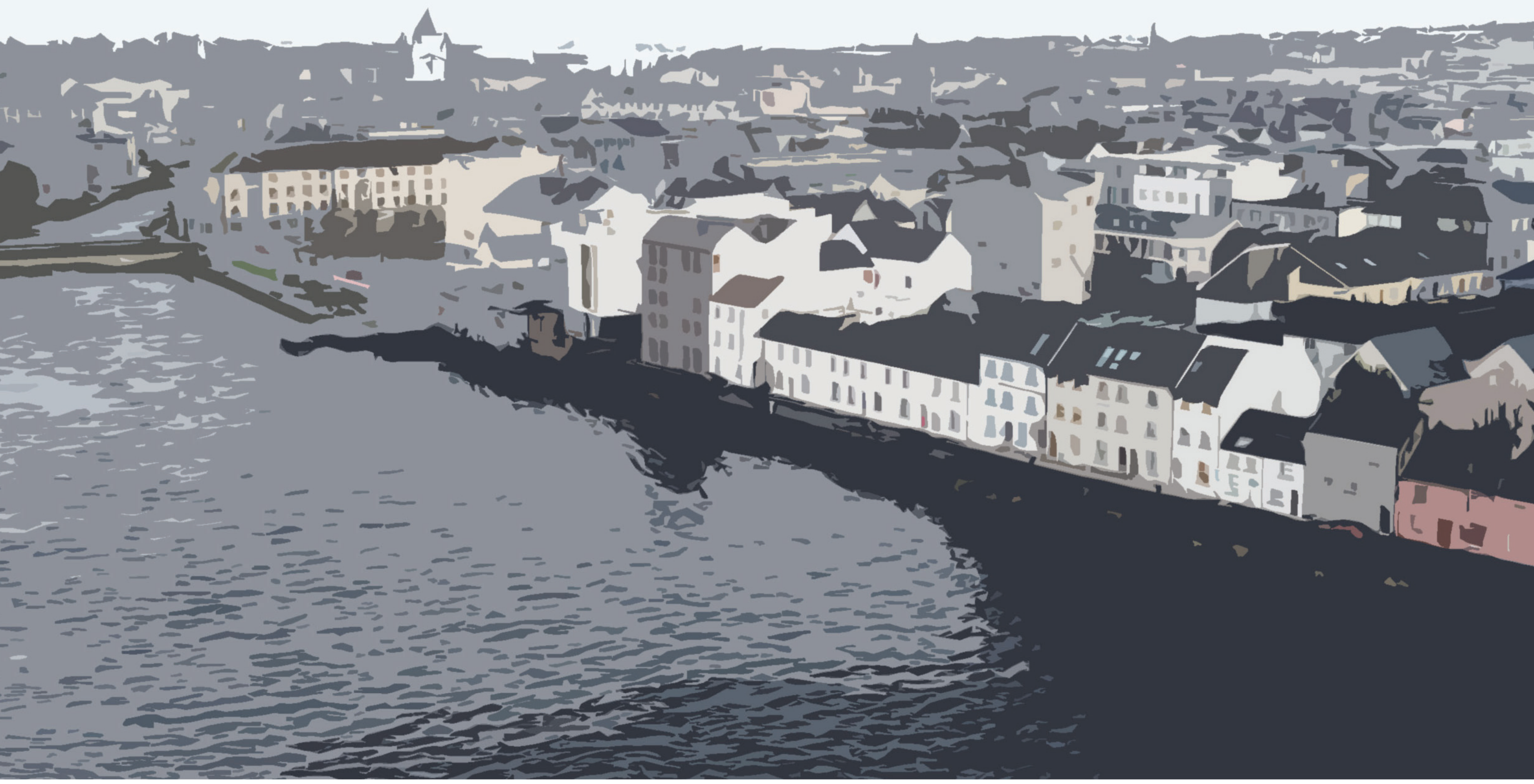
Coirib go Cósta
Scéim Faoisimh Tuilte Chathair na Gaillimhe
Galway City Flood Relief Scheme

Galway City Flood Relief Scheme
Hydraulics Report

May 2025



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OPW
Oifig na nOibreacha Poiblí
Office of Public Works

Comhairle Cathrach na Gaillimhe
Galway City Council

ARUP

Galway City Council

"Coirib go Cósta" Flood Relief Scheme

Hydraulics Report

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Abbreviations

1D	1 Dimensional
2D	2 Dimensional
AD	Above Datum
AEP	Annual Exceedance Probability
ANN	Artificial Neural Network
AOD	Above Ordnance Datum
BFI	Baseflow Index
CFRAM	Catchment Flood Risk Assessment and Management
CFRMP	Catchment Flood Risk Management Plan
CWWS	Coastal Wave and Water Level Study
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EA	Environment Agency
EE	Empirical Equations
FFL	Finished Floor Level
FMP	Flood Modeller Pro
FRS	Flood Relief Scheme
FSR	Flood Studies Report
FSU	Flood Studies Update
GIS	Geographic Information System
GPE	Gaussian Process Emulator
HEFS	High-End Future Scenario
HEP	Hydrological Estimation Point
ICWWS	Irish Coastal Wave and Water Level Study
ING	Irish National Grid
ITM	Irish Transverse Mercator
JP	Joint Probability
MRFS	Middle-Range Future Scenario
MSCP	Multi Story Car Park
OD	Ordnance Datum
QMED	Median annual maximum flood flow
SA	Sensitivity Analysis
SWL	Still Water Level

USBPR	US Bureau of Public Roads
WCFRAM	Western Catchment Flood Risk Assessment and Management
WL	Water Level
WOT	Wave Overtopping

Executive Summary

Arup has been commissioned by Galway City Council to develop a Flood Relief Scheme (FRS) for Galway City which is referred to as the Coirib go Cósta project. The overall scheme will consist of flood alleviation measures as required across the scheme area which includes the River Corrib and its tributaries/canals and offtakes from Lough Corrib to the sea and along the coast from west Salthill to Ballyloughane, including the area of the docks. The scheme will offer the required standard of protection against fluvial and coastal (i.e. tidal and wave overtopping) flooding.

This Hydraulics report is produced as part of Stage I of the project and details the hydraulic analysis undertaken for the existing baseline scenario. Hydraulic modelling undertaken as part of the optioneering phase of the project will be detailed in the Options report which will be produced at a later stage in the project.

Two separate hydraulic models have been developed as part of the study:

- A coupled fluvial/tidal 1D/2D model of the River Corrib and all of its principal tributaries and canals/mill races/offtakes has been developed in Flood Modeller (referred to as FM) and Tuflow software. The model has been used to assess both the fluvial and tidal flood risk within the main urbanised area of Galway City. The boundary conditions of the model have been derived from the detailed hydrological assessment and tidal water level analysis undertaken as part of the project;

- A standalone coastal 2D model of the floodplain within the scheme area has been developed in Tuflow Quadtree software. The model has been used to assess the risk of direct tidal inundation and wave overtopping across the scheme area. The wave boundary conditions of this model have been derived from a detailed wave overtopping assessment of the study area which was undertaken in line with the methodology outlined in the Eurotop manual.

The 1D/2D fluvial/tidal hydraulic model has been calibrated against recorded water level data for two separate in-bank flood events (from 2020 and 2022) and has also been validated against the tidal out-of-bank flood event that occurred in February 2014. It is evident from the findings of the calibration runs that the 1D/2D fluvial/tidal hydraulic model is well able to reproduce maximum flood extents and maximum water levels across the study area for small and large flood events. The model is therefore deemed suitable to simulate fluvial and tidal events across Galway as part of the study.

The standalone 2D coastal model has not been calibrated to any historic event due to a lack of suitable data with which to calibrate the model to and also to derive calibration boundary conditions. The model has therefore been developed following our extensive experience in developing models as well as following the best practice internationally in developing models. The coastal model is therefore also deemed suitable for use in the study in simulating coastal flood across the study area.

The calibrated fluvial/tidal model was used to simulate flood events along the River Corrib including its primary tributaries and canals. The maximum fluvial flood extent in Galway City for the design 1% (100yr) Annual Exceedance Probability event is not extensive as the flows are largely contained within the river channels and canals for the event. Water does however get out of bank at the downstream end of Eglinton Canal and at Claddagh Basin but this is due primarily to the influence of the tide on the total water levels at the downstream end of the model. A total of 19 properties are at risk of inundation for the 1% AEP fluvially dominated event. For the fluvial 0.5% (Q200) and 0.1% (Q1000) AEP events, the Dyke Road embankment is overtopped which leads to extensive flooding in Terryland. The quays at Spanish Arch and the left bank of the Middle River are also overtopped for the fluvial 0.5% and 0.1% AEP events and lead to flooding of Galway City to the east of the River Corrib. AEP is the probability of a flood event of a certain magnitude being equalled or exceeded in any given year. For example, a 1% AEP flood has a 1% or 1 in 100 chance of occurring or being exceeded each year.

Significant areas of the scheme area are also at risk from coastal flooding i.e. both direct tidal inundation and wave overtopping (WOT). The areas at risk include the City Centre, the area of the docks, the areas adjacent to Grattan Road/Whitestrand Avenue and Salthill Road Lower as well as Salthill and all along the Upper

Salthill road. A number of undeveloped green areas are also at risk of inundation. Over 1000 properties are at risk for the combined tidal/WOT 0.5% AEP event.

The potential impact of climate change was also assessed as part of the study in line with best national and international practice. The flood risk to Galway in the climate change scenarios is significantly increased when compared with the current scenario. The maximum flood extent is significantly increased in the area around the Dock area, Spanish Arch, Claddagh Quay, and Eglinton Canal and results in a greater number of properties being inundated when compared with the current scenario.

A number of sensitivity analysis runs of the 1D/2D fluvial/tidal model were undertaken to assess how the 1% AEP design fluvial water levels for the existing scenario may vary under different modelling assumptions. It was found from the analysis that the design water level can vary by as much as 200-250mm under different assumptions of the model. This will be considered further as part of the optioneering of the scheme.

Following a detailed review of the Sruffnacashlaun stream/culvert, it was decided to exclude it from the scheme, as flood risk within this small and heavily urbanised catchment is a function of the drainage system which is being assessed separately by GCC.

1. Introduction

1.1 Context

The Office of Public Works (OPW), in partnership with Galway City Council (GCC) and other Local Authorities, have completed a Catchment Flood Risk Assessment and Management Study (CFRAMS) for the Western River Basin District, which includes the catchment of the River Corrib. The Catchment Flood Risk Management Plan (CFRMP), which was published in 2018, concluded that a flood relief scheme for Galway City would be viable and effective for the community.

Arising from the CFRMP, Arup has been commissioned by Galway City Council to develop a Flood Relief Scheme (FRS) for Galway City which is referred to as the Coirib go Cósta project. The overall scheme will consist of flood alleviation measures across the scheme area which includes along the River Corrib and its tributaries/canals, Salthill as well as the area of the docks. The scheme will offer the required standard of protection against fluvial and coastal (i.e. tidal and wave overtopping) flooding.

There are five stages to the project:

- Stage I: Identification and development of a preferred scheme
- Stage II: Planning process
- Stage III: Detailed construction design, compilation of Work Packages and the preparation of Tenders for Contracts
- Stage IV: Construction supervision and Project Management Services
- Stage V: Handover of works

This Hydraulics report is produced as part of Stage I of the project and details the hydraulic analysis undertaken for the existing baseline scenario. Hydraulic modelling undertaken as part of the optioneering phase of the project will be detailed in the Options report.

This report should be read in conjunction with the project Hydrology Report[1] that has also been produced as part of Stage I of the Project.

1.2 Scope

The scope of the hydraulic analysis is to:

- Develop a dynamic 1D/2D hydraulic model of the River Corrib and its main tributaries for the reaches within the scheme area;
- Develop a 2D hydraulic model of the coastal floodplain within the scheme area;
- Derive stage-discharge relationships at relevant hydrometric gauges, which informs on the rating curve reviews that have been undertaken at the gauges (please refer to the Hydrology report);
- Calibrate the hydraulic model using all available data from past flood events, including hydrometric data, photographs, videos, press articles and anecdotal information;
- Undertake a wave overtopping assessment and analysis;

[1] Galway City Council (2021), *Galway City Flood Relief Scheme Hydrology Report,* consultants Arup and Hydro Environmental Ltd, June 2022

- Simulate a range of fluvial and coastal design flood events with the hydraulic models for the current scenario. The Annual Exceedance Probability[2] (AEP) events to be considered are: 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1%.
- Climate change scenarios are to be assessed with the fluvial model for the 10%, 1% and 0.1% events for both the Mid-Range Future Scenario (MRFS) and the High-End Future Scenario (HEFS);
- Climate change scenarios are to be assessed with the coastal model for the 10%, 0.5% and 0.1% events for both the Mid-Range Future Scenario (MRFS) and the High-End Future Scenario (HEFS);
- Produce flood maps in GIS format for the current and climate change scenarios;
- Undertake sensitivity analysis of the hydraulic model which includes assessing the impacts of changes on the Salmon Weir operation, roughness values and other modelling parameters;
- Calculate flood depths at every property within the study area for a range of return period events for use in the economic damage's assessment;
- Produce a hydraulics report which details the findings of the study.

1.3 Study and Scheme Area

The study area for the project is presented in Figure 1.3.1 and consists of the Hydrological Units of Management (UoM) 29, 30 and 31, the Galway Bay Southeast, Corrib and Owengowla. The main hydrological area of focus is the River Corrib catchment, which flows from Lough Corrib southwards to the sea at Galway Docks. The catchment includes a total lake surface area of approximately 285km^2 which includes Lough Corrib, Lough Mask and Lough Carra. The scheme area is also indicated on the figure.

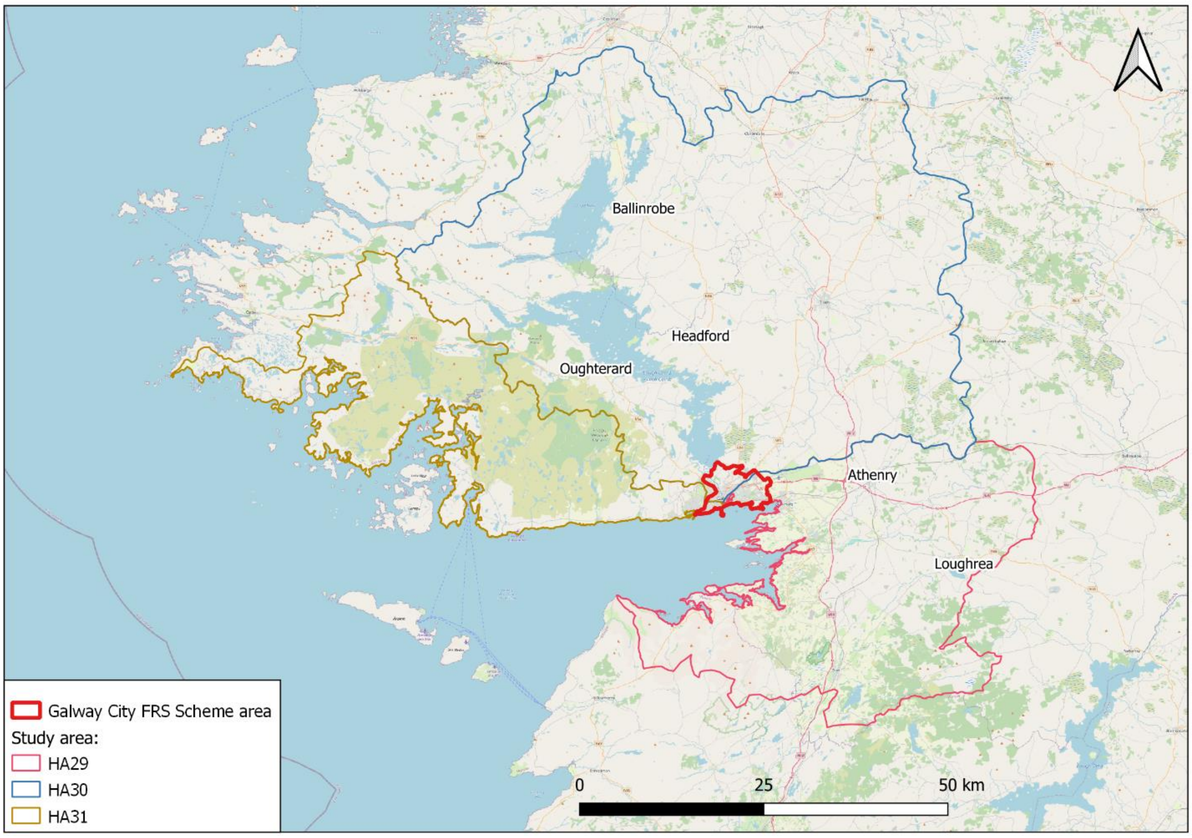

Figure 1.3.1 Study and scheme areas (Map data from OpenStreetMap)

[2] Annual Exceedance Probability (AEP) is the probability, typically expressed as a percentage, of a flood event of a given magnitude being equalled or exceeded in any given year. For example, a 1% AEP flood event has a 1%, or 1 in a 100, chance of occurring or being exceeded in any given year.

The primary watercourses discharging into Lough Corrib, as well as their catchment extents, are presented in Figure 1.3.2 and are listed in Table 1.

Table 1 Primary Catchment areas

Catchment	Area (km^2)
Lough Mask outflow via Cong Canal	892 km^2
Cross River	66 km^2
Black River	204 km^2
Headford River	45 km^2
Cregg River	61 km^2
Clare River	1108 km^2
Habhain Cor Na Mona River	26 km^2
Habhain Thir Na Cille	85 km^2
Owenree River	23 km^2
Owenriff River	67 km^2
Aughnanum River	29 km^2
Loch an Chip River	89 km^2

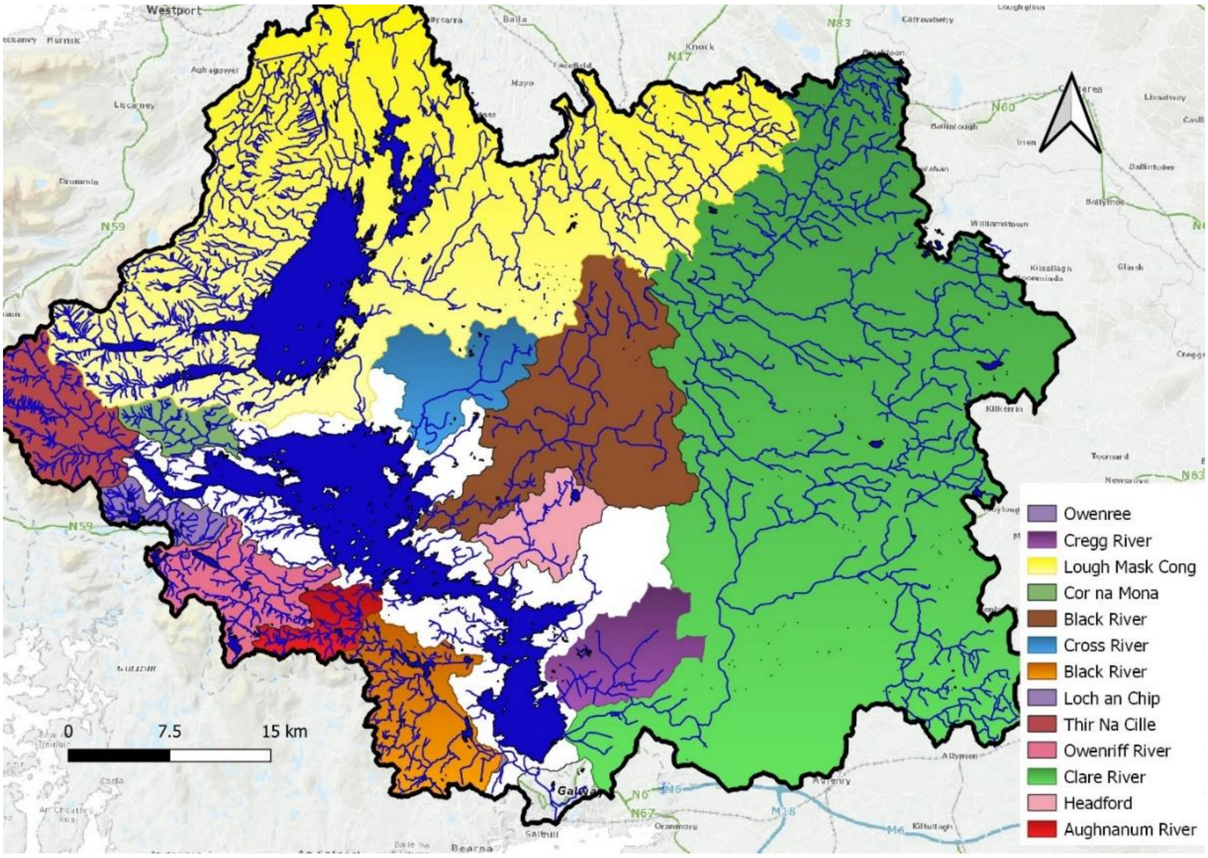

Figure 1.3.2 Main catchment areas draining to Lough Corrib

A close-up view of the scheme area is presented in Figure 1.3.3. It can be seen from the figure that the scheme area includes the full length of the River Corrib from Lough Corrib to the sea, the centre of Galway City as well as a circa 13km length of the coastline which faces onto Galway Bay.

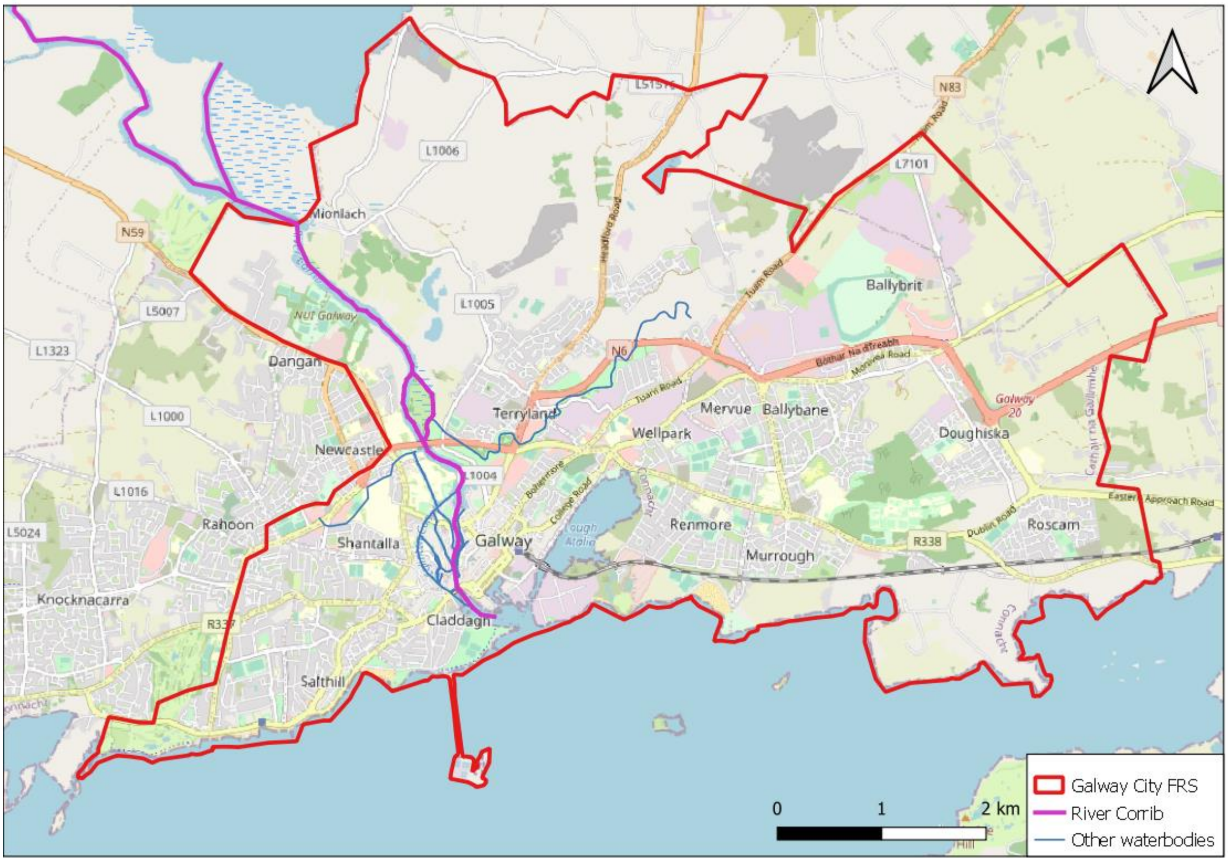

Figure 1.3.3 Scheme area, River Corrib, and other waterbodies

1.4 Overview of the primary watercourses

1.4.1 The River Corrib

The River Corrib channel connects Lough Corrib to the sea at Galway Bay and has an approximate length of 9km in the scheme area. Its flow is regulated by the Salmon Weir Sluice Barrage (Figure 1.4.1) which was originally constructed in 1852 as part of the original Corrib drainage and navigation scheme. The barrage was re-designed and constructed again in its latest form by the OPW as part of the Corrib-Clare Arterial drainage scheme in 1959. Further information on the Salmon Weir is included in Section 5.3.3.

Figure 1.4.1 Salmon weir sluice barrage

Directly upstream of the Salmon Weir, the River Corrib splits into the three distinct channels: the Eglinton Canal (west), the main River Corrib (centre) and the Middle River/Friar's river (east). Figure 1.4.2 presents a schematic of the various channel alignments.

West Canal System

The Eglinton Canal splits into a series of mill races and canals most of which flow under buildings and penstocks before re-joining the River Corrib at several locations downstream. This network of channels is referred to as the West canal system.

The University of Galway Old Engineering building and Madeira Court buildings are located over two of the watercourses of the West Canal system: the Gaol river and the Parkavara river, respectively. Flows are controlled under these buildings via a series of culverts and penstocks. Flows along the River Clare are also controlled with a penstock at St. Josephs Patrician School (The 'Bish'). These hydraulic structures are shown in Figure 1.4.3.

A number of weirs have been constructed at the downstream ends of the mill races and canals on the West canal system in order to regulate the flow.

Central Branch

The central branch of the River Corrib flows over the Salmon Weir and underneath a series of large bridges before discharging at Galway Bay. The key structures along this branch are the Salmon Weir barrage, Salmon Weir bridge and Wolfe Tone bridge, as shown in Figure 1.4.2.

East Canal System

The east branch splits into the Middle River and Friar's /Slaughterhouse river before discharging back into the Corrib at two different locations. This network of channels is referred to as the East canal system.

Further information on the key hydraulic structures in Galway City are included in Section 5.4.

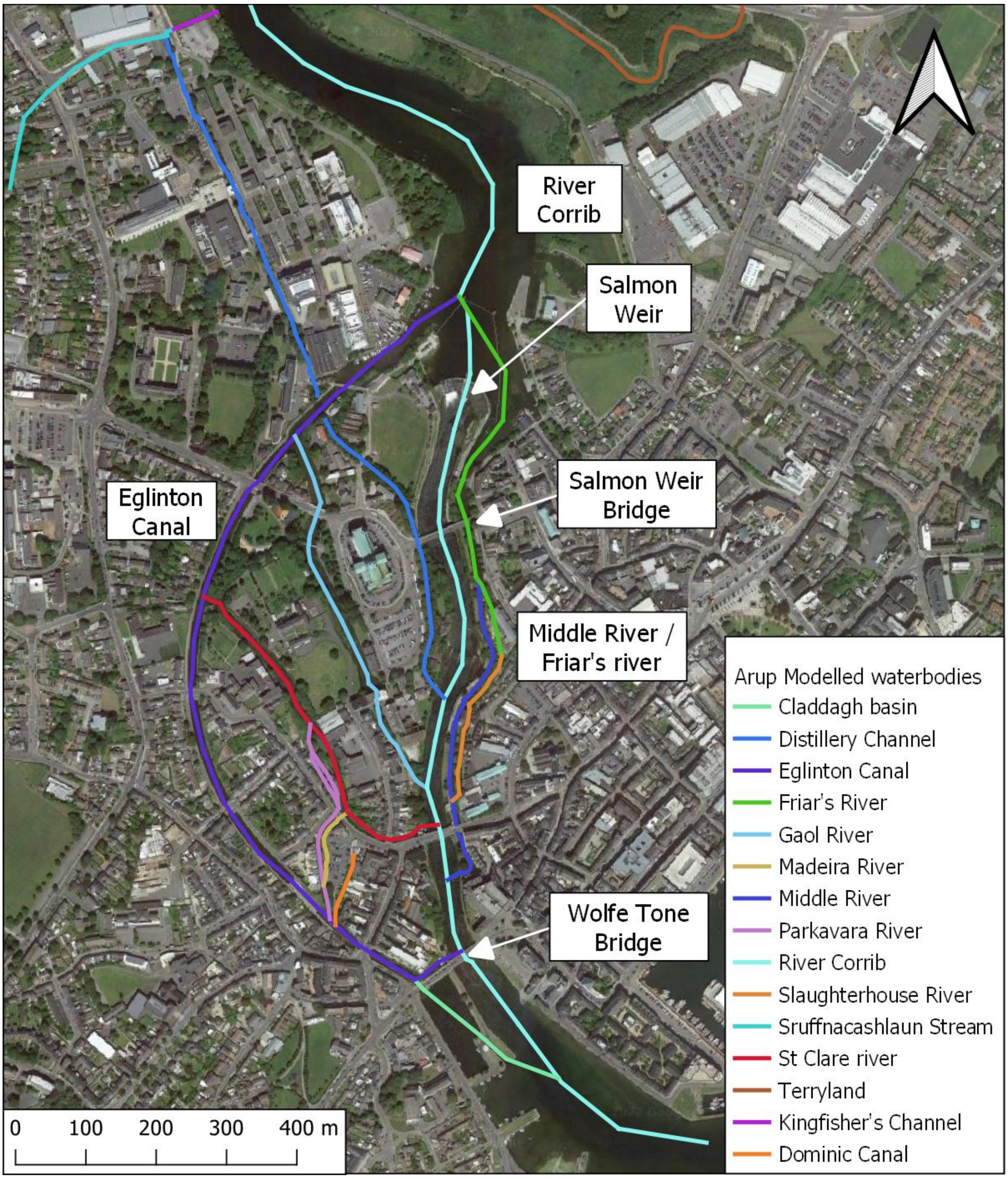

Figure 1.4.2 Waterbodies in Galway City and River Corrib key hydraulic structures

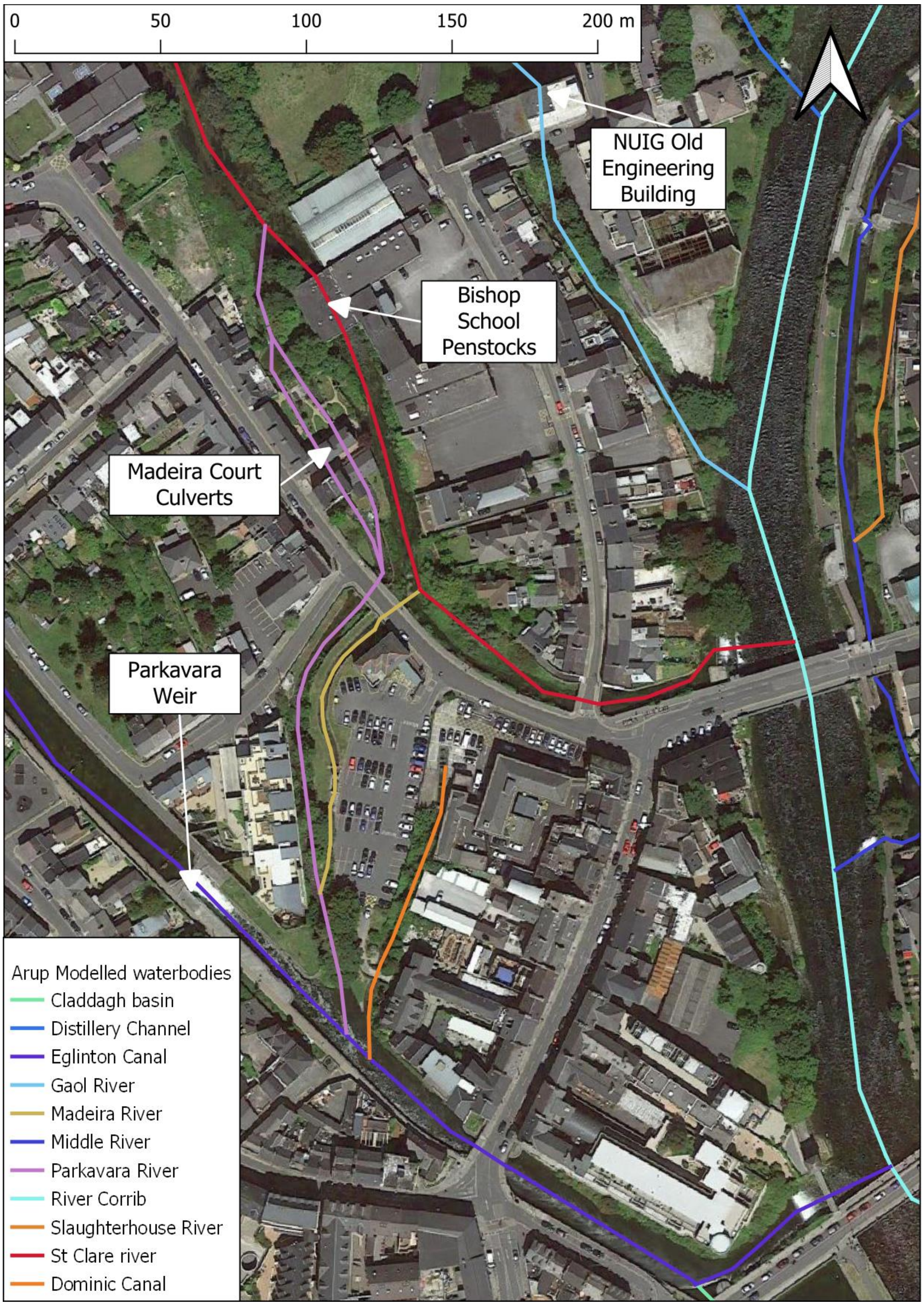

Figure 1.4.3 Other key structures in west mill race system

The river is tidally influenced as far as the Salmon Weir for significant tidal flood events. There are no major tributaries discharging into the River Corrib within the scheme area downstream of Lough Corrib. The local catchment area of the water course (i.e., the area from its exit point of Lough Corrib and Galway Bay) is $7km^2$ which is 0.6% of the total catchment area.

1.4.2 The Distillery channel

The Distillery channel (Figure 1.4.4) has a catchment area of approximately $2.5km^2$ and flows in a North South direction through the grounds of the University of Galway. Both the Sruffnacashlaun Stream and a series of drainage networks from the Newcastle and Dangan areas of Galway drain into the channel.

The channel is connected to the River Corrib via the Kingfisher's channel. This connection is however controlled by penstocks which we understand are closed by the University of Galway during large flood events.

The channel flows underneath the Eglinton canal through a culvert which is referred to as the Sruffnacashlaun Siphon. The channel discharges to the River Corrib downstream of the Salmon Weir Bridge and upstream O'Brien's Bridge. The channel is also connected to the Eglinton canal via the Huntsman canal, directly downstream of the Siphon.

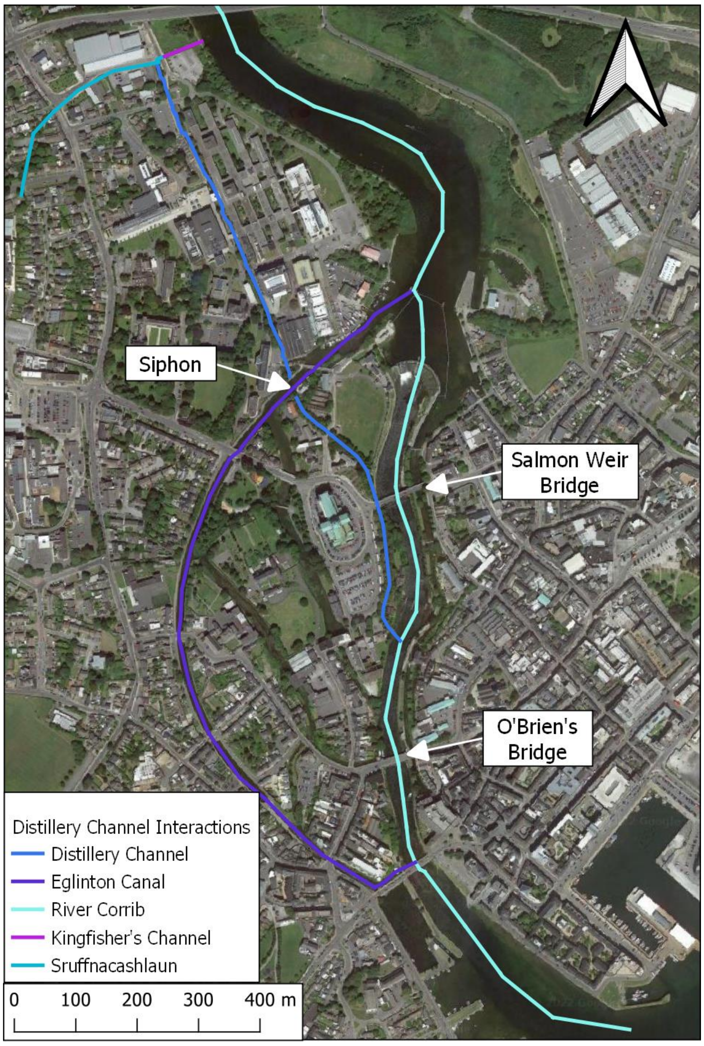

Figure 1.4.4 Distillery channel connections

1.4.3 The Terryland Stream

The Terryland stream flows in a North Easterly direction and discharges to two sinkholes (Figure 1.4.5) before discharging to the sea via subterranean conduits within the karst limestone bedrock.

The catchment is karstic with an approximate catchment area of $9km^2$. Historically the Terryland basin was flooded by the River Corrib. During the 1850's however a flood embankment was constructed along the eastern section of the Corrib as part of the Corrib Drainage and Navigation Scheme. This structure blocks overland flow from the Corrib from entering the Terryland catchment.

The embankment (which is known as the 'Dyke Road embankment') is a formal flood defence maintained by the OPW and works in conjunction with the Clifden Rail embankment, which runs perpendicular to it (refer to Section 5.4.9 for further detail on this). A small culvert entrance has been identified in the Clifden Rail embankment and is further described in Section 5.4.9.

The Terryland stream in the present day is principally fed by groundwater via the sinkholes and discharges from storm water outfalls which service the surrounding urbanised areas.

A public water intake channel near Jordan's island is currently used to abstract water from the River Corrib at approximately $35,000m^3$/day for treatment and distribution to the public water supply system.

The Old Terryland Waterworks is located along the Terryland stream. This plant is now abandoned but was historically used to pump water. The turbines located within the building currently block flows from the River Corrib from entering the Terryland stream (Figure 1.4.7 and Figure 1.4.8).

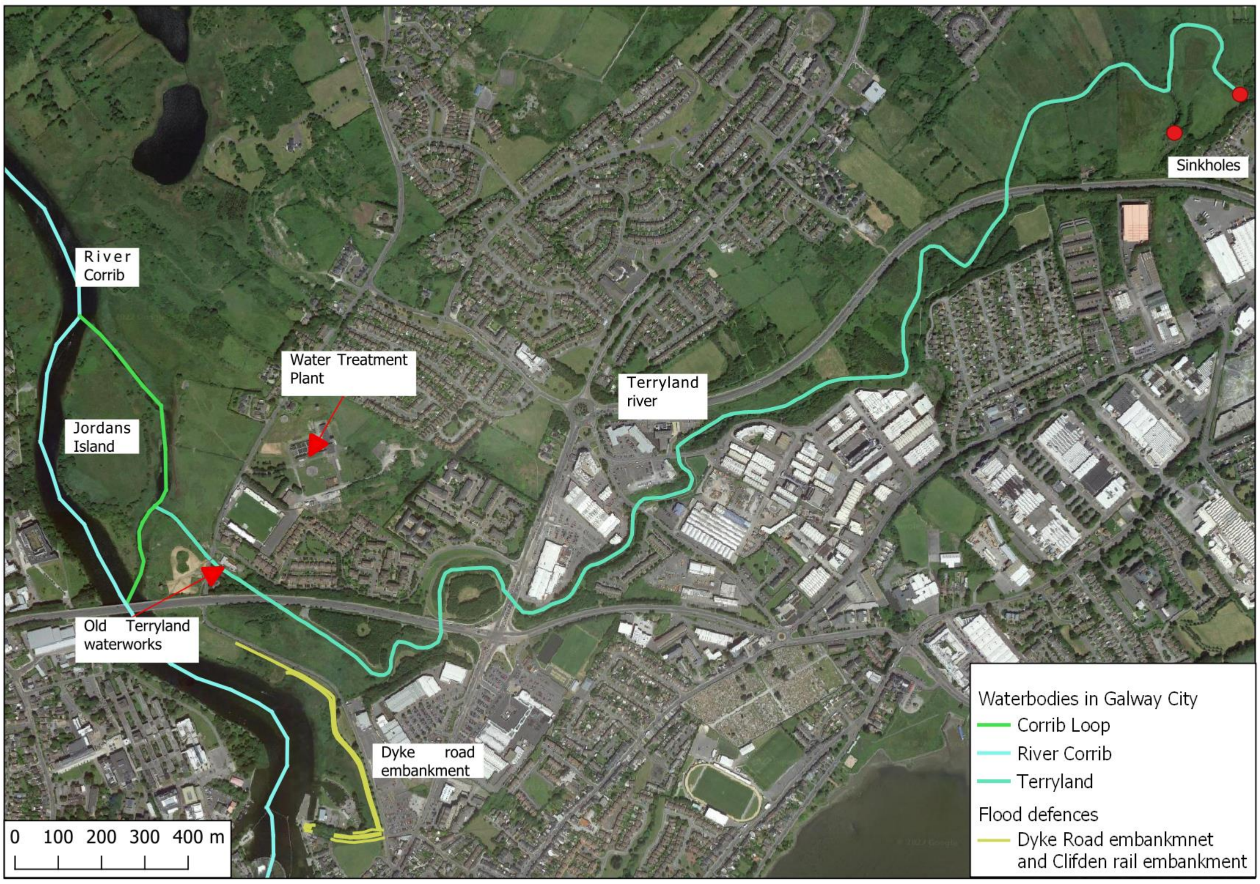

Figure 1.4.5 Terryland river and hydraulic features

Figure 1.4.6 Dyke road embankment

Figure 1.4.7 Turbines in the Old Waterworks (photograph taken by Arup on site visit)

Figure 1.4.8 Still water in the Waterworks (photograph taken by Arup on site visit)

1.5 Hydraulic models developed as part of the study

Two separate hydraulic models have been developed as part of the study:

- A coupled fluvial/tidal 1D/2D model of the River Corrib and all of its principal tributaries and canals/mill races has been developed in Flood Modeller Pro (referred to as FMP) and Tuflow. The model includes all of the hydraulic structures that influence the hydraulics in the scheme area. The model has been used to assess both the fluvial and tidal flood risk within the main urbanised area of Galway City.
- A standalone coastal 2D model of the entire coastal floodplain within the scheme area has been developed in Tuflow Quadtree. The model assesses the risk of direct coastal inundation from tidal surge and wave overtopping across the scheme area. This model does not account for the hydraulic structures within the various river channels and neither does it explicitly include any of the fluvial inflows. This approach is justified as the purpose of the model is to assess coastal flood risk across the wider scheme area which is not sensitive to the influence of the various hydraulic structures and fluvial input.

The extents of both models are shown in Figure 1.5.1. It is noted that both models are set in ITM and utilise the OD Malin OSGM15 datum.

The extents of the models have been set so that all the areas at risk of flooding are included within the model domains. Areas with the Scheme Area that are not included in the models are not considered to be at risk of flooding due to the absence of any significant watercourses within these areas.

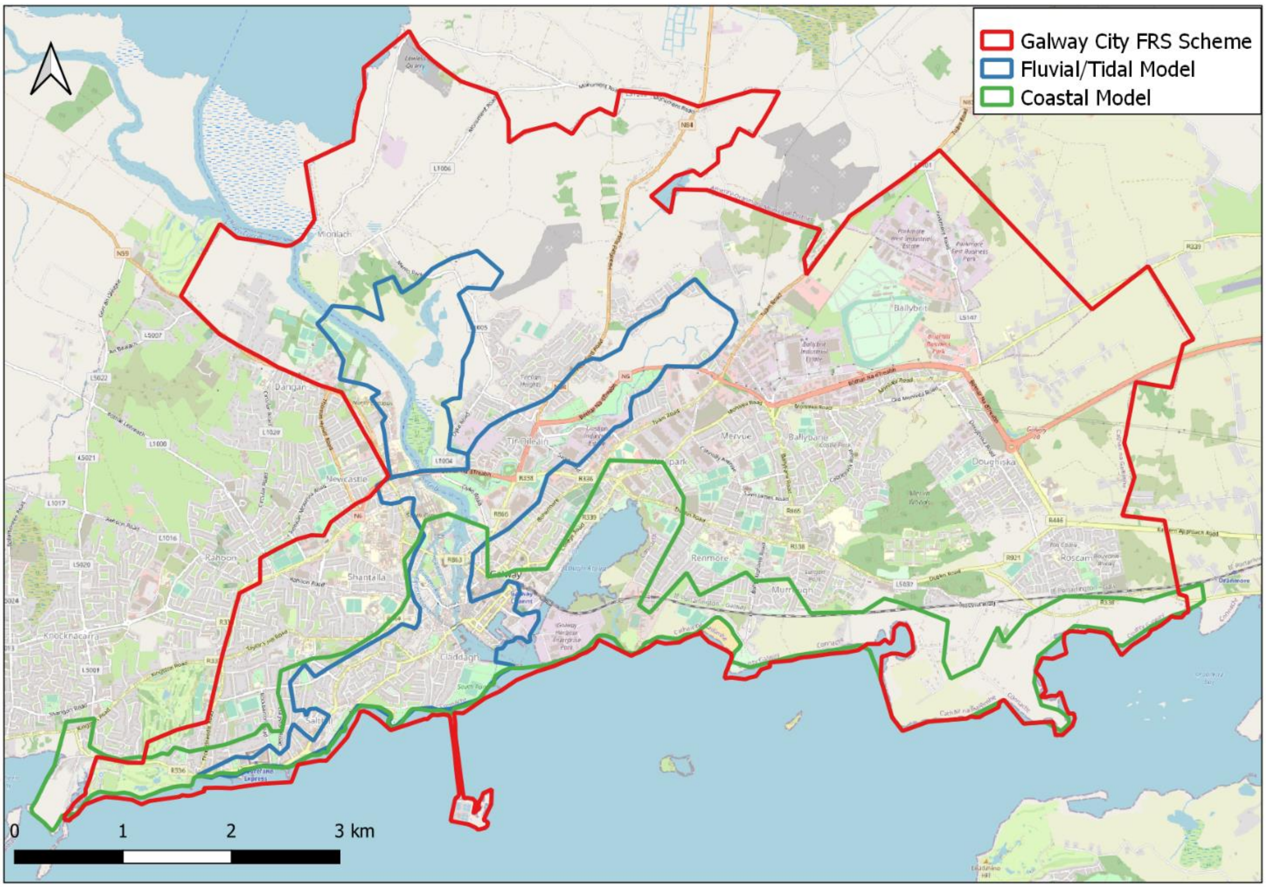

Figure 1.5.1 Hydraulic model extents - Galway City FRS

1.6 Overview of the report

Section 1 presents an overview of the Galway Flood Relief Scheme Project and outlines the objectives of the hydraulic modelling element of the study.

Section 2 describes the various datasets utilised as part of the study. Section 3 outlines how the hydrological estimation has been used as part of the hydraulic modelling. Section 4 describes the wave overtopping analysis and its methodology.

The development of the various elements of the model is described in Section 5 of the report while Section 6 presents the calibration of the fluvial/tidal model. An overview of the existing scenario design model runs is presented in Sections 7 to 9 which are to be read in conjunction with the flood maps which are presented as digital deliverables.

Section 10 presents the finding of the Sensitivity Analysis runs (including climate change simulations). Modelling assumptions and limitations are included in Section 11. The overall conclusions of the hydraulic modelling are presented in Section 12.

Six appendices are included with the report:

- Appendix A: Hydraulic model results in GIS format, including flood extents, depths, velocities, and node information
- Appendix B: 1D Hydraulic model results in plot and tabular format (longitudinal plots and water level, flow, velocity, and Froude number at each node)
- Appendix C: Structure sheets
- Appendix D: QA information and model log
- Appendix E: Model stability plots
- Appendix F: Qualitative blockage risk assessment
- Appendix G: Wave Overtopping Results

2. Data collection and analysis

2.1 Overview

This chapter details the datasets that have been used in the development and running of the hydraulic models.

2.2 Mapping

A suite of maps of varying resolutions (1:1,000 and 1:2,500) have been used as part of the construction of the hydraulic models. These maps are the most recent available and have been provided under licence from Ordnance Survey Ireland (OSi).

The OSi Prime2 dataset has also been used as part of the hydraulic modelling construction for identifying different surface types in the floodplain model and also for delineating the footprint of buildings. The Prime2 data was supplied to Arup under license by OPW.

2.3 Survey data

2.3.1 River survey data

The 1D component of the fluvial/tidal hydraulic model has used channel and structure cross sectional survey data from two separate surveys:

- Western CFRAM survey (from 2013);
- Galway City FRS Infill and validation survey (from 2021).

Both of these datasets are now described.

2.3.2 Western CFRAM data

A detailed channel and structure survey of a number of the primary watercourses in the River Corrib catchment was undertaken as part of the Western CFRAM study. The survey was undertaken by CCS Surveys between July 2012 and February 2013 as part of the National Survey Contract 6, Work Package 4. Additional infill surveys for more complex structures were undertaken in September 2013 (WCFRAM Infill Contract 4).

Cross sections were surveyed at varying longitudinal intervals along the channels. Within the study area of this project the average spacing between the cross sections in the rural parts downstream of Lough Corrib was circa 150m with the sections extending into the floodplain on either side of the channel (approximate cross section length of 100-150m). In the urbanised area of Galway City, the longitudinal cross section spacing was reduced to circa 80m for greater accuracy.

Other surveys undertaken as part of the Western CFRAM include:

- Building threshold surveys for a limited number of buildings in Salthill, Father Griffin, Spanish Arch area and the University of Galway buildings (100 properties in Galway City Centre and approximately 75 properties along Salthill promenade).
- Bathymetric surveys of 22 cross section perpendicular to the Galway Bay coastline from Blackrock Beach to Ballyloughane Beach
- Flood defence surveys for some of the bank walls along the Corrib, the Eglinton Canal, St Clare river and the Distillery Channel, and Dyke Road Embankment
- Additional structure surveys of complex structures along the Corrib or structures that changed after the original surveys.

The Western CFRAMS Hydraulic Modelling report[3] was also reviewed in detail as part of this project to understand the preceding work including any noted assumptions or shortcomings in the survey or the CFRAMS hydraulic model.

The Western CFRAM survey data were recorded in ING geospatial system, mAOD Malin OSGM02 geoid.

2.3.3 Galway City FRS Infill surveys

As part of this project Arup undertook an extensive review and gap analysis of the Western CFRAM survey data. Arising from the findings of the review the following infill surveys were commissioned and procured as part of the project under the OPW Survey framework:

1. Channel and structure surveys (Lot 1b)
2. Culvert and CCTV surveys (Lot 4)
3. Flood defence surveys (Lot 1b)
4. Building threshold surveys (Lot 1b)

The infill surveys were recorded in IRENET95, mAOD Malin OSGM15 geoid.

Each of these infill surveys are now described.

2.3.4 Channel and structure surveys (Lot 1b surveys)

The surveys undertaken as part of the Western CFRAM provided very good coverage of most watercourses within Galway City. A number of additional survey requirements were however identified which were subsequently surveyed as part of the Infill Survey undertaken by Murphy Geospatial between May and August 2021.

The following criteria governed the scope of the infill survey:

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[3] Office of Public Works (2015), *Western CFRAM Study – Hydraulic Modelling Report Unit of Management 30-31*, JBA Consulting, September 2015

- watercourses that were not surveyed before, such as the Sruffnacashlaun stream and Lough Atalia;
- watercourses and structures that changed significantly since the Western CFRAM survey was undertaken, such as the Distillery channel and Parkavara gates;
- key structures such as the Salmon Weir Barrage which were not surveyed in the level of detail required to meet the needs of this project;
- additional cross sections where large spacing between the existing CFRAM sections was identified, and
- ensuring that a number of cross sections and hydraulic structures surveyed as part of the Western CFRAM surveys were resurveyed in order to assess sedimentation/erosion along the channel and or validation purposes.

Augmenting the CFRAM survey data with the project infill survey ensures that the Galway City FRS hydraulic model is sufficiently detailed and robust and meets the requirements of the flood relief design project.

Figure 2.3.1 presents the Western CFRAM channel surveys (blue lines), the Galway City FRS channel surveys (red lines) and the Lot 4 culvert & CCTV surveys (black lines). It can be seen from the image that the centre of the city is extensively covered with cross section data.

The Galway City FRS infill surveys were provided in both the OSGM02 and OSGM15 geoids. The accuracy band of the survey was classified as “D” which has a vertical accuracy of +/-10mm on hard details and +/-25mm on soft details. This is deemed sufficiently accurate to meet the needs of the project.

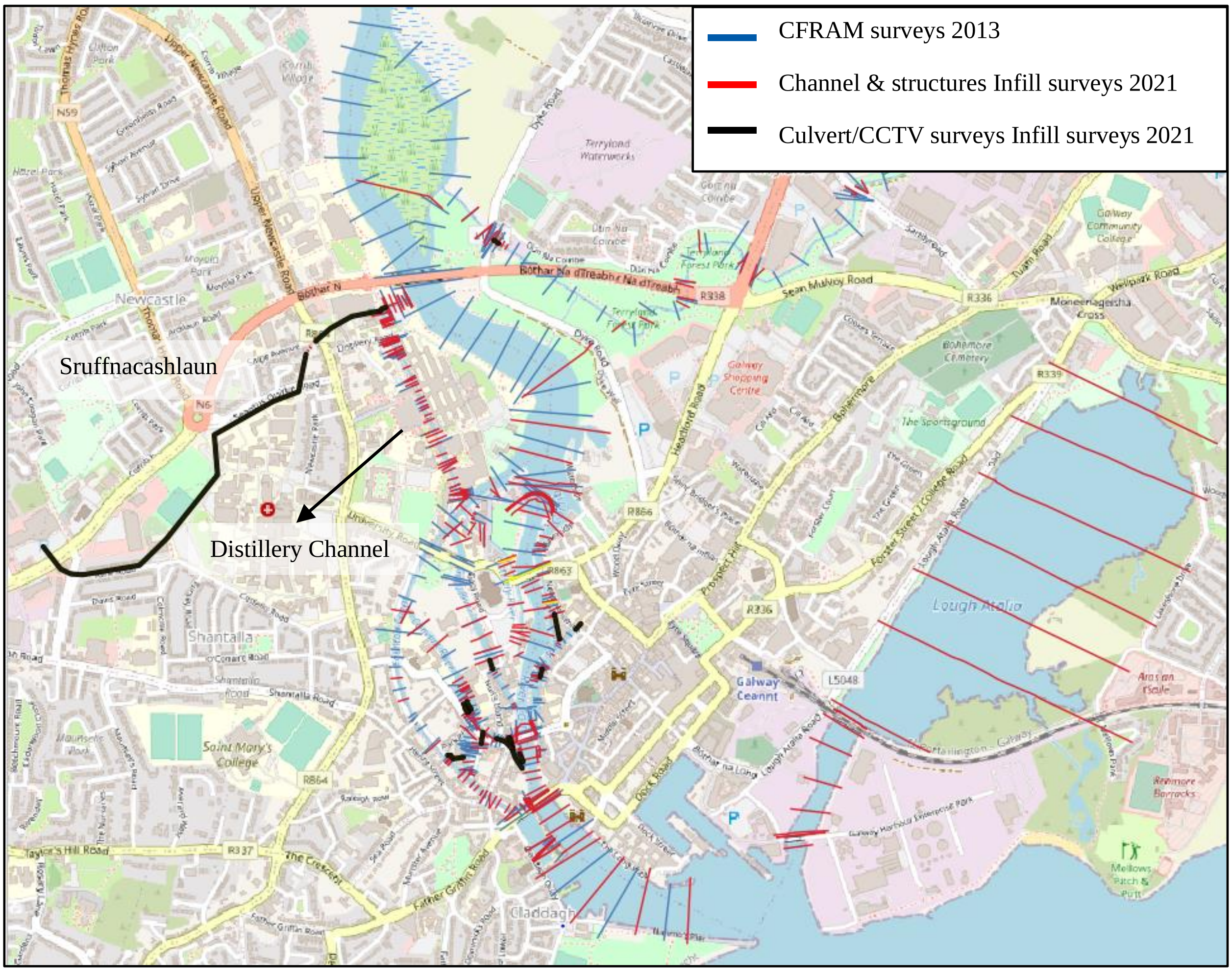

Figure 2.3.1 Survey cross sections – Town Centre

Comparisons were made between the 2013 CFRAM surveys and the 2021 infill surveys for different reaches as part of our quality assurance of the data.

For the majority of reaches there is no evidence of any significant change in the bed levels between the two surveys. Infill cross sections from the 2021 survey were therefore utilised with the 2013 survey to form a composite cross section dataset.[4]

Engineering works (including dredging and replacement of culverts and other structures) were however undertaken along the Distillery Channel by the University of Galway. The entire CFRAM dataset for this reach was therefore discarded and the infill survey was used in the model.

The 2021 infill survey also provided more geometric details of some structures, such as the weirs connecting the mill races to the River Corrib and the Salmon Weir Barrage. In such cases, the information from the infills were used to replace assumptions made during the CFRAM study.

For the large majority of structures, the 2021 infill surveys were used to validate the original surveys. Overall, the two surveys agreed well and where discrepancies were identified, Murphy Geospatial were asked to revisit the site and validate their surveys.

2.3.5 Culvert & CCTV surveys (Lot 4 surveys)

A survey of a number of significant pipes and culverts was undertaken as part of the study by Amelio Group between September 2021 and March 2022.

The survey included CCTV camera surveys, route tracing and geometric surveys. The aim of the survey was to record the internal dimensions, conditions, and constrictions within the culverts to inform the hydraulic analysis, as well as record sedimentation to support the blockage analysis. The culverts requested for surveys are shown in black lines in Figure 2.3.1.

A number of culverts within the mill races and canal systems were not able to be surveyed due to both Health & Safety risks (high flow conditions, presence of debris and rough grounds) and access issues (heavy vegetation or presence of trash screens). The inlet and outlets of the majority of these culverts were however surveyed. These culverts are listed as:

- Culvert upstream Parkavara Weir, connecting Eglinton Canal to Parkavara (Modelling Ref: 30EGLI00041O)
- Culverts from St Clare river to Grannary buildings (Modelling ref: 30GMRA00005O)
- Culverts under Madeira court buildings, Parkavara (Modelling ref: MACT00006R and MACT00006L)
- Culvert from St Clare river to Dominic (Modelling ref: 30GMRA00015O)
- Culvert upstream of Slaughterhouse stream (not modelled)
- Culverts under the University of Galway Old engineering building (NUNS00013O1).

The location of these culverts is presented in Figure 2.3.2.

[4] If significant differences in the bed levels between the 2013 and 2021 surveys had been observed, the 2013 survey would have been deemed to not be representative of bed levels in 2021. The 2013 survey would therefore not have been considered as part of the hydraulic model development.

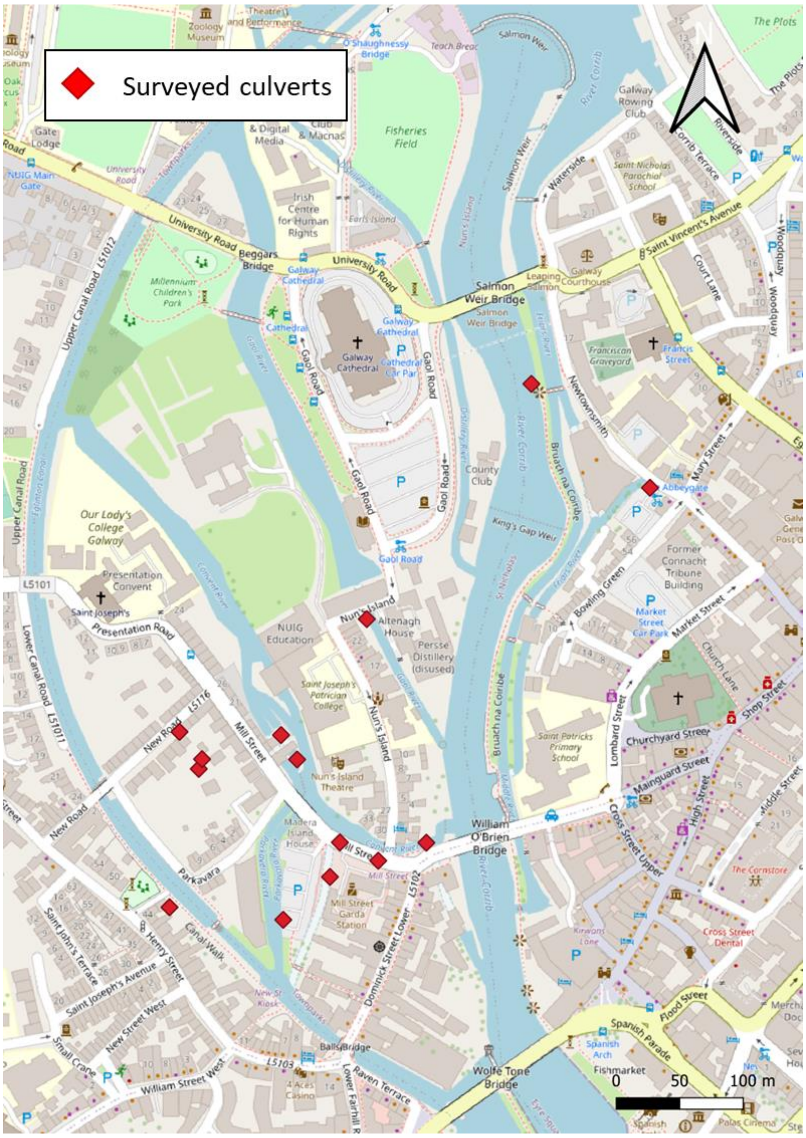

Figure 2.3.2 Culverts surveyed by Amelio Group (map background by OpenStreetMap)

A CCTV survey of the Sruffnacashlaun culvert was undertaken as neither the culvert or the stream were surveyed as part of the Western CFRAM or included in the CFRAM hydraulic model. Circa 760m of the total culvert length of 1466m was surveyed with CCTV.

A series of structural defects in the culvert were identified by Amelio Group as part of the CCTV survey and were presented as part of their reporting in their deliverable package. The findings of their survey[5] will be considered by Arup as part of the optioneering for the scheme except for the Sruffnacashlaun stream/culvert as it falls outside the scope of the flood relief scheme (refer to Section 5.1).

The above information and surveyed data have been considered as part of the model build of the 1D element of the fluvial hydraulic model and as part of the blockage analysis of the culverts. The data will also be considered as part of the Optioneering.

The residual uncertainty on the internal structural conditions of some of the culverts will be taken into account during the blockage analysis and damages assessment.

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[5] Amelio identified 11 sections with Grade 4 structural defects (best practice suggests consideration should be given to repairs to avoid potential collapse.) Amelio assigned 9 sections Grade 3 defects (best practice suggests consideration should be given to maintenance activities in the medium term), as they were noted to have settled deposits with up to 10% of the cross-sectional area loss. 2 sections were assigned Grade 4 operational defects (consideration should be given to maintenance activities to avoid potential blockages) with 25% of the cross-sectional area loss due to hard settle deposits. 14 sections were reported to have Grade 5 operational defects (best practice suggests that the pipe is at a high risk of backing up or causing flooding), reporting obstacles within the pipes, such as external pipes and large objects and 5-25% of cross-sectional area loss.

2.3.6 Galway City FRS Flood defence surveys (Lot 1b surveys)

Additional flood defence surveys were undertaken as part of the Galway City FRS in order to ensure the flood defences are represented accurately both within the hydraulic model and also as part of the input to the wave overtopping analysis. The flood defence data also informs the Defence Asset Database. The flood defence surveys included:

- the entire Galway coastline from the Caravan Park to Ballyloughane Beach;
- the Dyke Road and Clifden rail embankments;
- the channel walls at Distillery channel;
- quay walls at the Leonardo Hotel;
- the embankment along the right bank of the River Corrib directly downstream the Salmon Weir
- The areas around the Claddagh, Long Walk, Docks, Nimmos pier and Wolfe Tone bridge.

The extents of the above surveys are shown in Figure 2.3.3 and Figure 2.3.4.

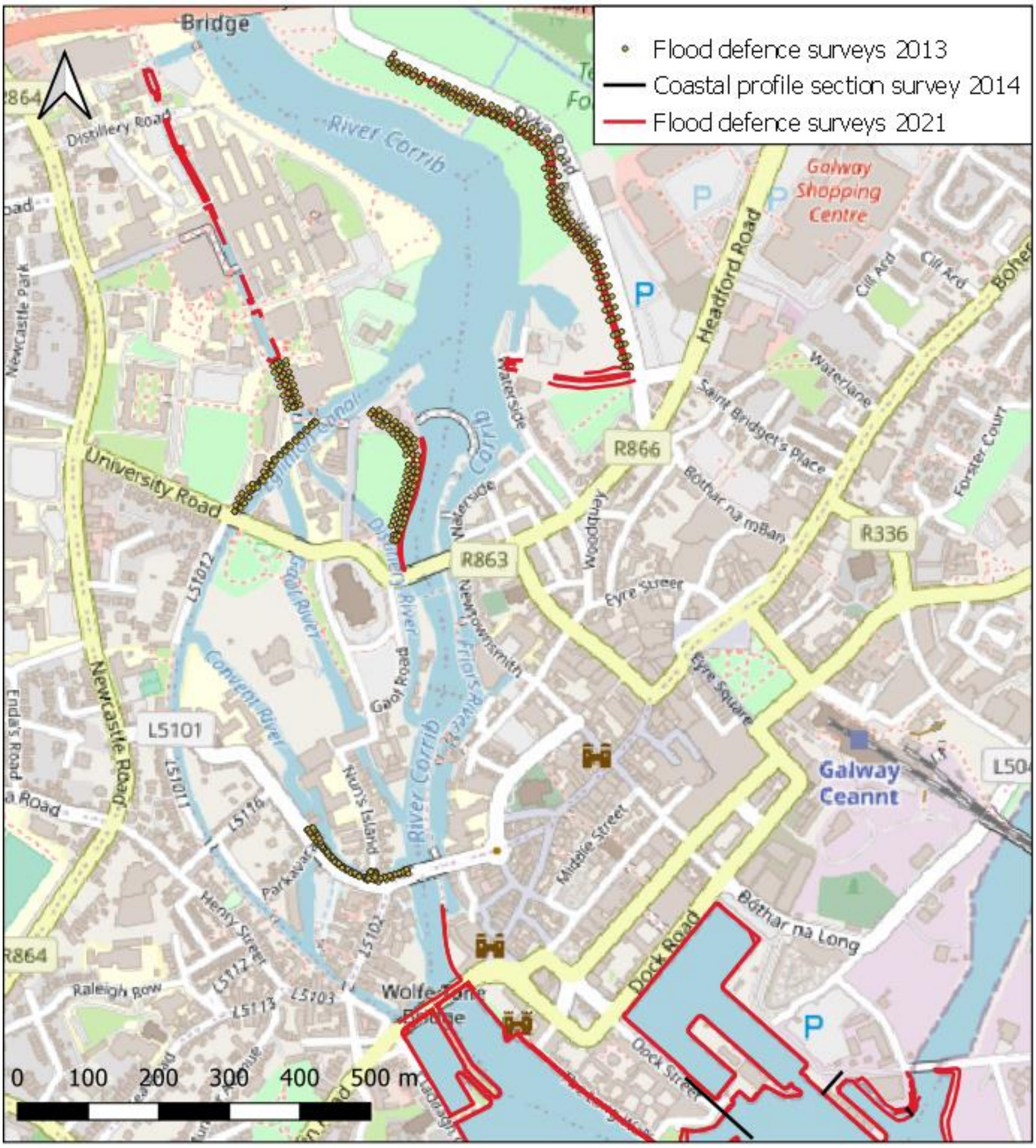

Figure 2.3.3 Flood defence surveys – Galway City

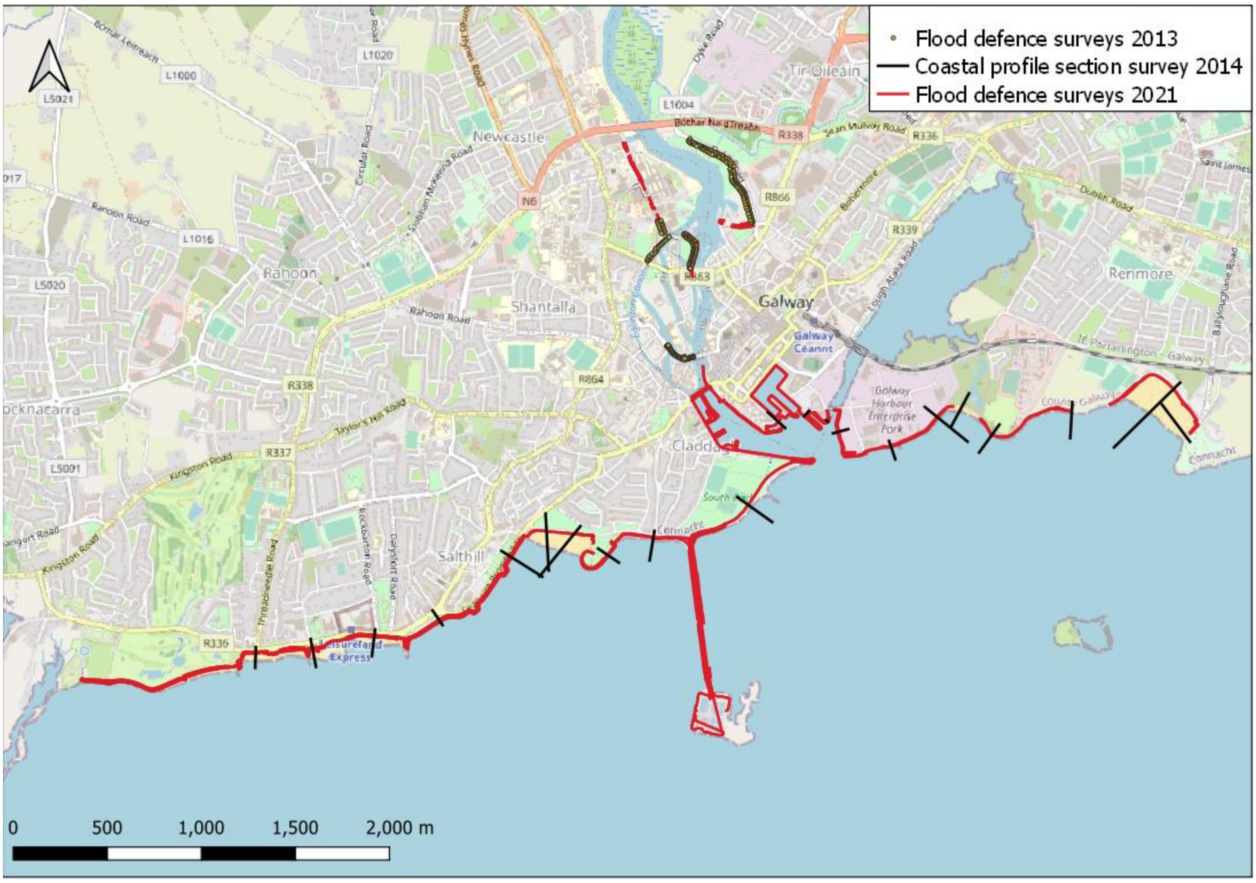

Figure 2.3.4 Flood defence surveys – Galway Bay

2.3.7 Galway City FRS Building threshold surveys (Lot 1b surveys)

Building threshold surveys are undertaken to improve the accuracy of building representation within a model, which is key when undertaking damages assessment.

Additional building threshold surveys were undertaken as part of the Galway City FRS Lot 1b surveys by Murphy Geospatial. The CFRAM flood extents for a series of extreme events were used to specify the extent of the threshold surveys, while also applying a buffer. In total, 2614 properties were surveyed in 2021.

2.3.8 Gaps in surveys

As noted in the previous sections, there are a number of gaps in the datasets due to issues encountered by the surveyors on site. These gaps and how they have been addressed as part of the project are presented below. The reader is also referred to Section 11 – Model limitations and assumptions.

- The internal geometric parameters for a number of long culverts were not able to be surveyed. It was therefore assumed that the internal dimensions could be represented by either the upstream or downstream face of the culvert - whichever face provided the smallest constriction in flow was adopted.
- It was not possible to collect geometric information and/or CCTV surveys of the culverts of the University of Galway Old engineering building that is located on Gaol river (NUNS). It has been assumed as part of the study that the culverts allow flows of up to $5m^3/s$. The impact of blockages or smaller geometry that allows less flows to pass will be undertaken as part of a blockage assessment.
- Sruffnacashlaun Siphon on Distillery channel, under Eglinton canal – Several historic surveys of this structure were undertaken some of which provide conflicting data. The geometry of the Siphon in the model is based on information taken from two different surveys: the recent 2021 Infill Surveys and a long section of the structure from 2014. It is recommended that a blockage scenario of the Siphon is assessed.
- Threshold levels were not recorded at circa 70 buildings within the Q100/T200 floodplain. The average ground elevation values across the building footprints from the Lidar DTM were instead used to set the threshold levels for these properties. This assumption will be considered further when assessing damages.

2.4 Digital terrain model

The Digital Terrain Model (DTM) is a bare earth representation of the floodplain topography in which all the buildings and vegetation have been removed. It is used in the model to define the ground elevations of the 2D model grid and represents a critical aspect of the model. Two different Lidar DTMs have been utilised in this study:

- The DTM used to inform the fluvial/tidal modelling is taken from the Western CFRAM Study. This Lidar data was captured between November 2011-August 2012 at a 2m grid resolution. This Lidar data was inspected as part of the initial QA of the datasets and was found to be representative of existing ground conditions in the city centre and fluvial dominated area. Figure 2.4.1 presents a snapshot of the Lidar dataset of the scheme area superimposed over an aerial image of the scheme area. It is noted that the gaps in Lidar data at the northeast of the Scheme area are not required for the purposes of the study and as such further surveys in these areas were not undertaken.

- From our QA of the Lidar data it was found that there were some minor areas where 2011/2012 data was no longer representative of existing ground levels due to recent developments in wider coastal floodplain area. The DTM used to inform the WOT/Coastal model is therefore taken from a recent OPW coastal aerial Lidar survey which was undertaken by Fugro in 2021. This 2021 data is fully representative of the present day ground levels across the scheme area.

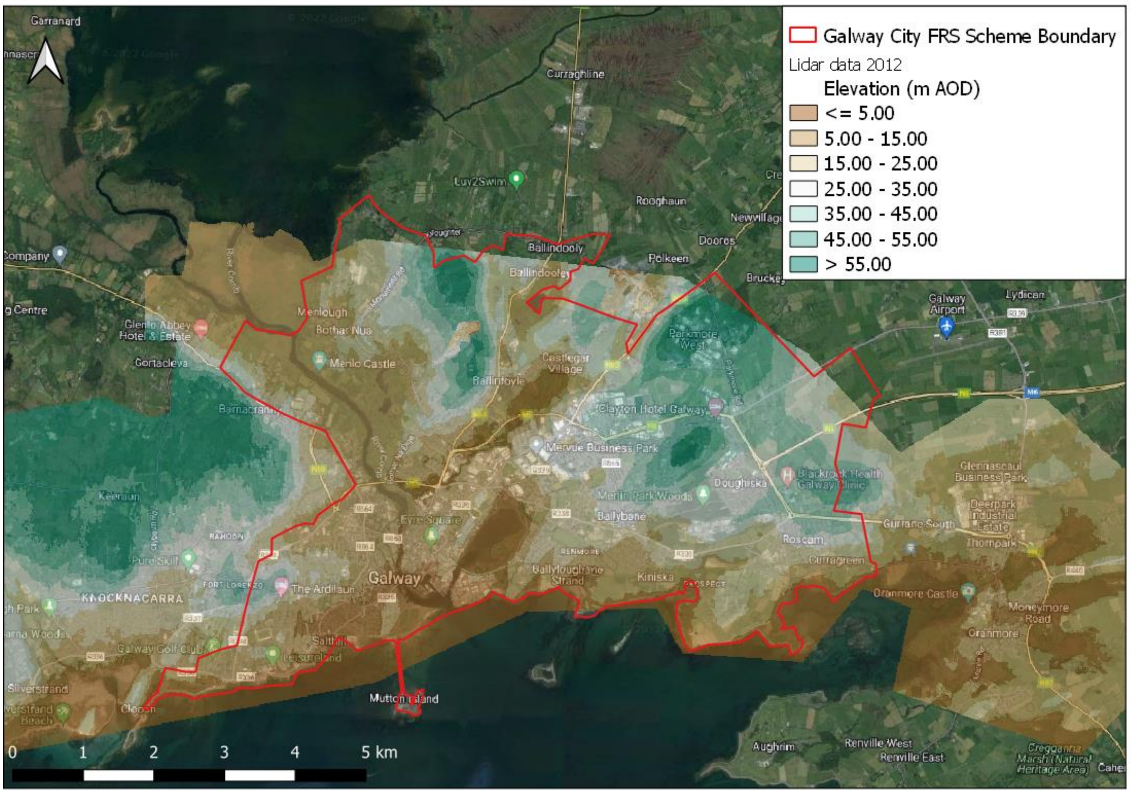

Figure 2.4.1 DTM in the Scheme area

2.5 Model calibration event data

Calibration of the model is required as part of fine-tuning and adjusting the model to ensure it represents the flood conditions of the area. The following datasets are available for the calibration of the fluvial/tidal model.

2.5.1 Gauged data

There are currently six OPW gauging stations installed within the Scheme Area. The Marine Institute also maintain gauges in Galway Port. The gauges are listed in Table 2 and their location is plotted in Figure 2.5.1.

Table 2 In-bank data sources (listed from downstream to upstream location)

Gauging station	Data	Period of records
Galway Port	Water Level	2007- present
Wolf Tone (30061)	Water Level (tidally influenced)	1950 – present (considered unreliable before 2009 by OPW)
Barrage D/S (30097)	Water Level only	Since 14/09/2021 - present
Barrage U/S (30099)	Water Level only	1990- present
Quincentennial bridge (30096)	Water Level only	Since 29/07/2021 – present
Dangan (30098)	Water Level only	1986- present
Terryland (30117)	Water Level only	Since 11/07/2021 - present

Figure 2.5.1 Location of OPW's gauging stations (orange circles), and the Marine Institute's Galway Port gauging station (green circle) (Map data from OpenStreetMap)

Three of the OPW gauges were installed following recommendations arising from the hydrological analysis of this study and have therefore only been operational since Q3 2021.

All the gauging stations record water levels, with Wolfe Tone station and Galway Bay station being tidally influenced.

2.5.2 Calibration events

The Galway City fluvial/tidal 1D/2D model has been calibrated to a number of historic flood events. These are listed as:

- Fluvial flood event in February 2020. This event is mainly in-bank within the city centre;
- Fluvial flood event in February 2022. This is the most recent event and the gauges installed as part of the Galway City FRS project have been utilised as part of the calibration;
- Tidal flood event in February 2014. This event caused out of bank flooding in a number of areas and has been used to calibrate out-of-bank flow in the model.

The key parameters of the calibration events as well as a summary of the available data is presented in Table 3. The data used to inform the model calibrations is also described in the following sections.

Table 3 Events used to calibrate the Galway City model

Date	Flood source	Peak flow/level (severity)	Data
Fluvial: Feb-Mar 2020	Fluvial in bank event (~1 in 10)	343m^3/s – all gates of the Salmon weir were open	Gauge data (in bank) at 3 gauging stations (waterlevel.ie).
Fluvial: February 2022	Fluvial in bank event (<1 in 2)	230m^3/s - all gates of the Salmon weir were open	Gauge data (in bank) at 5 gauging stations (waterlevel.ie).
Tidal: Feb 2014	High tide, storm surge & wave overtopping (~1 in 20)	3.59m AD - all gates of the Salmon weir were open	Gauge data at 3 gauging stations (waterlevel.ie) Photographs, wave data, tide data, flood extents, threshold & topo surveys of affected areas around Claddagh, Father Griffin, Spanish Arch and Docks (JBA flood event report)

The Coastal 2D model has not been calibrated against any historic coastal flood event. There are a number of reasons for this:

- The absence of any wave data from along the coastline of the scheme area during an event means that it is not possible to know what wave heights and direction were incident during the event. It is therefore not possible to accurately generate WOT volumes for a calibration event due to absence of boundary condition data;
- The uncertainty associated with WOT methods is significant. Even if wave data were available at the site the volumes associated with a historic event would as a consequence be very uncertain which may lead to erroneous conclusions being made on the calibration;
- WOT is the dominant historic mechanism of flooding in Salthill. We are not aware of any pure tidal event that has inundated the Salthill area such that a tidal-only calibration run has not been considered.

The absence of a calibration event for the coastal model is however not deemed to impact on the findings of the model for the following reasons:

- High quality data has been used to define the geometry of the model and best practice in modelling has been followed in the development of the model. The model is therefore correctly set up and utilises the best available geometric data;
- The coastal model does not contain any structures. The specification of a range of coefficients associated with various culverts/bridges etc is therefore not relevant to the model;
- The results of the coastal model are comparable with the results of the fluvial/tidal 1D/2D model in the common area of the models which allows us to draw confidence on the performance of the coastal model particularly given that the 1D/2D model has been calibrated against recorded data.

2.5.3 February 2020 fluvial flood event data

Water level measurements from three of the gauging stations were available for the February 2020 calibration event: the Dangan gauge, Barrage U/S gauge and Wolfe Tone Bridge gauge.

Water levels from the Dangan gauging station were used as the upstream flow boundary of the calibration model while the water level records from the Barrage U/S gauge and Wolfe Tone Bridge gauges have been used to calibrate the model (Section 6). Data from the Galway Port gauge was used to provide the downstream water level boundary of the calibration model.

In order to avoid introducing the recorded fluctuations in water level from the gauge into the model, the gauged 15-min readings from the Dangan gauging station were averaged to a 6-hr interval as shown in Figure 2.5.2.

The flood event lasted for several weeks. It is not practical to model the entire duration of the event as the computational burden to do so would be very significant. It is however not necessary to model the full duration of the event as this study is mainly concerned with the maximum flow conditions and it can be seen from the plot below (Figure 2.5.2) that a quasi-steady state is reached for the peak of the event. The calibration model was therefore simulated for 10 days (21/02/2020 to the 03/03/2020) which covers the peak of the event. The calibration period is indicated in Figure 2.5.2.

The February 2020 flood event approximates to a return period of circa 10 years on the River Corrib. Arup has confirmed that all of the Salmon Weir gates were open during the event and the calibration model has been configured to represent this.

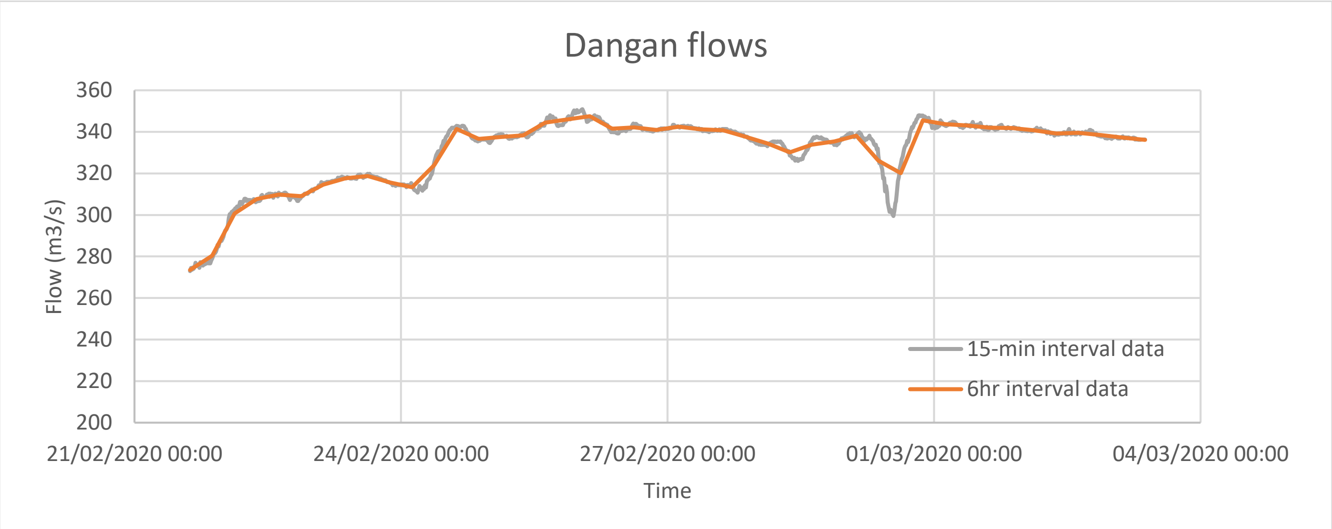

Figure 2.5.2 February 2020 flood flows at Dangan gauge

2.5.4 February 2022 fluvial event data

Water levels measurements from five of the gauging stations were available for the February 2022 calibration event: the Dangan gauge, Barrage U/S gauge, Wolfe Tone Bridge gauge, Quincentennial Bridge and Barrage D/S.

As with the February 2020 calibration model set up, 6 hr averaged flows from the Dangan gauge were used as the upstream boundary condition (Figure 2.5.3) while data from Galway Port was used as the downstream boundary. Data from the other gauges was used to calibrate and validate the model.

It can be seen from Figure 2.5.3 that a large jump in water level occurs on 24/02/22 14:30. The OPW have confirmed that this increase in water level relates to a circa 2 hour closure of a number of the gates which was undertaken to facilitate a request from emergency services. The increase in water level is observed at the other gauges in the vicinity of the Salmon weir. The impact of the gate closure is not accounted for in the boundary condition of the calibration model and is therefore not simulated by the model. There will therefore be a minor discrepancy when comparing the model results to the data for this short 2-hour period.

The February 2022 flood event reached a peak level of circa 230m^3/s which corresponds to a return period of less than 2 years on the River Corrib. Arup has confirmed that all of the Salmon Weir gates were open during the event (with the exception of the short closure noted above) and the calibration model has been configured to represent this.

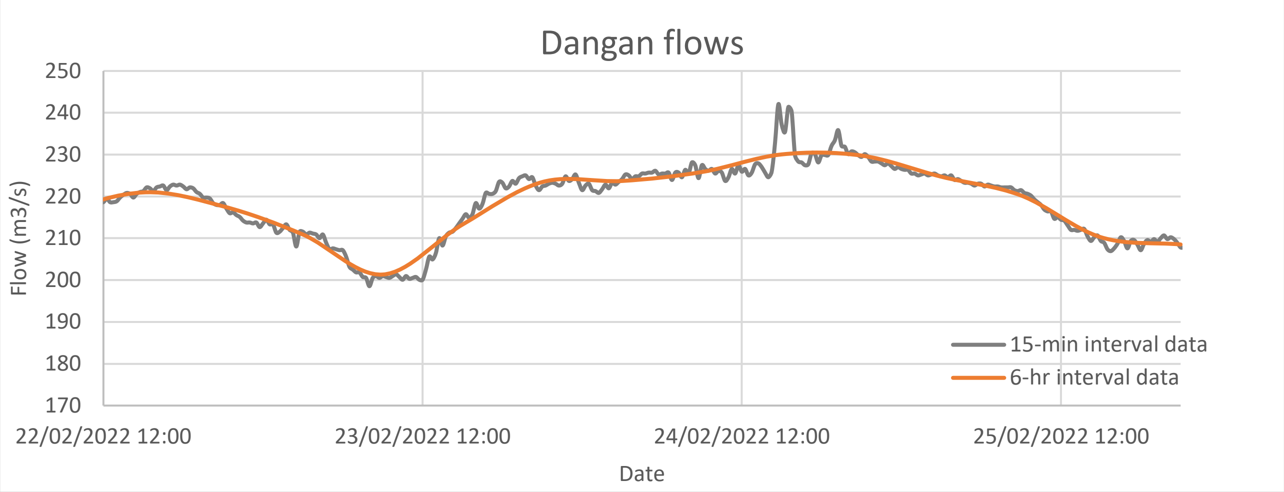

Figure 2.5.3 February 2022 flows at Dangan gauge

2.5.5 February 2014 tidal flood event

The February 2014 flood event was tidally dominated and caused out of bank flooding at numerous locations in the City centre. Water levels from the event were recorded at a number of tidal gauges as indicated in Figure 2.5.4: Galway Port, Oranmore Bridge (29015) and Wolfe Tone gauges. The peak water level at Galway Port was 3.59m AOD and at Oranmore it was recorded as 3.66m AOD. When the water level gradient across Galway Bay is considered, it can be seen from Figure 2.5.4 that the recorded peaks are well matched which adds confidence to the records for the tidal gauges. It is noted that the tidal levels correspond approximately to a 20-year tidal flood event.

Data from the Dangan gauge was used as the upstream boundary of the calibration model while data from Galway Port was used as the downstream boundary.

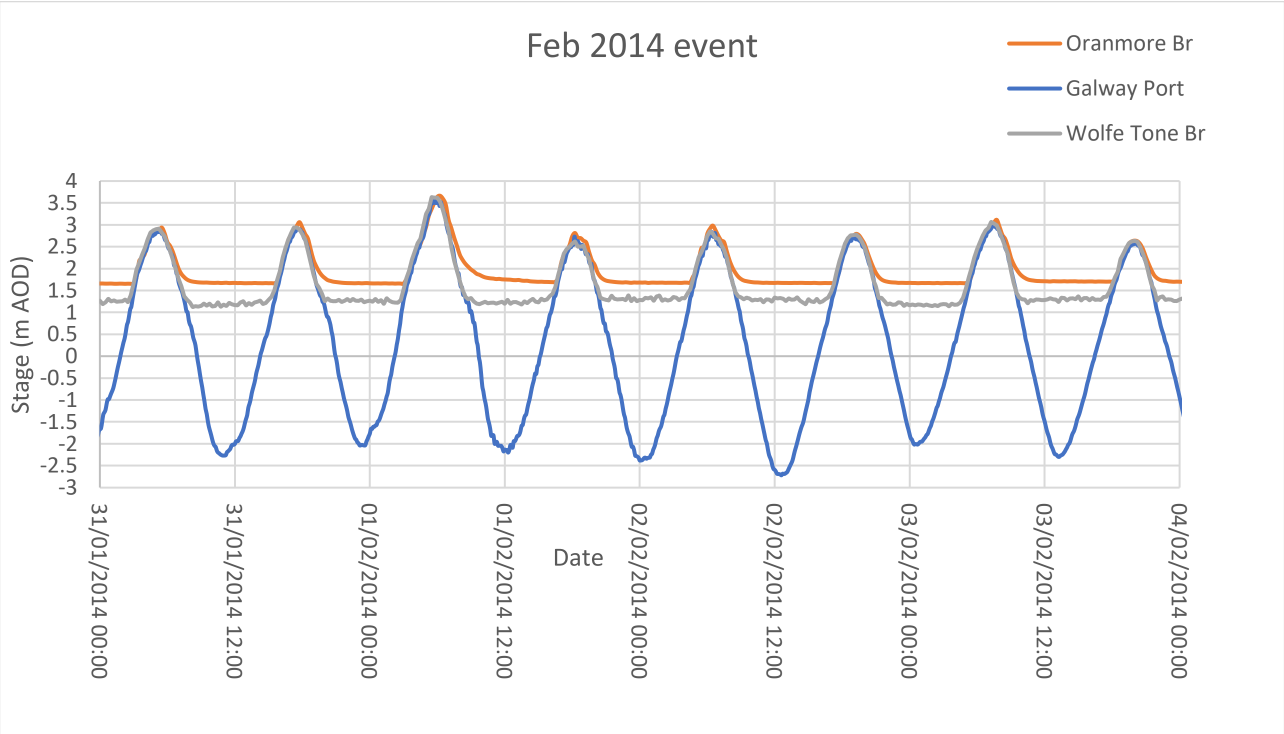

Figure 2.5.4 Gauged Water Levels for the February 2014 event at Galway Port and Oranmore

Flooding during the February 2014 event was also experienced in Salthill and resulted from wave overtopping in combination with the tidal flooding. It is not possible to accurately simulate a historic wave overtopping event due to a lack of data on wave conditions at the sea/land interface i.e., directly at Salthill and along the coastline of the scheme area. The calibration for this event is therefore only focused on the still water level (SWL) tidal component which impacted Galway City centre.

Estimated maximum flood extents and depths from the event in Galway City were collected by the Western CFRAM consultants after the event and have been used as part of this study to inform the model calibration. The extents are presented in Figure 2.5.5. The properties that were affected by flooding and other possible properties are shown as well in coloured dots. An estimated 107 properties flooded as a result of the flood event in Galway City and Salthill areas.

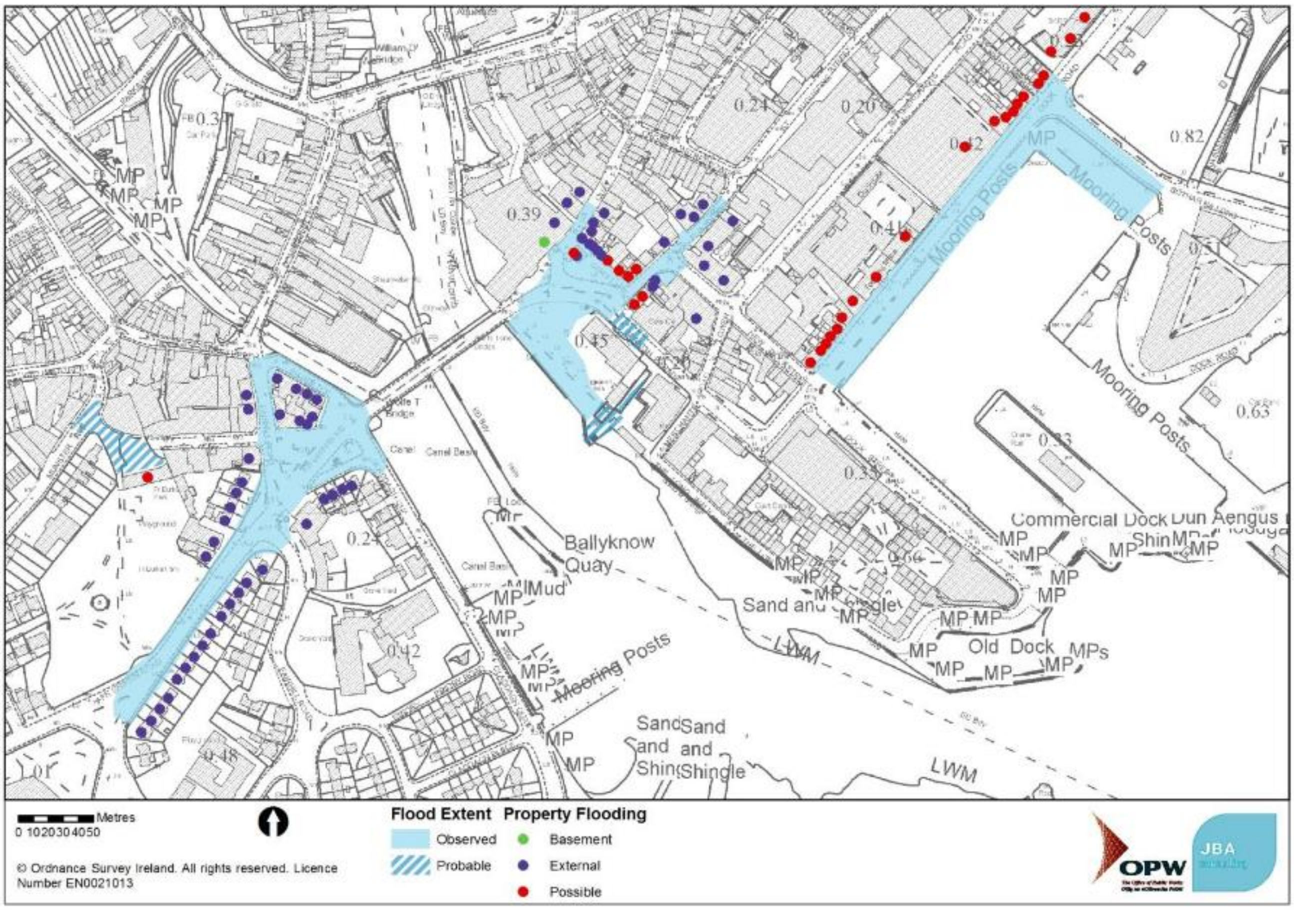

Figure 2.5.5 Map of flooding in Galway City Centre (JBA report)

The above flood extents are drawn from observations during site visits and interviews with locals. There were no records or survey of water or wrack marks following the flood event.

As part of our QA of the historic datasets, we have compared the gauged data from the 2014 event with the flood extents as estimated by the Western CFRAM consultant. The tidal gauge records from both Galway Port and Wolfe Tone Bridge indicate that tidal levels exceeded 3.5m AOD for at least 30min and 45mins respectively (see Figure 2.5.6). This is deemed to be sufficiently long to allow for flood water to inundate all the areas immediately adjacent to the Corrib than are set below 3.5m AOD. This area is shown in green in Figure 2.5.7 and has been estimated by taking a horizontal cut through the Lidar dataset. It can be seen from the figure that the extent of the area which falls below 3.5m AOD is larger than the flood extent as estimated by the CFRAM consultant (Figure 2.5.5). The CFRAM extent may therefore not be an accurate representation of the maximum extent of the event. This is considered further in the calibration section of the report.

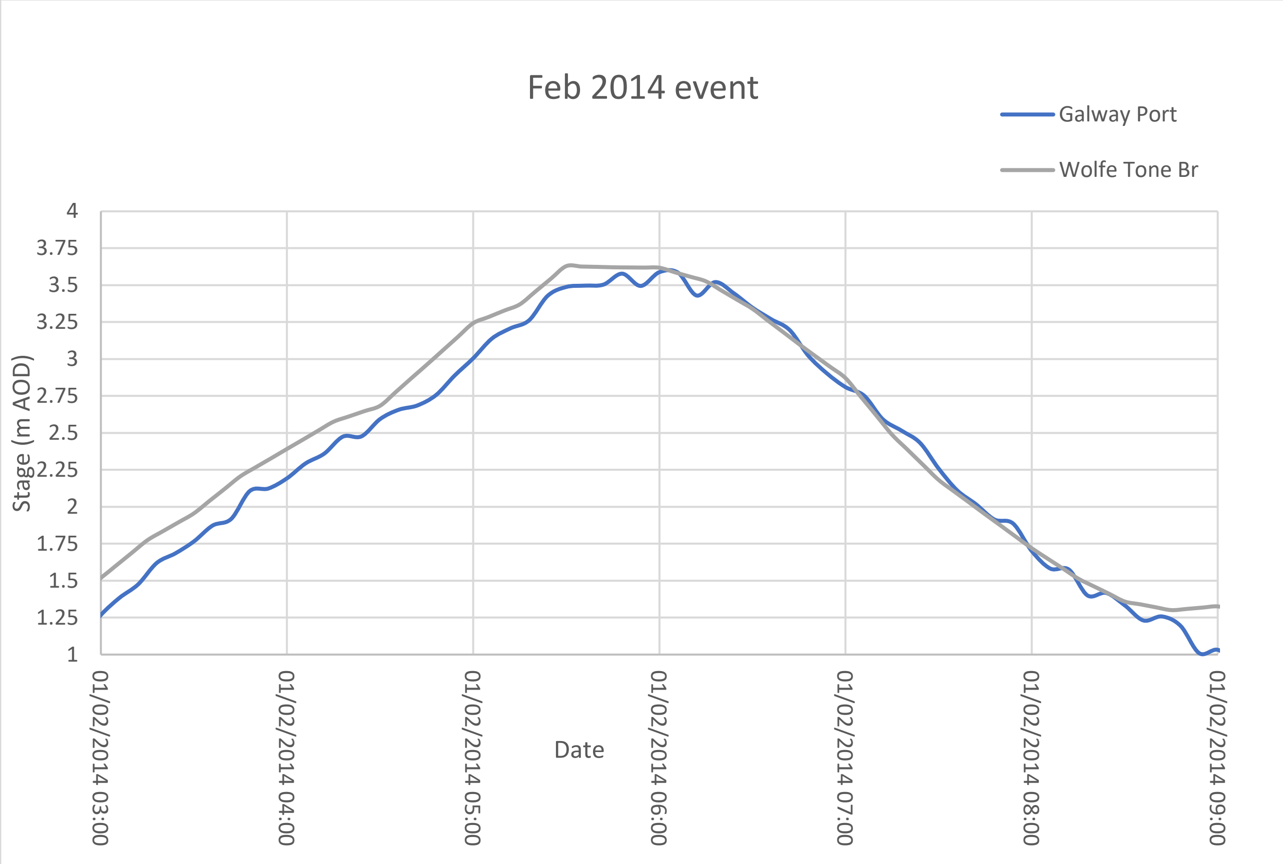

Figure 2.5.6 Peak tide during the February 2014 event, Wolfe Tone and Galway Port gauges

Figure 2.5.7 Lidar extents below the 3.5m AOD level

Figure 2.5.8 Flooding in Galway City, junction of Flood Str and New Dock Str (01/02/2014, Source: JBA report, Galway Harbour Company onFacebook)