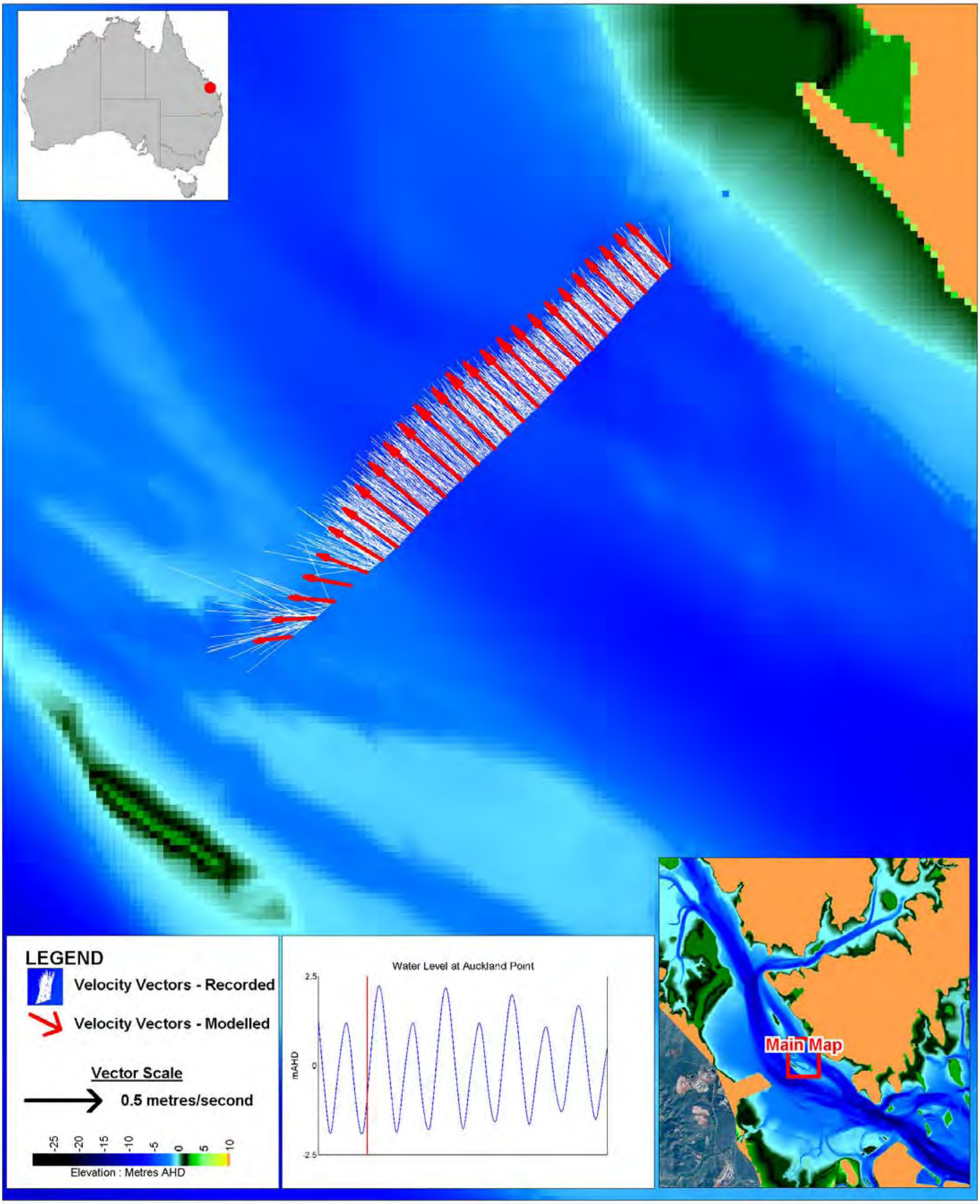

Title:

ADCP Transect Curtis 004

Figure: F-48

Rev: A

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Scale - Inset

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Scale - Main Map

BMT WBM

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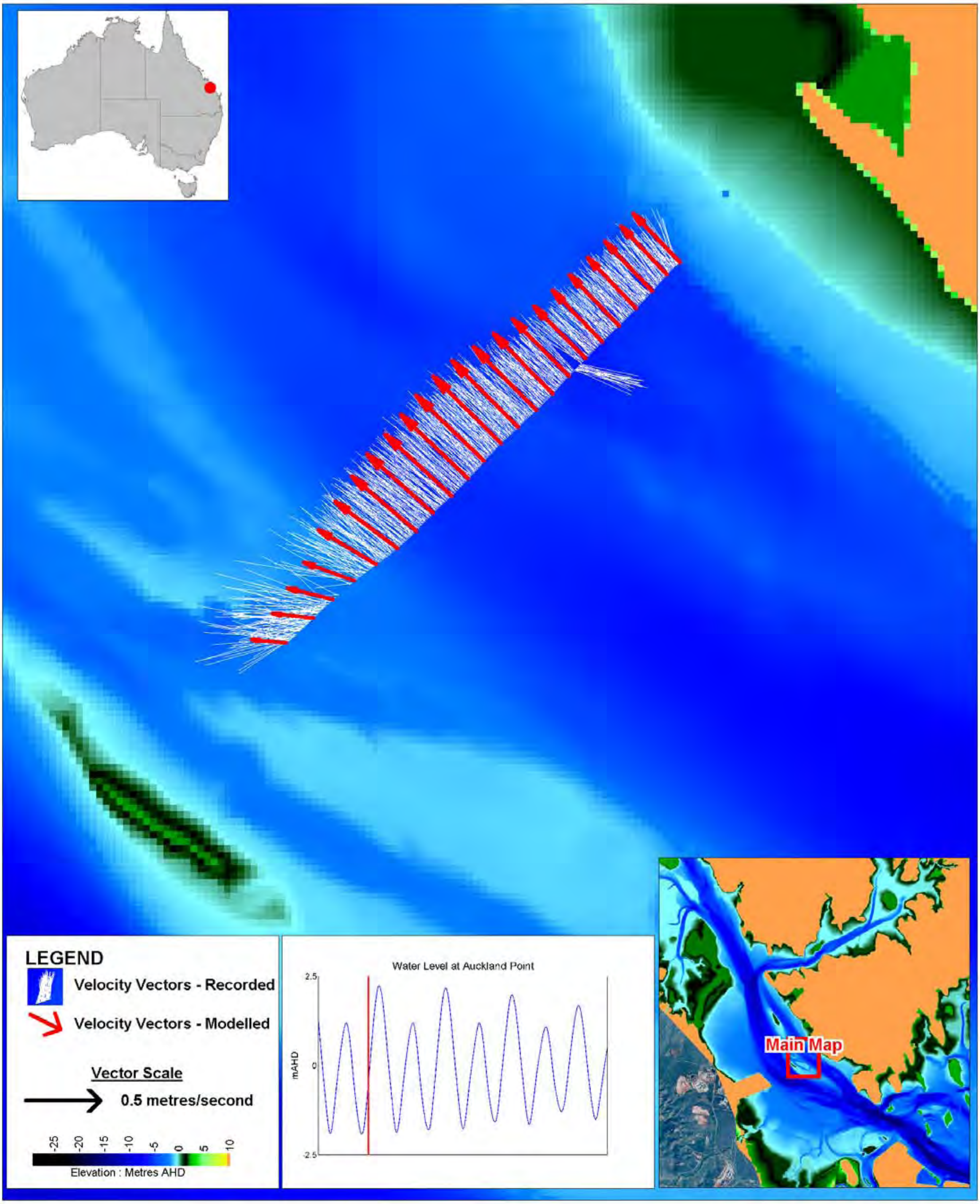

Title:

ADCP Transect Curtis 006

Figure: **F-49**

Rev: **A**

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Scale - Main Map

BMT WBM
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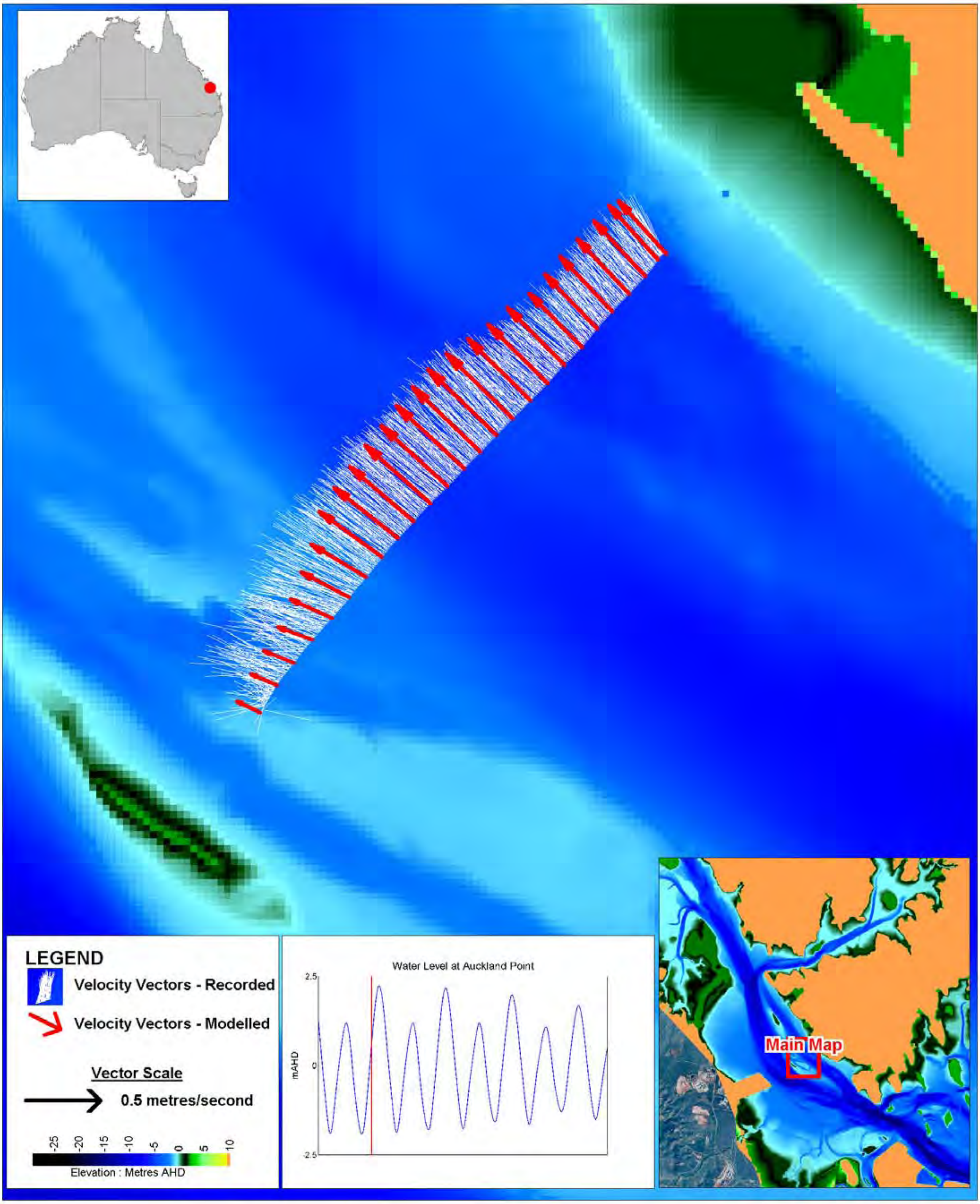

Title:

ADCP Transect Curtis 008

Figure: **F-50**

Rev: **A**

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Scale - Main Map

BMT WBM

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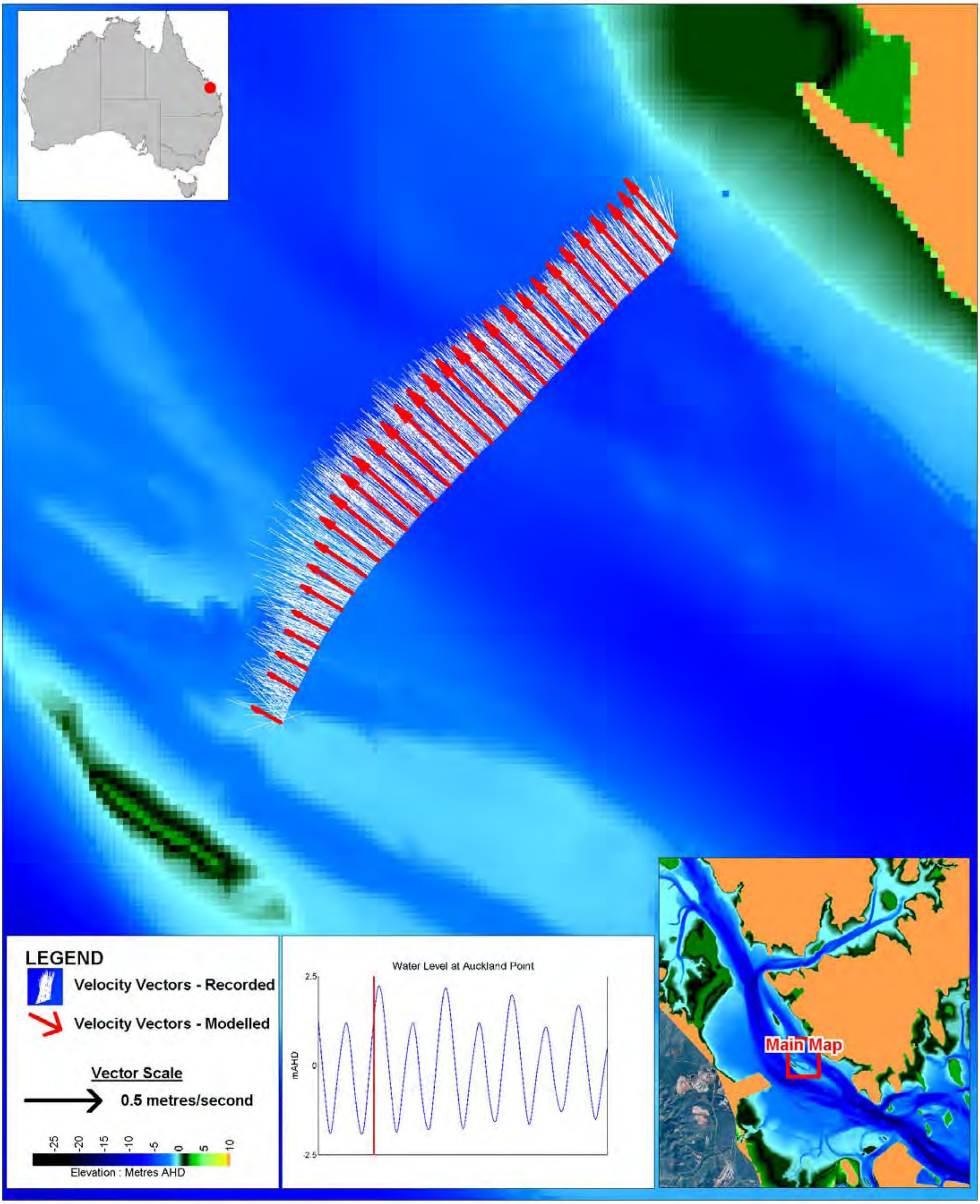
Filepath : \\wbmfs2\drafting\B17382_I_clw_Glad Strategic\DRG\Calib\ADCP\June2009\COA_050_090929_Curtis_Trans8.wor



Title:

ADCP Transect Curtis 010

Figure: **F-51**

Rev: **A**

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Scale - Inset

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Scale - Main Map

BMT WBM

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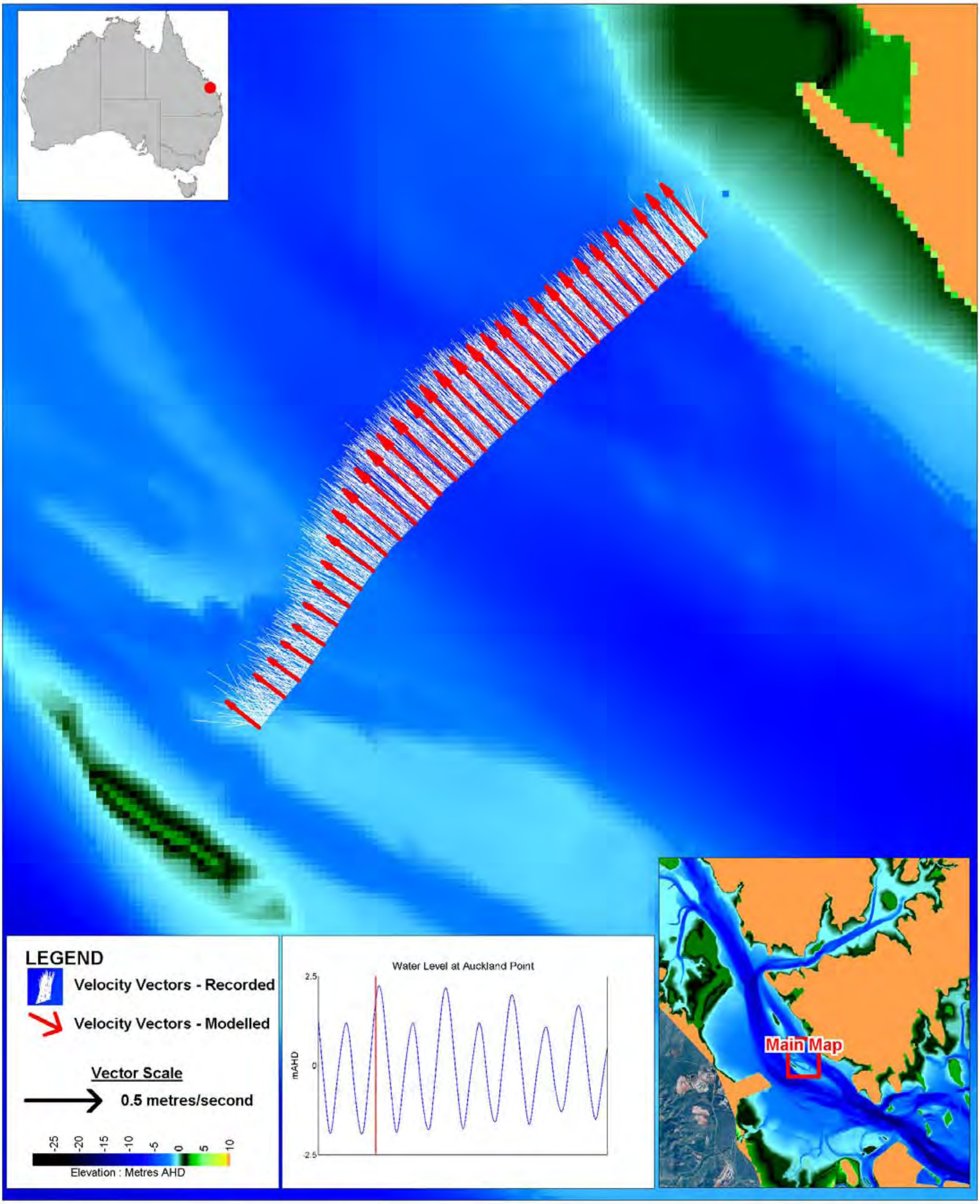
Filepath : \\wbmfs2\drafting\B17382_I_clw_Glad Strategic\DRG\Calib\ADCP\June2009\COA_051_090929_Curtis_Trans10.wor



Title:

ADCP Transect Curtis 012

Figure: **F-52**

Rev: **A**

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N

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Scale - Inset

0 150 300m

Scale - Main Map

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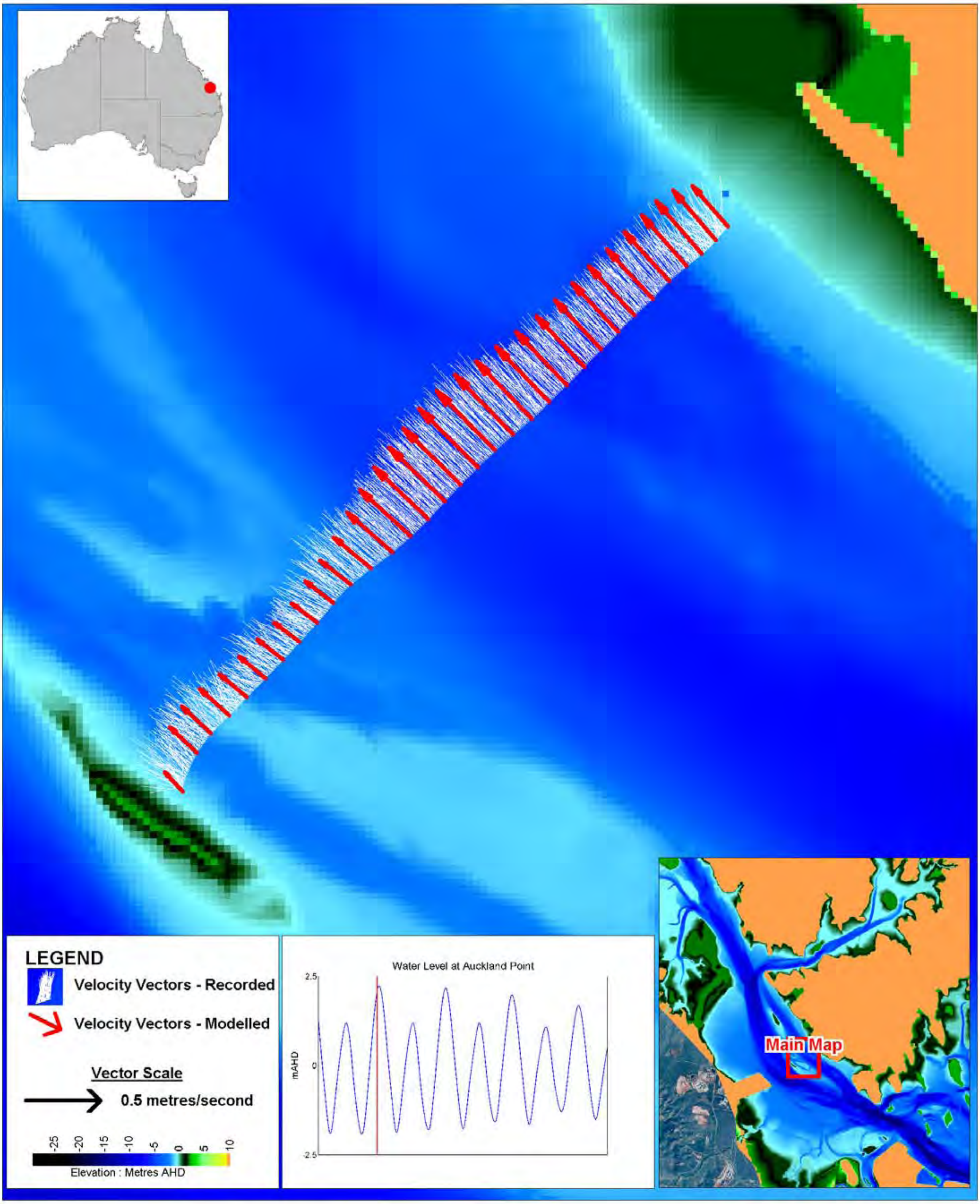
Filepath : \\wbmfs2\drafting\B17382_I_clw_Glad Strategic\DRG\Calib\ADCP\June2009\COA_052_090929_Curtis_Trans12.wor



Title:

ADCP Transect Curtis 014

Figure: **F-53**

Rev: **A**

N

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Scale - Inset

0 150 300m
Scale - Main Map

BMT WBM
www.wbmpl.com.au

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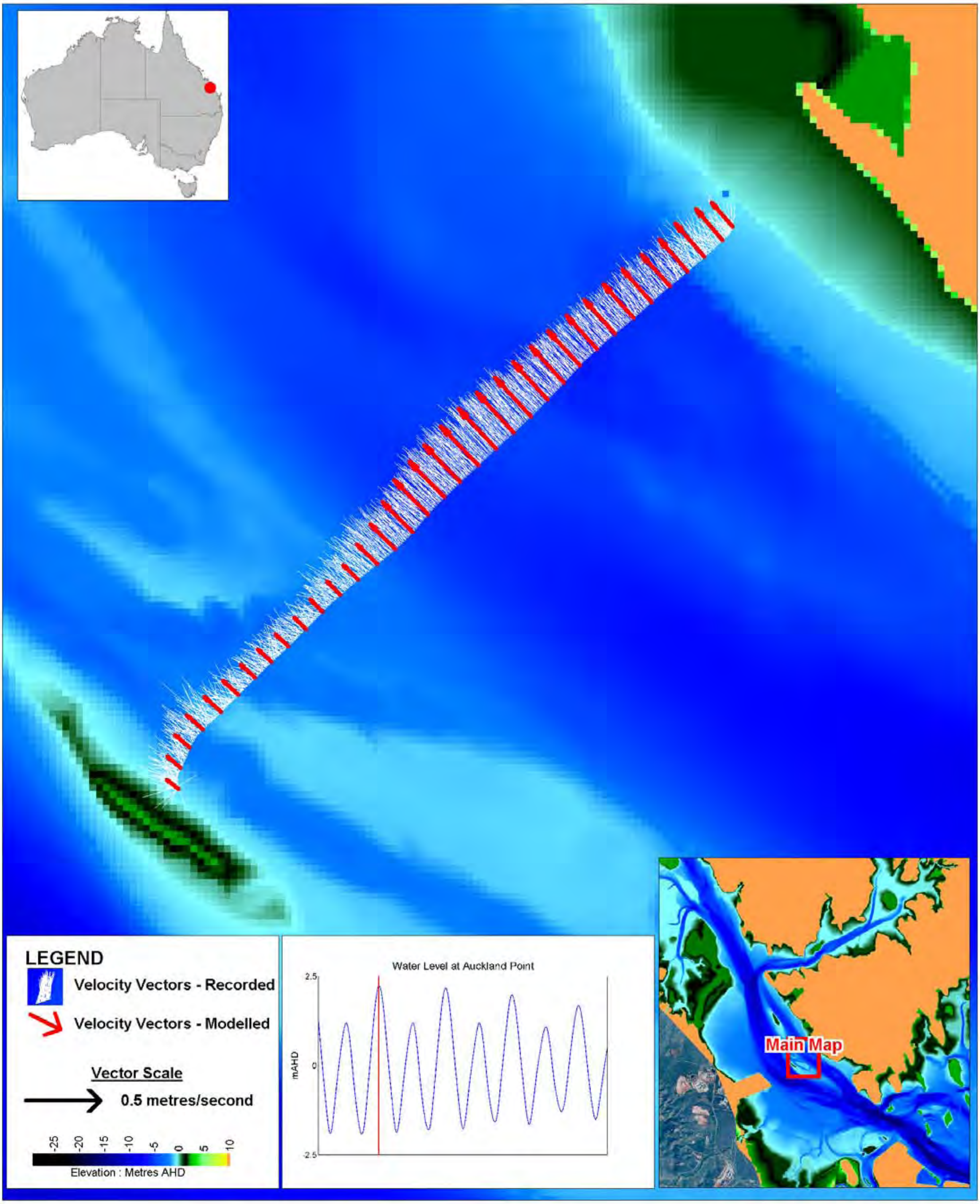

Title:

ADCP Transect Curtis 016

Figure: **F-54**

Rev: **A**

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Scale - Inset

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Scale - Main Map

BMT WBM
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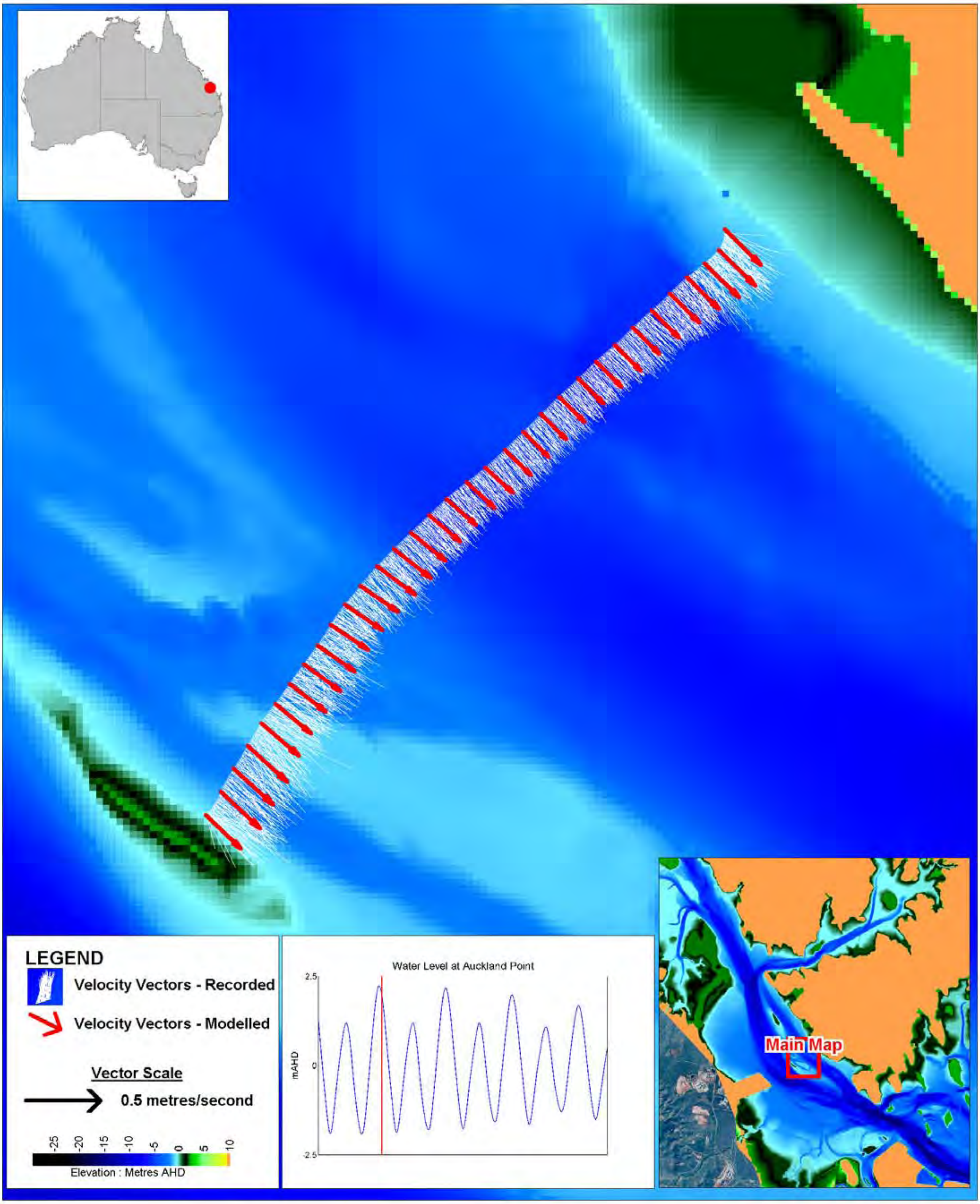

Title:

ADCP Transect Curtis 018

Figure: **F-55**

Rev: **A**

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Scale - Inset

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Scale - Main Map

BMT WBM
www.wbmpl.com.au

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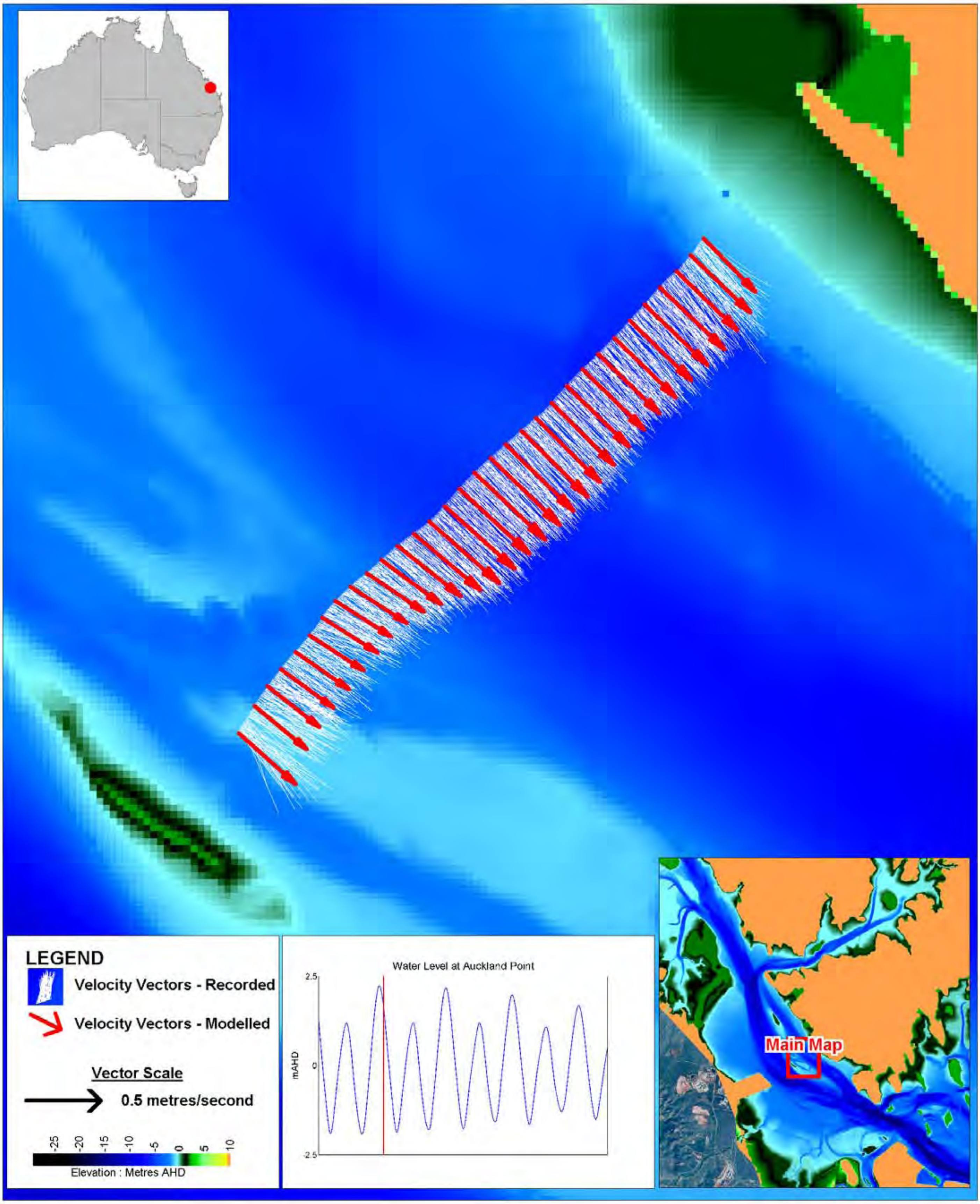

Title:

ADCP Transect Curtis 020

Figure: **F-56**

Rev: **A**

N

0 5 10km
Scale - Inset

0 150 300m
Scale - Main Map

BMT WBM
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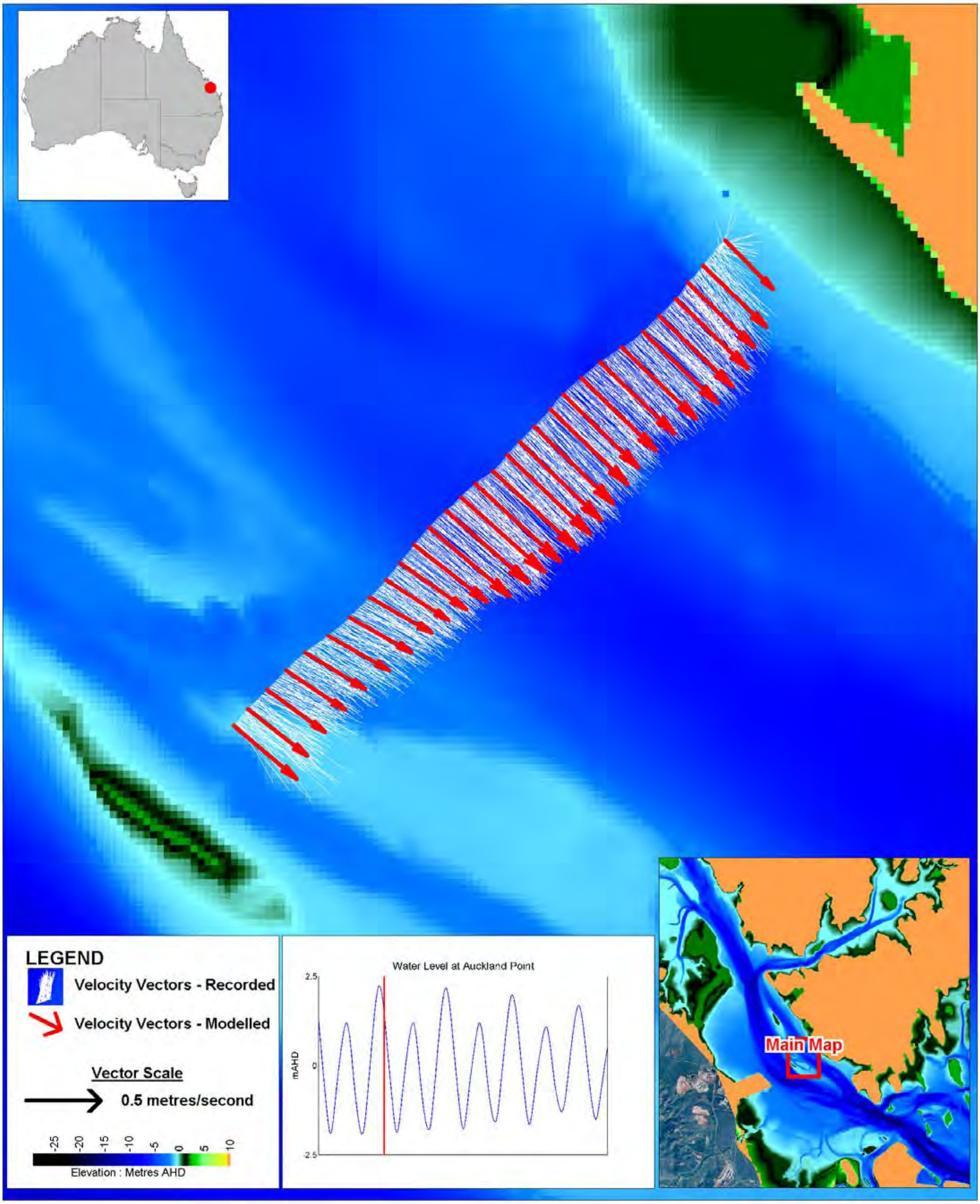

Title:

ADCP Transect Curtis 021

Figure: **F-57**

Rev: **A**

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N

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Scale - Inset

0 150 300m
Scale - Main Map

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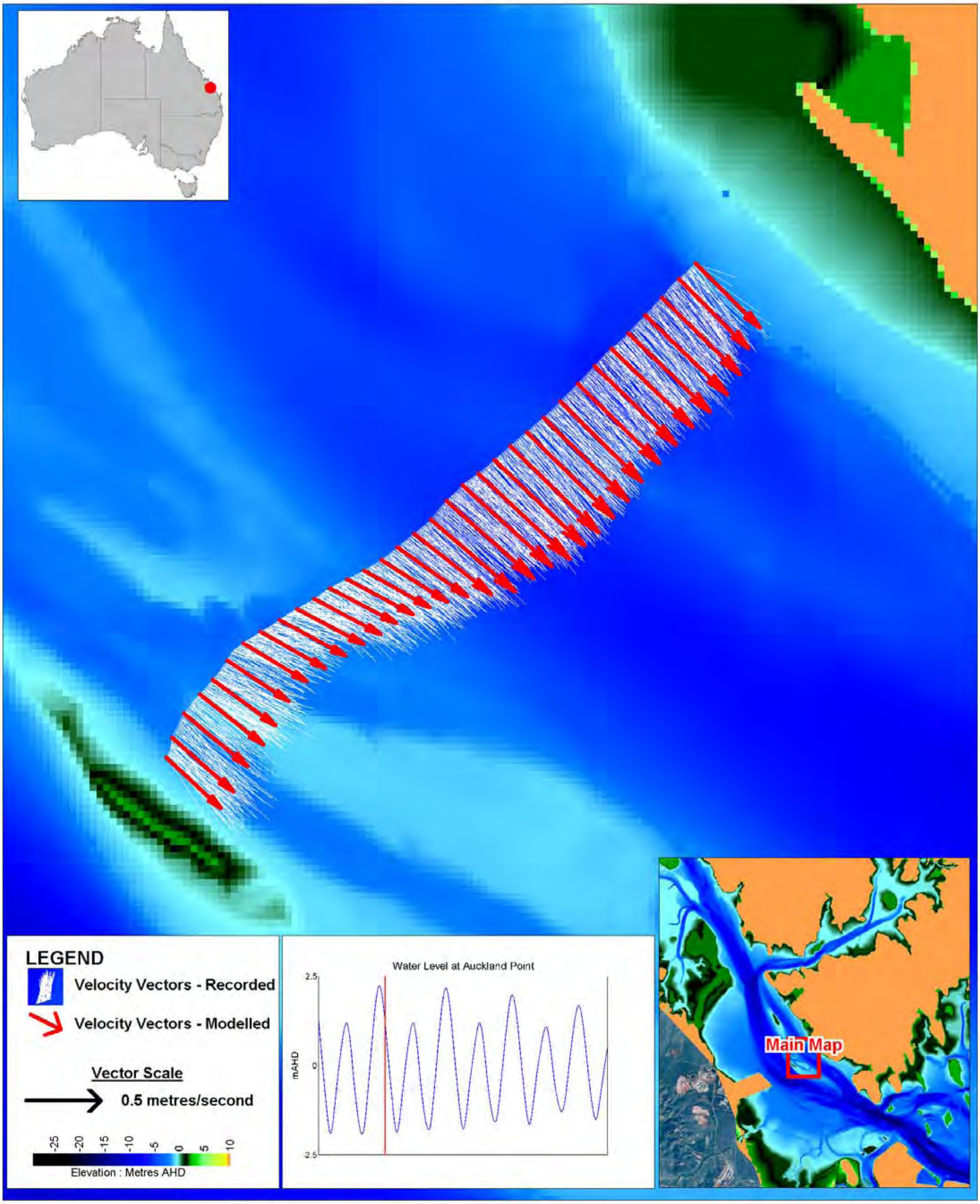

Title:

ADCP Transect Curtis 022

Figure: **F-58**

Rev: **A**

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N

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Scale - Inset

0 150 300m

Scale - Main Map

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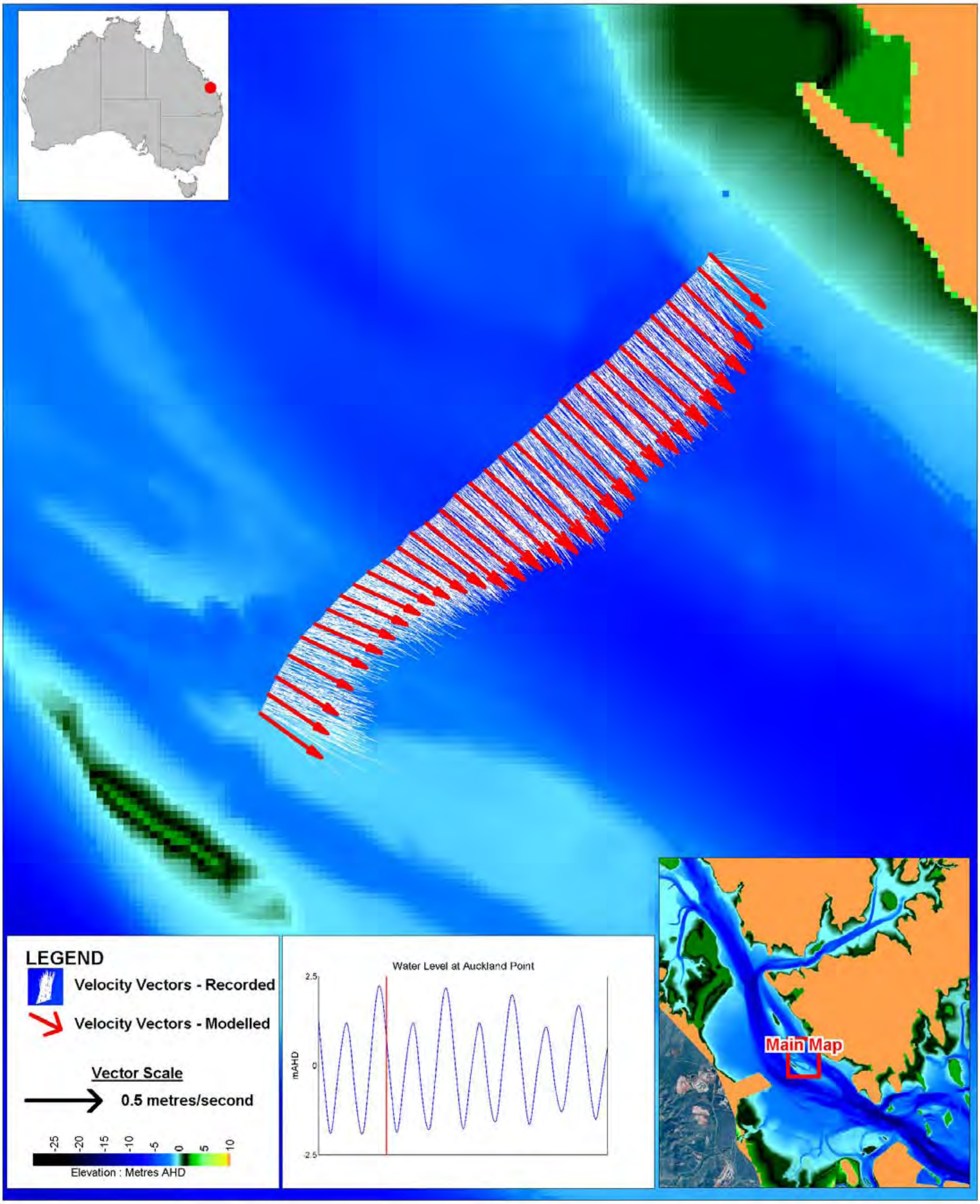

Title:

ADCP Transect Curtis 024

Figure: **F-59**

Rev: **A**

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Scale - Inset

0 150 300m
Scale - Main Map

BMT WBM
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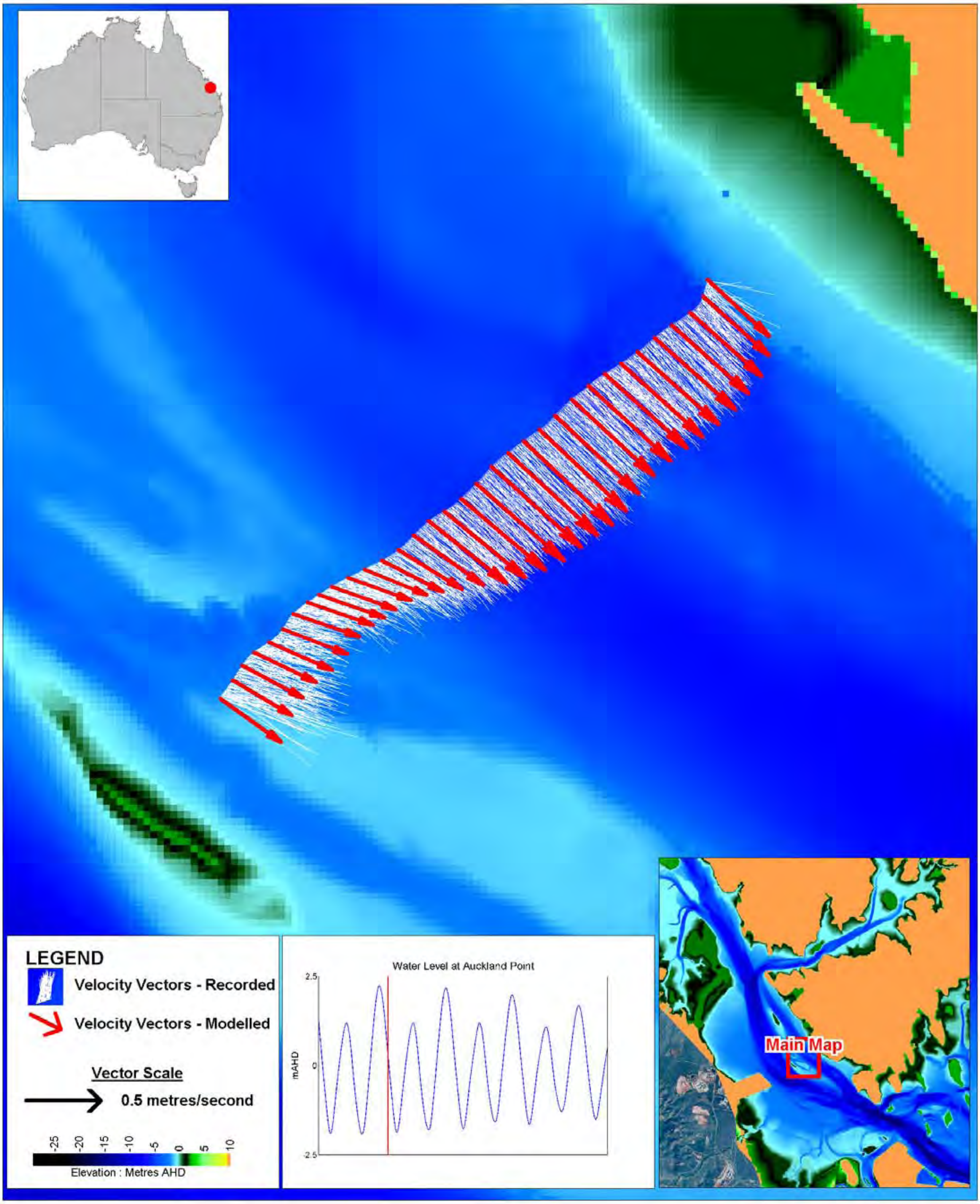

Title:

ADCP Transect Curtis 026

Figure: **F-60**

Rev: **A**

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N

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Scale - Inset

0 150 300m

Scale - Main Map

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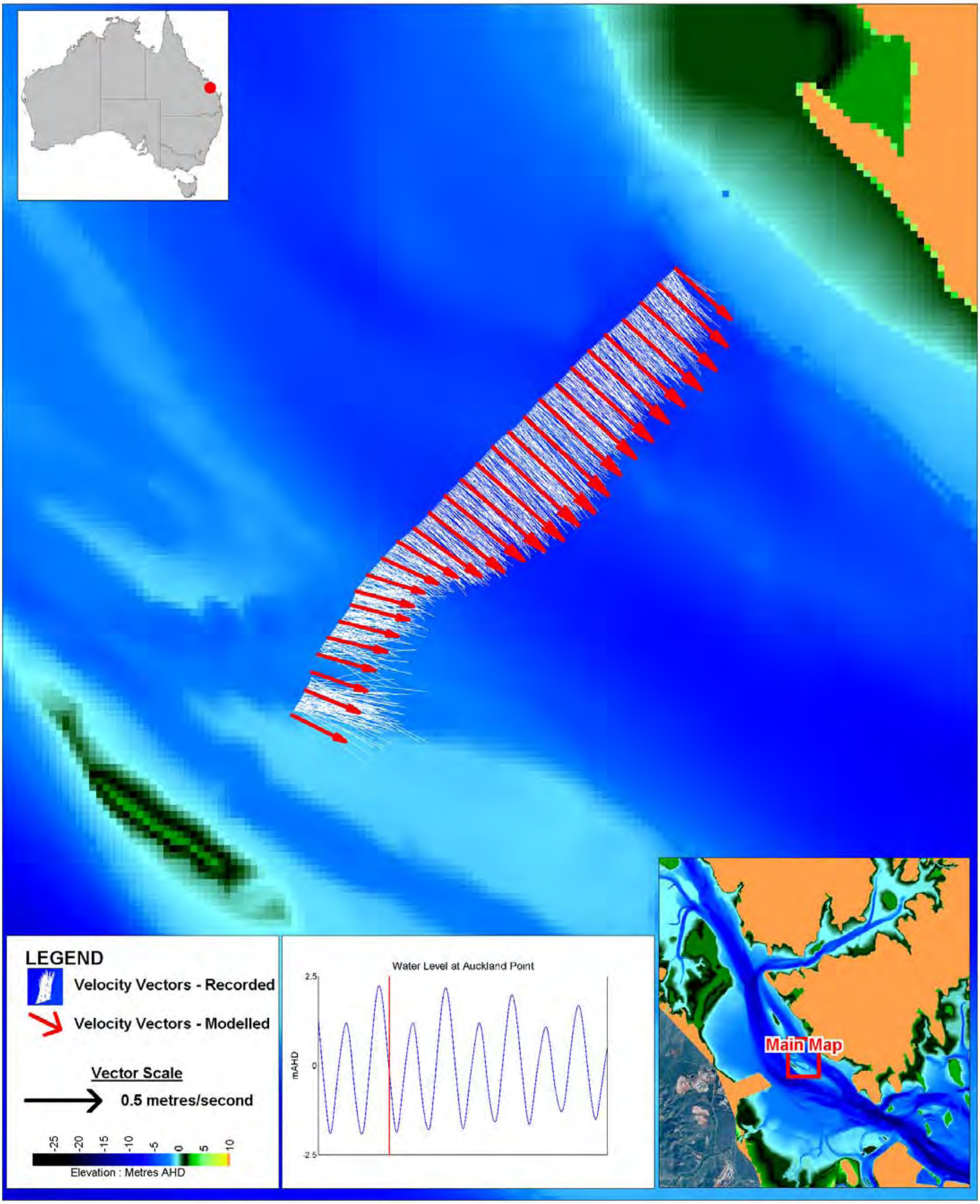

Title:

ADCP Transect Curtis 028

Figure: **F-61**

Rev: **A**

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Scale - Inset

0 150 300m
Scale - Main Map

BMT WBM
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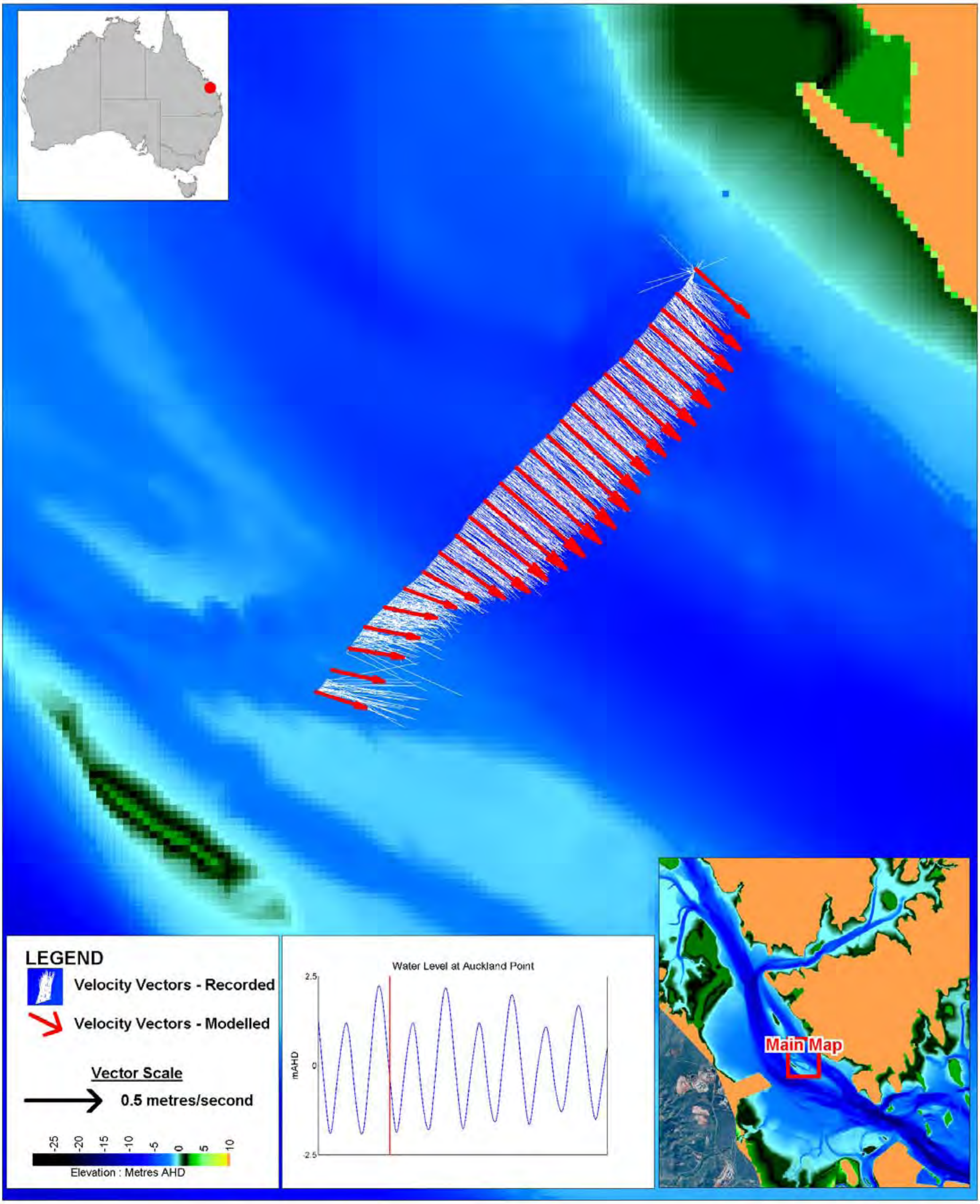

Title:

ADCP Transect Curtis 029

Figure: F-62

Rev: A

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N

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Scale - Inset

0 150 300m
Scale - Main Map

BMT WBM
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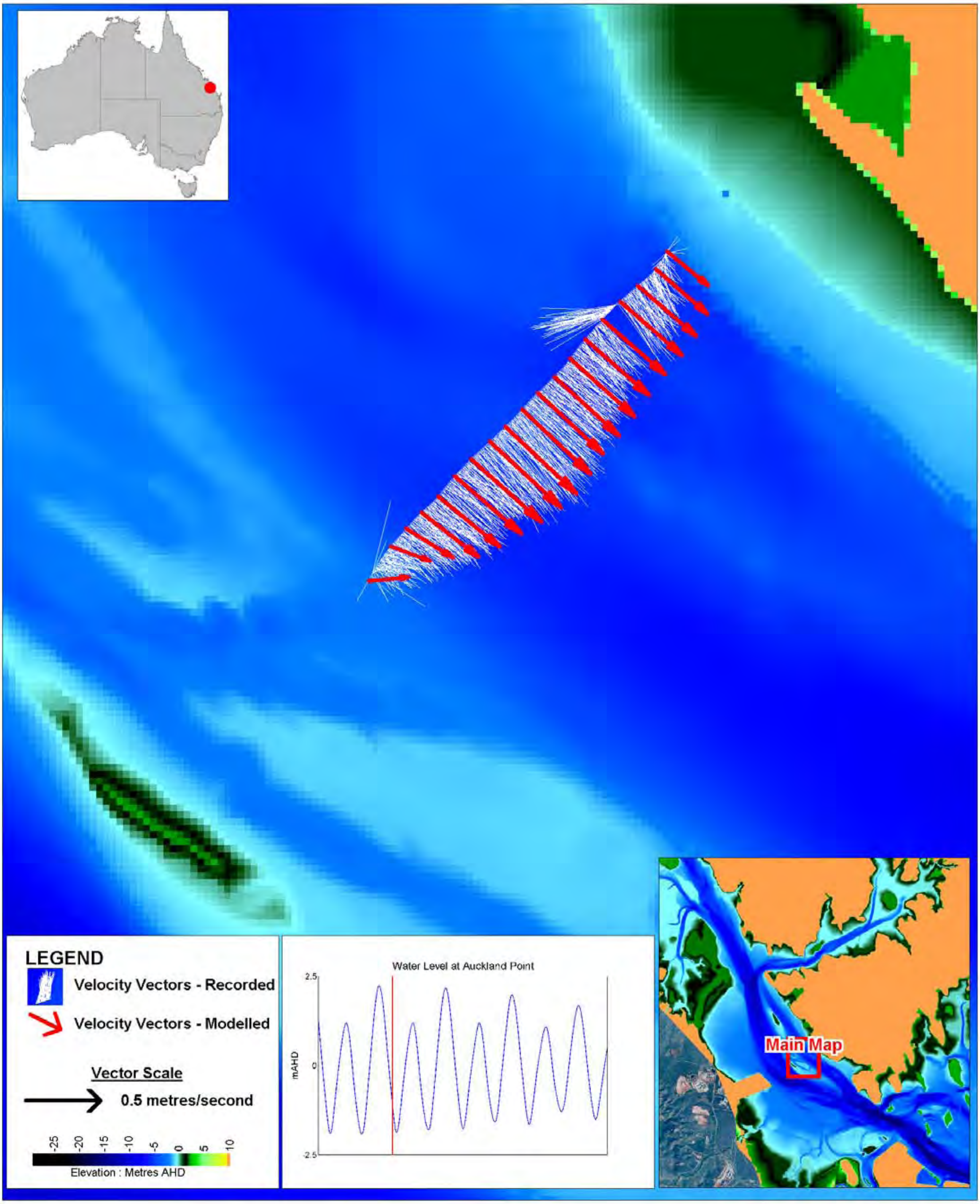

Title:
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Figure: F-63

Rev: A

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Scale - Inset

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Scale - Main Map

BMT WBM
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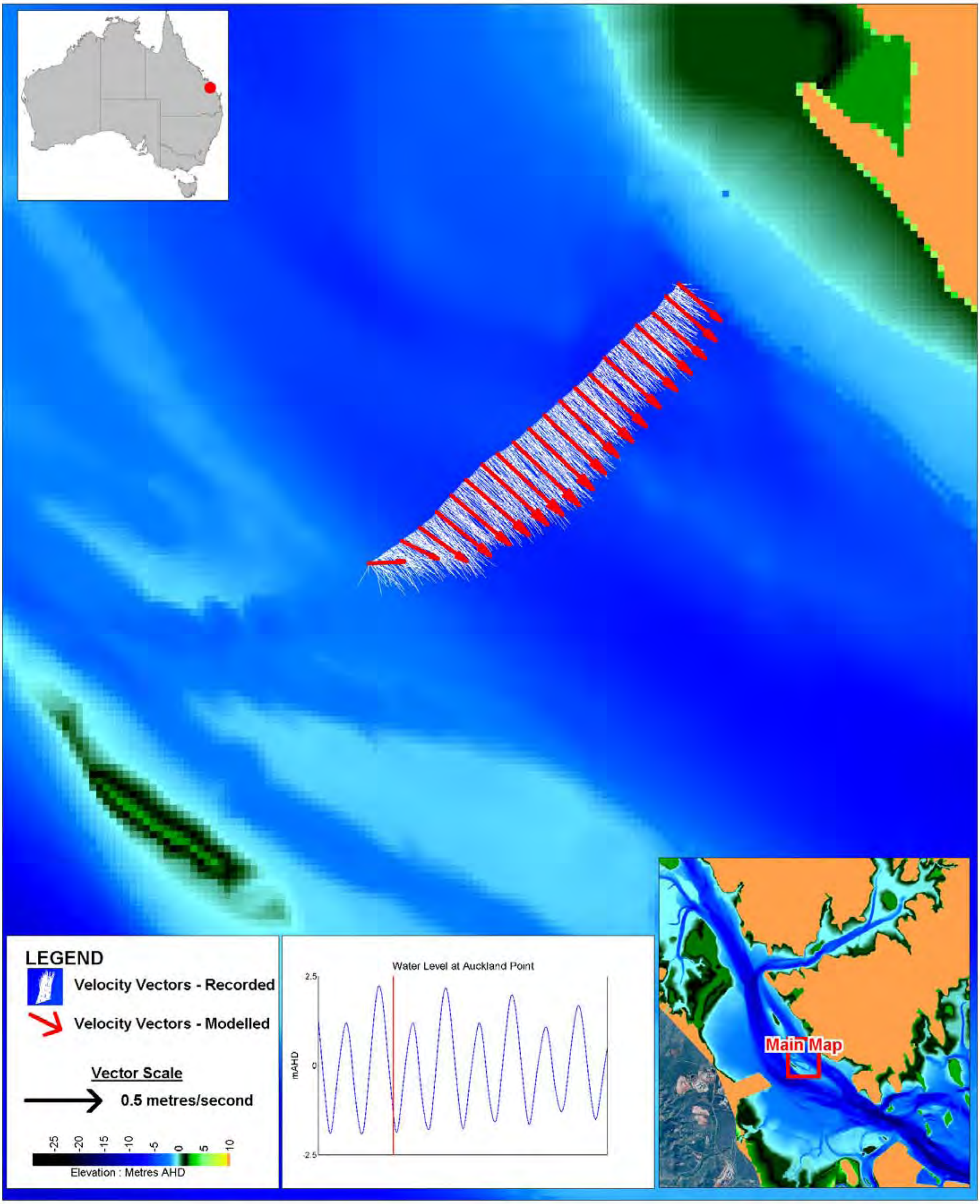

Title:

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Figure: **F-64**

Rev: **A**

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Scale - Inset

0 150 300m

Scale - Main Map

BMT WBM

www.wbmpl.com.au

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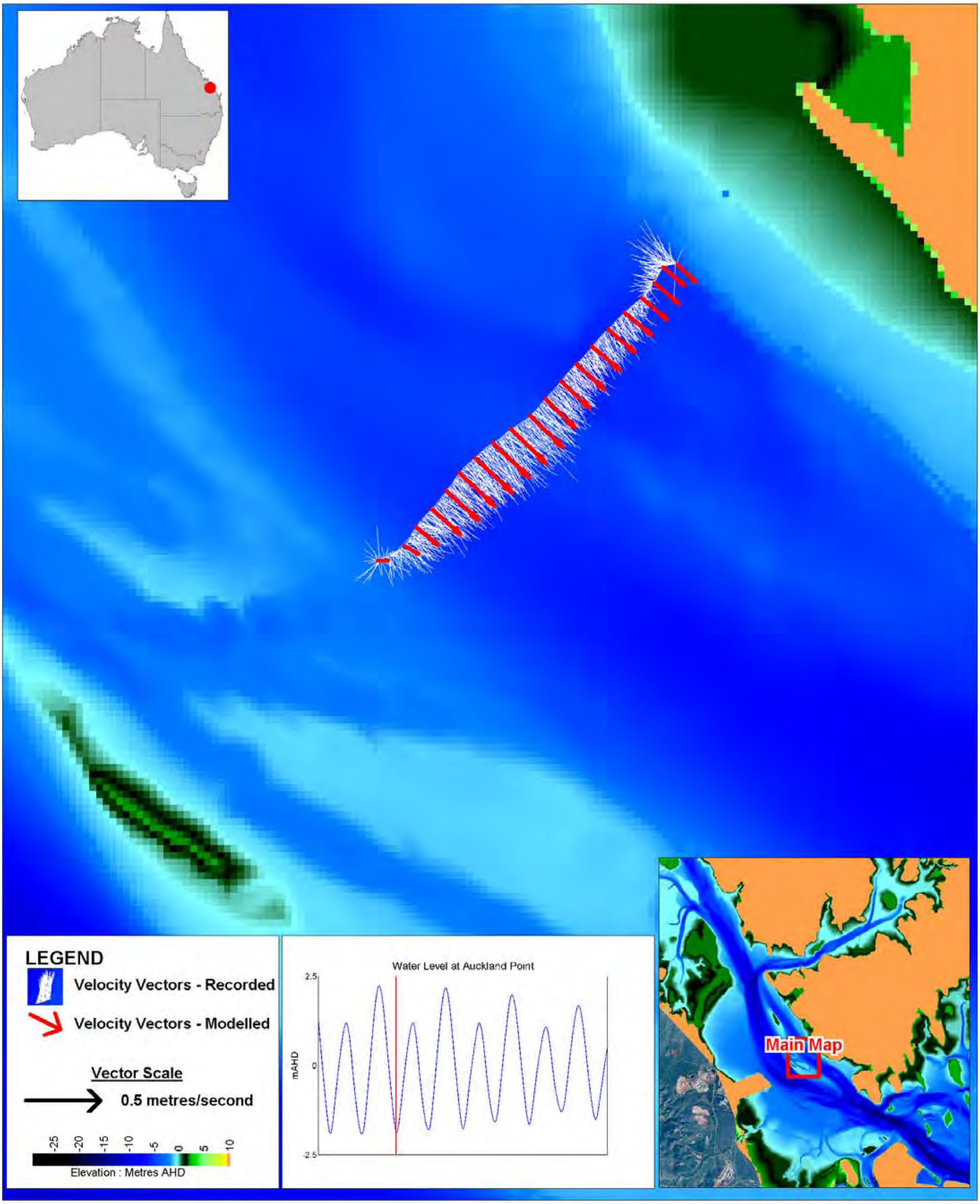

Title:

ADCP Transect Curtis 036

Figure: **F-65**

Rev: **A**

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Scale - Inset

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Scale - Main Map

BMT WBM
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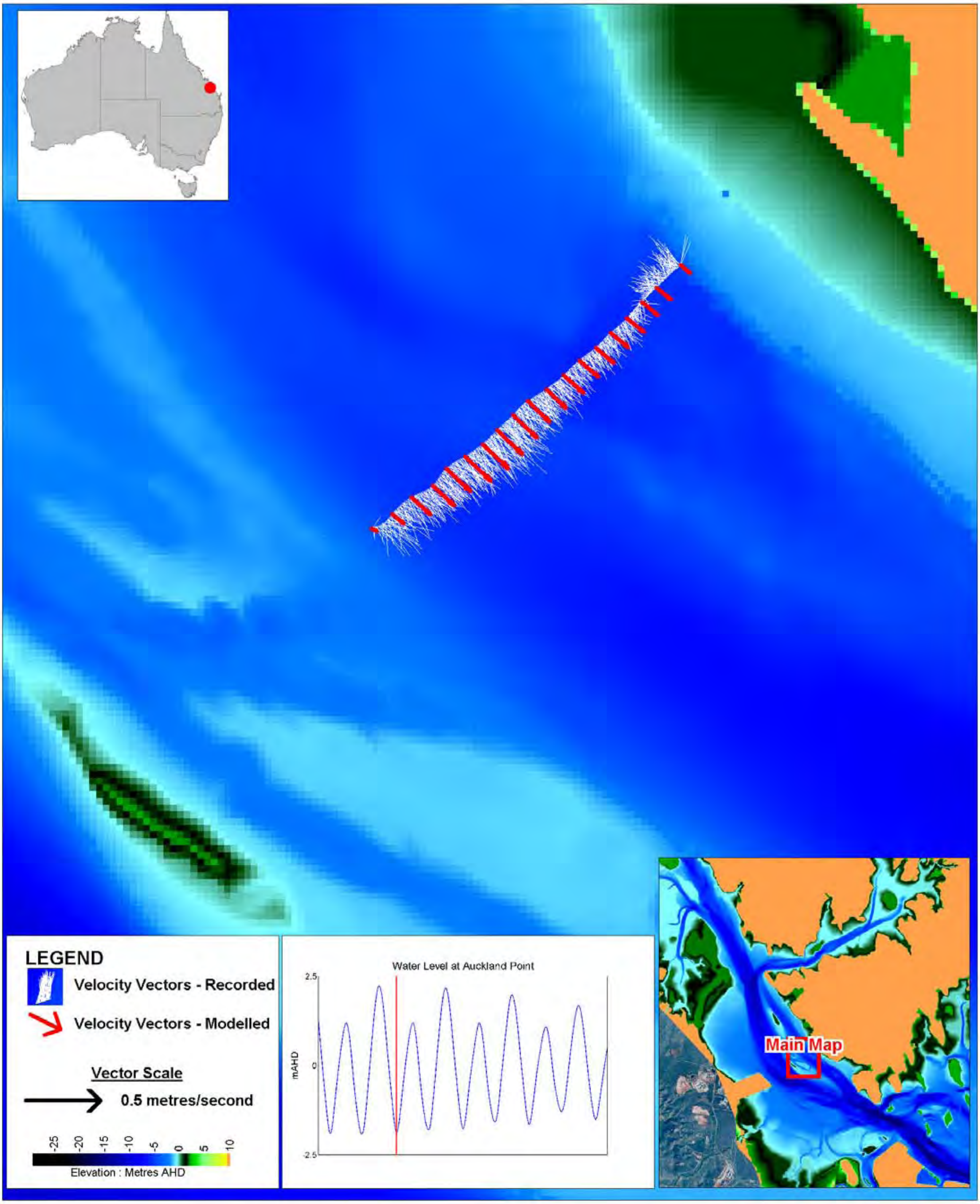

Title:

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Figure: **F-66**

Rev: **A**

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Scale - Main Map

BMT WBM
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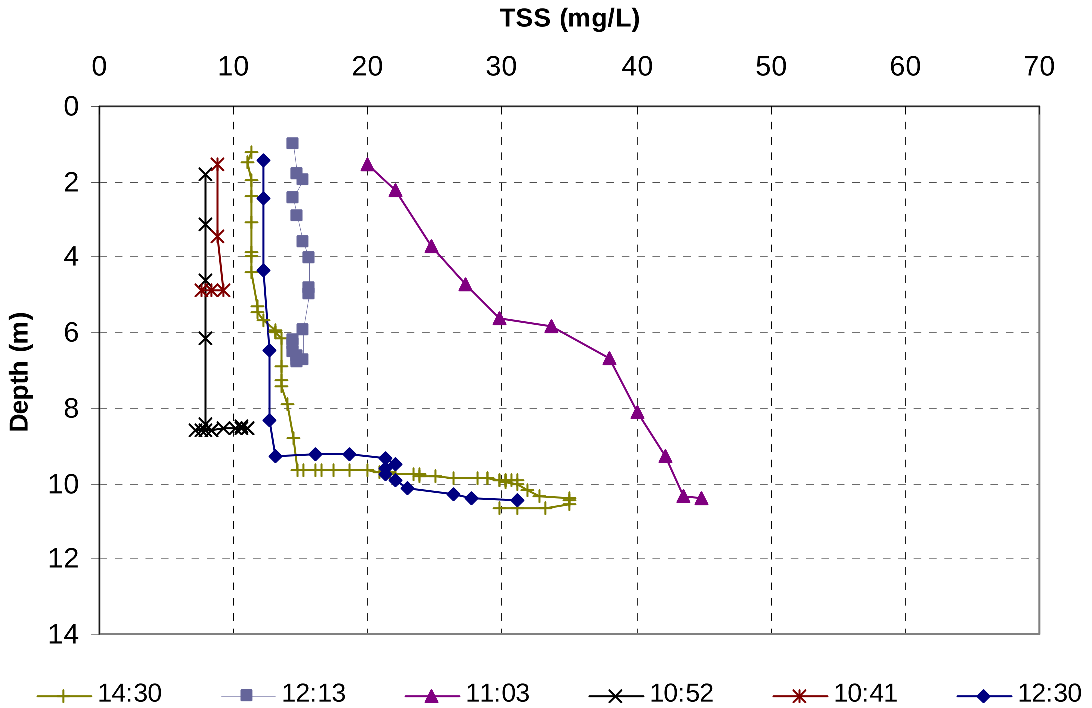
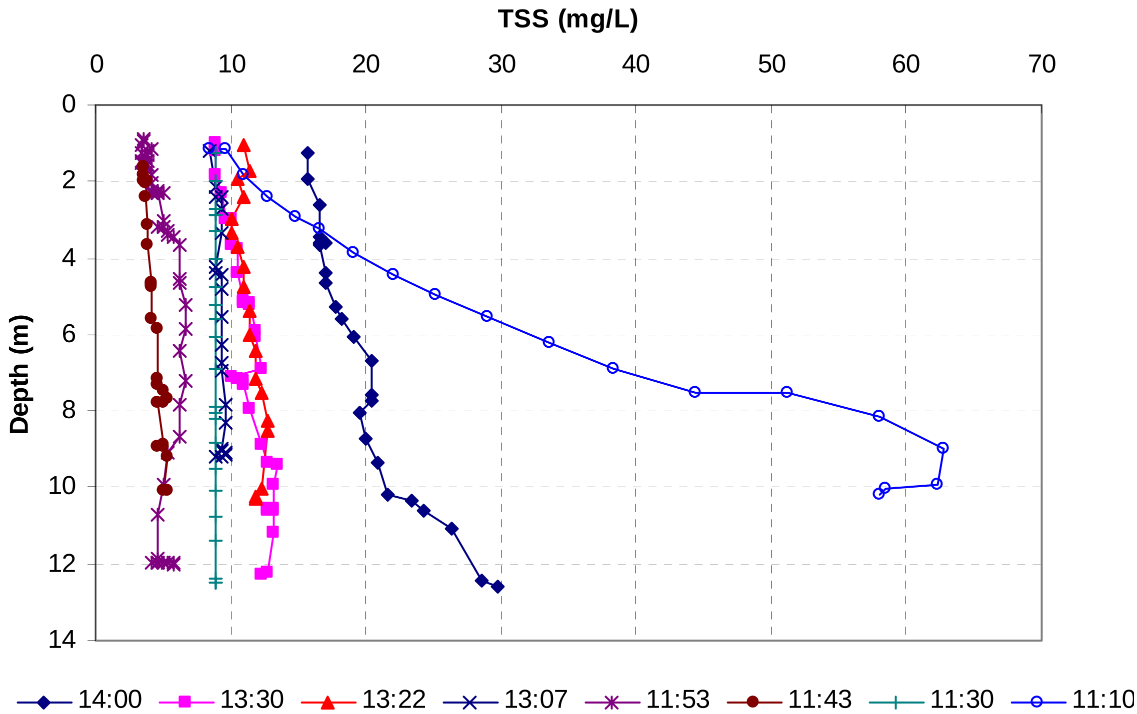
Filepath : \\wbmfs2\drafting\B17382_I_clw_Glad Strategic\DRG\Calib\ADCP\June2009\COA_066_090929_Curtis_Trans37.wor

APPENDIX G: "WOMBAT" DREDGE PLUME MONITORING PLOTS



(a) 29/06/2009



(b) 30/06/2009

Figure G-1 Profiles of TSS Derived from Turbidity Measurements:
(a) 29th June 2009 and
(b) 30th June 2009.

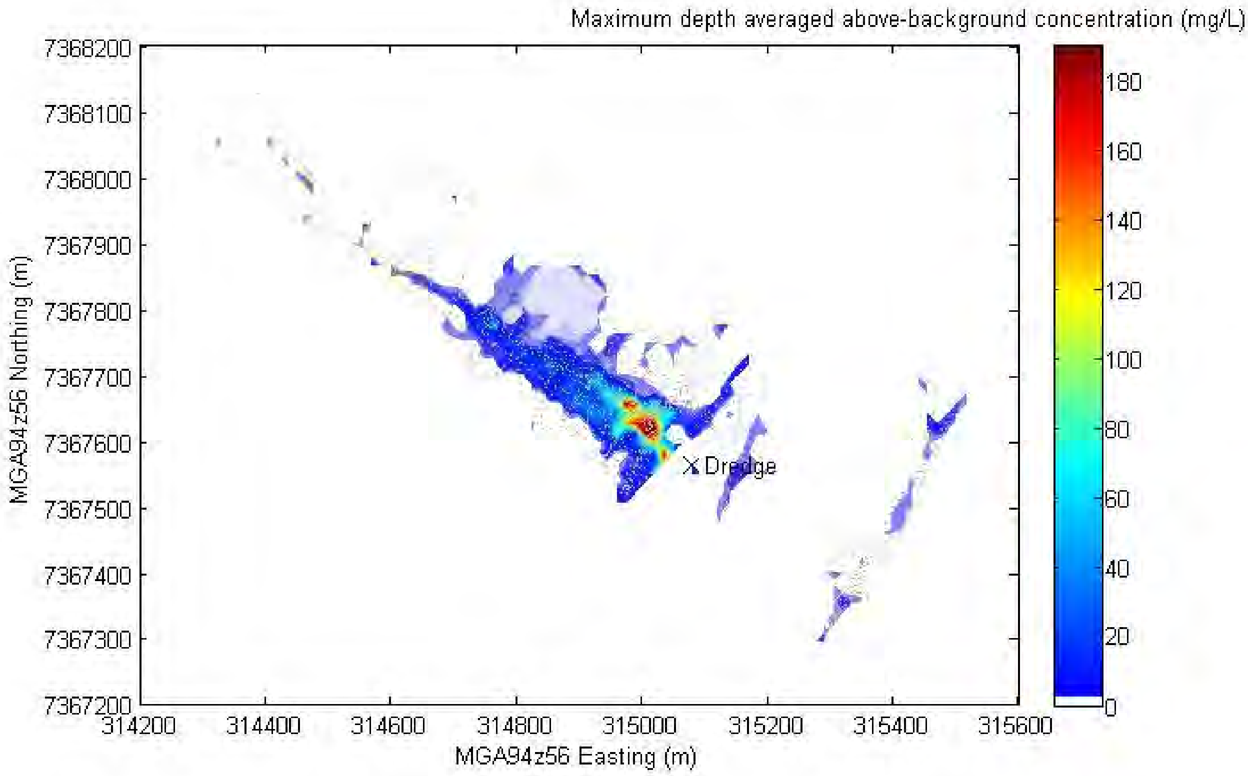


Figure G-2 Maximum Depth Averaged TSS (above background)

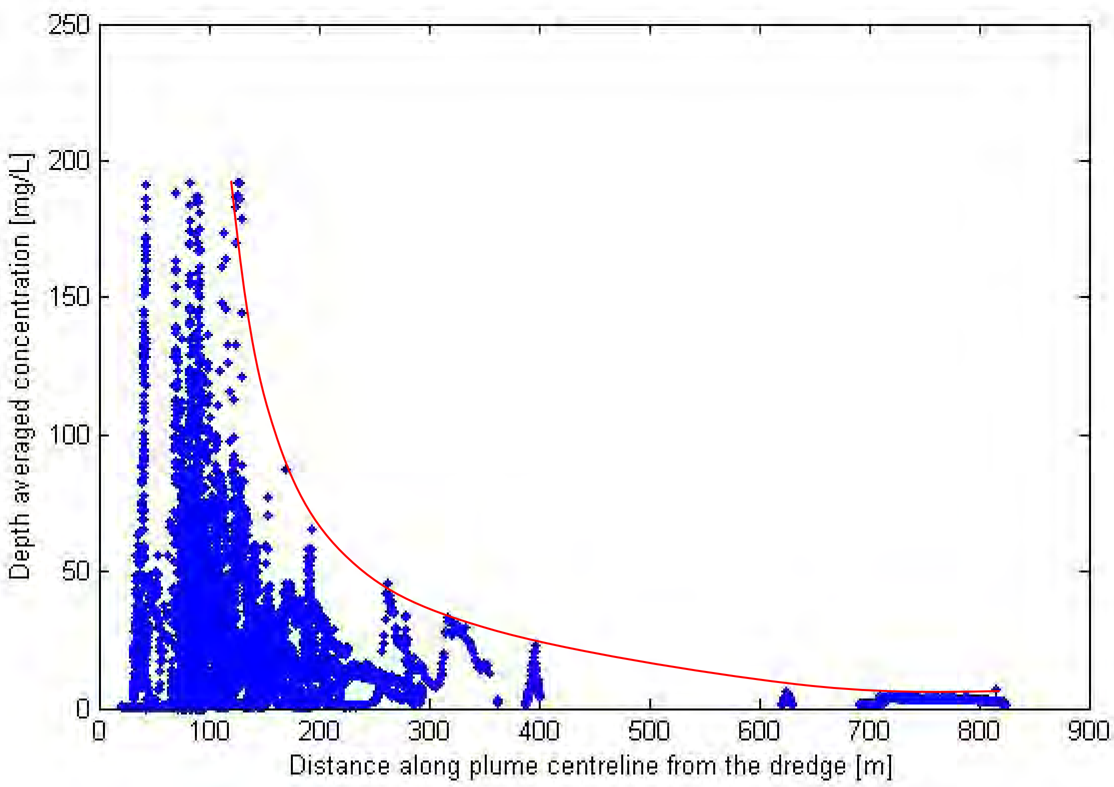


Figure G-3 Depth averaged TSS (above background) along Plume Centreline

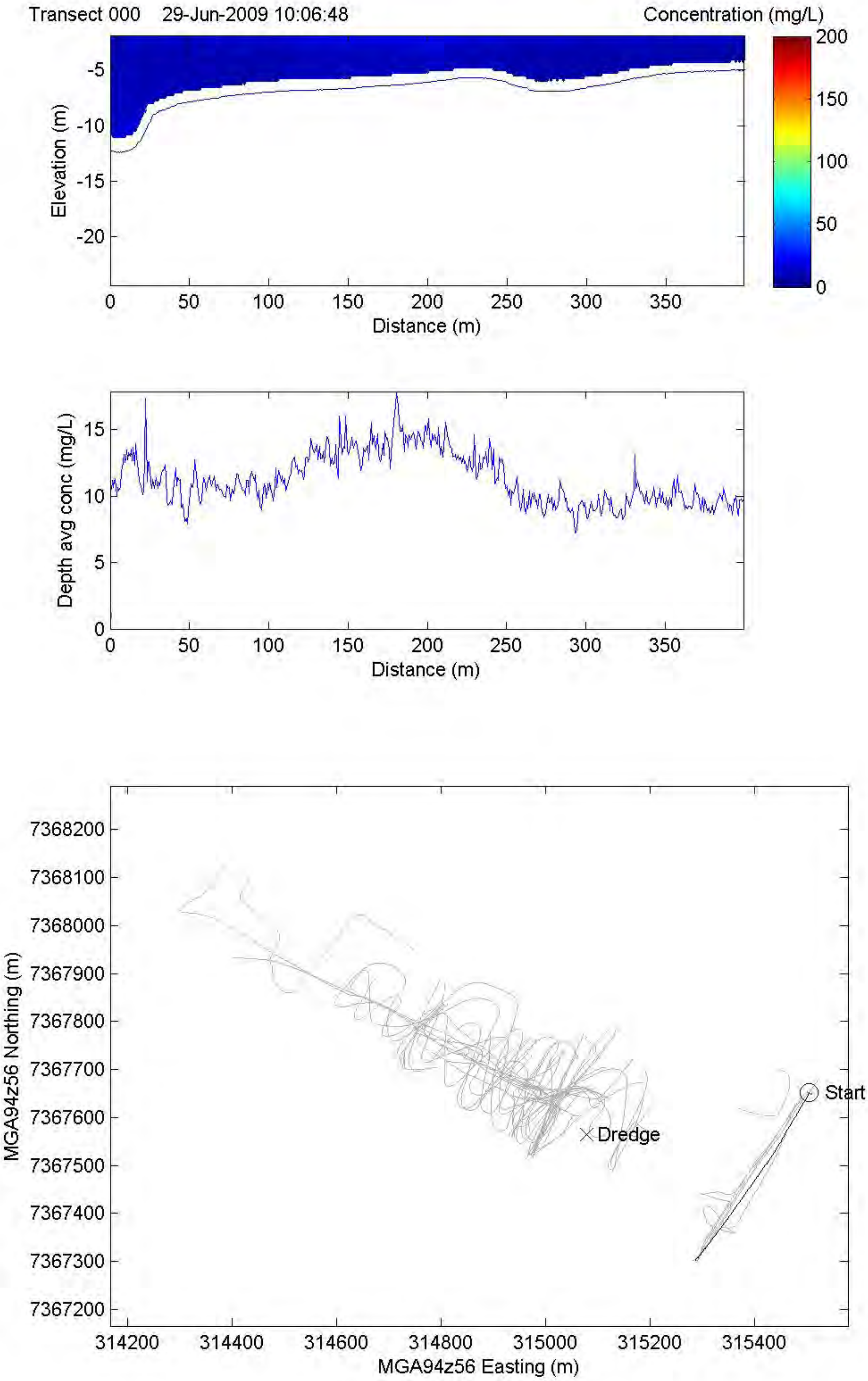


Figure G-4 Transect 000

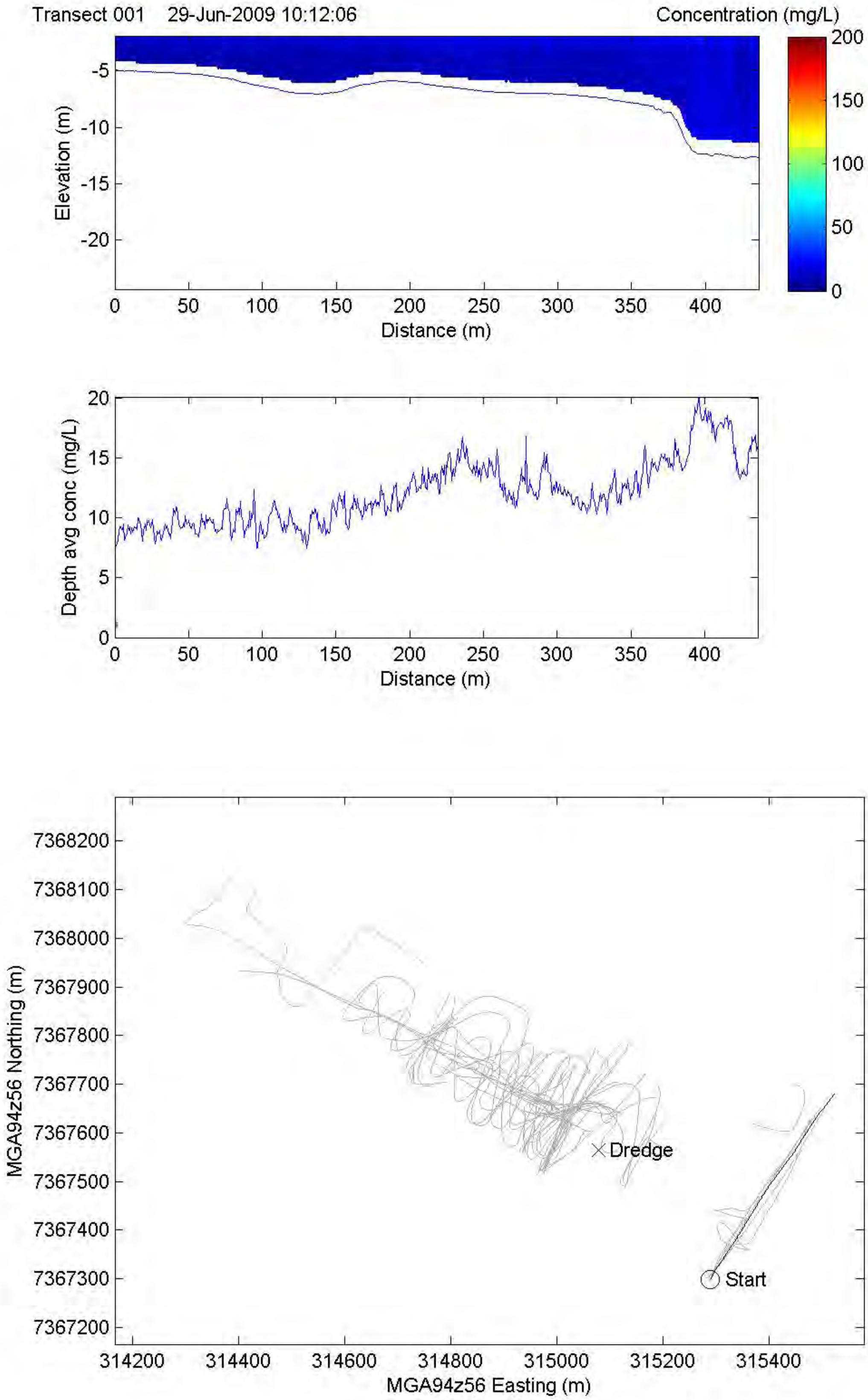


Figure G-5 Transect 001

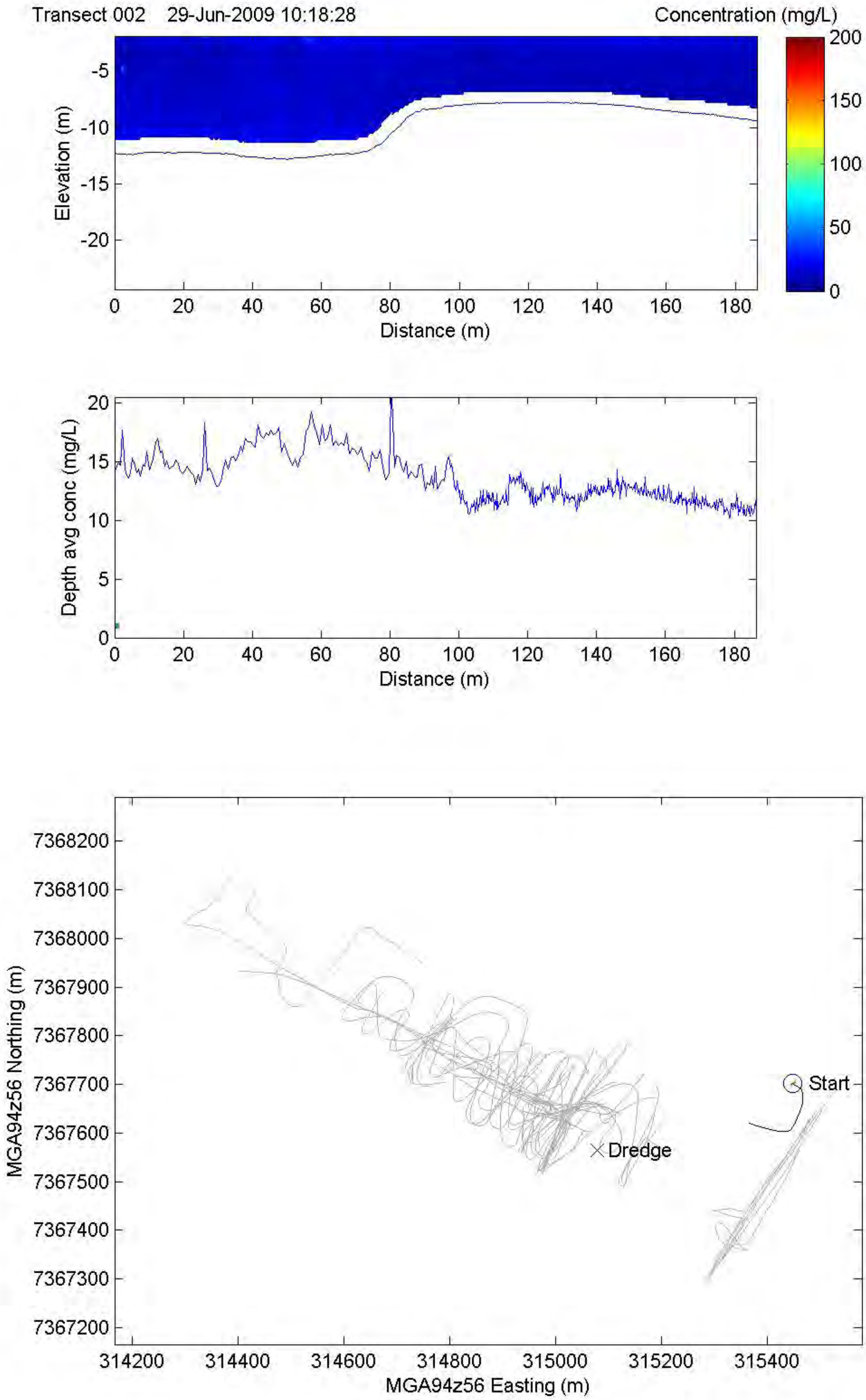


Figure G-6 Transect 002

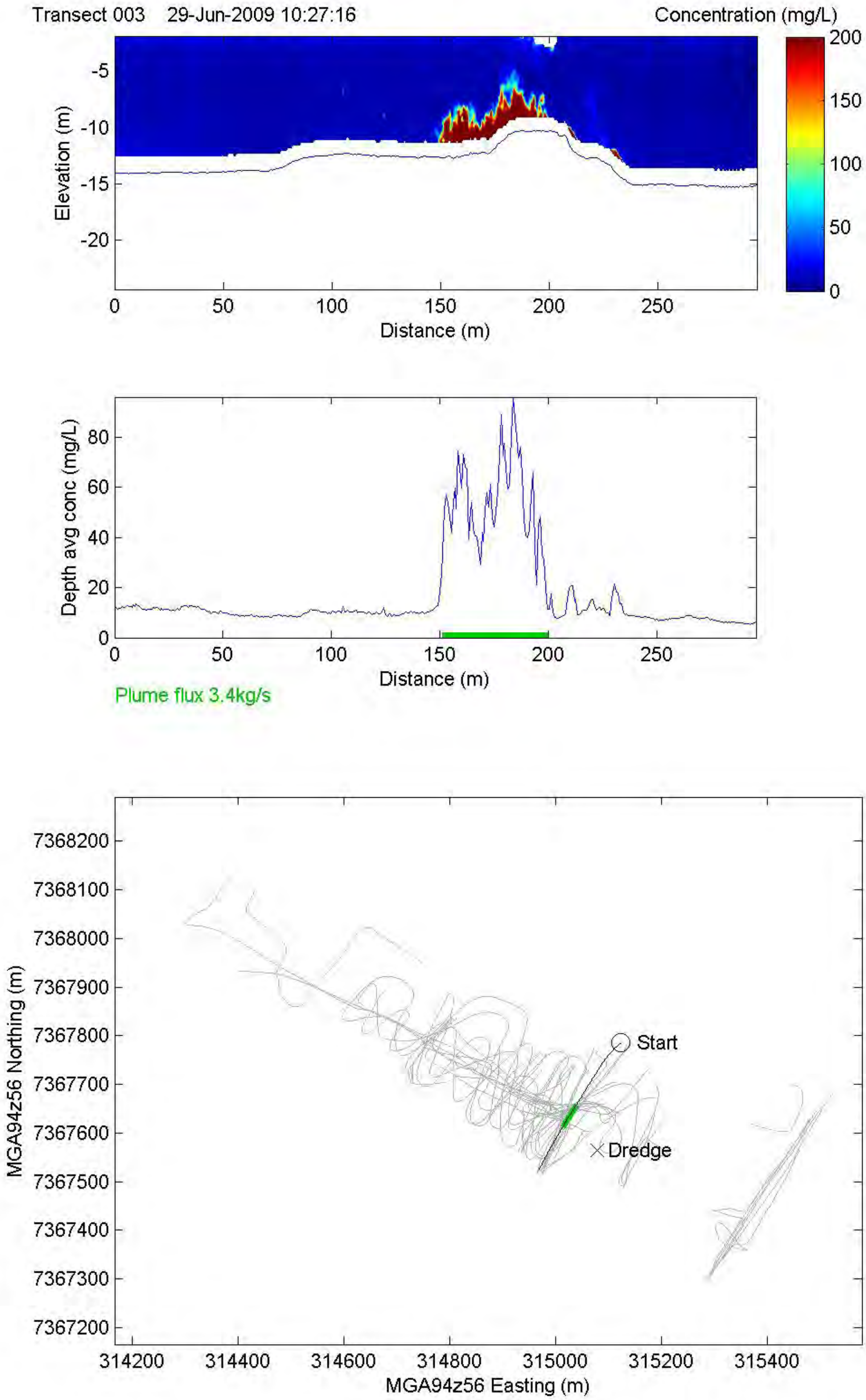


Figure G-7 Transect 003

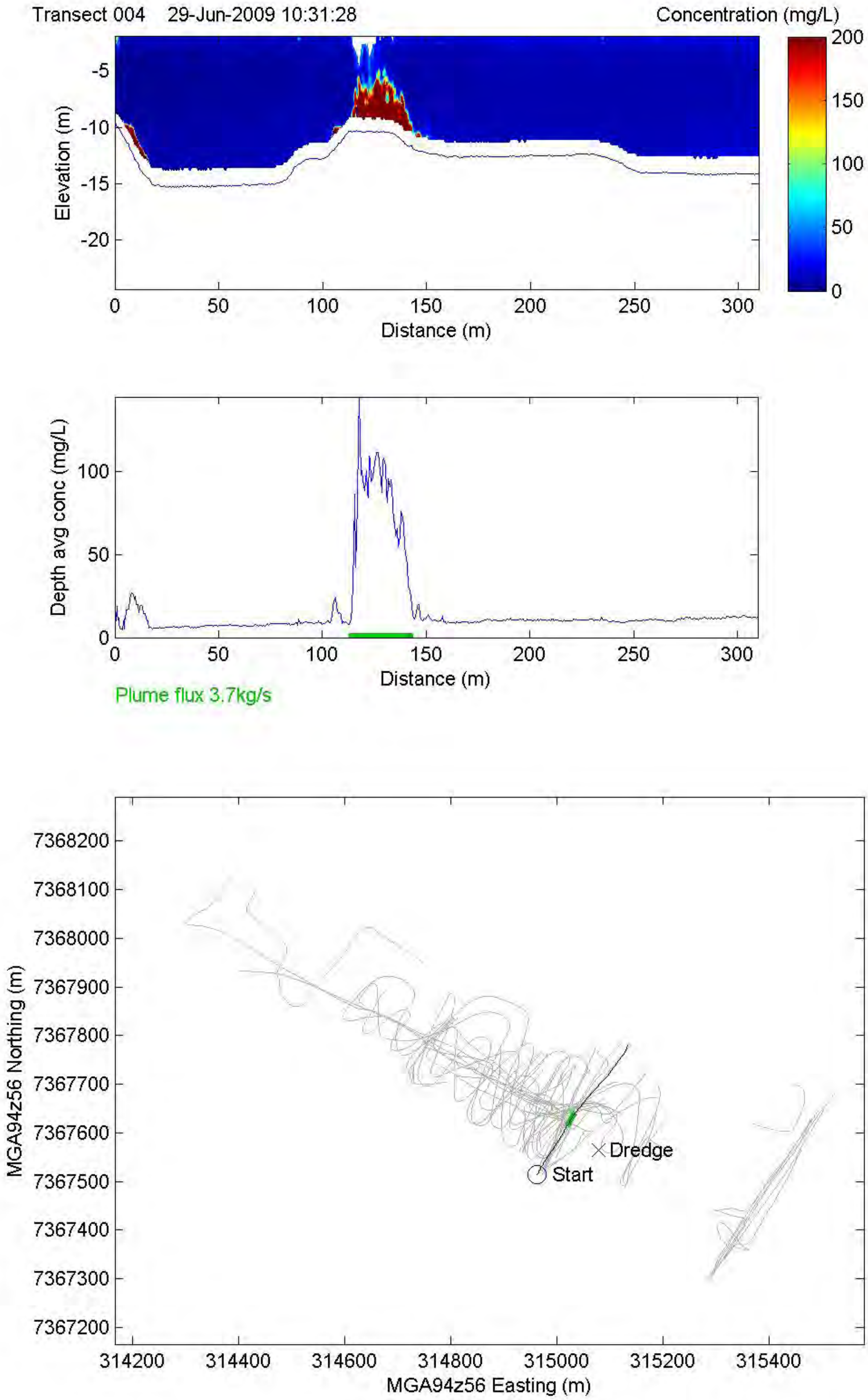


Figure G-8 Transect 004

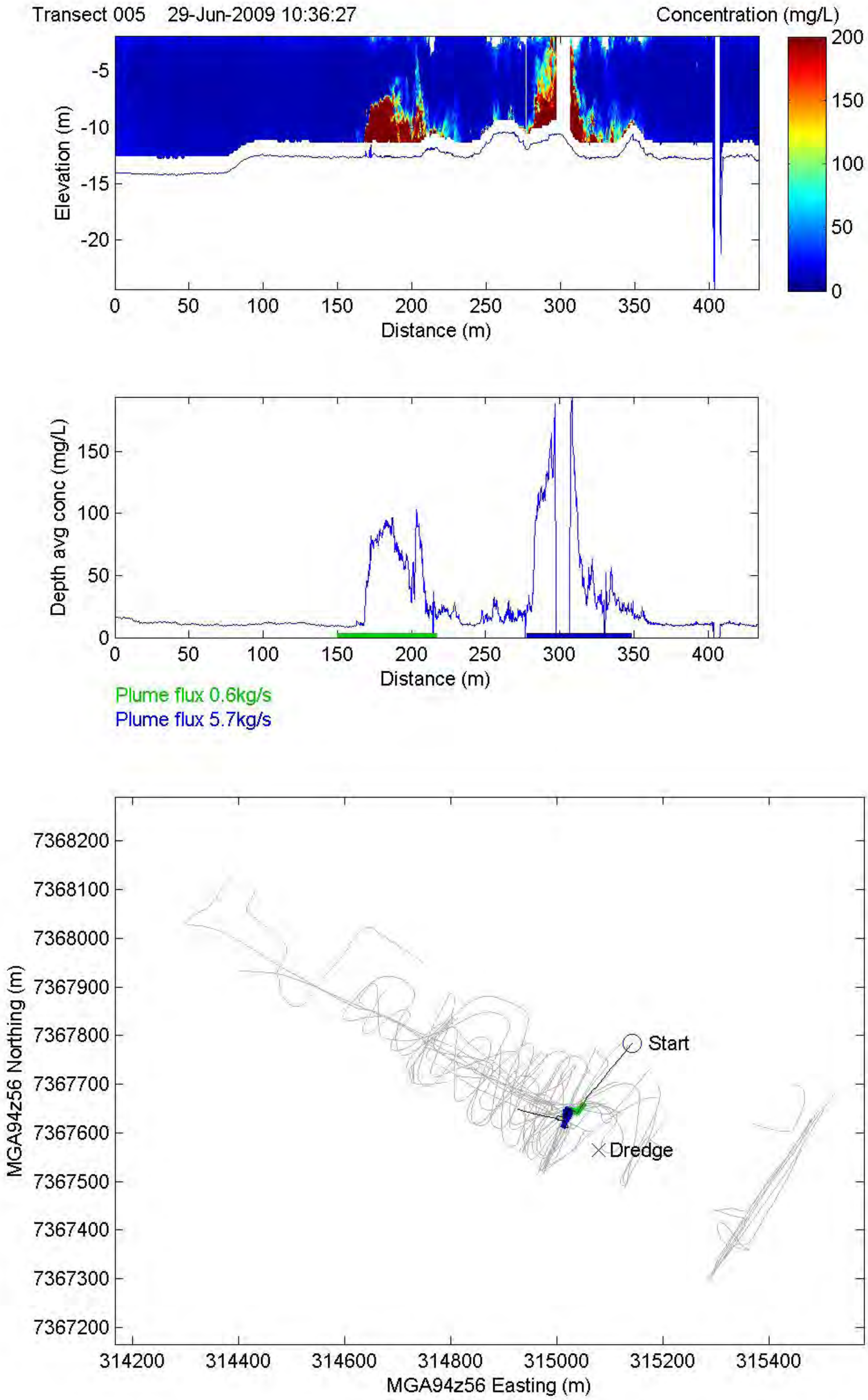


Figure G-9 Transect 005

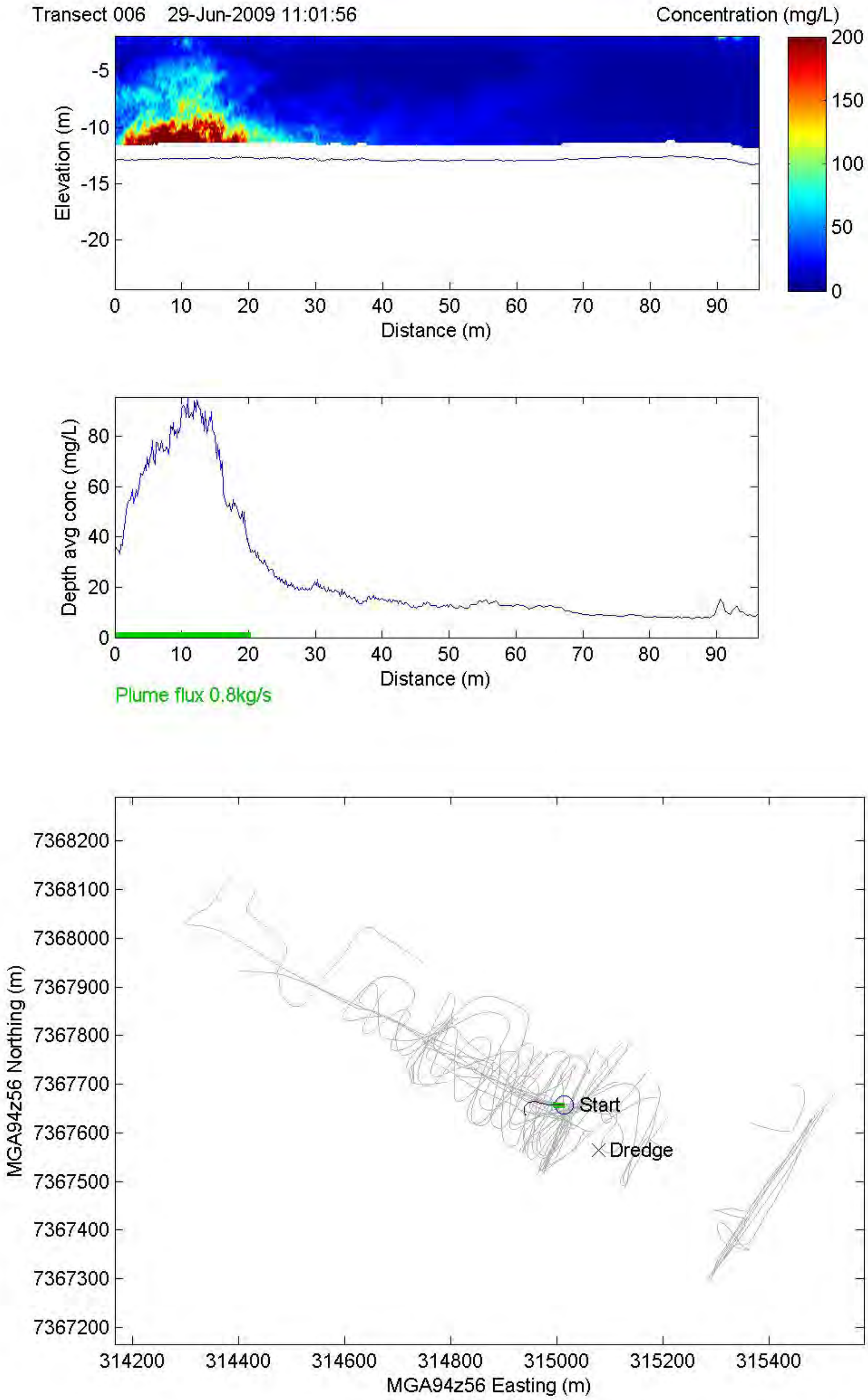


Figure G-10 Transect 006

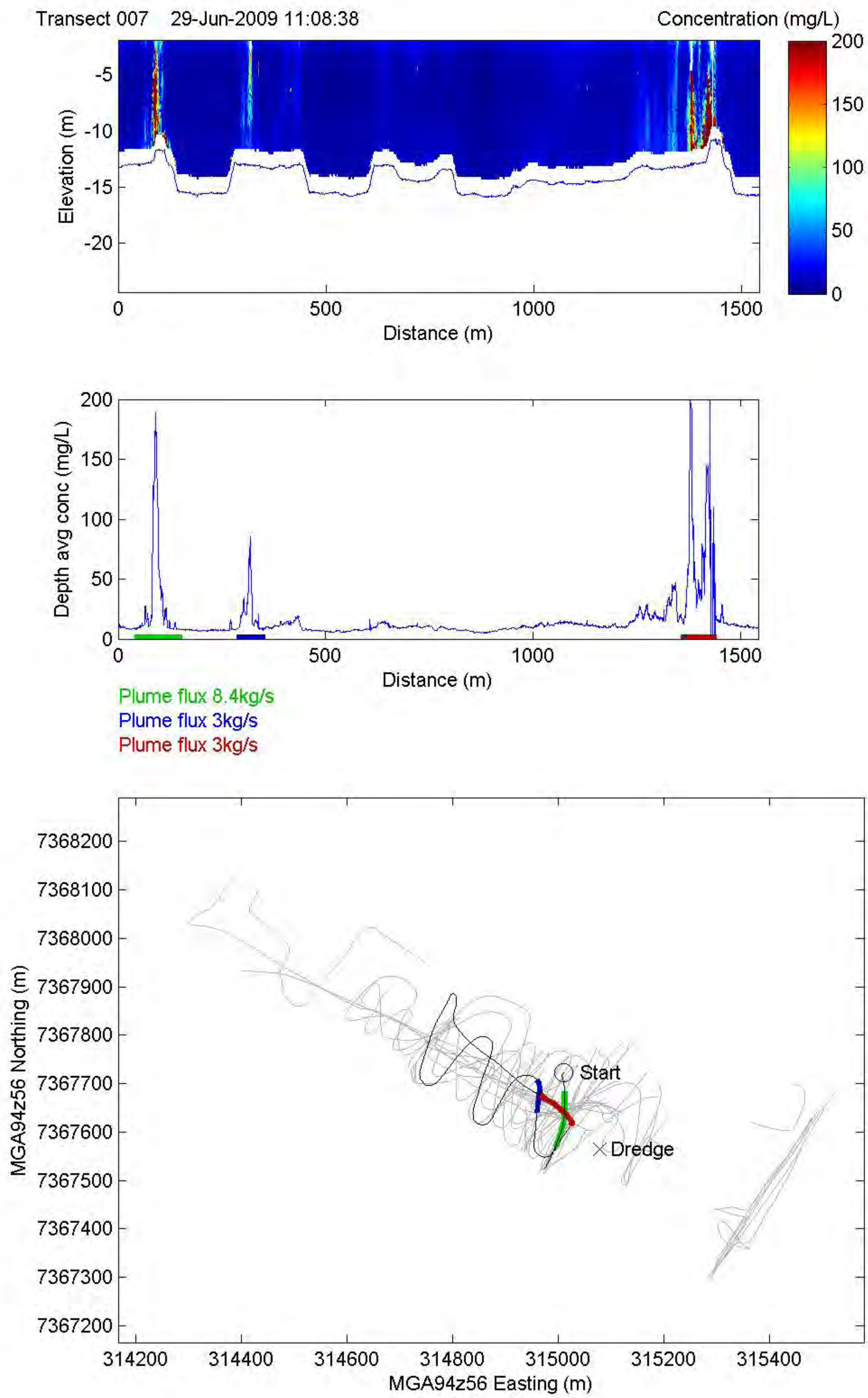


Figure G-11 Transect 007

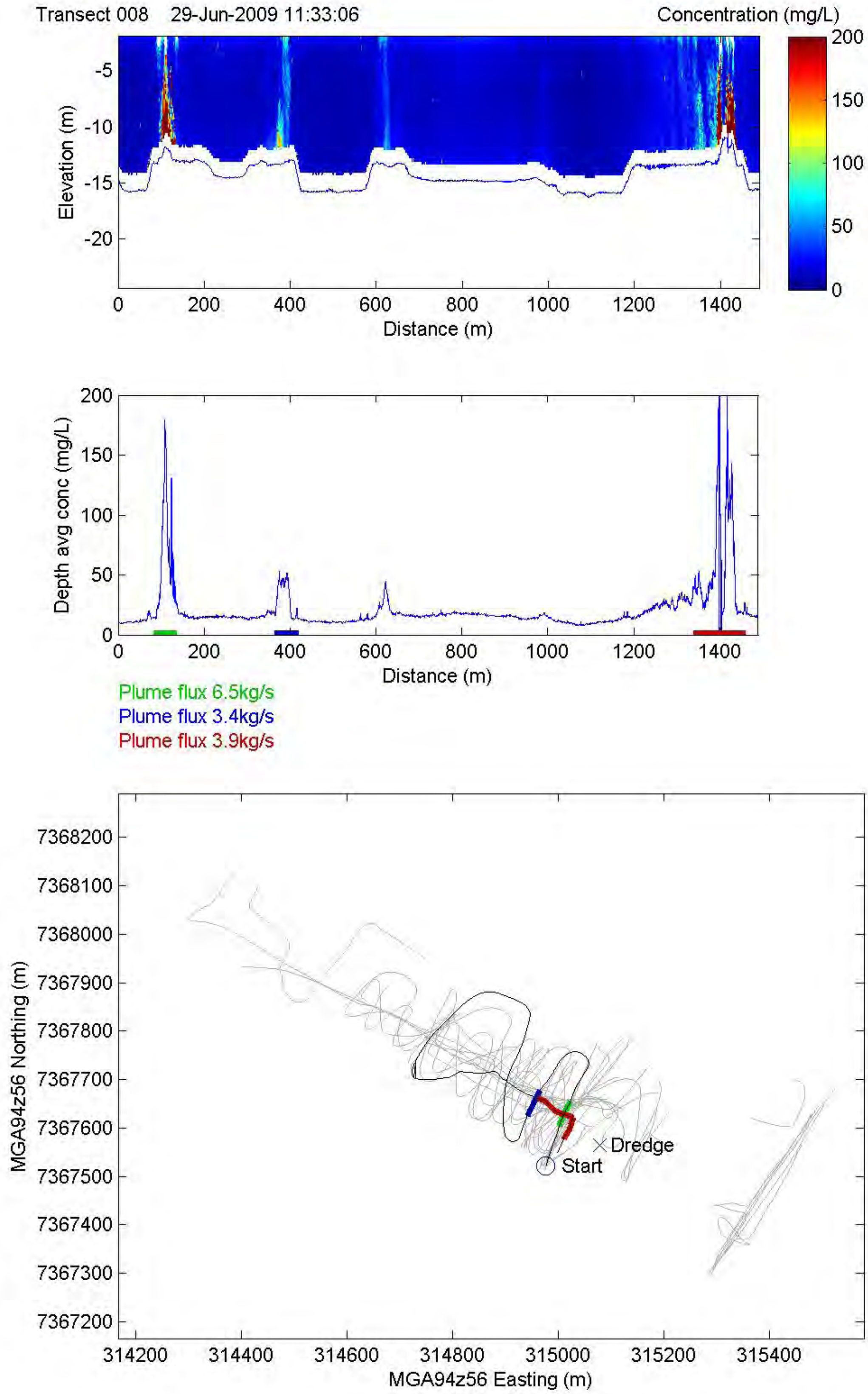


Figure G-12 Transect 008

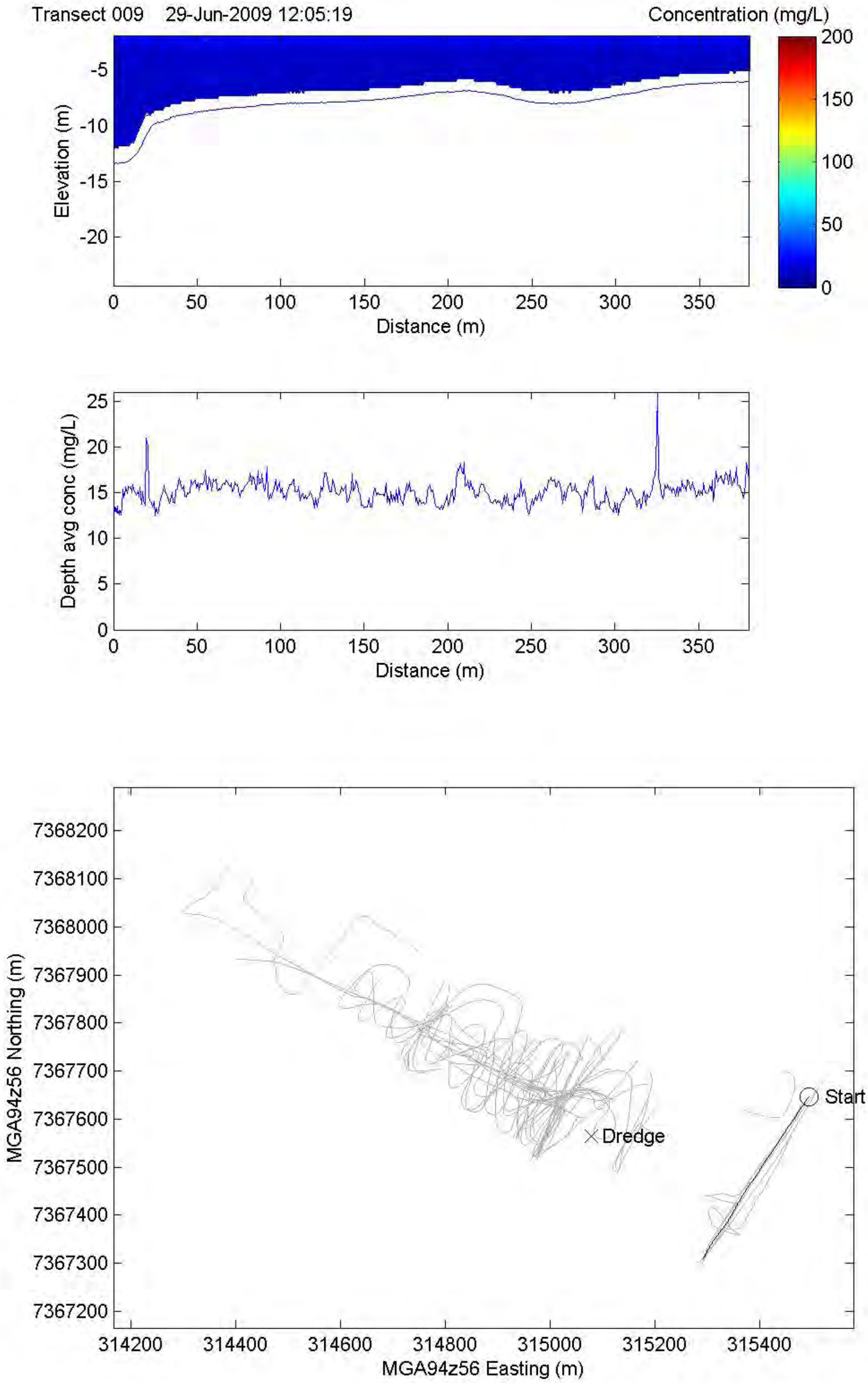


Figure G-13 Transect 009

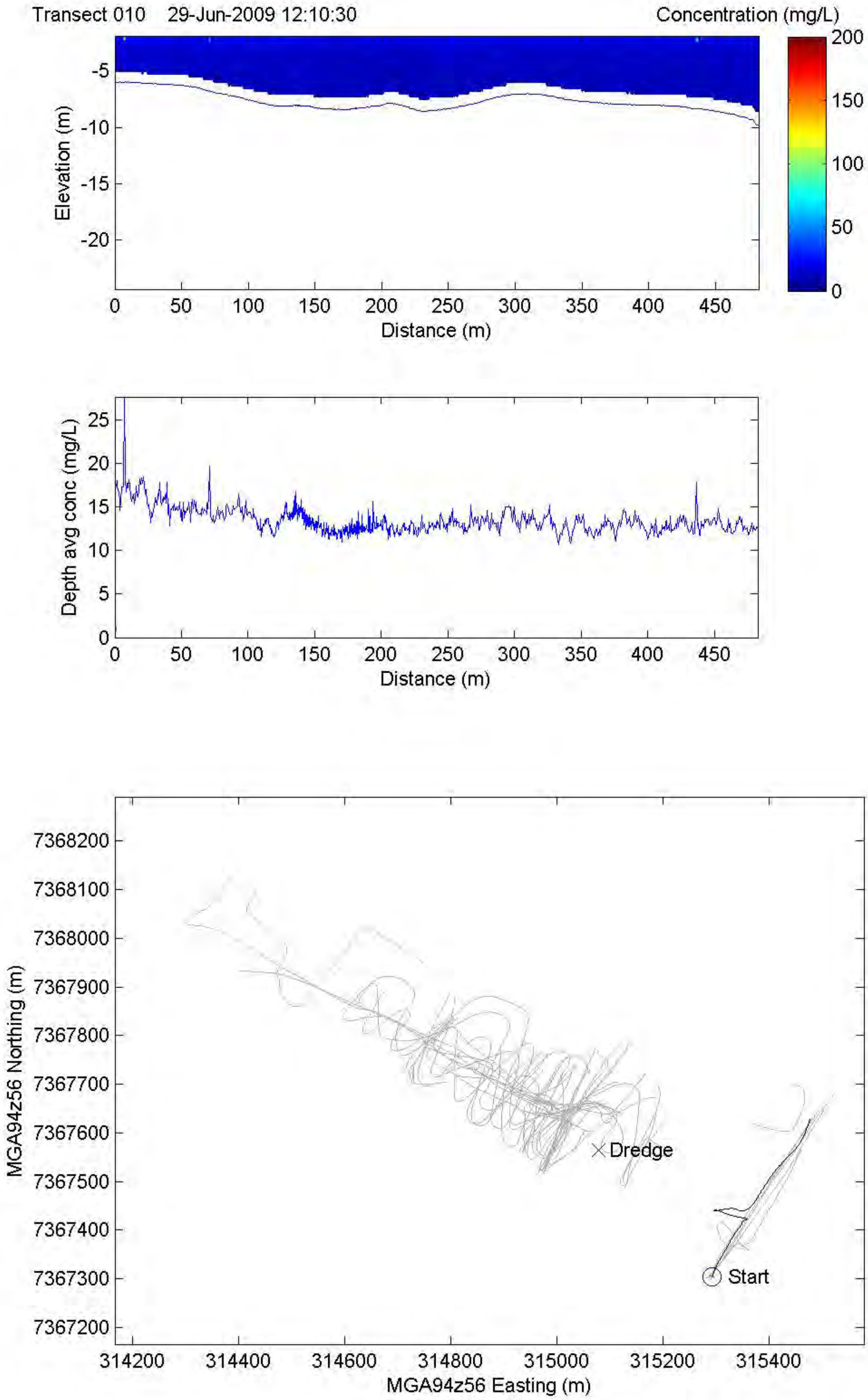
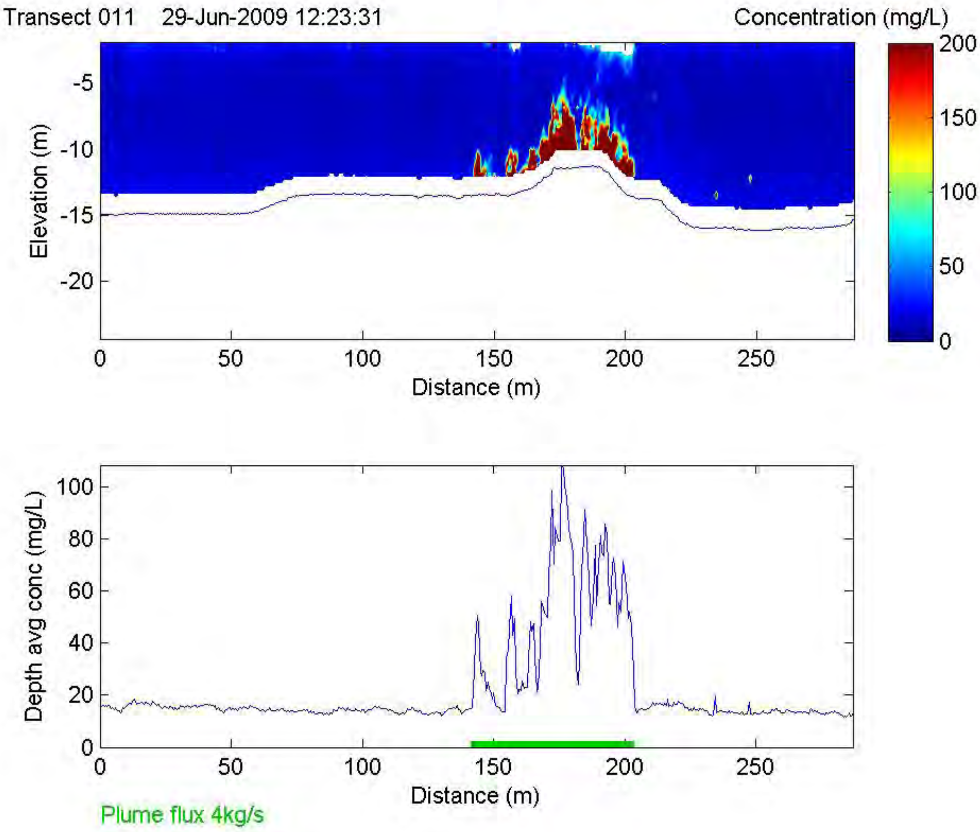


Figure G-14 Transect 010



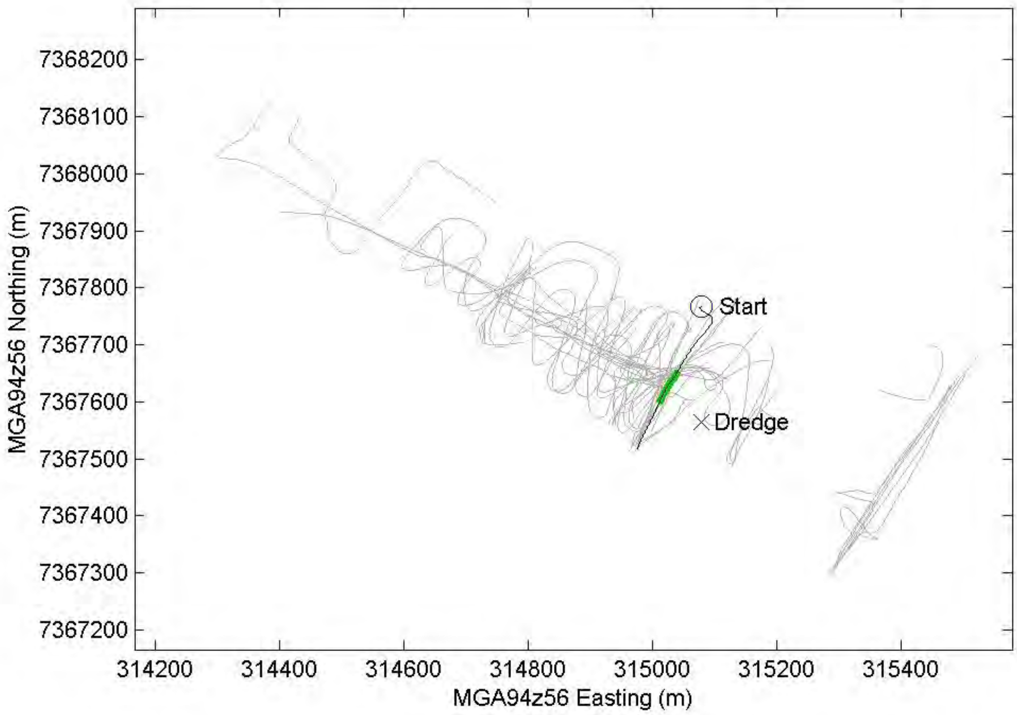


Figure G-15 Transect 011

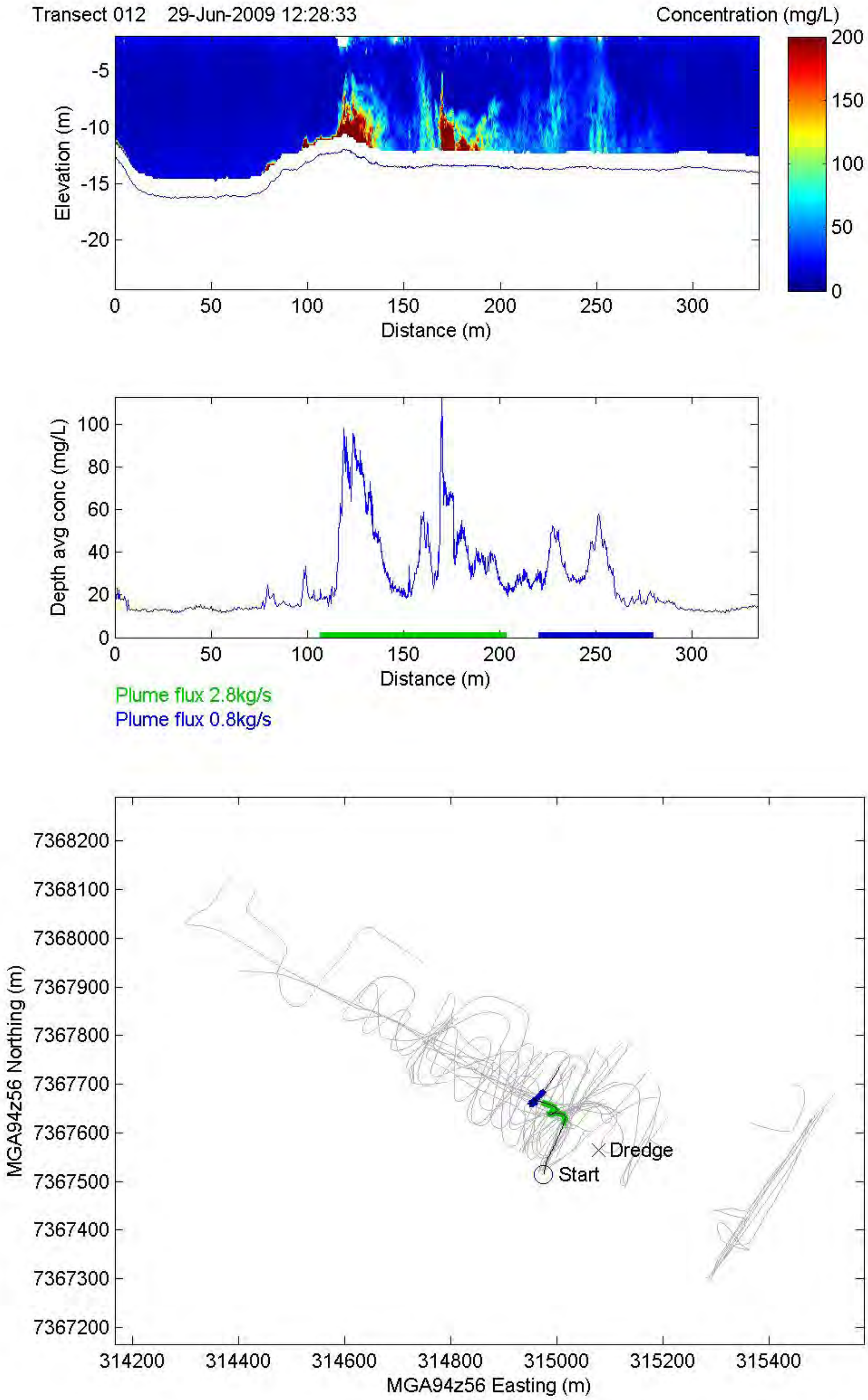


Figure G-16 Transect 012

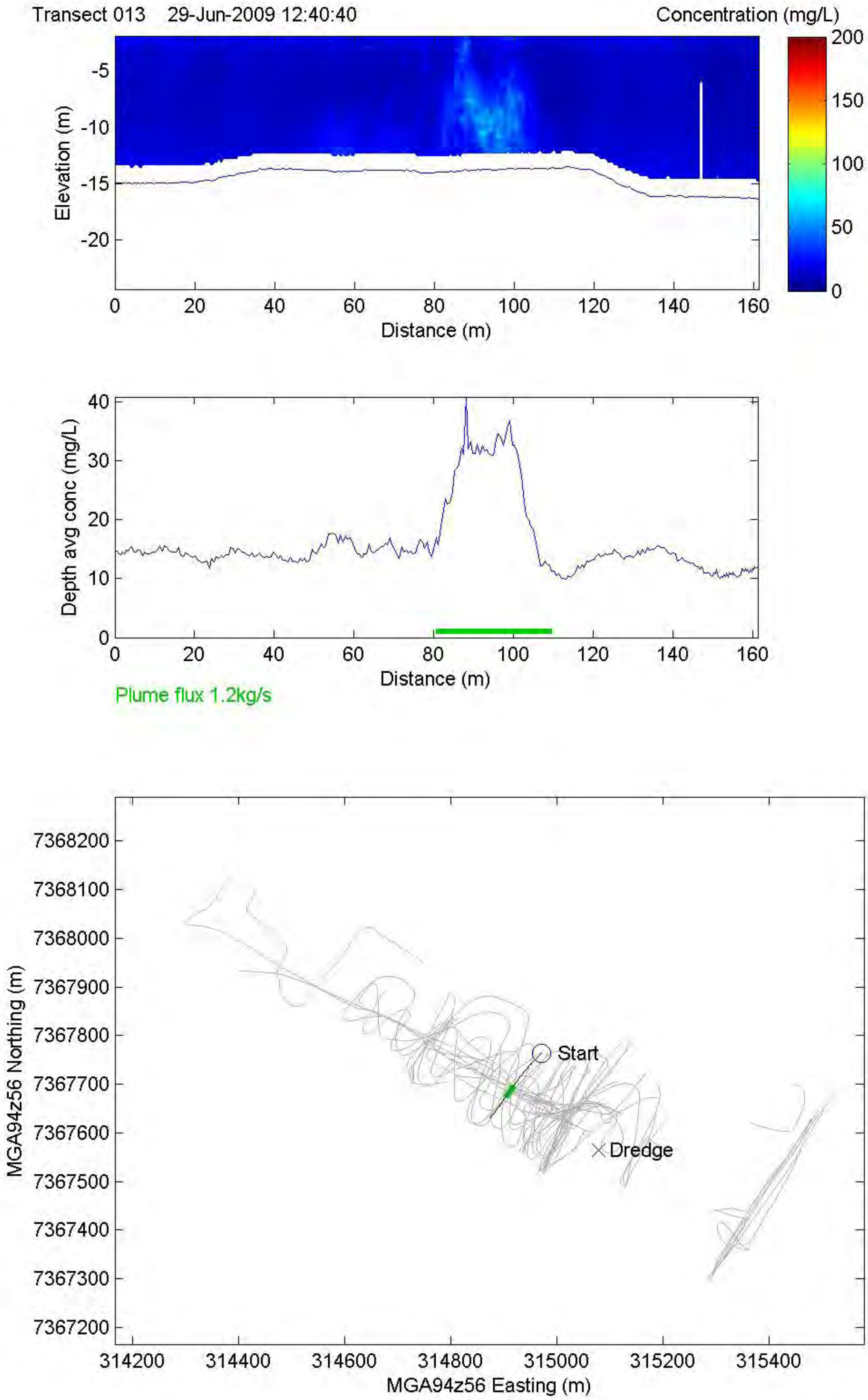


Figure G-17 Transect 013

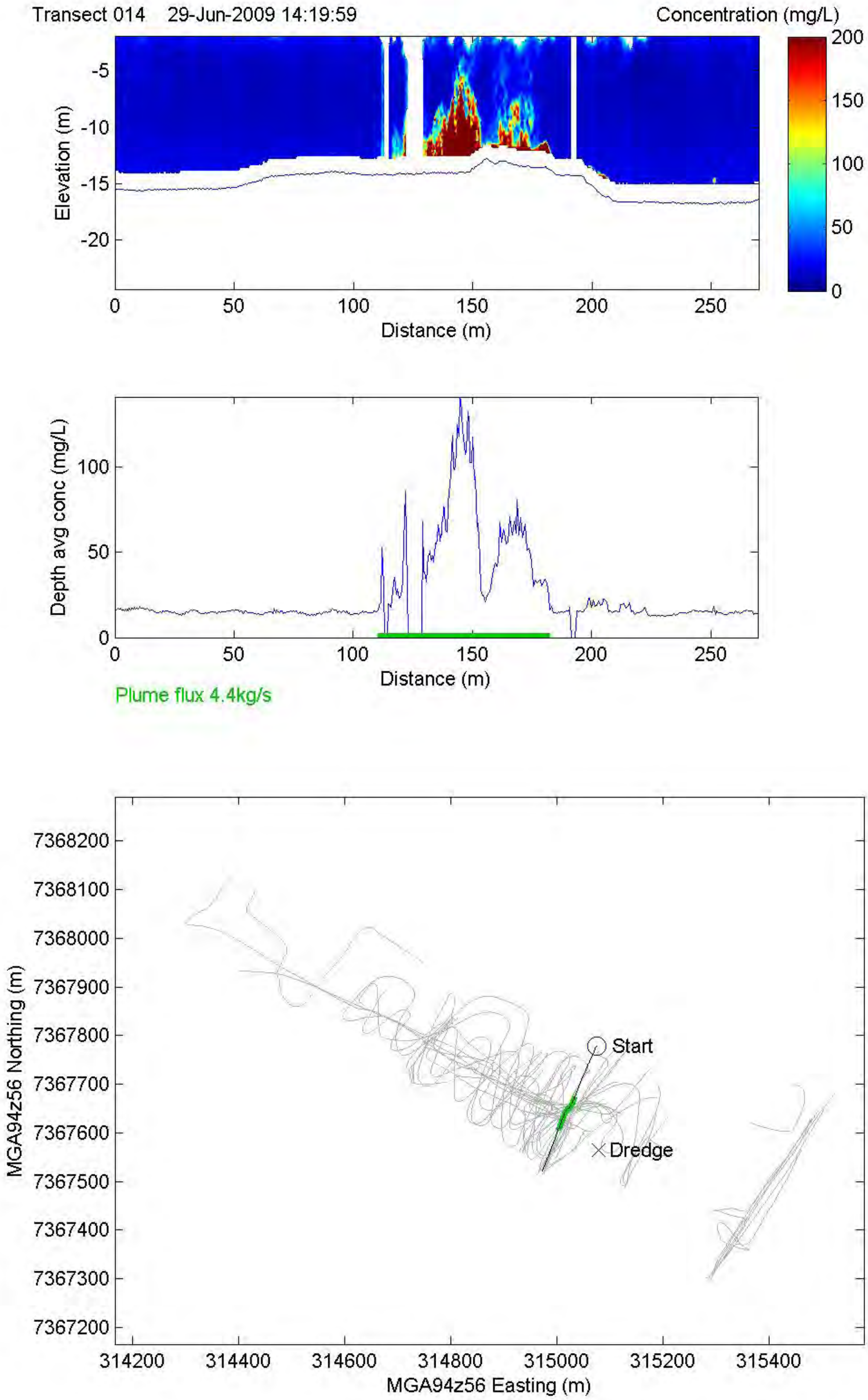


Figure G-18 Transect 014

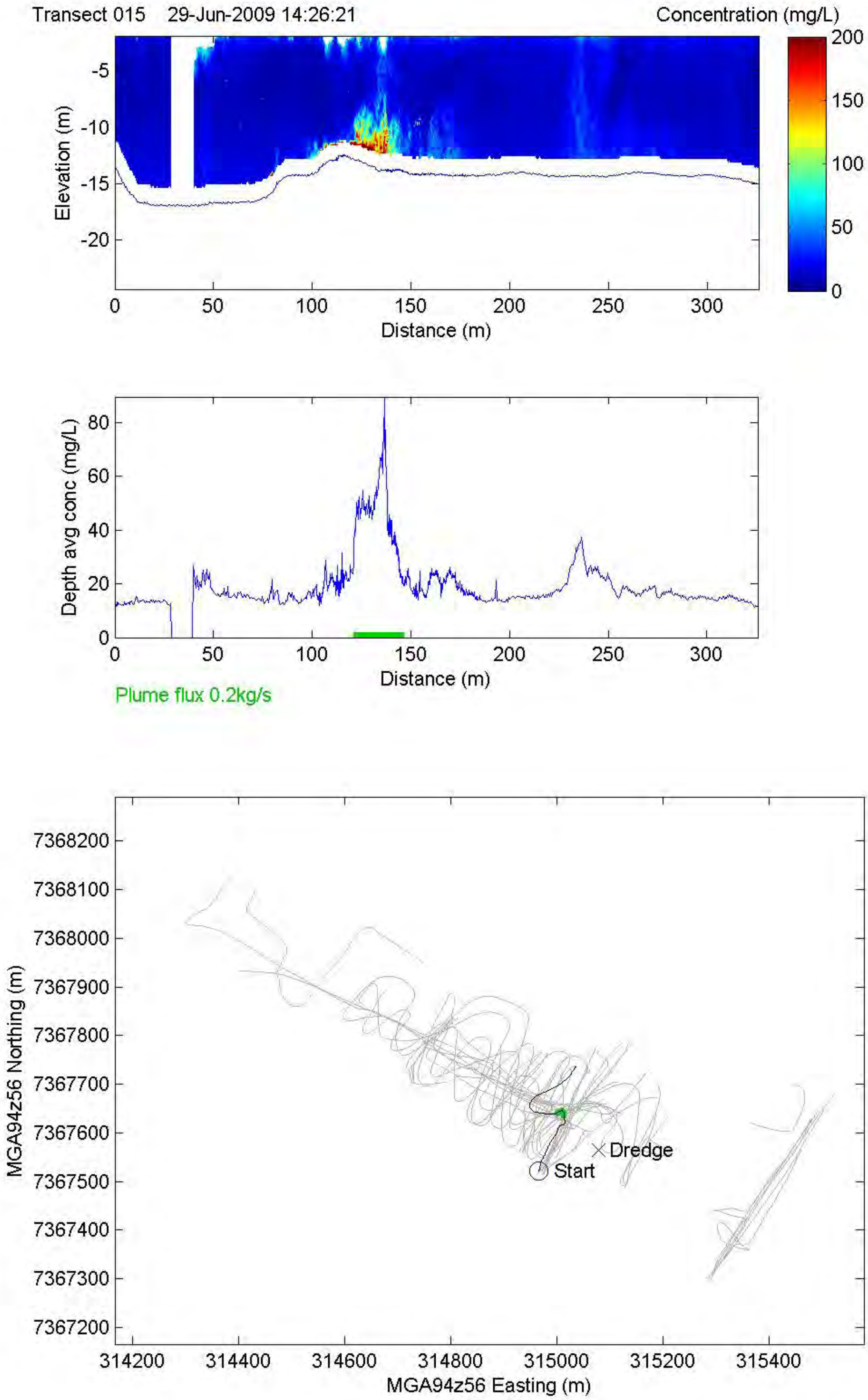


Figure G-19 Transect 015

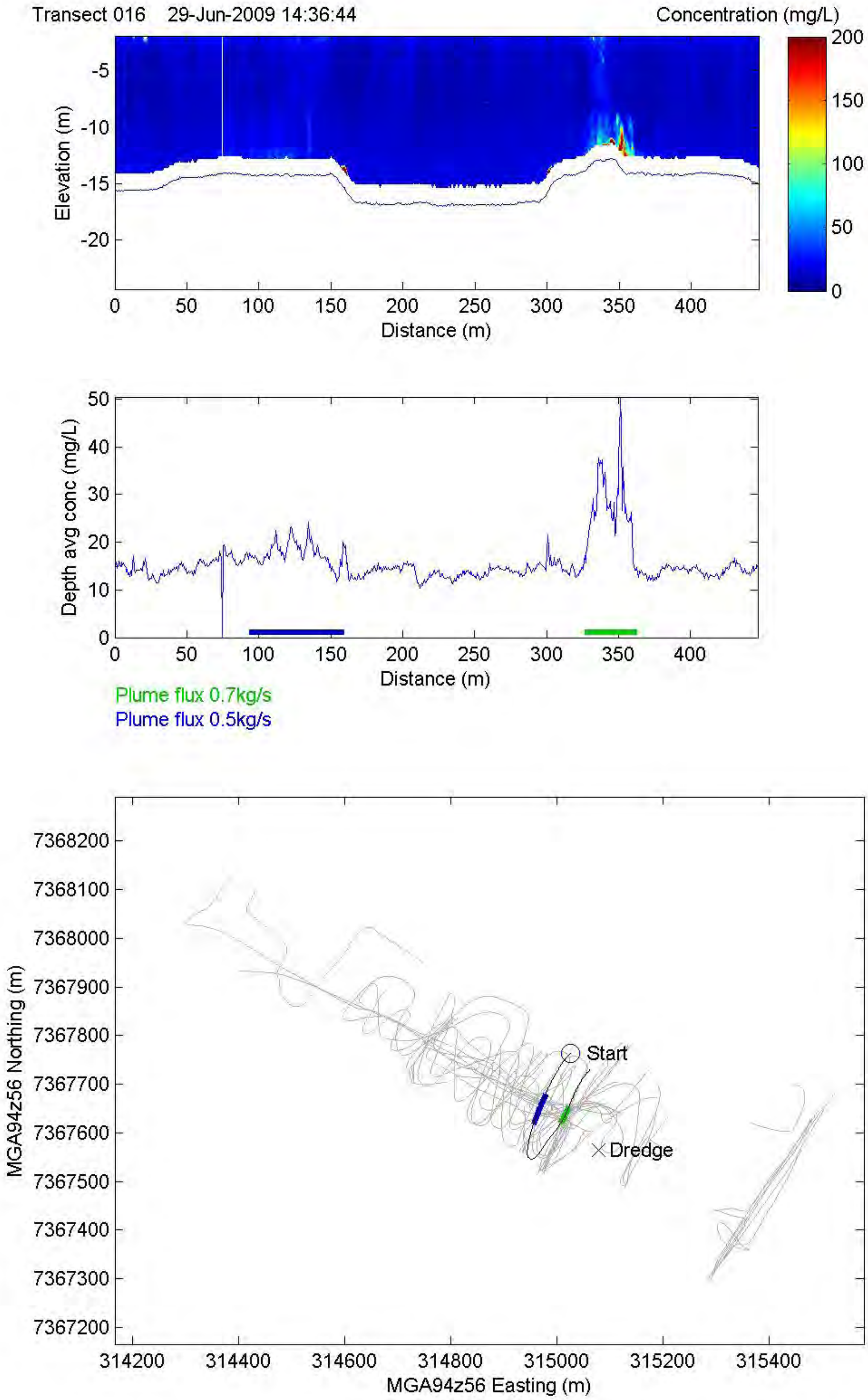


Figure G-20 Transect 016

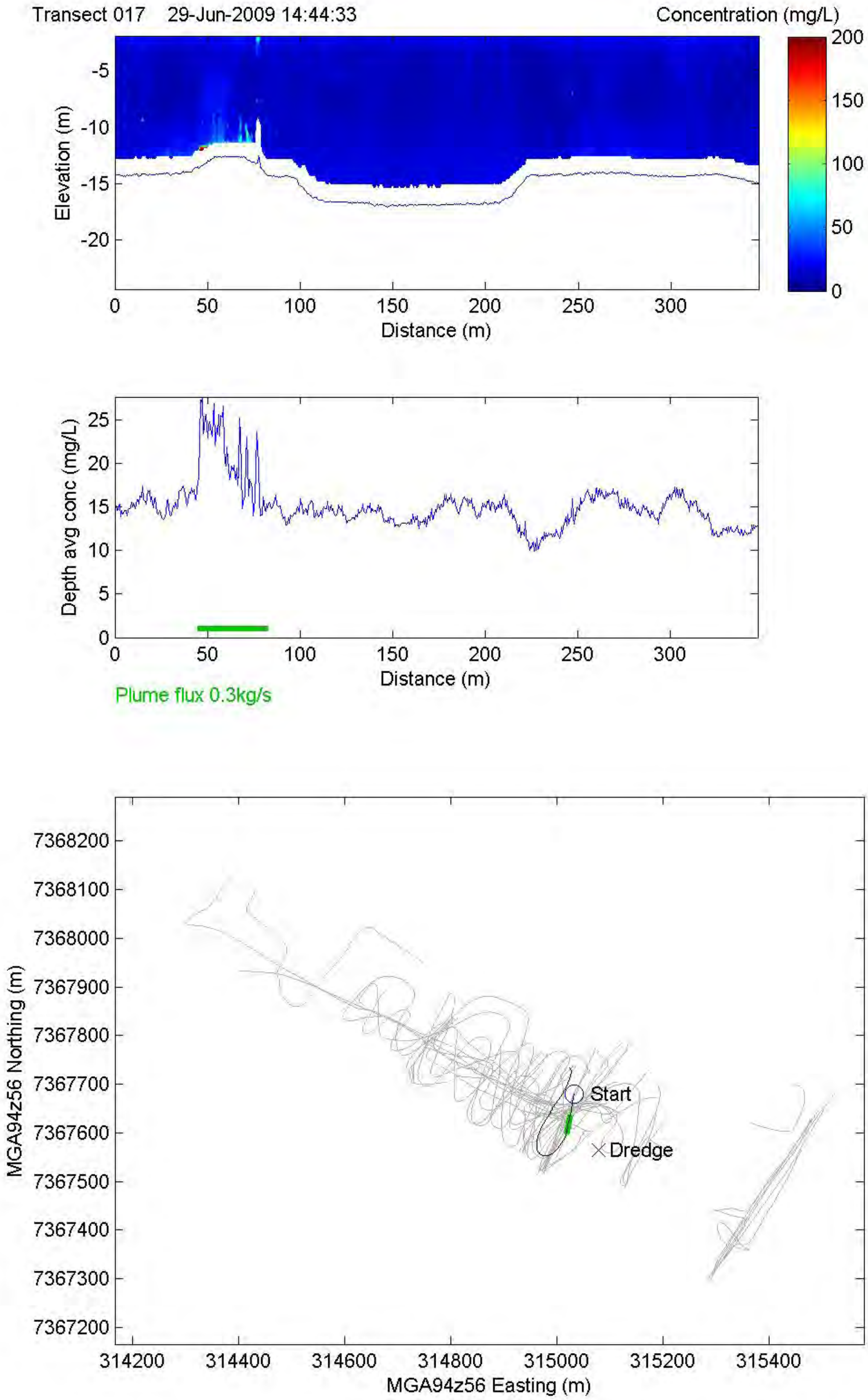


Figure G-21 Transect -17

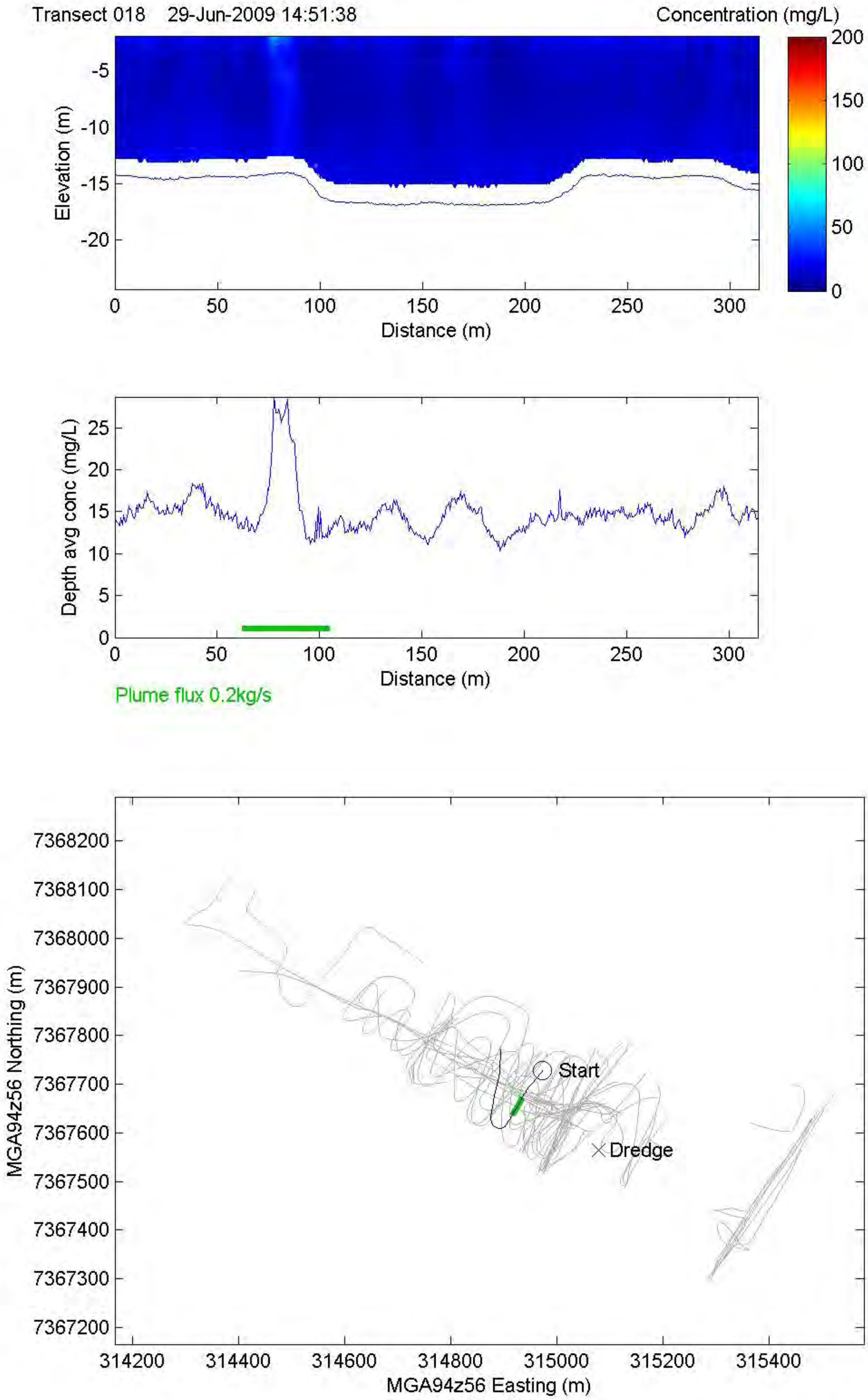


Figure G-22 Transect 018

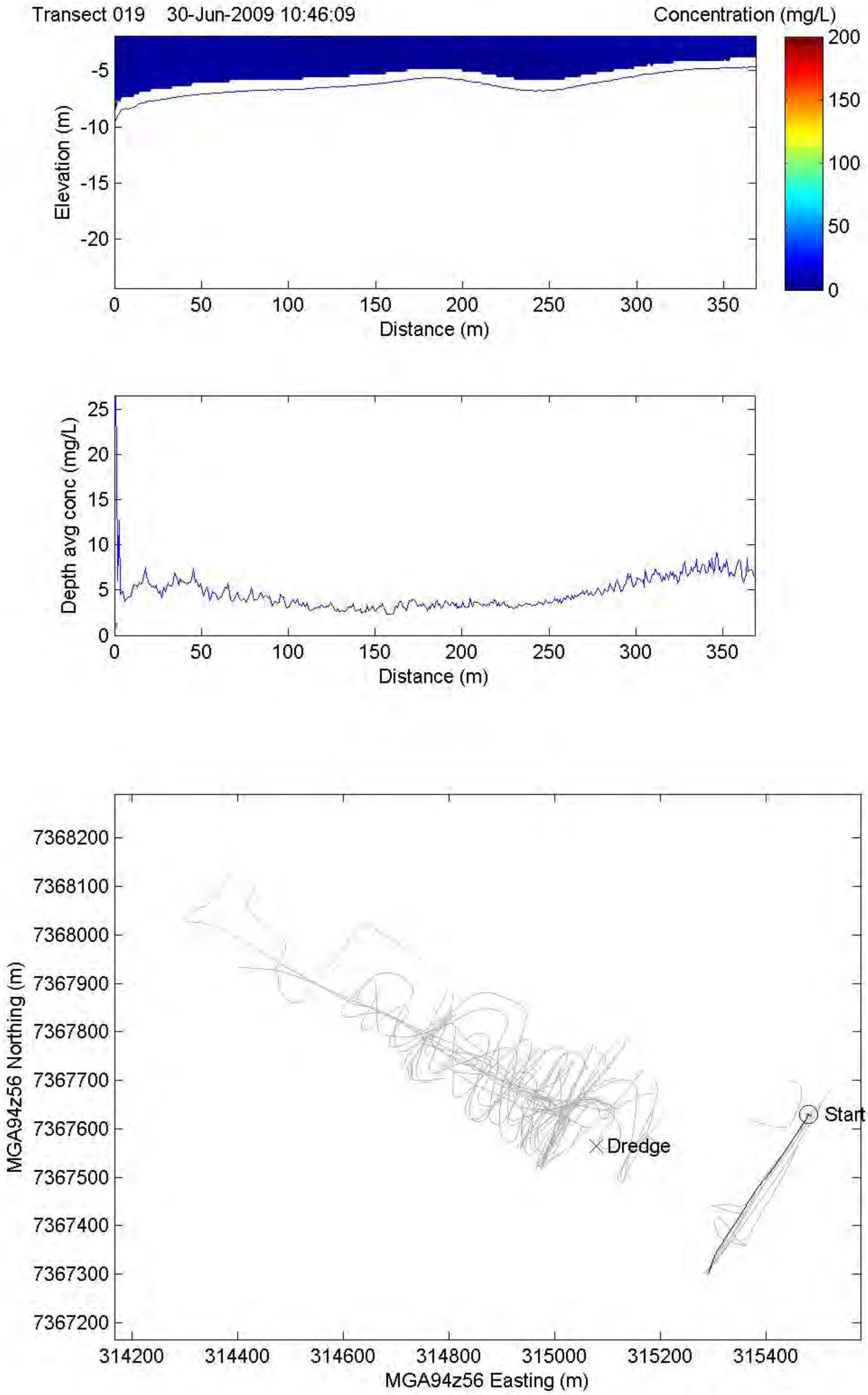


Figure G-23 Transect 019

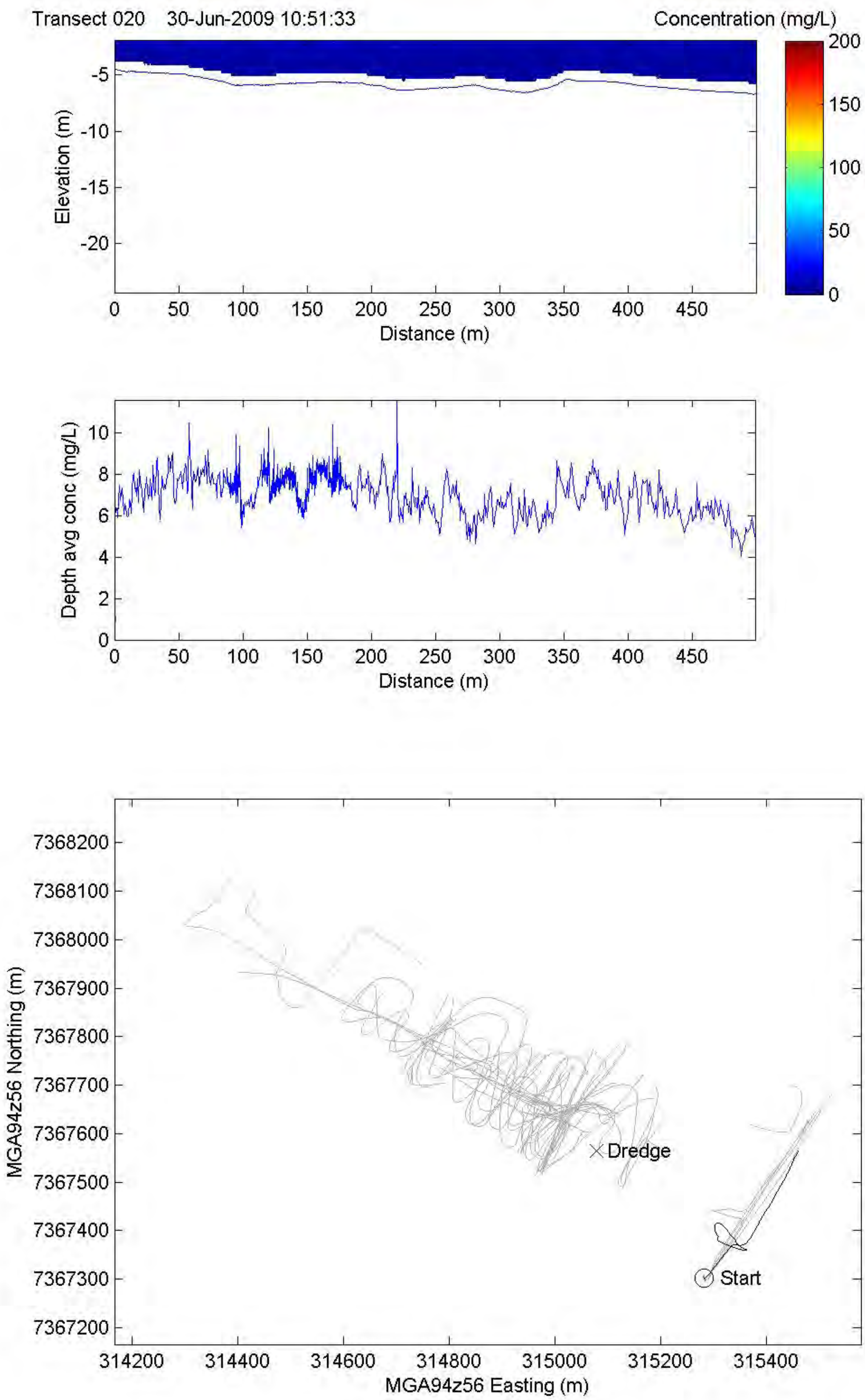


Figure G-24 Transect 020

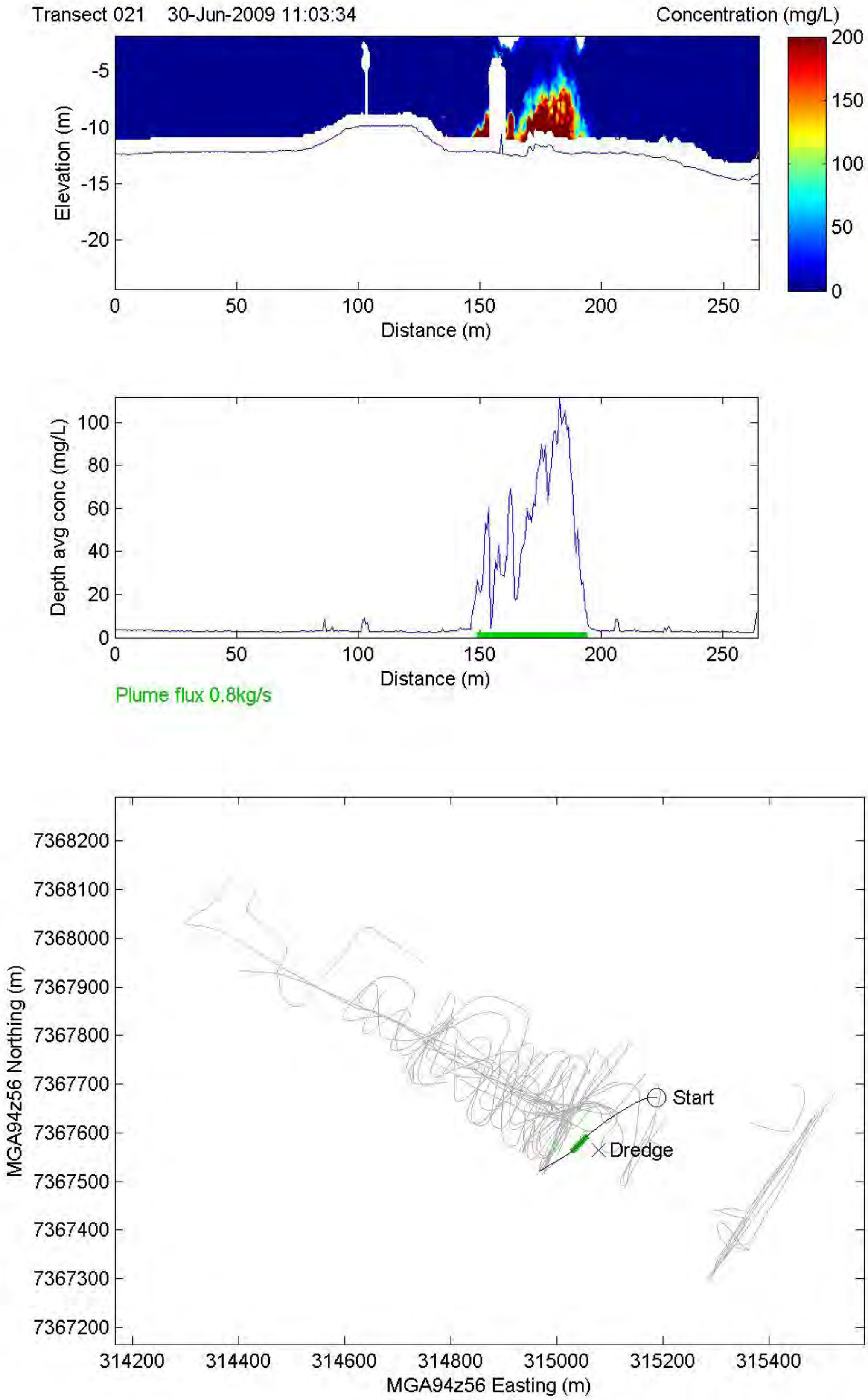


Figure G-25 Transect 021

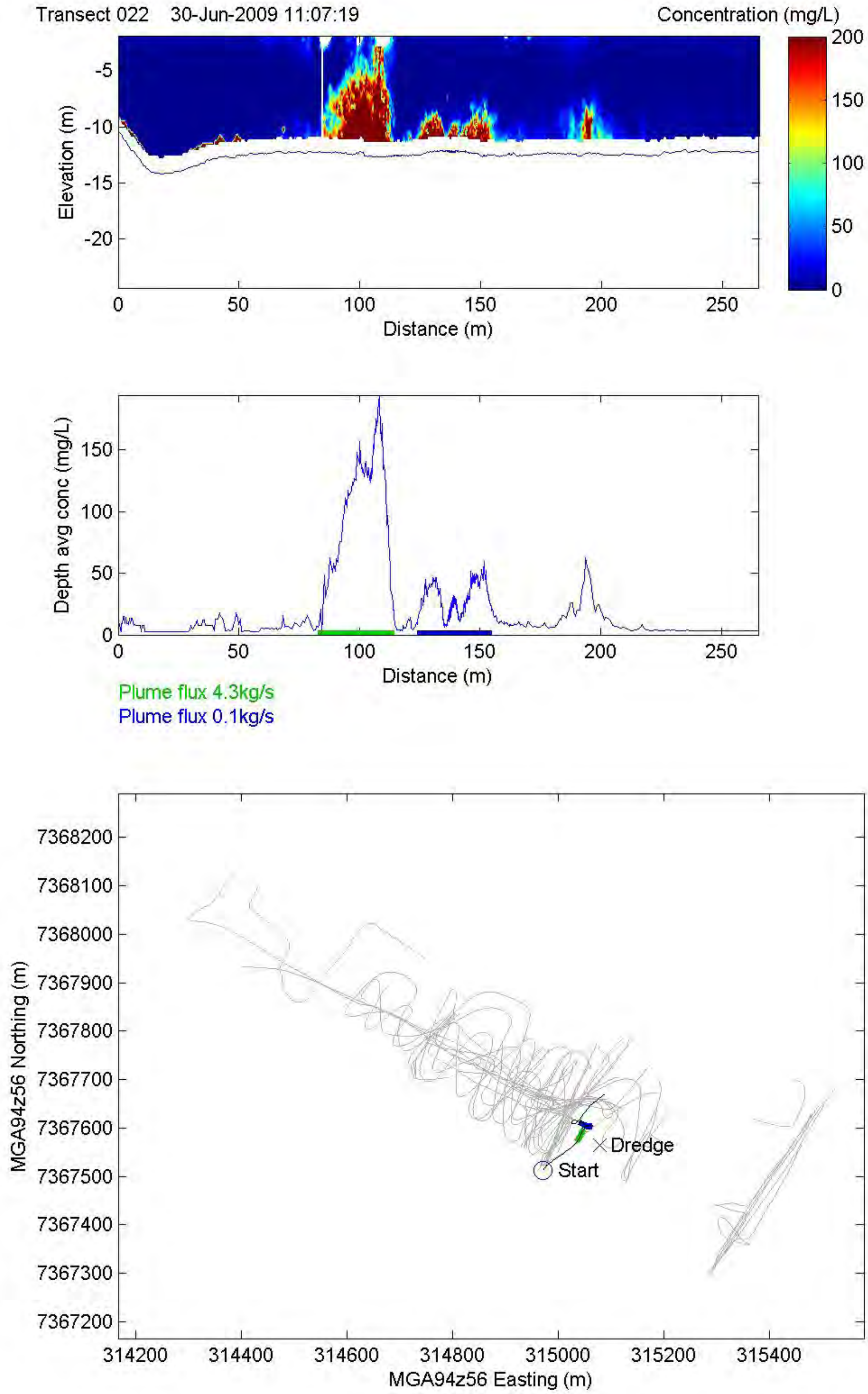


Figure G-26 Transect 022

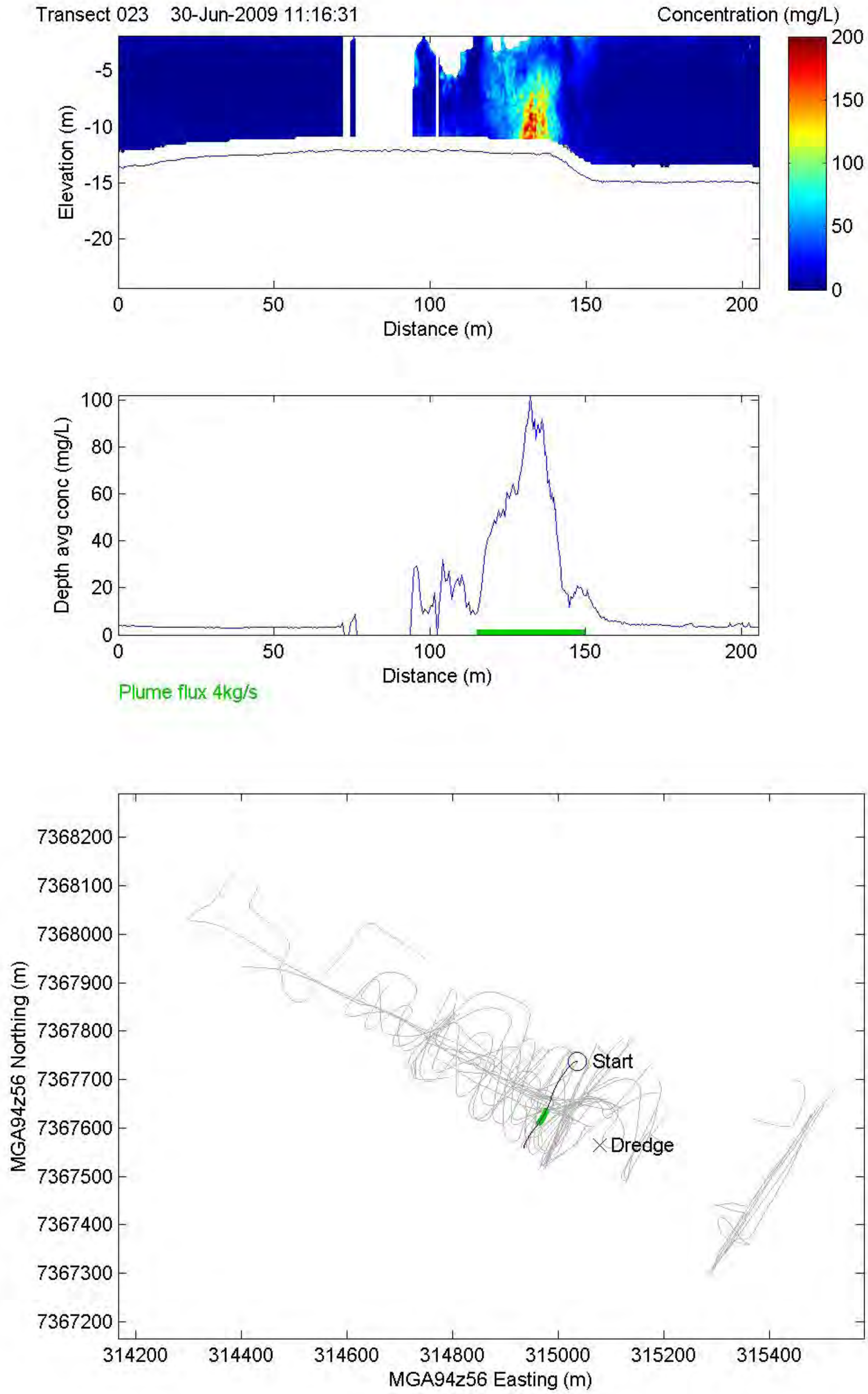


Figure G-27 Transect 023

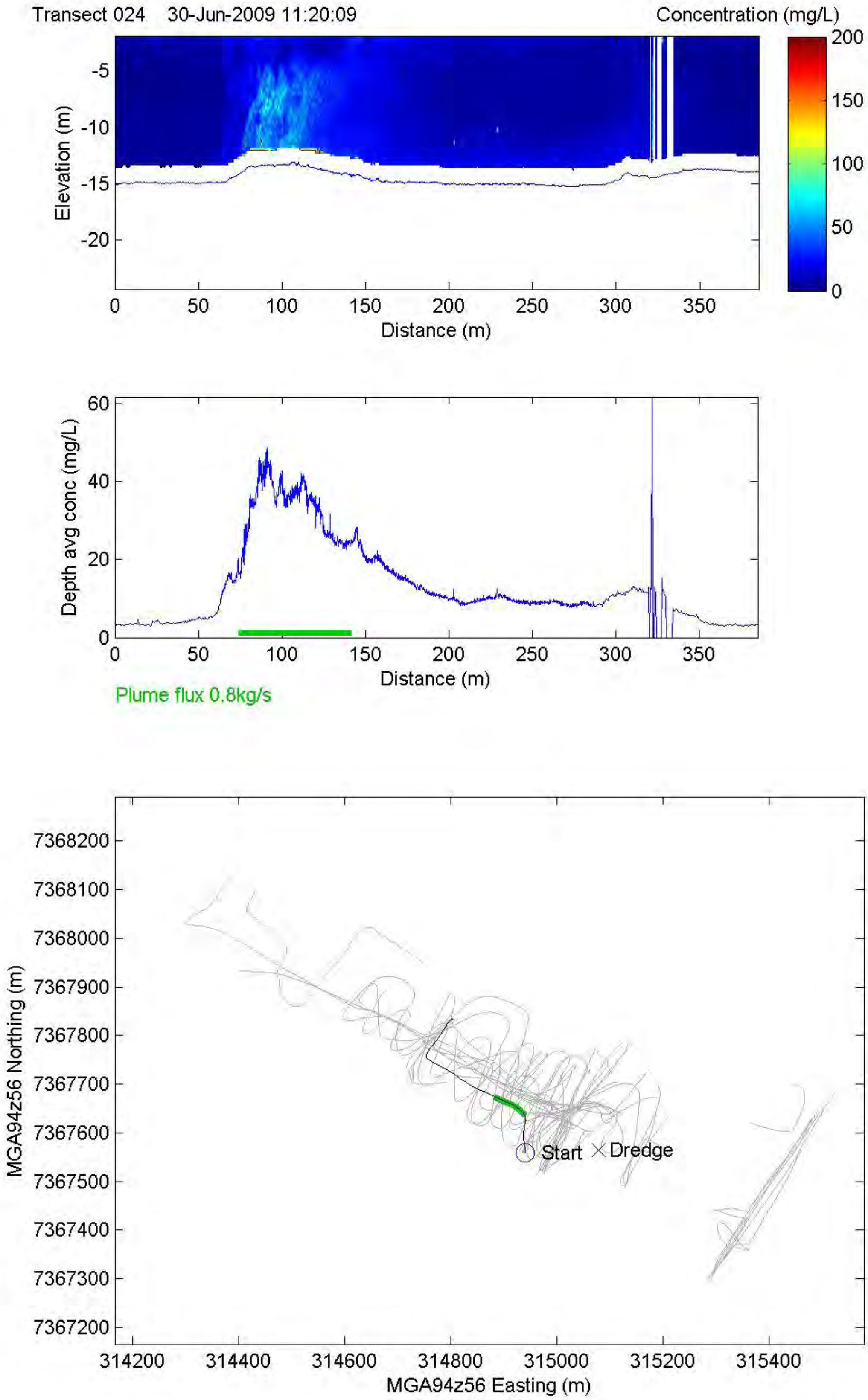


Figure G-28 Transect 024

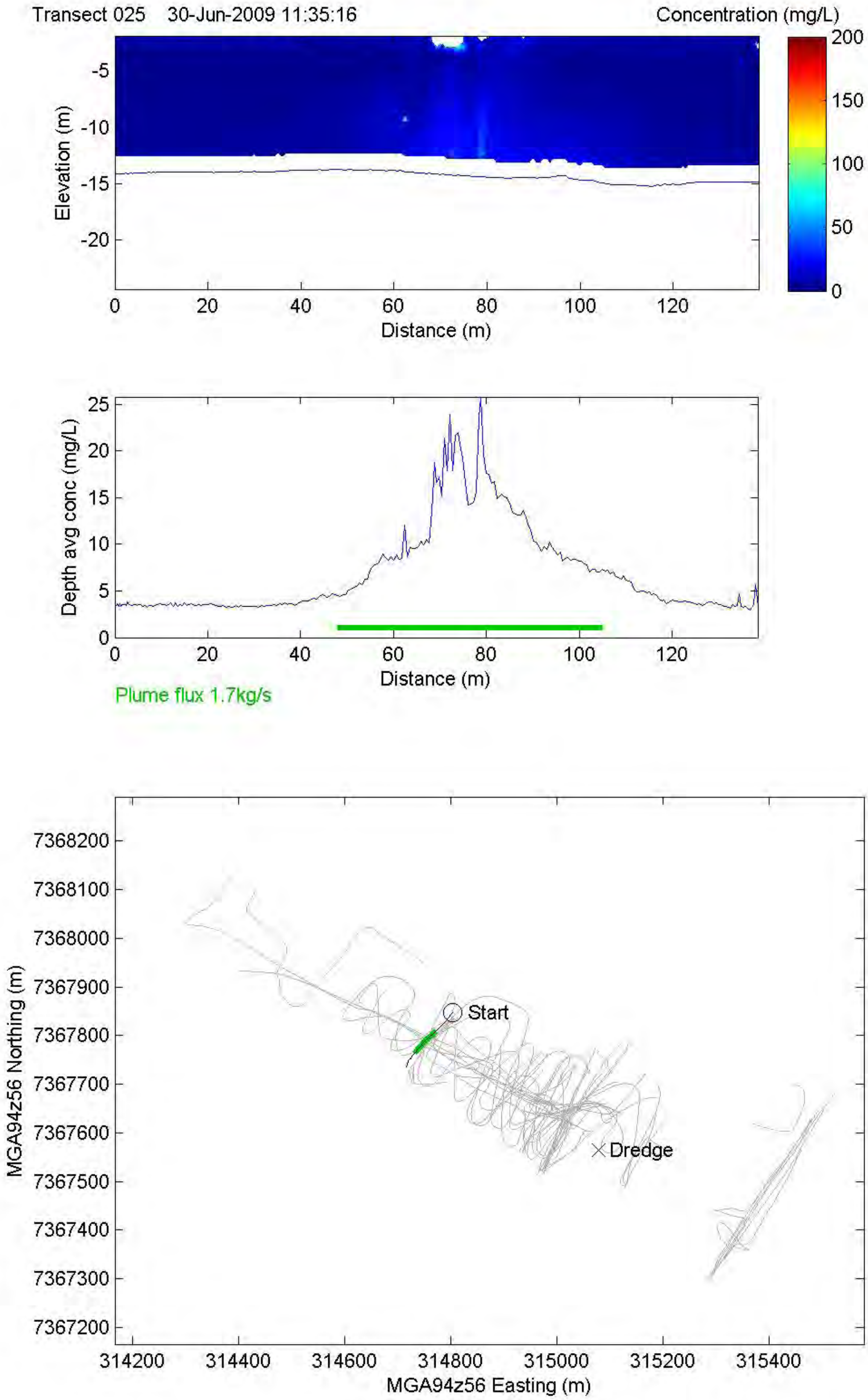


Figure G-29 Transect 025

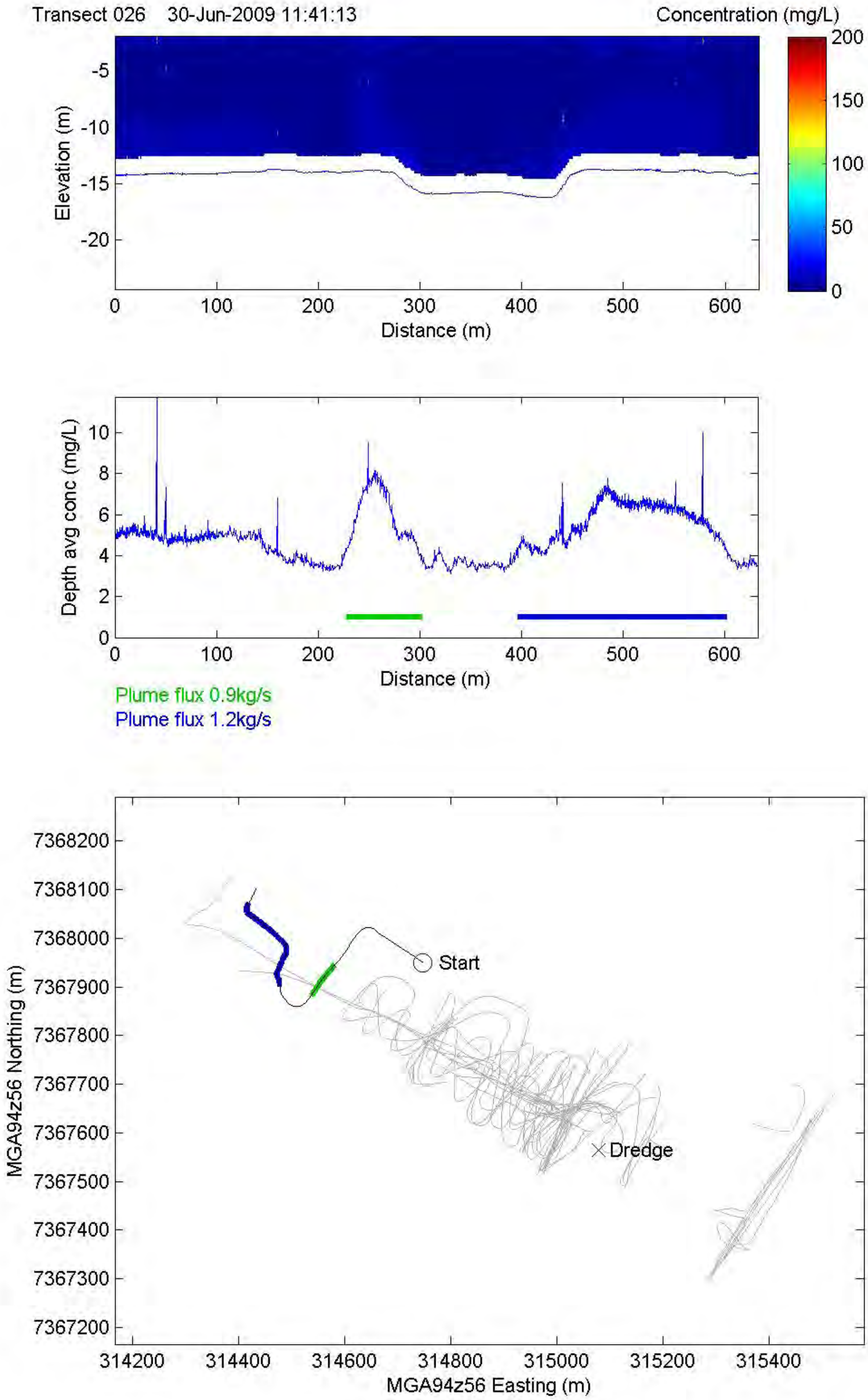


Figure G-30 Transect 026

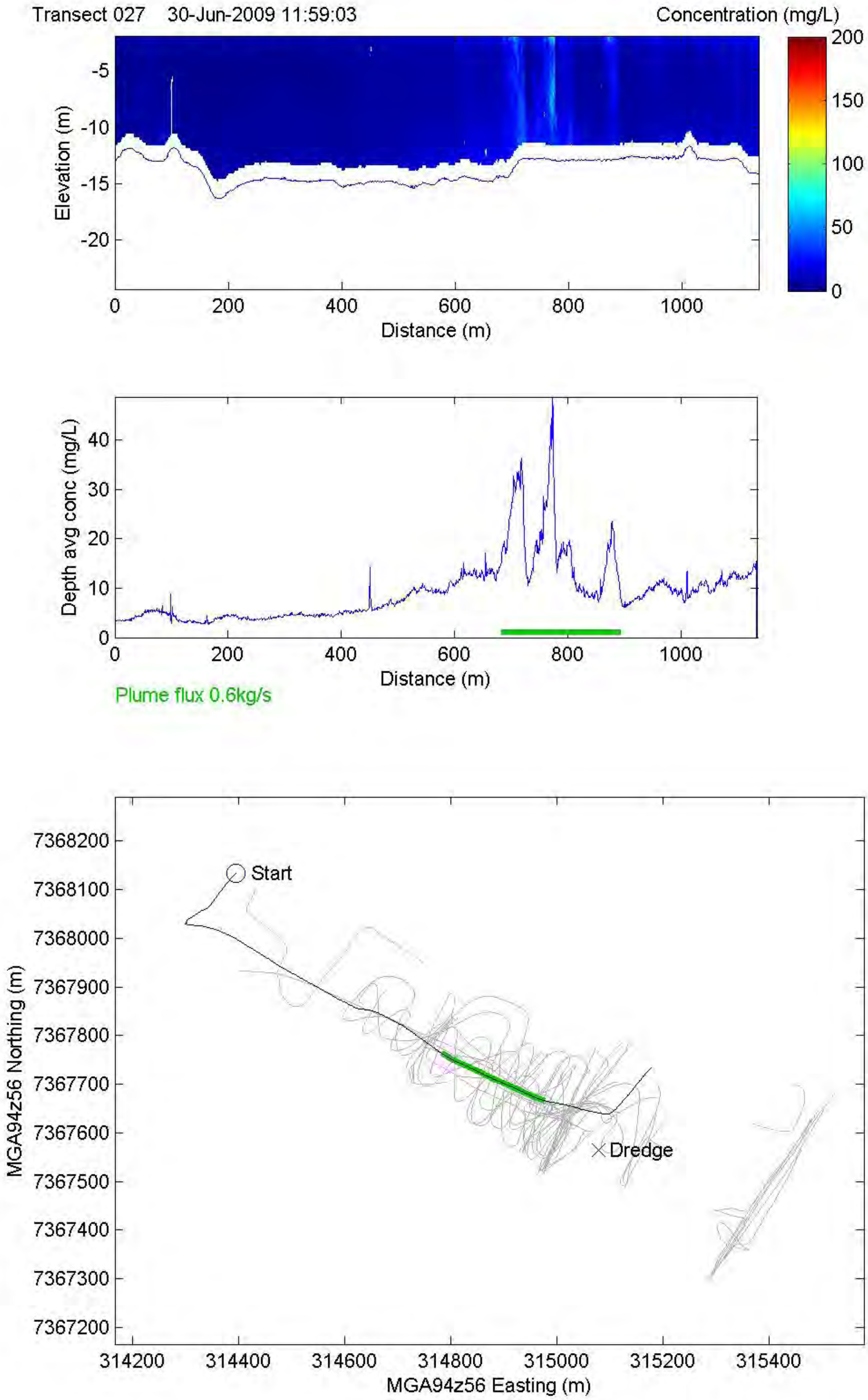


Figure G-31 Transect 027

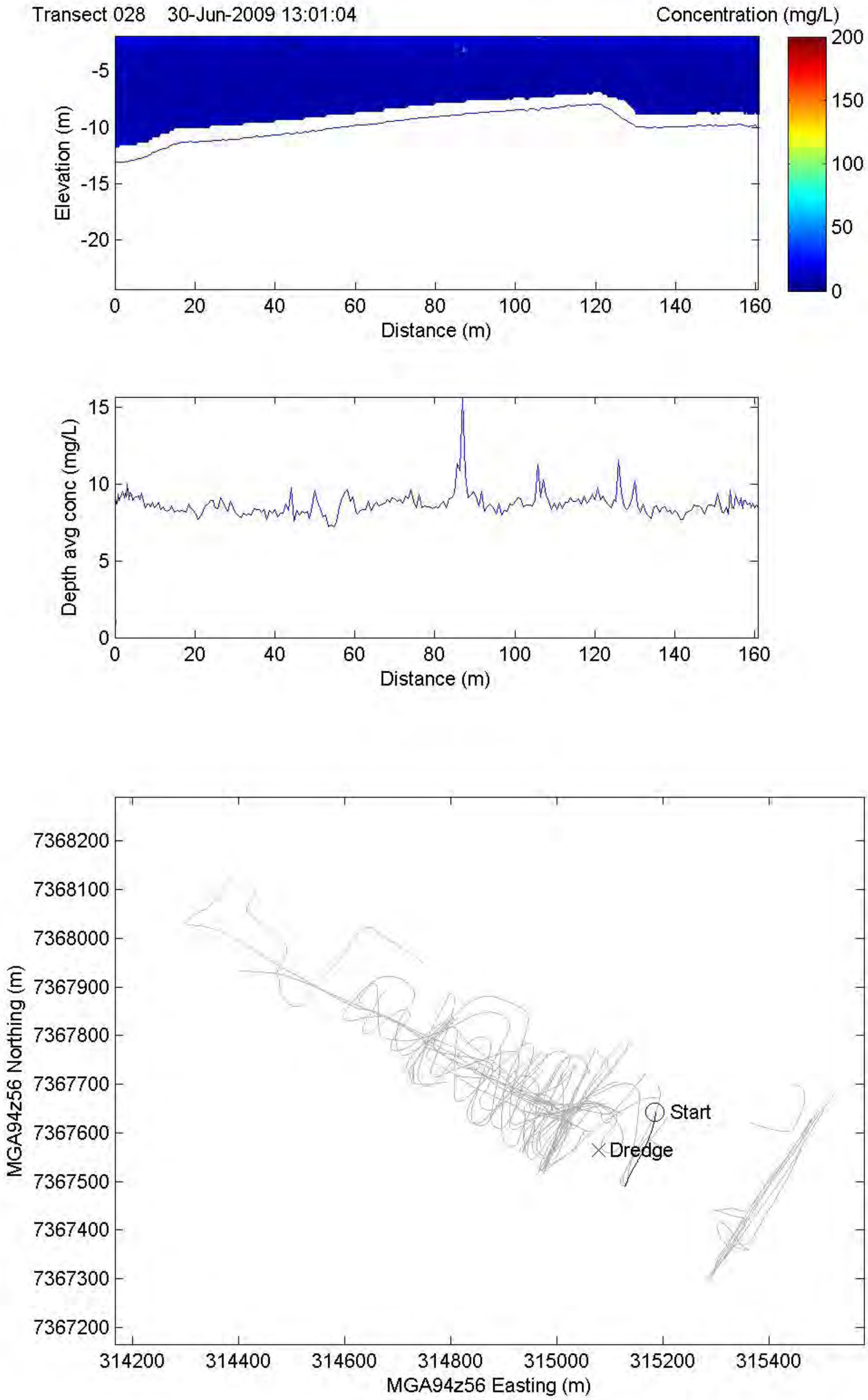


Figure G-32 Transect 028

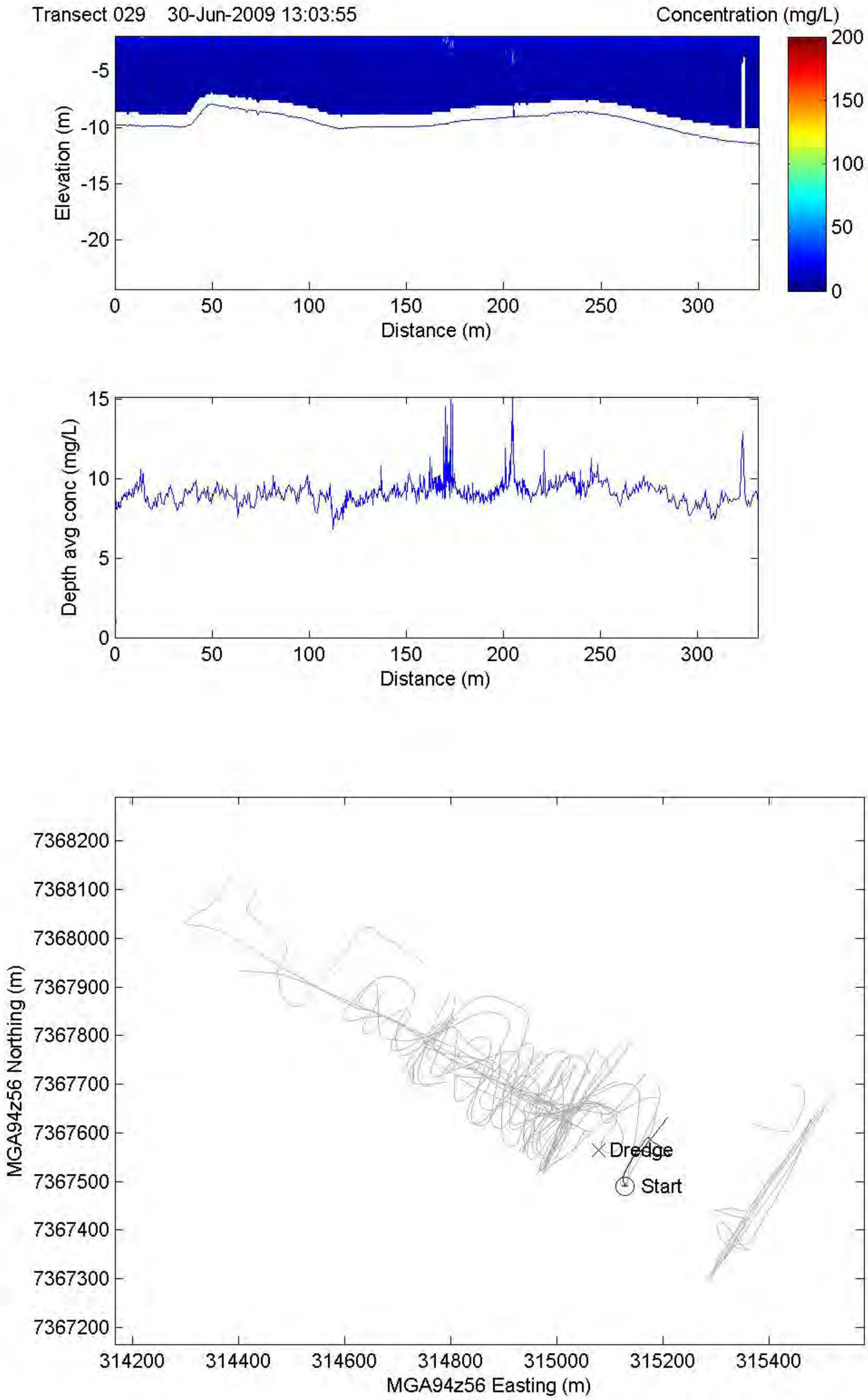


Figure G-33 Transect 029

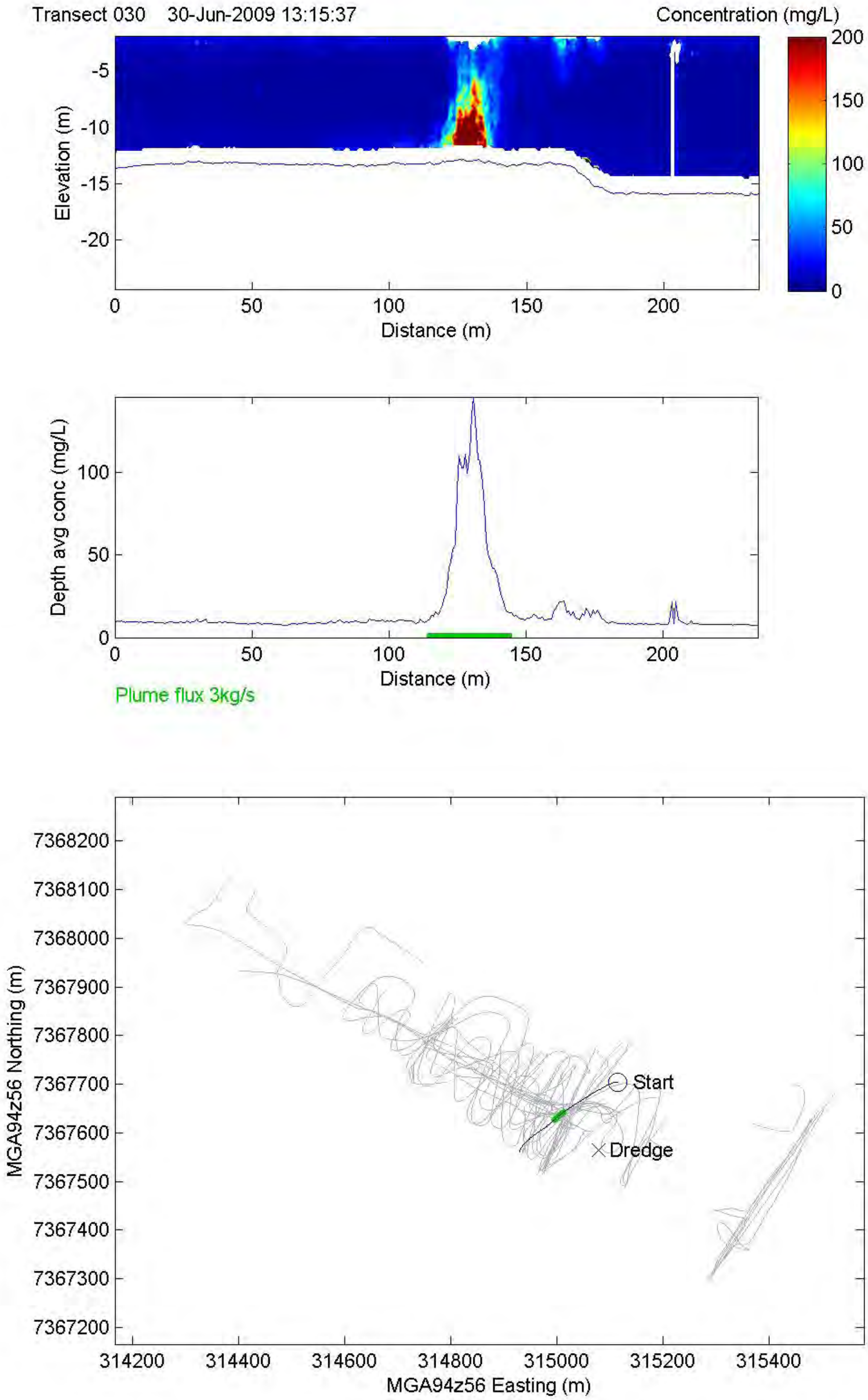


Figure G-34 Transect 030

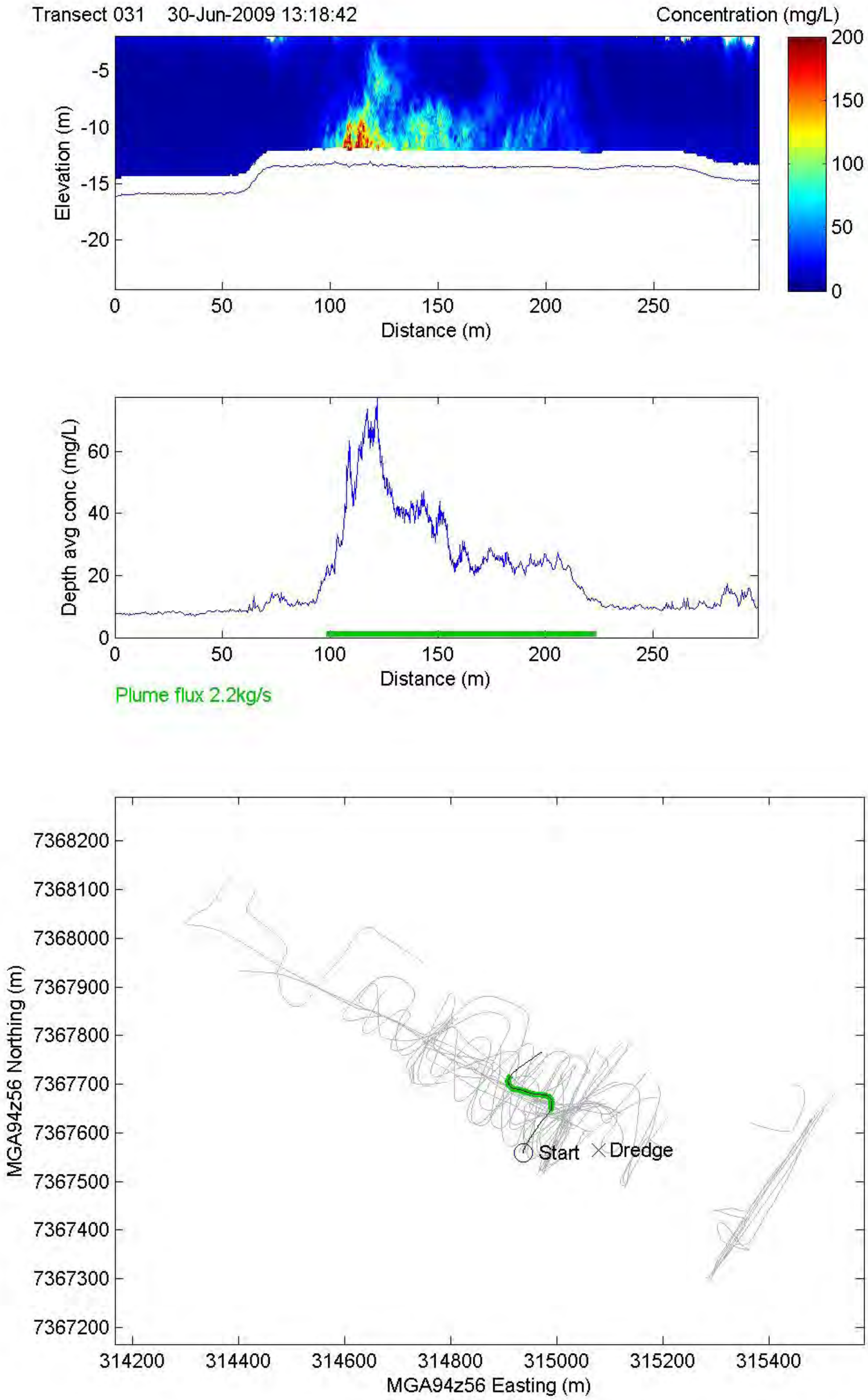


Figure G-35 Transect 031

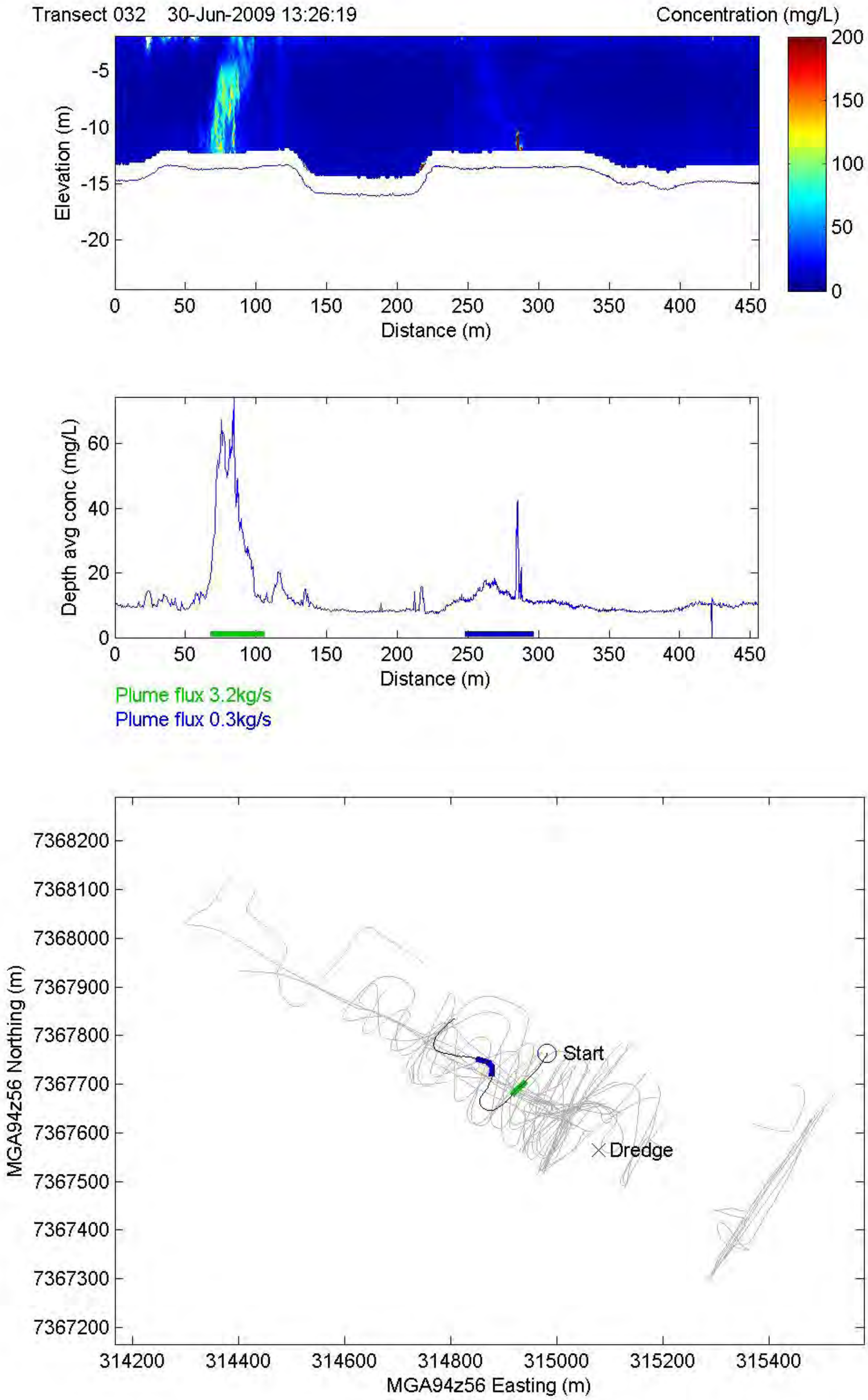


Figure G-36 Transect 032

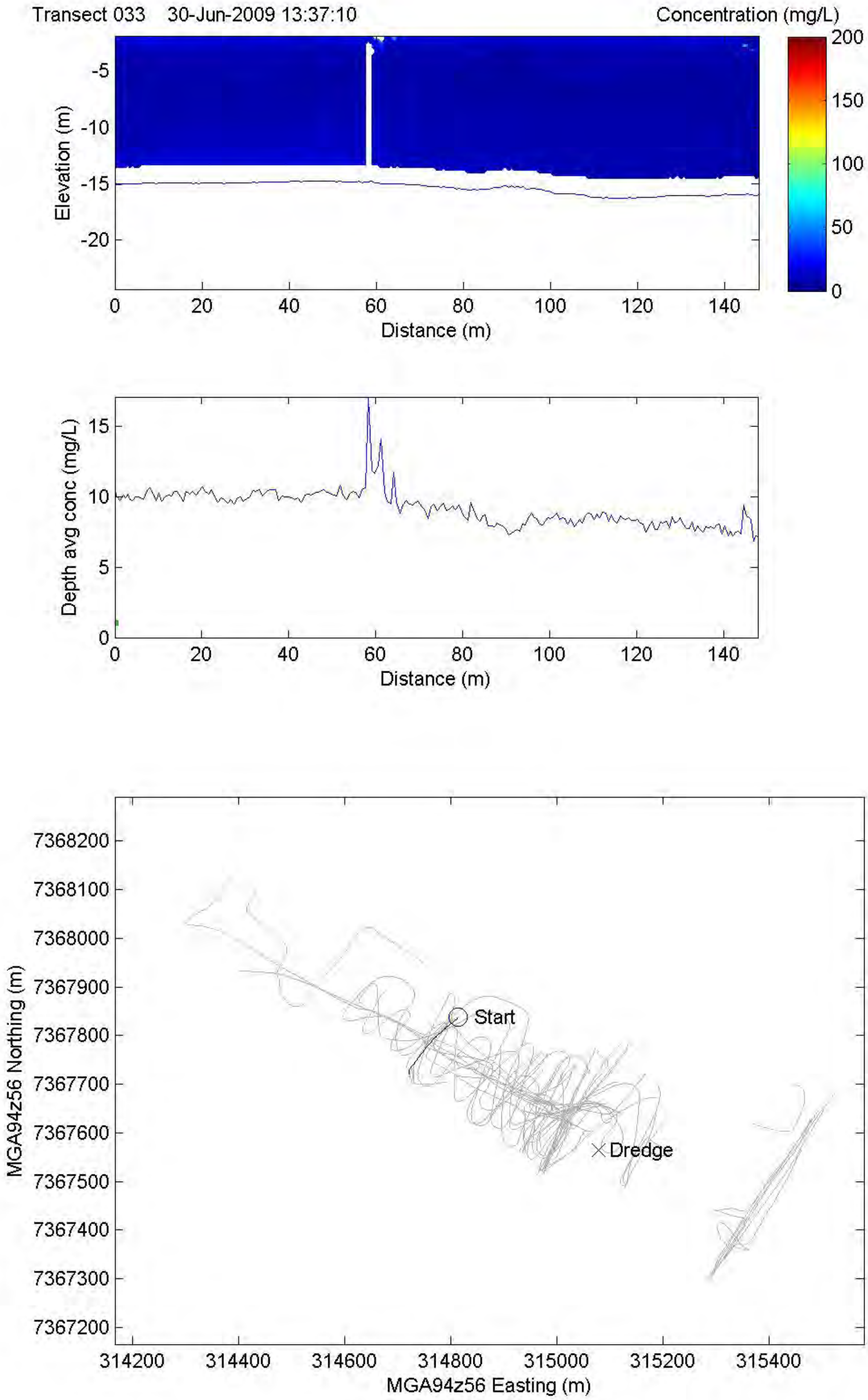


Figure G-37 Transect 033

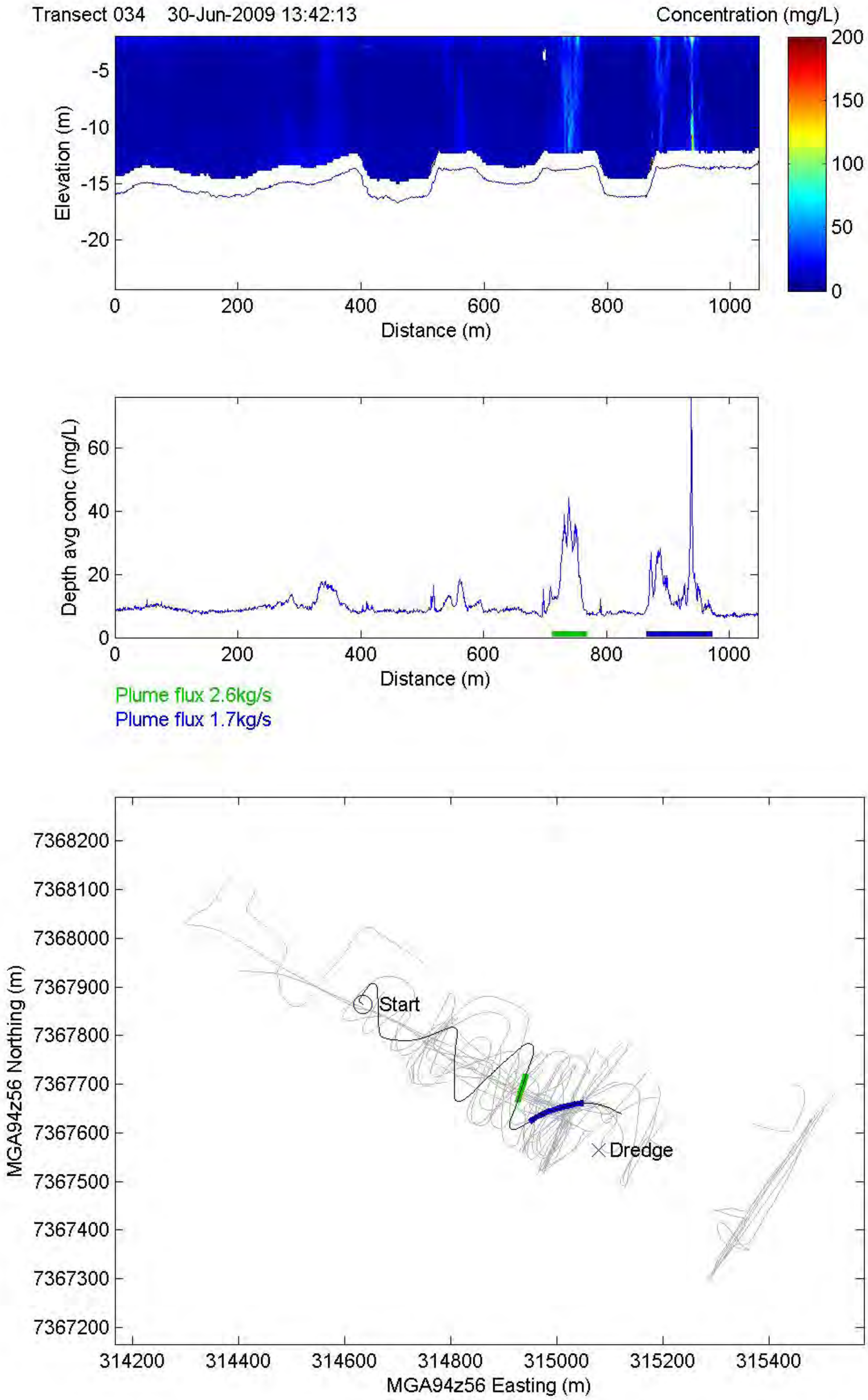


Figure G-38 Transect 034

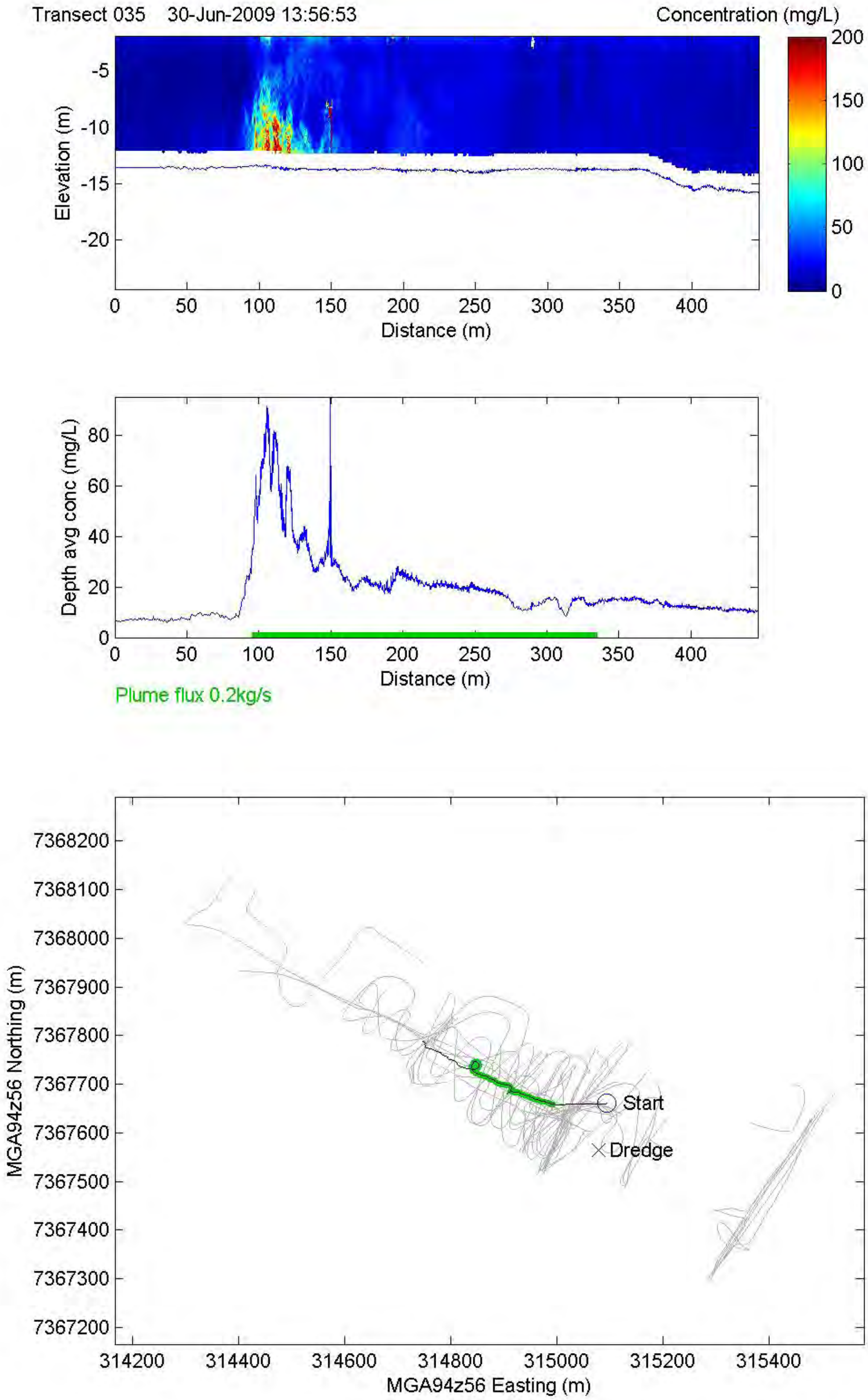


Figure G-39 Transect 035

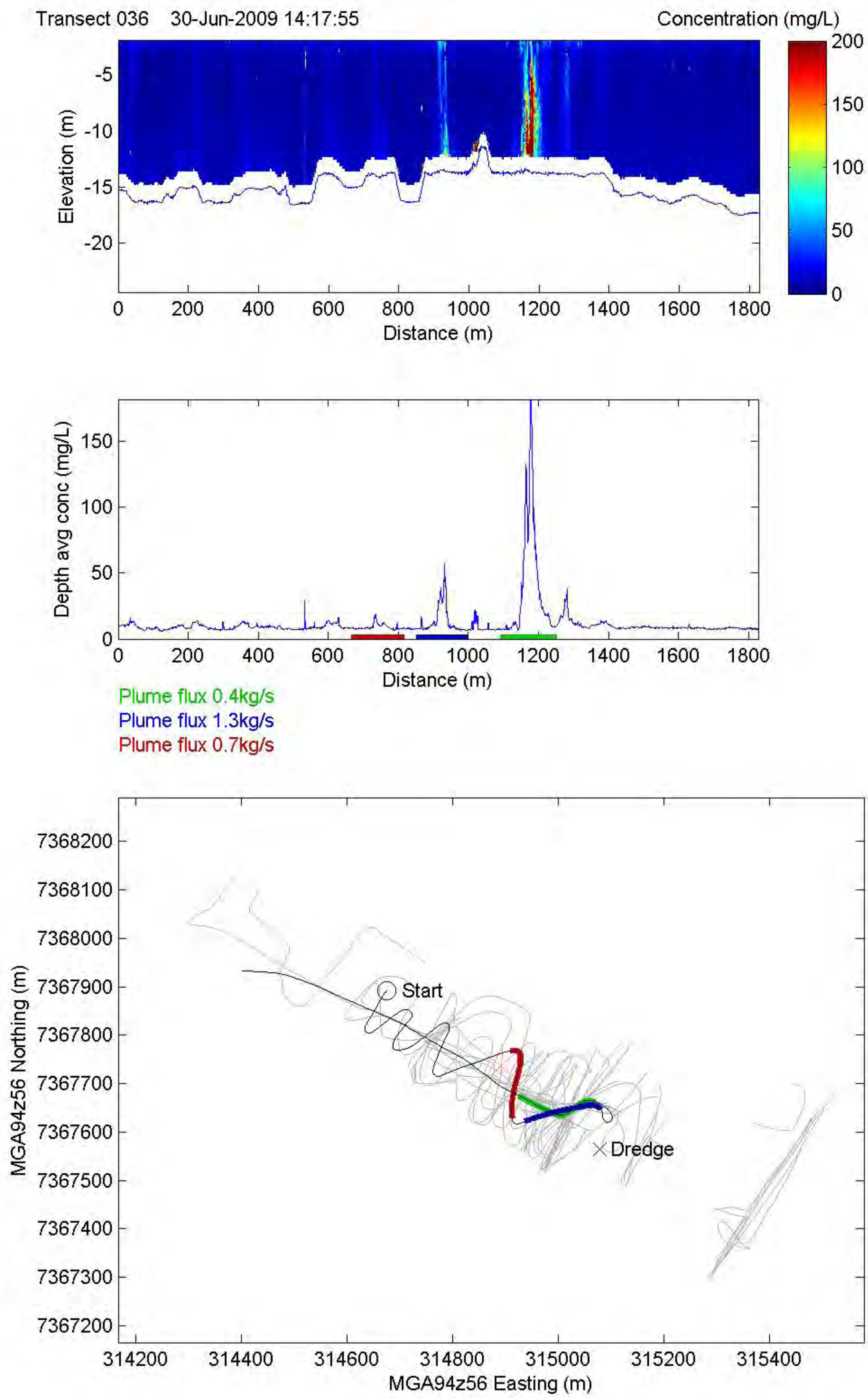


Figure G-40 Transect 036

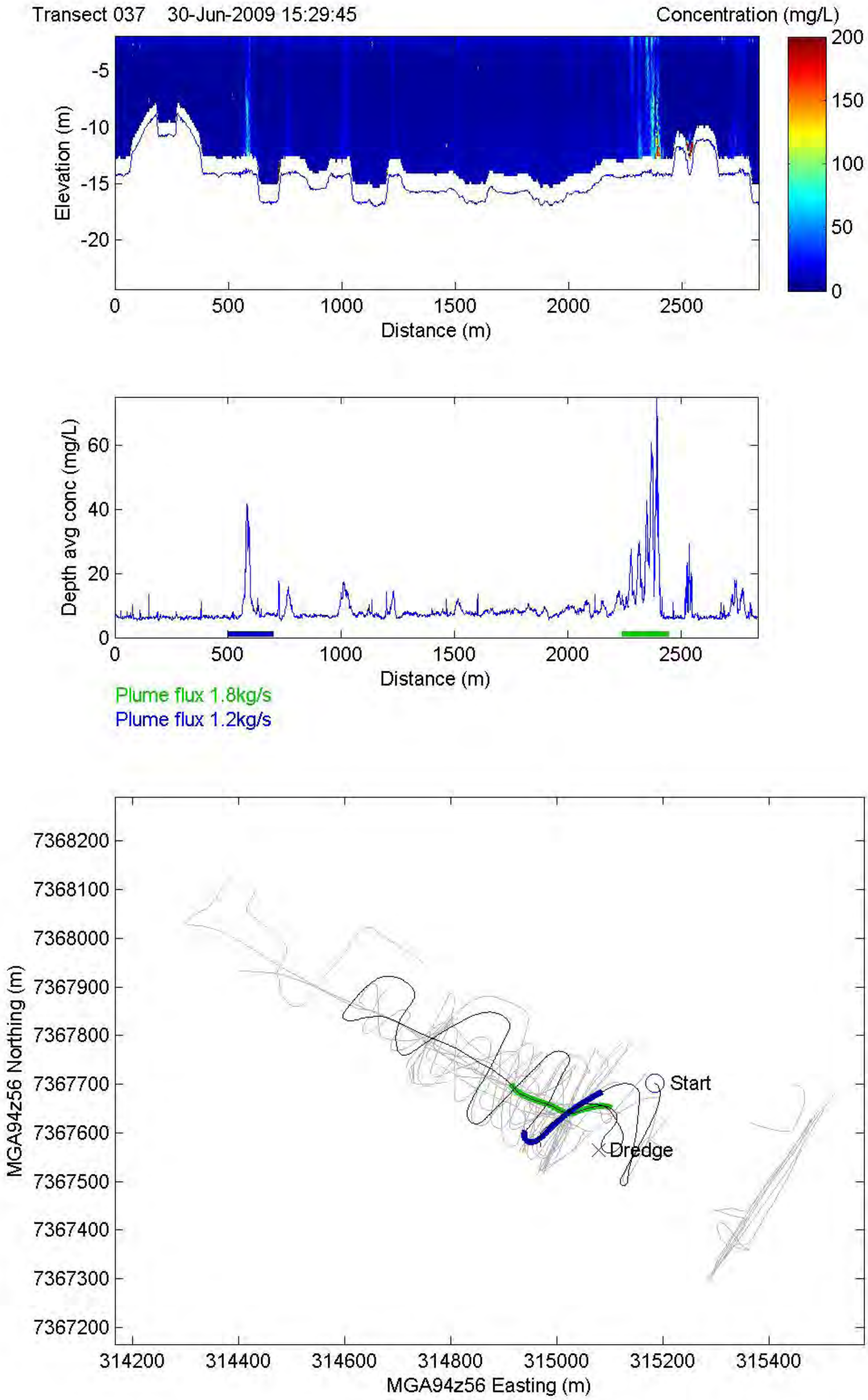


Figure G-41 Transect 037

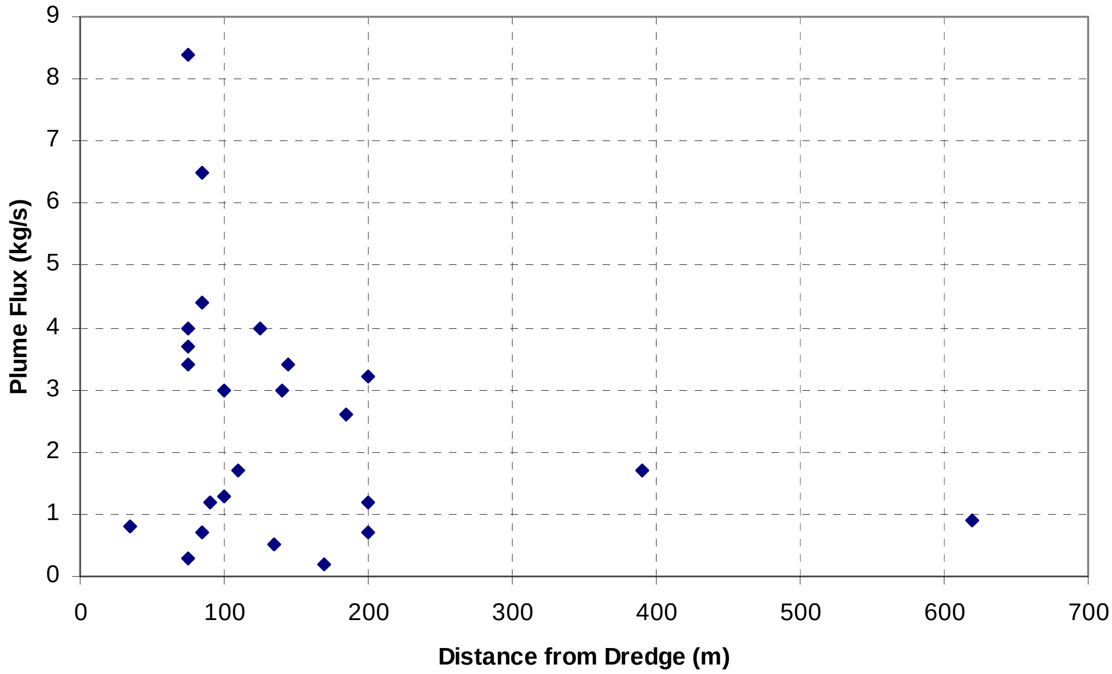


Figure G-42 Plume Flux versus distance from dredge

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