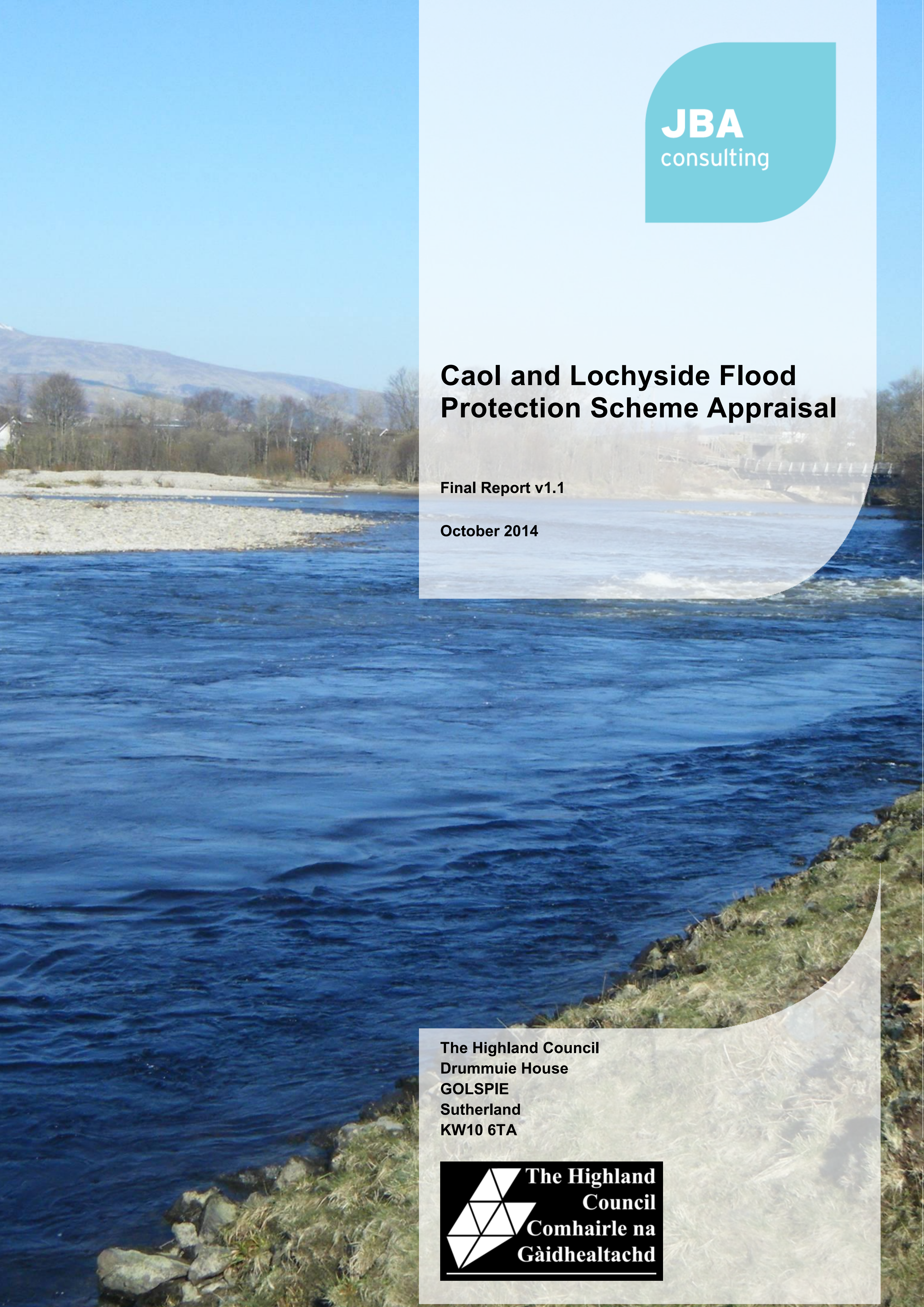

JBA consulting

# Caol and Lochyside Flood Protection Scheme Appraisal

**Final Report v1.1**

**October 2014**

**The Highland Council**
**Drummuie House**
**GOLSPIE**
**Sutherland**
**KW10 6TA**

The Highland Council
Comhairle na Gàidhealtachd

# JBA project manager

Angus Pettit
JBA Consulting
Port Neuk
1 Longcraig Road
South Queensferry
EDINBURGH
EH30 9TD

# Revision history

| Revision Ref / Date Issued | Amendments | Issued to |
|---|---|---|
| Draft report v1.0 / July 2014 | - | Garry Smith |
| Draft report v1.1 / September 2014 | Revisions to economics due to inclusion of threshold level date. | Garry Smith |
| Final report v1.1 / October 2014 | Revision to report structure, additional flood defence option and minor amendments following THC review. | Garry Smith |

# Contract

This report describes work commissioned by Garry Smith, on behalf of The Highland Council, by a letter dated 2 August 2013. Highland Council's representative for the contract was Garry Smith. Angus Pettit, Dan Rogers, Dave Cameron, Jonathan Garrett and Josh Harris of JBA Consulting carried out this work.

Prepared by ............................ Jonathan Garrett BEng MICE

Engineer

Prepared by ............................ David Cameron BSc PhD MCIWEM CWEM CSci

Senior Analyst

Prepared by ..................................................Daniel Rodger BEnvSci, MEng, GradDipGIS

Senior Coastal Engineer

Prepared by ............................ Angus Pettit BSc MSc CEnv MCIWEM C.WEM

Principal Analyst

Reviewed by ............................ Caroline Anderton BSc MSc CEnv MCIWEM C.WEM

Principal Analyst

Reviewed by ............................ David Bassett BSc MSc CEnv MCIWEM C.WEM

Director

JBA consulting

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JBA Consulting has no liability regarding the use of this report except to The Highland Council.

# Acknowledgements

JBA Consulting would like to thank members of The Highland Council team for the provision of data, information and resources to inform the project. We would also like to thank SEPA, and in particular Mark Simpson and Anita Spurway for the provision of river flow data to support the hydrology.

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# Executive summary

The Caol and Lochyside areas of Fort William to the north of the River Lochy confluence with Loch Linnhe have historically been subject to flooding from both tidal and fluvial sources. The last significant flood event occurred in 2005 from a storm surge in Loch Linnhe combined with relatively high flows in the River Lochy.

The Highland Council in response to this historic flooding has commissioned a number of studies to investigate flood risk in this area and to develop an outline Flood Protection Scheme. It is now the intention of The Highland Council to develop this further into a Flood Protection Scheme (FPS) under the Flood Risk Management (Scotland) Act 2009.

JBA Consulting has been commissioned by The Highland Council to aid this development of a FPS for Caol and Lochyside areas of Fort William. JBA has carried out a number of tide-surge studies of Loch Linnhe for SEPA and The Highland Council. The aim of the project is to update this previous analysis to ensure that the most appropriate design levels are used within an updated appraisal.

This aim of the appraisal is to fully revise all tidal, wave and hydrological inputs to identify properties at risk from joint probability flood events from Loch Linnhe (tidal) and the River Lochy (fluvial) and to assess the economic feasibility of a Flood Protection Scheme.

Due to the complexity of river and coastal interactions a SWAN (Simulating Wave Nearshore) model and an ISIS model were developed to represent as closely as possible scenarios for different return periods. Due to uncertainties in the previous modelling survey data, a completely new survey (cross sections) of the River Lochy and the estuary was undertaken for use in the ISIS model.

Flood mapping has been prepared using LiDAR data and based on a number of independent and joint probability model runs (tidal and wave run-up, fluvial, joint probability tide and fluvial). The impacts of climate change have also been consider and mapped for the independent flood mechanisms. Flood mapping suggests that the previous defence alignment (from the 2007 feasibility report) are still applicable although the 200 year flood elevations and extents are now predicted to be larger, with implications for the extent of works required.

The previous analysis considered a Flood Protection Scheme providing protection up to a 100 year event, either with or without an allowance for climate change. Current guidance and best practice suggests that the scheme should aim to be designed to provide a 200 year standard of protection although other standards can be considered if economic.

Flood damages have been derived for two joint probability scenarios: 1) High tide and wave run-up and 2) fluvial and tidal (without waves). The former joint probability scenario has only been applied to the area that would likely to be impacted by a combined tide and wave event (the frontage of Caol back to Kilmalliie Road (B8006) as this wave run-up analysis is not applicable behind the spit that protects the estuary. The latter joint probability scenario assumes a tidal only downstream boundary (without the impact of waves) for the same reason.

Analysis of flood damage to Caol and Lochyside from the fluvial-tide joint probability flood event suggests that the scheme (based on updated costs) is not economically viable. However, the inclusion of the tide-wave joint probability flood event, substantially increases flood damages and makes the proposed scheme economically viable.

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# Abbreviations

2D .................................. Two Dimensional (modelling)
ALTBAR .......................... Mean catchment altitude (m above sea level)
AMAX............................. Annual Maximum
AOD ............................... Above Ordnance Datum
AP .................................. Annual probability
BFIHOST ........................ Base Flow Index estimated from soil type
CFBD ............................. Coastal flood boundary dataset
DEM ............................... Digital Elevation Model
DPLBAR.......................... Index describing catchment size and drainage path configuration
DPSBAR ......................... FEH index of mean drainage path slope
EA .................................. Environment Agency
ESL ................................ Extreme sea-level
FARL.............................. FEH index of flood attenuation due to reservoirs and lakes
FCERM .......................... Flood and Coastal Erosion Risk Management
FEH................................ Flood Estimation Handbook
FPEXT ........................... FEH index describing floodplain extent
FPS ................................ Flood Protection Scheme
GIS................................. Geographical Information System
ISIS ................................ Hydrology and hydraulic modelling software
LiDAR............................. Light Detection And Ranging
mAOD ............................ metres Above Ordnance Datum
NGR ............................... National Grid Reference
OS.................................. Ordnance Survey
PROPWET...................... FEH index of proportion of time that soil is wet
PVc ................................ Present Value Cost
QMED ............................ Median Annual Flood (with return period 2 years)
ReFH.............................. Revitalised Flood Hydrograph method
SAAR ............................. Standard Average Annual Rainfall (mm)
SEPA ............................. Scottish Environment Protection Agency
SPRHOST....................... Standard percentage runoff estimated from soil type
SWAN ............................ Simulating Waves Nearshore
SWL ............................... Still water level
Tp................................... Time to Peak
TSL ................................ Total sea level
UKCP09 .......................... UK climate projections 09

# Definitions

| | |
|---|---|
| **Annual probability** | The probability of a specific flood event in any one year presented as a percentage. For example, the annual probability of a 200 year event (a 1 in 200 chance of the event occurring in a year) is 0.5%. |
| **Appraisal** | A method designed to identify the most sustainable combination of structural and non-structural measures to tackle flooding from rivers, the coast and urban surface water. |
| **Benefit cost analysis** | A financial technique to express the benefits of the project as a ratio of project costs. This will be applied to measures that are classed as “feasible” in the Flood Risk Management Strategy. |
| **Catchment** | A river catchment includes all the land drained by a river and its tributaries |
| **Flood protection** | The protection of an area from inundation of flood water through the use of specifically designed and certified products. |
| **Flood Protection Scheme** | Flood alleviation structures that form a scheme promoted under the Flood Risk Management 2009 Act. |
| **Flood risk** | A measure of the likelihood of flooding occurring |
| **Still water level** | The average sea surface elevation over an area at any instant excluding localised variations due to wave and wave set-up but including tidal elevations and surges. |
| **Montane** | Of, relating to, growing in, or being the biogeographic zone of relatively moist cool upland slopes below timberline dominated by large coniferous trees |
| **One in 200 year flood** | A flood that has the probability of being exceeded on average once every 200 years. Also expressed as a flood which has a 0.5% probability of being exceeded in any year. |
| **Return period** | The flood return period is a measure of the rarity of an event - the longer the return period, the rarer the event. It is the average length in time (usually in years) separating flood events of a similar magnitude. |
| **Whole life cost** | Whole life costing (WLC) takes account of the total cost of an item over its whole life. It includes the cost of maintaining and operating the item and is a mechanism to deliver improved value for money. |

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# 1 Introduction

## 1.1 Background and objectives

JBA Consulting has been commissioned by The Highland Council to provide guidance in the development of a Flood Protection Scheme under the Flood Risk Management (Scotland) Act 2009 for the Caol and Lochyside areas of Fort William. The aim of the report is to update previous analysis of hydrological and coastal inputs, identify properties at risk of flooding from both coastal and fluvial sources, update flood damages and review the previous costs and extents of previously assessed flood mitigation measures. Several studies have been undertaken in the past which have been referenced in this report. The objectives of this report have been achieved by:

- **Review and update of coastal processes and fluvial hydrology** - The update provides extreme sea level results using the 2009 Tide Surge report[1] as a basis. The hydrology review also includes a review and update of the River Lochy, River Lundy and Allt a Mhuillinn flood flows.
- **Review and update of flood level predictions** - The joint probability analyses examined:
    a. Extreme sea level versus wave height
    b. Extreme sea level versus river flow
    c. The worst case scenario combination for the Flood Protection Scheme
- **Review and update of flood mapping** - Fluvial and coastal flood depth maps with and without an allowance for climate change have been generated for the following return periods:
    a. 1:2 year
    b. 1:5 year
    c. 1:10 year
    d. 1:50 year
    e. 1:100 year
    f. 1:200 year
    g. 1:500 year
- **Review and update of the flood damage assessment** - A new flood damage estimate has been derived based on the updated flood maps using guidance from the Scottish Government[2] and the Flood Hazard Research Centre (FHRC) Multi-coloured Manual[3].

The report will provide evidence to support the development of flood protection measures or the scheme.

## 1.2 Report structure

In addition to this introductory chapter, the report includes the following chapters and appendices:

- **Chapter 2 (Flood risk drivers)** reviews the mechanisms of flood risk in the study area and outlines the methodology taken for the study.
- **Chapter 3 (Flood estimation approach)** Describes the derivation of fluvial flood estimates.
- **Chapter 4 (Extreme conditions)** outlines the extreme analysis used to quantify extreme sea-levels, wave conditions and river flows for use in the flood modelling.
- **Chapter 5 (Wave modelling)** describes the methods taken to model wave conditions in Loch Linnhe, which contribute to wave run-up and flood inundation.

[1] (JBA Consulting (February 2009). Tide-Surge Modelling for the Firth of Lorne / Loch Linnhe System – Extreme Sea Level and Modelling Report.
[2] Scottish Government (2012). The Flood Risk Management (Scotland) Act 2009. Flood Protection Schemes – Guidance for Local Authorities. Chapter 5 - Project Appraisal: Assessment of economic, environmental and social impacts
[3] Penning-Rowsell et al., 2013. Flood and Coastal Erosion Risk Management - A Manual for Economic Appraisal

- **Chapter 6 (Flood modelling)** Describes the inputs into the hydraulic model and presents the hydraulic model outputs.
- **Chapter 6 (Worst case outlines)** Shows the joint probability flood outline.
- **Chapter 7 (Cost benefit-analysis)** Provides a cost benefit ratio.
- **Chapter 8 (Conclusions and recommendations)** provides a summary of the project and key recommendations.

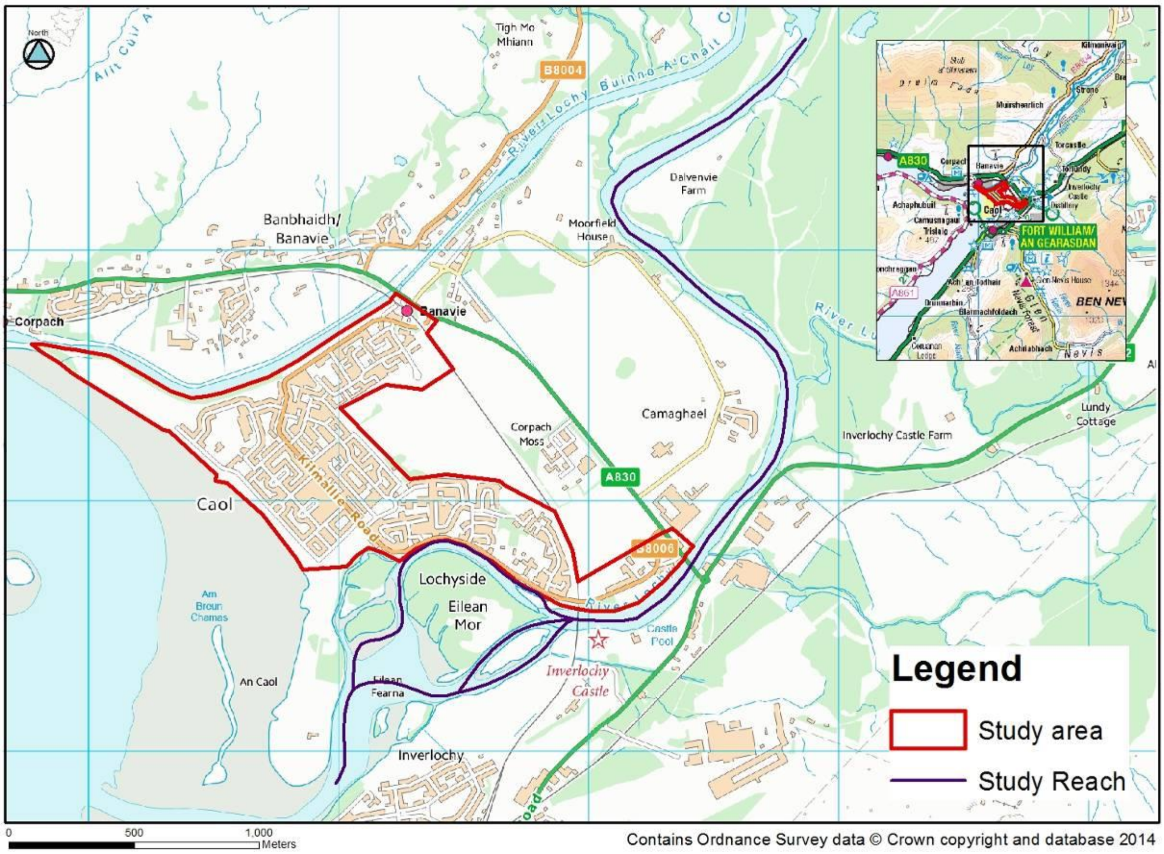
## 1.3 Description of study area and surveyed reach

This project was undertaken for the coastal town of Caol, Western Scotland. Figure 1-1 is a location map of Caol showing its position at the tip of Loch Linnhe.

Figure 1-1: Caol location map (Contains Ordnance Survey data © Crown Copyright and database 2014)


The town of Caol is situated between the River Lochy to the east, the Caledonian Canal to the north and Loch Linnhe to the south and west. The study area is as shown in Figure 1-2 and it extends from the A830 road bridge along the north bank of the River Lochy and along Caol's foreshore to the Caledonian Canal encompassing Caol and excluding the waste water plant.

Figure 1-2: Study area shown in red, extent of river reach shown in purple




## 1.4 Previous reports

The Highland Council have commissioned a number of studies that have investigated flooding in Caol. A summary of these reports is given in Table 1-1 below.

Table 1-1: Previous reports

| Title, author & date | Description |
|---|---|
| Tide-Surge Modelling for the Firth of Lorne / Loch Linnhe System – Extreme Sea Level and Modelling Report (JBA Consulting, February 2009) | Numerical modelling of tide – surge and derivation of extreme sea levels for various points around the Firth of Lorne and Loch Linnhe |
| Fort William Flood Study, Caol & Lochyside – Feasibility Report (Draft) (Scott Wilson, October 2007) | Analysis of extreme sea levels, joint probability analysis, flood level assessment, flood mapping, flood damage assessment, outline FPS design, desktop GI, initial environmental screening, costing of FPS, and economic assessment |
| River Lochy Flooding, Fort William and Caol, Flood Risk Mapping / Pre-Feasibility Study (Mott Macdonald, September 2005) | Fluvial modelling, preliminary analysis of extreme sea levels, indicative flood mapping, & initial economic assessment |
| Fort William Flood Prevention Scheme, Surface Water Drainage for New and Future Housing Developments at Caol / Lochyside (Mott Macdonald, March 1993) | Examines the interaction between surface water drainage from Caol / Lochyside / Blar Mhor and fluvial flooding in the River Lochy |
| Fort William Flood Study, Review of 1992 Flood (Mott Macdonald, September 1992) | Review of flooding against previous work and updates to river modelling completed previously |

| Title, author & date | Description |
|---|---|
| Fort William Flood Study, Review of Flooding at Bentalla Nursery, Banavie (Mott Macdonald, May 1992) | Review of flooding and investigation of possible solutions |
| Fort William Flood Study, Flood Alleviation Measures for Ben Nevis Distillery (Mott Macdonald, April 1992) | Determination of solutions for flood alleviation |
| Fort William Flood Study (Mott Macdonald, June 1991) | Fluvial modelling of the River Lochy, investigation of flood alleviation options, investigation of flooding at Caol and Blar Mhor |
| Fort William Flood Study, Report of Initial Investigations (Mott Macdonald, February 1990) | Summary of previous flooding, initial hydrological analysis, recommendation for further study |

This report aims to update the key underlying drivers of flood risk and to revise the modelling undertaken to determine design flood levels, review flood options and to assess the economic viability of the option choices.

# 2 Flood risk drivers

## 2.1 Historic flood events

Caol has witnessed flooding in the past from both the coast and the River Lochy. Table 2-1 lists historic flood events affecting Caol from 1957 to the present day. Previous assessments have followed on from high river flows on the River Lochy, although the most recent flood risk was from high sea levels and wave overtopping in 2005. The table below illustrates the complex interaction between coastal and fluvial processes acting in Caol.

Table 2-1: Recorded flood events

| Date | Reference | Conditions | Flooding extent in study area |
|---|---|---|---|
| 2005 | The Highland Council | High sea level (4.44mAOD). River Lochy flow of between 400m$^3$/s and 500m$^3$/s. | Water level above grass bank between beach and road resulting in flooding to approximately 20 properties, gardens and a number of vehicles |
| 1992 | Highland Regional Council, Fort William Flood Study Report (September 1992) | High river flows (previously estimated to be 1,525m$^3$/s) and heavy rainfall (105mm in 24hrs) | Reached the road level at Lochyside and Mossfield (recorded level of 3.71mAOD) but did not flood properties |
| 1989 | Highland Regional Council, Fort William Flood Study Report (February 1990) | High river flows (previously estimated to be 1,400m$^3$/s) and heavy rainfall (80mm in 24hrs) | 23 houses at the rear of Caol – caused by surface water drainage infrastructure being overwhelmed. Flooding reported on the B8006 and reportedly "…rose to within 50mm of flooding houses in Mossfield Drive" (however 1992 report (below) reports recorded levels of 3.65mAOD) |
| 1981/2 | Highland Regional Council, Fort William Flood Study Report (February 1990) | No records | Flooding reported in the Mossfield Drive area – no further details given |
| 1974 | Highland Regional Council, Fort William Flood Study Report (February 1990) | High tides and high winds | Flooding reported on the B8006 and reportedly "…reached the doors of houses" in Mossfield area. Flooding may have also affected houses in Caol (no written records found) |
| 1957 | SEPA Interview with long term resident of Corpach | High tides and high winds | Anecdotal record of flooding, but may have caused some flooding in Caol |

## 2.2 Mechanisms of flooding

Caol is located on the northern shoreline of Loch Linnhe, a sea loch situated on the west coast of Scotland, and adjacent to the River Lochy. Flooding within Caol can occur due to four processes; from extreme sea-levels surging into the Loch, from wind-generated waves breaking over the foreshore, from river flows exceeding the bank level of the River Lochy and inundating the surrounding floodplain and finally from surface water. Each process could occur in isolation or, during some cases, occur simultaneously to produce extreme flooding. The coastal and fluvial drivers for flood risk are described below.

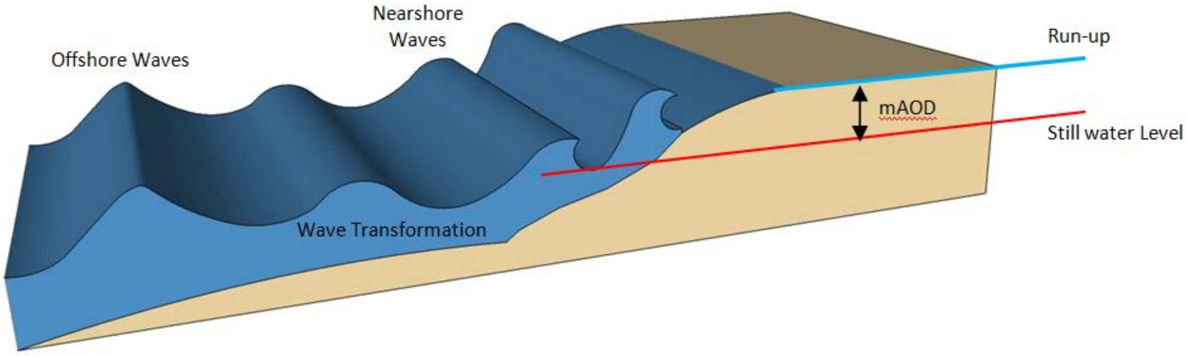
### 2.2.1 Coastal processes

Loch Linnhe is connected to the Atlantic Ocean via the Firth of Lorne to the south and the Sound of Mull to the south-west. The Loch is approximately 50km long and has a funnel shaped form. To the south, between Port Appin and Duror, the width of the loch spans up to 7km, while north of Corran the width reduces from less than 2km to approximately 1km adjacent to Fort William.

The geometry of Loch Linnhe is believed to have a major influence on the local drivers for coastal inundation. The Loch is protected from large open sea waves propagating towards Caol, thus reducing the potential for high wave overtopping. The funnel like shape of the Loch acts to converge storm surges leading to increasing elevations upstream. The long straight water body of the Loch, results in a long fetch, which can 'push' water further into the channel through a process known as wind setup, and can produce locally generated wind waves that can exacerbate flood risk at Caol, or other communities within the northern Loch. Finally, flooding can be observed at a distance inland, even if there is not an overland connection; the mechanism for this flooding is thought to be the penetration of sea water into unflapped storm water drainage systems.

A second aspect of coastal flood risk is due to wave run-up. Wave run-up can occur when wind-generated waves propagate to a shoreline, break over the foreshore and run up and into the community. As this occurs, the waves have the potential to cause damage to any infrastructure located behind the foreshore, either through scour, inundation or high flows. Wave run-up is a complex process controlled by the state of the sea (water depth and wave properties) and the geometry of the beach and foreshore, as shown in Figure 2-1. It is often the case that wave run-up can lead to inundation above the still-water level, and can reach an elevation higher than the height of the wave. For example, the maximum wave run-up during a sea-level of two metres and a wave height of one metre can exceed three metres.

Figure 2-1: Components of wave run-up

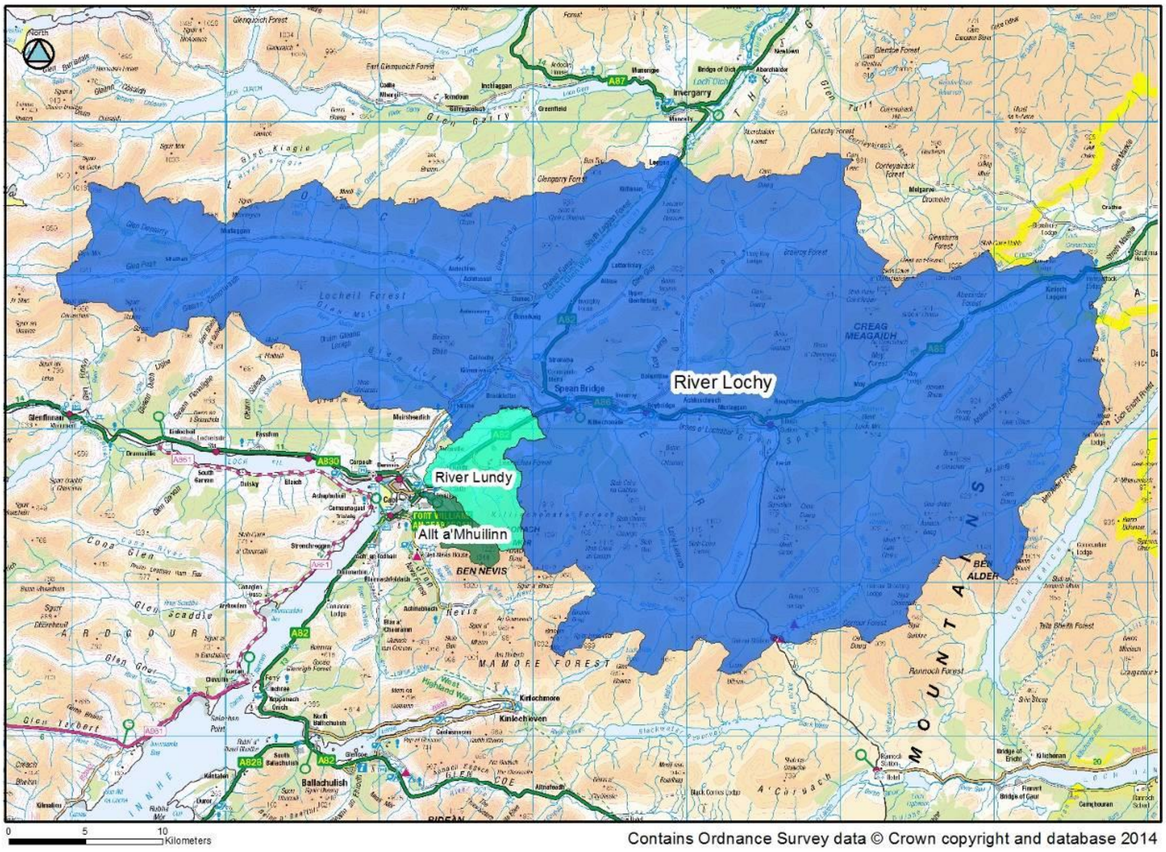



### 2.2.2 Hydrologic processes

The settlement of Caol lies at the base of three river catchments; the River Lochy, the River Lundy and the Allt a' Mhuilinn catchment. The extents of these catchments are shown in Figure 2-2. The Lochy is by far the largest catchment covering an area of 1264km$^2$ compared to an area of 37km$^2$ and 11km$^2$ for the River Lundy and Allt a' Mhuilinn respectively. The Lochy catchment is mainly rough grazing, montane habitats and moorland with some forestation. The catchment contains four large lochs which are controlled by 3 dams for hydropower generation. The upper catchment topography is steep and mountainous with a maximum elevation of 987mAOD. The bedrock geology is predominantly impermeable bedrock with approximately 50% coverage of superficial deposits.

The Caledonian Canal lies to the north of Caol and connects the Scottish east coast at Inverness with the west coast at Corpach. It was constructed in the early nineteenth century.

Figure 2-2: Hydrological catchment extents




### 2.2.3 Surface water

Surface water flooding is a risk to Caol as the area is naturally in a hollow between the raised beach front and the surrounding land. The risks from surface water flooding were reviewed by the 2007 Fort William Flood Study and have not been further assessed for the purposes of this assessment.

It should be noted that SEPA have recently released surface water flood maps that are available on line[4]. These show that there are isolated areas within the site where surface water flooding could pond during flooding or tide locking of drainage outfalls. This information should be reviewed further at the next stage of the analysis to ensure that mitigation measures can be designed as part of the FPS.

## 2.3 Discussion on geomorphology

The Lochy estuary is geomorphologically active with gradually moving channels and bars over time. Based on a review of past maps the estuary has changed over time in response to changing flow and tidal conditions.

A review of old maps[5] suggests that over the last 150 years the overall location of the channel upstream of the weir and railway bridge has not changed significantly and has been relatively stable. Below the bridge and weir however, the channels have moved in response to variable flows and tidal conditions within this estuary.

Currently the River Lochy splits into three channels downstream of the Rail Bridge. The northwest channel flows adjacent to Caol. There is a central, minor channel, beginning at the weir that flows in a south westerly direction. Finally the Lochy channel represents the main channel which takes the majority of the flow from the weir under normal flow conditions to the south, immediately joined by the outflow from the Alcan power station as shown in Figure 2-3.

[4] http://map.sepa.org.uk/floodmap/map.htm
[5] http://maps.nls.uk/

The northwest channel is very susceptible to deposition and a large gravel bar can be seen across the entrance to the channel. Deposition is also occurring to a lesser extent in the central channel.

Figure 2-4 has been produced by digitising maps from 1939, 1955-1961 and 2005. Although the older maps cannot be relied on to give a truly accurate bank location they none the less provide a good indication of the channel location and how it has changed over time.

Figure 2-3: Aerial view of channel split downstream of foot and rail bridge


Figure 2-4: Erosion and deposition in channel from 1939 to present

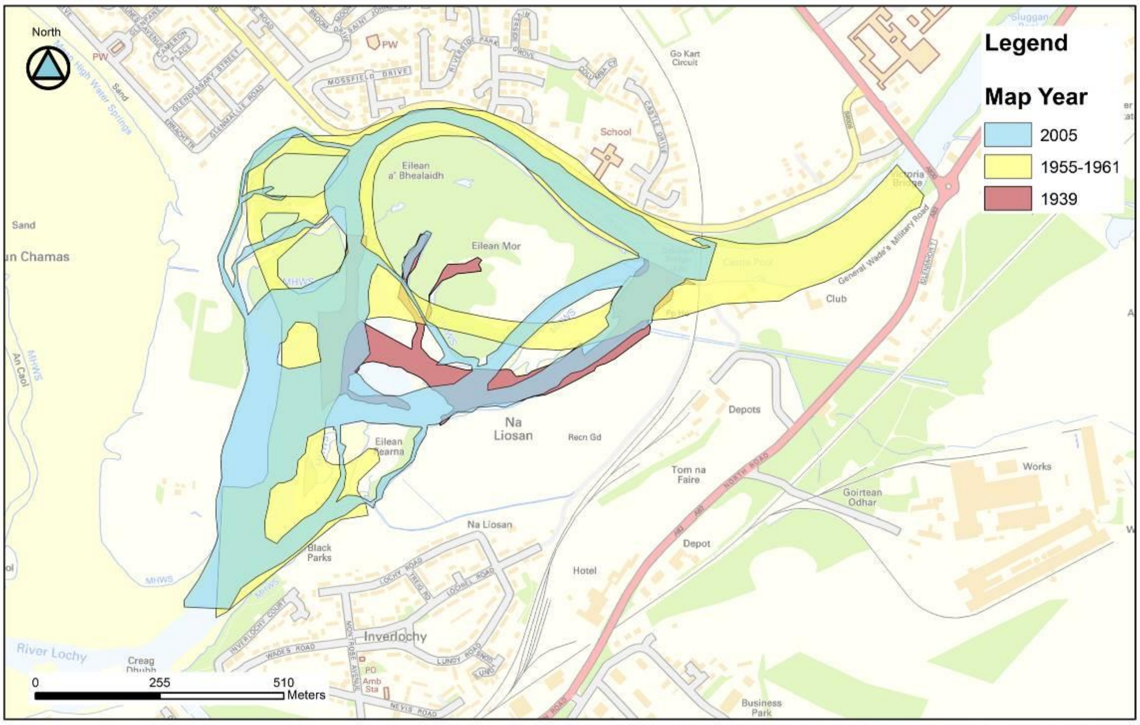


Figure 2-4 above shows that the central channel formed after 1961. It also shows that the channel has migrated north over time and has in 2005 returned to its location from 1939. The spit of land separating the estuary from the sea has been eroded on its eastern side but its alignment is relatively stable.

The above analysis illustrates the long term changes occurring within the channel and estuary. Whilst these changes are to be anticipated and are a natural process, there may be a number of anthropogenic drivers for these changes including:

- Presence and gradual erosion of the weir
- Presence of the Alcan outfall that enters the Lochy downstream of the weir
- Presence of waste water treatment works on spit
- Bridge crossings

Whilst is it difficult to anticipate future changes to the layout of channels and the above influences, the channels appear to generally be constrained and only reworking mobile bars within the wider estuary extents. Despite this, there is the possibility that changes to the geometry of the channels could increase flood levels in certain locations over the long term.

Whether this is occurring, and if there is any medium term net aggregation or deposition along the line of defences proposed is uncertain and can only be validated through long term monitoring. The baseline survey carried out for this project can of course be used as a first baseline against which to compare changes in the future.

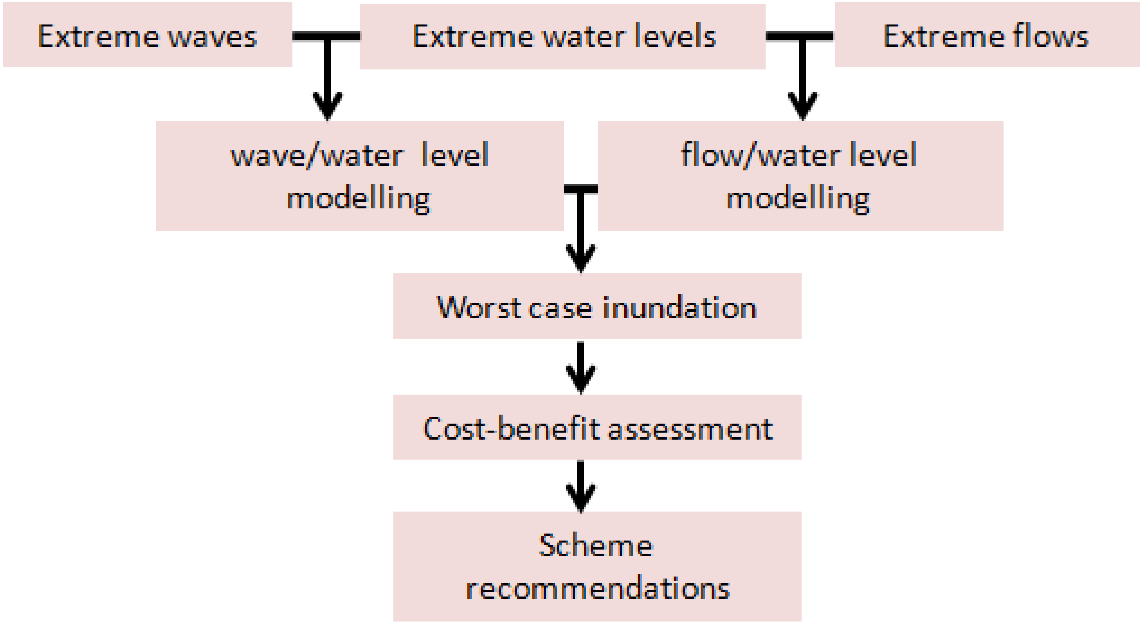
For design purposes, we recommend that a suitable freeboard is included within the design, together with the correct design of defences to counter future possible erosion and seepage beneath flood defences.

## 2.4 Methodology

In order to update the flood inundation due to either coastal or fluvial flooding the following steps have been undertaken, as shown in Figure 2-5:

- **Identify extreme conditions:** The extreme still-water level (SWL), wave/wind conditions and flows have been identified or calculated for Caol.
- **Undertake joint probability assessments:** The potential for extreme water levels, waves or river flows to occur simultaneously has been assessed using a joint probability assessment. This has been undertaken with respect to extreme sea-level vs. river flow and extreme sea-level vs. wave height.
- **Calculation of extreme conditions:** The worst case coastal and fluvial conditions have been calculated for Caol. This has included wave, hydrological and hydraulic modelling for a range of return periods and joint probability conditions.
- **Review and update flood mapping:** The flood extent resulting from the worst-case coastal and fluvial inundation has been mapped to identify the areas exposed to a flood risk.
- **Review and update flood damages and economic appraisal:** Current guidance by the Scottish Government indicates that all proposed schemes, must undertake a benefit-cost analysis to justify the costs and identify the most appropriate option. The benefits are calculated based on the present value of damages (PVd) avoided for the life of the project. If present value capital and maintenance costs (PVc) are exceeded by the benefits then the scheme is cost effective.

Figure 2-5: Flow diagram outlining the steps undertaken in this study




## 2.5 Available data

A range of data were used in the development of numerical models, as described below:

- **Extreme wave information:** which was estimated based on design wind speeds for the Loch, using wave-growth formulations outlined in the industry standard 'Revetment Systems against Wave Attack: A Design Manual'[6]. This method has been used as the Loch is not exposed to ocean waves, but are widely adopted wave conditions for enclosed lochs, lakes or water bodies in the UK. The approach requires extreme wind conditions for the Loch, which have been adopted from the 'Floods and Reservoir Safety Manual'[7].
- **Extreme sea-level information:** which are estimates of the level that the sea is expected to reach during extreme storm events (ranging between 1:1 year to 1:1,000 year return period events). These data have been adopted from the Environment Agency (EA) Coastal Flood Boundary Dataset (CFBD)[8]. These extreme SWL estimates are based on the combination of the underlying astronomical tide and the passage of a storm surge (but not including wave action). The CFBD dataset can be accessed in a geographical information system (GIS) format that includes the sea-level estimates for points along a 2km chainage.
- **Extreme flow information:** The Flood Estimation Handbook (FEH) was used to generate fluvial flood hydrographs. When these flows are inputted in a hydrological model a flood level is derived. These flood levels are used to estimate flood extents and required flood defence heights.
- **Tide and surge data:** which are based on a tide gauge located at Corpach. This gauge has been operating since 2002 with sea-levels supplied as 15 minute total sea-level (TSL) data[9]. For each time step the surge at the gauge can be calculated by subtracting the astronomical tide from the TSL. The gauge is positioned adjacent to the Corpach Basin, west of the British Waterways Office.
- **Ground elevation data:** a Digital Elevation Model (DEM) with a 1m spatial resolution was used, which has been based on LIDAR data provided by The Highland Council.

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[6] McConnell, K., 1998, Revetment Systems against Wave Attack: A Design Manual. Thomas Telford, London.

[7] ICE, 1996, Floods and Reservoir Safety. 3rd Edition. Thomas Telford, London.

[8] Environment Agency (2011), 'Coastal flood boundary conditions for UK mainland and island's, Project: SC060064/TR2: Design sea-levels. Environment Agency, Feb 2011.

[9] Total sea-level is the combination of the underlying astronomical tide and any surge that has occurred. It is the sea level that actually occurs on any given day.

# 3 Flood Estimation Approach

## 3.1 Flood Estimation Approach

In order to provide a comprehensive assessment of flood risk, both fluvial flood flows and tidal flood levels were derived for a variety of return period floods (or annual probabilities as shown in Table 3-1). A joint probability analysis was then conducted and a combination of peak flow and tidal events used as input to the hydraulic model.

Table 3-1: Annual probability and associated return period

| Annual Probability (%) | Return period (years) |
| --- | --- |
| 50 | 2 |
| 20 | 5 |
| 10 | 10 |
| 4 | 25 |
| 2 | 50 |
| 1 | 100 |
| 0.5 | 200 |
| 0.2 | 500 |

## 3.2 Design Peak Fluvial Flows

Important inputs into flood risk assessment are the analysis of historic floods (where data are available), and estimation of flood flows for a range of annual probabilities or 'design' events. Flood estimates for catchments of this size and type are undertaken using the Flood Estimation Handbook (FEH). The FEH offers three methods for analysing design flood flows: the Statistical, the Rainfall Runoff, and hybrid methods. The Statistical method combines estimation of the median annual maximum flood (QMED) at the subject site with a growth curve, derived from one of three methods; (a) a pooling group of gauged catchments that are considered hydrologically similar to the subject site, (b) through single site analysis of a nearby gauge, or (c) a combination of the two through the use of an enhanced pooling group. The Rainfall Runoff method combines design rainfall with a unit hydrograph derived for the subject site. Hybrid methods involve a combination of the two. Both the Statistical and Rainfall Runoff procedures require the derivation of catchment descriptors. For this study these were abstracted digitally using the FEH CD ROM v3 (Table 3-2). The Rainfall Runoff method has been revised (as the Revitalised FEH method, ReFH), but ReFH has not yet been adopted in Scotland.

Table 3-2: FEH CD-ROM Catchment descriptors for the Lochy, Allt a Mhuillin and River Lundy

| Descriptor | Lochy at Camisky | Allt a Mhuillin | River Lundy |
| --- | --- | --- | --- |
| AREA ($km^2$) | 1264.46 | 10.87 | 37.12 |
| ALTBAR (mAOD) | 443 | 593 | 285 |
| BFIHOST | 0.386 | 0.437 | 0.393 |
| DPLBAR (km) | 36.1 | 4.89 | 7.3 |
| DPSBAR (m/km) | 242.8 | 395.1 | 203.2 |
| FARL | 0.778 | 0.958 | 0.992 |
| FPEXT | 0.0414 | 0.0252 | 0.0751 |
| FPDBAR | 0.933 | 0.601 | 1.276 |
| FPLOC | 0.923 | 0.386 | 0.614 |
| PROPWET | 0.83 | 0.81 | 0.81 |
| SAAR (mm) | 2191 | 2760 | 2170 |
| SAAR4170 (mm) | 2151 | 2692 | 1981 |
| SPRHOST | 51.11 | 43.47 | 46.51 |
| URBEXT1990 | 0.0003 | 0.0014 | 0.0015 |
| URBEXT2000 | 0.0001 | 0.0006 | 0.0005 |

Flood estimates were calculated for the three main watercourses:

1. The Lochy (at Camisky gauging station). The Lochy is artificially influenced through hydropower generation and catchment transfer. As such, pooling group analysis (which is based around natural catchments) is unlikely to produce realistic flood estimates for this site. Single site analysis of the 34 year Annual Maximum (AMAX) flow series at the Camisky gauge was therefore used as the primary source of data.
2. The River Lundy (at the Lochy confluence). This is an ungauged, rural site and the pooling group approach is most suitable.
3. The Allt a Mhuillin (at the Lochy confluence). Again, this is an ungauged, rural site and the pooling group approach is most suitable.

In each case, the Rainfall Runoff method was also used for comparison. ReFH was also used for reference purposes only.

The flood estimates are shown in Table 3-3. From this table, it can be seen that the Statistical method estimates are not as high as the Rainfall Runoff method estimates. For example, for the Lochy at Camisky, the 1:200 year flood is estimated to be about 2078 $m^3/s$ using single site analysis, but 3793 $m^3/s$ to 4614 $m^3/s$ using the Rainfall Runoff method and ReFH, respectively. This is a common finding in flood studies involving large rural catchments.

Table 3-3: Flood estimates: comparison of methods

| | Lochy at Camisky | | | | Allt a Mhullin | | | River Lundy | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Annual Probability (AP) (%) | Statistical (single site using standard SEPA annual ratings) | Statistical (single site using single rating 27MP1) | Rainfall-runoff | ReFH | Statistical (pooling group) | Rainfall-runoff | ReFH | Statistical (pooling group) | Rainfall-runoff | ReFH |
| 50 | 741 | 742 | 1040 | 1424 | 18 | 18 | 23 | 52 | 42 | 59 |
| 20 | 989 | 998 | 1471 | 1814 | 23 | 27 | 30 | 67 | 63 | 77 |
| 10 | 1163 | 1172 | 1744 | 2116 | 26 | 33 | 35 | 78 | 75 | 90 |
| 4 | 1405 | 1409 | 2136 | 2498 | 31 | 42 | 43 | 94 | 94 | 108 |
| 2 | 1607 | 1602 | 2477 | 2845 | 35 | 49 | 49 | 107 | 111 | 123 |
| 1 | 1830 | 1811 | 2803 | 3261 | 40 | 57 | 58 | 122 | 127 | 142 |
| 0.5 | 2078 | 2039 | 3194 | 3766 | 45 | 66 | 68 | 140 | 147 | 164 |
| 0.2 | 2449 | 2374 | 3793 | 4614 | 52 | 80 | 85 | 166 | 177 | 204 |
| 0.5 + climate change | 2494 | 2447 | 3833 | 4519 | 54 | 79 | 81 | 168 | 176 | 197 |

### 3.2.1 Consideration of rating curve extrapolation at Camisky

As is common practice at SEPA gauging stations, annual rating curves (stage-discharge relationships) are used to convert stage to flow. Annual rating curves are used to account for changes in bed characteristics which may affect estimation of important low flow characteristics such as Q95. However, the use of a different rating curve each year can result in inconsistent extrapolation for flood flows. For the SEPA gauging station data used in the HiFlows-UK[10] project, this issue was addressed through the development of independent high flow ratings which would be applicable for as long as the high flow control at a given gauging station remained constant.

However, the Lochy at Camisky was not included in HiFlows-UK because of the artificial influences experienced within the catchment. Although SEPA did develop a single high flow rating in 2003 for Camisky, this rating was not commonly implemented and was exceeded by flood flows on the Lochy during 2006. SEPA are currently working towards a common extrapolation for Camisky but have not yet finalised the rating curve. The provisional curve (27MP1) was made available to JBA Consulting[11].

In order to provide an indication of the influence of rating curve extrapolation, rating 27MP1 was applied to the Camisky AMAX stage data to provide a new AMAX series of flood flows. Single

[10] http://www.ceh.ac.uk/data/nrfa/peakflow_overview.html
[11] Email from Mark Simpson dated 27-8-2013

site statistical analysis was then used to produce flood frequency estimates and the estimates compared with those obtained from single site analysis of the AMAX flows derived using the annual ratings.

From Table 3-3, it can be seen that the flood flow estimates are very similar between the two datasets for annual probability events more frequent than the 1:50 year event. From the 1:100 year flood onwards, the flood estimates derived from the annual ratings are slightly higher. For example, the 1:200 year flood is estimated as being 2,078m³/s using the annual ratings and 2,039m³/s using 27MP1. While these results do indicate that the use of annual ratings has an influence on the flood estimates at Camisky, the influence is not too substantial and use of the annual rating estimates will be erring on the precautionary side. According to correct hydrological procedures and UK guidance, the flood estimates obtained from the annual ratings were retained for this analysis.

For this study the Statistical method using the standard rating was chosen as the most appropriate. It is compared to previous flows in Table 3-4.

### 3.2.2 Comparison with previous model results

The flood flow estimates used in the River Lochy Flooding Fort William and Caol Flood Risk Mapping report by Mott MacDonald in 2005 are higher than JBA Consulting's current estimates. Table 3-4 below depicts the differences. The previous analysis used a value for extreme flood events of 90% of the rainfall-runoff analysis in order to the conservative. This method choice provides the main reason for the differences between the two analyses.

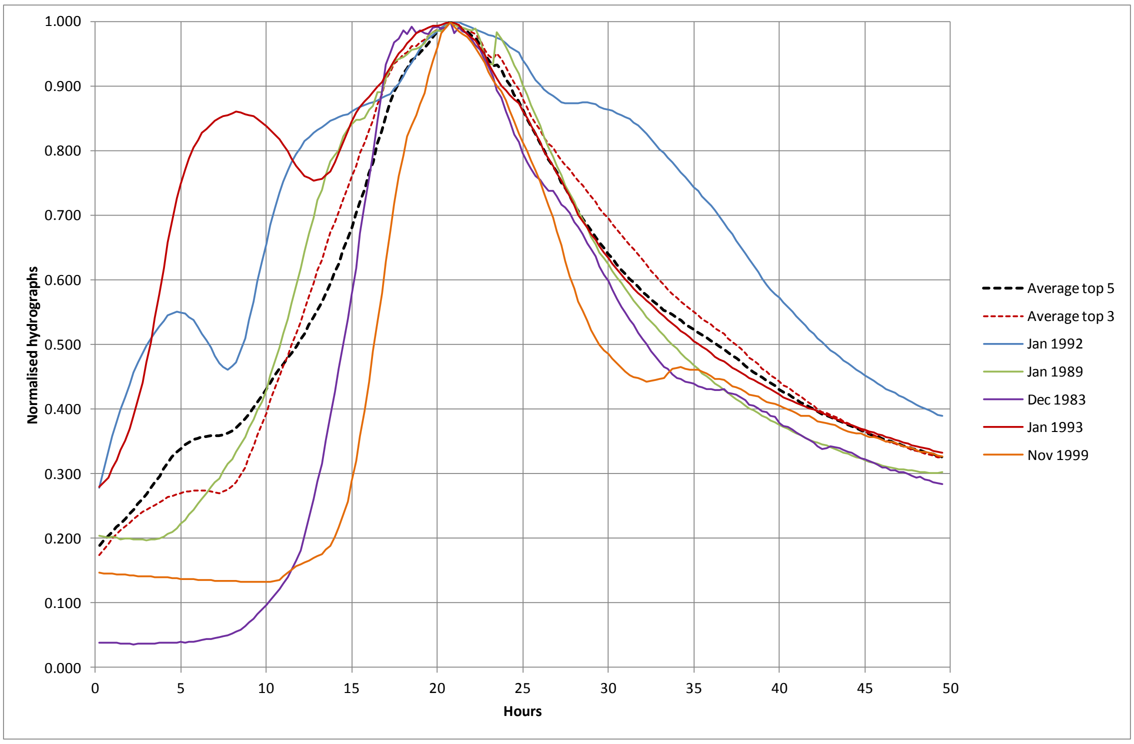
Table 3-4: Return period and equivalent flows from Mott and JBA

| River Lochy flow estimates ($m^3/s$) | | | |
|---|---|---|---|
| Mott | | JBA | |
| 1:50 year | 1,760 | 1:50 year | 1,607 |
| 1:100 year | 2,100 | 1:100 year | 1,830 |
| 1:200 year | 2,450 | 1:200 year | 2,078 |
| 1:500 year | 3,040 | 1:500 year | 2,449 |
| 1:200 year + CC | - | 1:200 year + CC | 2,494 |

## 3.3 Design Hydrograph

JBA in-house Hydrometric Database software was used to derive a design hydrograph for input to the ISIS model. The design hydrograph was derived from taking an average of several observed flood hydrographs, normalised by peak magnitude. Care was taken to ensure that suitably representative hydrographs were used. For example, double peaked events or events with long recession periods were excluded. After a period of testing an average based upon five observed hydrographs was selected (Figure 3-1 and Table 3-5).

Figure 3-1: Normalised hydrographs for the largest 5 useable flood events. The average hydrographs derived from the largest 3 and largest 5 events are also shown.




The advantage of this approach is that it is based entirely upon observed data and therefore preserves the observed hydrograph shape as much as is possible. Traditional methods such as the Rainfall-Runoff method provide a triangular type hydrograph which may not be appropriate in all cases (e.g. in heavily artificially influenced catchments such as the Lochy).

Table 3-5: Top five flood events used in estimating the design hydrograph

| Event date | Flow ($m^3/s$) |
|---|---|
| 2 January 1992 | 1,524 |
| 15 January 1989 | 1,421 |
| 27 December 1983 | 1,252 |
| 17 January 1993 | 1,074 |
| 30 November 1999 | 943 |

## 3.4 Climate change

The magnitude and frequency of flooding is expected to increase due to the influence of climate change. The changing world climate will lead to changes in snowfall and rainfall patterns. In order to estimate the expected impact of climate change to flooding within Caol, the extreme fluvial conditions have been altered to reflect the latest UK climate change guidance by adding a factor to increase peak flows.

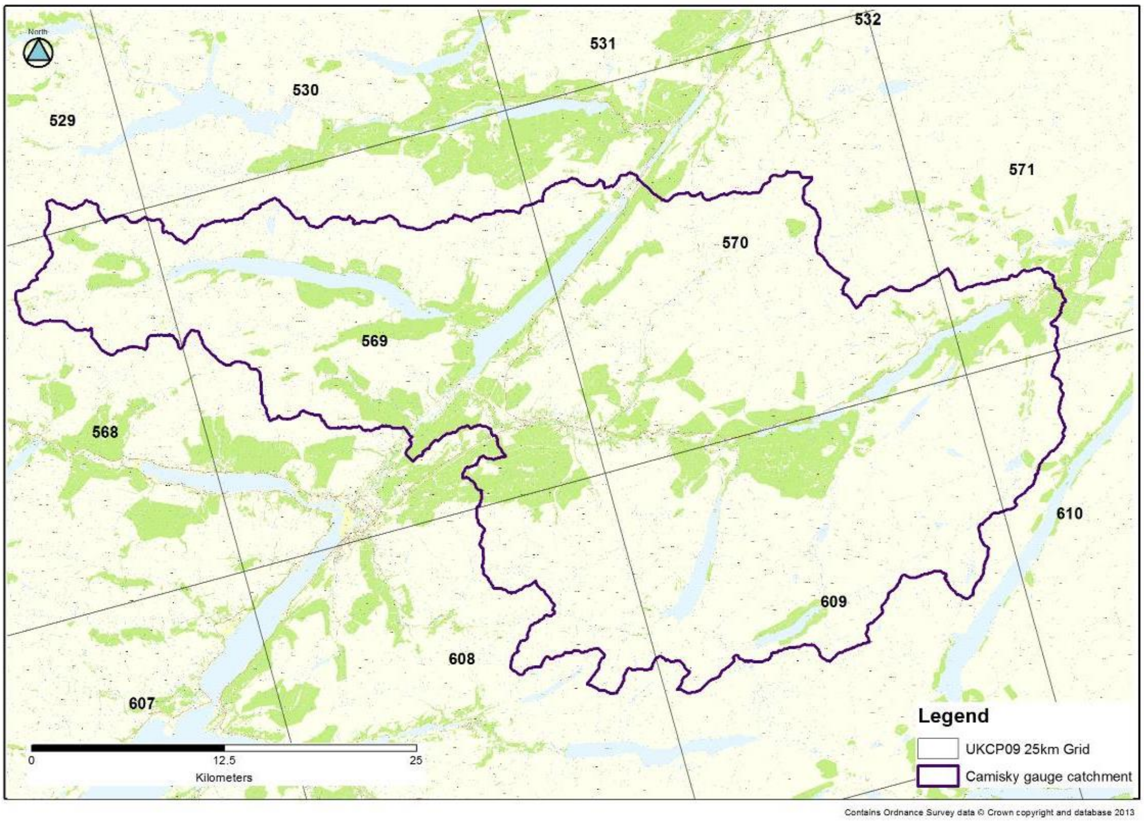
### 3.4.1 Fluvial climate change allowance

Typically for flood studies, the potential effects of climate change are considered by up scaling design flood flows by a factor of 20%. A 20% value was also adopted in this study (as defined by the last row in Table 3-3). However, in order to provide some context as to this 20% value, output from UKCP09 was considered.

UKCP09 provides scenarios for the upper and lower range of possible percentage increases in rainfall for 25km squares for the entire country. This information was extracted from the online data source for the 'worst case' scenario; the high emissions scenario. The percentage increase in monthly rainfall for winter months (December to February) was used as a proxy for future increased flood flows, by assuming that a percentage increase in rainfall translates to the same increase in flood flows.

Cumulative Density Functions (CDFs) of the UKCP09 percentage rainfall changes for the winter months (December to February) were downloaded from the UKCP09 website user interface. The Lochy catchment is large and is located across eight different UKCP09 grid boxes (Table 3-6 and Figure 3-2). For the purposes of analysis, it was assumed that the 90%, 50% (median) and 10% intervals on the CDFs were representative of potential changes in rainfall (and flow) in the area. These values were extracted for each of the eight grid boxes and then both an arithmetic average and a catchment area weighted average of those estimates calculated in order to provide overall climate change estimates (for the 90%, median, and 10% intervals) for the Lochy catchment (Table 3-6). The catchment area weighted average should be more realistic than the arithmetic average as it takes account of the Lochy catchment area in each grid box. The arithmetic average assumes equal weighting across each grid box, irrespective of catchment area.

Figure 3-2: The River Lochy Catchment (to Camisky) within the UKCP09 25 km grid boxes




From Table 3-6 it can be seen there is a large variation in projected climate change across the eight grid boxes. For example, the median value ranges from 0 to 35%. The higher values are generally associated with grid boxes which include western coastal areas (for example, grid boxes 529 and 568) and the lower values are generally associated with inland areas. The variation is also reflected in the different averaging approaches. When an arithmetic average is taken, the climate change values are 0%, 13% and 30%, for the 10th, median and 90th percentile, respectively. When a catchment weighted average is applied, the corresponding range is -3%, 8% and 21% respectively.

In this context, the 20% allowance for climate change is approximately equivalent to the catchment weighted average value for the 90th percentile value for 2080s under the high emissions scenario. As the 90th percentile represents an upper bound of potential change, the 20% allowance value can be interpreted as conservative at this location.

Table 3-6: Lochy climate change estimates for the winter period (December to February) for the 2080s (2070 to 2099)

| UKCP09 Grid box | 90% | Median | 10% | Catchment area (km$^2$) | Fractional area |
|---|---|---|---|---|---|
| 529 | 66 | 35 | 12 | 5.14 | 0.004 |
| 568 | 62 | 33 | 12 | 61.71 | 0.049 |
| 569 | 20 | 5 | -7 | 351.82 | 0.279 |
| 570 | 20 | 6 | -5 | 341.44 | 0.270 |
| 571 | 16 | 4 | -7 | 38.37 | 0.030 |
| 608 | 32 | 17 | 5 | 96.79 | 0.077 |
| 609 | 14 | 5 | -3 | 326.75 | 0.259 |
| 610 | 7 | 0 | -7 | 40.88 | 0.032 |
| Arithmetic average | 30 | 13 | 0 | | |
| Catchment weighted average | 21 | 8 | -3 | | |

# 4 Extreme sea level and wave conditions

The estimation of flood extents requires quantification of extreme sea-level and wave conditions. Each of these elements has a given probability of occurring which is proportional to their magnitude; meaning that relatively small events can occur on a frequent basis, while larger events occur less frequently. It is common to define these conditions by their annual probability (AP) which is used to estimate the likelihood of an extreme event occurring within a given year, or their expected return period which is based on the average time expected between occurrences.

For this study a range of return periods have been used, ranging from the 1:1-year to the 1:1,000 year flood events. This section describes the methods used to either select or calculate the extreme sea-level, wave conditions and river flows for this study.

## 4.1 Extreme sea-levels

### 4.1.1 Adopted extreme sea-levels

There have been a number of scientific studies undertaken to estimate extreme SWLs for Loch Linnhe, the Scottish lochs and the Scottish coastline. A general timeline of the studies relevant to this project are described below, which defines the most recent levels that are to be adopted for Caol.

In 2009 JBA Consulting developed the 'Tide-Surge Modelling for the Firth of Lorne/Loch Linnhe System – Extreme Sea-level and Modelling Report'[12] (2009-*draft*) for The Highland Council. The study extended throughout the Firth of Lorne and Loch Linnhe, and used a statistical analysis to calculate extreme SWLs throughout the Loch. Since the issue of the Highland Council report, a number of new studies have been undertaken that have superseded the project in terms of their method of statistical analysis, and as such, the THC report has not been adopted.

The SEPA, Environment Agency and Defra project 'Coastal Flood Boundary Data Study (CFDB)[13]' was undertaken by a consortium including JBA. This study involved the derivation of a new national dataset of extreme sea-levels for the Scottish coastline. Whilst this dataset covers the majority of Scotland, it does not extend up tidal estuaries and lochs, and consequently no new extreme sea-level estimates were derived for Caol. However, the CFBD study did involve considerable investment with respect to updating the underlying statistical methods used to calculate extreme sea-levels.

Following the CFBD study, JBA was commissioned by SEPA as part of the Coastal Flood Hazard Study[14] to update the original extreme sea-level estimates derived for THC (i.e. the Feb 2009 study). This project utilised the new statistical methods developed as part of the CFBD project, which was used to extend the extreme sea-level estimates into the majority of the coastal lochs in Scotland. The extreme SWLs produced as part of this study include Loch Linnhe and represent the most contemporary and reliable estimates available for Caol.

The extreme SWLs produced by the Coastal Flood Hazard Study have been were extracted at the closest possible location to Caol (OS NGR 210157, 775610) and are presented in Table 4-1.

12 JBA (2009) 'Tide-Surge Modelling for the Firth of Lorne/Loch Linnhe System – Extreme Sea-level and Modelling Report'12, DRAFT, (JBA Consulting, Feb 2009

13 Coastal flood boundary conditions for UK mainland and islands, Project: SC060064/TR2: Design sea-levels. Environment Agency, Feb 2011.

14 Coastal Flood Hazard Study (2012)

Table 4-1: Extreme sea-levels at Caol, Loch Linnhe

| Return period (years) | SWL (mAOD) |
| --- | --- |
| T1 | 3.23 |
| T2 | 3.40 |
| T5 | 3.63 |
| T10 | 3.82 |
| T20 | 4.01 |
| T50 | 4.27 |
| T100 | 4.48 |
| T200 | 4.69 |
| T500 | 4.98 |
| T1000 | 5.21 |

## 4.2 Extreme wave and wind conditions

There are currently no widely adopted extreme wave condition estimates for enclosed lochs, lakes or water bodies in the UK. Previous studies conducted within Loch Linnhe have applied analytical wave-grown calculations to estimate extreme conditions, which does not take into consideration the local bathymetry or friction along the shoreline of the Loch (which may be considerable due to the long-narrow shape), does not consider wave transformation or breaking and is known to over-estimate wave conditions[15].

For this assessment, a more reliable method of producing wave height estimates has been undertaken, using a numerical wave model to simulate wave growth and propagation through the Loch. To calculate the nearshore wave heights at Caol, a third generation SWAN (Simulating WAves Nearshore) wind-wave model was used, which calculates waves due to the friction expressed by extreme wind speeds over water.

Wind speeds have been estimated using an industry standard approach outlined in the document 'Revetment Systems against Wave Attack: A Design Manual'. The method involves estimating design wind speeds for different return periods using base estimates of the 50-year wind speed from the ‘Floods and Reservoir Safety Manual’[16] and adjusting these estimates to other return periods using a number of correction factors, as shown below.

$$U_D = U_b S_a S_d S_p S_f S_w \qquad \text{(Eq 1)}$$

Where: $U_D$ is the design wind speed (m/s) calculated as a function of 50-year basic hourly wind speed (m/s) $U_b$; an altitude factor $S_a$; a directional factor $S_d$; a probability factor $S_p$; a duration factor $S_f$; and an over water speed-up factor $S_w$. Values for each factor have been used from the in the Revetment System Manual.

The orientation of Loch Linnhe aligns with the strongest wind speeds for the UK, which generally originate from the south-west. Therefore the largest waves at Caol are assumed to originate when winds blow from this direction, which also coincides with the longest fetch length. In order to calculate extreme wind speed values for the wave transformation model, the worst-case wind directions from 220 degrees with a fetch of 53km has been used for all return periods. Table 4-2 shows the extreme wind speed values. These wind speeds have been assessed in conjunction with extreme sea-levels and a joint probability assessment has been conducted to identify coinciding wind and water level conditions to use as boundary condition in the SWAN Model, refer to Section 5.

[15] McConnell, K., 1998, Revetment Systems against Wave Attack: A Design Manual. Thomas Telford, London.
[16] ICE, 1996, Floods and Reservoir Safety. 3rd Edition. Thomas Telford, London.

Table 4-2: Extreme wind speed calculations

| Return period (years) | Wind speed (m/s) |
|---|---|
| T1 | 21.89 |
| T2 | 24.25 |
| T5 | 27.11 |
| T10 | 28.75 |
| T20 | 30.38 |
| T50 | 32.67 |
| T100 | 34.30 |
| T200 | 35.93 |
| T500 | 38.25 |

## 4.3 Climate change

The magnitude and frequency of coastal flooding is expected to increase due to the influence of climate change. The changing world climate will lead to changes to sea-levels and weather patterns. In order to estimate the expected impact of climate change to flooding within Caol, the extreme sea-levels have been altered to reflect the latest UK climate change guidance.

### 4.3.1 Sea-level

Sea-level rise due to climate change is required to predict future impacts on flooding. UK Climate Projections 09 (UKCP09)[17] has been used to determine climate change allowance for sea-level rise. Within UKCP09, estimates for sea-level rise are provided under three emissions scenarios Low, Medium and High, and further refined by percentile confidence ratings of 5, 50 and 95. For this study the medium emissions scenario and 95th percentile confidence rating is used to calculate the expected change to sea-level rise. Under this emissions scenario the present day sea-level (or extreme SWL) is expected to increase by 0.66m over the next 100-years to 2113 at Caol. Table 4-3 shows the resulting extreme SWL including climate change at Caol.

Table 4-3: Extreme sea-levels accounting for climate change

| Return Period (years) | Climate change SWL (mAOD) (present day SWL + 0.66m) |
|---|---|
| T1 | 3.89 |
| T2 | 4.06 |
| T5 | 4.29 |
| T10 | 4.48 |
| T20 | 4.67 |
| T50 | 4.93 |
| T100 | 5.14 |
| T200 | 5.35 |
| T500 | 5.64 |
| T1000 | 5.87 |

[17] UK climate projections, 2009

# 5 Wave modelling

A wave transformation model was required to simulate how waves change or 'transform' as they propagate from deep water to shallow water. The wave heights calculated at the nearshore were then used to calculate run-up heights and flood inundation extents at Caol. This chapter describes the development of the model and the manner in which it was used in the study.

## 5.1 Modelling approach

All storm scenarios calculated in the coastal joint probability analysis were modelled using the SWAN spectral wave model, run through the Deltares D-WAVE modelling shell. SWAN is a third generation wave model incorporating complex physics for the description of nearshore processes. It is an open source package used widely for research and commercial application, developed by internationally recognised experts at the Delft University of Technology. The model is capable of simulating the following nearshore wave transformation processes:

- Wind-wave interactions, which is the transfer of wind energy into wave energy, leading to the growth of waves.
- Shoaling, which is the build-up of energy as a wave enters shallow water, causing an increase in wave height.
- Refraction, which is the change in wave speed as waves propagate through areas of changing depth, causing a change in wave direction.
- Wave breaking, which is the destabilisation of a wave as it enters shallow water, causing broken waves with the characteristic whitewash or foam on the crest.
- Wave dissipation, which limits the size of waves through white-capping, bottom friction and depth-induced breaking.
- Diffraction, which is the spreading of wave energy behind structures, headlands and islands, which causes waves to change direction.

## 5.2 Wave modelling

### 5.2.1 Computational mesh

A computational curvilinear grid was developed for Loch Linnhe using a varying grid resolution. The grid resolution ranged from 150m at the offshore southern boundary, where depths vary between 85m to 100m and increased towards the study area to ensure a resolution of no greater than 15m in the nearshore zone adjacent to Caol.

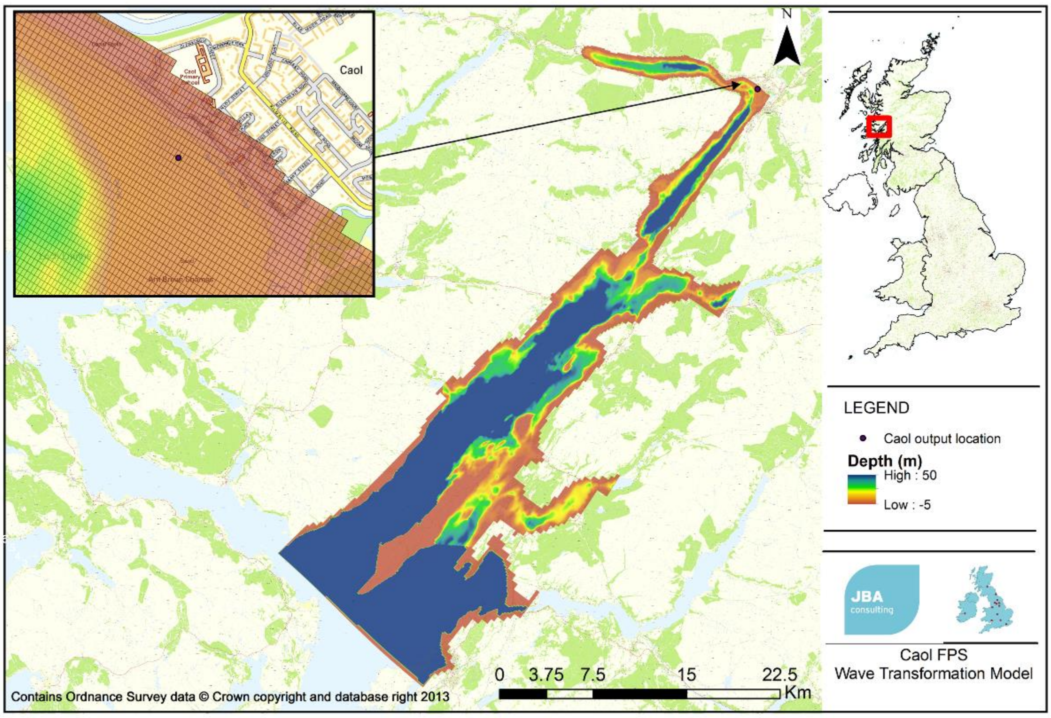
### 5.2.2 Bathymetry

In order to accurately represent wave propagation into Caol bathymetric data of Loch Linnhe and the foreshore in front of Caol was needed and was acquired from FINDmaps. Bathymetry for the wave model was taken from two sources. An offshore bathymetric dataset supplied by FINDmaps, that consisted of a 10m DEM providing depth data to ordnance datum Newlyn. Low tide topographic data of the Caol beach front and town were supplied by THC with elevation data corrected to ordnance datum Newlyn.

A seamless DEM was created by merging the offshore bathymetry with the land topography data. Where the offshore and topographic data overlapped, the higher resolution topographic data were used. Prioritising the datasets in this way ensures that the best quality data were used where they were available. The data was also inspected, once merged, to ensure that the locations where datasets intersected did not contain depth discontinuities, which would distort wave transformation processes.

The computational mesh and the bathymetry for the study site are shown Figure 5-1.

Figure 5-1: Wave transformation model extent




### 5.2.3 Model setup

The SWAN model can represent a range of physics and numerical schemes that were selected for this project based on their use in similar numerical modelling projects. The model was run in third generation mode which considers all the physical processes described in Section 5.1 (including refraction, bottom friction, depth induced breaking, whitecapping and diffraction) amongst other parameters. The SWAN model was run by specifying a constant wind speed and water level determined by the wind/wave joint probability analysis. The general shape of this frequency spectrum was specified as the default JONSWAP type spectrum. Energy dissipation due to whitecapping was incorporated based on the KOMEN[18] physics parameterisation scheme, the default of the SWAN model. Energy dissipation due to depth-induced breaking was based on the default bore model of Battjes and Janssen (1978)[19] which considers the bottom bathymetry of the surf zone, a Rayleigh probability density function of random breaking waves and calculates energy loss through headloss calculations over a hydraulic jump. Energy dissipation due to bottom friction was based on the JONSWAP scheme, based on the default parameters within the SWAN model.

The lack of nearshore model data did not allow for calibration of the model. Therefore, where possible the default options of the model were used, offering the best estimate of model parameters. Sensitivity testing was carried out to assess the significance of the model output to input changes.

For each simulation, the wave model produced a set of gridded results across the model domain as well as nearshore conditions for the output site located 100m offshore. The key nearshore conditions extracted from the wave model are:

- Hs – Significant wave height (m)
- Dir – Mean wave direction using the nautical convention (degrees from north)
- Tp – Peak wave period (s).

These outputs were then used as inputs for run-up calculations below.

[18] Van der Westhuysen, A. J., M. Zijlema, and J. A. Battjes. 2007. Nonlinear saturation based whitecapping dissipation in SWAN for deep and shallow water, Coastal Engineering, 54, 151-170.

[19] Battjes J.A.& J.P.F.M. Janssen (1978): Energy loss and set-up due to breaking of random waves, Proc. 16th Int. Conf. Coastal Engineering, ASCE, 569-587

# 5.3 Run-up

Run-up is the vertical difference between the SWL and the elevation water can reach due to wave action, as shown in Figure 2.1. Run-up is highly dependent on wave parameters and the underlying bathymetry. Wave conditions for run-up calculations have been extracted from the wave transformation model directly offshore of Caol (refer to Figure 5-1). The bathymetry has been extracted from the LiDAR DEM. This section discusses the steps taken to calculate run-up at Caol.

## 5.3.1 Run-up calculations

Run-up was calculated using wave parameters taken from the SWAN model. An empirical calculation was made using the methodology described in the industry standard EurOtop manual[20]:

$$\frac{R_{u2\%}}{H_{m0}} = C_1\ \gamma_b\ \gamma_f\ \gamma_\beta\ \xi_{m-1.0} \text{ with a maximum of } \frac{R_{u2\%}}{H_{m0}} = \gamma_f\ \gamma_\beta \left(C_2 - \frac{C_3}{\sqrt{\xi_{m-1.0}}}\right) \quad \text{(Eq 2)}$$

Where:

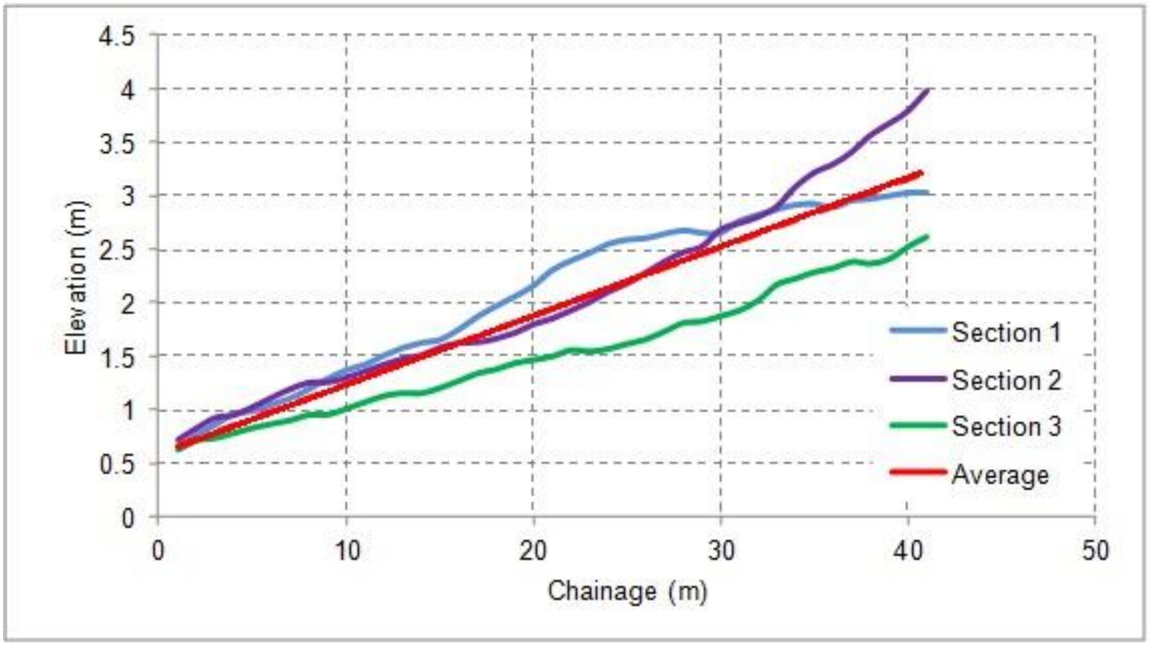
$R_{u2\%}$ = wave run-up height exceeded by 2% of incoming waves (m),

The calculation uses the empirical coefficients $C_1$, $C_2$, $C_3$ based on deterministic parameters, and accounts for the influence of a berm, $\gamma_b$ ,roughness, $\gamma_f$ ,oblique waves, $\gamma_\beta$ ,and the breaker parameter,$\xi$.

## 5.3.2 Slope schematisation

A slope of 1:12 was used to represent the run-up slope at Caol. This was calculated by extracting three profiles of the beach along the Caol foreshore and taking an average of the profiles, shown in Figure 5-2.

Figure 5-2: Profile schematisation analysis




# 5.4 Derivation of wave run results

The SWAN model has been used to calculate nearshore wave conditions based on the results of the joint probability sea-level and wind speed analysis. Following wave modelling, the calculated nearshore wave heights were then used to calculate the maximum wave run-up for each return period.

[20] Eurotop, 2007, wave overtopping of sea defences and related structures: Assessment manual.

# 6 Fluvial modelling

## 6.1 Previous modelling

Mott MacDonald developed a hydraulic model which was previously used to assess flood levels at Caol. This was provided to JBA Consulting to review and update. The original survey data was taken 24 years ago in 1990. The data was then modified by Mott MacDonald for the River Lochy Flooding - Fort William and Caol Flood Risk Mapping Report in September 2005 as well as additional survey data being taken along the right hand channel of the estuary (the Caol side) below the Rail Bridge in May 2005.

Following initial reviews of the data and cross section information, it was decided by JBA and The Highland Council to update this model completely using new survey information. This update was undertaken for the following reasons:

- Previous use of a bespoke modelling package.
- Age of original survey in a gravel bed river (1990) and unavailability of original survey sections for review.
- Uncertainties in the exact location of the cross sections originally surveyed.
- Changes to the weir downstream of the railway bridge.
- Uncertainties in the accuracy of cross sections.
- Uncertainties in the hydraulic modelling of the bridges.

The accuracy of the previous survey data was assessed against LiDAR data and was found to be lacking in detail and accuracy. Additionally a review of the low flow channels in the estuary from historic maps shows substantial change over time. Details of cross sectional differences as well as the mapping of the change of the estuary over time are detailed in Appendix D.

## 6.2 Flood modelling introduction

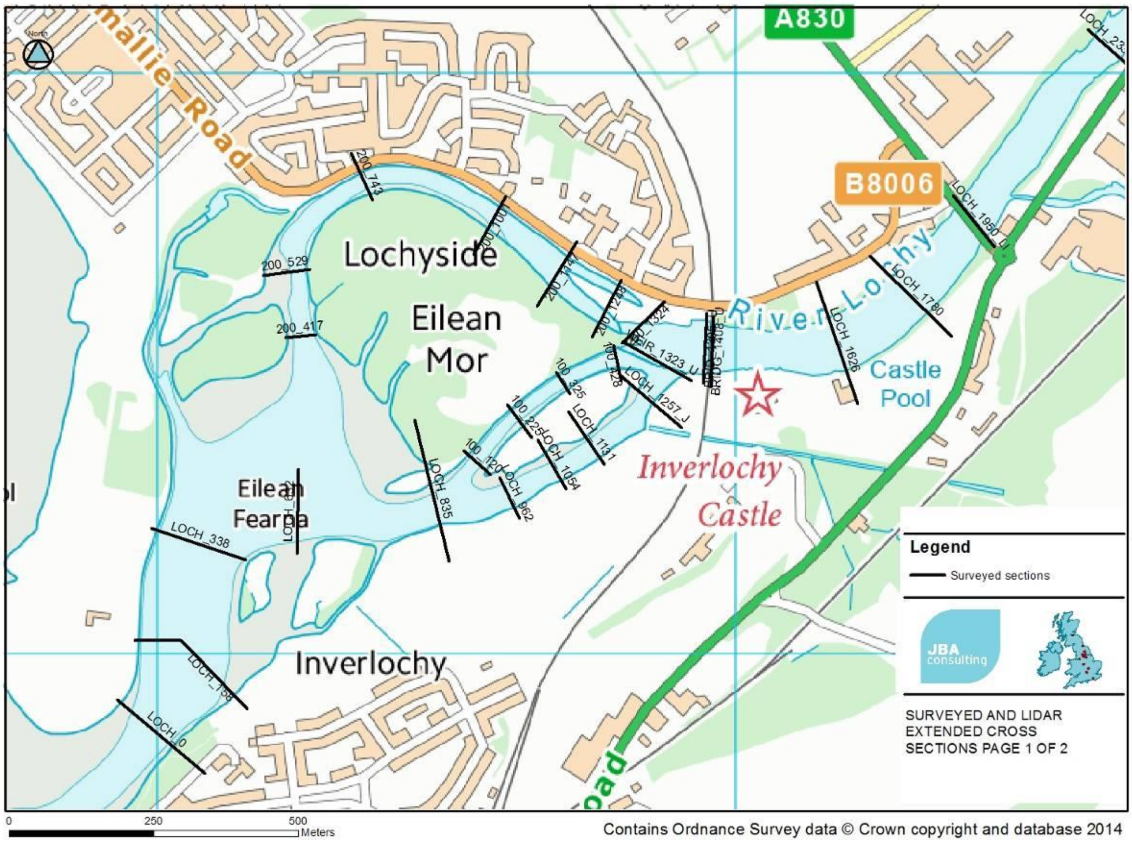
The chosen river modelling package used for this investigation was ISIS, developed by CH2M Hill. The software is designed to model steady and unsteady flow in open channels and can simulate the rise and fall of a full flood event hydrograph and will account for storage effects on water levels. An unsteady model also takes account of the variable flow entering the reach at the upstream end during a storm event and a rising and falling tide at the downstream end.

## 6.3 Survey data

To create a model that represents current channel conditions a new topographic survey was undertaken by JBA Consulting and supported by Aspect, Land and Hydrographic Surveyors in February 2014. Aspect provided a Z-boat SBES System to aid the survey. The Z-boat is an innovative survey system which utilising a remote control boat to undertake a single beam bathymetric survey. JBA Consulting carried out the land based portion of the survey and compiled the channel bed data collected by the Z-boat.

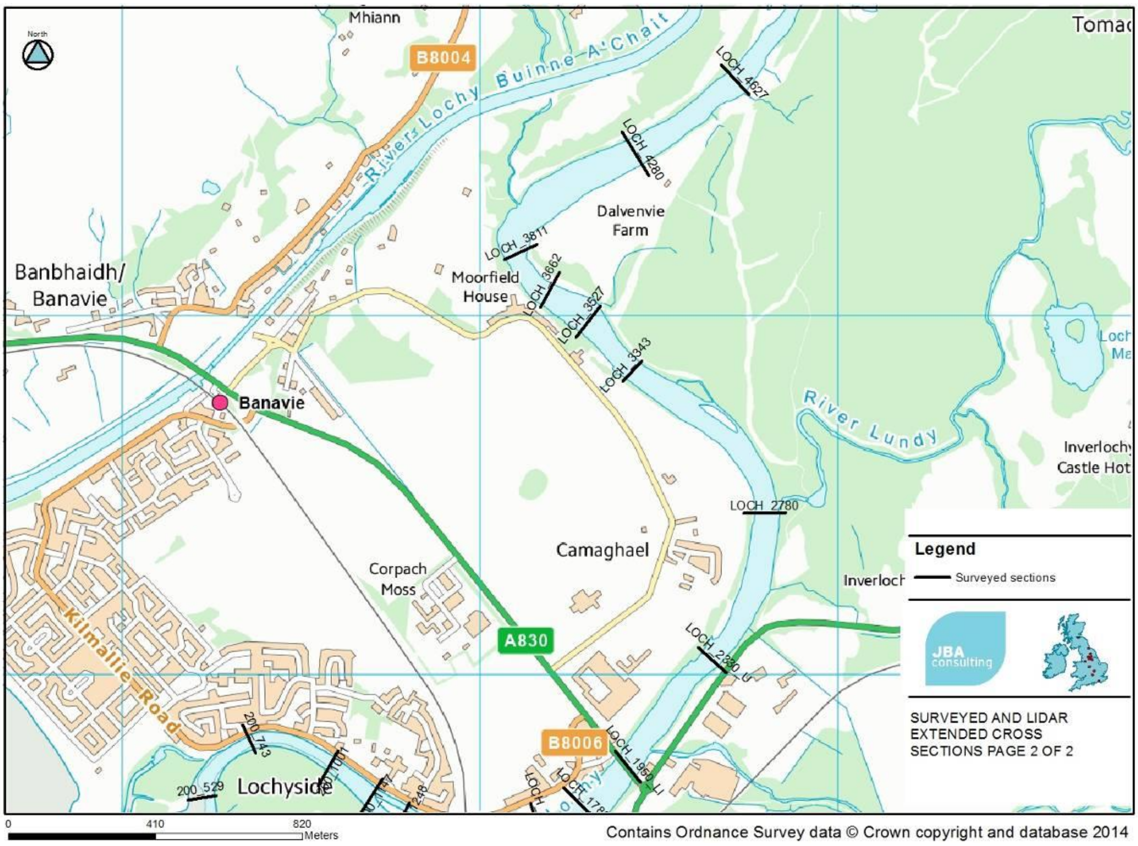
The survey extends from the mouth of the estuary OS NGR NN 1099 7487, and includes the two additional channels formed around Eilean Mor, to 4.6km upstream by Blar Meanbh at NGR NN 1287 7785. The main channel has been labelled as LOCH sections while the centre channel is labelled '100' sections and the channel that runs adjacent to Kilmallie Road is labelled as '200' sections. The location and extent of the surveyed cross sections are shown in black in Figure 6-1.

Figure 6-1: Surveyed cross sections - figure 1 of 2




Contains Ordnance Survey data © Crown copyright and database 2014

Figure 6-1: Surveyed cross sections - figure 2 of 2




Contains Ordnance Survey data © Crown copyright and database 2014

## 6.4 Extension of survey data

At certain cross sections the survey data was extended. This extension was carried out at locations where the topographic survey would have been physically very difficult to obtain for example on the heavily vegetated island in the centre of the estuary. The survey data was also extended where the modelled flood levels reached the initial survey limits. The survey was extended using LiDAR as shown in Figure 6-2 and Figure 6-3. The dashed red line is the LiDAR extended cross sections whilst handpicked points are represented by an orange triangle.

Figure 6-2: Surveyed and LiDAR extended cross sections figure 1 of 2

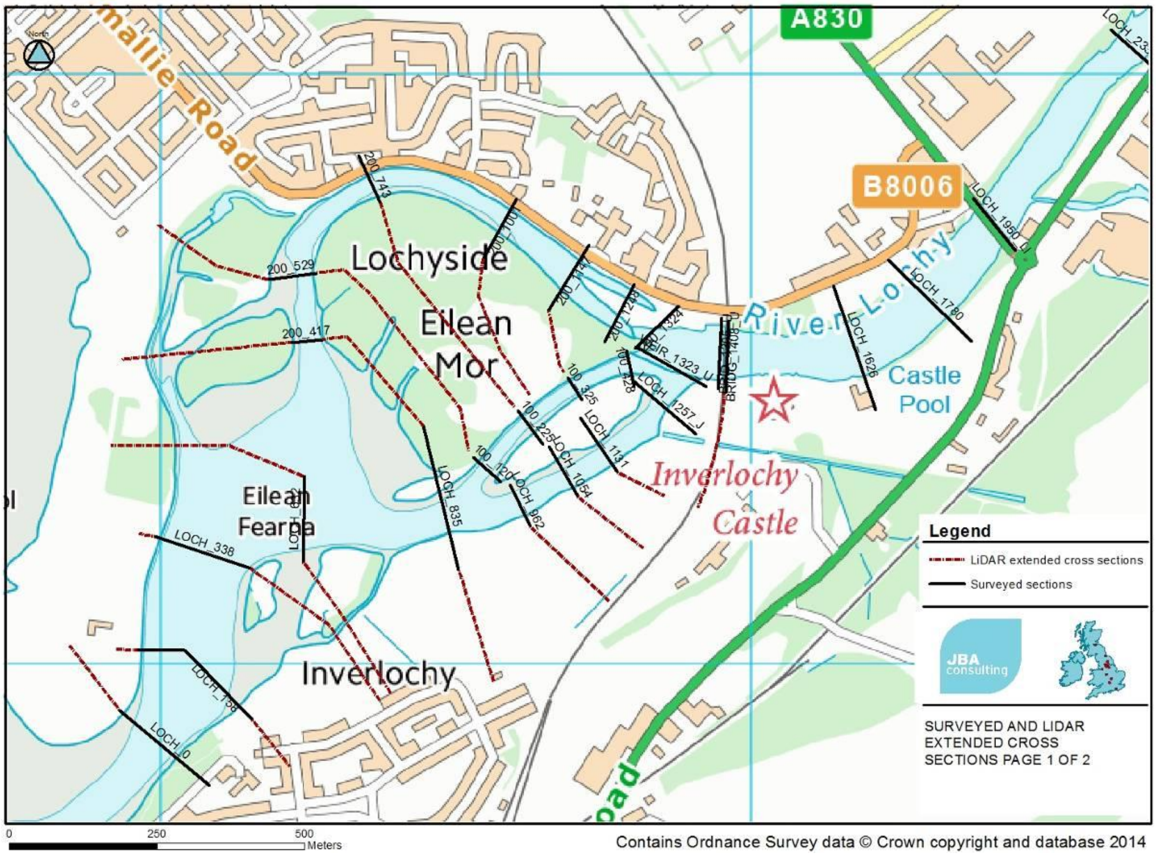
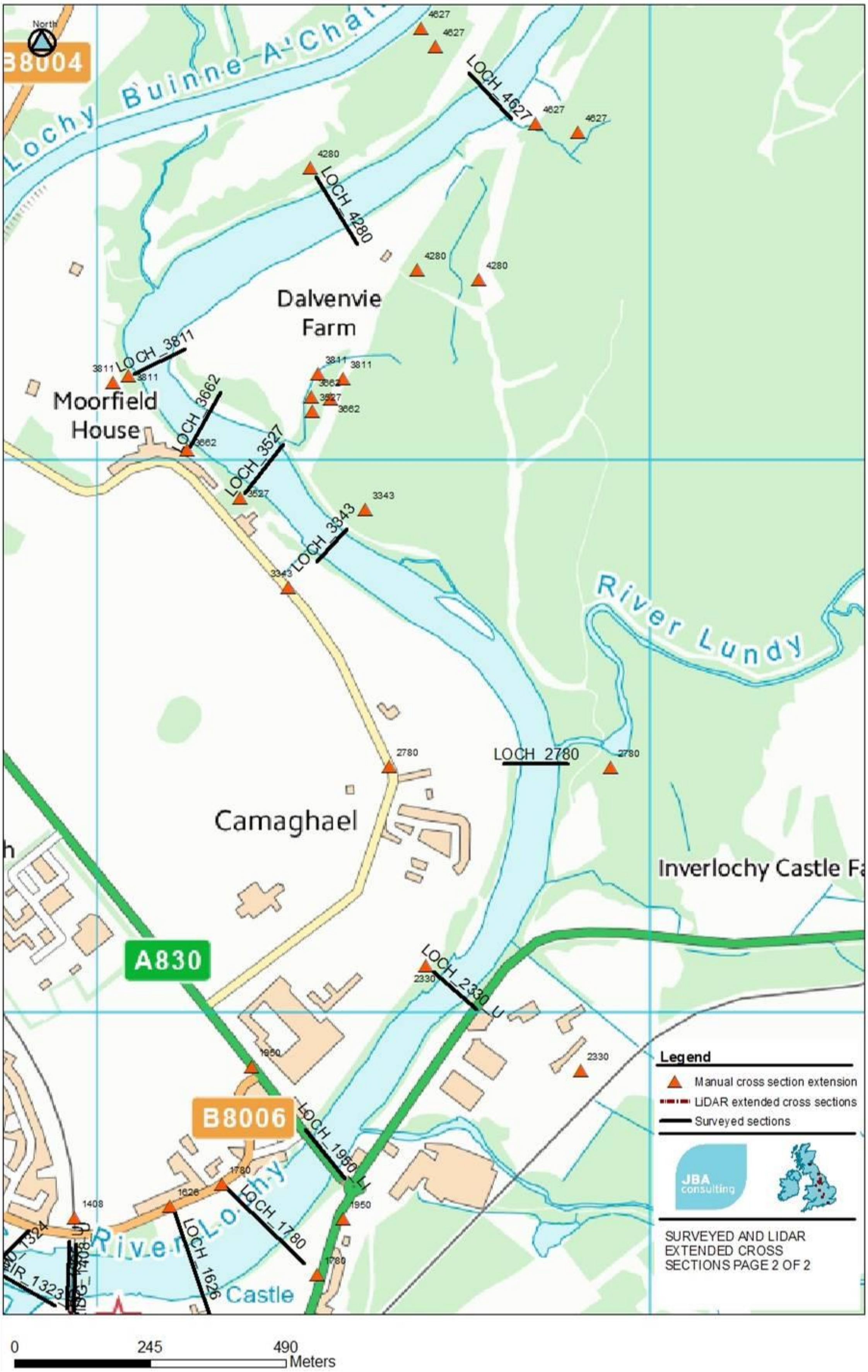


Figure 6-3: Surveyed and LiDAR extended cross sections figure 2 of 2



## 6.5 Hydraulic model

The surveyed and extended cross sections formed the basis of the hydraulic model. Other important factors in the design of a hydraulic model include the incorporation of structures, roughness coefficients and boundary conditions.

### 6.5.1 Major structures

There are four structures on the River Lochy which affect the flow hydraulics of the watercourse. These are:

- the A830 road bridge,
- the Fort William to Banavie railway bridge,
- Soldier's foot bridge and;
- an old weir across the width of the main channel below the rail bridge.

These have been incorporated into the Caol model. Cross sections and details of the structures are available in Appendix D.

The combined influence of the rail bridge and the footbridge was found to have a very significant effect on flood level upstream of the rail bridge. A number of scenarios were run although final model runs assumed that the bridges were modelled using the dual bridge function in line with best practice (essentially represented as a single bridge). The modelling assumes the minimum soffit of the two bridges (the footbridge) and the maximum deck level of the railway bridge, as indicated by the red lines marked on Figure 6-4. Between these two levels, the bridge is modelled to be completely blocked which, due to the highly complex steel lattice structure and high debris load within the river, is to be anticipated and conservative for the purposes of flood defence design.

Figure 6-4: The railway and footbridge downstream (taken from right bank)

Due to uncertainties associated with the modelling of this bridge, information on the afflux on the bridge should be measured in the next high flow event as it is critical to model levels in this reach.

Spill model units were applied to each bridge in the model to allow the model to simulate flows overtopping the structures. Spill units were also added to the coastal spur on which the wastewater plant sits. This allowed for flows to pass over and back over this spur during high water level/ flood flow events.

### 6.5.2 Manning's 'n' roughness

A Manning's 'n' value of 0.03 was used for the river channel. Manning's 'n' values of 0.03 to 0.10 were used for floodplain areas, depending upon location. A Manning's 'n' value of 0.06 was used as the value for vegetated banks. The nature of the floodplain ranged from grazed grass land to dense woodland.

## 6.6 Boundary conditions

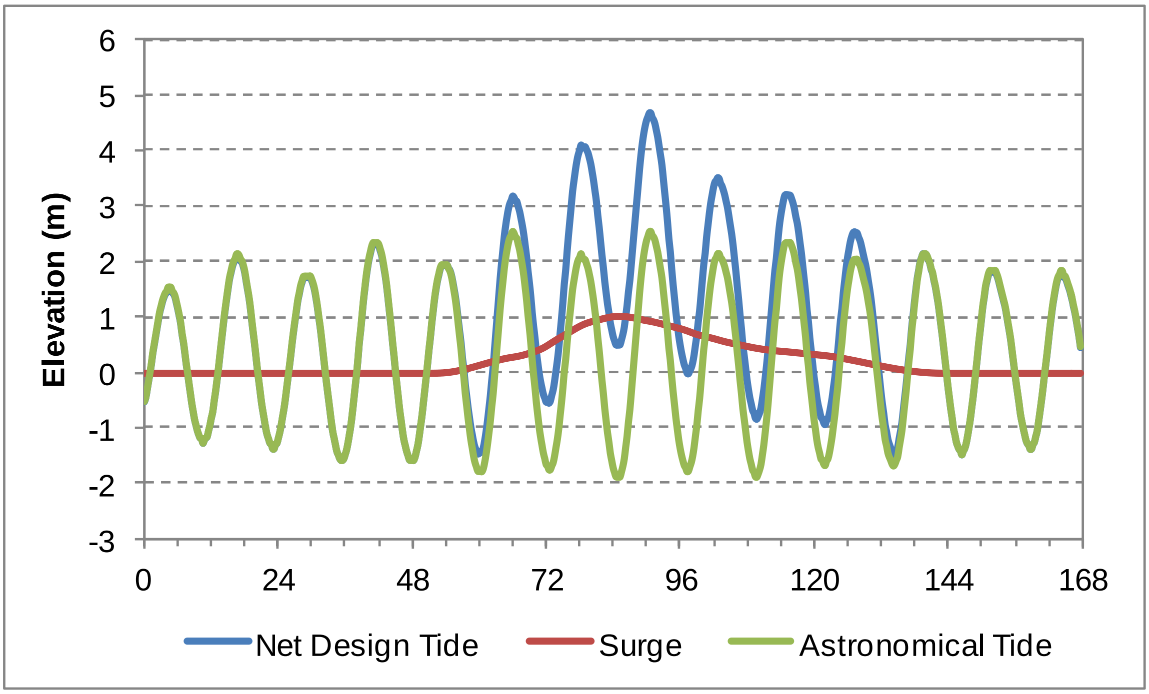
The boundary conditions consisted of three inflow points, one for each of the three watercourses, and one tidal outflow point at the downstream end.

### 6.6.1 Tidal boundary derivation

The tidal boundaries used for the joint probability simulations were generated based on tidal predictions for the Oban region. It takes into account diurnal variations combined with storm surge and extreme sea water level. In order to be able to consider the volume of water during an event, as opposed to just the peak overtopping rate, a full tidal harmonic was required.

This was undertaken using the methodology presented within the Defra Coastal Extremes project[21]. The method uses a base astronomical tidal curve and combines this with a surge curve to give the required resultant tidal peak for a given return period. The parameters used within the analysis are noted in Table 7-1, with the resultant tidal harmonic for the 1:200 year event displayed in Figure 7-5.

Figure 6-5: 200 year tidal harmonic for Corpach




[21] Coastal Flood Boundary Conditions for UK Mainland and Islands – Project SC060064TR2: Design Sea Levels, February 2011

Standard procedures recommend that the maximum surge is set to coincide with the low tide prior to the peak, thus resulting in the worst case scenario in terms of potential flood risk.

Table 6-1: Tidal boundary parameters

| Parameter | Value |
|---|---|
| Base tide curve peak level for Corpach (Highest Astronomical Tide (HAT))[22] | 2.52 mAOD |
| Date at Corpach[22] | 27 September 2023 |
| Surge shape | Tobermory (profile 36) |

The tidal graph for the 1:200 year flood plus climate change scenario was also considered, with the predicted sea level rise added to the whole series.

Tidal boundary peaks were aligned with the peak of the flow from the River Lochy as the river flows are anticipated to peak for a prolonged period (due to the catchment size and runoff response), thus increasing the probability of the peak conditions aligning.

### 6.6.2 Downstream boundary assumptions

The following assumptions were used for each model run and joint probability assessment:

- **Fluvial only model runs -** The annual maximum still water level tide was chosen as the downstream boundary tide for the fluvial flow model runs.
- **Coastal only model runs** - Model not run but maximum wave run-up and SWL results used for mapping (Table 7-1).
- **Joint probability fluvial runs** - return period fluvial flows with associated joint probability downstream boundary level from Table 7-3.
- **Joint probability coastal runs** - return period tidal levels with associated joint probability inflow from Table 7-4.

[22] Admiralty Tide software

# 7 Joint probability analysis

Flooding in the Caol area may come from either coastal or fluvial sources or the interdependence of the two. The coastal sources can be broken into two separate elements:

- Still water sea level (SWL)
- Wave run up

The previous chapters have derived peak fluvial flows, peak still water sea level and maximum wave run-up for a range of return periods. This chapter discusses the interaction one element has on the other and derives the joint probability outcome from pairings of these elements.

The three pairings that have been considered are:

- Wave run-up and SWL
- Fixed fluvial return periods against still water sea level.
- Fixed still water sea level against fluvial flows

Wave run-up and fluvial flows are independent of each other so have not been paired.

## 7.1 Wave and water levels

When considering extreme coastal events it is important to specify an appropriate coincident sea-level. Extreme waves occurring during extremely high sea-levels pose a far greater coastal flood risk than if they occurred during lower sea-levels. However, it is inaccurate to simply assign, for example, a 1 in 200-year wave height with a 1 in 200-year sea-level and state that this is the 1 in 200-year flood risk. The probability of this concurrent occurrence is in fact much lower, defined by the dependence relationship between the two variables.

In order to establish suitable SWL/wave height and SWL/river flow values for each return period a joint probability assessment has been undertaken using the methodology outlined in the publication 'Joint Probability: Dependence Mapping and Best Practice'[23]. The analysis has been undertaken using the probability data described in the previous sections for extreme sea-levels, waves (based on wind conditions) and river flows.

A desk study approach for the wave run-up/SWL joint probability analysis was undertaken for this project. Due to the location of Loch Linnhe joint probability analysis was performed on extreme storm surge to represent extreme still-water levels, and extreme wind speeds to represent extreme wave heights. The level of dependence between each of the two variables has been adopted based on a statistical regression analysis of the recorded surge measured at the Corpach water level gauge and the historic offshore wind conditions based on the hindcast dataset. This value was validated against published surge vs. dependence values (0.23) at the study site shown in Figure 7-1.

[23] 'Defra (2003) 'Joint Probability: Dependence Mapping and Best Practice', Report: FD2308/TR1, Defra/Environment Agency, July 2003.

Figure 7-1: Present and future values of dependence between surge and wind speed (source: Defra, 2003)

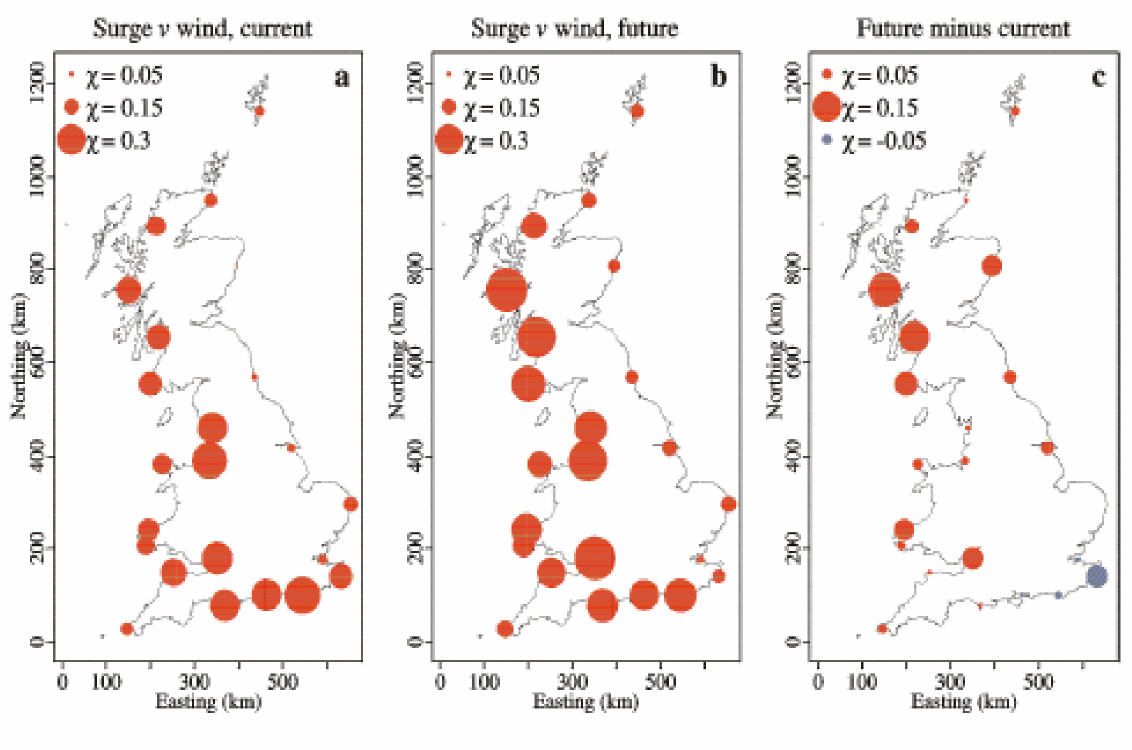
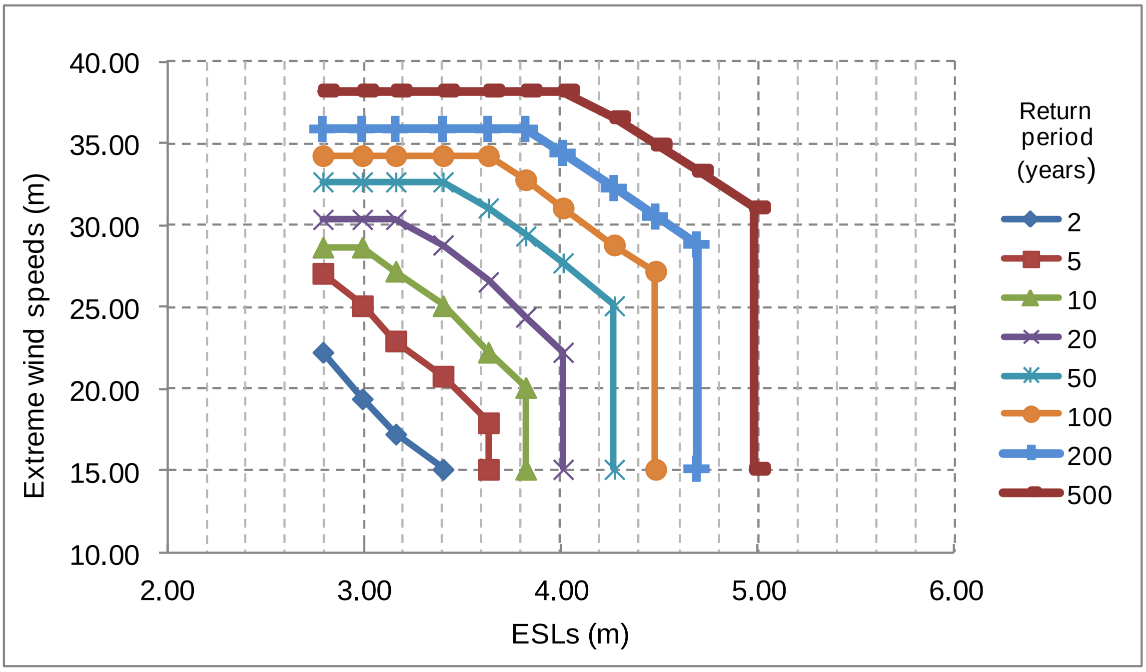



Figure 7-2 shows the variations of water level and wind speed at each respective return period that will be used as the driving conditions of the wave transformation model. A full table of results can be found in Appendix A.

Figure 7-2: Joint probability results between Extreme Wind Speeds and Extreme Sea Levels (ESLs)



### 7.1.1 Run-up results

The results of the coastal joint probability scenarios have been assessed to find the worst case run-up for each return period for the present day and present day plus climate change, as shown in Table 7-1.

Table 7-1: Worst case run-up results

| Return Period (years) | Maximum run-up + present day still water level (mAOD) | Maximum run-up + still water level + climate change (mAOD) |
|---|---|---|
| T1 | 3.48 | 4.15 |
| T2 | 3.72 | 4.40 |
| T5 | 3.97 | 4.65 |
| T10 | 4.24 | 4.91 |
| T20 | 4.45 | 5.12 |
| T50 | 4.74 | 5.48 |
| T100 | 4.97 | 5.71 |
| T200 | 5.27 | 5.94 |
| T500 | 5.58 | 6.26 |

### 7.1.2 Sensitivity testing

Sensitivity testing was carried out to assess the relative influence of the dominant parameters of the wave model. This was undertaken by altering the wind speeds by an amount considered to be within the typical variance of the data, in this case by increasing and decreasing extreme wind speeds by 10%. The resulting wave conditions were extracted from the model and used to calculate the resulting wave run-up. Table 7-2 shows the revised worst case run-up of each joint probability return period and the percentage error when compared to the initial results.

The sensitivity analysis indicate the model is not highly sensitive to changes in design wind speed, with the average change in wave height just 0.61%. This indicates that if adopted extreme wind speeds were to increase by up to 10% the change in run-up would be minimal. This supports the concept that wave conditions are primarily controlled by depth, and therefore sea-level.

Table 7-2: Worst case run-up heights and the associated percentage errors

| | Run-up height (mAOD) | | | Percentage error (%) | |
|---|---|---|---|---|---|
| Return period (years) | Normal wind speed (m/s) | Plus 10% wind speed (m/s) | Minus 10% wind speed (m/s) | Plus 10% wind speed | Minus 10% wind speed |
| T1 | 3.48 | 3.49 | 3.47 | 0.30 | -0.38 |
| T2 | 3.72 | 3.74 | 3.71 | 0.34 | -0.47 |
| T5 | 3.97 | 4.04 | 3.96 | 1.53 | -0.37 |
| T10 | 4.24 | 4.25 | 4.17 | 0.38 | -1.52 |
| T20 | 4.45 | 4.46 | 4.43 | 0.32 | -0.43 |
| T50 | 4.74 | 4.75 | 4.72 | 0.37 | -0.37 |
| T100 | 4.97 | 5.06 | 4.95 | 1.75 | -0.42 |
| T200 | 5.27 | 5.29 | 5.17 | 0.41 | -1.75 |
| T500 | 5.58 | 5.61 | 5.55 | 0.41 | -0.51 |
| T1 climate change | 4.15 | 4.20 | 4.14 | 1.15 | -0.33 |
| T2 climate change | 4.40 | 4.41 | 4.38 | 0.33 | -0.44 |
| T5 climate change | 4.65 | 4.71 | 4.63 | 1.39 | -0.35 |
| T10 climate change | 4.91 | 4.93 | 4.89 | 0.38 | -0.40 |
| T20 climate change | 5.12 | 5.14 | 5.10 | 0.31 | -0.41 |
| T50 climate change | 5.48 | 5.50 | 5.39 | 0.37 | -1.57 |
| T100 climate change | 5.71 | 5.74 | 5.69 | 0.40 | -0.45 |
| T200 climate change | 5.94 | 5.97 | 5.92 | 0.41 | -0.46 |
| T500 climate change | 6.26 | 6.28 | 6.23 | 0.37 | -0.44 |
| Average percentage error | | | | 0.61 | -0.61 |

## 7.2 Flow and sea levels

Flooding in the Caol area may come from either tidal or fluvial sources or a combination of the two. In order to examine the degree of dependence between these two sources of flooding, published Defra and Environment Agency[24] guidance was consulted. This guidance uses the measure $\chi$ as an indication of dependence, where low values of $\chi$ indicate low correlation and high values of $\chi$ indicate strong correlation.

The guidance contains only limited information for gauging stations in the Western Highlands in general and no information for the Loch Linnhe area in particular. However, analysis of daily mean flow data from the SEPA gauging station at Camisky together with the surge component of the tidal data from the SEPA Corpach station on Loch Linnhe (obtained by subtracting the astronomical tide from the recorded tidal levels) indicated a moderately positive correlation between daily mean flow and tidal surge.

A modest correlation was therefore assumed and a $\chi$ value of 0.03 used (from SEPA gauging station 86001 at Little Eachaig at Dalinlongart as reported in the Defra/EA guidance). Examples of the joint probabilities are shown in Table 7-3. This matrix gives the joint probability return period for any given marginal return period in the first column (either flow or tide).

The return period values for both flow and tide are then used to define corresponding values for each parameter in the following two tables. The tidal levels corresponding to specific flows are listed in Table 7-4 and the flows corresponding to specific tidal levels are listed in Table 7-5.

Table 7-3: Desk based joint probability estimates based on modest correlation between river flow and tide: probability combinations

| | Overall Joint Exceedance Return Period (Years) | | | | | |
|---|---|---|---|---|---|---|
| | 2 | 75 | 100 | 200 | 500 | 1000 |
| Marginal Return Period (Years) (Flow or Tide) | Corresponding Marginal Return Period (Years) for Tide or Flow | | | | | |
| 0.16 | 0.023 | 31.64 | 56.25 | 200.00 | 500.00 | 1000 |
| 0.5 | 0.007 | 10.13 | 18.00 | 72.00 | 450.00 | 1000 |
| 1.33 | 0.003 | 3.79 | 6.75 | 27.00 | 168.75 | 675 |
| 2 | 0.002 | 2.53 | 4.50 | 18.00 | 112.50 | 450 |
| 5 | | 1.01 | 1.80 | 7.20 | 45.00 | 180 |
| 10 | | 0.51 | 0.90 | 3.60 | 22.50 | 90 |
| 25 | | 0.20 | 0.36 | 1.44 | 9.00 | 36 |
| 50 | | 0.10 | 0.18 | 0.72 | 4.50 | 18 |
| 75 | | 0.07 | 0.12 | 0.48 | 3.00 | 12 |
| 100 | | | 0.09 | 0.36 | 2.25 | 9 |
| 200 | | | | 0.18 | 1.13 | 4.5 |
| 500 | | | | | 0.45 | 1.8 |
| 1000 | | | | | | 0.9 |

[24] Defra / Environment Agency Flood and Coastal Defence R&D Programme Use of Joint Probability Methods in Flood Management A Guide to Best Practice R&D Technical Report FD2308/TR2 March 2005

Table 7-4: Desk based joint probability estimates based on modest correlation between river flow and tide: tidal levels corresponding to specific flows

| | | Overall Joint Exceedance Return Period (Years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 5 | 10 | 25 | 50 | 75 | 100 | 200 | 500 |
| Fluvial return period (years) | Flow ($m^3/s$) | **Tidal Level (mAOD)** | | | | | | | | |
| 0.16 | 77 | 2.27 | 2.73 | 3.08 | 3.54 | 3.91 | 4.14 | 4.30 | 4.69 | 4.98 |
| 0.5 | 371 | 1.99 | 2.45 | 2.80 | 3.26 | 3.60 | 3.82 | 3.98 | 4.38 | 4.95 |
| 1.3 | 592 | 1.74 | 2.20 | 2.55 | 3.01 | 3.36 | 3.56 | 3.71 | 4.09 | 4.64 |
| 2 | 741 | 1.64 | 2.10 | 2.45 | 2.91 | 3.26 | 3.46 | 3.60 | 3.98 | 4.52 |
| 5 | 989 | | 1.87 | 2.22 | 2.68 | 3.03 | 3.23 | 3.37 | 3.73 | 4.24 |
| 10 | 1163 | | | 2.04 | 2.50 | 2.85 | 3.06 | 3.20 | 3.55 | 4.04 |
| 25 | 1405 | | | | 2.27 | 2.62 | 2.83 | 2.97 | 3.32 | 3.79 |
| 50 | 1607 | | | | | 2.45 | 2.65 | 2.80 | 3.14 | 3.6 |
| 75 | 1734 | | | | | | 2.55 | 2.69 | 3.04 | 3.5 |
| 100 | 1830 | | | | | | | 2.62 | 2.97 | 3.43 |
| 200 | 2078 | | | | | | | | 2.80 | 3.26 |
| 500 | 2449 | | | | | | | | | 3.03 |

Table 7-5: Desk based joint probability estimates based on modest correlation between river flow and tide: flows corresponding to specific tidal levels

| | | Overall Joint Exceedance Return Period (Years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 5 | 10 | 25 | 50 | 75 | 100 | 200 | 500 |
| Tidal return period (years) | Tidal Level (mAOD) | **Flow ($m^3/s$)** | | | | | | | | |
| 0.16 | 2.73 | Tidal only | 22.5 | 398 | 894 | 1253 | 1474 | 1644 | 2078 | 2449 |
| 0.5 | 2.99 | | Tidal only | 89 | 585 | 961 | 1166 | 1318 | 1721 | 2406 |
| 1.3 | 3.25 | | | Tidal only | 320 | 695 | 915 | 1064 | 1427 | 2017 |
| 2 | 3.40 | | | | 210 | 585 | 805 | 961 | 1318 | 1872 |
| 5 | 3.63 | | | | Tidal only | 337 | 557 | 713 | 1081 | 1576 |
| 10 | 3.82 | | | | | 150 | 369 | 525 | 900 | 1377 |
| 25 | 4.07 | | | | | Tidal only | 121 | 277 | 652 | 1137 |
| 50 | 4.27 | | | | | | Tidal only | 89 | 465 | 960 |
| 75 | 4.39 | | | | | | | Tidal only | 355 | 851 |
| 100 | 4.48 | | | | | | | | 277 | 773 |
| 200 | 4.69 | | | | | | | | 89 | 585 |
| 500 | 4.98 | | | | | | | | | 337 |

## 7.3 Design model runs

Design model runs have been carried out in three batches to produce a set of:

- Fluvial flood flows with and without the influence of climate change.
- Coastal flood maps with the combined influence of maximum wave run-up and maximum still water level with and without the influence of climate change.
- Joint probability flood depth mapping which selected the maximum flood depth of each of the joint probability fluvial and coastal flood depths for each return period.

All three of the above scenarios have been modelled for the 1:2 year, 1:5 year, 1:10 year, 1:20[25] year, 1:50 year, 1:75 year, 1:100 year and 1:200 year return period event. A matrix of all the different fluvial and tidal return periods was developed to capture the worst case scenario for each year. Running the hydraulic model with the tidal and fluvial boundaries given in Table 7-4 and Table 7-5 generated water levels at each cross section. The worst case was selected for each return period.

The 1:200 year return period was mapped for each case. From analysis of the 1:200 year joint probability scenario it was found that the worst case is a combination of the highest tide with the lowest fluvial flow and the lowest tide with the highest flow. Intermediate values were found to generate more moderated flood levels. This allowed future runs of tidal/fluvial combinations to be reduced to those shown in Table 7-2. In some cases the joint probability fluvial flow and tidal level were capped at minimum values where the joint probability predicted them to be lower than a realistic value. These minimum values are a fluvial flow of 140m$^3$/s and tidal level of 2.73mAOD.

Table 7-6: Worst case joint probability tidal/fluvial combinations

| | Joint probability tidal/fluvial combinations | | | |
|---|---|---|---|---|
| Return period | Tide (mAOD) | Fluvial (m$^3$/s) | Tide (mAOD) | Fluvial (m$^3$/s) |
| 1:2 | 3.4 | 140 | 2.73 | 741 |
| 1:5 | 3.63 | 140 | 2.73 | 989 |
| 1:10 | 3.82 | 140 | 2.73 | 1,163 |
| 1:20 | 4.07 | 140 | 2.73 | 1,405 |
| 1:50 | 4.27 | 140 | 2.73 | 1,607 |
| 1:75 | 4.39 | 140 | 2.73 | 1,734 |
| 1:100 | 4.48 | 140 | 2.73 | 1,830 |
| 1:200 | 4.69 | 140 | 2.80 | 2,078 |
| 1:500 | 4.98 | 140 | 3.03 | 2,449 |

## 7.4 Hydraulic model results - comparison with previous analysis

Where available water levels at cross sections located in approximately the same position in the Mott's model and the current model used in this report were compared. The cross sections that were compared are shown in Figure 7-3 and are tabulated in Table 7-7 and Table 7-8.

[25] The fluvial flows were calculated based on 1:25 year return period event while coastal events where based on 1:20 year event. To compare like for like the 1:25 year fluvial flows were classified as 1:20 year flows. This produces a conservative answer for this return period event.

Figure 7-3: Cross sections used to compare water surface elevations between models

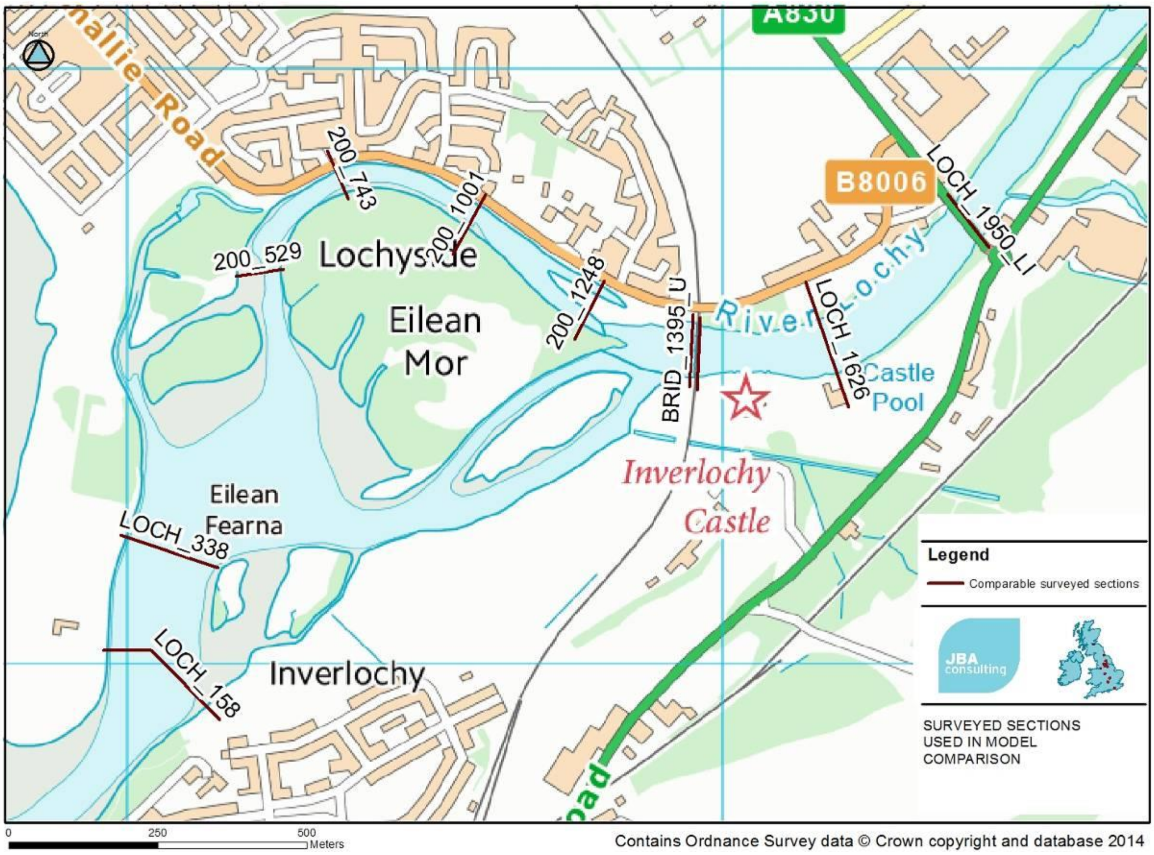



Table 7-7: Water level elevations comparison between JBA 1:100 year and Mott 1:50 year model (m AOD) which use similar flows

| Label | JBA 1:100 year (mAOD) 1,830m$^3$/s | Mott 1:50 year (mAOD) 1,760m$^3$/s |
|---|---|---|
| LOCH_1950_U | 6.65 | 6.10 |
| LOCH_1626 | 6.43 | 5.98 |
| BRIDG_1408_U | 5.98 | 5.50 |
| BRID_1395 | 5.01 | 4.99 |
| 200_1248 | 4.69 | 4.57 |
| 200_1001 | 4.79 | 4.57 |
| 200_743 | 4.62 | 4.57 |
| 200_529 | 4.53 | 4.57 |
| LOCH_338 | 4.49 | 4.57 |
| LOCH_158 | 4.48 | 4.57 |

Table 7-8: Water level elevations comparison between JBA 1:200 year and Mott 1:100 year model (m AOD) which use similar flows

| Label | JBA 1:200 year (mAOD) 2,078m$^3$/s | Mott 1:100 year (mAOD) 2,100m$^3$/s |
|---|---|---|
| LOCH_1950_U | 7.34 | 6.60 |
| LOCH_1626 | 7.22 | 6.47 |
| BRIDG_1408_U | 6.79 | 5.93 |
| BRID_1395 | 5.20 | 5.63 |
| 200_1248 | 4.91 | 4.85 |
| 200_1001 | 5.02 | 4.85 |
| 200_743 | 4.84 | 4.85 |
| 200_529 | 4.75 | 4.85 |
| LOCH_338 | 4.69 | 4.85 |
| LOCH_158 | 4.69 | 4.85 |

Table 7-9: Water level elevations comparison between JBA 1:500 year and Mott 1:200 year model (m AOD) which use similar flows.

| Label | JBA 1:500 year (mAOD) 2,449m$^3$/s | Mott 1:200 year (mAOD) 2,450m$^3$/s |
|---|---|---|
| LOCH_1950_U | 8.37 | 7.13 |
| LOCH_1626 | 8.18 | 6.98 |
| BRIDG_1408_U | 7.77 | 6.36 |
| BRID_1395 | 5.45 | 6.36 |
| 200_1248 | 5.18 | 5.16 |
| 200_1001 | 5.20 | 5.16 |
| 200_743 | 4.99 | 5.16 |
| 200_529 | 4.99 | 5.16 |
| LOCH_338 | 4.98 | 5.16 |
| LOCH_158 | 4.98 | 5.16 |

Overall the flood levels predicted in using the new model are higher for similar flows used in the previous modelling exercise. Reasons for this could be attributed to a number of factors including the modelling approach, bridge modelling, changes to bed and channel geometries and the erosion of the weir.

## 7.5 Flood mapping

Flood depth maps were generated from water levels at cross sections. GIS software was used to generate a digital water surface elevation based on these extended cross sections. The digital terrain model was then subtracted from the extended water surface elevation to give a flood depth at any point.

The following flood maps have been produced and are provided in Appendix C:

**C.1** **Coastal - Current conditions** (joint probability of tide and wave run-up)

2, 5, 10, 20, 50, 100, 200 year return periods

The flood elevations used are found in Table 4-1

**C.2** **Coastal - With climate change** (joint probability of tide and wave run-up)

2, 5, 10, 20, 50, 100, 200 year return periods with an allowance for sea level rise

The flood elevations used are found in Table 4-3

### C.3 Fluvial - Current conditions

2, 5, 10, 25, 50, 100, 200 year return periods

A table of the flood elevations used are found in Appendix A.2

### C.4 Fluvial - With climate change

2, 5, 10, 25, 50, 100, 200 year return periods with an allowance for increasing flows due to climate change

The flood elevations used are found in Appendix A.3

### C.5 Fluvial-Tide joint probability scenario

2, 5, 10, 20, 50, 75, 100, 200 year return periods

The flood elevations used are found in Appendix A.4

# 8 Flood level results and design considerations

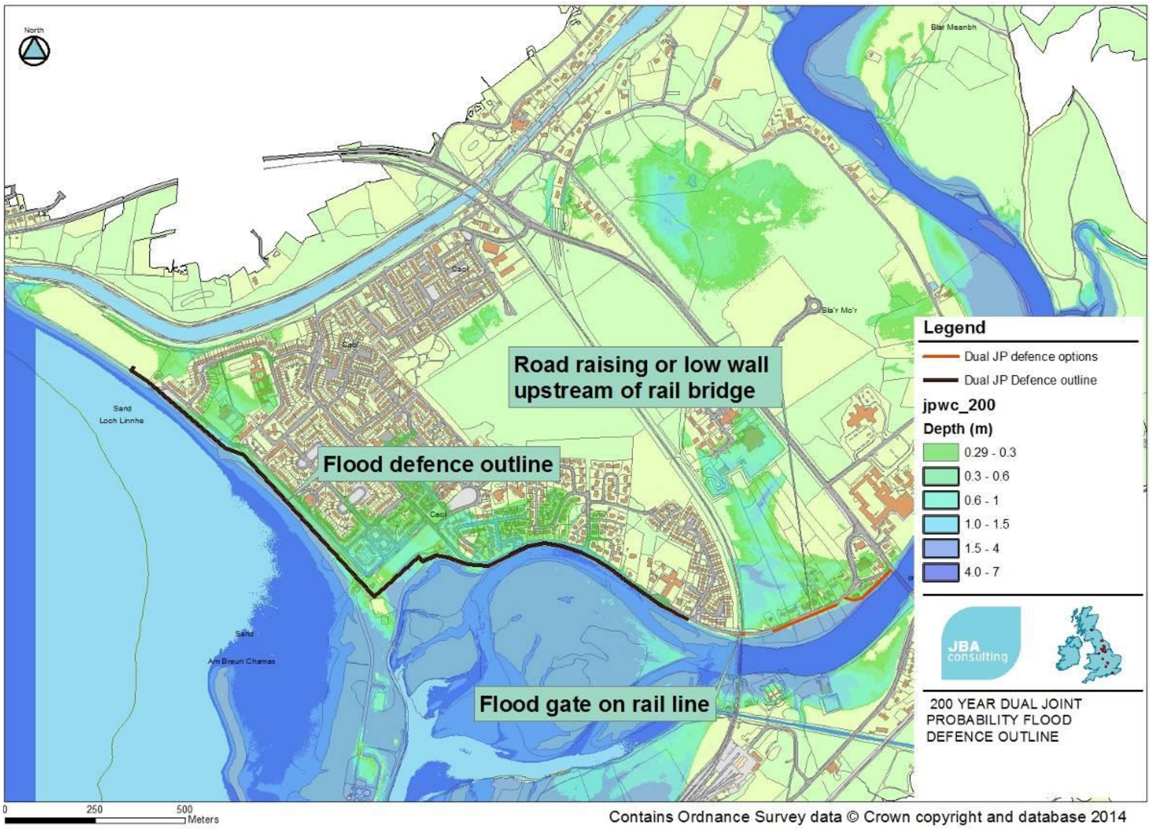
## 8.1 Options considered

The previous analysis considered a flood protection scheme (FPS) providing protection up to a 1:100 year event, either with or without an allowance for climate change.

The flood protection scheme at Caol would aim to alleviate fluvial and coastal flooding and to have a positive economic impact on the town, allowing for future development within the area protected by the scheme. Therefore the scheme should aim to be designed to provide a 200 year standard of protection as this is the current standard required for planning purposes and the threshold for unacceptable flood risk.

The extent of works adapted from the 2007 Fort William Flood Study report are shown in Figure 8-1 below. The scope of this chapter is to update the analysis in terms of flood levels to inform the scheme design. No separate flood defence options have been assessed as these have previously been investigated by previous reports.

Figure 8-1: Extent of scheme defences and alignment




## 8.2 Approach

Flood levels from each modelled scenario used to determine the joint probability levels have been summarised for each section along the northern bank of the River Lochy, together with a coastal level along the Caol frontage. These results have been extracted and presented for the 1:100 year, 1:200 year and 1:500 year) floods in Tables 8-1, 8-2 and 8-3 respectively.

Indicative wall heights have been derived for each relevant section and flood scenario to inform the design stage. These are indicative as levels may vary slightly between sections and a full longitudinal profile will be required to inform designs at more appropriate channel spacing.

Table 8-1: Defence height for 1:100 year standard of protection (mAOD)

| 1:100 year water level surface for each scenario (mAOD) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Label | Fluvial | JP Fluvial | JP Tidal | JP Fluvial & Tidal | JP Wave & Tidal | JP Dual combination | Right bank level |
| LOCH_1950 | 6.62 | 6.65 | 4.52 | 6.65 | 4.97 | 6.65 | Variable |
| LOCH_1780 | 6.33 | 6.38 | 4.51 | 6.38 | 4.97 | 6.38 | 7.16 |
| LOCH_1626 | 6.38 | 6.43 | 4.51 | 6.43 | 4.97 | 6.43 | 6.91 |
| LOCH_1408 | 5.91 | 5.98 | 4.50 | 5.98 | 4.97 | 5.98 | 6.6 |
| LOCH_1395 | 5.02 | 5.01 | 4.50 | 5.01 | 4.97 | 5.01 | 9.26 |
| 200_1324 | 5.05 | 5.03 | 4.50 | 5.03 | 4.97 | 5.03 | 6.33 |
| 200_1248 | 4.71 | 4.69 | 4.49 | 4.69 | 4.97 | *4.69 | 4.72 |
| 200_1147 | 4.83 | 4.84 | 4.50 | 4.84 | 4.97 | *4.84 | 4.62 |
| 200_1001 | 4.74 | 4.79 | 4.49 | 4.79 | 4.97 | *4.79 | 3.82 |
| 200_743 | 4.41 | 4.62 | 4.49 | 4.62 | 4.97 | *4.62 | 3.74 |
| 200_529 | 4.23 | 4.53 | 4.49 | 4.53 | 4.97 | *4.53 | 4.11 |
| Beach front | - | - | - | - | 4.97 | 4.97 | - |
| Joint probability dual combination applies Joint probability wave & tidal along shore front but not within estuary.<br>* This figure does not account for the uncertainty due to wave run-up in the estuary, to reduce the risk posed by this uncertainty an increase to JP Wave & Tidal level is recommended.<br>Cross section elevations for the lower portion of the estuary are available in Appendix A.4.<br>No allowance for freeboard has been included in these figures. | | | | | | | |

Table 8-2: Defence height for 1:200 year standard of protection (mAOD)

| 1:200 year water level surface for each scenario (mAOD) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Label | Fluvial | JP Fluvial | JP Tidal | **JP Fluvial & Tidal** | JP Wave & Tidal | **JP Dual combination** | Right bank level |
| LOCH_1950 | 7.30 | 7.34 | 4.73 | **7.34** | 5.27 | **7.34** | Variable |
| LOCH_1780 | 7.05 | 7.10 | 4.72 | **7.10** | 5.27 | **7.10** | 7.16 |
| LOCH_1626 | 7.18 | 7.22 | 4.71 | **7.22** | 5.27 | **7.22** | 6.91 |
| LOCH_1408 | 6.73 | 6.79 | 4.71 | **6.79** | 5.27 | **6.79** | 6.6 |
| LOCH_1395 | 5.20 | 5.20 | 4.70 | **5.20** | 5.27 | ***5.20** | 9.26 |
| 200_1324 | 5.25 | 5.25 | 4.70 | **5.25** | 5.27 | ***5.25** | 6.33 |
| 200_1248 | 4.91 | 4.91 | 4.70 | **4.91** | 5.27 | ***4.91** | 4.72 |
| 200_1147 | 5.00 | 5.08 | 4.70 | **5.08** | 5.27 | ***5.08** | 4.62 |
| 200_1001 | 4.91 | 5.02 | 4.70 | **5.02** | 5.27 | ***5.02** | 3.82 |
| 200_743 | 4.57 | 4.84 | 4.70 | **4.84** | 5.27 | ***4.84** | 3.74 |
| 200_529 | 4.46 | 4.75 | 4.70 | **4.75** | 5.27 | ***4.75** | 4.11 |
| Beach front | - | - | - | - | 5.27 | **5.27** | Varies |
| Joint probability dual combination applies Joint probability wave & tidal along shore front but not within estuary.<br>* This figure does not account for the uncertainty due to wave run-up in the estuary, to reduce the risk posed by this uncertainty an increase to JP Wave & Tidal level is recommended.<br>Cross section elevations for the lower portion of the estuary are available in Appendix A.4.<br>No allowance for freeboard has been included in these figures. | | | | | | | |

Table 8-3: Defence height for 1:500 year standard of protection (mAOD)

| 1:500 year water level surface for each scenario (mAOD) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Label | #Fluvial (200cc) | JP Fluvial | JP Tidal | JP Fluvial & Tidal | JP Wave & Tidal | JP Dual combination | Right bank level |
| LOCH_1950 | 8.45 | 8.37 | 5.01 | 8.37 | 5.58 | 8.37 | Variable |
| LOCH_1780 | 8.28 | 8.07 | 5.01 | 8.07 | 5.58 | 8.07 | 7.16 |
| LOCH_1626 | 8.43 | 8.18 | 5.00 | 8.18 | 5.58 | 8.18 | 6.91 |
| LOCH_1408 | 8.05 | 7.77 | 5.00 | 7.77 | 5.58 | 7.77 | 6.6 |
| LOCH_1395 | 5.54 | 5.45 | 4.99 | 5.45 | 5.58 | *5.45 | 9.26 |
| 200_1324 | 5.58 | 5.53 | 4.99 | 5.53 | 5.58 | *5.53 | 6.33 |
| 200_1248 | 5.24 | 5.18 | 4.99 | 5.18 | 5.58 | *5.18 | 4.72 |
| 200_1147 | 5.26 | 5.25 | 4.99 | 5.25 | 5.58 | *5.25 | 4.62 |
| 200_1001 | 5.17 | 5.20 | 4.99 | 5.20 | 5.58 | *5.20 | 3.82 |
| 200_743 | 4.92 | 4.98 | 4.99 | 4.99 | 5.58 | *4.99 | 3.74 |
| 200_529 | 4.81 | 4.88 | 4.99 | 4.99 | 5.58 | *4.99 | 4.11 |
| Beach front | - | | | | 5.58 | 5.58 | Varies |

Joint probability dual combination applies Joint probability wave & tidal along shore front but not within estuary.
* This figure does not account for the uncertainty due to wave run-up in the estuary, to reduce the risk posed by this uncertainty an increase to JP Wave & Tidal level is recommended.
No allowance for freeboard has been included in these figures.
# 500 year event is close to the 200 year + climate change event. 200year+cc = 2493 $m^3$/s. 500year = 2449 $m^3$/s
Cross section elevations for the lower portion of the estuary are available in Appendix A.4
No allowance for freeboard has been included in these figures.

The results above clearly indicate that the extent of scheme defence layout does not vary significantly between the 1:100 year and 1:200 year option (the 1:200 year option extends as far upstream as Section 200_1248 to 200_1324, compared with the 100 year option extending to between Section 200_1324 and 200_1248. The differences in flood wall heights are also not too significant (maximum wall height differences of 0.2m).

### 8.2.1 Impact of climate change

The results for the 1:500 year flood are essentially the same as the 1:200 year plus climate change for the fluvially controlled section of the River Lochy. Table 8-3 clearly indicates that this option, and providing a scheme to protect against the 1:200 flood with an allowance for climate change would be significantly greater both in extent of works and elevation of defences. This is particularly the case for the reach upstream of the Railway Bridge (Section LOCH_1408).

### 8.2.2 Freeboard

To achieve the required standard of protection a freeboard is added to the estimated peak water level to give a high level of confidence that the scheme will protect to the standard intended. The freeboard should take into account physical processes such as waves as well as a safety margin to allow uncertainties to the estimation of peak flows and the prediction of peak water levels.

### 8.2.3 Wave run-up and overtopping rates

Wave run-up is effected by a number of factors. Wave run-up has been calculated based on beach slope and wind speed while current has been considered. Taking proactive measures to reduce wave run-up such as rock armour, setting back berms or a recurve wall could reduce the defence heights along the sea front. Furthermore an average slope was used to define the wave run-up; further detailed analysis along the frontage could change the defence heights at the detailed design stage.

No wave overtopping calculations have been carried out as part of derived defence height. Overtopping of a flood defence wall into an urban area must be limited to rate which allows for safe access through the area on foot, and available/designed drainage behind the defence. Measures to reduce wave overtopping include recurve walls or fronting the base of the wall with rubble. It is recommended that detailed design works take into account these design options to optimise the defence height along the frontage.

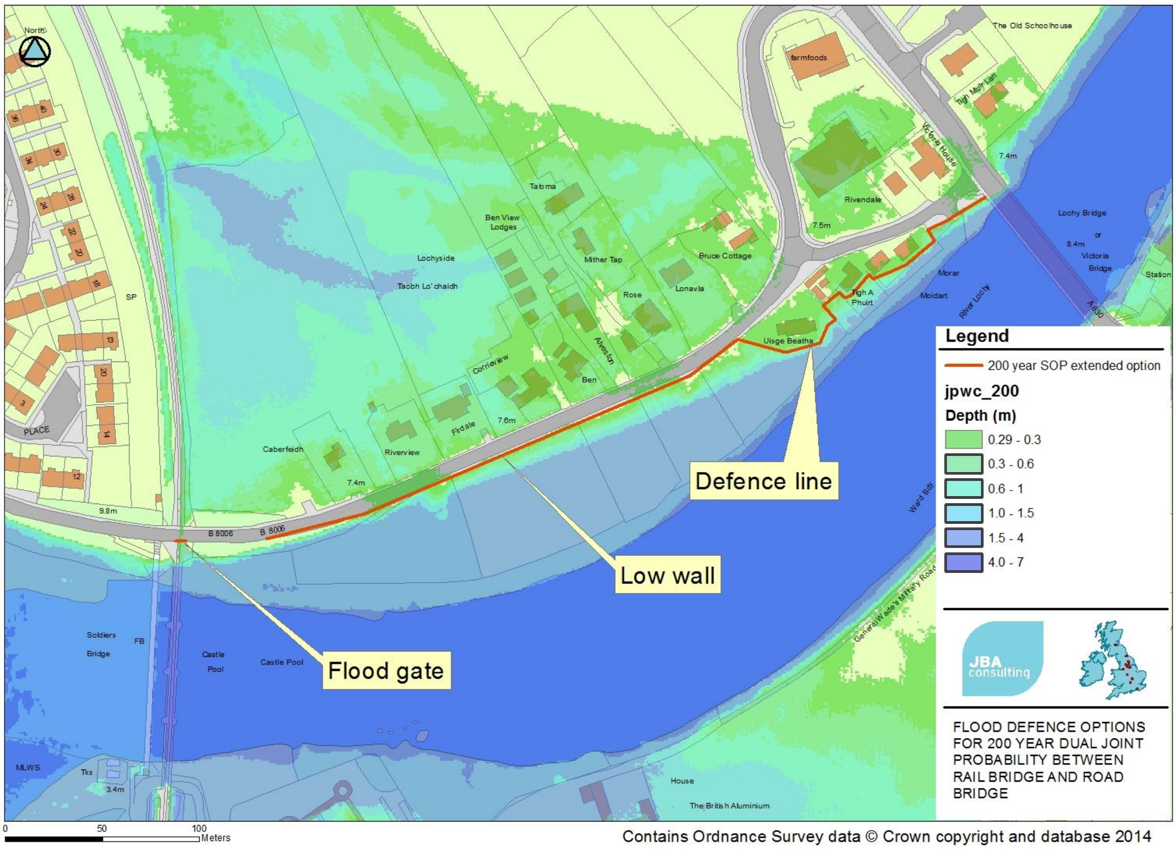
## 8.3 Impact of flood risk upstream of railway

The new flood levels upstream of the Railway Bridge are higher than previous analysis, which has implications for the design, extent and alignment of the flood defences, should a complete and all-inclusive Flood Protection scheme be required. There are three aspects to consider:

- The need for a low wall along Kilmallie Road between the rail bridge and the A830. This will be required to prevent a very shallow depth of flooding over this road at the 1:200 year flood. The maximum depth is approximately 0.18m. The wall would therefore be required mainly to provide sufficient freeboard along this section of bank. The appropriate freeboard height would need to take cognisance of the risks associated with bridge blockage and the modelling assumptions used.
- The need for a flood wall downstream of the A830 and along the top of bank behind the Uisge Beatha, Tigh A Phuirt and self-catering properties.
- The need for either a gate across the railway beneath the A830 or extended embankments either side of the railway to prevent flooding of the railway and bypassing of flood events through this gap in the right bank.

These elements are presented along with the 1:200 year flood outline in Figure 8-2 below. The above defences are only required to provide a consistent 1:200 year standard of protection to the reach upstream of the railway.

Figure 8-2: Detail of indicative extended works required upstream of the railway bridge.




## 8.4 Flood protection options

Three flood protection scenarios are proposed in this report. The first option is the flood defence outline proposed in the 2007 Fort William Flood Study which extends along the Caol sea front to downstream of the rail bridge. This is the baseline defence option. The other two options are variations on this base line. The options are as follows:

- 1:200 year Standard of Protection (SOP) original option - Baseline defence to protect to the 1:200 year flood event.

- 1:100 year SOP option - Same as the base line defence except the level of protection is lowered to the 1:100 year standard.
- 1:200 year SOP extended option - Base line defence with protection provided upstream of the rail bridge as shown in Table 8-2.

Cost benefit analysis for the above options are presented in Table 10-4.

# 9 Flood damage assessment

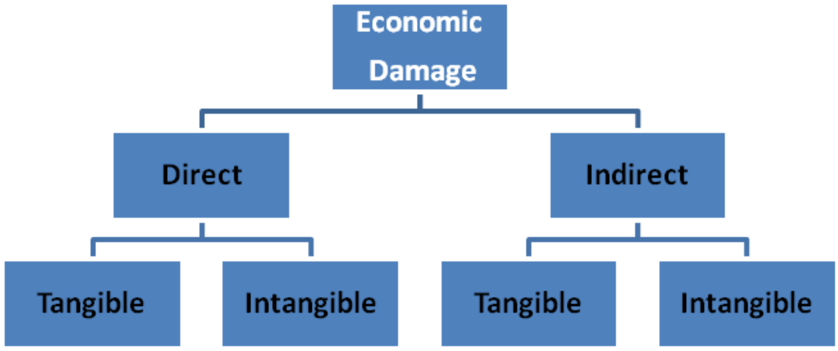
## 9.1 Introduction

Cost estimates for the scheme were previously estimated as part the Fort William Flood Study by Scott Wilson in 2007. These costs have been updated to take into account the revised modelling undertaken for the purpose of this study.

## 9.2 Methodology

Flood damage assessment can include direct, indirect, tangible and intangible aspects of flooding, as shown in the Figure 9-1. Direct damages are the most significant in monetary terms, although the MCM and additional research provide additional methodologies, recommendations and estimates to account for the indirect and intangible aspects of flood damage.

Figure 9-1: Aspects of flood damage




Flood damage estimates have been derived for the following items:

1. Direct damages to residential properties;
2. Direct damages to commercial and industrial properties;
3. Indirect damages (emergency services);
4. Intangible damages associated with the impact of flooding;
5. Damage to vehicles;
6. Emergency evacuation and temporary accommodation costs.

The following assumptions and additional data were used to improve and provide the necessary information to supplement the above datasets.

### 9.2.1 Data and assumptions

The FHRC Multi Coloured Manual (MCM) provides standard flood depth/direct damage datasets for a range of property types, both residential and commercial. This standard depth/damage data for direct and indirect damages has been utilised in this study to assess the potential damages that could occur under each of the options. Flood depths within each property have been calculated from the hydraulic modelling by comparing predicted water levels at each property to the LiDAR ground levels.

A mean, minimum and maximum flood depth within each property is derived by JBA's in-house Flood Risk Metrics (FRISM) tool based on the range of flood depths within the building footprint. At this stage, the mean flood damages have been presented although commentary on this aspect is given in 9.3.2.

The following assumptions, presented in the Table 9-1, were used to generate direct flood damage estimates.

Table 9-1: Damage considerations and method

| Aspect | Values used | Justification |
|---|---|---|
| Flood duration | <12hrs | Although flooding is likely to pond, water is not anticipated to inundate properties for prolonged periods. |
| Residential property type | MCM code 1 - residential sector average | Residential property types provided are unclassified. |
| Non-residential property type | Standard 2013 MCM codes applied | Best available data used. |
| Upper floor flats | Upper floor flats have been removed from the flood damage estimates. | Whilst homeowners may be affected it is assumed that no direct flood damages are applicable. |
| MCM damage type | MCM 2013 data with no basements | Most up to date economic analysis data used. Basements are not appropriate for the type of properties within the study area. |
| MCM flood type | MCM 2013 fluvial depth damages for combined fluvial-tidal scenario. Salt water depth damages used for tidal-wave scenario. | Best available data used. |
| Threshold level | Threshold values survey. | Best available data used. |
| Socio-economic equity | Census data used to obtain relative distributional Impacts weightings (see Section 9.2.8) | Best available data used. |
| Property areas | OS MasterMap used to define property floor areas. | Best available data used. |
| Capping value | Residential properties based on house prices from Zoopla. Commercial properties valued from rateable values for individual properties (supplied by SAA). | Best available data used. |
| Vehicle damages | £3,600 per property flooded to a depth greater than 0.35m | MCM 2013 recommendation. |
| Evacuation and rental costs | MCM Table for evacuation costs (Initial Assessment) | MCM 2013 recommendation. |
| Emergency services | 10.7% uplift factor | MCM 2013 recommendation. |
| Intangible damages | MCM Table 4.7 (value of £286 per property per year) | MCM 2013 recommendation. |

### 9.2.2 Property data set

The property data set used The Highland Council property Gazetteer as the basis for property data set.  The CAG data provided information on property address and gave an indication of the property use. The dataset was amended geographically where necessary using information from MasterMap and floor area data was extracted. The CAG property use classification was updated to the current MCM coding (MCM 2013) for the formation of the property data. Commercial properties were valued based on commercial council tax information collected from the Scottish Assessors Association website. Residential properties were valued based on current retail prices from the Zoopla website. Where the house market price for a particular street was unavailable or out of date the average property price for the postcode was selected.

A flood damage estimate was generated using FRISM. FRISM is an ArcGIS add-in that computes a range of flood risk metrics based on flood hazard and receptor data. Each property data point was mapped on to its building's footprint. FRISM was then used to calculate the damage that occurs from the depth of flooding over the floor area of the building. Both the mean (based on mean flood water depth across the building floor's area) and maximum (based on maximum flood water depth occurring over the building floor's area) flood damage estimates have been calculated and are presented in Table 9-8.

### 9.2.3 Intangible damages

Current guidance indicates that the value of avoiding health impacts of fluvial flooding is of the order of £286 per year per household. This value is equivalent to the reduction in damages associated with moving from a do-nothing option to an option with an annual flood probability of 1:100 year standard. A risk reduction matrix has been used to calculate the value of benefits for different pre-scheme standards and designed scheme protection standards.

### 9.2.4 Indirect damages

The multi coloured manual provides guidance on the assessment of indirect damages. It recommends that a value equal to 10.7% of the direct property damages is used to represent emergency costs. These include the response and recovery costs incurred by organisations such as the emergency services, the local authority and SEPA.

### 9.2.5 Indirect commercial damages

Obtaining accurate data on indirect flood losses is difficult. Indirect losses are of two kinds:

- losses of business to overseas competitors, and
- the additional costs of seeking to respond to the threat of disruption or to disruption itself which fall upon firms when flooded.

The first of these losses is unusual and is limited to highly specialised companies which are unable to transfer their productive activities to a branch site in this country, and which therefore lose to overseas competitors. The second type of loss is likely to be incurred by most Non Residential Properties (NRPs) which are flooded. They exclude post-flood clean-up costs but include the cost of additional work and other costs associated with inevitable efforts to minimise or avoid disruption. These costs include costs of moving inventories, hiring vehicles and costs of overtime working. These costs also include the costs of moving operations to an alternative site or branch and may include additional transport costs.

Chapter 5, Section 5.7 of the MCM (2013)[26] recommends estimating and including potential indirect costs where these are the additional costs associated with trying to minimise indirect losses. This is by calculating total indirect losses as an uplift factor of 3% of estimated total direct NRP losses at each return period included within the damage estimation process.

### 9.2.6 Evacuation losses

The MCM (2013) provides guidance on the losses associated with evacuation (getting people safely out of homes during an event and temporary accommodation costs whilst properties are repaired). Costs recommended are based on flood depths and property type as shown in the Table 9-2.

Table 9-2: Evacuation losses from the FHRC MCM (2013)

| MAXIMUM DEPTH INSIDE PROPERTY (CM) | EVACUATION COSTS BY PROPERTY TYPE (£) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DETACHED | | | SEMI-DETACHED | | | TERRACED | | | FLAT | | |
| | Low | Mid | High | Low | Mid | High | Low | Mid | High | Low | Mid | High |
| 0-1 | 681 | 1,007 | 1,631 | 609 | 865 | 1,419 | 588 | 838 | 1,387 | 532 | 782 | 1,330 |
| 1-10 | 1,308 | 1,928 | 3,126 | 1,169 | 1,653 | 2,714 | 1,126 | 1,600 | 2,652 | 1,018 | 1,491 | 2,540 |
| 10-20 | 2,511 | 3,662 | 5,954 | 2,232 | 3,108 | 5,126 | 2,146 | 3,002 | 5,001 | 1,928 | 2,781 | 4,776 |
| 20-30 | 2,694 | 3,928 | 6,387 | 2,394 | 3,334 | 5,499 | 2,302 | 3,221 | 5,364 | 2,069 | 2,984 | 5,123 |
| 30-60 | 3,625 | 5,269 | 8,575 | 3,216 | 4,458 | 7,363 | 3,090 | 4,303 | 7,179 | 2,772 | 3,980 | 6,850 |
| 60-100 | 4,342 | 6,299 | 10,256 | 3,848 | 5,320 | 8,793 | 3,696 | 5,134 | 8,572 | 3,312 | 4,744 | 8,175 |
| 100+ | 6,965 | 10,045 | 16,383 | 6,154 | 8,438 | 13,981 | 5,905 | 8,132 | 13,617 | 5,275 | 7,491 | 12,965 |

[26] Penning-Rowsell et al., 2013. Flood and Coastal Erosion Risk Management - A Manual for Economic Appraisal

Total property counts per return period for each depth classification have been extracted and used to total evacuation losses based on Table 9-2 (assuming Mid values and semi-detached properties - the most prominent property type in Caol).

### 9.2.7 Vehicle losses

Chapter 4, Section 4.5.7 of the MCM (2013) recommends that the average loss associated with vehicle damage during flood events should be determined using a value of £3,600 per property flooding to a depth greater than 0.35m. This value has been applied to all properties flooding to a depth greater than 0.35m within Caol for each return period flood event assessed and the AAD and PVd calculated as normal.

### 9.2.8 Socio-economic equity

Work on the impacts of flooding on individuals has shown that flooding may affect people according to aspects such as their income. The rationale being that a loss will matter more to a person on low income compared to someone with a high income. Current advice from the Scottish Government, based on advice from the Treasury Green Book recommends that Distributional Impacts (DI) analysis should be undertaken if it is 'necessary and practical'.

Assessing whether it is necessary is based on the mix of social grades and levels of income within the appraised area. Analysis of the 2001 Census data for Caol indicates that there are a high proportion of lower social group households. Table 9-3 illustrates this proportion and indicates that 49% of people in Caol are in the 'DE' social grade. Thus, the 'DE' social grade is predominant and the analysis of DI is deemed to be necessary.

Table 9-3: Proportion of social grades within Caol

| Location | All people | AB | C1 | C2 | D | E |
|---|---|---|---|---|---|---|
| Caol | 2369 | 203 (9%) | 453 (19%) | 541 (23%) | 673 (28%) | 499 (21%) |
| The total number of people represents those aged 16+ for which a grade can be applied. | | | | | | |

The above data is believed to represent the area at risk of flooding well and indicates that a significant number of the properties protected by a Caol FPS are predominantly a lower social grade. It is recommended that the residential damage estimates should be scaled based on the social grade weighting factors as shown in Table 9-4 below.

Table 9-4: Total weighted factors by social grade group

| Class | AB | C1 | C2 | DE |
|---|---|---|---|---|
| Weighting | 0.74 | 1.12 | 1.22 | 1.64 |
| % of properties | 9 | 19 | 23 | 49 |
| Factors are provided in Chapter 5 (section 4.1.22) of the Scottish Government's Flood Prevention Scheme guidance document. | | | | |

The total return period damages have been scaled by the social grade weighting factors and the percentage of people in each social grade.

## 9.3 Properties at risk

Table 9-5 shows the total number of properties inundated for each return period for both joint probability scenarios. Flood depth maps are provided in Appendix C for the "Joint probability fluvial & tidal" and the "Joint probability wave & tidal" scenarios. The "Joint probability dual combination" is formed by counting all the properties affected by either of the two joint probability scenarios. Where flooded properties occur in both scenarios, only the highest depth and damage has been extracted to avoid double counting.

Table 9-5: Number of properties flooded within appraisal area for the Do Nothing scenario

| Scenario | 2 year | 5 year | 10 year | 20 year | 50 year | 100 year | 200 year | 500 year |
|---|---|---|---|---|---|---|---|---|
| Joint probability fluvial & tidal | 0 | 0 | 2 | 17 | 44 | 95 | 176 | 261 |
| Joint probability wave & tidal | 0 | 7 | 30 | 49 | 83 | 132 | 202 | 262 |
| Joint probability dual combination | 0 | 7 | 30 | 50 | 93 | 171 | 296 | 387 |
| Properties counted are those where the flood level is above finished floor level of the property. | | | | | | | | |

The breakdown between residential and non-residential properties for the combined damage scenario is provided in the table below and illustrates that the majority of flood damages are incurred by the high proportion of residential properties.

Table 9-6: Total properties protected and flood damages

| Scenario | Properties at risk | Total direct property damages (AAD) | Proportion of total damage |
|---|---|---|---|
| Residential | 274 | £399,000 | 98% |
| Non-residential | 23 | £7,000 | 2% |

### 9.3.1 Key beneficiaries

The top 10 properties with highest flood damages from all sources have been listed in Table 9-7 below. This illustrates that the highest flood damage results from residential properties predominantly on Alexander Square and Glenmallie Road. This area corresponds to the area of previous known flooding and ponding of flood water. The reason for high flood damages relates to high flood depths and frequent flooding in this area (all are flooded at the 1:5 year flood).

Table 9-7: Worst case joint probability tidal/fluvial combinations

| Ranking | Property address | Market value (£) | PVd Capped? | PVd (£k) |
|---|---|---|---|---|
| 1 | Serenata, 15 Mossfield Drive | 187,500 | No | 167.70 |
| 2 | Tigh A Chladaich, Glenmallie Road | 154,532 | Yes | 154.53 |
| 3 | 5 Alexander Square | 147,139 | Yes | 147.14 |
| 3 | 12 Alexander Square | 147,139 | Yes | 147.14 |
| 3 | 6 Alexander Square | 147,139 | Yes | 147.14 |
| 3 | 2 Alexander Square | 147,139 | Yes | 147.14 |
| 3 | 14 Alexander Square | 147,139 | Yes | 147.14 |
| 3 | 9 Alexander Square | 147,139 | Yes | 147.14 |
| 9 | 14 Glenmallie Road | 154,532 | No | 138.89 |
| 10 | 16 Glenmallie Road | 154,532 | No | 131.40 |

Some of the above properties have Property Level Protection (PLP) fitted to the properties (airbrick covers are visible on Google StreetView). Whilst PLP may be fitted, there is no evidence that the full suite of measures required to protect against all flood depths predicted exists (e.g. door guards, sump pumps and non-return valves). Indeed, the predicted flood depths for the 1:50 year flood event are greater than 0.6m and may thus overtop the defences.

### 9.3.2 Impact of depths assigned to properties

A property threshold level survey was undertaken for this study. JBA's flood damage assessment tool (FRISM) assesses the impact of variable flood depths over a property curtilage and generates flood damages based on the minimum, average and maximum depth within each building footprint. Although property thresholds are taken into account the maximum flood depths have been used for the purpose of this study.

## 9.4 Flood damages

### 9.4.1 Direct property flood damage

The event damages for each option are provided in Table 9-8 below. These represent the total potential flood damages based on the joint probability and combined worst case scenario. The damages include socio-economic equity adjustments.

Table 9-8: Direct property flood damage for each scenario with DI (£k)

| Scenario | 2 year | 5 year | 10 year | 25 year | 50 year | 100 year | 200 year | 500 year |
|---|---|---|---|---|---|---|---|---|
| Joint probability fluvial & tidal | 0 | 0 | 108 | 479 | 1,851 | 4,136 | 7,607 | 12,171 |
| Joint probability wave & tidal | 5 | 206 | 912 | 1,633 | 2,838 | 4,432 | 7,293 | 10,245 |
| Joint probability dual combination | 5 | 206 | 912 | 1,706 | 3,680 | 6,733 | 12,243 | 18,015 |

### 9.4.2 Summary of flood damages

A summary of total flood damages (except intangible damages which are treated separately in the analysis) are provided in Table 9-9. The AAD from these values is generated and converted into Present Value damages (PVd) as shown in Table 9-10.

Table 9-9: Total flood event damage for each scenario with DI (£k) (includes indirect damages, but not intangibles)

| Scenario | 2 year | 5 year | 10 year | 25 year | 50 year | 100 year | 200 year | 500 year |
|---|---|---|---|---|---|---|---|---|
| Joint probability fluvial & tidal | 0 | 0 | 141 | 599 | 2,245 | 5,053 | 9,215 | 14,894 |
| Joint probability wave & tidal | 6 | 266 | 1,133 | 2,045 | 3,567 | 5,613 | 9,165 | 12,976 |
| Joint probability dual combination | 6 | 266 | 1,133 | 2,128 | 4,546 | 8,318 | 14,972 | 22,095 |

Table 9-10: Summary of total flood damages (£k)

| Scenario | AAD damages | PVd damages | PVd capped | Intangible PVd |
|---|---|---|---|---|
| Joint probability fluvial & tidal | 200 | 5,964 | 5,840 | 950 |
| Joint probability wave & tidal | 423 | 12,597 | 10,539 | 1,180 |
| Joint probability dual combination | 509 | 15,166 | 13,061 | 1,635 |

### 9.4.3 Indirect and intangible damages

The total indirect and intangible present value damages (PVd) for the options are provided in Table 9-11 below. This indicates that the residential indirect and intangible damages are small when compared to the direct flood damages.

Table 9-11: Indirect and intangible annual average flood damages (PVd) (£k)

| Scenario | Emergency services | Vehicle damage | Evacuation costs | Intangible damages |
|---|---|---|---|---|
| Joint probability fluvial & tidal | 379 | 208 | 500 | 950 |
| Joint probability wave & tidal | 786 | 515 | 1,268 | 1,180 |
| Joint probability dual combination | 956 | 542 | 1,413 | 1,635 |

# 10 Cost benefit analysis

## 10.1 Introduction

This section discusses the economic appraisal carried out during this study. The methods of calculating the benefits and costs are outlined together with an assessment of the benefit-cost ratios for the range of options assessed.

Benefit cost analysis looks at a flood risk management strategy or practice and compares all the benefits that will be gained by its implementation to all the costs that will be incurred during the lifetime of the project.

In accordance with the Scottish Government appraisal guidance, benefits are taken as annual average damages avoided, expressed as their present value using Treasury discount rates. These are compared with the whole life cost of the capital and maintenance costs of selected options, expressed as present value. If the benefits exceed the costs for the option, the scheme is deemed to be cost effective and worthwhile for promotion.

Benefits are assessed as the flood damages that will be avoided by the implementation of a project. To calculate these it is necessary to assess the damages that are likely to occur under both the Do Nothing and Do Something scenarios. The benefits of any particular Do Something option can then be calculated by deducting the Do Something damages from the Do Nothing damages.

## 10.2 Guidance and standard data

The benefit-cost analysis of the flood alleviation options has been carried out based on the methodology given in the 'Flood Prevention Schemes: Guidance for Local Authorities' report[27] by the Scottish Executive, April 2005. The principles are summarised as follows:

- Derive the damages associated with do-nothing;
- Derive the damages associated with each scheme option;
- Derive the benefits (damages avoided) associated with each option;
- Derive the costs for each option; and
- Derive the benefit-cost ratios for each option.

In all cases, the benefits and costs are transformed into present values.

### 10.2.1 Assumptions

The following assumptions have been made:

- The life span of the scheme is assumed to be 100 years.
- Discounting of damages and scheme costs have been calculated using the revised Treasury discount rates as recommended by the 2003 revision to the Green Book[28]. This revision set a time varying discount rate of 3.5% for the first 30 years, 3% for years 31-75 and 2.5% for years 76-125. This equates to a Present Value factor of 29.81.

### 10.2.2 Climate change

Whilst climate change scenarios have been modelled to inform the level of flood risk, climate change has not being considered as part of the full joint probability assessment and flood damages. This is partly because additional design works would need to be considered to enable the scheme to be protected up to and including future climate change. Whilst this was previously considered by the 2007 report, the extent of flooding is significantly greater for climate change scenarios and the scheme design would need to be updated to reflect this.

[27] Flood Prevention Schemes: Guidance for Local Authorities. April 2005. Scottish Executive.
[28] The Green Book: Appraisal and Evaluation in Central Government, January 2003. HM Treasury.

## 10.3 Scheme costs

Scheme costs have not been updated for the purpose of this assessment. The original costs generated as part of the 2007 Fort William Flood Study, Caol and Lochyside Feasibility Report were £5.72m for the 100 year climate change scheme. These costs were based on a 2007 value and included direct construction costs, accommodation works for utilities, a 15% Preliminaries allowance, a 30% contingency allowance (in accordance with Treasury and Scottish Government guidance for a scheme level costing), and detailed design costs.

### 10.3.1 Uplift of costs to reflect additional works upstream of rail bridge

Although the flood levels and standard of protection proposed differ, as the extent of works are anticipated to be the same, the costs have not been revised at this stage, other than to reflect the additional works associated with extending the scheme upstream above the railway bridge. These additional works assume the following:

- 265m length of low wall along Kilmallie Road between rail bridge and A830 (£150/m)
- 160m length of flood defence wall with brick facing immediately downstream of A830 (£1320/m)
- Gate across railway beneath A830 (£20,000)
- Total additional cost = £271,000

### 10.3.2 Uplift of cost estimate to 2014 values

The above costs have been updated to allow for construction price changes between 2007 and 2014. The resulting capital costs have therefore been updated based on Output Price Index for New Construction[29] (public, non housing index) based on the following assumptions:

- 2007 Q2 index value of 109.1
- 2014 Q1 index value of 118.9 (latest available)
- Uplift factor of 1.09 or 9%

Based on the above uplift, the following costs are generated as shown in the Table 10-1. Three scenarios have been costed:

- 1:200 year standard of protection to the rail bridge (original extent of scheme). This is the 2007 costs with no adjustment other than updating the costs to 2014 values.
- 1:100 year standard of protection. This is the 2007 costs with no adjustment other than updating the costs to 2014 values.
- 1:200 year standard of protection extended upstream of the rail bridge. This is the 2007 costs updated with an allowance for works to extend the works upstream.

The above option costs assume that the costs are still valid and, whilst flood levels have changed, the cost variations by defence height are not significant. More detailed costing is required to confirm this assumption.

[29] https://www.gov.uk/government/publications/bis-quarterly-construction-price-and-cost-indices-january-to-march-2014

Table 10-1: Updated cost estimates (£k)

| Cost element | 1:200 SOP original option cost estimate (£k) | 1:100 SOP option cost estimate (£k) | 1:200 SOP extended option cost estimate (£k) |
|---|---|---|---|
| Previous cost estimate | 3,643 | 3,643 | 3,643 |
| Updated cost estimate for additional works | 3,643 | 3,643 | 3,914 |
| Updated cost to 2014 | 3,971 | 3,971 | 4,266 |
| Preliminaries (15%) | 596 | 596 | 640 |
| Detailed design costs (5%) | 199 | 199 | 213 |
| Land acquisition (not included) | 0 | 0 | 0 |
| Sub total | 4,766 | 4,766 | 5,119 |
| Total costs including 30% optimism bias | 6,196 | 6,196 | 6,655 |

An optimism bias of 30% has been retained at this stage of the appraisal following Scottish Government guidance. The value of £6.7 million should be used by The Highland Council for budgeting purposes.

## 10.4 Benefit-cost results for proposed scheme

A summary of the flood damage results for the proposed defence option based on the fluvial and tidal joint probability scenario are provided in the Table 10-2. The results suggest that the scheme based on the joint probability of fluvial and tidal conditions is unlikely to be justified as the economic benefits of protecting against flood risk are lower than the current cost estimates.

Table 10-2: Summary of benefit-cost calculation for fluvial and tidal joint probability (£k)

| | Do Nothing | 1:200 SOP original | 1:100 SOP | 1:200 SOP extended |
|---|---|---|---|---|
| PV damage (£k) | 6,791 | 3,896 | 3,014 | 1,836 |
| PV damage avoided (£k) | - | 2,895 | 3,777 | 4,955 |

A summary of the flood damage results based on the tide and wave joint probability scenario are provided in Table 10-3. The damages avoided are much greater for this scenario, suggesting that the scheme based on the joint probability of tide and wave conditions can be justified as the economic benefits of protecting against flood risk are greater than the current cost estimates.

It is also important to note that the flood levels assumed for this scenario assume that the maximum tide and wave run-up levels derived from the analysis can flood inland and would pond to these levels in the area up to Kilmallie Road. Further 2D modelling may be required to confirm that this is the case.

Table 10-3: Summary of benefit-cost calculation for wave run-up and tidal joint probability (£k)

| | Do Nothing | 1:200 SOP original | 1:100 SOP | 1:200 SOP extended |
|---|---|---|---|---|
| PV damage (£k) | 11,719 | 1,552 | 2,829 | 1,552 |
| PV damage avoided (£k) | - | 10,167 | 8,890 | 10,167 |

The damages for the combined results from both joint probability results are given in the Table 10-4. It is important to remember that these damages are not a combined total of the two results tables above, but based on the combined maximum depths and damages from each; the damage totals are therefore not double counted.

Table 10-4: Summary of benefit-cost calculation for dual joint probability (£k)

| | Do Nothing | 1:200 SOP original | 1:100 SOP | 1:200 SOP extended |
|---|---|---|---|---|
| Total PV costs (£k) | - | 4,766 | 4,766 | 5,119 |
| Total PV costs + Optimism bias (£k) | - | **6,196** | **6,196** | **6,655** |
| PV damage (£k) | 14,727 | 2,548 | 4,526 | 2,567 |
| PV damage avoided (£k) | - | 12,178 | 10,174 | 12,160 |
| Net present value (£k) | - | 5,983 | 3,974 | 5,506 |
| **Benefit-cost ratio** | **-** | **1.97** | **1.64** | **1.83** |

### 10.4.1 Economic preferred option

The three options assessed are economically viable with benefit-cost ratios greater than 1. Based on the economic appraisal carried out, the preferred option is the 1:200 SOP which is protection to the whole of Caol up to the rail bridge to the 1:200 year flood based on the existing defence alignment. This option has a benefit-cost ratio of 2.

The 1:200 SOP extended option which provides an all-inclusive flood protection to Caol is also economically viable at a slightly lower benefit-cost ratio of 1.8. The 1:200 SOP not only protects a larger number of properties but also protects access along the B8006 which could be compromised during the 1:200 year event. With a detailed survey and engagement with the effected land owners the cost of the extended defences could be reduced.

Whilst the preferred option for flood defences appears to offer a good cost effective scheme to protect Caol and Lochyside, The Highland Council may wish to further consider alternative sub-options prior to progressing with the scheme. These may include:

- The standard of protection to be offered.
- Whether the inclusion of climate change is realistic and cost effective.
- Whether Property Level Protection should be extended or offered in the short term to residents at risk whilst the scheme is progressed.

# 11 Conclusions and recommendations

A complete revision to the hydrological, tide and wave inputs to the Caol and Lochyside Flood Protection Scheme has been completed and the implications for scheme design presented. This analysis has fed through to a revised flood damage and economic appraisal to determine whether the scheme is economically viable and should continue through to the next stage; design and costing.

The flood risk to Caol and Lochyside is complicated by the dynamic nature of the watercourse and estuary and the combined flood risk from a number of sources. Best available data has been used to provide a new hydraulic model and inputs to determine current and future flood risk to the site.

The analysis undertaken suggests that whilst flood levels differ from previous analysis, the broad defence alignments generated by the previous 2007 study are still applicable, although detailed design will be required to modify defence heights and elevations through the reach.

Analysis shows that the original defence extent provides a 1:200 year standard of protection as far as the rail bridge. To provide a complete and all-inclusive scheme that protects all properties within the Caol and Lochyside area the scheme would need to be extended upstream of the rail bridge, although there are complications associated with this option.

Flood risk to the railway at these extreme events should be discussed between Network Rail and The Highland Council to consider; the implications for flood risk to the railway, bypassing of the defences at the point where the railway goes beneath the B9008 road and the need for additional embankment works along the railway or some sort of temporary gate/barrier at this location.

The economic analysis was carried out for three options:

- 1:200 year original,
- 1:100 year original and
- 1:200 year extended.

The analysis shows all three options are economically viable. With a benefit cost ratio of 2, the 1:200 year original option has the highest benefit cost ratio however the 1:200 extended, having only a slightly lower benefit cost ratio, protects a greater number of properties and prevents access along the B8006 from being comprised.

Whilst there are some assumptions regarding the flood damages and level of properties within the study area, the benefit-cost ratio of the options assessed is greater than 1 and therefore represents a robust situation; a benefit cost ratio greater than 2 indicates that the costs could be doubled, or the benefits could be overestimated by 100% and the scheme would still be worthwhile.

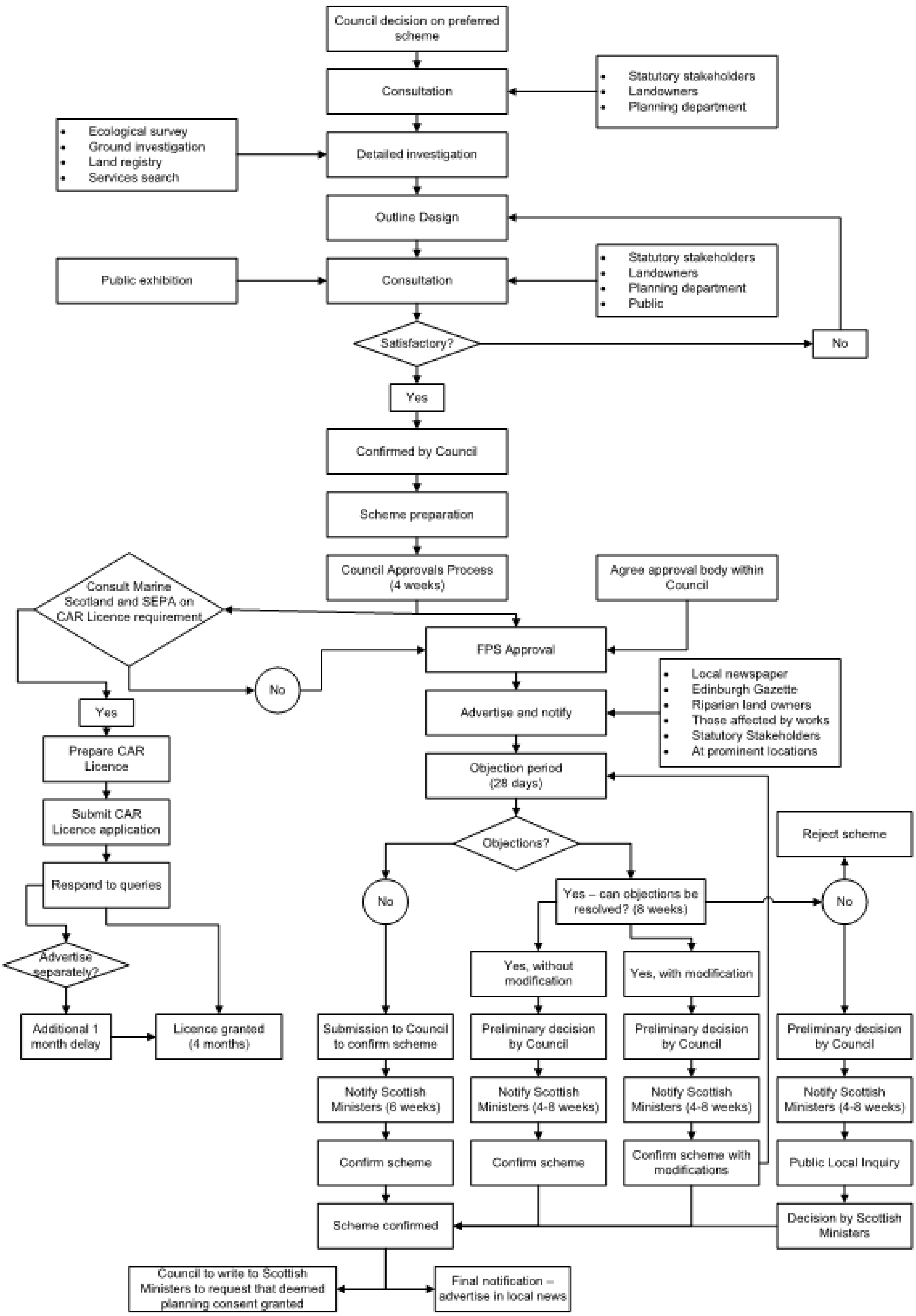
Further decisions and additional work should now be considered and undertaken by The Highland Council. Additional considerations may include the following:

- Continuing collation of calibration data, especially at high flow and tide conditions to help calibrate the model.
- Measures to reduce wave run-up heights and wave overtopping to decrease flood defence levels.
- The effect of climate change and the level of protection provided when climate change is considered.
- Geomorphological or repeat surveys to assess longer term changes in bed levels.
- Revised cost estimates.
- Stakeholder consultation.
- Consideration of surface water risks and design requirements.
- Consideration of the use of Property Level Protection in the short term prior to scheme completion.
- Consideration of works phasing.

### 11.1.1 Development of FPS

The Scottish Government is developing a set of guidelines to assist with the development of schemes and Flood Risk Management in general. At present guidance and the Act is focused on scheme development once all the mapping and risk assessment is undertaken by 2015. The key aspect is that the planning and consultation will be undertaken in the basin and local plan stages removing the requirement for planning permission. However, in the transitional stage consultation will be required. Prior to guidance, engagement with the Scottish Government's Flood Policy Team may be required. The process provided in Figure 8-1 is recommended.

Figure 11-1: Flood protection scheme process as defined under the Flood Protection (Scotland) Act 2009



# Appendices

# A Appendix - Joint probability results

## A.1 Coastal - Water level with corresponding wind speed

| Joint probability return period (years) | Water level (mAOD) | Wind speed (m/s) |
|---|---|---|
| T1 | 2.45 | 21.90 |
| T1 | 2.99 | 14.64 |
| T1 | 3.16 | 12.40 |
| T1 | 3.23 | 12.40 |
| T2 | 2.79 | 22.79 |
| T2 | 2.99 | 19.94 |
| T2 | 3.16 | 17.78 |
| T2 | 3.40 | 15.63 |
| T5 | 2.45 | 27.10 |
| T5 | 2.99 | 25.04 |
| T5 | 3.16 | 22.80 |
| T5 | 3.23 | 22.80 |
| T5 | 3.63 | 17.60 |
| T10 | 2.45 | 28.70 |
| T10 | 2.99 | 28.70 |
| T10 | 3.16 | 27.23 |
| T10 | 3.23 | 27.23 |
| T10 | 3.63 | 22.08 |
| T10 | 3.82 | 19.84 |
| T20 | 2.45 | 30.40 |
| T20 | 2.99 | 30.40 |
| T20 | 3.16 | 30.40 |
| T20 | 3.23 | 30.40 |
| T20 | 3.63 | 26.56 |
| T20 | 3.82 | 24.32 |
| T20 | 4.01 | 22.08 |
| T50 | 2.45 | 32.70 |
| T50 | 2.99 | 32.70 |
| T50 | 3.16 | 32.70 |
| T50 | 3.23 | 32.70 |
| T50 | 3.63 | 31.10 |
| T50 | 3.82 | 29.39 |
| T50 | 4.01 | 27.75 |
| T50 | 4.27 | 25.04 |
| T100 | 2.45 | 34.30 |
| T100 | 2.99 | 34.30 |
| T100 | 3.16 | 34.30 |
| T100 | 3.23 | 34.30 |
| T100 | 3.63 | 34.30 |
| T100 | 3.82 | 32.83 |
| T100 | 4.01 | 31.10 |
| T100 | 4.27 | 28.84 |
| T100 | 4.48 | 27.23 |
| T200 | 2.45 | 35.90 |
| T200 | 2.99 | 35.90 |
| T200 | 3.16 | 35.90 |
| T200 | 3.23 | 35.90 |
| T200 | 3.63 | 35.90 |
| T200 | 3.82 | 35.90 |
| T200 | 4.01 | 34.43 |
| T200 | 4.27 | 32.28 |
| T200 | 4.48 | 30.54 |
| T200 | 4.69 | 28.84 |
| T500 | 2.45 | 38.25 |
| T500 | 2.99 | 38.25 |
| T500 | 3.16 | 38.25 |
| T500 | 3.23 | 38.25 |
| T500 | 3.63 | 38.25 |
| T500 | 3.82 | 38.25 |

| Joint probability return period (years) | Water level (mAOD) | Wind speed (m/s) |
|---|---|---|
| T500 | 4.01 | 38.25 |
| T500 | 4.27 | 36.62 |
| T500 | 4.48 | 34.95 |
| T500 | 4.69 | 33.35 |
| T500 | 4.98 | 31.10 |

## A.2 Fluvial - Current conditions (mAOD)

| Label | 2 Year | 5 Year | 10 Year | 25 Year | 50 Year | 100 Year | 200 Year |
|---|---|---|---|---|---|---|---|
| LOCH_4627 | 8.87 | 9.43 | 9.77 | 10.19 | 10.51 | 10.85 | 11.22 |
| LOCH_4280 | 8.37 | 8.90 | 9.21 | 9.58 | 9.85 | 10.15 | 10.50 |
| LOCH_3811 | 7.60 | 8.09 | 8.45 | 9.01 | 9.46 | 9.94 | 10.43 |
| LOCH_3662 | 6.96 | 7.60 | 7.96 | 8.48 | 8.95 | 9.43 | 9.96 |
| LOCH_3527 | 6.92 | 7.52 | 7.90 | 8.36 | 8.75 | 9.14 | 9.60 |
| LOCH_3343 | 6.57 | 7.04 | 7.36 | 7.73 | 8.03 | 8.37 | 8.80 |
| LOCH_2780 | 5.66 | 6.32 | 6.77 | 7.36 | 7.84 | 8.37 | 9.01 |
| LOCH_2330 | 5.01 | 5.56 | 5.92 | 6.39 | 6.78 | 7.24 | 7.89 |
| BRID_1950_U | 4.68 | 5.15 | 5.45 | 5.85 | 6.19 | 6.62 | 7.30 |
| LOCH_1780 | 4.40 | 4.82 | 5.10 | 5.51 | 5.86 | 6.33 | 7.05 |
| LOCH_1626 | 4.27 | 4.71 | 5.00 | 5.44 | 5.83 | 6.38 | 7.18 |
| BRIDG_1408_U | 4.07 | 4.42 | 4.65 | 5.03 | 5.39 | 5.91 | 6.73 |
| LOCH_1395 | 3.96 | 4.24 | 4.42 | 4.65 | 4.83 | 5.02 | 5.20 |
| 200_1324 | 3.93 | 4.22 | 4.40 | 4.64 | 4.84 | 5.05 | 5.25 |
| LOCH_1257 | 3.64 | 3.82 | 3.95 | 4.08 | 4.19 | 4.30 | 4.48 |
| LOCH_1131 | 3.58 | 3.74 | 3.87 | 4.00 | 4.11 | 4.24 | 4.48 |
| LOCH_1054 | 3.56 | 3.73 | 3.85 | 4.00 | 4.12 | 4.25 | 4.49 |
| LOCH_962 | 3.49 | 3.64 | 3.74 | 3.88 | 4.01 | 4.16 | 4.44 |
| LOCH_835 | 3.44 | 3.56 | 3.66 | 3.79 | 3.90 | 4.10 | 4.39 |
| LOCH_338 | 3.32 | 3.38 | 3.44 | 3.52 | 3.60 | 3.97 | 4.28 |
| LOCH_158 | 3.30 | 3.35 | 3.39 | 3.46 | 3.55 | 3.93 | 4.25 |
| LOCH_0 | 3.26 | 3.28 | 3.30 | 3.34 | 3.46 | 3.86 | 4.19 |
| LOCH_632 | 3.36 | 3.45 | 3.52 | 3.63 | 3.73 | 4.02 | 4.32 |
| 100_120 | 3.47 | 3.61 | 3.72 | 3.85 | 3.97 | 4.14 | 4.41 |
| 100_225 | 3.49 | 3.64 | 3.75 | 3.89 | 4.00 | 4.15 | 4.43 |
| 100_325 | 3.59 | 3.77 | 3.89 | 4.03 | 4.14 | 4.26 | 4.47 |
| 100_428 | 3.64 | 3.82 | 3.95 | 4.08 | 4.19 | 4.30 | 4.48 |
| 200_417 | 3.45 | 3.61 | 3.73 | 3.89 | 4.02 | 4.16 | 4.43 |
| 200_529 | 3.48 | 3.64 | 3.77 | 3.94 | 4.08 | 4.23 | 4.75 |
| 200_743 | 3.55 | 3.75 | 3.90 | 4.10 | 4.25 | 4.41 | 4.57 |
| 200_1001 | 3.72 | 3.98 | 4.17 | 4.39 | 4.56 | 4.74 | 5.02 |
| 200_1147 | 3.79 | 4.07 | 4.26 | 4.49 | 4.66 | 4.83 | 5.08 |
| 200_1248 | 3.80 | 4.03 | 4.16 | 4.32 | 4.51 | 4.71 | 4.91 |
| LOCH_1323 | 3.86 | 4.13 | 4.31 | 4.53 | 4.71 | 4.90 | 5.10 |

## A.3 Fluvial - With climate change (mAOD)

| Label | 2 Year | 5 Year | 10 Year | 25 Year | 50 Year | 100 Year | 200 Year |
|---|---|---|---|---|---|---|---|
| LOCH_4627 | 9.22 | 9.81 | 10.18 | 10.63 | 10.99 | 11.40 | 12.06 |
| LOCH_4280 | 8.72 | 9.25 | 9.57 | 9.96 | 10.29 | 10.67 | 11.49 |
| LOCH_3811 | 7.88 | 8.49 | 8.98 | 9.63 | 10.14 | 10.65 | 11.45 |
| LOCH_3662 | 7.34 | 8.01 | 8.46 | 9.13 | 9.64 | 10.21 | 11.09 |
| LOCH_3527 | 7.28 | 7.94 | 8.35 | 8.89 | 9.32 | 9.83 | 10.56 |
| LOCH_3343 | 6.85 | 7.40 | 7.71 | 8.14 | 8.53 | 9.03 | 10.40 |
| LOCH_2780 | 6.06 | 6.83 | 7.34 | 8.03 | 8.60 | 9.31 | 10.05 |
| LOCH_2330 | 5.35 | 5.96 | 6.37 | 6.94 | 7.46 | 8.20 | 8.68 |
| BRID_1950_U | 4.97 | 5.49 | 5.84 | 6.34 | 6.83 | 7.66 | 8.45 |
| LOCH_1780 | 4.66 | 5.13 | 5.49 | 6.02 | 6.57 | 7.37 | 8.28 |
| LOCH_1626 | 4.53 | 5.04 | 5.42 | 6.01 | 6.65 | 7.50 | 8.43 |
| BRIDG_1408_U | 4.28 | 4.69 | 5.02 | 5.56 | 6.18 | 7.07 | 8.05 |
| LOCH_1395 | 4.13 | 4.44 | 4.64 | 4.90 | 5.10 | 5.26 | 5.54 |
| 200_1324 | 4.11 | 4.43 | 4.63 | 4.91 | 5.13 | 5.33 | 5.58 |
| LOCH_1257 | 3.75 | 3.96 | 4.07 | 4.23 | 4.35 | 4.59 | 4.86 |
| LOCH_1131 | 3.68 | 3.88 | 4.00 | 4.16 | 4.32 | 4.59 | 4.84 |
| LOCH_1054 | 3.66 | 3.87 | 3.99 | 4.16 | 4.33 | 4.60 | 4.85 |
| LOCH_962 | 3.58 | 3.75 | 3.88 | 4.06 | 4.27 | 4.56 | 4.81 |
| LOCH_835 | 3.51 | 3.67 | 3.78 | 3.95 | 4.22 | 4.51 | 4.76 |
| LOCH_338 | 3.36 | 3.45 | 3.52 | 3.74 | 4.10 | 4.41 | 4.67 |
| LOCH_158 | 3.33 | 3.40 | 3.46 | 3.70 | 4.06 | 4.38 | 4.64 |
| LOCH_0 | 3.27 | 3.31 | 3.33 | 3.62 | 4.00 | 4.32 | 4.59 |
| LOCH_632 | 3.41 | 3.53 | 3.63 | 3.80 | 4.14 | 4.45 | 4.70 |
| 100_120 | 3.56 | 3.73 | 3.85 | 4.01 | 4.25 | 4.53 | 4.78 |
| 100_225 | 3.58 | 3.76 | 3.88 | 4.05 | 4.26 | 4.54 | 4.79 |
| 100_325 | 3.70 | 3.90 | 4.02 | 4.18 | 4.32 | 4.58 | 4.87 |
| 100_428 | 3.75 | 3.96 | 4.07 | 4.23 | 4.35 | 4.59 | 4.86 |
| 200_417 | 3.54 | 3.74 | 3.88 | 4.07 | 4.26 | 4.54 | 4.79 |
| 200_529 | 3.57 | 3.79 | 3.94 | 4.13 | 4.30 | 4.58 | 4.81 |
| 200_743 | 3.67 | 3.92 | 4.09 | 4.31 | 4.47 | 4.68 | 4.92 |
| 200_1001 | 3.88 | 4.19 | 4.38 | 4.62 | 4.81 | 4.97 | 5.17 |
| 200_1147 | 3.96 | 4.29 | 4.48 | 4.72 | 4.90 | 5.06 | 5.26 |
| 200_1248 | 3.94 | 4.18 | 4.31 | 4.58 | 4.79 | 4.98 | 5.24 |
| LOCH_1323 | 4.03 | 4.33 | 4.52 | 4.78 | 4.99 | 5.16 | 5.42 |

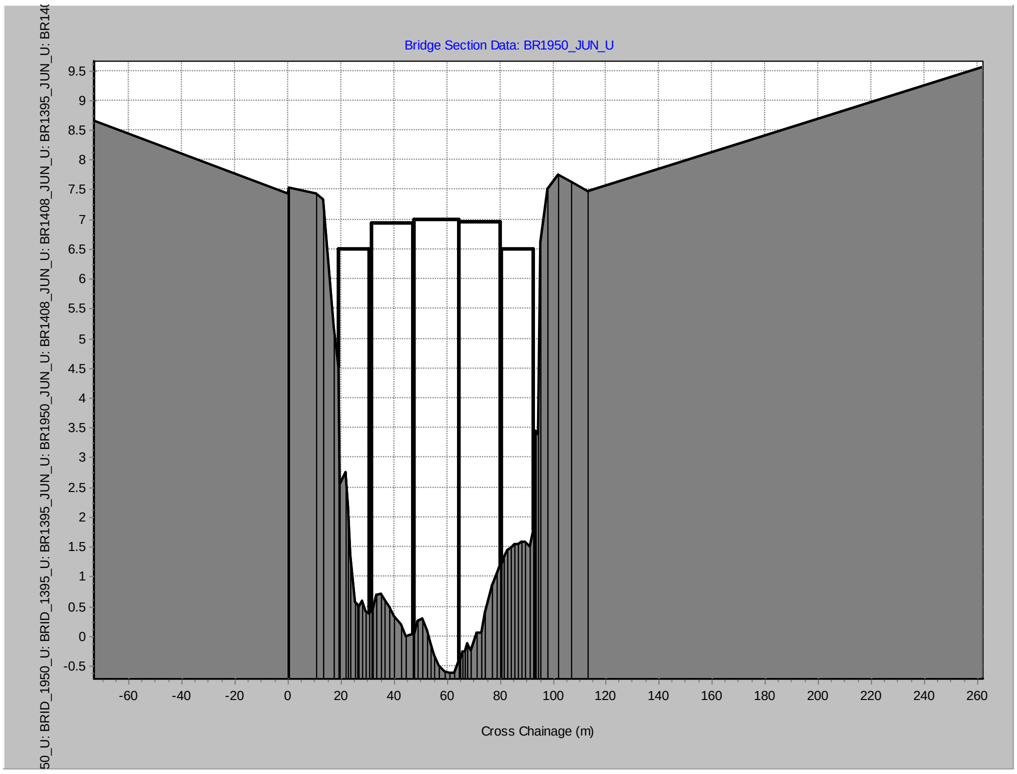
## A.4 Fluvial - tidal joint probability (mAOD)

| Label | 2 Year | 5 Year | 10 Year | 25 Year | 50 Year | 75 Year | 100 Year | 200 Year | 500 Year |
|---|---|---|---|---|---|---|---|---|---|
| LOCH_4627 | 8.87 | 9.43 | 9.77 | 10.19 | 10.51 | 10.71 | 10.85 | 11.22 | 11.75 |
| LOCH_4280 | 8.37 | 8.90 | 9.21 | 9.58 | 9.85 | 10.03 | 10.15 | 10.50 | 11.09 |
| LOCH_3811 | 7.60 | 8.09 | 8.45 | 9.01 | 9.46 | 9.74 | 9.94 | 10.43 | 11.12 |
| LOCH_3662 | 6.96 | 7.60 | 7.96 | 8.48 | 8.95 | 9.23 | 9.43 | 9.97 | 10.71 |
| LOCH_3527 | 6.92 | 7.52 | 7.90 | 8.37 | 8.75 | 8.98 | 9.15 | 9.60 | 10.29 |
| LOCH_3343 | 6.57 | 7.05 | 7.36 | 7.73 | 8.03 | 8.22 | 8.37 | 8.81 | 9.82 |
| LOCH_2780 | 5.65 | 6.33 | 6.77 | 7.37 | 7.85 | 8.16 | 8.38 | 9.02 | 9.79 |
| LOCH_2330 | 5.00 | 5.57 | 5.93 | 6.41 | 6.81 | 7.06 | 7.27 | 7.92 | 8.63 |
| BRID_1950_U | 4.66 | 5.16 | 5.47 | 5.88 | 6.23 | 6.46 | 6.65 | 7.34 | 8.37 |
| LOCH_1780 | 4.37 | 4.82 | 5.12 | 5.55 | 5.92 | 6.17 | 6.38 | 7.10 | 8.07 |
| LOCH_1626 | 4.23 | 4.71 | 5.03 | 5.49 | 5.89 | 6.18 | 6.43 | 7.22 | 8.18 |
| BRIDG_1408_U | 4.01 | 4.43 | 4.69 | 5.10 | 5.47 | 5.74 | 5.98 | 6.79 | 7.77 |
| LOCH_1395 | 3.86 | 4.19 | 4.38 | 4.63 | 4.82 | 4.93 | 5.01 | 5.20 | 5.45 |
| 200_1324 | 3.83 | 4.16 | 4.36 | 4.62 | 4.82 | 4.94 | 5.03 | 5.25 | 5.53 |
| LOCH_1257 | 3.46 | 3.70 | 3.84 | 4.09 | 4.33 | 4.46 | 4.55 | 4.74 | 4.99 |
| LOCH_1131 | 3.43 | 3.65 | 3.84 | 4.09 | 4.32 | 4.46 | 4.55 | 4.76 | 4.99 |
| LOCH_1054 | 3.43 | 3.65 | 3.84 | 4.09 | 4.32 | 4.46 | 4.56 | 4.76 | 4.99 |
| LOCH_962 | 3.43 | 3.65 | 3.84 | 4.08 | 4.29 | 4.43 | 4.53 | 4.74 | 4.99 |
| LOCH_835 | 3.42 | 3.65 | 3.83 | 4.08 | 4.28 | 4.40 | 4.50 | 4.71 | 4.99 |
| LOCH_338 | 3.41 | 3.64 | 3.83 | 4.08 | 4.28 | 4.40 | 4.49 | 4.69 | 4.98 |
| LOCH_158 | 3.41 | 3.64 | 3.83 | 4.08 | 4.27 | 4.39 | 4.48 | 4.69 | 4.98 |
| LOCH_0 | 3.41 | 3.63 | 3.82 | 4.07 | 4.27 | 4.39 | 4.48 | 4.69 | 4.98 |
| LOCH_632 | 3.42 | 3.64 | 3.83 | 4.08 | 4.28 | 4.40 | 4.49 | 4.70 | 4.98 |
| 100_120 | 3.42 | 3.65 | 3.84 | 4.08 | 4.28 | 4.42 | 4.51 | 4.72 | 4.99 |
| 100_225 | 3.43 | 3.65 | 3.84 | 4.08 | 4.28 | 4.42 | 4.52 | 4.72 | 4.99 |
| 100_325 | 3.43 | 3.65 | 3.84 | 4.09 | 4.32 | 4.45 | 4.54 | 4.74 | 4.99 |
| 100_428 | 3.46 | 3.70 | 3.84 | 4.09 | 4.33 | 4.46 | 4.55 | 4.74 | 4.99 |
| 200_417 | 3.42 | 3.65 | 3.83 | 4.08 | 4.28 | 4.42 | 4.51 | 4.73 | 4.99 |
| 200_529 | 3.42 | 3.65 | 3.83 | 4.08 | 4.29 | 4.44 | 4.53 | 4.75 | 4.99 |
| 200_743 | 3.43 | 3.65 | 3.84 | 4.09 | 4.37 | 4.52 | 4.62 | 4.84 | 4.99 |
| 200_1001 | 3.54 | 3.88 | 4.08 | 4.33 | 4.54 | 4.69 | 4.79 | 5.02 | 5.20 |
| 200_1147 | 3.64 | 3.98 | 4.19 | 4.44 | 4.62 | 4.74 | 4.84 | 5.08 | 5.25 |
| 200_1248 | 3.68 | 3.96 | 4.10 | 4.30 | 4.49 | 4.61 | 4.69 | 4.91 | 5.18 |
| LOCH_1323 | 3.75 | 4.07 | 4.26 | 4.50 | 4.69 | 4.80 | 4.89 | 5.09 | 5.37 |

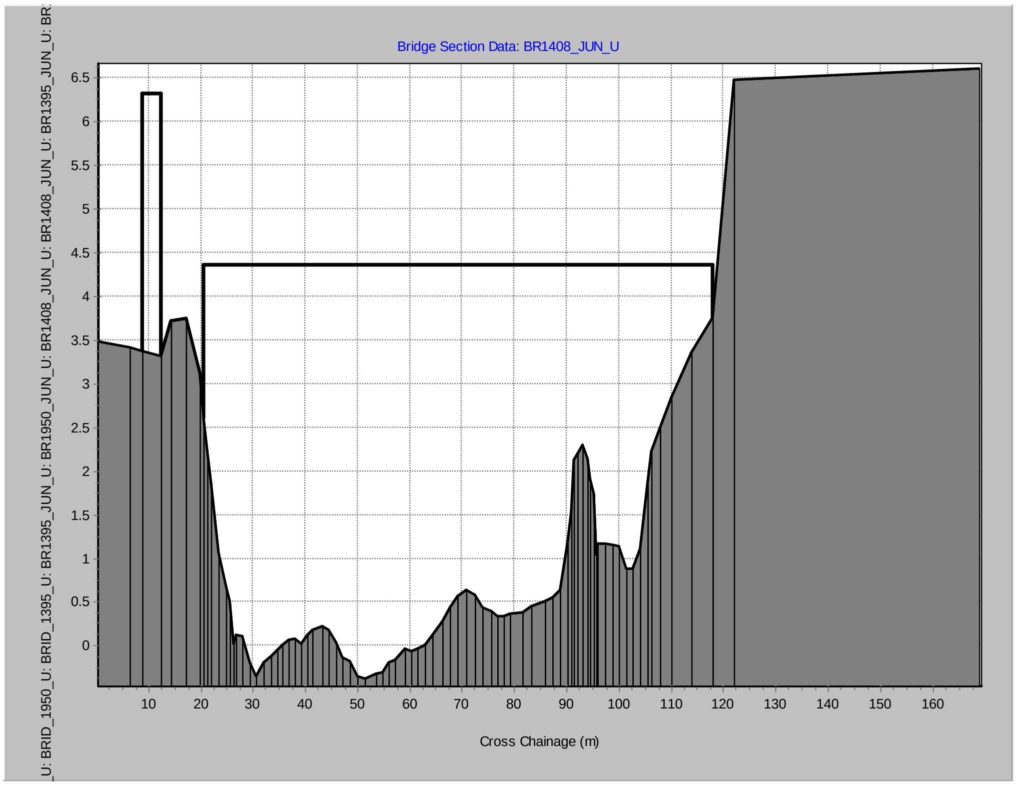
# B Appendix - ISIS Model

## B.1 Modelled structures cross sections

**Road Bridge - Model representation and photo**




**Dual bridge ( Soldier's foot bridge and rail way bridge) - Model representation and photo**




Note: Piers are not shown in cross section however they have been incorporated in the hydraulic calculations. They are built into the ISIS dual bridge function.

## Weir - Model representation and photo