Recovering legacy tidal records to elucidate trends in sea-level rise in Ireland

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- **Chapter 2 – Peer-reviewed Data Article:**
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Note: Minor editorial updates have been applied to the published manuscripts included in this thesis to ensure consistency, clarity, and accurate referencing, where requested by supervisors. Chapter 4 has also been updated in response to examiner feedback and to reflect an updated Glacial Isostatic Adjustment (GIA) model, resulting in revisions to aspects of the content and statistical outputs. Site-specific rates were additionally derived directly from the full posterior distributions rather than relying on derived rate summaries from the reslr package, allowing uncertainty to be propagated consistently through the posterior samples. Further corrections may be made in the published version following peer review of Paper 3 (Chapter 4); however, any such revisions will be limited to clarification, correction of minor errors, or refinement of presentation, and are not expected to alter the overall interpretations or main conclusions of the study.

Abstract

Over much of Ireland, long-term sea-level records are limited, yet a wealth of historical data exists in archives, often as paper marigrams. This thesis recovered, digitised, and integrated selected historical marigrams to produce a robust national dataset for assessing mean sea-level (MSL) change and coastal vulnerability. Data rescue focused on methodological accuracy, correcting distortions in paper charts—bends, skews, and grid misalignments—that could bias digitised records. Using Dún Laoghaire (1925–1931) as a case study, a correction framework quantified offsets between digitised traces and underlying grids at hourly intervals, improving accuracy to 1 cm, consistent with Global Sea Level Observing System standards. Validation against independent historical surveys and modern observations confirmed that tidal amplitudes, phase lags, and mean sea levels were accurately reproduced within expected observational uncertainties.

Building on this foundation, a structured training framework enabled students and citizen scientists to contribute high-quality digitised data, with case studies highlighting common error sources and quality assurance measures. This method is applicable to students, citizen scientists, and educators, and may facilitate future machine-learning development, currently limited by the complex visual nature of marigrams.

The thesis' central contribution is the first nationally consistent reconstruction of MSL change across Ireland from 1925 to 2024, achieved by integrating newly digitised southwestern records with existing datasets. Regional variability was identified, with long-term mean modelled instantaneous rates ranging from 0.40 mm yr^{-1} at Belfast in the north to 3.29–3.59 mm yr^{-1} at Cork and Tarbert in the south and southwest. The regional mean modelled instantaneous sea-level rise rate over 1925–2024 was 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01). Modelled instantaneous sea-level rates accelerated after 2000, exceeding 4 mm yr^{-1} and reaching ~6–7 mm yr^{-1} by 2024 at several sites. Residual uncertainties from observational gaps, digitisation errors, and short-term variability were quantified using Bayesian credible intervals—a statistical method providing a range of plausible values for sea-level trends. By combining historical data rescue, correction methods, and Bayesian modelling, this thesis provides a nationally consistent framework for reconstructing sea-level change. This framework supports citizen science and adaptation planning, while placing Ireland's sea-level trends in a global context.

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Glossary of Selected Key Acronyms

AI/ML: Artificial Intelligence / Machine Learning – computational methods that can assist in the digitisation of complex tidal records.

AR6: Sixth Assessment Report of the IPCC; the most recent comprehensive global climate assessment cycle.

BODC: British Oceanographic Data Centre – provider of marine data.

CD: Chart Datum – reference for nautical charts, typically below lowest astronomical tide.

CrI: Credible Interval; a Bayesian interval representing the range within which a parameter lies with a given probability (e.g. 95% CrI).

DST: Daylight Saving Time – time reference for data.

ENSO: El Niño–Southern Oscillation – climate oscillation in the tropical Pacific, including El Niño and La Niña events, affecting sea level, ocean temperature, and winds.

GAM: Generalised Additive Model; a flexible regression framework that models non-linear relationships using smooth functions.

GIA: Glacial Isostatic Adjustment – land-level changes affecting relative sea level.

GESLA: Global Extreme Sea Level Analysis – tide gauge dataset.

GNSS: Global Navigation Satellite System – GPS-like systems, including Galileo and GLONASS.

GOOS: Global Ocean Observing System – integrates ocean observations worldwide, including tide gauges, to support climate and ocean monitoring.

GLOSS: Global Sea Level Observing System – international tide gauge network coordinated by the IOC/UNESCO.

GTG: Geological Tide Gauge – proxy-based reconstruction of past sea level using salt-marsh microfossils (foraminifera).

GRU: Gated Recurrent Unit – type of recurrent neural network.

IOC: Intergovernmental Oceanographic Commission – oversees GLOSS and coordination of oceanographic observations.

IOD: Indian Ocean Dipole – climate oscillation in the tropical Indian Ocean affecting regional sea level, ocean temperature, and wind patterns.

IPCC: Intergovernmental Panel on Climate Change; the United Nations body responsible for assessing climate science.

Marigram: Graphical record of tidal measurements, showing high and low waters over time.

MCMC: Markov Chain Monte Carlo; a class of algorithms used to sample from posterior distributions in Bayesian inference.
MHW: Mean High Water – used in MTL calculations.
MI: Marine Institute – Irish national agency supporting marine research.
MLW: Mean Low Water – used in MTL calculations.
MSL: Mean Sea Level – average sea level over a long period.
MTL: Mean Tide Level; the average of Mean High Water and Mean Low Water.
mm yr^{-1}: Millimetres per year – unit of sea-level change.
NOC: National Oceanography Centre – UK oceanographic research centre.
NAO: North Atlantic Oscillation – climate oscillation affecting regional sea level.

NI-GAM: Noisy-Input Generalised Additive Model; a GAM framework that accounts for measurement error in both observations and inputs.

NTGN: National Tide Gauge Network (Ireland); coordinated network of tide-gauge stations used for monitoring sea level.
NTSLF: National Tide and Sea-Level Facility – historical tide-gauge dataset in Ireland.
OD: Ordnance Datum – a general fixed reference for elevations or sea level, typically tied to a local tide gauge.
ODD / OD Poolbeg: Historical Ordnance Datum in Dublin based on the Poolbeg tide gauge; a local vertical reference preceding ODM.
ODB: Ordnance Datum Belfast – vertical datum for Northern Ireland (~0.037 m below ODM).
ODM: Ordnance Datum Malin – standard vertical datum for Ireland (Malin Head).
ODN: Ordnance Datum Newlyn – UK tide gauge reference datum.
OPW: Office of Public Works – Irish government agency responsible for water infrastructure.
PSMSL: Permanent Service for Mean Sea Level – tide gauge data repository.
QC: Quality Control – procedures applied to tidal and sea-level data to ensure accuracy and consistency.

RLR: Revised Local Reference – converts metric measurements to standardized tide gauge units.
RSL: Relative Sea Level – sea level relative to the land at the measurement site.

SSL: Steric Sea Level – component of sea level change due to changes in temperature and salinity.
UHSLC: University of Hawaii Sea Level Centre – tide gauge dataset.

UNESCO: United Nations Educational, Scientific and Cultural Organization; a UN agency promoting international cooperation in education, science, culture, communication, and ocean science via the IOC.

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1. Introduction

1.1 Background and Context of Sea Level Rise and its Regional Impacts

The global rate of sea-level rise has almost tripled over the past century, from 1.3 mm yr^{-1} (1901–1970) to around 3.7 mm yr^{-1} (2006–2018) (El-Geziry, 2023). While the global increase is well established, regional variations in mean sea level (MSL) are often less well understood. Local differences in tidal patterns, non-tidal variations, and land movement can either amplify or reduce the risk of coastal flooding in different regions. In the UK and Ireland, for example, the relaxation of the geoid associated with Greenland Ice Sheet melting is expected to result in lower rates of relative sea-level rise compared with the global mean by 2100 (Palmer et al., 2018). Even within Ireland, relative sea-level rise is highly variable, with reduced rates in the northeast and higher rates in the southwest due to Glacial Isostatic Adjustment (Bradley et al., 2011).

The potential increase in sea level is by no means trivial. Globally, approximately 40% of the world's population lives in coastal areas (Arbinolo & Gamper, 2021), and around 100 million people live on low-lying land below the high tide line at present (Strauss et al., 2021). In the UK over one third of the population live within 5 km of the coast (Edwards, 2017), while in Ireland, around 40% live within the same distance (Wall et al., 2020). Ireland's coastal zones, including the cities of Dublin, Cork, and Galway, are particularly exposed to climate change impacts, including sea-level rise, storms, and flooding (Department of Communications Climate Action and Environment, 2018). In 2018, Ireland's ocean economy had a turnover of €6.2 billion and supported over 34,000 jobs, with much of its supporting infrastructure, such as ports and nearshore aquaculture, inherently exposed to sea level rise and coastal hazards (Government of Ireland, 2019). Changing exposure and vulnerability requires change in adaptation measures. There has been significant investment in flood defences in recent years such as the Dublin Coastal Protection Project (Cooke et al. 2005; Dublin City Council, 2022) and the planned Lower Lee Flood Relief Scheme (OPW & Arup, 2017). Good decisions require robust underpinning data, and this is a weakness in Ireland. The recent Irish Coastal Wave and Water Level Modelling Study highlighted "notable gaps in the availability of long term tidal records" in certain areas around the coast of Ireland (OPW & RPS 2020a, 33). Locally, Cork and Galway cities are highly vulnerable to flooding. Flooding has already caused significant economic and social disruptions in Ireland. For example, flood events in Cork in 2009 and 2014 resulted in economic losses of €90 million and €40 million, respectively (Hickey, 2010).

The Intergovernmental Panel on Climate Change Special Report on the Ocean and Cryosphere projected a likely upper limit for global mean sea level (GMSL) rise of approximately 1.1 m by 2100 (IPCC, 2019). Global studies on tidal change and storm surge characteristics also anticipate alterations in response to climate change (Haigh et al., 2020; IPCC, 2019). While variations in tides and storm surge are mainly influenced by regional and local factors, such as the morphology of coastal environments and sedimentation rates, changes in tidal characteristics with a regional (rather than local) footprint are also reported in response to shifting mean sea levels (Haigh et al., 2020). Even within Europe, potential impacts vary substantially: projected flood losses could triple by the 2020s, increase six-fold by mid-century, and exceed ten times current damages of €3.4 billion per year by the end of the century, with the highest impacts on industry, transport, and energy sectors, and the greatest regional losses expected in southern and southeastern Europe (Forzieri et al., 2018). Similarly, projections suggest that future flood damages across Europe could reach €24 billion per annum by 2050 (Doran et al., 2015). A local example occurred in 2018 when Storm Eleanor hit Galway, causing damages exceeding €0.5 billion, affecting over 150,000 customers, and resulting in six fatalities across Europe (Lau et al., 2022). Therefore, understanding climate extremes also requires consideration of sea-level change. An illustrative example is shown in Figure 1.1, depicting the flooding of Dominick Street during Storm Eleanor, where a storm surge of approximately 1.2 m combined with tidal water levels reaching approximately 3.7 m above mean sea level (MSL) demonstrates the potential impact of high water levels on streets located close to the coast (Creative Ireland, 2023).

Figure 1.1: Flooding on Dominick Street, County Galway, during Storm Eleanor, December 2018. Streets and buildings were inundated due to extreme storm surge (Creative Ireland, 2023).

Coastal erosion and sea-level rise are closely interconnected (Caloca-Casado, 2018), with sea-level rise accelerating and intensifying erosion processes. Various parts of Ireland are particularly vulnerable to coastal erosion, especially along the west coast. Notable heritage sites such as Dunbeg Fort, Skellig Michael, and Ballinskelligs Priory have experienced significant impacts due to climate change (McCormick & Nicolas, 2022). For instance, the erosion of the Rossbeigh coastal barrier in County Kerry over a 19-year period resulted in a 60% reduction in vegetated dunes, a breach over 1 km wide, and a significant shift in the barrier's orientation due to natural erosion processes (Nuyts et al., 2020).

Coastal erosion poses significant challenges in both Ireland and England, with rates expected to increase due to climate change and rising sea levels (Masselink et al., 2020). This erosion also has the potential to impact households and holiday homes close to the coastline. On Ireland's east coast, particularly in Wexford, coastal erosion has had profound emotional and social consequences. In Courtown, for example, the loss of beaches has led to a strong sense of place loss among residents, often described as solastalgia (Albrecht, 2005; Phillips et al., 2022). Adaptation measures, such as the installation of rock armour, while mitigating physical erosion, have further amplified these feelings of loss by altering the natural coastal landscape. Understanding climate extremes requires an integrated approach that considers the impacts of sea-level change alongside other environmental factors.

1.1.1 Sea level data records availability in Ireland

Knowledge of sea level variations is key to understanding coastal vulnerability and risks. Fundamental to this is the availability of appropriate sea level data. Many historical sea level records, known as marigrams, are graphical representations of tidal data for a given period of time. A single trace on a marigram usually represents one day, and marigrams often contain multiple overlapping traces showing a week of data on a sheet of graph paper. These records are produced by tide gauges (ink float or mechanical), which transform the physical vertical motion of the sea into a proportional, continuous record of water level variations (Murdy et al., 2015; McLoughlin et al., 2024a). Before the digital era, marigram traces were typically recorded on graph paper. A common technique involved measuring the rise and fall of a float within a vertical stilling well, which was connected to an ink pen that traced the measurements on graph paper attached to a rotating drum mechanism (McLoughlin et al., 2024a).

Historically in Ireland, marigrams—capturing continuous tidal curves or high/low water levels—were often recorded by port authorities and scientific institutions (Murdy et al., 2015; McLoughlin et al., 2024a). Metadata, which includes contextual information about the measurements, was preserved alongside the sea-level data to provide the necessary information for interpreting, reconstructing, adjusting for errors, and integrating historical tidal records (Latapy et al., 2023). Early Irish marigram records were archived locally, often by harbour offices or port authorities, rather than through a coordinated national system (Murphy et al., 2003). Similar practices were employed internationally, with records scattered across regional offices, research institutes, personal archives, naval archives, and libraries (Latapy, 2017), which complicates long-term access and integration for sea-level studies. These historical datasets, including archived tidal records, play a crucial role in understanding long-term sea level changes and assessing coastal vulnerability today, particularly in regions like Ireland where systematic observations were historically limited and often undocumented (Pugh et al., 2021).

Marigram datasets are available from various locations across Ireland, including Belfast (1901-2010), Dublin Port (1923-2003), Dún Laoghaire (1925-1931 ; McLoughlin et al., 2024b), Cork - Tivoli Port (data mainly recovered in the 1970s and 1980s), Limerick (Foynes and nearby locations, both fluvial and tidal), and Tarbert (Kerry). These sites collectively provide a valuable long-term record of historical sea levels across Ireland.

1.1.2 The importance of historical records in understanding sea level change

There are extremely useful close and consistent methods of monitoring sea level using modern day technology such as satellite observations to produce long term continuous records of sea level and to observe the factors driving sea level (Hamlington et al., 2023). However, it is also very important to consider that there are uncertainties within historical trends of sea level variation owing to the sparseness of instrumental data both regionally and globally (Hogarth, 2021). A record of at least 40 years duration is necessary to determine trends in mean sea level (Hogarth et al., 2021). However, shorter records have been shown to be useful for determination of mean sea level changes (Woodworth, 2018; Pugh et al., 2021). At the same time, these shorter records cannot inform of changes to rates of mean sea level rise. These shorter records are even useful for determination of tidal change (Pugh et al., 2021) although, in the absence of full records, estimation of the modulation of the 18.6-year nodal cycle must be estimated rather than directly calculated. Finally, statistics of non-tidal residual including storm surge require long, high frequency data to determine robustly statistics (Pugh & Woodworth, 2014). Therefore, the availability of long (>40 years), high-frequency, high-quality, datum-linked sea level data is crucial for understanding changing national and local vulnerability to sea level changes. In Ireland, digitised long records are rare and primarily confined to the northeast, along a line from Dublin to Malin Head, although additional historical charts exist elsewhere. However, significant efforts are underway to address this gap through data archaeology, such as the planned digitisation of marigrams from Cork and Tarbert (Kerry). Digitization of these records at high frequency (hourly or finer) is vital for improving understanding of tidal constituents, non-tidal residual statistics, and mean sea level in the southern and western regions, which are underrepresented along the Dublin–Malin line. Ultimately, this enhances coastal vulnerability assessments across Ireland.

Understanding changes in historical sea level rise is crucial for assessing coastal vulnerability and risks. In Ireland, while digital tide gauges are now widespread, they provide limited insight into historical sea level changes. Sea level rise since the late 20th century in Cork and Dublin has been higher than the global average, based on continuous records from Dublin and discontinuous records from Cork (C. Noone et al., 2024). Consequently, further efforts to rescue historical data and digitise tidal records are essential for gaining a more comprehensive understanding of sea level change in Ireland.

1.2 Historical and Technical Aspects of Tide Gauge Accuracy

Various methods were employed to obtain tidal measurements, including the use of tide scales carved into stone and tide boards with engraved markings. Early proposals for systematic tidal observation and measurement infrastructure can be traced back to Moray's 17th-century discussions of structured sea-level monitoring (Moray, 1666). These measurements were often recorded to the nearest quarter or half foot, as seen with the Standard Admiralty tide boards used in UK tidal surveys, which were marked in 0.25-foot increments (approximately 70 mm) (Hogarth, 2021). Higher resolution readings could be achieved by averaging data over the course of a month. Additionally, the use of a stilling well—a technique in use since at least the 18th century—enabled more accurate readings by reducing the influence of wave action. This setup allowed for precise measurements down to fractions of an inch, with one inch equalling just over 25 mm (Hogarth, 2021). In Britain, self-registering tide gauges introduced in the early 19th century provided significantly higher resolution compared to previous methods. However, their long-term accuracy was constrained because they were still calibrated using harbour tide scales (Hogarth et al., 2021). Over time, the design of these gauges evolved and became more robust, and growing interest in precise sea-level measurements led to improved calibration of gauges. In Figure 1.2, the typical structure of a tide gauge from the 20th century (specifically used in the 1970s) is shown (O'Sullivan, 1977) for recording tidal observations, with all the components listed. Daily tidal traces would be recorded on graphical paper using this type of tide gauge.

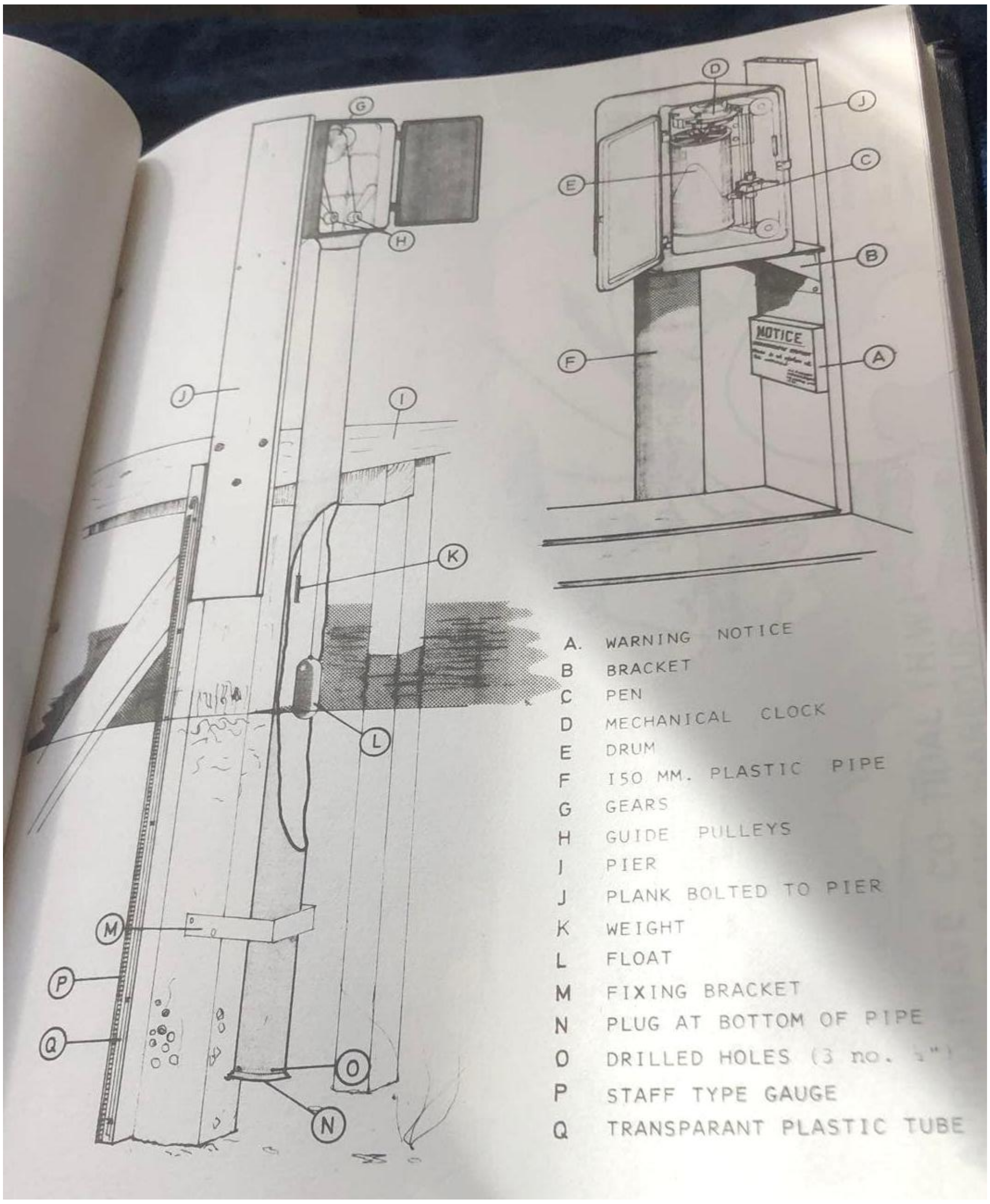


Figure 1.2: A sample structure of a typical tide gauge (and its components). These types of tide gauges were installed in Cork (Monkstown) . (Source: O'Sullivan, 1977).

It is vital that the vertical stability of a tide gauge datum is maintained to ensure accurate measurements (Hogarth, 2021). Although widely available discussions on such issues in Ireland appear to be limited, this could potentially be a concern in Dublin Port. The ongoing dredging and dumping activities associated with the Alexandra Basin Redevelopment (ABR) Project, as described in the Environmental Protection Agency (EPA) permits, involve significant alteration of sediment in the surrounding areas (RPS & Dublin Port Company, 2020). These activities could potentially influence the vertical control of the tide gauge datum, particularly if conducted in close proximity. Although sediment plume monitoring addresses environmental impacts, it does not specifically consider potential subsidence or ground movement that could affect tide gauge stability. This is notable given the recognized influence of vertical land motion on long-term sea level observations globally (Wöppelmann & Marcos, 2016). European Ground Motion Service (EGMS) data (Copernicus Land Monitoring Service, 2025) indicates that there may be ground movement in Dublin Port, which could potentially impact the accuracy of tide gauge data. Dredging in harbours and nearby rivers, including Dublin Port and the River Liffey, can alter recorded water levels and affect the accuracy of tide gauge data, with different dredging methods producing varying changes; for example, a major dredging project in 2016 lasted 42 days (RPS & Dublin Port Company, 2016). The variability in tide gauge data from Dublin Port, especially during the 1970s, 1980s, and 1990s (Shoari Nejad, 2023), could be influenced by factors such as digitisation errors, measurement inaccuracies, or natural variability in the data. While dredging may contribute to these variations, it cannot be definitively attributed as the sole cause. Additionally, the presence of the Leixlip Dam in Kildare could also impact the quality of tide gauge data in nearby Dublin Port.

1.3 Long-term Sea-Level Measurement Methods

Tide gauge measurements have been crucial for monitoring sea level rise since the 18th century, providing valuable insights into changes over the past few hundred years. However, these records are often sparse and inconsistently documented, which limits their ability to offer a comprehensive view of long-term sea level variations. Additionally, tide gauges cannot extend far enough back in time to capture geological-scale sea level changes. To address this limitation, researchers utilize alternative methods—such as salt marsh proxies, various microfossils (e.g., foraminifera, diatoms), geomorphological evidence, paleoclimate studies, and coral reef proxies—which provide valuable historical data to enhance our understanding of sea level changes over longer timescales (Walker et al., 2020; Roseby et al., 2023). For example, a study by Gerlach et al. (2017) reconstructed relative sea-level (RSL) rise over the past 2000 years using salt-marsh proxy data, including foraminifera, in the Gulf Coast of Florida, USA. The study combined these proxy data with tide-gauge records, revealing a continuous rise in RSL from around 0 CE, with acceleration starting around 1500 CE. Such a study demonstrates how proxy data, when combined with instrumental records, can offer critical insights into regional sea-level trends and help bridge the gap in data where tide gauges are absent or limited. These techniques enable the reconstruction of sea level changes over millennia, providing pivotal evidence of sea level change within these different time frames.

Salt marsh proxies can extend sea level reconstructions back centuries, providing valuable data that would otherwise be unavailable from tidal records alone. However, this data typically has lower temporal and vertical resolution and therefore greater uncertainties compared to the higher-resolution data obtained from tide gauges. Rossi et al. (2011) demonstrated strong agreement between a foraminifera-based relative sea level reconstruction from salt-marsh sediments in Brest, France, and the Brest tide-gauge record. This confirms the reliability of the transfer-function methodology and highlights the acceleration of sea level rise during the 20th century, observed in both proxy and instrumental datasets. Gehrels et al. (2020) found that sea-level rise along the Atlantic coast of North America, from Cape Hatteras to Nova Scotia, was faster during the 20th century than the global average. Their analysis of salt-marsh proxy records revealed natural multidecadal and centennial fluctuations, indicating that historical variability is an important factor in understanding regional sea-level dynamics. This suggests that the current acceleration in sea-level rise may result from both natural and anthropogenic influences. Roseby et al. (2023) applied the saltmarsh microfossil-based (foraminifera) 'geological tide gauge' (GTG) approach in Dublin, Ireland, developing two independent RSL records. They found a century-scale rise of 1.5 ± 0.9 mm yr^{-1} over the last 200 years, broadly consistent with the Dublin Port tide gauge record (1.1 ± 0.5 mm yr^{-1}) and, when corrected for glacio-isostatic adjustment, 1.6 ± 0.9 mm yr^{-1} since the start of the 19th century. What is exceptional about this study is that their findings align very well with the more accurate, shorter-term data from the Dublin Port tide gauge (1938-2016) (Shoari Nejad et al., 2022). However, there were some issues, such as decadal-scale variability observed in the 1980s and 1990s in the Dublin Port tide gauge records. Roseby et al. (2023) also suggest similar decadal-scale variability occurred during these decades. They propose that the cause of this variability could be anthropogenic and local, rather than part of a broader regional pattern, as other locations in Europe, such as Newlyn and Brest, did not experience similar fluctuations.

Research by Barlow et al. (2014) provides a 2000-year perspective on relative sea-level (RSL) changes in northwest Scotland. Their records indicate RSL remained stable within ±0.4 m, with a generally negative regional tendency reflecting local glacio-isostatic uplift. Recent biostratigraphic shifts suggest a possible 20th-century positive tendency, which could indicate accelerated sea-level rise, although the signal is muted and later than observed elsewhere in the western North Atlantic. The study applied foraminiferal transfer functions to reconstruct past sea levels, providing valuable insights into regional variability, while also noting methodological challenges such as dataset noise. These findings are crucial for informing future sea-level projections, particularly in the context of climate change. Methods such as palaeo-sea level reconstructions play a pivotal role in understanding glacio-isostatic rebound, particularly in relation to the British-Irish Ice Sheet (Bradley et al., 2023). These reconstructions can aid in identifying where the greatest levels of sea level rise occurred and contribute to our understanding of the long-term impacts of ice sheet dynamics on sea levels. Collectively, these studies highlight the importance of uncovering long-term records. Despite their limitations, these proxy records are valuable for complementing instrumental sea-level data, particularly in regions like Europe and the United States, where tide gauge records typically do not extend as far back in time. While proxy records offer valuable long-term insights, they generally lack the temporal resolution and precision available from tide gauge data over recent centuries. Consequently, enhancing the digitisation and accessibility of historical tide gauge records is essential for advancing our understanding of regional sea level changes.

1.4 Understanding Drivers of sea level change

Sea level is influenced by a combination of factors and consists of three main components: mean sea level (MSL), tides, and non-tidal residuals caused by weather and other atmospheric variables (Pugh & Woodworth, 2014; Pugh et al., 2021). Mean sea level, representing the average height of the ocean's surface, rose globally at 3.4 ± 0.6 mm yr^{-1} from 2001 to 2019, driven by thermal expansion of seawater (1.3 ± 0.1 mm yr^{-1}) and melting of land-based ice (2.0 ± 0.5 mm yr^{-1}) (Bagnell & DeVries, 2023). Tides, the periodic rise and fall of sea level caused by the gravitational pull of the Moon and Sun and the Earth's rotation (Figure 1.3), can also vary over longer timescales due to factors such as the 18.6-year nodal cycle (Pugh & Woodworth, 2014). Non-tidal residuals (NTRs) encompass short-term fluctuations driven by atmospheric pressure, wind, and storm surge, contributing to variability in local water levels (Serafin et al., 2017). While astronomical tides are largely predictable, these residuals, combined with changes in mean sea level, highlight the complexity of coastal water level dynamics and the challenges in assessing the impacts of sea level rise on flooding and erosion.

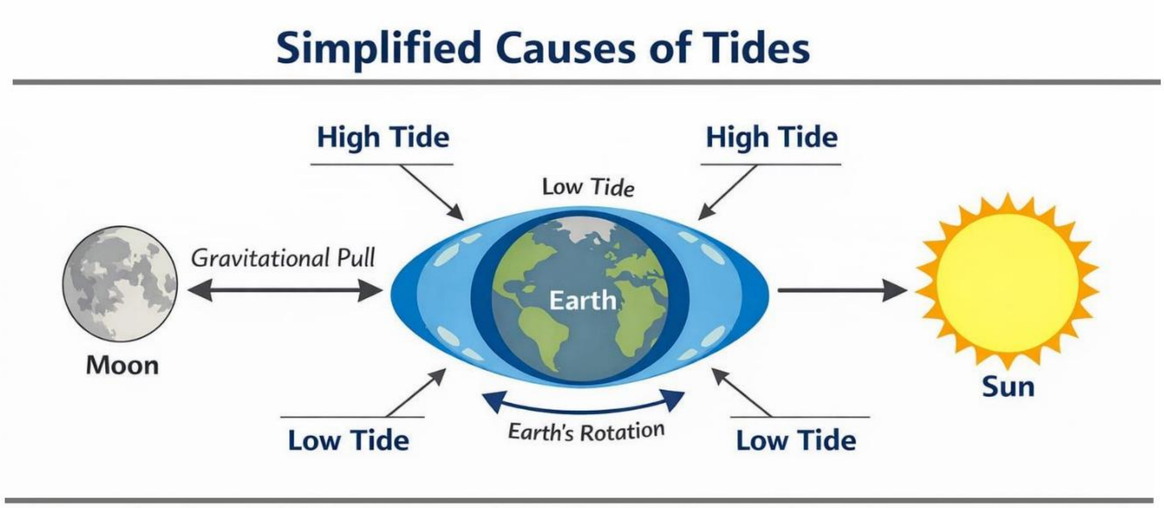


Figure 1.3: Simplified representation of tidal forcing, illustrating key tidal processes, synthesised from O'Sullivan (1977) and Pugh & Woodworth (2014).

While some drivers of sea-level rise are anthropogenic, natural processes also contribute significantly. Global mean sea level (GMSL) changes since 1900 have resulted from a combination of ice-mass loss—predominantly from glaciers and the Greenland Ice Sheet—thermal expansion of the oceans, and human activities such as water impoundment in reservoirs (Frederikse et al., 2020). In addition to long-term mean sea-level changes, extreme sea levels at the coast are influenced by short-term processes such as tides, storm surge (wind setup), and wave setup (Pugh & Woodworth, 2014).

There are significant non-climate-related drivers of sea level rise which must be acknowledged, including anthropogenic influences such as dam construction and natural factors like volcanic eruptions and interannual climate variability. Notably, large-scale dam construction in the 1960s and 1970s impounded large volumes of water, temporarily slowing global sea level rise, marking an anthropogenic influence that was not climate-driven (Chao et al., 2008). Natural events such as volcanic eruptions, particularly the emission of sulfur dioxide (SO_2) from eruptions like Mount Pinatubo, can reduce solar radiation and cause temporary cooling, which in turn slows ocean heat accumulation and steric sea level rise (Church et al., 2005; Church & White, 2011). Parra et al. (2024) project changes in sterodynamic sea level—defined as sea level variations driven by the combined effects of ocean density changes (temperature and salinity) and ocean circulation—as well as ocean–atmosphere dynamics in the Eastern Tropical Pacific under different future climate scenarios, highlighting regional variability in sea level rise due to wind, temperature, and salinity changes.

Ocean warming and consequent thermal expansion are driven by the Earth's increasing energy imbalance, primarily caused by elevated greenhouse gas concentrations such as CO_2, which trap heat in the atmosphere and oceans (Cazenave & Le Cozannet, 2014). More than 90% of the excess energy from greenhouse gas emissions has been absorbed by the oceans, raising ocean temperatures and driving thermal expansion, a major contributor to sea level rise (Venegas et al., 2023). The rise in ocean heat content since the mid-20th century provides a clear indicator of the global energy imbalance and has contributed directly to observed sea level rise (Marti et al., 2022). Modern monitoring of sea level and its components is achieved using tide gauges, satellite altimetry, Argo floats for ocean temperature and salinity, and GRACE satellites for ice and hydrological mass changes (Cazenave & Le Cozannet, 2014).

The sea level rise pattern shows non-linear trends, with a slowdown in the mid-20th century followed by a resumption of more rapid rise in the late 20th and early 21st centuries (Church & White, 2011). These changes have been influenced by both natural factors, like volcanic eruptions, and human activities, such as large-scale water impoundment. The understanding of these drivers has been enhanced by recent improvements in observational data and analytical methods, offering a clearer picture of past and future sea level changes.

Understanding the temporal and vertical resolution of sea-level data is crucial for accurately interpreting observed trends and changes (Sterlini et al., 2017). Such variations arise from a combination of factors, including local weather conditions, far-field effects, and interregional characteristics.

One important cause of the variations in sea level is the variability due to local weather: Since the early 19th century, it has been recognized that sea level varies at different sites due to local wind conditions and atmospheric pressure (Sturges & Douglas, 2011). By the late 1800s, it was understood that variations in tide gauge records from nearby stations often showed a high correlation, particularly over weekly or monthly timescales, with local weather conditions being the primary driver. For instance, adjusting mean sea level (MSL) data using a scaled version of local air pressure successfully reduced this variability (Hogarth, 2021). Recent studies have investigated the role of atmospheric variables, such as wind stress and atmospheric pressure, in driving sea level variability in coastal waters. Seasonal and weather-band variations in these variables can produce short-term sea level fluctuations in coastal regions, including storm surges and seiches. For instance, Zubier & Eyouni (2020) demonstrated this in the eastern central Red Sea using a Non-linear Auto-Regressive Network with eXogenous inputs (NARX).

The far-field effects are another crucial driver of sea level change. By the early 20th century, researchers observed that sea level variations could be correlated across large distances, with tide gauge records from stations several hundred kilometres apart showing similar interannual trends (Hogarth, 2021). This correlation was linked to large-scale atmospheric and ocean variations. During El Niño–Southern Oscillation (ENSO) events, a characteristic pattern of sea level variation is the Pacific-wide seesaw between the eastern and western boundaries, driven by thermosteric and meteorological processes associated with El Niño and La Niña. In particular, studies of the Guayas delta, Ecuador, have shown that this effect can lead to substantial landward amplification of extreme sea levels (Belliard et al., 2021). Recent studies show that changes in Pacific trade winds, influenced by tropical Indian Ocean warming, can alter ENSO variability, which may drive interannual fluctuations in sea level and complicate the interpretation of long-term trends (Ferster et al., 2023). To account for these patterns, climate indices derived from temperature and atmospheric datasets are widely used to represent the influence of large-scale climatic variability, including the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the North Atlantic Oscillation (NAO) (Silini et al., 2023). These indices provide a standard framework for interpreting regional sea level variability in terms of large-scale climate forcing and associated circulation anomalies, with ENSO–IOD interactions in the Indian Ocean particularly well documented (Kersalé et al., 2022).

For example, by averaging tide gauge records from opposing regions, such as San Francisco and Sydney, a smoother representation of Pacific Sea level can be obtained, which helps reduce the impact of natural variability (Hogarth, 2021). These efforts in understanding long-distance teleconnections contribute to more accurate assessments of global sea level changes, particularly in relation to steric sea level (SSL). SSL variations, as seen in recent studies, play a significant role in global sea level changes, with a rising trend of 0.64–0.97 mm yr^{-1} observed from 1980 to 2020. These variations are influenced by ENSO, as fluctuations in temperature and salinity due to ENSO events contribute substantially to sea level anomalies both in the equatorial Pacific and globally (Xie et al., 2024). This understanding improves our ability to account for far-field ocean effects and helps in better assessing the causes and trends of regional mean sea level fluctuations.

Local weather patterns, coastal geometry, and bathymetry strongly influence sea level variability in the UK and Ireland. Hydrodynamic tide and surge models, which incorporate these factors, provide more accurate estimates of extreme sea levels than simpler models that only account for atmospheric pressure changes (Camus et al., 2024). The mouths of the Severn and Avon in the UK are known for some of the world's largest tidal ranges. Hydrodynamic modelling attributes this, in part, to a primary resonant tidal period of approximately 8 hours in the Severn Estuary (Liang et al., 2014). The extreme tidal ranges are also partly due to tidal resonance, where the estuary's length and depth correspond to approximately a quarter of the tidal wavelength, amplifying tidal amplitudes (Pugh & Woodworth, 2014). Parts of the Irish coastline, including the Shannon Estuary, experience substantial water level fluctuations due to local wind conditions and coastal geometry, as shown by detailed hydrodynamic modelling (OPW & RPS, 2020a). However, interpreting these spatial variations in water level can be challenging due to inconsistencies in local tide gauge records and land levelling. In both Ireland and Britain, the accuracy of tidal predictions is often limited by the varying quality of tide gauge records. Additionally, land movements caused by processes such as Glacial Isostatic Adjustment (GIA) further complicate these predictions (Bradley et al., 2023). GIA effects, where land is either rising (e.g., parts of Scotland and Belfast, Northern Ireland) or subsiding (e.g., southern England and parts of Ireland, including Cork, Tarbert, and Galway), contribute to differences in relative sea-level trends. These regional land motion trends must be carefully considered in sea level studies to avoid misinterpretation of local sea level rise (Edwards & Craven, 2017). Furthermore, tide gauge datum shifts in both the UK and Ireland further complicate the separation of local and global sea level changes.

Relative sea level (RSL) change across Ireland is spatially variable, with slower rates in the northeast and faster rates in the southwest due to Glacial Isostatic Adjustment (GIA) following the Last Glacial Maximum (Bradley et al., 2011). This regional variability must be considered when interpreting tide gauge and historical sea-level records, particularly in the southwest, where land subsidence contributes to higher apparent sea-level rise relative to the northeast (Bradley et al., 2011; 2023) (Figure 1.4). Comparing historical and contemporary sea-level records with modelled GIA rates provides an opportunity to better understand regional variations in relative sea-level rise across Ireland, especially in underrepresented areas where historical tide gauge and marigram records are scarce.

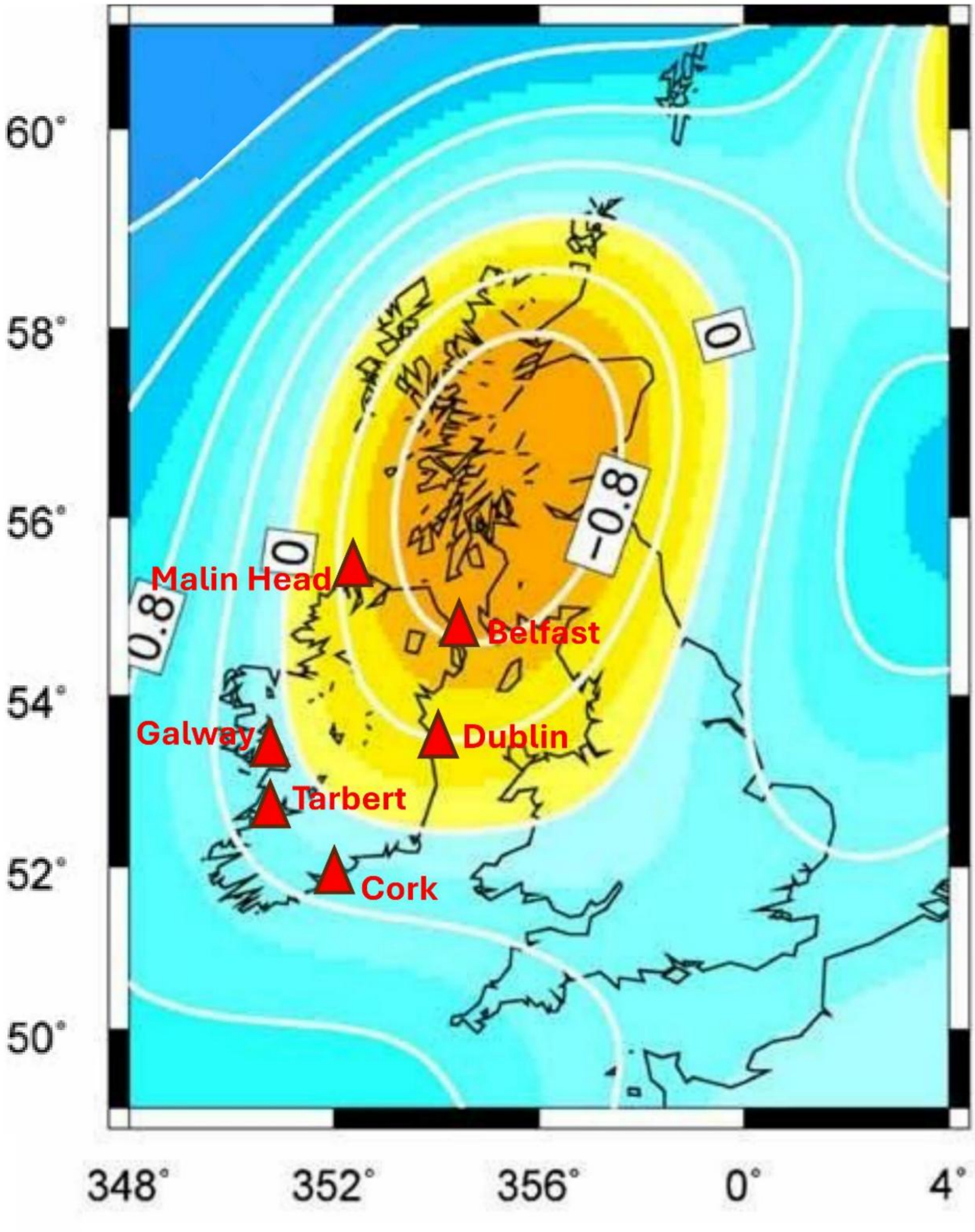


Figure 1.4: Locations (red triangles) of the key tide gauge-based sea level observations in Ireland from the Permanent Service for Mean Sea Level (PSMSL; Holgate et al., 2013), Murdy et al., 2015, and other sources, superimposed on relative sea level rates associated with Glacial Isostatic Adjustment (Figure from Bradley et al., 2011; coordinates approximate). Negative values indicate relative fall in sea-level.

1.5 Data Rescue and Quality Control

Much tidal data in Ireland, even toward the end of the 20th century, remained in paper format until the 1980s, and in some cases until the early 2000s (e.g., Dublin Port), despite the availability of digital storage. The types of data recorded include high and low waters, which may be tabulated or presented in tidal chart (marigram) format (Bradshaw et al., 2015, McLoughlin et al., 2024a). Historically, in the context of Ireland, data from as early as the 1840s was recorded in tabulated format (Airy, 1851; O'Sullivan, 1977). These records consist of observations taken at various intervals, such as hourly readings or high and low water times. As with other climate-related datasets, such as rainfall records or weather observations (Ryan et al., 2018; Hawkins et al., 2019), these historical records should be digitized to ensure preservation and accessibility. Proper documentation of metadata, particularly time references such as time zone or reference time standard (UTC), is essential to ensure accurate interpretation and comparison of tidal records.

When scanning tidal charts (marigrams), extra care is essential due to their fragile condition, which may include bends, folds, or damage. These imperfections can significantly affect the accuracy of digitised data if not properly addressed. To preserve data integrity, high-quality scanning methods, such as drum or flatbed scanners, are recommended to minimize image distortion. Storing scans in formats like TIFF is commonly preferred for high-resolution archival purposes, although the format's flexibility and variability require careful management to ensure consistency and long-term usability (Fornaro et al., 2017). However, it should be noted that TIFF may not always be suitable depending on the software used or the way the data is accessed. Some images may be in photographic form. When necessary, damaged documents should be prepared for scanning by reinforcing their borders to prevent further degradation.

A major challenge hindering the acceleration of data rescue initiatives is the lack of labour (human input) necessary to carry out this work (Wilkinson et al., 2019). This issue is particularly relevant to tidal data due to the complex structure of the records. While there are automated and manual resources available to digitise tidal marigram records (Pons et al., 2016; McLoughlin et al., 2024a), complexities still arise. Some traces are relatively simple to digitise, such as those where only one trace appears on the chart for a week, but the process becomes much more complex with more challenging records. In cases where historical images contain poor-quality tidal traces, automated extraction methods may not be effective, and manual intervention becomes time-consuming with software. Emerging artificial intelligence (AI) and machine learning (ML) methods have potential to assist in digitising intricate tidal records, though challenges remain for overlapping or low-quality traces. Unfortunately, some records, due to their sheer complexity, may be impossible to digitise. For example, tidal records may span up to a month of data, with stoppages. In cases like a marigram from the Shannon Estuary in 1984 (Figure 1.5), overlapping traces make it nearly impossible to determine the dates or accurately digitise the data.

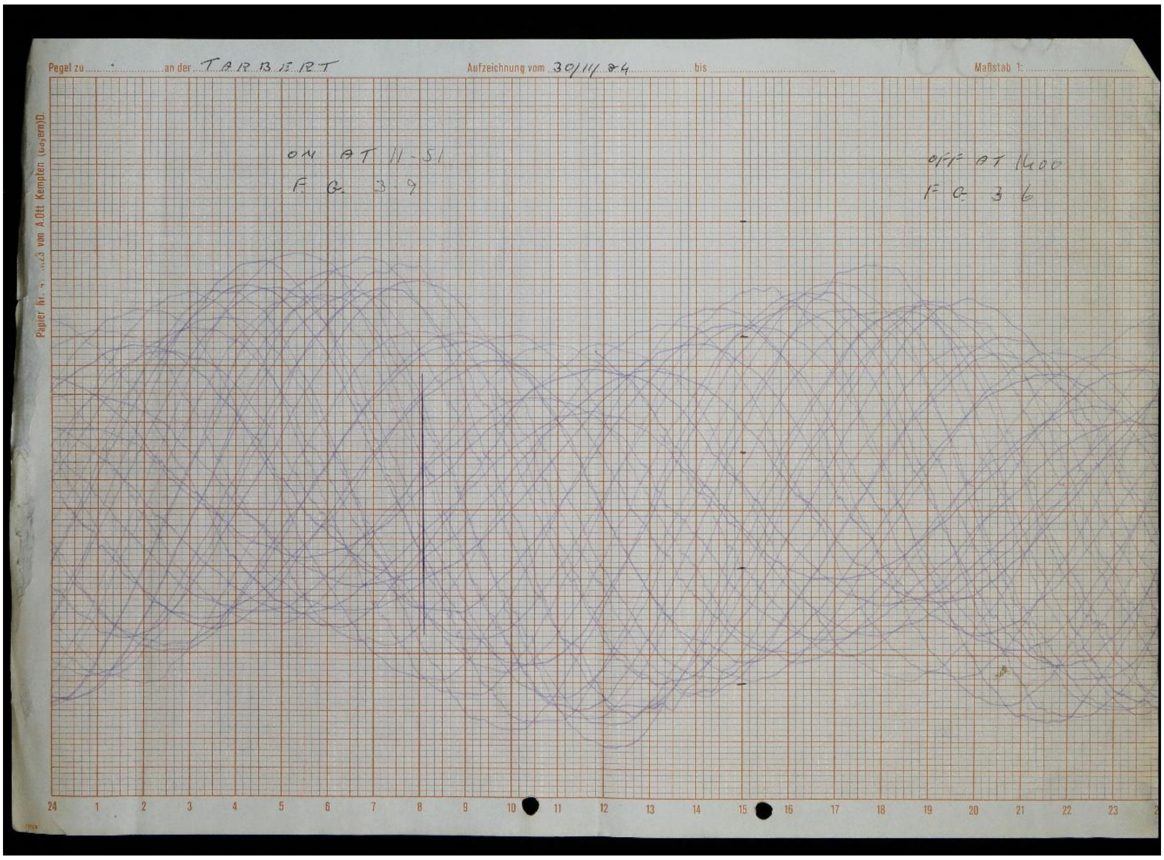


Figure 1.5: An example of a difficult marigram to digitise, due to over a month of overlapping daily traces that are difficult to distinguish, along with a break in at least one of the traces, causing further confusion. Data courtesy of the OPW (personal communication, 2024).

The data is invaluable for understanding sea level change and filling crucial gaps in our knowledge. Long historical records provide information that modern sea level monitoring techniques, such as satellite altimetry, cannot capture. However, missing data in long records is common, often due to station closures or issues with instrumentation. This leads to significant consequences, as it means that variations or extreme events may be overlooked or missed (Woodworth et al., 1999). Metadata is a crucial component of historical tidal data, helping to locate, interpret, and digitise records. It can include information such as the location of the tide gauge site (e.g., name, latitude, longitude), instrument characteristics, benchmark and vertical datum information, and notes describing how the data were recorded or processed. However, metadata quality and consistency vary, and physical inspection of the original records is often necessary (Bradshaw et al., 2015).

More recent initiatives have emerged to rescue and better understand sea level data. The Global Sea Level Observing System (GLOSS) (SONEL, 2025) operates under the auspices of UNESCO's Intergovernmental Oceanographic Commission (IOC, 2008), coordinating tide gauge stations worldwide to monitor sea level changes. However, the GLOSS dataset itself has not been updated in recent years and has effectively been superseded for high-frequency sea-level studies by more temporally resolved datasets, such as UHSLC and GESLA (Haigh et al., 2023). Its primary goal is to support oceanographic and climate research by coordinating a global network of tide gauges. At the core of this network is the GLOSS Core Network (GCN), which includes a wide range of strategically located tide gauge stations (IOC, 2008). These stations monitor sea level changes worldwide, providing essential data for studying climate change, sea level rise, and ocean circulation.

For context, GLOSS contributes to the Global Ocean Observing System (GOOS) by coordinating tide gauge stations worldwide and providing quality-controlled observations. While this thesis does not directly use GLOSS data, many GLOSS stations feed into datasets archived at the PSMSL and UHSLC, ensuring the reliability and global consistency of the tide gauge records used here (Caldwell, 2013).

All digitised GLOSS data undergo careful quality control. International collaboration is essential for standardizing QC procedures. Coordinated by the IOC, GLOSS operates a global tide gauge network following established data collection and QC protocols (IOC, 2008). While originally focused on research, many GLOSS stations now provide near-real-time data to support tsunami warning systems and climate monitoring. These stations also serve as calibration points for satellite altimetry and contribute to geophysical and oceanographic studies.

The Permanent Service for Mean Sea Level (PSMSL) complements GLOSS by archiving long-term tide gauge records and applying rigorous QC to ensure dataset accuracy and homogeneity. These records are crucial for analysing long-term sea level trends (PSMSL, 2019). Together, GLOSS and PSMSL form the foundation of global sea level monitoring, integrating both historical and modern data to produce reliable long-term records. GLOSS employs key quality control parameters (Table 1.1), including specific flags to guide users in data validation. For instance, a flag of 0 indicates that no quality control has been applied to the data. A flag of 1 denotes good quality data that has been verified as consistent with real phenomena. Flag 3, labelled “probably bad” (previously “doubtful”), marks data that appear unusual and may not reflect real phenomena. Flag 4 identifies obviously erroneous data, and flag 9 indicates missing values (UNESCO/IOC, 2020). With quality-controlled data archived in repositories like the PSMSL, these long-term sea level records can be used according to established standards.

Table 1.1: GLOSS Recommendation numerical quality flag values. (Source: UNESCO/IOC, 2020).

FLAG	MEANING	DEFINITION
0	No quality control	No quality control procedures have been applied to the data value.
1	Good	Good quality data value that is not part of any identified malfunction and has been verified as consistent with real phenomena during the quality control process.
3	Probably bad(previously ‘doubtful’)	Data value recognised as unusual during quality control that forms part of a feature that is probably inconsistent with real phenomena.
4	Bad (previously isolate spike or wrong value)	An obviously erroneous data value.
9	Missing	The data value is missing.

1.6 Citizen science

Understanding historical climate data is critical for comprehending long-term environmental climate change (Purohit, 2024). These records offer invaluable insights into past climatic conditions, directly informing contemporary climate research and policymaking. However, the sheer volume and complexity of historical data present formidable challenges (Schnase et al., 2016), demanding significant resources for transcription and digitisation. Ensuring the accuracy and validation of such data adds additional layers of complexity, requiring meticulous scrutiny and verification (Brunet et al., 2020).

Citizen science, defined as the engagement of volunteers in collecting, observing, and recording data for scientific research (Robinson et al., 2021), has emerged as a practical solution to address the substantial resource demands of transcribing and digitising large datasets, including historical climate records. Over the past decade, citizen science has seen a remarkable surge in popularity (Bonney, 2021), driven by advancements in technology, particularly the widespread use of smartphones and cloud-based data platforms. These innovations have revolutionized data collection, enhancing accessibility and accuracy across scientific domains, including climate data collection (Bonney et al., 2014; Bonney, 2021). By mobilizing volunteers—particularly students—this approach enables the efficient collection and digitisation of data, contributing to the creation of expansive datasets that inform critical research questions (Christine & Thinyane, 2021; Atias et al., 2023; Lacerda et al., 2023). Citizen science mobilizes volunteers broadly to digitise data, whereas service-learning involves structured partnerships between students and scientists, combining data rescue with educational objectives and skill development (Mateus et al., 2021). Crowdsourcing for data rescue is an efficient and effective method for digitising large volumes of data observations in a timely manner (Brönnimann et al., 2018).

In parallel with citizen science, structured initiatives such as the Atmospheric Circulation Reconstructions over the Earth (ACRE), directed by Rob Allan at the Met Office, have rescued large volumes of historical meteorological records. These efforts support long-term reanalysis projects, including the 20th Century Reanalysis (20CR), by providing quality-controlled, digitised data from archival sources (Allan et al., 2016). While ACRE is not a citizen science initiative, it complements volunteer-driven projects by enabling systematic and standardized data rescue.

Citizen science continues to play an important role in climate research. S. Noone et al. (2024) demonstrate that student-led projects, such as Climate Data Rescue Africa (CliDaR-Africa), can digitise historical climate records, improving the temporal and spatial coverage of observations in regions with incomplete datasets. Earlier work by Noone et al. (2019, 2021) highlights the effectiveness of citizen science in student-based assignments for overcoming technical challenges and the persistent gaps in global climate observations, underscoring the continuing need for coordinated data rescue initiatives (Randriamarolaza et al., 2022).

There are large-scale citizen science initiatives, such as OldWeather.org (https://www.oldweather.org/), that engage volunteers in digitising historical weather records. Coastal projects, such as the SCORE initiative, engage local communities in monitoring sea-level rise and related threats, including flooding and coastal erosion. Programs such as Smart

Pebbles and CoastSnap enable citizens to collect and analyse data, complementing traditional scientific methods to enhance early warning systems and support adaptation strategies (see: ATU SCORE, https://www.atu.ie/news/score-innovative-citizen-science-activities-and-smart-pebbles-to-tackle-climate-change-in-coastal-areas; CoastSnap, https://www.coastsnap.com/). These initiatives highlight the potential of citizen science to support data collection and monitoring in coastal environments. Collaboration between citizen scientists and professionals produces mutually beneficial outcomes while providing educational value for participants. Given these benefits—advancing research and enhancing participant skills—citizen science is poised to play a crucial role in data rescue and sea-level monitoring. With ongoing technological advances and the growing diversity of projects, this approach offers significant opportunities in sea-level science, including tidal digitisation, monitoring sea-level rise, and rescuing historical climate data.

1.7 Atmospheric Corrections and Seasonal Effects on Sea Level Data

Atmospheric corrections and the removal of seasonal effects are vital for accurately calculating mean sea level (MSL). These factors significantly impact sea level measurements, and their proper adjustment ensures that sea level data reflect long-term trends rather than short-term fluctuations caused by weather or seasonal patterns.

Atmospheric pressure is one factor contributing to regional ocean dynamic sea level variations. High-pressure systems depress the sea surface, while low-pressure systems cause it to rise. These variations are spatially heterogeneous but do not affect global mean sea level (Fox-Kemper et al., 2021).

A critical step in correcting tide gauge data for atmospheric influences is the removal of barometric pressure effects, which act through the ocean's inverted barometer response (Piecuch et al., 2016). Atmospheric pressure is typically measured at nearby weather stations or using barometers and then removed from tide gauge sea level measurements. When immediate local measurements are unavailable, atmospheric pressure data can be obtained from reanalysis datasets, such as the Copernicus Climate Change Service ERA5 data (Hersbach et al., 2023; Copernicus Climate Change Service, 2025, https://cds.climate.copernicus.eu/) or NOAA 20CRv3 dataset (Slivinski et al., 2019; NOAA PSL, 2025, https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html). Applying this correction ensures that measured sea level primarily reflects ocean variations rather than short-term atmospheric or weather-related fluctuations (Ghomsi et al., 2024).

Wind stress is another atmospheric variable that needs to be removed during sea level processing. Strong winds, particularly over large bodies of water, can generate ocean surges and temporarily raise sea level. Storm surges are largely driven by wind stress, which increases with the square of wind speed, and their impact is generally greater in shallow coastal waters (Andrée et al., 2022). Surge height also depends on local bathymetry, coastal geometry, and the fetch — the distance over which the wind blows. Coastal sea level variability is also influenced by processes such as wind-driven ocean circulation, which can produce localized anomalies (Woodworth et al., 2019). In regions where wind effects are pronounced, further corrections using weather models may be applied to adjust sea level data.

Seasonal effects also significantly impact sea level fluctuations. In Ireland, these are primarily driven by local ocean circulation, seasonal wind patterns, and thermal expansion, which together modulate coastal water levels throughout the year. Contributions from precipitation and polar or glacial melt are comparatively small. Ocean thermal expansion contributes to seasonal sea level variability (Widlansky et al., 2020) on a global scale, but its impact on Irish coastal waters is minimal. During summer months, the ocean surface warms, causing water to expand and sea level to rise. This effect is most noticeable in tropical regions, where temperature changes are more pronounced. Conversely, in colder months, thermal contraction of seawater lowers sea level, particularly in tropical regions. Changes in the storage of water in reservoirs, soils, snowpack, aquifers, glaciers, and polar ice sheets can also significantly affect global mean sea level (Cazenave & Nerem, 2004). These factors are region-specific and may have less impact in other areas.

Given the variability of ocean and atmospheric influences, long-term sea level trends in regions like Ireland and Britain are affected by multi-decadal fluctuations in ocean circulation, such as the Atlantic Multidecadal Oscillation (McCarthy et al., 2015). In the context of Irish and UK sea level reconstructions, properly accounting for both long-term climate-driven variations and shorter-term seasonal effects is fundamental to isolating true long-term sea level trends from transient fluctuations, thereby improving the reliability of historical tide gauge records.

1.8 Sea Level Datums

A datum is a fixed reference point or surface used as a baseline for measuring elevations, depths, and sea level. Datums provide consistency and precision when determining Mean Sea Level (MSL), which, in principle, is calculated as the average sea level over the 18.6-year nodal cycle (Pugh & Woodworth, 2014) to account for tidal variations, ensuring a stable reference.

There are two key datum categories:

1. Local Datums: These are often associated with a specific region, also called regional datums (Kumar, 1988); a local datum aligns with the geographic and oceanographic conditions of a given area. These datums are used for navigation, construction, and other applications such as flood defences.

2. Global Datums: These datums are part of a worldwide reference system, such as the World Geodetic System 1984 (WGS84). They are used for broad-scale applications including GPS, satellite navigation, and global climate studies. The Earth's shape is defined by the geoid, an equipotential surface that closely represents Mean Sea Level (MSL) on a global scale (Janssen, 2009). While global datums provide consistency across continents, understanding their relationship to local and national datums is essential for accurate coordinate transformations.

Mean Tide Level (MTL) is defined as the arithmetic mean of high and low water levels at a given location and may differ from Mean Sea Level (MSL) depending on local tidal characteristics (Woodworth, 2017). At many locations, these differences are typically on the order of centimetres and may be small relative to observational uncertainties in historical sea-level datasets. Accordingly, MSL and MTL may be treated as equivalent where such differences are negligible compared to dataset uncertainties. Global sea level data, such as those from the Permanent Service for Mean Sea Level (PSMSL, Holgate et al., 2013), are adjusted to specific datums (Figure 1.6). In Ireland and Britain, surveys from the 1800s, such as those by Airy (1851) and Haughton (1856), along with maps and tide benchmarks, provide valuable historical information that helped establish specific local datums. However, the accuracy of these historical data must be considered when interpreting sea level changes.

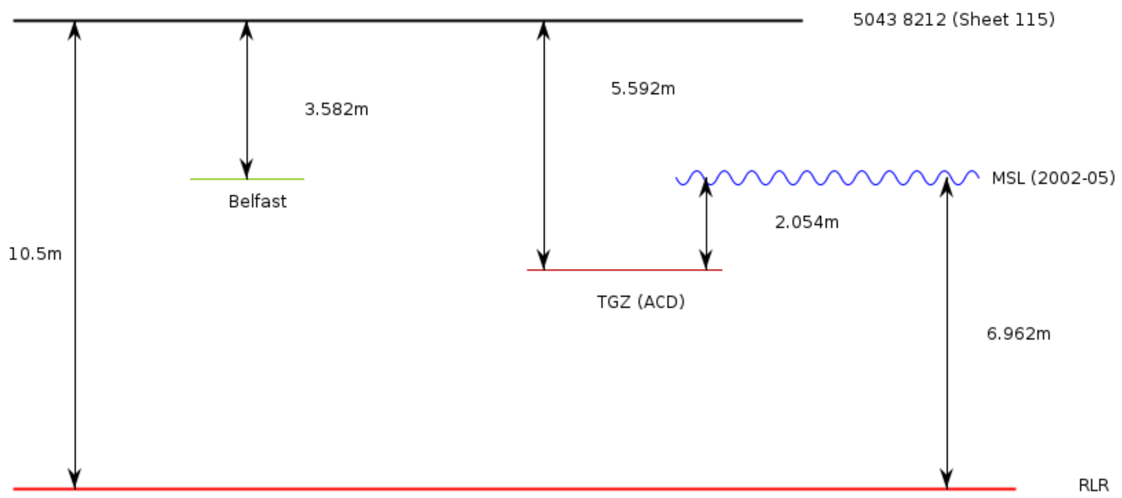


Figure 1.6: Revised Local Reference (RLR) diagram for Bangor, illustrating the steps to convert local measurements for datum adjustments (Holgate et al., 2013; PSMSL: https://psmsl.org/data/obtaining/rlr.diagrams/1856.php).

In Ireland, levelling traditionally relied on ground-based methods using theodolites and staffs (Pugh, National Oceanography Centre (NOC), UK, personal communication, 2022). These methods have since been supplemented, and in some cases replaced, by satellite- and GPS-based systems, which provide three-dimensional positions and incorporate modern geoid data (Prendergast, 2004). Comparisons between traditional and modern levelling require careful consideration of the potential errors inherent in each approach.

For ground-based levelling, precision depends primarily on the quality of execution, including rigorous cross-checking of measurements. The Ordnance Survey categorizes triangulation networks as Primary, Secondary, or Tertiary, with accuracy decreasing from Primary to Tertiary (Prendergast, 2004). The national levelling project of 1842 would have followed the highest standards available at the time. Although exact accuracy is undocumented, the 1842 levelling was likely at least as accurate as, and possibly slightly better than, later Secondary levelling. For Secondary levelling, accuracy is generally estimated as ± 5 mm $\times \sqrt{\text{distance (km)}}$ (Harley, 1975). Satellite-based systems provide centimetre-level precision in relative positioning; however, regional uncertainties in geoid models can affect absolute vertical accuracy. In Ireland, the OSGM15 geoid generally aligns closely with mean sea level across much of the country, but deviations of several decimetres have been documented in parts of the west coast, including west of Galway, due to geoid fitting limitations and legacy height data (OPW & RPS 2020a, Society of Chartered Surveyors Ireland, 2020). In Cork Harbour, comparisons between historical levelling from 1842 and modern tide gauge measurements show mean sea level differences of only a few centimetres over several kilometres, indicating that geoid-related effects are minimal in regions with relatively smooth topography (Pugh et al., 2021). This demonstrates that, where geoid behaviour is well constrained, high-precision levelling and GNSS-based surveys can achieve centimetre-level accuracy over tens of kilometres.

Historical sea level measurements were converted to Ordnance Datum Malin (ODM) to enable comparison with modern observations (Kirby et al., 2023). In Northern Ireland, Ordnance Datum Belfast (ODB) lies about 0.037 m below ODM (Database of British and Irish Hills, 2022). Where stable historical benchmarks were available, such as those at Courtown, they were used directly (~1 cm accuracy). Since the 1842 benchmarks listed by Cameron (1855) were seldom accessible, late 19th-century maps ("1888") were most frequently employed. These historical references could be adjusted to ODM using available conversion tables (Dixon, 1949; Andrews, 1975), achieving estimated accuracies of ~3 cm (Pugh, personal communication, 2022). Measurements originally referenced to Ordnance Datum Dublin (ODD, Poolbeg) were converted to ODM to ensure consistency across datasets.

1.9 Research gaps, aims and objectives

The following research gaps have been identified based on the above overview:

Research Gap 1: A challenge to understanding sea level rise, particularly in the south and west of Ireland, is the retrieval of historical sea level/marigram records, many of which remain undigitized in archival form. There is an ideal opportunity to collect/borrow and digitise these historical records to understand changes in historic sea level rise.

Research Gap 2: To date, there has been limited detailed discussion in the literature surrounding issues associated with the digitisation of historical sea level records. Excellent digitising software exists, but all would have accuracy limitations when digitising marigram record images that contain small bends/shifts or skews. Even if almost microscopic, they throw off the accuracy of digitised points. There exists the opportunity to design a robust methodology on how to counteract these issues to ensure better accuracy in digitisation (accuracy within 1 cm).

Research Gap 3: There has been limited exploration of incorporating students into an assignment-based citizen science model for digitising historical sea level records. Developing targeted training tutorials could significantly streamline the digitisation process, while also evaluating the potential for students to make meaningful contributions to the digitisation of tidal data.

Research Gap 4: Mean sea level change for Dublin Port has been analysed in the period 1938-2016 in the context of historical Irish mean sea level changes (Shoari Nejad et al., 2022). However, there is data available on Dún Laoghaire from 1925-1933 that could be digitised to high frequency. In the south of Ireland, Pugh et al. (2021) assessed sea level change in Cork. This work relied upon only six weeks of data. There exists the possibility to digitise records of years of data in Cork (1970s and 1980s) and Kerry (Tarbert), contextualizing historical mean sea level changes to present mean sea level in the east and southwest of Ireland.

The following thesis research objectives have been identified to address these research gaps:

Thesis Objective 1: Retrieving all available historical marigram archives of sea level along the east, north, south, and west coasts of Ireland to initiate the digitisation process.

Thesis Objective 2: Advancing the methodology needed for the digitisation of historical marigrams.

Thesis Objective 3: To integrate citizen science into college assignments, involving students in the digitisation of historical sea level records, with the goal of testing the feasibility and effectiveness of this approach.

Thesis Objective 4: To contextualize the historical Irish mean sea level changes along the east and south coasts of Ireland and validate all digitised QC data with other published sea level data for similarities in trends and frequencies.

The derived data will be uploaded to the Zenodo repository. The resulting dataset will provide a greater understanding of mean sea level changes around Ireland (1925–2024). For the first time, records will be available to contextualize mean sea level changes along the south and southwest coasts, as well as the north and east coasts of Ireland. This information will also aid in identifying coastal vulnerability and informing policy adaptation.

1.10 Thesis structure

Following my 2023 departmental review, I applied to progress to the PhD by Publication route. The application was approved by the Departmental Research Student Progress Committee (DRSPC) in June 2023. In line with the requirements of the PhD by Publication, three manuscripts were prepared for submission to peer-reviewed journals. Each manuscript addresses the primary objectives of my research and was aligned with journals that are reputable, open access, and appropriate to the field.

The thesis is presented as a collection of these manuscripts, each forming a separate chapter. An overarching Introduction, Discussion, and Conclusion provide context and demonstrate the original contributions of the research to the field. Details of the publications are provided below. Each paper includes co-authors, with the final paper in particular involving collaborators from ICARUS, Maynooth University, Trinity College Dublin, and the University of Limerick (UL). Additional contributions to the final paper were provided by Lionel Swan (Research Assistant, Summer 2024), who assisted with the digitisation of the Tarbert dataset; Maeve Upton, who provided guidance on the use of the Reslr package for analysing mean sea level; and Robin Edwards, who offered insights on Glacial Isostatic Adjustment (GIA).

- **Chapter 2** presents the methodology for the accurate digitisation of historical sea-level records. This paper details key processes for digitising historical marigrams, achieving an accuracy of approximately 1 cm, and highlights challenges associated with converting archival tidal records into usable digital datasets. The chapter includes access to the Dún Laoghaire dataset: McLoughlin, P.J., McCarthy, G.D., Nolan, G., Lawlor, R. & Hickey, K. (2024) The accurate digitization of historical sea level records. Geoscience Data Journal, 11, 790–805. Available from: https://doi.org/10.1002/gdj3.256

- **Chapter 3** presents a student-led initiative integrating the digitisation of historical tidal records into undergraduate and postgraduate teaching. Building on prior efforts from the MSc Climate Change programme (2022–2023) and the GY369 Oceanography module (2024), students engaged with both modern tidal datasets from Kilrush (2019–2021) and historical records from Dún Laoghaire Harbour. A structured digitisation model was implemented in which participants first digitised training datasets that were benchmarked against known values to ensure quality control: McLoughlin, P., Nolan, G., Hickey, K. and McCarthy, G.D. (2026), Evaluating student involvement in sea-level data rescue. *Weather*. https://doi.org/10.1002/wea.7757
- **Chapter 4** utilises rescued tidal data from Dún Laoghaire (1925–1931), supplemented by data from 1932–1933, alongside long-term datasets from Dublin Port, Belfast, Malin Head, Cork, Tarbert, Kilrush, and Galway. These integrated records provide a century-scale reconstruction of mean sea-level change around Ireland and assess the influence

of Glacial Isostatic Adjustment on regional trends. This work is presented in the manuscript "A Century of Mean Sea-Level Change in Ireland (1925–2024)", submitted to Ocean Science in December 2025. Minor revisions may arise following peer review. The preprint is currently available online: McLoughlin, P.J., Swan, L.D., Nolan, G., Hickey, K., Upton, M., Edwards, R. and McCarthy, G.D. (2026), A Century of Mean Sea-Level Change in Ireland (1925–2024). *EGUsphere* (preprint). https://doi.org/10.5194/egusphere-2025-6404

- **Chapter 5**. integrates the core findings of the three publications, summarises the principal conclusions, addresses limitations, and identifies avenues for future research.

2. The accurate digitization of historical sea level records

Understanding regional sea level variations is crucial for assessing coastal vulnerability, with accurate sea level data playing a pivotal role. Utilizing historical sea level marigrams can enhance datasets, but current digitisation techniques face challenges such as bends and skews in paper charts, impacting sea level values. This study explores often-overlooked issues during marigram digitisation, focusing on the case study of Dún Laoghaire in Ireland (1925–1931). The methodology involves digitising the original marigram trace and underlying grid to assess offsets at the nearest ft (foot) interval on the paper chart, corresponding to changes in the water level trace for each hour interval. Subtracting the digitised value from the known value (the actual measurement) allows for the determination of differences, which are then subtracted from each hourly trace value. Overall, processing 1 year of data can take up to 6 days, including 2–3 days for digitising the marigram trace and a further 3 days for digitising grid values required for adjustments. After adjusting for offsets ranging from −3.962 to 13.716 mm (millimetres), the study improves the final accuracy of sea level data to approximately the 10 mm level. Notably, data from 1926 and 1931 exhibit modest offsets (<7 mm), while other years show more substantial offsets (>9–14 mm), emphasizing the importance of adjustments for accuracy. Such 10 mm accuracy is compatible with requirements of the Global Sea Level Observing System. Comparing the adjusted digitised data with other survey data shows similar amplitudes and phase lags for Dún Laoghaire in both the historical and modern datasets, and there is an overall mean sea level rise of 1.5 mm/year when combined with the available data from the Dublin region.

2.1 Introduction

Globally, mean sea level (MSL) is rising at a rate of 3–4 mm/year, and this rise is accelerating (Nerem et al., 2018; Dangendorf et al., 2017, 2019; Van Alphen et al., 2022). Knowledge of changes in historical sea level rise is key to understanding coastal vulnerability and risks. In Ireland, over 40 digital tide gauges, installed in the 2000s and managed by the Office of Public works (OPW) and the Marine Institute, are used to record present-day sea-level changes, forming part of the National Tide Gauge Network (Cámaro Garcia et al., 2021; Dwyer, 2013). However, data prior to the 21st century are rare in Ireland. Ireland has some long-term records of mean sea level, and these records are limited to the northeast of the country (Dublin Port from 1938, Belfast Harbour from 1901/1902, and Malin Head from 1958) (Figure 2.1, inset map). Nevertheless, only Belfast Harbour is digitised to high frequency at 10-min intervals (Murdy et al., 2015). Historical Marigram records are a graphical representation of tidal data for a given period of time. A single trace usually represents a day, while multiple overlapping traces may represent a week on a sheet of graph paper. Marigram records originate from historical gauges equipped with rotating paper chart recorders, used to measure tidal fluctuations. A float within a vertical stilling well, connected to an ink pen tracing measurements on graph paper fixed to a mechanized rotational drum, records the tidal rise and fall (Das, World Meteorological Organization, 1978; International Hydrographic Bureau, 1960; Murdy et al., 2015). Prior to the digital era, these traces were usually recorded on graph paper, with the X-axis representing hours and the Y-axis representing height, often in feet relative to Chart Datum. Marigram datasets exist in various locations throughout Ireland. For example, datasets are available from Belfast Harbour (1901/1902–2010), Dublin Port (1923–2003), Dún Laoghaire Harbour (mid-1920s and early 1930s), Cork (primarily Tivoli data recovered in the 1970s and 1980s), Kerry (Tarbert from the 1960s) and Wexford (Kilmokea, potentially with data from the 1960s, and other locations noted by Murphy et al., 2003), as shown in Figure 2.1's inset map. Otherwise, Ireland has numerous locations of historical sea level data recorded, with many additional sites located mainly to the north (see Figure 2.1). Some of these locations have been catalogued by the Permanent Service for Mean Sea Level (PSMSL), as documented by Holgate et al. (2013).

Figure 2.1: Shows the main map indicating the approximate location of Dún Laoghaire Harbour, where the marigram data was recorded. The inset map displays the known locations of other historical sea level data in Ireland.

Marigram structures can vary depending on their time span and can be complex to digitise. There is a plethora of software available to digitise raw images, regardless of their structures, which can successfully extract data from an image. One well known software developed in the 2000s is the NUNIEAU tool kit for the digitisation of marigrams. This software is used in an automated way to speed up the digitisation of marigrams and increase the accuracy of digitisation (Bradshaw et al., 2015; Pons et al., 2016; Ullmann et al., 2005). However, there are limitations to this software. Where there are multiple traces overlapping on a marigram image of poorer quality, the software falters and struggles to detect the correct traces, especially if the traces do not match the predicted tide. As NUNIEAU has poor ability to digitise blurred or overcrossing traces, this requires human cleaning. Murdy et al. (2015) digitised marigrams using the proprietary Biosoft software 'UnGraph' (no longer available), which allowed them to trace over the marigram traces quickly. They note that UnGraph is better able to find its way over complex crossovers than NUNIEAU.

It is not a difficult task to find a software that can digitise marigram traces. However, even with the appropriate software selections, one must be mindful of the issues associated with digitising, some of which are obvious while others are quite hidden. One common issue with digitisation is the barrel lens distortion of images (Talke & Jay, 2017). A Barrel distortion is an optical effect that causes straight lines to appear curved outward, resembling a barrel shape, in images captured with a camera or observed through a lens system. Two other very common issues in the digitisation of historical marigram records are timing errors and datum shifts (GLOSS Group of Experts, 2013; Gouriou et al., 2013). Digitising marigrams presents several challenges. These include lens distortions, skews or shifts in the image, variations in trace thickness, ink quality issues like blur, clock stoppages, gaps in recordings, missing data and minor inconsistencies such as changes in line thickness affecting the digitised values accuracy.

The aim of this paper is to illustrate the importance of validating digitised data and removing potential sources of error (using open-source software) to maintain historical sea level accuracy of 10 mm (1 cm), in accordance with the requirements for tide gauge records specified by the Global Sea Level Observing System (GLOSS) (Intergovernmental Oceanographic Commission (IOC), 2012). While this study focuses on marigrams, the approach can be applied to other historical meteorological records—such as barographs, thermographs, fluvial hydrographs, and rain-charts—taking into account instrument-specific characteristics like trace scale, temporal resolution, and potential distortions. The methodology involves (i) digitising scanned marigrams at hourly intervals; (ii) identifying sources of error within 10 mm accuracy by computing offsets between the original and adjusted data; (iii) comparing the digitised (unadjusted) data with the rectified (adjusted) data; and (iv) validating and contextualizing the adjusted data by comparing it with nearby site data.

2.2 Data Description and development methodology

2.2.1 Data location and description

The dataset located from Dún Laoghaire Harbour (formally known as Kingstown) near Dublin (Figure 2.1) used in this paper ranges from 1925 to 1931. There are noticeable discrepancies in data quality across different years, ranging from very well-documented marigrams to instances of poor quality with significant data blurring and missing segments, particularly during periods when the tide gauge ceased operation. One issue is that there are sporadic gaps where more than half a year of 1930 is missing. Unfortunately, where large gaps exist, it is not possible to reconstruct the missing data. In these cases, the adopted approach is to omit periods with substantial gaps (e.g., more than half a year missing in 1930) from long-term analyses. However, shorter continuous periods of data (e.g., at least two consecutive months) can be retained for tidal analysis, as even limited records can still provide useful information on tidal characteristics (Pugh et al., 2021). Table 2.1 provides information on the number of available images, an approximation of the percentage of good and poor-quality images among the available images and the number of missing images. It is expected that each year should have approximately 52 marigrams. However, in some cases, this number may be higher, particularly when there is less than 1 week of traces in a marigram.

Table 2.1: Description of the number of images and their quality for each year, categorized as good or poor.

Year	Number of images	% good/reasonable quality images (Approx)	% poor quality images (Approx)	Number of missing images
1925	50 (1 partial copy image)	80	20	3
1926	38	76	24	14
1927	45	71	29	7
1928	37	70	30	15
1929	52	77	23	0
1930	22	64	36	30
1931	41	68	32	11

- *Note*: Poor quality images are most often defined as those with two or more traces that are significantly broken, faded, replaced with pencil, illegible, or containing spurious thick lines.

The marigram images are of mixed quality traced in ink. Some images are of very good quality while many others have issues such as ink trace blur, gaps in the data from tide gauge stoppages and prolonged gaps in the data (1930 with more than 6 months loss of data). The datum for this data is CD (Chart Datum). The chart's X-axis represents hours, ranging from 24 to 0, with forenoon tides on the right and afternoon tides on the left, while the Y-axis measures height in feet relative to CD (Figure 2.2). The X-axis orientation in this chart differs from other marigram images, such as those in Belfast Harbour (Murdy et al., 2015) and Dublin Port, which start at 0 and end at 24 h, moving from left to right.

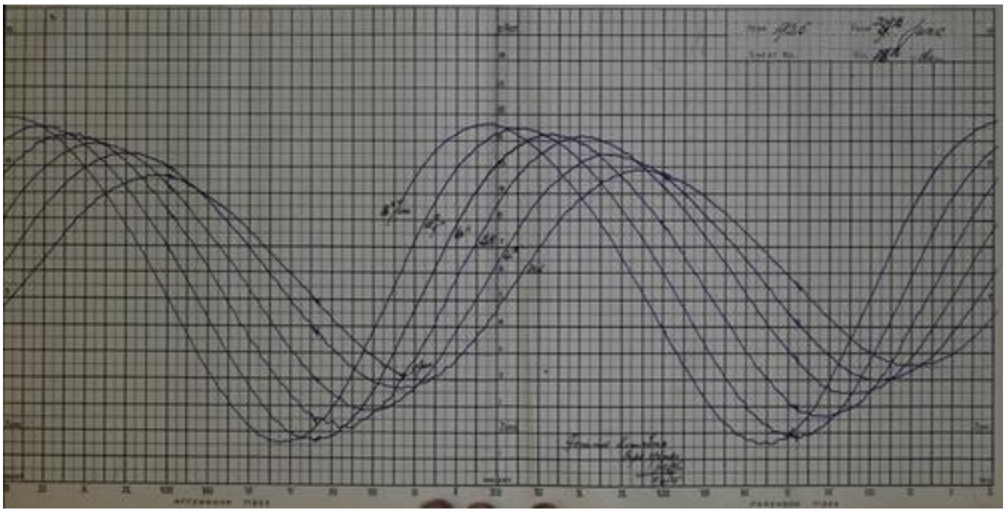


Figure 2.2: Shows a marigram in Dún Laoghaire from June 1925, with the X-axis representing time in hours (ranging from 24 to 0) and the Y-axis indicating the water level in feet relative to CD.

2.2.2 Data preparation

A Metis EDS professional digital scanner was used in the digitisation of all historical marigram archives, the same scanner that was employed in the scanning and digitisation of rainfall records (Ryan, 2021; Ryan et al., 2018). Marigrams were initially scanned as TIFF images and subsequently converted to JPG format to ensure compatibility with open-source software and to reduce file size, as TIFF files were too large to be efficiently handled during processing. The images were then organised in chronological order using a date-based naming convention (e.g. 15–22nd_June_1931) based on their respective dates and year.

2.2.3 Development of digitisation methodology

2.2.3.1 Point digitisation of scanned images at hourly intervals

There are many open-source digitising tools such as DataThief (2023), Engauge Digitizer (2023), WebPlotDigitizer (Rohatgi, 2022) and GetData Graph Digitizer (2023). In this instance, free open-source software was tested (Engauge Digitizer, WebPlotDigitizer and GetData Graph Digitizer) for digitising marigrams.

However, a limitation of many of these software packages was that they were only available as desktop versions. Online web versions were preferred because they offered greater versatility, allowing access from different desktops without the need for downloading and installation. The

Online WebPlotDigitizer (2023) and WebPlotDigitizer software packages were investigated. WebPlotDigitizer's free version had limited resources, such as restricted zooming capabilities, and required additional purchases for certain components. WebPlotDigitizer, created by Ankit Rohatgi, was equally as useful at extracting points and was open source, allowing zoom in options and scaling. Consequently, it was selected as the appropriate digitising software.

When calibrating the X and Y grid of the marigram image in WebPlotDigitizer, the X-axis (hours) is scaled from 0 to 24, while the Y-axis (ft) is scaled from 2 to 10. We begin the Y-axis scaling at the 2-ft (foot) interval instead of 0 because this upper value typically exhibits less skewness along the line, offering a more reliable reference point for scaling all images consistently. The X-axis is scaled at both ends (0 and 24), ensuring comprehensive coverage, whereas the Y-axis is scaled in the centre of the image, where each ft interval is labelled (Figure 2.3).

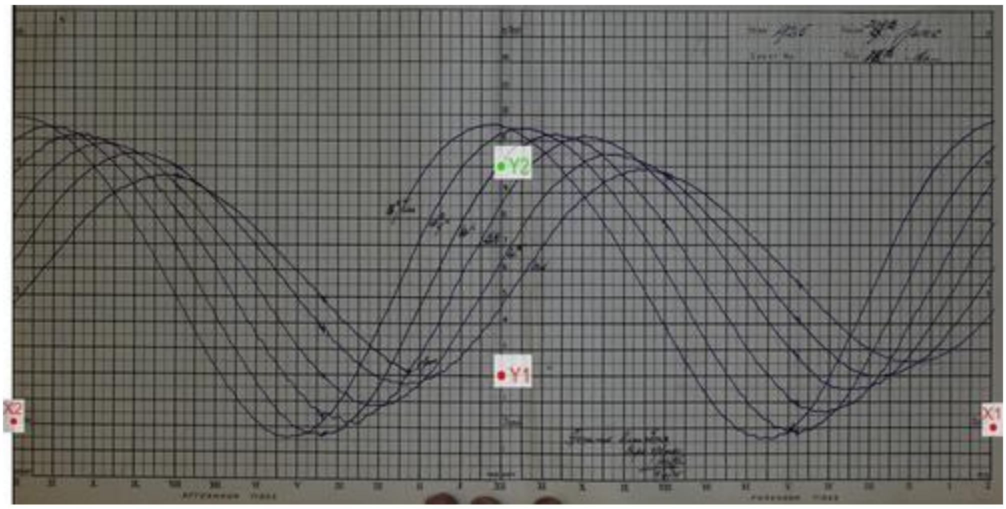


Figure 2.3: Illustrates the scaling process in WebPlotDigitizer. The X-axis (X1 = 0-hour, X2 = 24-h) and Y-axis (Y1 = 2 ft, Y2 = 10 ft) are defined.

Accurate scaling of marigrams is essential to mitigate potential axis offsets. For instance, the second ft interval (2 ft) is often chosen as Y1 due to its straighter alignment, which minimizes overall distortions compared to starting at 0. However, exceptions may arise. If the line at 2 ft exhibits distortion or reduced line thickness, or if the 24-h mark is compromised, alternative intervals may be chosen to enhance accuracy. For example, the value at the zero- or first-ft interval (in some cases) could be chosen instead of 2 ft, or the previous 23-h mark could be scaled to 23 instead of 24, provided it aligns with the ft value selected. To ensure uniform interpretation and mitigate potential distortions, the marigram data in this study was calibrated with the values of interest consistently aligned with the top line thickness for both upper and lower bounds.

The steps taken to ensure as accurate as possible calibration do not remove or reduce the overall distortions or skews in the image; the methodological steps taken to do this are discussed in the next Section (2.3.2).

Data typically recorded at tide gauge stations in the UK has hourly data up to the 1990s and better resolution data (15 min) from the 2000s onwards (Woodworth et al., 2017). Hourly intervals are suitable for calculating mean sea level (MSL) and non-tidal residuals, as well as for tidal analysis and associated applications (Pugh et al., 2021; Pérez-Gómez et al., 2021). Owing to the age and coarse resolution of many marigram images, hourly intervals were appropriate for digitising the Dún Laoghaire records. A point is manually positioned, as closely as possible to the centre of the line thickness, on each marigram trace at every hour (0–23) to obtain each daily record (Figure 2.4), ensuring accuracy. The centre is chosen as the best fit for accuracy because placing the point too high or too low on the trace would not accurately reflect the actual hourly values. Twenty-four (24) points were placed on each marigram trace, corresponding to the 0–23 h period on the day in question. Providing context for this observation is important. The 24-h point on each marigram trace slightly differed from the 0-h point on the subsequent day's trace. Notably, the 24-h trace appeared cropped at the end of the images, inaccurately representing its actual value. As the 24-h trace from each day is also reproduced by the 0-h point on the following day, it was omitted from each daily digitisation.

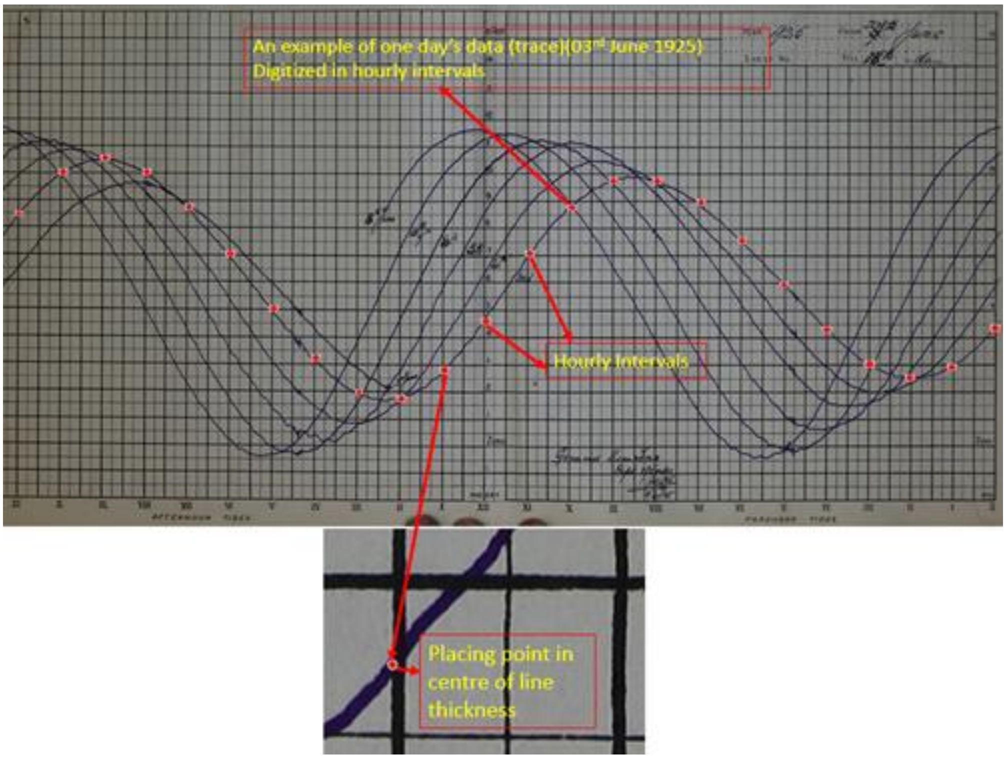


Figure 2.4: Manually point placing at each hour in the marigram trace, here the point is placed as closely as possible to the middle of the trace for the given hour.

The centring of the point on the trace in each image is important. However, where the traces are narrow, as in 1925, uncertainties in placing the point at the centre would not be significantly problematic. If, for example, the point was placed close to the top or bottom of the trace provided, it would not significantly offset the data. Tests were carried out on digitised marigrams to assess the effect of point placement within the trace. In these tests, a fully centred digitisation was compared with digitisations where points were placed slightly above or below the centre of the trace. Over a 7-day period, the resulting differences were small, typically in the range of 1–5 mm, indicating that minor deviations from perfect centring do not significantly affect the extracted values.

2.2.3.2 Overcoming issues of image skews and distortions

There are distortions in images stemming from the camera used for the scans (Akondi et al., 2021; Stankiewicz et al., 2018), and there are hidden shifts or skews in the image. In addition, there could already have been skews in the paper marigrams themselves, resulting in the lines of the grid not being straight, thus resulting in offsets (Figure 2.5). Furthermore, variations in line thickness along the X-axis can occur due to scanning resolution, ink dispersion, or degradation of the original paper records, which affects the visual clarity of the trace during digitisation.

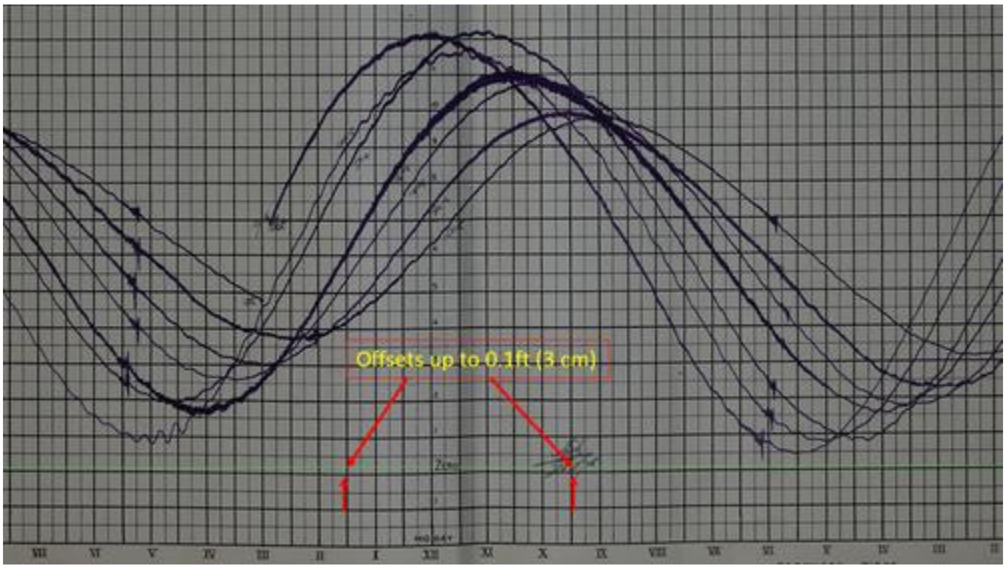


Figure 2.5: Green line straight across shows the offset of the marigram from the straight line showing that values would be off considerably in some places. (Note this is a different marigram than other image examples and is more zoomed in).

While methods were developed to try and resolve some common issues, such as the sharp contrast between the background paper and pencil line (Talke et al., 2020), issues of skews remain. These issues are problematic because they can distort both the X and Y axes, leading to inaccuracies in recorded values during digitisation. This can result in discrepancies of 1 cm or more when using software packages.

To correct skews, bends and distortions, the images were initially straightened and realigned using MATLAB®, by applying geometric transformation based on the underlying grid. Despite the apparent improvement, which gives the appearance of reduced tilts and skews, the actual value offsets recorded by WebPlotDigitizer in the initially distorted areas persisted in the realigned images. The persistence of value offsets despite the apparent improvement in image quality can be attributed to the inherent distortions present in the original images.

Using a reduced grid approach, a single point (selecting a ft interval in the middle of the traces) was placed at each hour on the image, adjusted to match the trace's value offsets for that hour (Figure 2.6). This is a simplified approximation of full digitisation. However, the method is less robust than full trace digitisation and is more susceptible to localised errors, particularly in areas with larger vertical offsets such as the upper and lower parts of the trace. While it can achieve overall accuracy within approximately 10 mm in some cases and reduces digitisation time, it introduces greater uncertainty in hourly values compared to the full-resolution methods discussed.

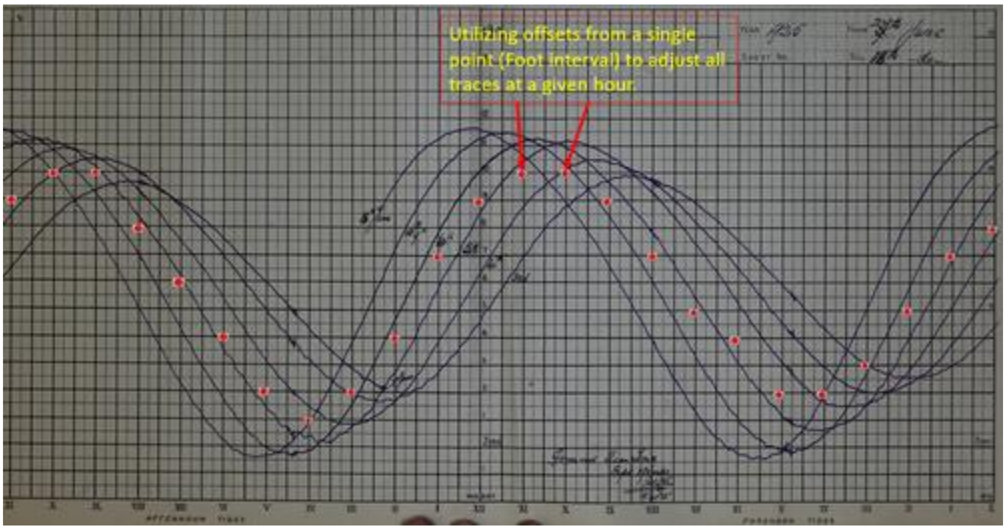


Figure 2.6: Demonstrates the Reduced Grid Approach, where a single point is placed at the midpoint (ft interval) of marigram traces per hour to offset discrepancies. However, this method may lead to reduced accuracy due to variations in offsets between upper and lower traces.

To address these challenges, a new technique was developed. In this method, the underlying grid of the marigram is digitised at each hour by identifying the nearest ft interval in the grid (Figure 2.7). If the nearest ft interval was offset from its actual value, a correction would be applied. For example, if the trace at a given hour touched the 3-ft interval, but it was recorded as 3.09 ft in WebPlotDigitizer, the digitised values would need to be adjusted by 0.09 ft for that given hour. In some instances, using the nearest ft interval may not be possible due to a blur of ink trace or a distortion. In such cases, we use the ft interval that is closest. For example, if the trace falls between 3 and 4 ft, closer to 3 ft, but there is an issue, at 3 ft, such as a distortion or blur of ink trace, we would use the 4 ft point.

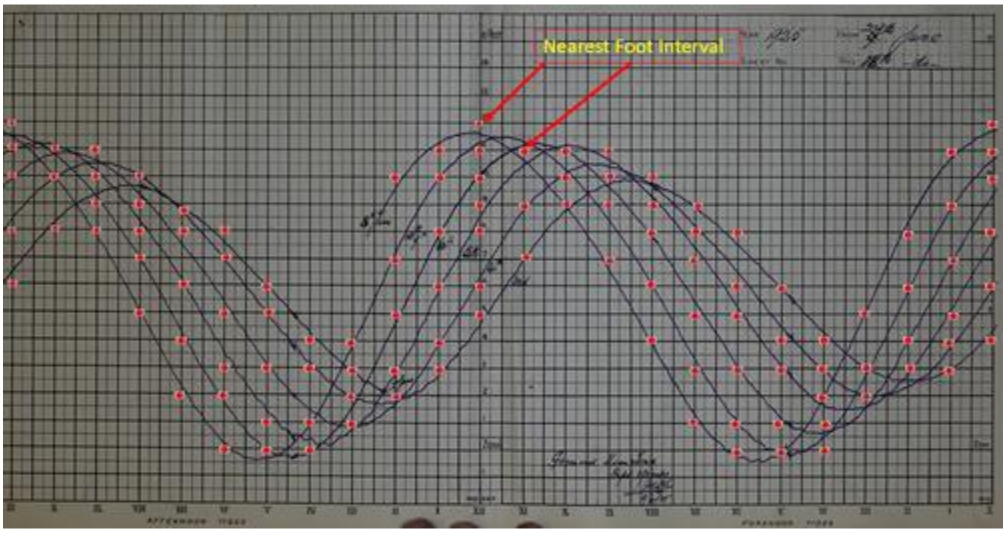


Figure 2.7: Digitising the underlying grid of a marigram at each nearest ft interval for each hour is used to accurately estimate the value of the trace between two different ft intervals at the point intersecting the marigram trace.

A flow chart (Figure 2.8) describes the entire approach. It begins with the digitisation of traces, followed by capturing the grid values at each nearest ft interval for the given hour on the daily marigram traces, calculating offsets (recorded nearest ft less its actual ft) and so forth down to adjusting the digitised data for better accuracy. It is essential to digitise the underlying grid. This method involves applying adjustments to each digitised marigram by saving the relevant grid values associated with each marigram, and subsequently using these saved values to modify the digitised data.

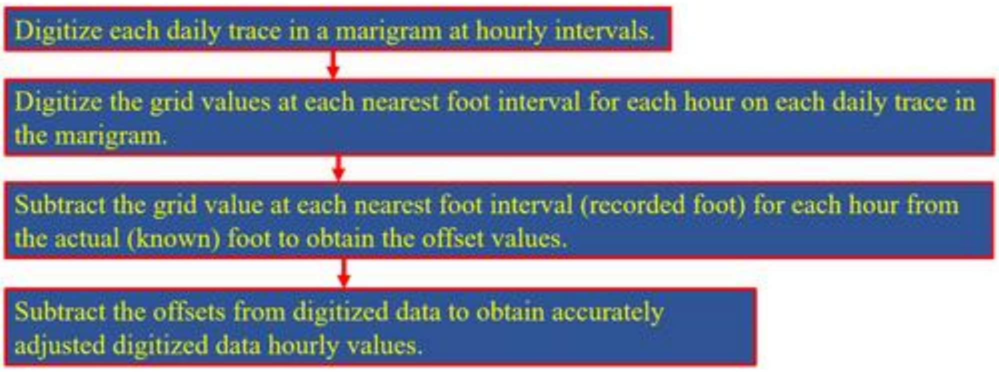


Figure 2.8: Simplified flow chart of the Methodology employed to accurately adjust marigram data.

2.2.4 Data management and quality control

Quality flags were applied to identify and flag any erroneous data (UNESCO/IOC, 2020) arising from issues such as tide gauge stoppages or any bad data. All marigram images were thoroughly inspected and marigram traces with stoppages or loss of data, including big spurious thick lines often seen near clock stoppages, bad quality data with extremely faded traces or other possible errors were excluded. In some cases, there were minor clock stoppages with a broken pencil trace rejoining the trace. However, instances with stoppages, even if occurring only once during any hour, were generally excluded from the analysis. This exclusion was implemented due to the potential inaccuracies in recordings associated with these stoppages. Nevertheless, marigrams with small malfunctions in the pen trace, as long as they did not stop at the hourly intervals, were included. Checks were conducted to ensure that the continuing trace was not offset. Any trace which had data missing (sometimes on half day traces leading into a new marigram) was discarded if the trace did not touch any of the hourly intervals.

In some cases, marigrams with mostly bad data were entirely discarded. However, in many instances where at least some of the traces were noted as good quality even in poorer quality images, they were included in digitisation. In some years, such as 1930, if a trace had a solid pencil trace joining a pen trace, and if the trace was shaped correctly overall, and provided the pencil trace did not predominate much of the trace, it was kept. Traces that exhibited irregular shapes, including abrupt changes or irregular patterns on marigrams, were discarded, as they may indicate data malfunctions. It was observed in a few marigram images where the end of a trace ended at the 14th hour and started on a new marigram at the 14th hour, there were offsets of over 0.5 ft. In one instance, for the 14th June 1926, it was observed that the 14th hour value was 9.78 ft, but where the 14th started on a new marigram its value was 10.54 ft, showing a significant offset between the marigrams of 0.76 ft. This is quite a substantial offset between the marigrams. In these cases, mainly the last value on the previous marigram was chosen as correct due to the presumed continuity of the data stream. The decision is informed by the potential for operational perturbations, such as drum changes or calibration inconsistencies, which may introduce variability in subsequent measurements. Thus, prioritizing the last recorded value on the preceding marigram aligns with the aim of minimizing the influence of such operational factors on data integrity.

In 1925, three distinct marigrams were available: 02nd–09th November, 07th–14th November, and 09th–16th November. This availability of three marigrams during overlapping dates can be attributed to the need for re-recording and additional monitoring efforts aimed at improving data quality. Due to stoppages in some of the traces and instances of bad data, supplementary recordings were likely conducted to ensure comprehensive and reliable data collection. Notably, the first marigram exhibited malfunctions during the period of the 02nd to the 09th of November, with a thick spurious line detected on the 07th and incomplete missing data on the 08th and 09th. Only data from the 08th and 09th of November were utilized from the second image (covering 07th to 14th November), which shared overlapping dates. However, the third marigram, covering the period from the 09th to the 16th of November, was selected for use for the remaining traces due to the image's longer date span. In the common overlapping part of the second and third image traces, variations in the height of the trace for the 09th were observed.

There was no full year of data in any of the years concerned due to the data exclusion criteria and missing marigrams, resulting in days with good data. Table 2.2 summarizes the number of days in each year.

Table 2.2: Number of days in each year digitised after quality approval check.

Year	Number of days
1925	288
1926	226
1927	222
1928	218
1929	299
1930	105
1931	232

All digitised and quality-controlled marigrams were merged into a data file for their respective year. For the final quality check, one third of the marigrams were randomly re-digitised. Any offsets exceeding 5 mm between the original and repeat digitisation's were subsequently adjusted with the re-digitised data. Both the unadjusted data and data adjusted for offsets were analysed for consistency and accuracy.

2.2.5 Datum conversion of data

The adjusted digitised data for 1925–1931 were converted from ft to m (metres) and adjusted to ODM (Ordnance Datum Malin). CD (Chart Datum) was 1.75 ft above OD (Ordnance Datum Dublin) (ODD) (Figure 2.9). Notably, ODD is 2.722 m below ODM (Personal communication from the Office of Public Works—OPW, 2023). Data were corrected to factor in the 2.722 m difference. The adjusted digitised data were converted to m (metres), and the difference between ODM (2.722 m) and CD (1.75 ft converted to metres) was subtracted from the adjusted digitised data.

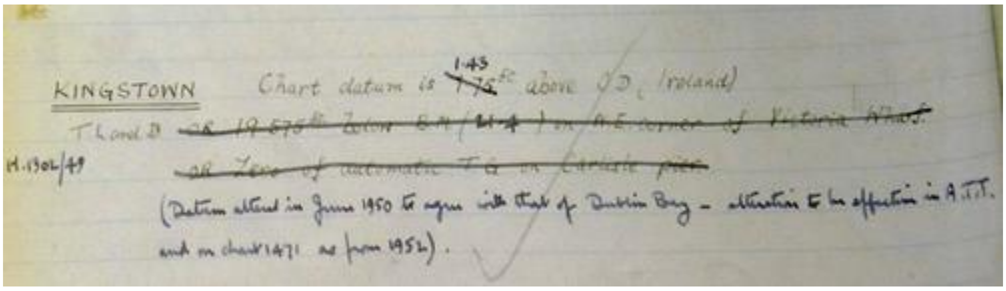


Figure 2.9: Dún Laoghaire (formally known as Kingstown) Ledger provides the CD height of 1.75 ft above OD/ODD Ireland pre-1950. Value was adjusted to 1.43 ft post 1950.

2.2.6 Data validation

To validate the adjusted digitised data, we conducted an analysis of tidal constituents, with a particular focus on the predominant M2 component (Pugh & Woodworth, 2014). The Amplitude (m) and Phase Lag (°) were extracted for the M2 component using the oce Package in R, a specialized tool for oceanographic tidal analysis (Kelley et al., 2022). The Greenwich Phase Lags are calculated using the Oce package in R. The analysis covered all months for each year, except for several exceptions. In 1926, April was excluded due to significant data gaps. In 1927, December was discarded due to substantial data loss. In 1931, February, March and December were excluded due to large data gaps. The year 1930 was omitted from the analysis because it only contained 105 days of scattered data, making it unsuitable for calculating M2 (Amplitude and Phase Lag). Only 1925 and 1929 had the M2 calculated based on data from all their months. Additionally, the Dún Laoghaire Harbour data recorded in 1842 and 2014 underwent the same Amplitude and Phase Lag calculations using the oce package to provide a basis for comparison with the 1925–1931 data. The M2 calculations (using the oce package) were carried out on the data converted to m (metres) at ODM, ensuring consistency in units and reference datum for the analysis.

2.3 Results

2.3.1 Examining the unadjusted and adjusted data (pre-ODM and ODM conversion) and the adjusted digitised data post ODM conversion

The offsets between digitised (unadjusted) and adjusted digitised data, in feet relative to CD (Chart Datum), and the adjusted digitised data, converted to ODM (Ordnance Datum Malin), are summarized in Table 2.3. The most significant differences occur in the years 1927–1929, with each year exhibiting an offset exceeding 13 mm between the digitised and adjusted data. Notably, in 1928, the largest deviation of 13.716 mm was observed. Conversely, 1926 shows a modest offset within the 10 mm accuracy range. In 1931, an outlier stands out with an adjusted MSL increase of just under 4 mm, deviating from other years. The years 1925 and 1930 closely approach the 10 mm offset, falling just over 0.5 mm short. Treating 1931 as an exception and averaging offsets for 1925–1930 reveals an average offset exceeding 10 mm. These results highlight that unadjusted, digitised data may often exhibit a significant offset beyond the 10 mm accuracy range. Table 2.3 outlines the MSL relative to m (metres) at ODM for each year (using the adjusted digitised data), representing the adjusted sea level data converted to ODM.

Table 2.3: Comparison of Yearly MSL values pre-ODM conversion (unadjusted and adjusted data) and converted to ODM for the adjusted data only.

Year	Digitised MSL (ft)	Adjusted MSL (ft)	Difference (ft)	Difference (mm)	Adjusted MSL converted to ODM (m)
1925	6.488	6.457	0.031	9.449	−0.221
1926	6.604	6.583	0.021	6.401	−0.182
1927	6.529	6.485	0.044	13.411	−0.212
1928	6.642	6.597	0.045	13.716	−0.178
1929	6.399	6.355	0.044	13.411	−0.252
1930	6.496	6.465	0.031	9.449	−0.218
1931	6.516	6.529	−0.013	−3.962	−0.199

2.3.2 Validation of tidal data

The M2 amplitudes and phase lags for Dún Laoghaire, spanning from the initial 1842 Airy tidal point survey (the first systematic tidal reference survey for Ireland) to the latest available data in 2014, are summarized in Table 2.4 (1930 excluded due to poor data availability). Notably, during the years 1925–1931, the Amplitudes showed close agreement, with a standard deviation of 0.03 m. The Phase Lags also demonstrated consistency, characterized by a standard deviation of 0.9°.

Table 2.4: Shows the Amplitude and Phase Lags of Dún Laoghaire data (1930 excluded due to poor data availability).

Year	Amplitude (m) M2	Phase lag (°) M2
1842	1.27	323.1
1925	1.31	325.6
1926	1.30	327
1927	1.30	326.5
1928	1.26	327.4
1929	1.26	326.3
1931	1.25	324.9
2014	1.36	325.2

- *Note*: No Nodal adjustments made to this data.

The Amplitudes and Phase Lags for the initial and latest survey years (1842 and 2014) closely align with the 1925–1931 data. All yearly Amplitudes fall within the range of 1.25–1.36 m, and Phase Lags range from 323.1° to 327.4°. When amalgamating the entire dataset (1842, 1925–1931 and 2014), the Amplitude standard deviation is 0.04 m, and the Phase Lags standard deviation is 1.4°, reinforcing the consistent nature of tidal characteristics over time.

2.4 Discussion of results

The results of this paper highlight the significance of accurate marigram digitisation, revealing potential offsets of up to 14 mm. Notably, in the years 1926 and 1931, only modest offsets were observed, well within the 10 mm accuracy (Intergovernmental Oceanographic Commission (IOC), 2012). Regarding the adjusted digitised data, it is crucial to note that without corrections, the results would exhibit many offsets, some exceeding 13 mm, immediately altering the data by nearly 10 mm. Three years (1927–1929) out of the seven had offsets exceeding 13 mm, while 1925 and 1930 were just over 0.5 mm short of reaching the 10 mm threshold. Examining rates of change over time, offsets of 10 mm or more could distort the data values and compromise accuracy.

Consideration may be given to employing a reduced grid approach, assigning a single-point value to adjust for all trace offsets at a given hour, as outlined in the methodology (Figure 2.6). While this approach would be less labour-intensive, it comes at the cost of potentially mis-scaling many adjusted values, given that the trace values on the upper and lower bounds of the image would differ and may not always result in overall offsets within 10 mm. Regardless of the quality of the marigrams, whether utilizing an automated digitisation tool package (Pons et al., 2016) or a manual point-based digitisation method, both approaches necessitate the readjustment of values to ensure accuracy. The findings presented in this study emphasize the significance of this process. Even software packages capable of adjusting image tilts cannot eliminate inherent hidden distortions in marigram images, significantly impacting the accuracy of data values.

The close alignment of M2 Amplitudes and Phase Lags across the 7 years of adjusted digitised data signifies stability in the timing and magnitude of tidal variations. The small Amplitude standard deviation of 0.03 m during 1925–1931 indicates minimal variability, emphasizing the reliability of these values. Similarly, the standard deviation of Phase Lags, approximately 0.9°, though relatively small, indicates a close proximity of Phase Lag values to the mean. When considering data from 1842, 1925–1931 and 2014 together, the Amplitude standard deviation of 0.04 m and a Phase Lags standard deviation of 1.4° illustrate the consistency in the nature of tidal characteristics. However, the 1842 comparison data covers late June to August, spanning parts of both months, suggesting potential complexities in interpreting its Phase Lag and Amplitude. These findings highlight the consistency of tidal characteristics over the studied years, illustrating that the data aligns well together.

When comparing the Dún Laoghaire Harbour data with available Belfast Harbour data, notable similarities emerge in the daily averages (Figure 2.10). Visual examinations reveal consistent positive peaks of daily averages. These peaks are observed concurrently throughout various months in both Belfast Harbour and Dún Laoghaire Harbour datasets. Similarly, smaller negative peaks align temporally in each year for both locations. The remarkable consistency in the frequency of occurrences across the datasets is particularly significant. While the geographical separation between Dún Laoghaire Harbour and Belfast Harbour introduces some differences in peak occurrences, the Dún Laoghaire Harbour data exhibits similar patterns each year, albeit with more data gaps.

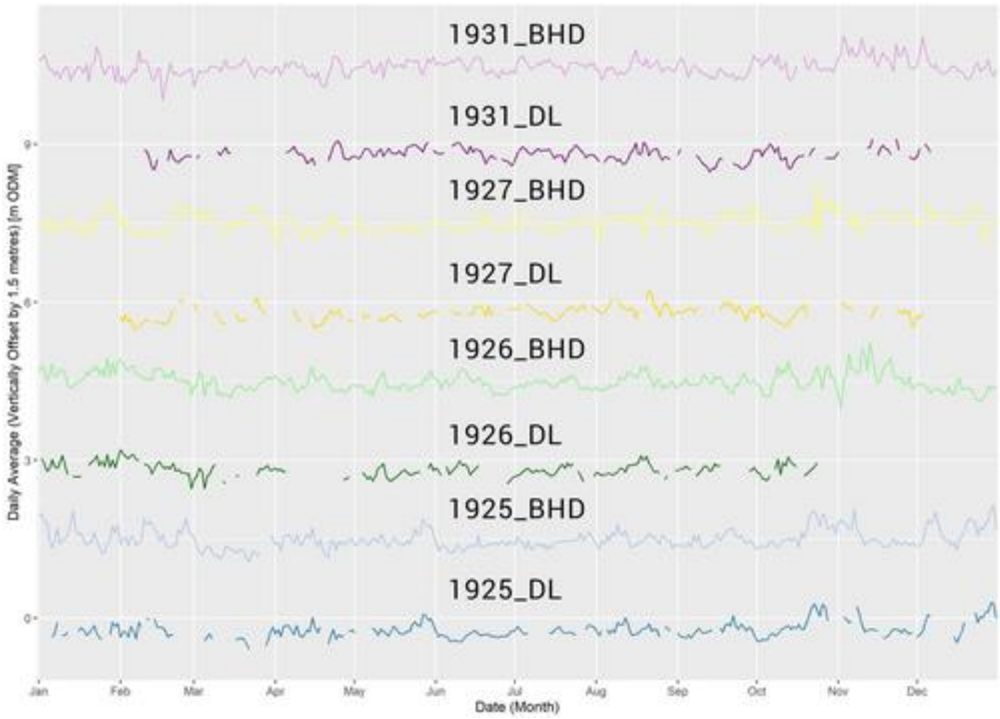


Figure 2.10: Daily average water levels for Dún Laoghaire Harbour (DL) and Belfast Harbour (BHD) comparisons, with each yearly record vertically offset by 1.5 m for visualization. Records from 1928 to 1930 are missing for Belfast Harbour.

The correlation coefficient of 0.715 between the water level data (daily averages) from Dún Laoghaire Harbour and Belfast Harbour (Figure 2.11) indicates a strong relationship between the observations at these two locations. This high correlation suggests that fluctuations in water levels at one site reliably correspond to those at the other. However, while the correlation is strong, there may be instances of scatter in the highest water levels, indicating some degree of variability. This variability could be influenced by factors such as tidal characteristics, weather events or local geography (Orford & Murdy, 2015; Woodworth, 2010). Nevertheless, the significant correlation highlights the overall coherence and synchronicity of water level patterns between the two harbours, reinforcing the reliability and consistency of the recorded data across both locations.

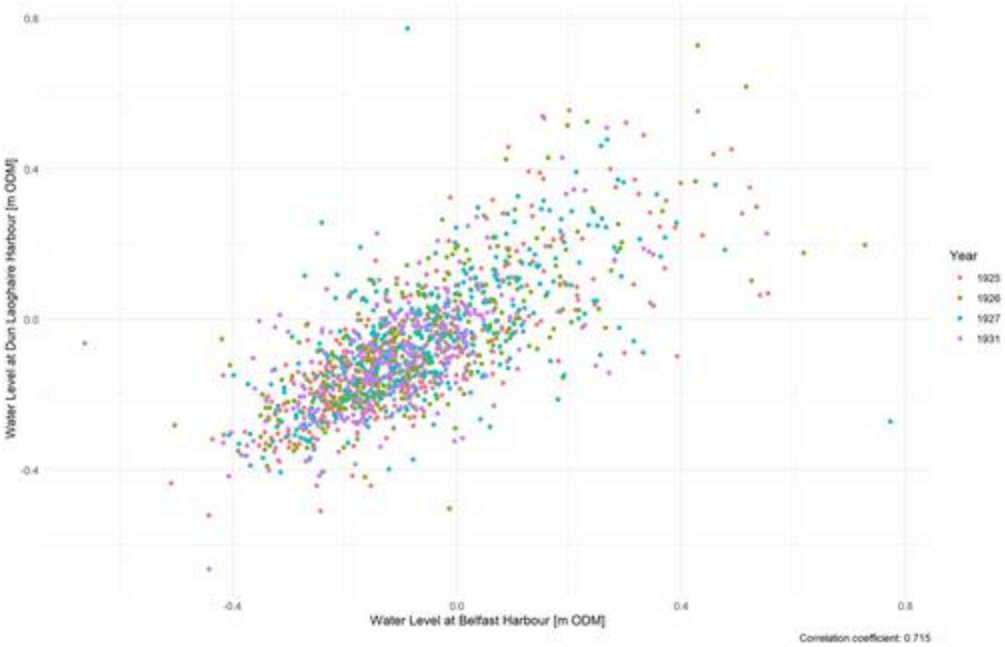


Figure 2.11: Presents a combined plot of water levels (daily averages) for Dún Laoghaire Harbour and Belfast Harbour, showing a strong correlation coefficient of 0.715 between the two locations. However, there is notable scatter among the highest water levels.

The adjusted digitised data from Dún Laoghaire Harbour were compared with surveys conducted in 1842 and 2014 within the same harbour. Additionally, comparisons were made with the Dublin Port Mean Tide Level (MTL) dataset spanning from 1938 to 2016 (Shoari Nejad et al., 2021), and with Howth MSL data from The Marine Institute covering the years 2007–2018. The observed values align with a reported rise in annual mean sea level, as illustrated in Figure 2.12, with a linear trend represented by a dashed line, with the grey envelope indicating the variability in the data. On average, there is an increase of around 1.5 mm/year. It is worth noting that some years in the Dublin Port dataset do not fit with a rise in sea level, as previously reported (Shoari Nejad et al., 2022). However, a detailed discussion on the issues and variability in this data is beyond the scope of this paper. The Howth data also indicates a rise in sea level when compared with Dún Laoghaire and Dublin Port data.

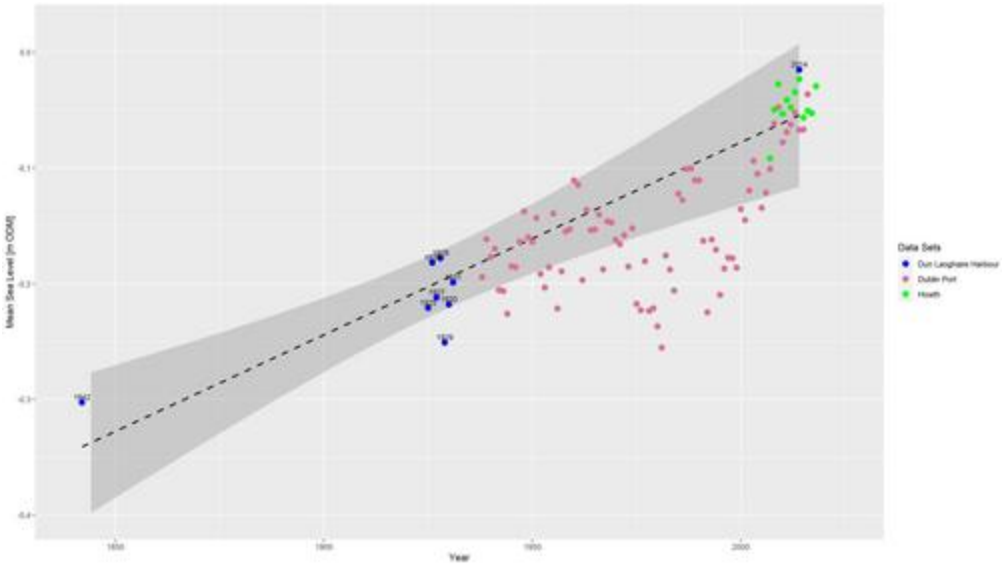


Figure 2.12: Adjusted (digitised data) annual MSL values for Dún Laoghaire Harbour (1925–1931), 1842 and 2014, compared with Dublin Port data (1938–2016) and Howth data (2007–2018). Dashed line: linear trend; Grey envelope: data variability.

2.5 Potential dataset use and limitations

2.5.1 Dataset use

The yearly adjusted Mean Sea Level (MSL) values for 1925–1931 in Dún Laoghaire exhibit significant variability. The absence of months in some years may skew annual averages, especially for spring, autumn or winter months, affecting yearly MSL calculations. Due to data quality issues and missing records, calculating MSL on a full year, as recommended by PSMSL (2025), was not always possible. However, for the focus of accurate digitisation in this paper, this limitation is acceptable. Notably, 1925 and 1929 provide the most complete data, representing lower MSL levels. This suggests potential for further investigation, including breaking down the data into smaller time series for seasonal or monthly analyses, in line with approaches used by Pugh et al. (2021) in a similar context. The protocol for discarding traces with missing data prioritized quality standards, focusing on severe fading or thick lines indicative of errors. For future work, consideration could be given to interpolating discarded daily traces with gaps where possible, potentially increasing the number of data points in the time series and enabling more comprehensive analyses. The data generated in this methodological paper can be utilized for additional tidal analysis and more accurate estimations of sea level rise in Dublin from historic times. Notable similarities in comparative analyses may also benefit from independent buddy checking (Hogarth et al., 2020) or cross-validation, although this was not implemented in the present study.

2.5.2 Limitations of dataset

Issues that are commonly associated with tide gauges include instrumentation error (Lennon, 2015). Additionally, problems such as blur, accuracy, time gaps, missing data, bad data, clock errors and datum errors are commonly associated with marigrams (Latapy et al., 2023). The marigram recording instrumentation is prone to error, and the actual value may not always be centred within the line thickness, particularly when the pen wears down. Many of these issues occur in the Dún Laoghaire dataset. It must be noted there is a limit to the accuracy in digitizing the marigrams and performing adjustments regardless of what technique is used will not remove the inherent sources of instrumentation error such as potential inaccurate recordings (caused by the changing of the drum) and clock timing errors, which we have not addressed in this paper. The year 1930 is an exception. Due to its small and sporadic timeseries, it should be treated with caution as there was much bad data and numerous stoppages. There are also some distortions in the image where even using the nearest ft to correct small offsets can remain. Where bad distortions occur, usually on the lower bounds of some images (where lens distortions often occur), the values may correct themselves in the middle of the given ft. While this would mean the offset adjustment could alter the actual value in some cases, it would not be enough to significantly impact the accuracy of the data. However, this point needs to be noted. The accurate digitisation of these records is time-consuming. Overall, it can take up to 6 days to process a year of data: two to 3 days for digitising (excluding digitising the underlying grid values for adjustment) and another 3 days for digitising the grid values for adjustments.

2.6 Dataset Access

The data are freely available from the open access PANGAEA data publisher (https://doi.pangaea.de/10.1594/PANGAEA.967078) (McLoughlin et al., 2024b). The dataset comprises three main levels of data. Level 0 contains compressed zip files with raw marigram images from 1925 to 1931, organized into subfolders for Good_Quality_Images and Poor_Quality_Images. These separate the good and poor-quality images. Level 1 provides digitised data for each year in a compressed zip file, featuring Excel files (named for each year) with columns for hour (representing the time each point is digitised), height (in ft relative to CD) and datetime. These files, suffixed with '_DL_Digitised', contain raw digitised data without adjustments to hourly intervals. Level 2 presents adjusted data in a compressed zip file (with a structure similar to level 1), where values have been corrected for offsets by subtracting the nearest ft grid values from known ft values. Each adjusted data file (year), suffixed with '_DL_Adjusted', includes columns for hour (representing the time of measurement), height (in ft relative to CD) and datetime, the height values are adjusted for offsets ensuring accuracy within 10 mm (1 cm). Additionally, the Grid_Values zip (folder) contains yearly Excel files with columns for hour (representing the time of measurement), recorded foot interval, actual foot interval, offsets and datetime. Although not one of the main levels, this data is crucial for ensuring the overall accuracy of the adjusted data.

2.7 Conclusion

The aim of this methodological paper was to bring the accuracy of the marigram data within 10 mm (1 cm), which has been achieved. Seven years of marigram data from Dún Laoghaire Harbour, Ireland (1925–1931), were digitised at hourly intervals, with some gaps in the records. A methodology has been developed based on freely available open-source software, enabling point-based digitisation of the marigram traces. A method of adjustments was developed to correct for distortions in the underlying images. Finally, the adjusted digitised data was converted to m (metres) at ODM. The recovered data is consistent with an overall rise in sea level.

The final data was validated by:

1. Local tidal Amplitudes in Dún Laoghaire Harbour, Dublin, ranged from 1.25 to 1.36 m, with Phase Lags ranging from 323.1° to 327.4°.
2. Daily MSL values from another tide gauge in Ireland, for common years (1925–1927 and 1931) exhibited remarkably similar patterns, with almost identical peaks and troughs.
3. Annual MSL values in the Dublin region, after adjustment and correction, aligned with data from other sources, demonstrating an annual sea level rise of around 1.5 mm.

These validations reinforce the reliability of the adjusted digitised marigram data and support the evidence for a continuous sea level rise in the region. While designed for marigrams, this methodology can also be applied to other historical meteorological records—such as barographs, thermographs, fluvial hydrographs, and rain-charts—to support the digitisation and validation of long-term climate datasets.

3. Evaluating student involvement in sea-level data rescue

This study develops a framework to train and evaluate undergraduate students (non-experts) in digitising tidal marigrams (graphs of sea-level changes). Using data from Kilrush (County Clare) and Dún Laoghaire (County Dublin) in Ireland, it highlights best practices and challenges, especially misidentification, formatting errors and calibration issues. While most students performed well, the study highlights ways to identify those needing improvement. Focusing on error-checking, the findings refine digitisation methods with quality assurance, preparing students and citizen scientists for climate research. Supported by visual materials, these techniques aid citizen science, enhance education and may support future machine learning development.

3.1 Introduction

As the climate crisis continues to escalate, expanding our understanding of past climate and extremes has become more critical than ever. Historical sea-level data hold significant value, providing essential insights into coastal processes such as flooding, erosion and sea-level rise – factors that directly influence climate change assessments and adaptation efforts (Talke & Jay, 2013; Pugh et al., 2021). The preservation and digitisation of historical climate records, often referred to as climate data rescue, play a crucial role in filling gaps in our knowledge (Hawkins et al., 2023; Mateus et al., 2021; Ryan et al., 2018). This challenge affects many parts of the world, such as Ireland, Asia, South America and Africa, where long-term tidal records remain scarce or incomplete. Despite their importance, many sea-level records remain undigitised, limiting accessibility. In particular, the digitisation of historical tidal records is a complex process that requires specialised skills and precise attention to detail (Talke & Jay, 2017; Latapy et al., 2023).

In this context, climate data rescue – preserving and digitising historical records – emerges as a critical strategy to broaden access to data and inform both scientific research and policy decisions (Allan et al., 2016; World Meteorological Organization, 2016; Mateus et al., 2021). It presents a unique opportunity to engage students and the wider public in meaningful data management and climate science activities (Williams et al., 2022). Student involvement in data rescue projects not only helps preserve valuable data but also fosters a deeper appreciation for climate science and data management, leading to successful outcomes (Phillips et al., 2018; Ryan et al., 2018). For example, a similar initiative at the National University of Ireland, Galway, engaged 357 participants in digitising over 775 000 historical Irish daily air temperature records. A post-project survey found that 87% valued the data, 88% had a positive experience and 42% showed interest in climate-related careers after participating, highlighting the initiative's impact (Mateus et al., 2021). However, unlike that project, digitising tidal records was more complex due to their graphical nature and the precise timing required, particularly for tidal turning points, and therefore required careful planning.

Tidal records are often represented graphically on charts called ‘marigrams’. These charts display the rise and fall of sea levels or tides, over a specific period (e.g. Figure 3.1). They often show multiple tidal traces on a single sheet, with each trace representing sea-level fluctuations over a specific period, typically a day. While other types of historical data, such as written records in ledgers, can be transcribed manually with relative ease, tidal records require advanced techniques due to the precise timing needed for measurements and the challenge of resolving inconsistencies in the data (Latapy et al., 2023).

Undergraduate students were used as non-expert contributors within a structured training framework to assess whether individuals with general scientific training can reliably carry out high-resolution digitisation of tidal records. They were selected as an intermediate group between untrained members of the public and experienced practitioners, possessing sufficient scientific background to engage with technical material while still exhibiting typical learning-related error patterns that enable evaluation of training design and quality assurance procedures. In contrast, experienced practitioners would be expected to minimise such novice error patterns, whereas untrained members of the public would introduce excessive variability, making this cohort suitable for evaluating the reliability and robustness of the digitisation workflow.

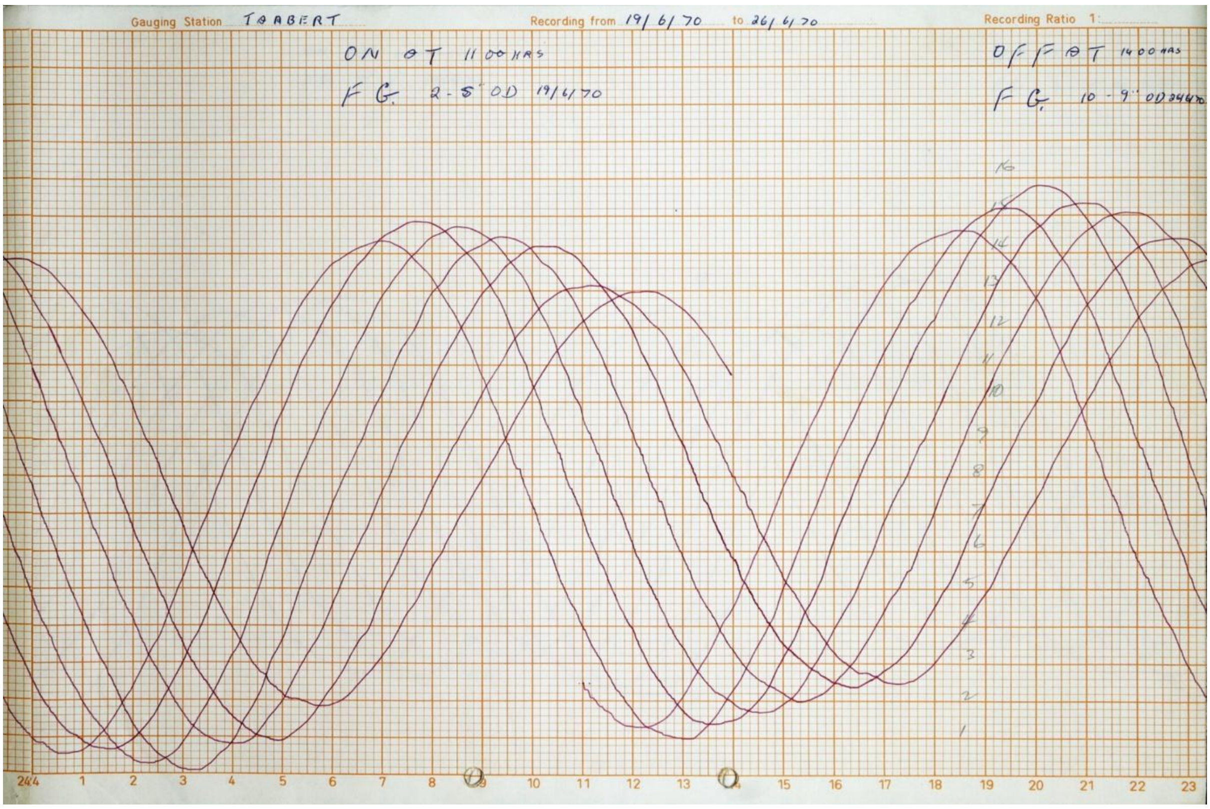


Figure 3.1: Example of a marigram (visual trace of tidal levels), showing approximately 1 week of daily tidal traces from 19 to 26 June 1970, in Tarbert, County Kerry, Ireland.

The study involves geography undergraduate students from the third-year 2024–2025 cohort at Maynooth University, tasked with digitising constructed training datasets and more complex real historical tidal data. This assignment was part of Maynooth University's GY369 Oceanography (Phase 1) and GY310B Geography Research Workshops (Phase 2) modules.

The tidal records used for student training include both training datasets (generated from modern tide gauge data) and historical datasets, selected to provide practical experience in digitising and analysing different types of tidal data.

- Kilrush Harbour: Modern Marine Institute tidal data, formatted to resemble historical marigrams, used to train students (Phase 1).
- Dún Laoghaire Harbour (1925): The training tidal data were created using real historical tidal data (McLoughlin et al., 2024a, 2024b) (Phase 2A – Training). Students digitised both the training and historical tidal data (Phase 2B), which were derived from the same dataset.

The datasets are designed to both train students and assess their accuracy in digitising tidal records. This study primarily focuses on evaluating digitisation skills while developing a robust error-checking benchmark to ensure data quality. It also identifies common digitisation challenges, offers insights into students' understanding of tidal data and helps prepare them for future contributions to climate and weather research through improved training in oceanography and climate science. By engaging students in digitising both historical and modern tidal data, this study not only supports climate data preservation but also advances systematic quality control, enhances citizen science education and lays the groundwork for potential future machine learning applications. In this context, the structured and quality-checked digitised outputs produced by students may serve as benchmark datasets for training and evaluating future automated feature extraction approaches. Building on Edwards' (2010) concept of the 'vast machine' – the global infrastructure behind climate knowledge – this project trains students to digitise and standardise historical sea-level data, preparing them to participate in global climate data systems. Accurate digitisation of tidal records is essential for calculating realistic weather-driven tidal residuals – such as storm surges and coastal flooding – thereby advancing our understanding of weather impacts on coastal environments.

3.1.1 Motivation for assignment setting

This study builds on prior student-led tidal data digitisation efforts in climate and oceanography courses, which revealed key challenges in maintaining data quality and consistency.

For instance, in 2023, postgraduate students in the Climate Change MSc programme worked with tidal records from Tivoli, Cork. While some students produced accurate results, others struggled with scaling and interpreting the data, leading to inconsistencies. Similarly, an undergraduate project involving 54 students digitising tidal records from Dublin Port found that only 22 of the resulting datasets met high-quality standards. A major issue in both cases was the absence of a reliable method for verifying digitised data. Attempts to benchmark the Dublin Port data against predicted tidal patterns – based on mathematical tidal harmonics – proved inadequate for accurate validation.

To address these challenges, we developed a two-phase approach that integrates real-time quality control and cross-referencing with verified tidal records. In Phase 1, students digitised training images based on modern tidal data from Kilrush (2019–2021). Phase 2 extended this approach by generating training images from historical tidal records of Dún Laoghaire Harbour, previously digitised in another project (McLoughlin et al., 2024a), and by digitising the original historical images. Students worked with both training datasets – derived from historical records and the original archival data – enabling hands-on practice, cross-validation and improved accuracy (McLoughlin et al., 2024b). This method, described in the next section, establishes a replicable model that includes an assessment of quality for future digitisation projects.

3.2 Application of assignment in the classroom

3.2.1 Working with a modern training dataset: Kilrush Harbour (Phase 1)

In the first phase, students worked with tidal data from Kilrush Harbour (2019–2021). These modern data were downloaded from the Irish Marine Institute's ERDDAP server and replotted to resemble a historical marigram with seven daily traces on a single image (Figure 3.2). This setup allowed for immediate comparisons of student-digitised data with known tide levels. Students extracted high and low tidal points from these marigrams. Each student was provided with 4 weeks' worth of data and tasked with identifying the highest and lowest tidal points using WebPlotDigitizer – software that allows users to extract data points from images or plots (Rohatgi, 2024). Differences between student digitisations were also examined to identify common sources of error, including calibration issues and point placement inaccuracies. Even in this controlled dataset, the task design allowed small inter-student differences, mainly due to calibration settings and point selection during digitisation.

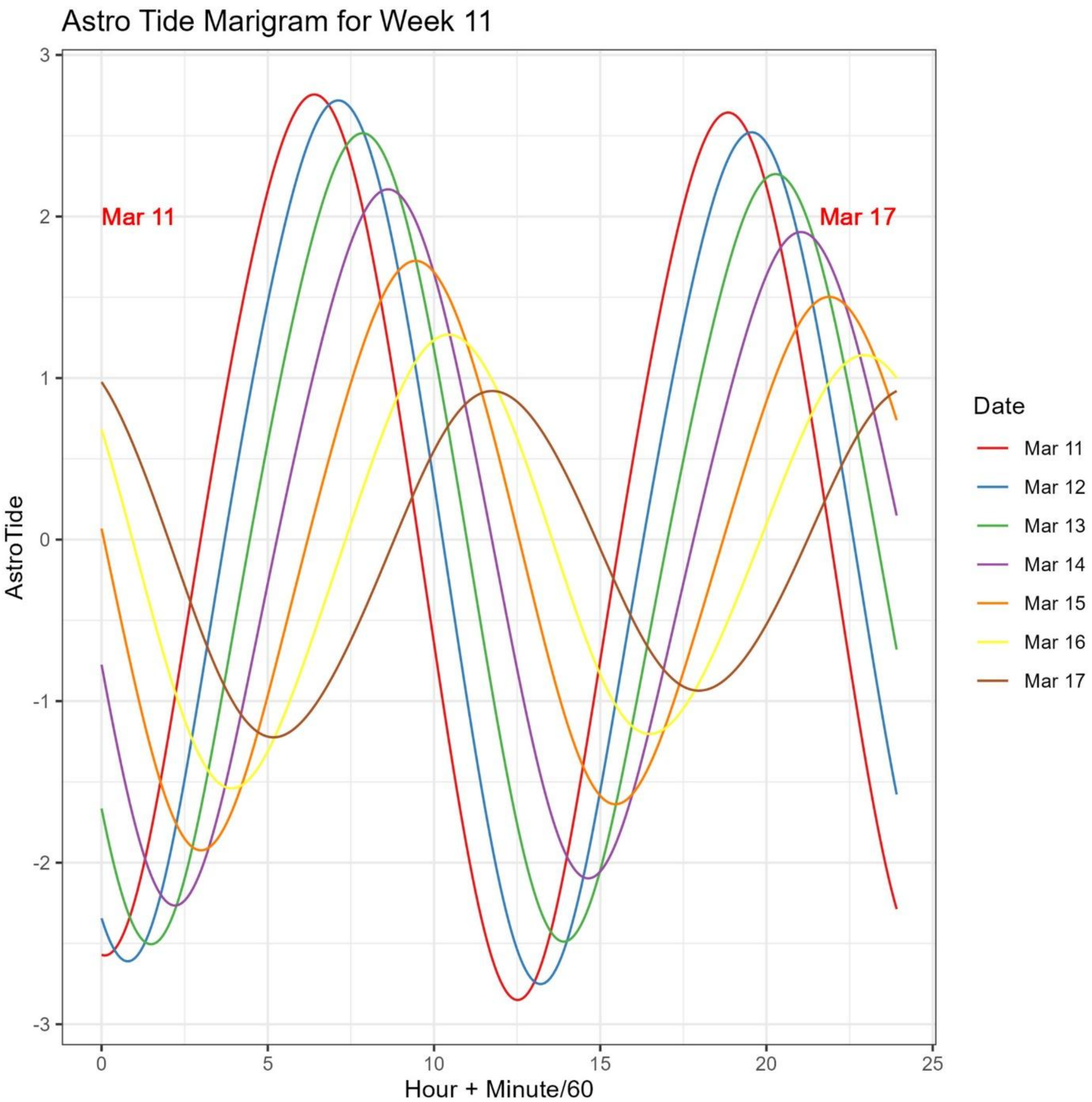


Figure 3.2: Tidal chart (marigram) generated for Kilrush Harbour, showing 1 week of tidal data from 11 to 17 March 2020. The X-axis represents hours, and the Y-axis represents metres relative to Ordnance Datum Malin (ODM).

Before starting, students attended a workshop on key tidal concepts. These included tidal range (the height difference between high and low tides) and tidal interval (the time between consecutive tides). They also learned about tidal reference levels, including mean tide level (MTL), which is the average height of the tide over a specific period, as well as mean high water (MHW) and mean low water (MLW), which represent the average heights of the highest and lowest tides, respectively. As a supplementary exercise, students calculated these values from their digitised data; however, no results from this task are reported, as the main project focused solely on digitisation.

Having extracted the tidal data using the WebPlotDigitizer software (Rohatgi, 2024), students entered it into Microsoft Excel, where they recorded the tidal heights and corresponding times for further analysis. Excel was used to calculate key measurements, such as tidal range and intervals, using a pre-prepared template. Excel templates are commonly employed in the digitisation of historical data (Inayatillah et al., 2022). Students also calculated the mean tide level (MTL) and average high and low water levels. This staged design was intended to progressively develop student competency, from identification of key tidal extremes to higher-resolution hourly digitisation in Phase 2, where applicable.

3.2.2 Digitising tidal data from marigrams: Phase 2A – training and Phase 2B – historical data digitising for Dún Laoghaire Harbour

In the second phase, students from the GY310B Research Workshops module participated in training activities using tidal charts from Dún Laoghaire Harbour for the year 1925. Some students had previously completed the GY369 Oceanography module (Phase 1), which provided foundational knowledge in tidal data analysis. Specifically, 10 of the 16 students in Phase 2 had undertaken Phase 1. Each student digitised two tide charts (marigrams): one from a training dataset, which was based on predicted tide levels derived from the historical Dún Laoghaire dataset (1925) (Phase 2A – Training), and another from actual historical records (McLoughlin et al., 2024b) (Phase 2B – Historical Data Digitising). The training dataset (Phase 2A) used model-predicted tide levels for learning purposes, while the historical records (Phase 2B) consisted of real archival data.

Students also used WebPlotDigitizer (Rohatgi, 2024) for extracting data from both the training and historical images to record tidal levels at hourly intervals. This differed from the first phase, where students only recorded the highest and lowest tide levels each day instead of capturing data at hourly intervals. No tidal reference calculations were undertaken. In this phase, students digitised each trace at hourly intervals (Figure 3.3). Many historical images show bends and distortions (see McLoughlin et al., 2024a) caused by damage to the original paper charts and by the way they were scanned or photographed. These distortions include tilting from angled cameras, warping from uneven paper and even slight stretching or bending from camera lenses. While these issues could affect the precision of measurements, they did not matter for our purposes, as the main goal was to teach digitisation skills.

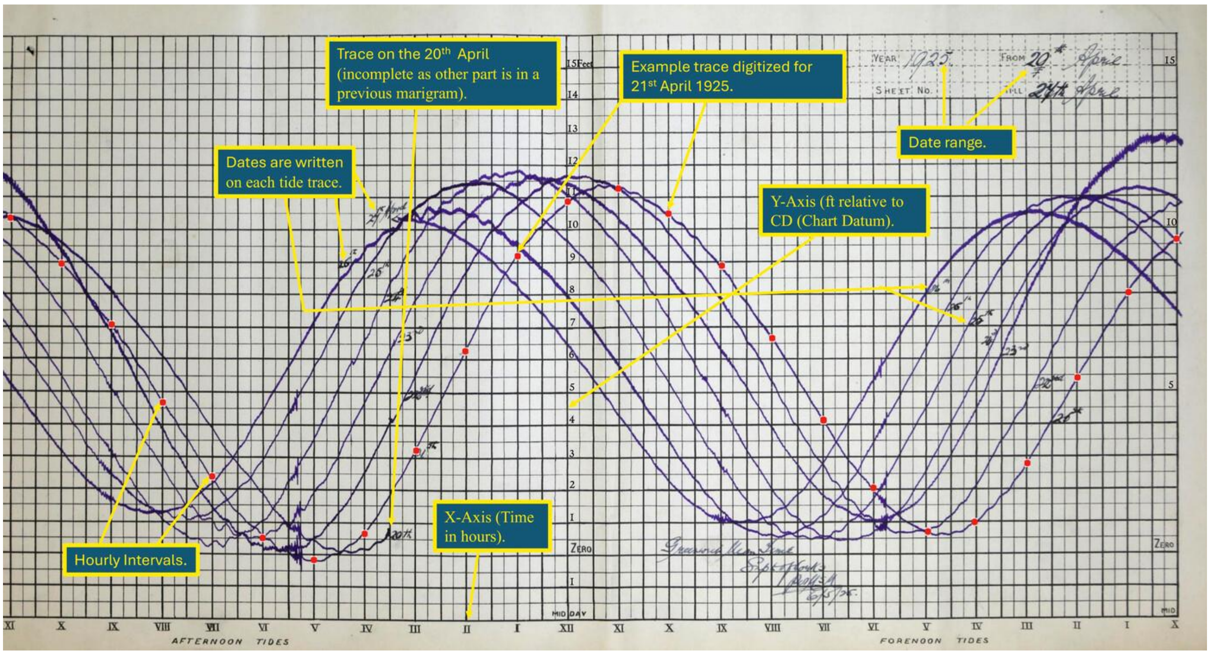


Figure 3.3: Example of a tidal chart (marigram) from Dún Laoghaire, Dublin, Ireland, for 20–27 April 1925, showing hourly intervals digitised on a trace (April 21). In this image, the X-axis is oriented from right to left, which differs from the usual left-to-right format seen in other charts. This reversed orientation is important to note, as it may require students to adjust their data extraction process, especially when aligning the chart with other data sources that follow the conventional left-to-right format. The X-axis represents hours, and the Y-axis represents feet relative to the Chart Datum (McLoughlin et al., 2024a, 2024b). The date is written in pen on each trace.

Two students independently digitised the same tidal charts in Phase 1 only; this was not repeated in Phase 2. While this replication offered insight into digitisation consistency and inter-operator variability, discrepancies were systematically addressed through an automated error-checking procedure in R, allowing controlled correction of errors while retaining information on individual variation.

3.2.3 Resources and students' supports

To facilitate learning, a variety of resources were provided based on previous cohort experiences, emphasising their role in supporting student success in citizen science initiatives (Harlin et al., 2018; O'Donnell, 2023). Essential resources included tutorial videos, detailed data extraction manuals, colour-coded marigram images and immediate tutor support for queries. Additionally, a questionnaire was developed in Phase 1 to assess educational impact and gather feedback on student learning experiences. Materials, including tutorial videos, were made available in advance, allowing for immediate feedback and troubleshooting as tasks were introduced (McLoughlin et al., 2025).

3.2.4 Corrections and quality control measures

To ensure the accuracy and reliability of the digitised tidal data, a series of quality control measures was implemented by the lead author. Students were not responsible for quality checking or validating their data; their role was limited to manual digitisation.

- Kilrush data review: Tidal data digitised and submitted by students were compared with predicted tide levels using R software. Discrepancies between expected and recorded values were automatically flagged, visually inspected using R plots, logged and corrected by the author.
- Dún Laoghaire data review: Similarly, digitised data were checked by the author against predicted tide levels and historical records (McLoughlin et al., 2024b). Discrepancies were flagged, visualised and logged for identification and correction.

Comprehensive instructions for this error-checking process can be found in the relevant links provided in the Data availability statement, including code for generating tidal images (training data), as described by McLoughlin (2025).

3.3 Findings

3.3.1 Student success and challenges in tidal data digitisation

A total of 70 participants engaged in Phase 1 of the module, which focused on digitising tidal data from the Kilrush Training dataset. In Phase 2, 16 participants worked with tidal data from Dún Laoghaire Harbour, divided into two sub-phases: Phase 2A, which involved training data, and Phase 2B, which used real historical tidal images. These findings provide valuable insights into students' abilities to digitise historical tidal data.

As shown in Figure 3.4, 44 out of 70 students (approximately 63%) in Phase 1, 11 out of 16 students (approximately 69%) in Phase 2A and 9 out of 16 students (approximately 56%) in Phase 2B produced work that was deemed ‘Acceptable (Minor Revisions)’. Each student's work was evaluated against a verified reference dataset, with deviations under 5 cm considered ‘minor’ errors for correctly identified tidal highs and lows in Phase 1. These outputs were mostly accurate, with deviations for high or low tide points typically under 1–2 cm. For hourly interval digitisation of historical charts, overall accuracy generally remained within 3 cm, accounting for image distortion and trace clarity. Minor issues that required attention included simple adjustments such as correcting naming conventions, fixing minor date errors, or – in Phase 1 – correcting the identification of a few tidal points. Similarly, in Phases 2A and 2B, minor issues included misidentifying or inaccurately digitising small sections of a trace. However, the overall work was of high quality and suitable for use.

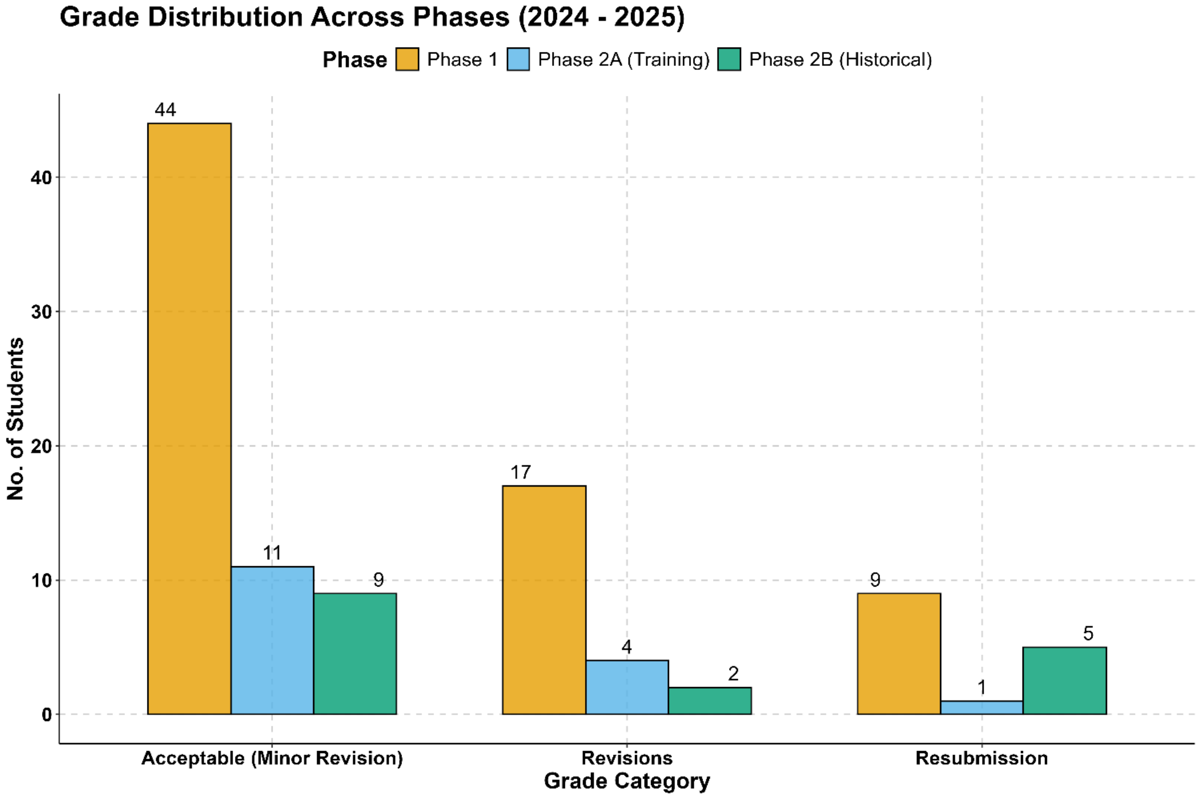


Figure 3.4: Results from Kilrush (Phase 1) and Dún Laoghaire Harbour (Phase 2A and 2B). The 'Acceptable (Minor Revisions)' category includes data that is usable with only minor issues, such as missing points or slight misidentifications. 'Revisions' refers to data with more noticeable errors, such as misplaced tidal points or hourly intervals. 'Resubmission' denotes data that is largely inaccurate, including significant errors or cases where no submission was made.

In addition, 17 students in Phase 1, 4 in Phase 2A and 2 in Phase 2B produced data that required more substantial revisions (categorised as 'Revisions'). Despite these issues, their outputs were still considered suitable for use once corrections were applied, demonstrating a solid understanding of the digitisation process. Common issues in Phase 1 included missing a small number of tidal points (typically no more than 3–4), formatting issues in Excel and minor inaccuracies in point placement. In Phases 2A and 2B, additional challenges included misplacement of hourly intervals in the data and formatting errors, such as incorrect date entries in Excel. In Phase 2B, where students digitised historical images, the primary issue was the misidentification of overlapping traces. Some students correctly digitised certain traces but mixed up parts of others where overlaps occurred, which was expected due to the increased complexity of the Dún Laoghaire images.

A notable challenge was the percentage of students submitting work that required resubmission due to significant errors or lack of submission (categorised as 'Resubmission'). In Phase 1, 13% of students (9 out of 70) submitted work deemed unsuitable and categorised as 'Resubmission'. This proportion decreased to 6% (1 out of 16) in Phase 2A but increased to 31% (5 out of 16) in Phase 2B. Due to the small sample sizes, these findings should be interpreted with caution, and no formal statistical tests were conducted. Of the 16 students in Phase 2, 10 had previously completed Phase 1. These students achieved a slightly higher average total score (13.28 out of 15, or 88.5%) compared to those without prior experience (12.5 out of 15, or 83.3%) – a difference of 0.78 points, which corresponds to 5.2% of the total possible score – based only on those who submitted all required work. This suggests that while prior experience provided a slight advantage, students without it still performed well, indicating that the training was effective overall. This increase in resubmissions for Phase 2B was expected due to the more complex nature of the Dún Laoghaire images, which featured overlapping traces and coarser grid intervals. The primary reasons for resubmission across all phases included calibration errors (incorrectly scaling the X and Y axes of the image), consistent misidentification or misdating of traces and Excel formatting issues such as incorrect date and datetime entries.

The analysis revealed common student errors across all phases, including Excel formatting issues, digitisation mistakes, calibration errors and challenges with overlapping traces in historical data. In Phase 1, some students uniquely misidentified tidal highs or lows, especially on days with only three tidal points, where the next point extended into the following day. These results highlight the need for robust error-checking methods. Comparing student work with verified datasets helps pinpoint specific weaknesses and guide improvements in digitisation. Furthermore, most students who performed well in Phase 2A also did well in Phase 2B, indicating the training dataset effectively prepared them for the complexities of real historical data.

3.4 Student perceptions: learning, engagement and preferences (Phase 1)

Regarding the perceptions of the oceanography assignment, 67 students completed the Phase 1 questionnaire, with the majority finding the task valuable for their learning. Specifically, 39% of students strongly agreed that the assignment was valuable (Question 6), and 36% strongly agreed that it provided insights into sea-level data rescue (Figure 3.5), with 61% agreeing. Overall, the response distribution shows expected inverse patterns between positively and negatively framed questions, consistent with coherent response behaviour across the questionnaire. Additionally, 96% agreed or strongly agreed (Question 9) that the task helped them develop valuable skills related to the experimental digitisation of tidal data, which is essential for understanding oceanographic data. Furthermore, approximately 90% agreed or strongly agreed that the process of working with marigram images (digitisation) was clear and easy to follow, although 10% disagreed or strongly disagreed with its clarity (Question 4), highlighting areas for improvement in the task design. Figure 3.5 summarises the Phase 1 questionnaire responses.

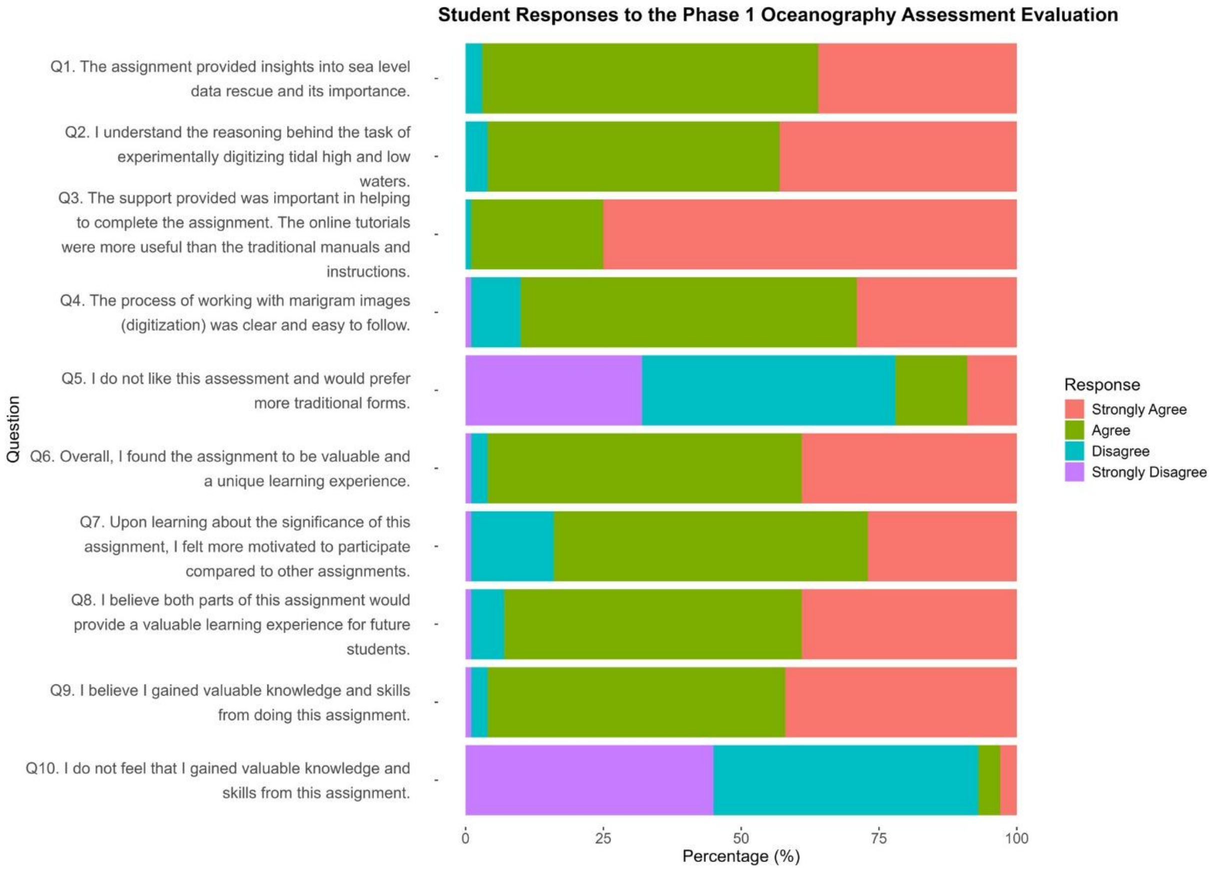


Figure 3.5: Questionnaire results (Phase 1) on student perceptions of the oceanography assignment's teaching and learning process.

Among all respondents, 84% agreed or strongly agreed that the assignment increased their motivation to participate compared to other assignments, suggesting that the unique nature of this task was a key factor in student engagement. Additionally, 46% of students disagreed, and 31% strongly disagreed that they preferred traditional learning methods over the current non-traditional assignment format (Question 5).

Moreover, 93% of students agreed or strongly agreed that this assignment would provide a valuable learning experience for future students, indicating sustained interest in data rescue activities. Of these, 39% strongly agreed that the assignment would provide a unique learning experience for future students, with 54% agreeing that it would offer a valuable learning experience (Question 8), showing strong appreciation for the novelty of the task. Of the 67 students, 99% strongly agreed or agreed that the video tutorials were more effective than traditional manuals (Question 3).

These findings (Table 3.1) suggest that, while some students may prefer traditional learning methods, the assignment was perceived by the majority as a valuable learning experience that increased engagement and highlighted the importance of tidal and climate data rescue. While these results reflect self-reported perceptions gathered through the questionnaire and not directly measured learning outcomes, they nonetheless offer useful insights into student engagement and perceived skill development.

Table 3.1: Summary of some key student perceptions of the oceanography assignment's teaching and learning process based on the questionnaire.

Contributor group	Perceptions
All respondents (N = 67)	• Positive learning experience: 39% (n = 26) strongly agreed that the assignment was valuable (Question 6) • Insightful assignment: 36% (n = 24) strongly agreed, 61% (n = 41) agreed, 3% (n = 2) disagreed that the assignment provided insights into sea-level data rescue and its importance (Question 1) • Clear process: 28% (n = 19) strongly agreed, 61% (n = 41) agreed, 9% (n = 6) disagreed, 1% (n = 1) strongly disagreed that the process of digitising tidal waters was clear and easy to follow (Question 4) • Support and motivation: 75% (n = 50) strongly agreed that the support provided was useful, and tutorials were more helpful than traditional manuals (Question 3) • Preference for traditional learning: 9% (n = 6) strongly agreed, 13% (n = 9) agreed, 46% (n = 31) disagreed and 31% (n = 21) strongly disagreed with the statement, suggesting a preference for the current non-traditional learning format over traditional methods (Question 5)
Strongly agree respondents (varied n)	• Useful learning: 42% (n = 28) strongly agreed that the assignment helped them gain knowledge (Question 9) • Valuable future experience: 39% (n = 26) strongly agreed that the assignment would provide a valuable learning experience for future students (Question 8)
Agree respondents (varied n)	• Clear process and instructions: 61% (n = 41) agreed that the digitisation task was clear (Question 4) • Engagement with content: 57% (n = 38) agreed that the assignment motivated participation (Question 7)
Disagree respondents (varied n)	• Lack of clarity: 9% (n = 6) disagreed that the digitisation task was clear (Question 4) • Preference for traditional learning: 46% (n = 31) disagreed with the statement that they prefer more traditional methods, suggesting they favoured the current non-traditional assignment format (Question 5)
Strongly disagree respondents (varied n)	• Preference for traditional learning: 31% (n = 21) strongly disagreed with preferring traditional methods over the non-traditional format (Question 5) • Limited learning value: 45% (n = 30) strongly disagreed that they did not gain valuable knowledge from the assignment (Question 10)

- For the full visual distribution of response categories (Strongly Agree, Agree, Disagree, Strongly Disagree), see Figure 3.5.

3.5 Discussion, recommendations and conclusion

The results from the previous section highlight both the potential of students and the challenges in digitising tidal data, which affect broader data rescue efforts. While many students successfully digitised tidal data in all phases, several encountered challenges, including issues with software calibration, Excel formatting and mixing up overlapping traces in Phase 2B. In Phase 1, which focused on extracting daily high and low tidal points, some students incorrectly identified these points, especially on days with three tidal points instead of four. These challenges compromised data accuracy and quality, emphasising the need for targeted interventions. This study presents preliminary digitisation error estimates as a first step towards a detailed, station-specific error budget for historical tidal data. We compared student digitisation results from Kilrush and Dún Laoghaire Harbour training datasets with predicted tides and validated historic Dún Laoghaire records against a trusted reference (McLoughlin et al., 2024b). A 1 cm target accuracy was set for synthetic training data. Residuals from one student's Kilrush digitisation (Phase 1), shown in Figure 3.6, ranged from −0.83 cm to +0.47 cm, with a standard deviation of ~0.33 cm. Absolute errors – mostly classified as 'Acceptable (Minor Revision)' (<5 cm) as shown in Figure 3.4 – provide a quantitative framework for accuracy, reflecting the performance of students whose errors typically remained within ±1 cm overall in the training datasets.

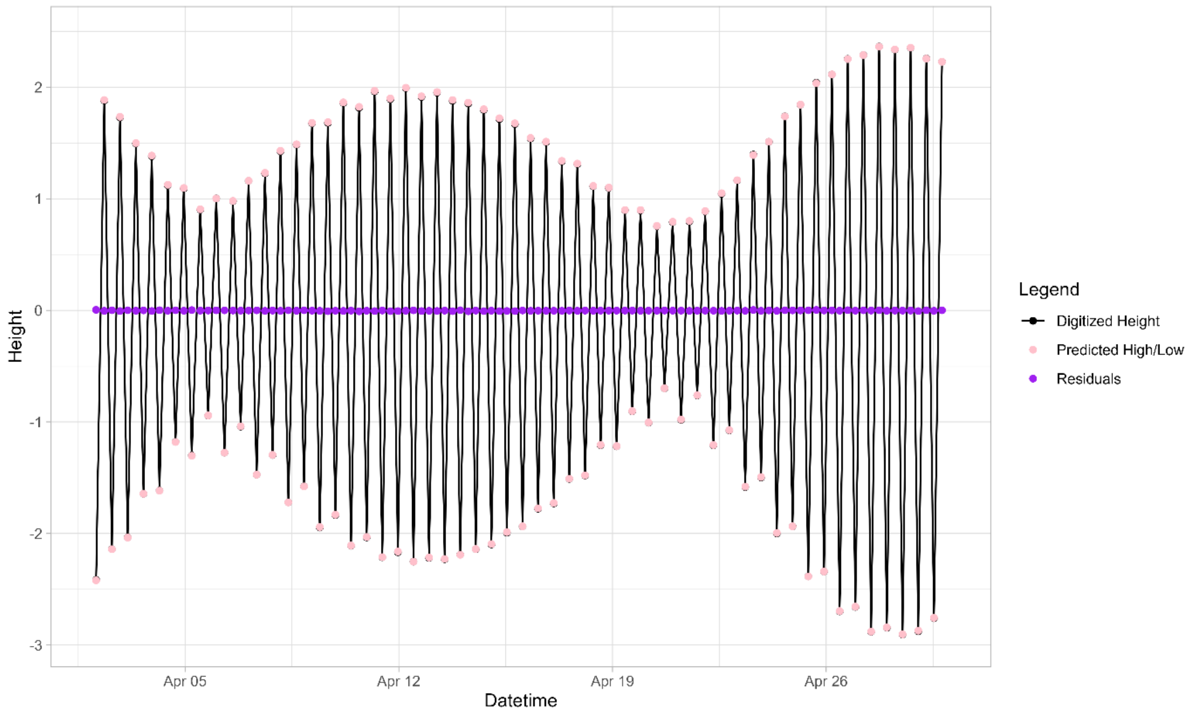


Figure 3.6: Comparison between digitised high and low tide points from a student's digitisation (black dots, almost fully hidden beneath pink dots due to excellent accuracy) and predicted tide levels (pink dots) at Kilrush Harbour. Purple dots represent the residuals – the quantitative differences between predicted and digitised values – offering a clear visualisation of the error distribution. This residual analysis supports preliminary estimates of digitisation error and serves as an initial step towards developing a station-specific error budget.

Preliminary comparisons showed that student digitisations of synthetic data had errors under 1 cm, while historical tide record digitisations – validated against available archival station records – had errors between 1 and 3 cm due to image quality. A 1 cm target was set for training data, with up to 3 cm considered acceptable for historical images. However, 1 cm remains the ideal accuracy for historical sea-level data, which require distortion corrections (McLoughlin et al., 2024a). This study addresses digitisation errors only, excluding datums or tide gauge calibration uncertainties.

Previous studies reinforce these findings and underscore the importance of precise digitisation. Wöppelmann et al. (2008) demonstrated the long-term stability of the Brest tide gauge through benchmark and datum continuity analysis, highlighting the importance of reliable physical reference systems for ensuring the integrity of historical sea-level records and, in turn, the need to minimise digitisation errors when working with such datasets. Talke et al. (2020) reported early tidal records with uncertainties of several centimetres, often due to outdated systems or degraded reference points. Even with modern tools, uncertainty estimation remains essential for quality control. McInnes et al. (2024) showed that common student digitisation errors can be detected and corrected by comparing results with predicted tides.

Future work should create detailed error budgets for each station and time period by combining student digitisation results with historical data uncertainties. A dynamic error model – tracking how uncertainty varies over time or by source – can inform re-digitisation priorities and data confidence. These insights are crucial for Bayesian analyses, where the quality of the data influences the assumptions built into the models. The error budget presented here lays the groundwork for this broader effort.

Training individuals in the accurate digitisation of historical tidal records is crucial for reconstructing long-term sea-level trends that directly inform climate change assessments, weather variability studies and coastal adaptation planning. These high-quality datasets enhance understanding of climate-driven sea-level variability and extreme weather phenomena, such as storm surges, while complementing other environmental datasets — including fluvial records, barographs, thermographs, and rain-charts — thereby supporting integrated modelling and enhancing predictions of diverse climate and weather hazards.

Based on our findings, with 63% success in Phase 1, 69% in Phase 2A and 56% in Phase 2B producing acceptable work (with minor revisions), it is clear that most students grasped the task through the workshops and online tutorials. The findings indicate that prior training provided a modest performance boost, but students without previous experience still performed nearly as well, demonstrating the overall effectiveness of the training programme.

Digitising tidal data (marigrams) is more complex than digitising other types of data, such as tabulated records, due to the intricate nature of tidal curves and overlapping traces. However, both data types require precise identification of key turning points, such as high and low tides, where accurate timing is critical. Overall, these error patterns provide a structured indication of where targeted training and workflow refinements can reduce future digitisation errors. This greater complexity highlights the technical challenges of working with graphical data, a contrast to previous studies focused on transcription-based data (Ryan et al., 2018; Mateus et al., 2020; Mateus et al., 2021). This type of data may require more pretraining and error-checking to achieve success rates comparable to more established data rescue initiatives (Hawkins et al., 2019).

To address these challenges, educational institutions should provide structured digitisation training for complex datasets. Strengthening collaborations, fostering interdisciplinary learning (Aryee et al., 2025) and securing funding will enhance quality and reach. Automated error-checking and tutorial videos would further improve accuracy and efficiency. Effective training and standardised protocols are essential to maintain data integrity (van der Velde et al., 2017).

We have established a model for digitisation, where the student or citizen scientist first digitises training tidal data images, followed by real historical images from Dún Laoghaire. If successful, the user progresses to digitising real data; if not, they revert to the training data (Figure 3.7). These data are systematically benchmarked against known answers, ensuring reliable quality checks.

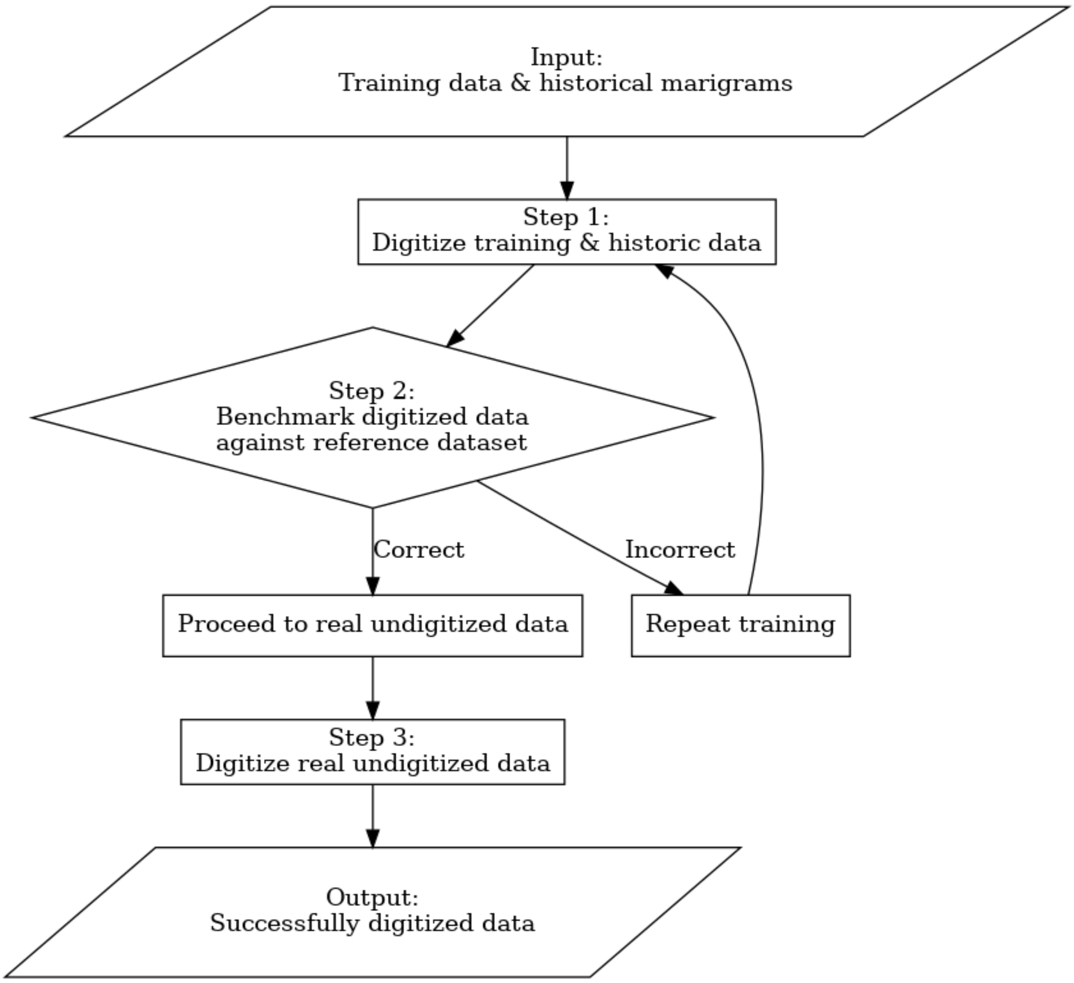


Figure 3.7: A workflow chart illustrating the digitisation process, including training, benchmarking against reference datasets and progressing to real data digitisation based on accuracy.

This methodology applies to three key areas: (1) digitisation projects that offer resources and methods to train students, citizen scientists, or professionals; (2) educator-led training exercises that provide hands-on experience with digitisation techniques; and (3) the structured preparation of datasets that may support future automation efforts. While not implemented in this study, future work could explore machine learning techniques – particularly image recognition – as a tool to assist with automated feature extraction in marigram digitisation. Such tools could complement manual workflows by increasing efficiency and consistency. However, the complexity and variability of historical marigrams currently pose challenges for automation, and further research is needed to assess feasibility. Due to current complexities, machine learning development is beyond the scope of this study but remains a promising avenue for future research. Student feedback from our questionnaire for Phase 1 indicates that the learning resources were valuable, helping them develop critical skills and insights. However, to ensure digitisation projects produce meaningful climate datasets, more intensive training and resources are needed. Training focused on digitising daily high and low tidal points (astronomical tides) and hourly intervals. Students were not asked to analyse non-tidal residuals like storm surge, which cause real deviations from predicted tides, and so were not guided to distinguish these from digitisation errors. Future materials should address this to better interpret and link such deviations to weather events. Integrating citizen science frameworks into research and educational activities, and partnering with professionals or retirees, can enhance engagement and support research on storm surges, sea-level rise, and climate change.

While 84% of students felt more motivated, 93% expressed interest in this assignment as a model for future work, suggesting sustained engagement with data rescue activities. The student perceptions observed in this study align closely with findings from other climate data rescue projects (Ryan et al., 2018; Mateus et al., 2021). Similar to previous studies, students found the assignment engaging, gained practical experience with historical data, and valued the structured tutorials. Additionally, 96% of students agreed that the task helped them develop key digitisation skills. The perceived novelty of the task, clarity of instructions, and practical skill development reflect the positive outcomes reported in the earlier studies. These parallels arise from structured guidance and clear instructional support. Consistent with Ryan et al. (2018) and Mateus et al. (2021), these findings highlight that providing structured templates, clear instructions and supportive tutorials reduces errors, enhances skill development, and sustains engagement in climate data rescue activities. This study did not include formal pre- and post-assessments. Future research could incorporate such methods to more rigorously evaluate student learning outcomes – particularly in tidal processes, data interpretation and the climate relevance of historical datasets.

A case study from the Williamstown tide gauge in Port Phillip Bay, Melbourne, illustrates the value of comprehensive training (McInnes et al., 2024). This study extended historical sea-level records by nearly 100 years, yielding valuable insights for sea-level trend analysis and climate adaptation planning. While this success highlights the potential of student-led digitisation projects, our findings suggest that achieving comparable outcomes would require more extensive training.

To ensure that digitisation projects involving complex tidal data contribute meaningfully to climate research, it is essential to adopt a comprehensive training approach. Systematic error-checking is also crucial to maintain high data quality. We have developed a training method applicable to students, citizen scientists and educators, which may also support future machine learning model development – a step currently limited by the complex visual nature of marigrams. Refining this approach and fostering collaboration among participants will enable future digitisation efforts to preserve high-quality historical tidal data and deepen our understanding of sea-level trends and climate impacts. By improving digitisation accuracy through targeted training, this approach strengthens the foundation for producing reliable climate and weather data from historical archives, crucial for climate resilience research.

4. A Century of Mean Sea-Level Change in Ireland (1925-2024)

Understanding mean sea level (MSL) change is crucial for assessing coastal vulnerability and guiding adaptation planning, particularly by identifying regions most at risk. Central to this understanding is the availability of long-term sea-level data. In Ireland, digitized records longer than 40 years are rare and mostly confined to the northeast; however, data archaeology—including the digitization of historical marigrams—can fill spatial and temporal gaps where undigitized records exist. Previous studies have focused primarily on individual sites in the north and east. Here we show that integrating previously undocumented records from the southwest with well-documented datasets provides a comprehensive assessment of MSL change across the country. We find clear regional variability, with the highest mean rates in the south and west. Long-term mean instantaneous rates, derived from a mixed-effects Generalized Additive Model (NI-GAM), vary systematically between regions, reflecting coherent spatial patterns in relative sea-level change. The model estimates rates from the posterior predictive distribution and captures structured spatio-temporal variability through a dominant regional component and site-level deviations, while accounting for observational uncertainty. Rates range from ~0.40 mm yr^{-1} at Belfast to 3.29–3.59 mm yr^{-1} at Cork and Tarbert in the south and southwest. The regional mean modelled instantaneous sea-level rise rate over 1925–2024 is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01), with an increase from approximately 1.20 mm yr^{-1} (95% CrI: 0.58–2.07 mm yr^{-1}) during 1925–2000 to 4.58 mm yr^{-1} (95% CrI: 3.34–5.57 mm yr^{-1}) during 2000–2024. After applying atmospheric and datum adjustments and accounting for GIA within a Bayesian framework, these historical records provide a robust basis for reconstructing regional sea-level rise and contextualising future coastal risk.

4.1 Introduction

Mean Sea Level (MSL) is the long-term average height of the sea surface at a given location, calculated over a period sufficient to smooth out short-term variations such as tides, storm surges, and weather (Hünicke et al., 2015; Pugh & Woodworth, 2014). Globally, mean sea level has risen at approximately 3–4 mm yr^{-1} over recent decades, with satellite altimetry showing ~3.3 mm yr^{-1} over 1993–2021 and ~4 mm yr^{-1} over 2006–2016 (Hamlington et al., 2024; Llovel et al., 2023). Evidence further indicates an accelerating trend, from ~2.1 mm yr^{-1} in the early 1990s to ~4.5 mm yr^{-1} in 2023 (Hamlington et al., 2024). If this trend continues, an additional ~169 mm of global sea-level rise could occur over the next three decades, consistent with mid-range projections from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (Hamlington et al., 2024). Understanding MSL changes from tide-gauge and archival data is essential for quantifying long-term trends and interactions with tides, storm surges, and extreme events, providing critical information for coastal planning and adaptation at global and local scales (Talke et al., 2018). However, the magnitude and expression of these changes are strongly influenced by regional and local factors. In Ireland, coastal cities such as Cork and Galway are highly vulnerable to flooding. In 2009 a major flood event in Cork led to around €100 million of damages to commercial and residential property (Olbert et al., 2017). Annual economic damages from coastal flooding in Britain are currently estimated at approximately £360 million and are projected to increase two- to threefold by the end of the century (Haigh et al., 2022). Approximately 40% of Ireland's population lives within 5 km of the coast, including major cities (Wall et al., 2020), making coastal areas highly vulnerable. Given Ireland's similar coastal exposure and geographical position, it is also likely to face significant costs and challenges.

Ireland has a modern network of over 40 tide gauges through the National Tide Gauge Network (NTGN), installed in the 2000s and managed by the Office of Public Works (OPW) and the Marine Institute (MI) (Cámaro García et al., 2021). However, only a few sites, including Malin Head, Dublin Port, and Belfast, provide long-term (>40 years) continuous records, which are incorporated into the Permanent Service for Mean Sea Level (PSMSL) data set (Holgate et al., 2013). Digitized historical series are concentrated in the north and east of the island, including Malin Head (1958–2002; Holgate et al., 2013, extended to the present with MI and OPW data), Dublin Port (1938–present), and Belfast (1901–2010; Murdy et al., 2015, Figure 4.1), whereas records along the south and west coasts are sparse and often of relatively short duration. This uneven geographic coverage makes it difficult to detect regional trends in MSL, as large portions of the coast remain unmonitored. A minimum of 40 years is generally required to robustly determine trends in MSL (Hogarth et al., 2021). Recent work in Britain shows the benefits of systematically recovering and integrating historical tide-gauge data into a unified framework and has yielded a robust two-century MSL curve, reduced uncertainties, and revealed long-term accelerations. Similar historical data rescue and integrated analyses across multiple Irish sites are needed to overcome the limited spatial and temporal coverage of existing records.

Tide gauges record Relative Sea Level (RSL), the height of the sea relative to the land on which they sit. Land levels (relative to the centre of the Earth) can change due to geological processes, of which Glacial Isostatic Adjustment (GIA) is the only one that can be modelled globally (Tamisiea and Mitrovica, 2011; Bradley et al., 2011). Across Ireland, RSL change varies markedly, with lower rates in the northeast and higher rates in the southwest, primarily due to GIA (Bradley et al., 2011). During the Last Glacial Maximum, the thickest ice extended from Scotland into Northern Ireland, thinning toward the southwest (Scourse et al., 2021). Following deglaciation, collapse of the forebulge caused land subsidence in the southwest and uplift in the northeast, producing spatial contrasts in RSL trends, including localized sea-level fall in parts of the northeast. Quantifying these impacts is complicated by the range of outputs among available GIA models, including variability within individual subfamilies. Understanding past ice-sheet dynamics is therefore critical not only for explaining historical RSL variations across Ireland but also for refining GIA models, thereby enhancing predictions of future sea-level rise (Clark et al., 2022; Bradley et al., 2023). This is particularly important on the island of Ireland, where regional differences in land movement and sea-level response make accurate projections essential for coastal planning. GIA models differ due to variations in ice-sheet histories, Earth rheology assumptions, and differences in spatial and temporal resolution and calibration approaches (Bradley et al., 2023). GLAC1D (1D Glacial Model) uses physics-based, glaciologically self-consistent ice-sheet simulations (Tarasov et al., 2012), whereas ICE-6G (Ice Sheet model version 6G) models are tuned to fit global RSL and crustal motion observations (Peltier, 2015). Regional Bradley-type models, including those based on BRITICE-CHRONO reconstructions, are specifically calibrated to British–Irish RSL and GNSS (Global Navigation Satellite System) datasets (Bradley et al., 2023). These differences strongly influence predicted vertical land motion rates, as demonstrated by studies showing high sensitivity to upper-mantle viscosity and uncertainties in deglaciation histories (Bradley et al., 2011; Bradley et al., 2023). Consequently, modelled uplift rates can vary substantially, meaning the choice of GIA model can affect corrected sea-level trends.

In this paper, we aim to gather sea-level data from across Ireland, including the south and west where records are sparse, to improve understanding of both MSL changes and the influence of GIA. The objectives are to:

i) Integrate and analyse new records from the south and southwest to investigate MSL changes in regions with limited long-term observations.
ii) Reconstruct the historical MSL for Ireland using quality-assured sea-level data.
iii) Evaluate the effect of applying deterministic GIA corrections on regional sea-level trends.
iv) Contextualize historical MSL changes across Ireland and evaluate their implications for vulnerable coastal areas.

4.2 Data Collection and Digitization

The six sites analysed in this study are Belfast Harbour, Malin Head, Dublin Port, Cork, Galway, and Tarbert (Figure 4.1). Supplementary records from nearby gauges were also included where available—for example, Bangor (supplementing Belfast), Portrush (supplementing Malin Head), Kilrush Lough (supplementing Tarbert, officially Tarbert Island), Galway (supplementing Galway Harbour for 1967–1970), and Arklow Harbour, Howth Harbour, and Dún Laoghaire Harbour (supplementing Dublin Port). By integrating data from multiple sources, this study fills key gaps and provides new insight into spatial variability in sea-level trends.

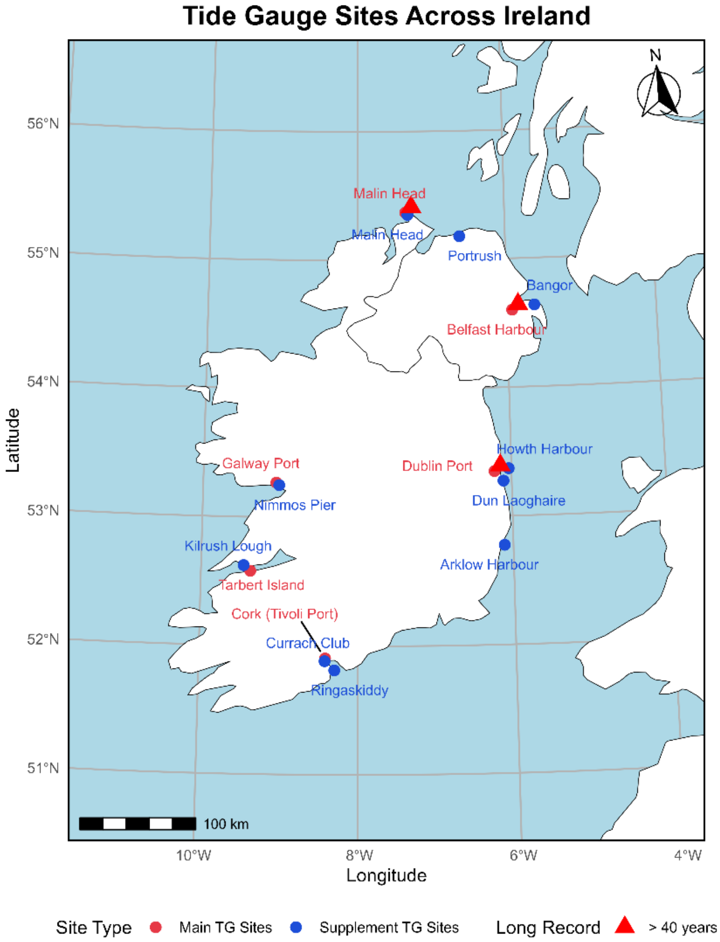


Figure 4.1: The six primary tide-gauge (TG) sites are shown in red. Supplementary TG sites, shown in blue, are located near the main TG sites (red) and are used to fill gaps or improve record quality. Long-record sites (>40 years; Belfast Harbour, Dublin Port, and Malin Head) are indicated with red triangles, with records spanning 60–100 years.

Tide-gauge data were obtained from the Permanent Service for Mean Sea Level (PSMSL, Holgate et al., 2013), a key global repository of sea-level observations. Mean Tide Level (MTL) records were obtained from the PSMSL repository for the periods used in this study. MTL is defined as the average of Mean High Water (MHW) and Mean Low Water (MLW) and can differ slightly from Mean Sea Level (MSL) (Woodworth, 2017). For the purposes of this study, MTL is treated as equivalent to MSL. The following sites were included:

- Malin Head (1958–1995); higher-resolution data are available in the Global Extreme Sea Level Analysis (GESLA) database, but their quality has not been independently verified.
- Bangor (2011–2015).
- Portrush (1996–2015).
- Dublin Port (1938–2001).

Modern data for Malin Head were obtained from the Office of Public Works (OPW, 2004–2008) and the Marine Institute (MI, 2009–2024).
The PSMSL holds a Mean Tide Level (MTL) record for Belfast Harbour, but it does not extend beyond 1963. For this study, we used the 1902–2010 Belfast dataset digitized by Murdy et al. (2015), which provides high-resolution 10-minute intervals for most of the record, except for 1990–2000, which is provided at hourly intervals.

Historical data for Dún Laoghaire Harbour (formerly Kingstown) spanned 1925–1931 and were obtained from McLoughlin et al. (2024). Data for two additional years (1932–1933) were recovered from raw marigrams; however, these records are less reliable due to thicker, less accurate traces—particularly in 1933, when frequent clock stoppages affected the data. Only the months of June to August in each year were digitized. Marigrams were digitized at hourly intervals using WebPlotDigitizer (Rohatgi, 2024), employing the full-grid method described by McLoughlin et al. (2024) for severely distorted images, achieving an estimated accuracy of approximately 1 cm.

Data for Dublin Port, updated and corrected for bias in modern observations, were available as yearly means (Shoari Nejad et al., 2022). For this study, we used the Dublin Port record spanning 1938–2001. Tide-gauge observations after 2001 exhibit considerable divergence, suggesting potential instrument malfunction and reduced reliability. To ensure continuity and extend spatial coverage, modern sea-level data from the NTGN were added to the Dublin Port record, comprising measurements from Arklow (2003–2006; managed by the OPW) and Howth (Dublin, 2007–2024; MI).

In the far west of Ireland, tidal records for Galway (1967–1970), near Nimmo's Pier, were obtained from the British Oceanographic Data Centre (BODC) archive (BODC, 2025). The dataset contained both Julian Day and human-readable calendar dates (yyyy-mm-ddThh:mm:ss) at hourly intervals; these were converted to a standard datetime format for analysis. Data for 1967 and 1970 were incomplete. Tide-gauge data for Galway Port were obtained from the NTGN (MI; 2007–2024).

For all sites, all datasets except the PSMSL MTL monthly means were extracted at hourly intervals for consistency, and all digitized data originally in feet were converted to metres.

4.2.1 Cork Harbour

To the southwest of Ireland, tide-gauge data for Cork Harbour were obtained from Port of Cork engineers and archival reports. The dataset includes measurements from Tivoli Port for 1971–1974 and 1976/1977, 1981–1984, and more recent records from a modern tide gauge for 2001–2005 and 2010–2011. The 2001–2005 and 2010–2011 Tivoli records were already available digitally and therefore did not require manual digitization. The 1970s and 1980s records were in marigram (pencil trace) format (Figure 4.2), with measurements spanning 06:00 am–06:00 am the following day in most images. They were digitized at hourly intervals using WebPlotDigitizer (Rohatgi, 2024) with the reduced grid method described by McLoughlin et al. (2024), achieving an accuracy of approximately 1 cm (0.01 m) per measurement.

Complementing these data, tide-gauge measurements spanning several months, from October 1976 to January 1977, were obtained from a Cork Harbour pollution report for Monkstown (O'Sullivan, 1977). These pen-trace records were digitized at hourly intervals, with time steps from 00:00 to 23:00 (i.e., 24 hourly values per day). All data were standardized to hourly intervals for consistency. Modern OPW tide-gauge measurements from Ringaskiddy (2012–2021) and Currach Club (2022–2024) were included in the record.

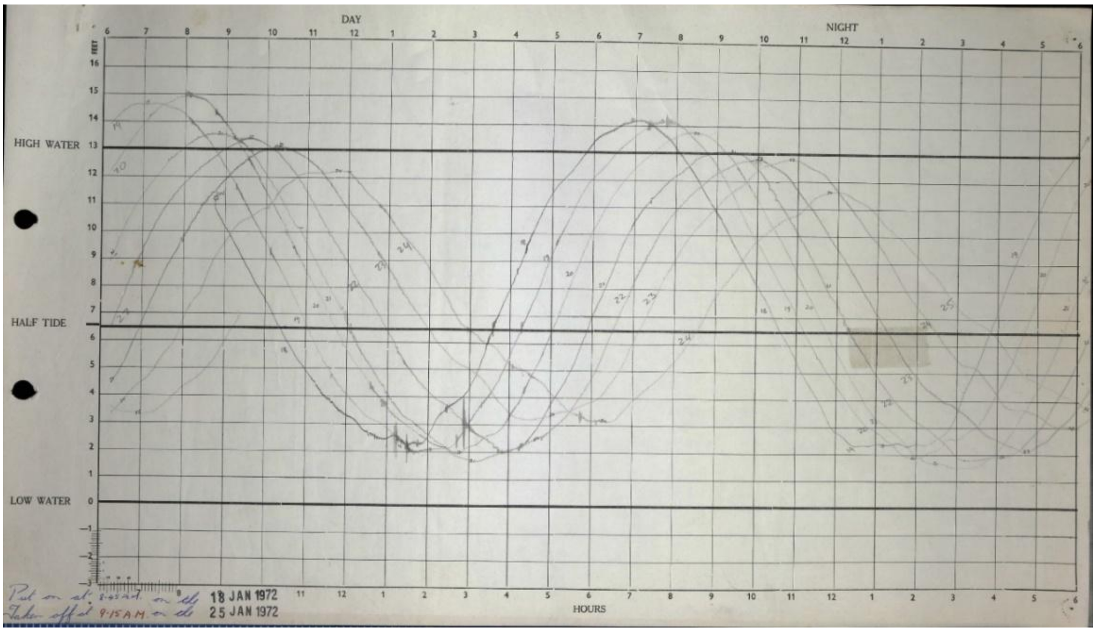


Figure 4.2: Example of a Cork marigram with a pencil trace. The X-axis represents time from 06:00 am–06:00 am the following day, and the Y-axis shows water level in feet relative to chart datum. Dates are indicated above the pencil traces. Data courtesy of Port of Cork engineers (personal communication, 2022).

4.2.2 Tarbert Island

An additional dataset spanning 1964–1986 for Tarbert Island, Kerry, representing the longest tide gauge record from the southwest of Ireland included in this study, was provided in feet (1964–1977) and metres (1979–1986) relative to OD Poolbeg, with data from 1978 omitted due to extensive gaps and poor quality. Timing offsets were noted throughout the digitization process but were generally minor and tended to balance out overall. Some handwritten notes were difficult to interpret, and the data were therefore left unchanged, as they appeared in only one or two images. In rare cases of duplicate-dated traces, where uncertainty existed regarding the correct trace, only one was retained. Additionally, some dates were estimated when information was absent. While these instances could affect dataset accuracy, they are fully documented for transparency (Figure 4.3A–D). Figure 4.3A shows marigrams spanning up to one month, an issue also reported by Latapy et al. (2023) when tide sheets were not changed regularly; such records were excluded from digitization. In future work, AI-based methods could potentially separate overlapping traces to enable digitization of longer marigrams.

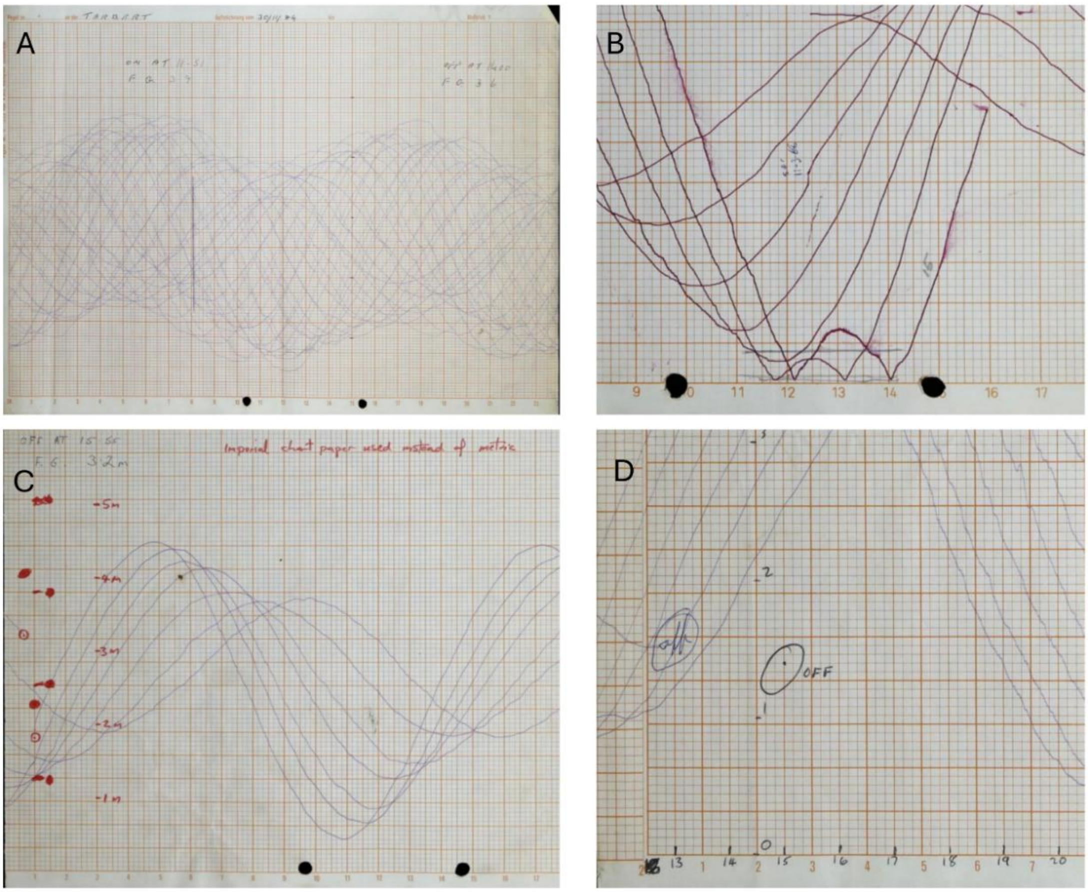


Figure 4.3: Examples of marigrams requiring careful digitization: (A) Tarbert marigram spanning nearly one month, making accurate digitization nearly impossible; (B) Daily low tides intercepting or approaching the X-axis, requiring manual correction; (C) Variations in graph paper type and unit scaling, with conversion factors indicated (e.g., one metre = four or 3.2 grid boxes); (D) Visible timing offsets requiring alignment corrections based on handwritten X-axis annotations. Data courtesy of the OPW (personal communication, 2024).

The Tarbert dataset presented significant challenges, particularly timing offsets and related errors. Traces at the beginning or end of marigrams were occasionally discarded if severely misaligned with the hourly grid, even when the opposite end aligned correctly. Testing marigrams from 1964 and 1965 revealed deviations from the correct hourly intervals; however, the mean offset per marigram was typically within 1 cm.

Marigrams from the 1960s and 1970s often exhibited low tides that touched or nearly touched the X-axis before rebounding upward (Figure 4.3B). In these cases, manual correction was applied: the difference between the rebound peak and the base point on the X-axis was measured and subtracted to improve tidal estimates. This issue was absent after 1979, when data were digitized in metres relative to Ordnance Datum Dublin (ODD) rather than feet. On imperial chart paper, one metre was represented by four grid boxes, whereas on metric chart paper, the spacing of the grid resulted in roughly 3.2 boxes per metre (Figure 4.3C). This difference reflects the design of the chart grids, not a scaling error.

Timing offsets between the recorded hour and the digitized hourly grid occasionally caused recorded times to deviate by up to ~30 minutes (Figure 4.3D). Analysis of each marigram showed that the corresponding mean water-level offset remained well within 20 mm, within the allowable margin between digitization and instrumentation. Because MSL is computed as a temporal average over extended periods, encompassing many tidal cycles, these temporal misalignments have a negligible effect on MSL calculations, rendering the dataset suitable for MSL analysis.

The tidal images were generally of excellent quality and were digitized using WebPlotDigitizer (Rohatgi, 2024). Although some manual adjustments were necessary, where handwritten notes or other anomalies occurred, most of the data—despite bends in the images—could be digitized directly without employing the grid or reduced grid method described by McLoughlin et al. (2024). The digitization process itself introduced an uncertainty of approximately 1 cm; however, accounting for additional factors such as timing offsets and necessary adjustments, an overall uncertainty of ±2 cm was assigned to the Tarbert dataset. For Tarbert, nearby Kilrush Lough data (2018–2024) were incorporated into the record to provide modern observations, owing to the close proximity and similar tidal characteristics.

4.3 Datum Conversions

Sea-level data for all sites were adjusted to Ordnance Datum Malin (OD Malin; sometimes referred to as ODM). Records reported relative to Ordnance Datum Belfast (OD Belfast) or Ordnance Datum Dublin (ODD, i.e., OD Poolbeg) were converted to OD Malin.

For Malin Head, the PSMSL Revised Local Reference (RLR) data were first converted from millimetres to metres. A PSMSL RLR datum offset of 3.977 m was applied to convert the data to metres, following the station-specific RLR procedure, and an additional datum correction of 3.136 m was applied based on the OPW OD Malin datum information valid up to 2018. The Malin Head benchmark offset of 3.06 m was not used, as it aligns the series only to the local benchmark and not fully to the national OD Malin vertical datum. These corrections, with a total adjustment of 7.113 m, align the RLR series with both the local tide-gauge benchmark and the OD Malin datum, bringing the data accurately to OD Malin. These adjustments are of critical importance for accurate sea-level reconstruction and rely on detailed historical documentation to ensure reliability.

In Belfast, a datum of −2.01 m (National Tidal and Sea Level Facility, 2025) was used to convert data from Chart Datum (CD) to OD Belfast. To convert from OD Belfast to OD Malin, an additional 0.037 m was applied, reflecting the average difference between Malin Head and Belfast (Prendergast, 2004). For Portrush, 8.600 m, with an additional 1.604 m and 0.037 m, was added to reference OD Malin. Similarly, Bangor data were adjusted by subtracting 10.500 m, adding 3.582 m, and adding 0.037 m to convert to OD Malin.

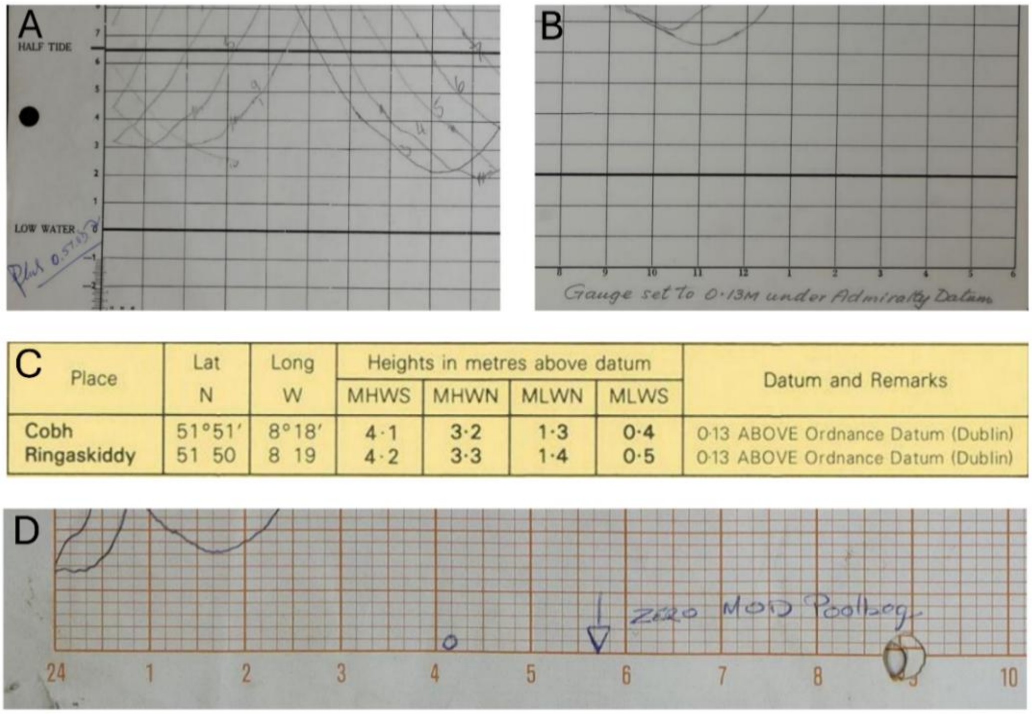
To the east of Ireland, the Dún Laoghaire sea-level data were adjusted following McLoughlin et al. (2024). The local datum of 2.722 m, minus the chart datum of 1.75 ft (0.533 m), results in a 2.189 m correction to convert the data to OD Malin. This correction is applied to all available Dún Laoghaire records. Similarly, the Dublin Port PSMSL data (1938–2000) were converted to OD Malin using benchmark adjustments: subtracting 6.017 m from 10.594 m below the primary benchmark (BM, TGZ 1978), adding 0.238 m (difference between BM 1895 and TGZ port datum 1977), subtracting 0.436 m (1938–1977 relative to Port Datum, 0.436 m above Poolbeg OD), and adding 2.722 m (Dún Laoghaire datum). These steps resulted in a final correction of 7.101 m, applied to bring the PSMSL data to metres above OD Malin.

All Cork data were adjusted to OD Malin following the procedure outlined below. Historic records at Tivoli and Monkstown, originally tied to Ordnance Datum Dublin (ODD), were converted to OD Malin using the 2.752 m datum established by Pugh et al. (2021), which links ODD values to OD Malin through nearby benchmark levelling. Prior to conversion, site-specific adjustments were applied:

- For the 1970s Tivoli records, a correction of +0.174 m (0.57 ft) was applied based on contemporary notes (Figure 4.4A).
- For the 1980s Tivoli data, a correction of –0.13 m was applied, consistent with gauge documentation indicating the instrument was set 0.13 m below Admiralty Datum; this offset provided the best alignment with regional tide records (Figure 4.4B).

Modern Tivoli data from the early 2000s were adjusted by +0.13 m to bring values to OD Malin (Irish Water, 2005) (Figure 4.4C). After these corrections, all Cork datasets were successfully adjusted to OD Malin.

In the absence of a site-specific datum for Tarbert, the records indicate that the data are assumed to be referenced to ODD (Ordnance Datum Poolbeg; Figure 4.4D). Using this assumption, nearby datums were considered: Shannon is 2.705 m above ODD and Ballybunion is 2.704 m above ODD (OPW, personal communication, 2024). Based on this consistency, a correction of 2.705 m was applied to convert the Tarbert data to metres above OD Malin.



Place	Lat N	Long W	Heights in metres above datum MHWS	MHWN	MLWN	MLWS	Datum and Remarks
Cobh	51°51′	8°18′	4·1	3·2	1·3	0·4	0·13 ABOVE Ordnance Datum (Dublin)
Ringaskiddy	51 50	8 19	4·2	3·3	1·4	0·5	0·13 ABOVE Ordnance Datum (Dublin)

Figure 4.4: Datum adjustments applied to Cork (Tivoli) and Tarbert sea-level records at different periods: (A–C) Tivoli data—(A) 1970s corrected by +0.174 m (0.57 ft), (B) 1980s corrected by −0.13 m, consistent with gauge documentation and regional tide alignment, (C) early 2000s adjusted by +0.13 m to Ordnance Datum (Irish Water, 2005); (D) Tarbert records shown relative to ODD (0 m, OD Poolbeg). Note: 1964–1977 data were originally in feet relative to OD Poolbeg. (A–B, courtesy of Port of Cork engineers, personal communication, 2022; C, Irish Water, 2005; D, data courtesy of the OPW, personal communication, 2024).

For Galway, a datum correction of 2.732 m (OPW, personal communication, 2024) was applied to convert the data from ODD to OD Malin. BODC data for Galway, adjacent to Galway Harbour, show that the 1967 and 1968 records were reported in metres relative to mean sea level (MSL, denoted as 'ODN' in the BODC file) and can be directly referenced to OD Malin by subtracting 2.732 m. In contrast, the 1969 and 1970 records, also reported in metres, appeared higher than the 1967 and 1968 values. Metadata indicate that these records required a 3.048 m adjustment to align with the benchmark (TGZ; Table 4.1). After applying this adjustment, the 2.732 m datum was subtracted to reference all values to OD Malin.

Table 4.1: BODC metadata table showing datum relationships for Galway (BODC, 2025). Values from 1967–1968 are aligned with OD Malin (0.000 m offset). For 1969–1970, TGZ was −3.048 m; subtracting 3.048 m aligns these years with the earlier records.

Galway (Eire) Site History

Full site history and benchmark not yet available.

Datum Information

Year	Data rel to ACD	Data rel to ODN	Data rel to TGZ	TGZ rel to ODN	TGZ rel to TGBM	ACD rel to ODN
1967	0.201	0.000	0.000	0.000	not available	-0.201
1968	0.201	0.000	0.000	0.000	not available	-0.201
1969	-2.847	-3.048	-3.048	0.000	not available	-0.201
1970	-2.847	-3.048	-3.048	0.000	not available	-0.201

All modern sea-level data from the NTGN (OPW and MI) for the available sites were already fully referenced to Ordnance Datum Malin (ODM).

4.4 Validation of Tide Gauge data

All sea-level datasets underwent rigorous validation prior to inclusion in the MSL analysis. Monthly means for all non-PSMSL datasets were recomputed using the oce package (Kelley et al., 2022), which provides tools for tidal analysis and processing of oceanographic time series, ensuring consistent processing across the network. M2 tidal amplitudes and phase lags were calculated for all high-resolution datasets where temporal resolution allowed, based on the M2 constituent only, on a yearly basis. Where amplitudes or phase lags appeared unusually high or low, a monthly inspection was conducted to identify and flag poor-quality data. Statistical outlier detection was systematically applied across all sites by removing values exceeding ±3 standard deviations from the mean. Both M2 tidal constituents (amplitudes and phase lags) and z_0 (mean sea level) values were examined to identify and flag poor-quality observations, ensuring that all datasets incorporated into the MSL analysis were robust.

4.4.1 Validation of Tide Gauge Data: Historical and Modern Records

For the Belfast record, 1925 was chosen as the starting point instead of 1901–1902 because earlier records contained frequent gaps and inconsistencies, and to provide a 100-year overlap with the Dublin (Dún Laoghaire) record for robust comparison. The tidal record (Murdy et al., 2015; Figure 4.5) was generally consistent from 1925 to 1988, with M2 tidal amplitudes within ±0.1 m of 1.2 m and phase lags mostly between 325° and 326°. In contrast, the period 1989–2000 corresponds to operations of the Valeport BTH 700 tide gauge (TG4) at Milewater Basin, Belfast Harbour, during harbour redevelopments; these records required careful editing and validation before inclusion in the analysis. However, after omitting poor-quality or missing data, the dataset for this period was generally of good quality. Timing offsets were also identified and, where possible, corrected by adjusting certain years by one hour in specific months to improve temporal consistency.

The Bangor record (2011–2015; Figure 4.5) was used to fill gaps in the Belfast dataset due to the proximity of the stations. In Belfast, months with M2 tidal amplitudes exceeding 1.2 m by more than 0.1 m were flagged for exclusion, although no months actually exceeded this threshold. Statistical outlier detection further excluded monthly means exceeding three standard deviations from the overall mean, identifying February 1990 (Belfast) and December 2015 (Bangor) as outliers. While most months in 1985 (Belfast) did not exceed the ±3 standard deviations (SD) threshold, the annual mean (z_0) was ~0.2 m above all other years, indicating data quality issues; consequently, 1985 was excluded from further analysis.

The Malin Head record contains known data issues in the early 1990s (1992–1993), as documented by PSMSL. Hogarth et al., (2020) suggested that the Portrush record could serve as a more robust replacement for portions of the Malin Head data. Specifically, all of 1993 and the last three months of 1992 (October–December) were omitted from the Malin Head record, and Portrush data were used for 1996–2003 and 2015. Modern NTGN data for Malin Head (OPW, 2004–2008; MI, 2009–2024) completed the record. After removing the end of 1992 and 1993, statistical outlier detection was applied to further validate the data. Monthly mean values exceeding ±3 standard deviations from the station's overall mean were excluded. This led to the removal of February 1990 and April 2024. The verified Malin Head record is shown in Figure 4.5.

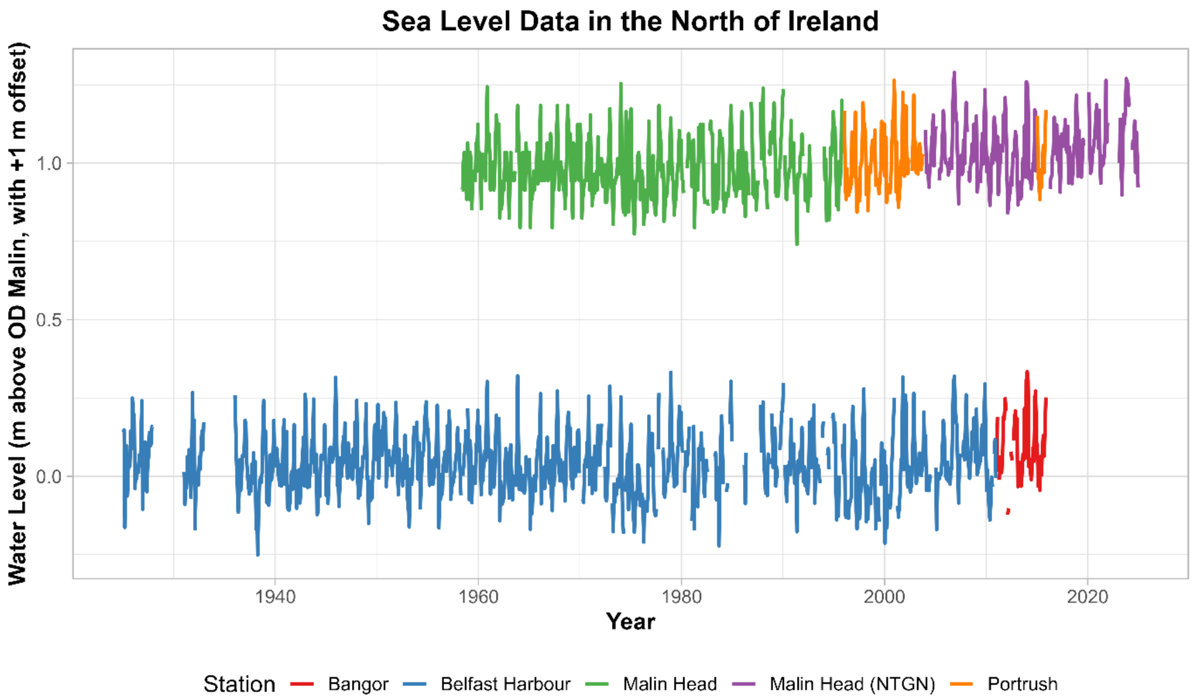


Figure 4.5: MSL for tide gauges in and around Northern Ireland, divided into two groups as described in the text. For clarity, Malin Head and Portrush records have been offset by +1 m relative to Belfast and Bangor, and all data are referenced to OD Malin. Bangor and Portrush records, used to supplement Belfast and Malin Head, are also referenced to OD Malin for consistency.

The Dublin Port tide gauge on the east coast (PSMSL, 1938–2001) exhibits unusual variations from the 1970s to early 1990s (Shoari Nejad et al., 2022). The timeseries for 1938–2001 is shown in Figure 4.6. Statistical outlier detection identified several potentially erroneous mean sea-level months—November 1960, July and December 1989, February and November 1990, and December 2000—which were subsequently removed from the analysis.

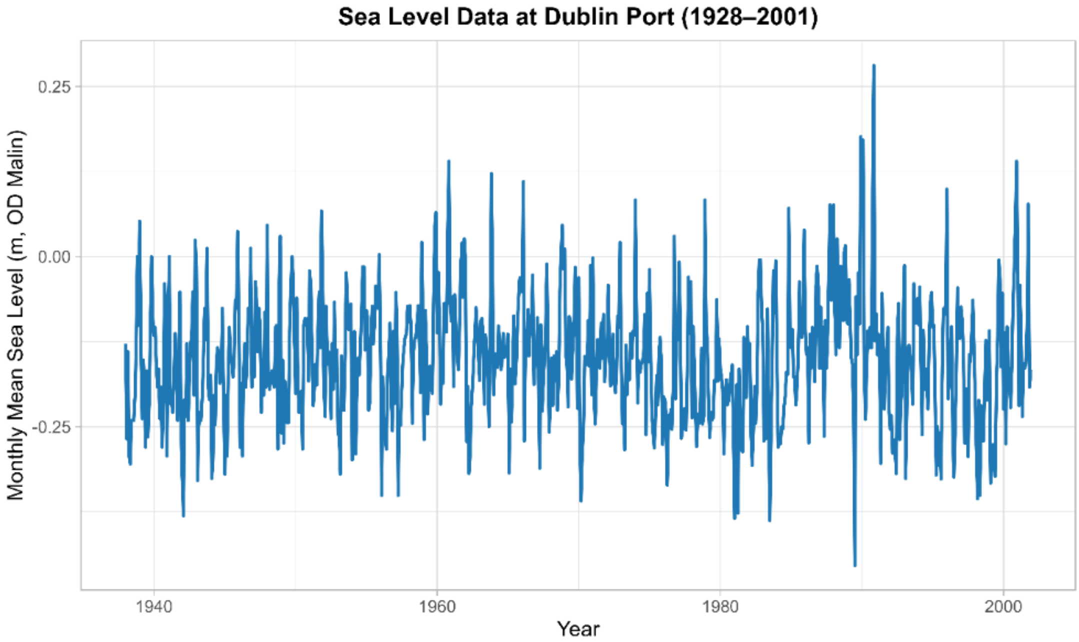


Figure 4.6: Monthly mean sea-level measurements at Dublin Port (1938–2001), showing periods of lower or higher monthly means, particularly from the mid-1970s to early 1990s.

Digitized Dún Laoghaire data for June–August 1932 and 1933 were of good quality, with amplitudes of 1.25 m and phase lags of 326.7° (1932) and 324.6° (1933), closely aligning with McLoughlin et al. (2024). No monthly mean exceeded three standard deviations from the overall mean.

To construct a near-continuous century-long record, modern sea-level data from NTGN OPW Arklow (2003–2006) and MI Howth (2007–2024) were integrated with the historical Dún Laoghaire (1925–1933) and Dublin Port (1938–2001) datasets. Monthly MSL were computed for all datasets, and the resulting values were largely consistent across the combined series. Only July 2024 from Howth was omitted due to a deviation exceeding three standard deviations from the mean.

For the south-west coast, the Cork dataset required several adjustments during validation, including computation of M2 amplitudes and phase lags. At Monkstown, only 1976 had a phase lag (153.1°) within the expected 144.4–154.1° range (Pugh et al., 2021). Tivoli initially showed phase lags of 167–175°, indicating a systematic daylight saving time (DST)-related offset, which was corrected by shifting timestamps back 1 h during late-March to October periods. Post-correction, Tivoli phase lags ranged between 150.9° and 153.8°. Only November and December 1982 were excluded, as their amplitudes fell outside the expected ~1.37–1.49 m range.

Modern Tivoli data (2001–2005, 2010–2011) generally agreed in amplitude (~1.37–1.49 m) and phase lag (~150.3°–160.2°). Outliers included 2001 (>185° phase lag) and slightly elevated 2002/2005 phase lags (~165.4°/162.5°), which were retained because their amplitudes fell within the expected range after exclusion of poor-quality months, leaving MSL unaffected.

NTGN OPW Ringaskiddy (2012–2021) and Currach Club (2022–2024) data were incorporated to further complete the Cork record. M2 amplitudes ranged ~1.40–1.49 m and phase lags ~144.6°–152.2°, consistent with Monkstown and Tivoli.

After initially checking the M2 amplitudes and phase lags to address any poor-quality data in the Tivoli and Monkstown datasets, and performing statistical outlier detection on all data up to 2024, no further potentially erroneous observations were identified, with all monthly means remaining within three standard deviations of the overall mean. The rectified Cork dataset is shown in Figure 4.7.

To assess tidal characteristics in the south-west of Ireland, two nearby sites, Tarbert and Kilrush Lough, were compared. Tarbert exhibited M2 amplitudes of ~1.55–1.66 m with phase lags of ~145.9°–156.2°, while Kilrush Lough (NTGN MI modern data, 2018–2024), located less than 11 km across the estuary, showed amplitudes of ~1.48–1.64 m and phase lags of ~144.6°–147.8°. Years with amplitudes outside these ranges were inspected. Any months causing deviations were excluded from the analysis, and if a year fell entirely outside the range, the whole year was excluded. This approach—inspecting years, excluding problematic months, and omitting entire years when necessary—was applied to all tide-gauge stations for which amplitudes and phase lags could be assessed.

Prior to direct comparison, the Tarbert dataset (1964–1986) exhibited systematic timing offsets, including a recurring one-hour discrepancy between late March and October due to uncorrected daylight saving time (DST), and a continuous one-hour offset from 1968 to 1970, expressed in GMT. Timestamps were corrected by shifting back one hour during DST periods and for the full years 1968–October 1971, resulting in the exclusion of approximately one hour of data per year.

Data from 1984–1986 were omitted because M2 amplitudes consistently fell below the expected range of 1.55–1.66 m, reaching 1.3–1.50 m; the corrected Tarbert time series is shown in Figure 4.7. For Kilrush Lough, four months in 2024 (January, February, September, and October) were omitted following M2 corrections and statistical outlier detection.

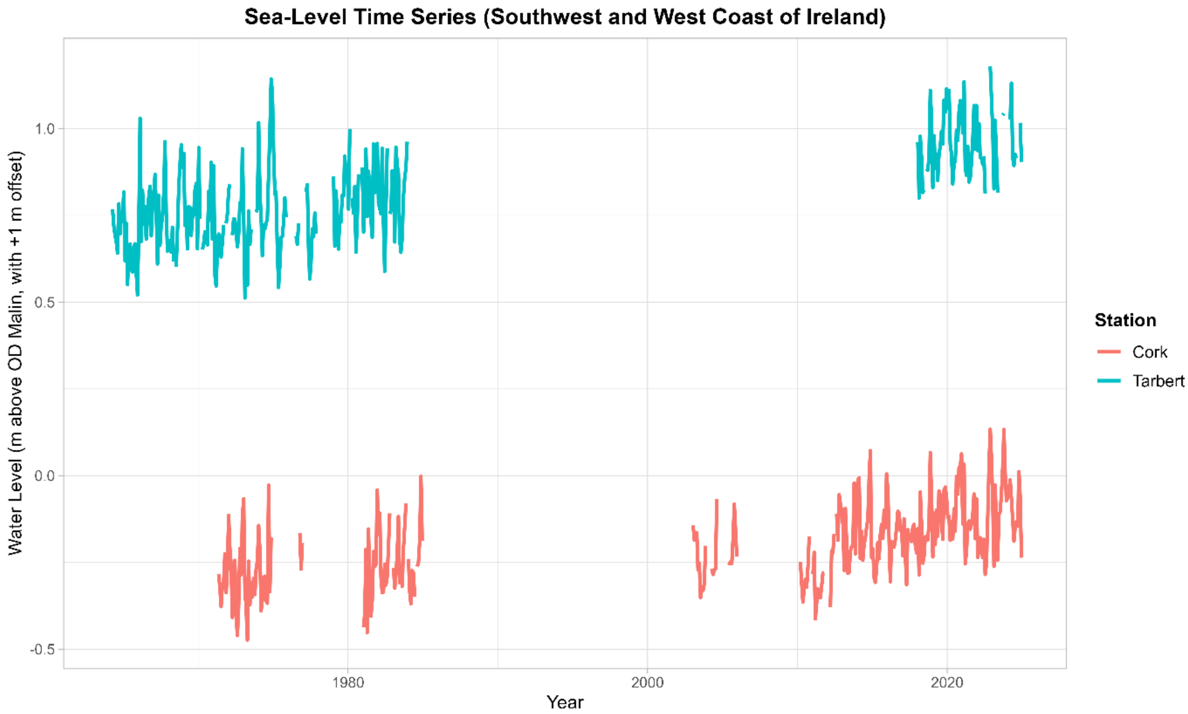


Figure 4.7: Sea-level data for Tarbert (1964–1983) and Kilrush Lough (2018–2024), merged into a single time series, and Cork sites (Tivoli, Currach Club, and Ringaskiddy), also merged into a single time series for display—adjusted to OD Malin and vertically offset by 1 m for clarity.

In western Ireland, the Galway record was assessed using both historical and modern datasets. The BODC data from Galway (1967–1970) were largely complete, with only a few hours missing on some days in 1968 and 1970; these were flagged as unreliable and excluded from the analysis. Modern Galway Port data (2007–2024) were supplemented with NTGN MI observations to fill gaps and ensure continuity in the historical record. Comparison of tidal harmonics between the 1967–1970 BODC dataset and modern Galway Port observations revealed only minor differences. M2 tidal amplitudes are slightly higher in the modern record (~1.46–1.59 m) than in the BODC data (~1.45–1.48 m), and phase lags differ slightly (~137.2°–142.3° vs. ~126.4°–128.8°), but overall the values remain in close agreement.

A summary of all tide gauges for which data were omitted due to poor quality and where supplementary data were incorporated is provided in Table 4.2.

Table 4.2: Summary of tide gauges with data omitted due to poor quality and where supplementary data were incorporated. Note: Years with fewer than three consecutive monthly observations were automatically discarded and may not all be explicitly listed.

Tide Gauge	Years/Months Omitted	Quality Issue	3-SD Outlier Detection Across Intervals	Supplement and Replacement Data
Malin Head	Feb 1990; Oct–Dec 1992 and 1993 omitted; 1996–2003 and 2015 replaced with Portrush data; Apr 2024 omitted (from 2003-2024 MI/OPW data). Portrush: Dec 2015.	Poor-quality data in the early 1990s; z_0 values exceeding three standard deviations from the mean.	PSMSL Malin Head (1958–2002); OPW Malin Head (2003–2008); MI Malin Head (2009–2024); Portrush (1996–2015).	Portrush PSMSL 1996–2003 and 2015; Malin Head OPW and MI 2003–2024.
Belfast Harbour	1985; Feb 1990; Dec 2015.	Amplitudes outside ±0.1 m of the M2 amplitude (1.2 m); z_0 values exceeding three standard deviations from the mean; potential datum control issues.	Belfast Harbour (1925–2010; outliers removed first); supplemented with Bangor (2011–2015) for final combined outlier detection.	Bangor PSMSL substituted for 2011–2015.
Dublin	Nov 1960; Jul and Dec 1989; Feb and Nov 1990; Dec 2000; Howth Jul 2024 (large spike, 3 SD from mean); Arklow Nov 2022 (used only to adjust Howth baseline in full record).	Monthly means (z_0) deviating by more than three standard deviations from the mean.	Dún Laoghaire (1925–1933); PSMSL Dublin Port (1938–2001); Arklow (2003–2006 used for MSL analysis; full 2003–2024 used for Howth offset correction); Howth (2007–2024).	Dún Laoghaire 1925–1933; Arklow 2003–2006 (full 2003–2024 used to compute Howth-baseline offset, but only 2003–2006 included in MSL analysis); Howth 2007–2024.
Cork (Tivoli)	1982 (Nov–Dec); 2001 (Jun–Sep); 2002 (Mar, Oct–Dec); 2004 (Mar); 2010 (Feb, Nov–Dec).	Monthly M2 amplitudes outside the yearly ranges were excluded: Tarbert 1.55–1.66 m; Kilrush Lough 1.48–1.64 m.	Due to the close proximity and similar tidal amplitudes, all stations were checked together.	Ringaskiddy 2012–2021; Currach Club 2022–2024.
Tarbert	1974 (Nov); 1976 (Oct, Nov); 1977 (Jun); 1978; 1979 (Jan–Feb); 1982 (Jan); 1984–1986. Kilrush Lough: Jan, Feb, Sept, and Oct 2024.	Monthly means causing yearly amplitudes to fall outside the ranges: Tarbert 1.55–1.66 m; Kilrush Lough 1.48–1.64 m.	Due to the close proximity, all data were checked together.	Kilrush 2018–2024.
Galway	1968–1970 (selected hours on some days omitted).	Unreliable data at Galway.	All data were checked together due to close proximity.	Galway Harbour 2007–2024.

4.4.2 Modern Tide Gauge Data: Quality and Corrections

Modern tide gauges still produce raw records that may contain inaccuracies and require validation (Aarup et al., 2019). All modern datasets accessed from the NTGN (MI and OPW) included quality flags indicating good, poor, or cautionary data. The absence of a "good" flag does not necessarily imply that the data are erroneous; rather, it indicates that the data should be treated with caution. Independent quality checks were conducted, including computation of M2 tidal constituents and comparison with co-located records where available. Monthly mean outliers exceeding three standard deviations from the mean were identified and removed from each tide-gauge record.

A consistent datum offset between the overlapping Arklow and Howth series was identified, likely arising from differences in vertical referencing (e.g., GNSS-derived heights relative to a geoid model rather than conventional levelling). The offset was quantified using the mean monthly discrepancy over the overlap period (2007–2024) and applied to the full Arklow series (2003–2024) to align it with the Howth datum. Two outliers in the Arklow 2007–2024 portion—November 2022 and May 2024—exceeding three standard deviations from the mean—were removed. Only the 2003–2006 observations were used in the present analysis, with no outliers within this interval. The corrected Arklow series (2003–2006) was then employed to extend the Dublin Port record into the early 2000s. Following these procedures, all modern NTGN observations used in this study—including the previously uncovered Tivoli (Cork) data from the early 2000s—met quality and consistency criteria (Figure 4.8).

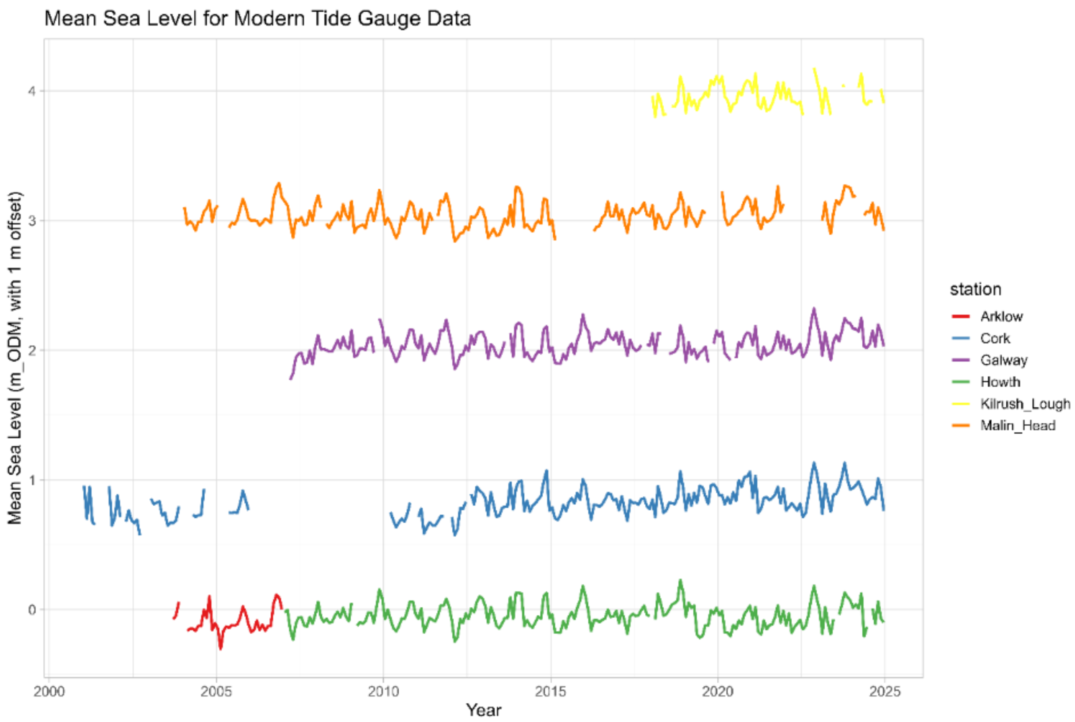


Figure: 4.8: Tide-gauge records (2000s) for Arklow, Howth, Galway, Kilrush Lough, and Malin Head. Each time series has been vertically offset for plotting clarity; Arklow and Howth are shown together after applying a fixed datum offset to align them.

As a final validation, to ensure the Dublin Port dataset aligns with the modern Arklow and Howth datasets, comparison with Shoari Nejad et al. (2022) shows a mean difference of 0.021 m and a standard deviation of 0.017 m. No obvious jumps were observed, with a maximum year-to-year difference of 0.071 m, indicating no datum issues.

4.4.3 Data Quality Control and Standardization

To ensure methodological consistency, only hourly intervals were extracted from modern datasets. Following standard validation practices, months were excluded from monthly averages if the total number of days that were either fully missing or had more than four missing hours was 15 days or greater. PSMSL records were exempt, as they are already provided as monthly means. This approach is consistent with recommendations from the UK National Tide Gauge Network, where monthly mean sea level values are not computed for months with more than 15 missing days, and gaps exceeding ~4 hours in the primary channel are treated as missing when calculating daily averages (UK Coastal Monitoring and Forecasting [UKCMF], 2014).

4.5 Data Processing and Sea-Level Modelling

4.5.1 Atmospheric Adjustments

In the processing of the MSL data, two reanalysis products were used to correct for atmospheric effects: the NOAA/CIRES/DOE 20th Century Reanalysis Version 3 (20CRv3; NOAA PSL, 2025; Slivinski et al., 2019) and ERA5 (Copernicus Climate Change Service, 2025). These corrections, including surface pressure and wind forcing, reduce high-frequency atmospheric variability and facilitate the identification of long-term trends in MSL.

20CRv3 provides a continuous record from 1806 to 2015 at 1° spatial resolution, making it well suited to historic tide gauge records such as Belfast (from 1925). Its extended temporal coverage and assimilation of historical observations allow long-term variability and trends to be assessed. However, the dataset terminates in 2015.

To cover the modern period, ERA5 was employed. ERA5 extends from 1940 to the present, with higher resolution (0.25°). Although not appropriate for pre-1940 applications, it is particularly valuable for correcting contemporary tide gauge data.

From both datasets, ocean surface pressure fields were used to compute anomalies, and 10 m u- and v-component winds were extracted for wind stress calculations. Land–sea masks were applied using the native mask from 20CRv3 and the ERA5-Land monthly product (Copernicus Climate Change Service, 2025). Together, these complementary reanalyses provide the atmospheric forcing fields required to correct both historic and modern records.

Surface pressure anomalies were calculated using a method adapted from Frederikse & Gerkema (2018), who accounted for atmospheric contributions to seasonal sea-level deviations. Land points were masked using the native land–sea mask, and the remaining ocean pressure values were averaged with cosine-latitude weighting to compute a weighted mean ocean pressure, which was then subtracted from each grid point to obtain anomalies. This ensures that the anomalies reflect ocean pressure variations relevant to sea-level changes near tide-gauge stations, avoiding contamination from continental pressure variations.

To remove the global atmospheric mass signal and isolate local variability, a latitude-weighted global mean surface pressure was computed at each time step (Eq.1):

$$P_{global}(t) = \frac{\sum_i P_i(t)\cos\varphi_i}{\sum_i \cos\varphi_i} \qquad (1)$$

where P_i(t) is the pressure at ocean grid point i and φ_i is its latitude. The cosine weighting accounts for the decreasing area of grid cells toward the poles, ensuring that the global mean accurately represents the mass-weighted atmospheric signal rather than a simple arithmetic mean.

The resulting surface pressure anomaly at each ocean grid point is given by (Eq.2):

$$P'_i(t) \; = P_i(t) - P_{global}(t) \tag{2}$$

After removing the global atmospheric signal, the pressure anomalies were averaged locally around each station to represent site-specific conditions, before computing wind stress and applying the regression model.

For each tide-gauge station, the local pressure anomaly was calculated by averaging all grid points within a 1° radius for 20CRv3, or by selecting the ERA5 grid point within ±0.25° showing the highest correlation with the local tide-gauge record, ensuring that the anomaly reflects site-specific atmospheric conditions at each station. This ensures that the anomaly represents local atmospheric forcing conditions relevant to each tide-gauge site.

Concurrent 10 m zonal (u) and meridional (v) wind components were extracted from the same reanalysis fields and converted to wind stress. Wind speed magnitude was first computed using (Eq.3):

$$|\mathrm{U}| \; = \sqrt{}(u^2 + v^2) \tag{3}$$

The drag coefficient C_D was parameterized following Smith (1980) (Eq.4):

$$\mathrm{C}_D = \begin{cases} 0.001 & if \;\mid U \mid < 7.5 \; m/s \\ 0.00061 + 0.000063 \mid U \mid & if \;\mid U \mid \geq 7.5 \; m/s \end{cases} \tag{4}$$

Wind stress components were subsequently calculated using (Eq.5):

$$\tau_x \; = \; \rho_{air} \, \mathrm{C}_D \mid U \mid \, u, \qquad \tau_y \; = \; \rho_{air} \, \mathrm{C}_D \mid U \mid \, v \tag{5}$$

where $\rho_{air} = 1.225$ kgm^{-3} is air density. This formulation ensures that both the magnitude and direction of the wind stress vector are physically consistent with the combined u- and v-components of the wind.

All input datasets—including PSMSL station monthlies and reanalysis fields for pressure and wind—were aggregated to monthly MSL means, so the regression was performed on monthly values. Atmospheric corrections were applied by fitting a multiple linear regression model to the observed monthly sea-level records at each station (Eq.6):

$$\mathrm{WaterLevel}(t) = \beta_0 + \beta_1 P'(t) + \beta_2 \tau_x(t) + \beta_3 \tau_y(t) + \beta_4 \sin\left(\frac{2\pi t}{365.25}\right) + \beta_5 \cos\left(\frac{2\pi t}{365.25}\right) + \beta_6 \sin\left(\frac{2\pi t}{183.63}\right) + \beta_7 \cos\left(\frac{2\pi t}{183.63}\right) + \varepsilon(t) \quad (6)$$

Here, t is time in days since the start of the record. β_0 is the intercept. β_1–β_3 are the coefficients for the atmospheric terms: β_1 corresponds to the sensitivity of water level to the local pressure anomaly $P'(t)$, typically ~ -0.010 m mbar^{-1}, β_2 to the zonal wind stress $\tau_x(t)$, and β_3 to the meridional wind stress $\tau_y(t)$. β_4–β_5 are the coefficients for the annual harmonic (sin and cos terms), and β_6–β_7 are the coefficients for the semiannual harmonic (sin and cos terms), which are included if statistically significant. $\varepsilon(t)$ is the residual representing the portion of sea-level variability not explained by the model.

At some tide-gauge stations, correlations between observed water level and atmospheric predictors (pressure anomaly $P'_i(t)$, $\tau_x(t), \tau_y(t)$) were weaker than at others. These differences reflect variations in local geography, coastal orientation, and sheltering from prevailing winds (Pugh & Woodworth, 2014). Predictors that were weak in their simple correlation or statistically insignificant in the multiple regression ($p > 0.05$) were omitted from the final model. In a few cases, terms that were marginally significant in the regression or weak in simple correlation were retained at specific sites—such as the semiannual harmonic at Dún Laoghaire and Galway, which slightly improved R^2—where they represented physically meaningful seasonal effects, ensuring that the model captured known local variability in water level. Importantly, a weak simple (Pearson) correlation does not imply that a predictor is unimportant in a multivariate regression. For example, τ_x exhibits negligible correlation with water level at some sites, yet remains statistically significant when included alongside atmospheric pressure and $\tau_y(t)$ because it explains variance conditional on those predictors. Similarly, in a few cases only one component of the semiannual harmonic (sine or cosine) was retained if the other was statistically non-significant; this preserves physically meaningful seasonal variability while simplifying the model. Consequently, all predictors that were statistically significant in the multiple regression were retained (Table 4.3).

Table 4.3: Regression terms included in atmospheric corrections for each tide-gauge site. Legend: Included = term included in the final regression; Omitted = term not included in the regression.

Site	$P'_i(t)$	$\tau_x(t)$	$\tau_y(t)$	$\sin\left(\frac{2\pi t}{365.25}\right)$	$\cos\left(\frac{2\pi t}{365.25}\right)$	$\sin\left(\frac{2\pi t}{182.63}\right)$	$cos\left(\frac{2\pi t}{182.63}\right)$	Notes / Supplement
Malin Head	Included	Included	Included	Included	Omitted	Included	Omitted	–
Portrush	Included	Included	Included	Included	Included	Included	Omitted	Supplement to Malin Head
Belfast	Included	Included	Included	Included	Included	Included	Omitted	Supplemented by Bangor data
Dublin Port	Included	Included	Included	Included	Omitted	Included	Omitted	–
Howth	Included	Omitted	Included	Included	Included	Included	Omitted	Supplement to Dublin Port
Arklow	Included	Omitted	Included	Included	Omitted	Omitted	Omitted	Supplement to Dublin Port
Dún Laoghaire	Included	Omitted	Omitted	Included	Included	Included	Omitted	Supplement to Dublin Port
Cork	Included	Included	Included	Included	Included	Included	Omitted	–
Tarbert	Included	Included	Included	Included	Included	Omitted	Omitted	Supplemented by Kilrush Lough data
Galway	Included	Omitted	Included	Included	Included	Included	Omitted	Supplemented by Galway Port data

To assess the effect of atmospheric adjustments on tide-gauge records, the mean and standard deviation (SD) of both the original and atmosphere-adjusted water levels were computed. These metrics provide a quantitative measure of the variability on timescales shorter than one year (seasonal and monthly) removed by the regression model. Results for all stations are summarized in Table 4.4. The atmospheric correction consistently reduced variability across all tide-gauge sites, as indicated by decreases in SD, demonstrating successful removal of pressure- and wind-driven effects. Changes in the mean water level were generally small, reflecting the removal of atmospheric contributions, with slightly larger adjustments observed at Dublin Port.

Table 4.4: Mean and standard deviation of observed and atmosphere-adjusted monthly mean sea levels at all tide-gauge sites. SD = standard deviation.

Site	Mean Water Level OD Malin (m)	SD Water Level (m)	Mean Atmosphere-Adjusted (m)	SD Atmosphere-Adjusted (m)
Malin Head	0.00	0.10	-0.01	0.05
Belfast	0.04	0.10	0.040	0.05
Portrush	0.01	0.09	-0.02	0.03
Dublin Port	-0.15	0.09	-0.20	0.05
Howth	-0.05	0.09	-0.10	0.05
Arklow	-0.09	0.09	-0.12	0.02
Dún Laoghaire	-0.20	0.08	-0.18	0.05
Cork	-0.20	0.12	-0.18	0.08
Tarbert	-0.19	0.14	-0.20	0.12
Galway	0.03	0.10	0.00	0.06

Including the atmospheric pressure anomaly term enables the regression to capture the local expression of the inverted barometer effect, which typically alters water levels by ~10 mm per mbar (Pugh et al., 2021), resulting in broadly consistent reductions in short-term variability (SD) and slight changes in mean water level at most tide-gauge sites in this study. Similar to Thompson (1980), the regression estimates site-specific sensitivity to atmospheric pressure and wind stress directly from observations. The resulting residuals represent sea-level variability with atmospheric effects removed. Figure 4.9 illustrates this atmospheric correction at Dublin Port, showing how the regression isolates true sea-level variability by removing the influence of pressure and wind stress.

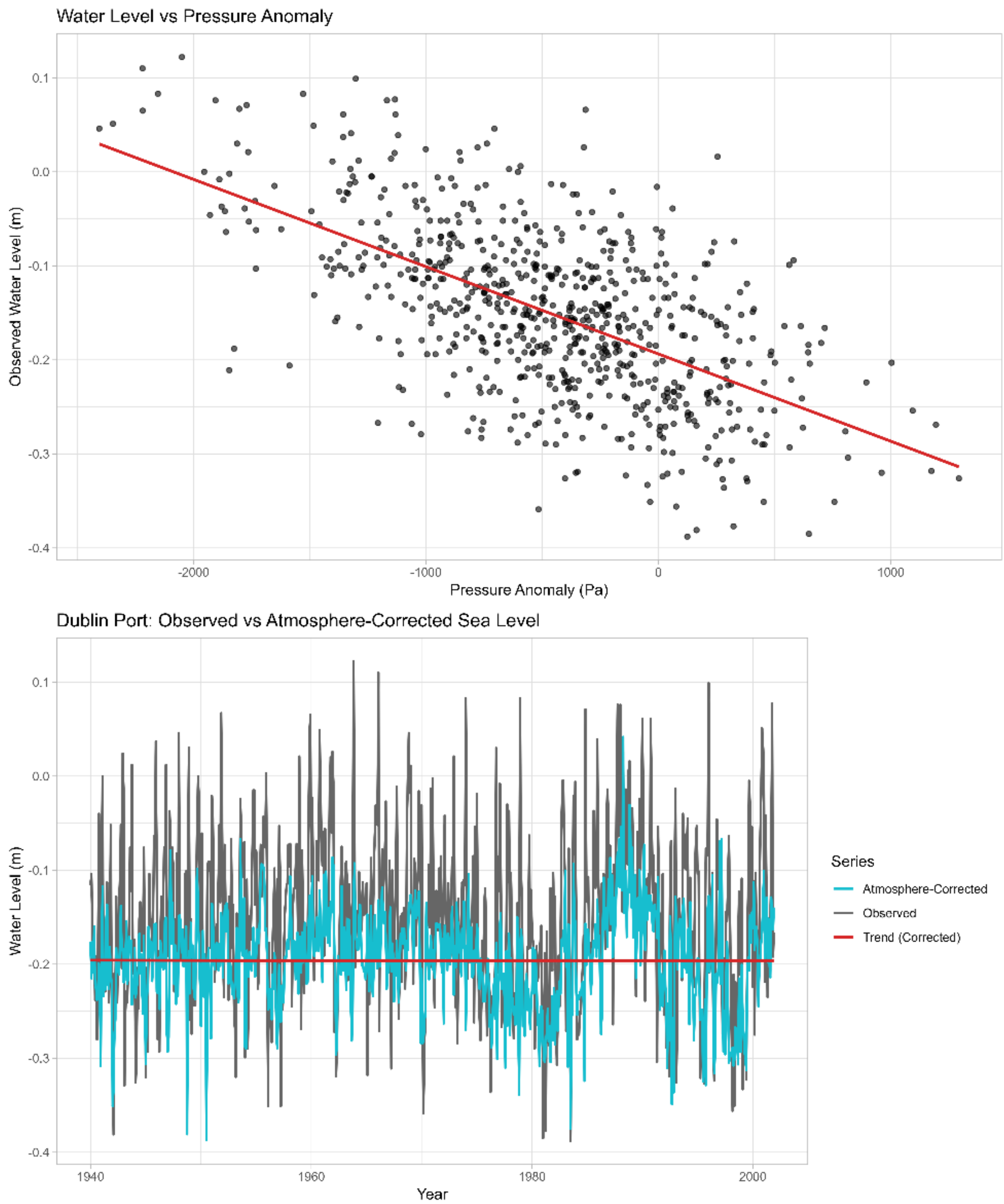


Figure 4.9: Atmospheric corrections applied to Dublin Port. Top: observed monthly mean water level versus pressure anomaly, showing a strong negative correlation (r = -0.599, p << 0.001 ; regression slope β_1, representing the change in water level per mbar, = –0.010 m mbar^{-1}). Bottom: observed versus atmosphere-corrected monthly mean water levels, with a linear trend fitted. The regression removes the combined effects of atmospheric pressure and local wind stress, leaving residuals that reflect true sea-level variability.

4.5.2 Tide-Gauge Station Selection and Atmospheric Corrections

Atmospheric pressure corrections were applied at tide-gauge sites across Ireland, depending on record length and data resolution. Sea-level variability is strongly influenced by atmospheric conditions, particularly atmospheric pressure (Johansson et al., 2022; Zubier & Eyouni, 2020; Pham et al., 2024; Dangendorf et al., 2024).

- Pre-1940 stations: Belfast (including Bangor) and Dublin Port (including Dún Laoghaire) were corrected using 20CRv3 (1° resolution), from which surface pressure and 10 m wind components were extracted. To account for coarse resolution near coastlines, all grid points within ±1° of each station were averaged to approximate local conditions. Record coverage: Belfast and Bangor (1925–2015), Dublin Port (1938–1939), Dún Laoghaire (1925–1933, merged with Dublin Port for 1938–1939).
- Post-1940 stations: Cork, Tarbert, Malin Head, Galway Port, Dublin Port, Arklow, Howth, and Portrush used high-resolution ERA5 (0.25°) for atmospheric correction. For each station, the ERA5 grid point within ±0.25° showing the highest correlation with the local tide-gauge record was selected, and surface pressure and 10 m wind components were extracted, ensuring that the anomaly represents site-specific atmospheric conditions at each station.

Atmospherically adjusted records from Dún Laoghaire (1925–1933) and Dublin Port (1938–2000) were tested for consistency. Linear trends for Dún Laoghaire (–1.30 mm yr^{-1}), Dublin Port (–0.036 mm yr^{-1}), and the combined record (–0.041 mm yr^{-1}) agree within uncertainty. Bootstrap slope-difference estimates (95 % CI: –0.193 to 0.205 mm yr^{-1}) and segment–interaction tests ($p \approx 0.988$) indicate no significant site-specific differences. Accordingly, the Dún Laoghaire record was merged with Dublin Port with negligible effect on the long-term trend, enabling construction of a continuous Dublin series (Figure 4.10).

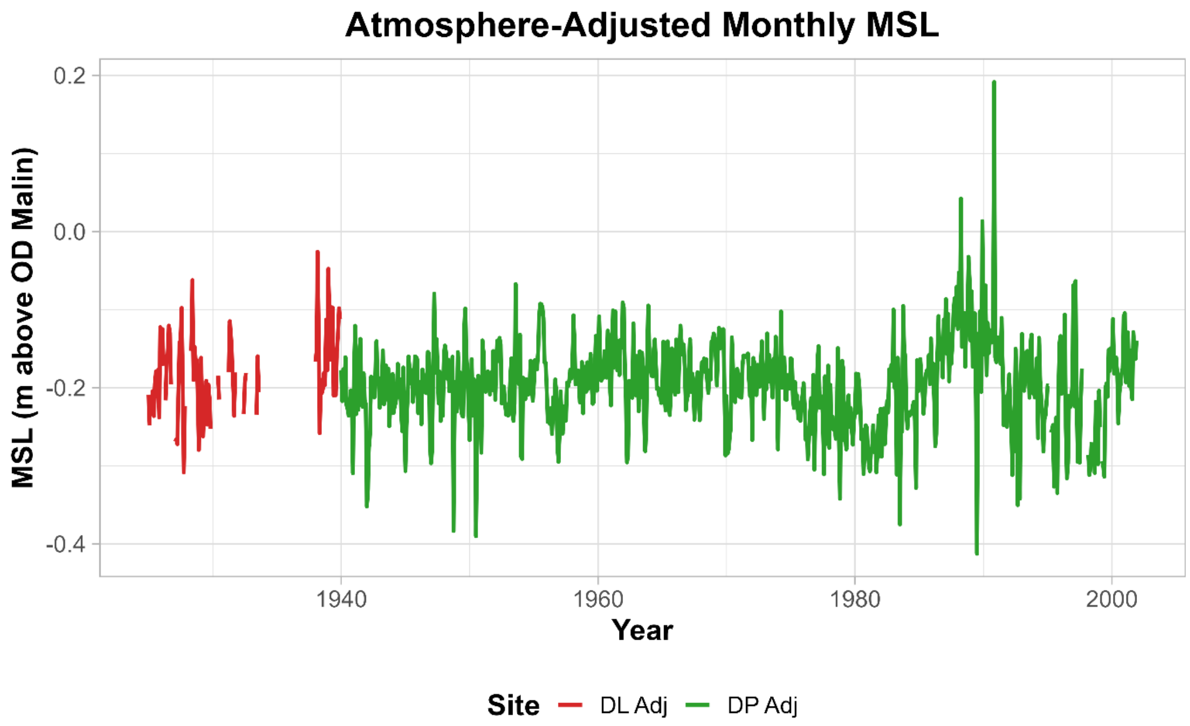


Figure 4.10: Time series of atmosphere-adjusted monthly mean water levels at Dún Laoghaire (DL Adj, red) and Dublin Port (DP Adj, green). There is no discontinuity between the 20CRv3 (DL Adj) and ERA5 (DP Adj) data. Atmospheric adjustments reduce high-frequency variability, emphasizing long-term sea-level trends.

PSMSL (2025) recommends computing annual mean sea level (MSL) from 11–12 monthly values. In practice, some years had fewer than 11 months of data. Here, MSL was calculated from all available monthly values, provided at least three consecutive months were present, to avoid spurious gaps.

4.5.3 GIA Corrections and Statistical Sea-Level Modelling

It is important to understand the role of GIA in shaping sea-level variability around Ireland, particularly due to regional differences between the northeast and southwest. To account for the isostatic component of vertical land motion (VLM), we applied corrections from 18 GIA models, including Bradley-type models (thick, thin, hybrid, North Sea; Bradley et al., 2011, 2023), ICE-5G and ICE-6G variants (standard, BC hybrid – hybrid boundary condition, VM5a – viscosity model; Peltier, 2004, 2015), and GLAC1D variants (BC hybrid – hybrid boundary condition, VM5a – viscosity model; Tarasov et al., 2012). These models differ in their ice-sheet history reconstructions, Earth rheology assumptions, and regional calibration strategies, resulting in spatially variable predictions of uplift and subsidence across Ireland.

By incorporating multiple GIA model families and variants, we account for differences between models in predicted VLM, capturing the uncertainty arising from model choice. This enables robust estimation of absolute sea-level rise (ASLR) (with site-specific VLM removed) from tide-gauge records. The aim was to identify the GIA model that minimises the inter-site variability of GIA-corrected relative sea-level (RSL) trends across Ireland. Model performance was assessed using the inter-site standard deviation of GIA-corrected relative sea-level (RSL) rates, with the optimal model defined as that which minimised this spatial spread, providing a data-driven measure of how effectively each GIA model explains the observed RSL−VLM structure prior to integration into the reslr framework. To evaluate the influence of GIA on RSL records, site-specific RSL data were corrected using all 18 candidate GIA models, and the resulting inter-site spread in linear RSL trends was computed for each model. The ICE-5G model (Peltier, 2004) was included in the full evaluation ensemble and subjected to the same performance assessment as all other models; however, it was not considered in the final model selection step due to its older-generation ice history and Earth rheology assumptions, limited GPS-constrained calibration, and the availability of more recent GIA reconstructions with improved observational constraints. This ensured that model selection was based on contemporary GIA models while maintaining a consistent and transparent evaluation framework across the full model ensemble. The Bradley_thick_71p510, Bradley_thick_Northsea1_71p510, and Bradley_thick_Northsea2_71p510 variants show very similar inter-site spread values, with differences that are negligible relative to the full model ensemble. This indicates that these models are effectively indistinguishable in terms of their performance metric. The Bradley_thick_71p510 model was selected as a representative member of this high-performing subset for further analysis. Differences between GIA models in predicted rates across sites are shown in Figure 4.11.

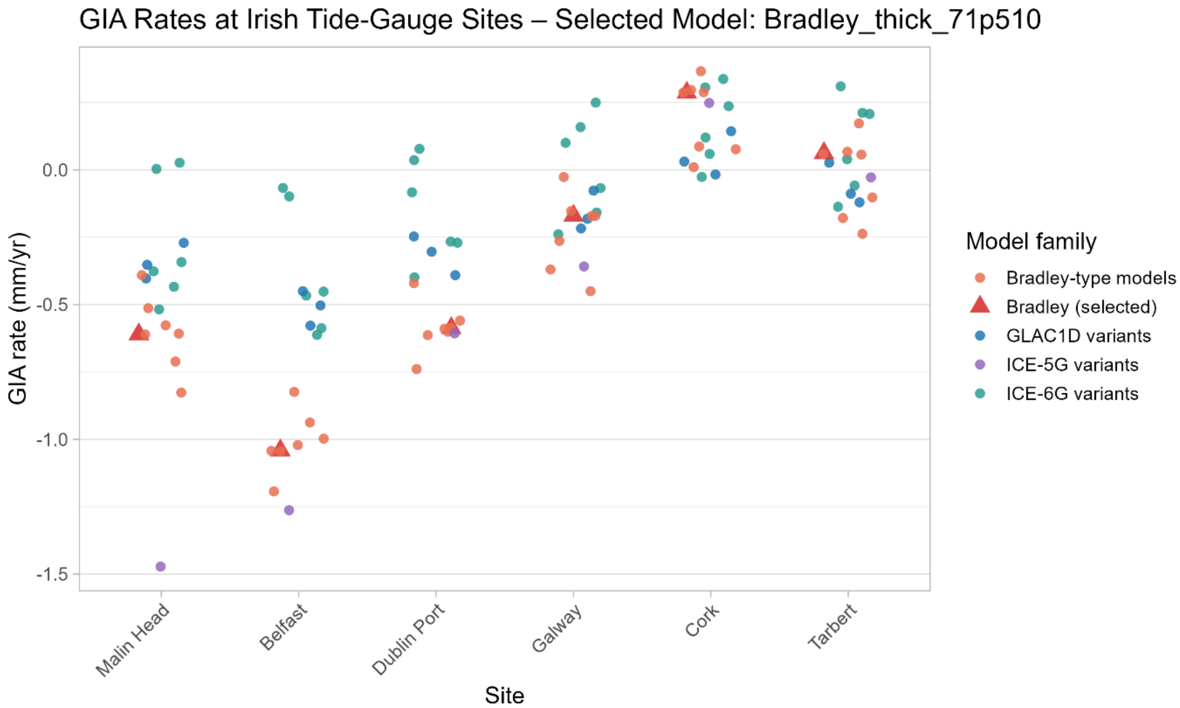


Figure 4.11: Yearly GIA rate corrections at six Irish tide-gauge sites. Red triangles indicate the selected Bradley_thick_71p510 model. Other symbols represent alternative GIA model families (Bradley-type variants, ICE-6G, ICE-5G, and GLAC1D). The selected Bradley_thick_71p510 model is consistent with other Bradley variants in producing the lowest inter-site spread. ICE-5G exhibits the largest deviations in predicted vertical land motion across sites, particularly in northern locations, relative to the modern model ensemble.

The longer tide-gauge timeseries, extending back ~100 years, often contain gaps, nonlinear fluctuations, and observational noise, requiring a more flexible approach. After applying atmospheric adjustments, nodal (18.6 yr) tidal-cycle effects (Pugh & Woodworth, 2014) were tested at Belfast, Dublin, and Cork—the only sites with sufficiently long, continuous records—and were found to alter long-term rates by <0.25 mm yr^{-1}, well below observational and model uncertainties. Given that other sites were too short to resolve the nodal signal and its impact was negligible, nodal corrections were not applied in the final analysis (Woodworth, 2012).

Long-term sea-level variability was modelled using the reslr package (Upton et al., 2024), which applies a Bayesian hierarchical framework with random effects and flexible spline-based functions within a spatio-temporal Generalised Additive Model (GAM) to represent non-linear trends. It accounts for measurement uncertainty in sea level observations and incorporates age uncertainty through the Noisy Input method (McHutchon & Rasmussen, 2011), producing posterior distributions for sea level and its rates of change.

The RSL field was modelled using a non-linear mixed-effects Generalized Additive Model (NI-GAM; Upton et al., 2024) to account for long-term trends, site-specific deviations, and observational uncertainty (Eq.7):

$$y_{ij} = f(x_j, t_i) + \epsilon_y, \epsilon_y \sim N(0, \sigma^2 + s_{y_{ij}}^2) \quad (7)$$

where y_{ij} is the observed RSL at site j and time i, $f(x_j, t_i)$ is the underlying sea-level process, and ϵ_y representing observational, digitisation, and measurement uncertainty.

The mean sea-level process was decomposed into regional and local components (Eq.8):

$$f(x,t) = r(t) + g(z_x) + h(z_x) + l(x,t) \quad (8)$$

where $r(t)$ is the regional time-varying component, $g(z_x)$ is a linear site-specific term (including externally supplied GIA rates), $h(z_x)$ is a site-specific constant offset, and $l(x,t)$ captures residual non-linear spatio-temporal variability. The regional term $r(t)$ is represented using cubic B-splines to capture smooth long-term variability across all sites.

Site-specific GIA rates were included as externally defined linear terms in the model decomposition. In this framework, GIA is included as a fixed linear correction at each site, based on externally derived model estimates rather than being dynamically estimated. GIA-corrected or “absolute” rates therefore refer to posterior rates after accounting for this linear site-specific component, and do not include non-linear GIA behaviour or other geophysical processes not represented in the model.

Measurement uncertainty in both RSL and age inputs was incorporated using the Noisy Input method, producing posterior distributions for sea level and its rates of change. The NI-GAM framework separates the process into regional, linear site-specific, site-level offset, and residual non-linear components, allowing both long-term trends and local deviations to be represented within a single hierarchical structure.

The model produces a shared regional component informed by all sites, enabling estimation of long-term sea-level change while accounting for uneven record lengths and gaps in the observational network. This hierarchical structure allows sites with shorter or fragmented records to be informed by the full dataset, improving constraint on regional trends.

Annual records were compiled with associated metadata (site, region, year, latitude, longitude). A conservative age uncertainty of 0.004 years was assigned to reflect minimal dating error, and a uniform RSL observational uncertainty of 2 cm was applied to account for instrumental, digitisation, and processing uncertainties. The linear rate uncertainty was set to 0.3 mm yr^{-1}, consistent with Upton et al. (2024). Figure 4.12 shows all tide-gauge sites used as input to the reslr model (datum: OD Malin, metres), illustrating spatial coverage, record length, and temporal gaps.

The NI-GAM model was fitted using reslr_mcmc() (Upton et al., 2024), which performs Bayesian MCMC sampling to estimate posterior distributions for spline coefficients and random effects, providing probabilistic estimates of regional and site-specific sea-level trends and their uncertainties. The arguments spline_nseg_t = 3 and spline_nseg_st = 2 define the temporal and spatio-temporal spline resolution, controlling the flexibility of the regional trend and local deviations. These values were selected to provide stable estimates across uneven record lengths, particularly at Galway, Cork, and Tarbert. For longer and more continuous records (>40 years), higher temporal flexibility (e.g., spline_nseg_t = 4) could be used to resolve additional long-term variability.

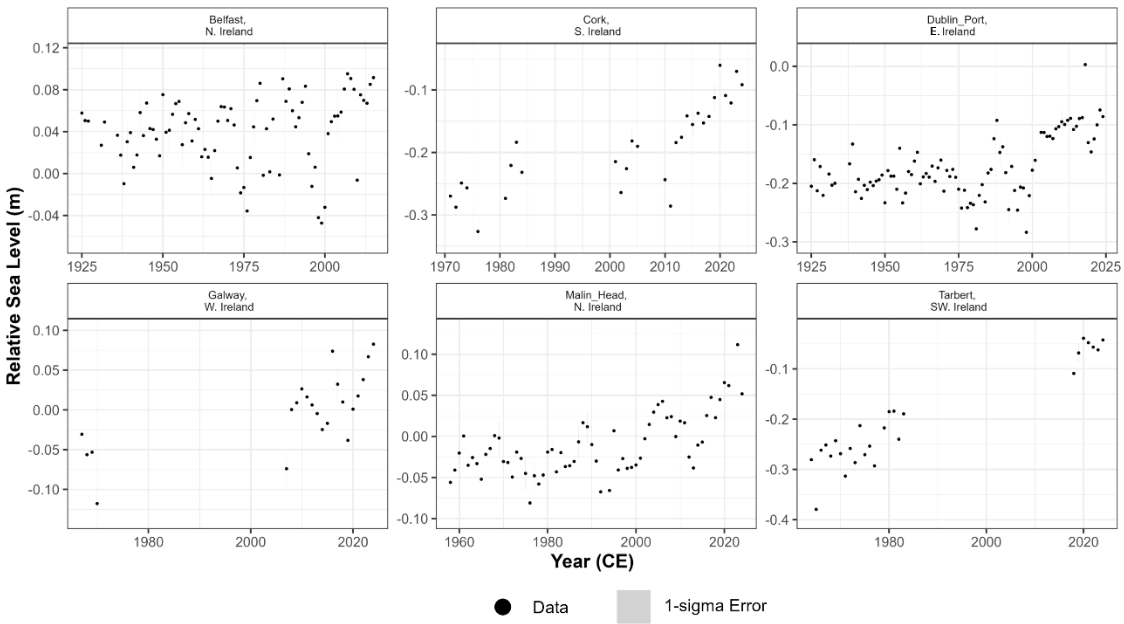


Figure 4.12: Tide-gauge sites used as input in the reslr package (datum: OD Malin, in metres). Annual RSL records are shown for each site, illustrating the spatial coverage, record length, and gaps in the dataset.

The NI-GAM model was fitted using reslr_mcmc() (Upton et al., 2024), which performs Bayesian MCMC sampling to estimate posterior distributions for spline coefficients and random effects, providing probabilistic estimates of regional and site-specific sea-level trends and their uncertainties. The arguments spline_nseg_t = 3 and spline_nseg_st = 2 specify the number of segments for temporal (regional) and spatio-temporal (local) B-splines, controlling how flexibly the model captures nonlinear trends over time and across sites. These values were chosen to accommodate gaps in sparser records, particularly at Galway, Cork, and Tarbert, while providing a robust fit. For longer, more consistent datasets (>40 years), a higher temporal flexibility (e.g., spline_nseg_t = 4) could be used to better resolve long-term variability.

Instantaneous sea-level rates are derived from the NI-GAM posterior by evaluating the derivative of the fitted spatio-temporal surface on the prediction grid (μ_pred_deriv, mm yr^{-1}). Site-level rates are then deterministically adjusted by removing the externally supplied linear GIA component from μ_pred_deriv, shifting only the absolute rate level without affecting the posterior structure. The corresponding regional derivative component (r_pred_deriv, mm yr^{-1}) represents large-scale coherent variability shared across sites. These derivatives are computed directly from MCMC posterior samples and summarised to produce the rate estimates reported in the Results section.

Site-level rates were adjusted by removing the linear GIA component to isolate its contribution to spatial differences between sites. This correction is deterministic and does not alter posterior uncertainty, which is fully propagated through the NI-GAM model.

4.6 Model Validation

We assessed the predictive performance of the NI-GAM model using 10-fold cross-validation with the cross_val_check() function from the reslr package (Upton et al., 2024). In this procedure, the dataset is repeatedly split into training and testing subsets to evaluate model accuracy. Site-specific RSL records with Age ≤ 2024 were used, along with site-specific linear GIA rates (linear_rate) and their associated uncertainties (linear_rate_err = 0.3) to account for measurement variability. For each fold, the Bayesian NI-GAM decomposition (model_type = 'ni_gam_decomp') was fitted with 5,000 MCMC iterations per chain. This included a 1,000 iteration burn-in, retaining every 5th iteration to reduce autocorrelation (thinning = 5), across three chains. Temporal and spatio-temporal B-splines were parameterized with spline_nseg_t = 3 and spline_nseg_st = 2—defining the number of segments used in the regional (temporal) and local (spatio-temporal) splines—to capture nonlinear trends over time and across sites.

Predictive performance was evaluated using out-of-sample empirical coverage, prediction interval widths, and error metrics—including mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE)—as well as by comparing predicted versus observed values.

The predictive performance of the NI-GAM model was evaluated across all site-specific RSL records, incorporating site-specific linear GIA rates from the Bradley_thick_71p510 model. The Bayesian NI-GAM decomposition captured nonlinear trends while accommodating gaps in shorter records.

The NI-GAM produced well-calibrated predictive intervals, with an overall coverage of 95.31%, consistent with the nominal 95% level, and site-specific coverage ranging from 0.931 (Cork) to 1.000 (Malin Head) (Table 4.5). Narrow and consistent prediction intervals indicate that observational uncertainty is well captured across all sites.

Table 4.5: Cross-validation performance metrics for each site. Coverage shows the proportion of observed RSL within the 95 % posterior predictive interval; PI width gives the interval width.

Site	Coverage (95 % PI)	PI Width (m)
Malin Head	1.000	0.133
Belfast	0.940	0.133
Dublin Port	0.936	0.133
Cork	0.931	0.136
Tarbert	0.962	0.136
Galway	0.955	0.137

Error metrics further support the model's accuracy. Mean errors (ME) were close to zero across all sites, indicating negligible bias in model predictions. Mean absolute errors (MAE) and root-mean-squared errors (RMSE) remained low (Table 4.6), indicating strong predictive performance for relative sea level (RSL) across all sites.

Table 4.6: Cross-validation error metrics by site. ME: mean error; MAE: mean absolute error; RMSE: root-mean-squared error.

Site	ME (m)	MAE (m)	RMSE (m)
Malin Head	-0.000559	0.0200	0.0249
Belfast	-0.000132	0.0245	0.0319
Dublin Port	-0.000283	0.0283	0.0366
Cork	0.000158	0.0281	0.0392
Tarbert	0.000182	0.0287	0.0392
Galway	0.000373	0.0304	0.0352

The comparison of observed and predicted RSL across all sites is presented in Figure 4.13. Most points closely follow the 1:1 line, and the narrow, consistent prediction intervals indicate that the NI-GAM effectively captures long-term trends, site-specific variability, and measurement uncertainty. Model performance is strongest at Malin Head in terms of error metrics, while other sites show broadly comparable performance with slightly wider intervals and greater scatter, reflecting higher observational uncertainty. Overall, cross-validation confirms that the NI-GAM provides accurate, well-calibrated predictions of RSL, supporting its use for assessing regional sea-level trends across Ireland.

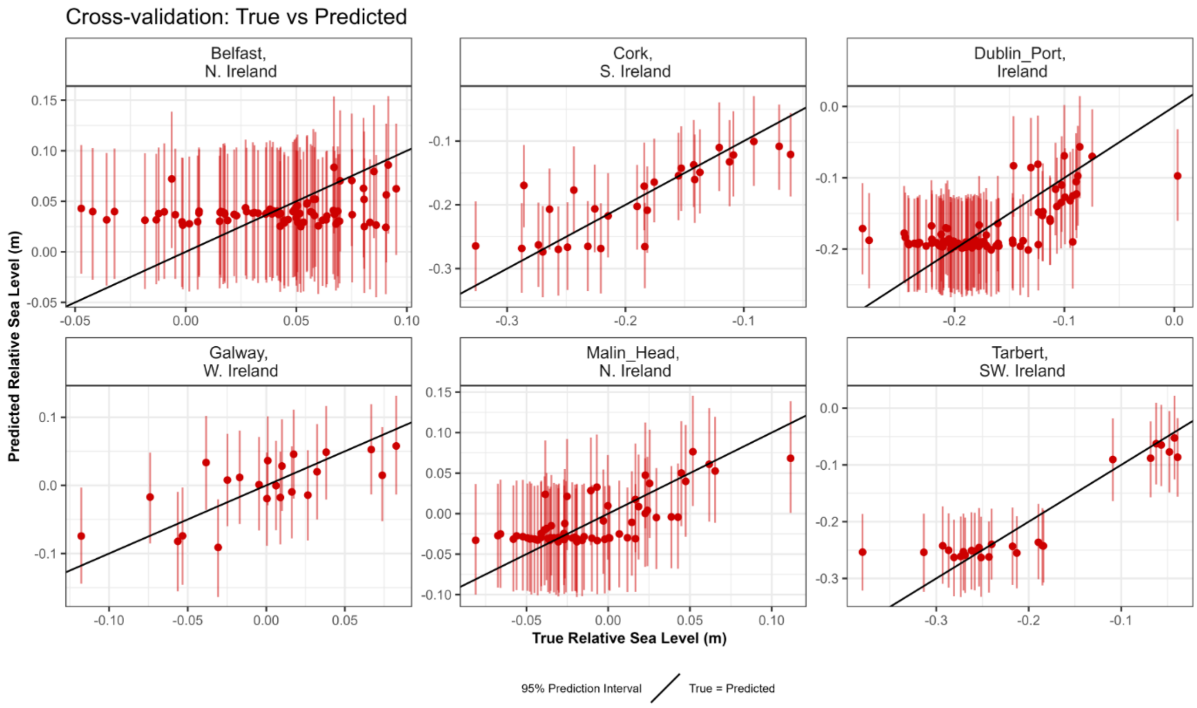


Figure 4.13: True versus predicted RSL from 10-fold NI-GAM cross-validation across all tide-gauge sites. Red points show posterior predictive means with 95 % intervals, and the black diagonal line represents the 1:1 reference; points near the line indicate strong predictive agreement.

4.7 Results

In these results, we report instantaneous sea-level rates derived from the posterior derivative field (μ_pred_deriv) of the NI-GAM model. These rates represent smoothed changes in sea level through time, rather than year-to-year differences in tide-gauge observations. Year-specific instantaneous rates are summarised using posterior means and 95% credible intervals (95% CrI), while period-mean rates are obtained by averaging the posterior derivative field (μ_pred_deriv) over the relevant time interval. Because the estimates are derived from a spatio-temporal smoothing model, instantaneous values may differ from raw annual observational differences.

Modelled sea-level rates show an overall increase from the late twentieth century into the 2000s. The 95% credible intervals for instantaneous rates widen toward the end of the record (Figure 4.14), reflecting increased posterior uncertainty associated with the spline boundary and reduced data support at the temporal edges of the NI-GAM fit. For Belfast, the final available model year (2015) shows a mean instantaneous rate of 4.05 mm yr^{-1} (95% CrI: 2.72–5.20). For sites extending to 2024, values are elevated across all locations. In 2024, Malin Head shows 5.58 mm yr^{-1} (2.95–8.11), Dublin Port 6.05 mm yr^{-1} (3.49–8.64), Galway 6.08 mm yr^{-1} (3.49–8.54), Cork 6.84 mm yr^{-1} (4.32–9.42), and Tarbert 7.21 mm yr^{-1} (4.70–9.75). These values represent posterior means of the instantaneous rate field.

Long-term mean rates are computed by averaging the posterior realisations of μ_pred_deriv (the instantaneous rate field) across all spatial grid cells belonging to each site, and then summarising these spatial averages across posterior draws. Malin Head exhibits a mean rate of 1.59 mm yr^{-1} (95% CrI: 1.15–2.01; 1958–2024), while Belfast shows 0.40 mm yr^{-1} (95% CrI: 0.07–0.74; 1925–2015), representing the lowest values across the network. Along the east coast, Dublin Port shows 1.30 mm yr^{-1} (95% CrI: 0.97–1.63; 1925–2024), while Galway records 2.44 mm yr^{-1} (95% CrI: 1.87–2.97; 1967–2024). Higher rates occur in the south and southwest, with Cork at 3.29 mm yr^{-1} (95% CrI: 2.76–3.85; 1971–2024) and Tarbert at 3.59 mm yr^{-1} (95% CrI: 3.08–4.24; 1964–2024).

Long-term instantaneous sea-level rates are summarised for site-specific time windows by averaging posterior realisations across each site. During the early–mid twentieth century, modelled rates are low and, in some cases, indistinguishable from zero within uncertainty. For example, Belfast (1925–2000) shows a mean rate of −0.12 mm yr^{-1} (95% CrI: −0.49 to 0.25), Dublin Port (1925–2000) shows 0.31 mm yr^{-1} (95% CrI: −0.05 to 0.67), and Malin Head (1958–2000) shows 0.34 mm yr^{-1} (95% CrI: −0.14 to 0.84). These results indicate substantial uncertainty and weakly constrained trends in the earlier portion of the record.

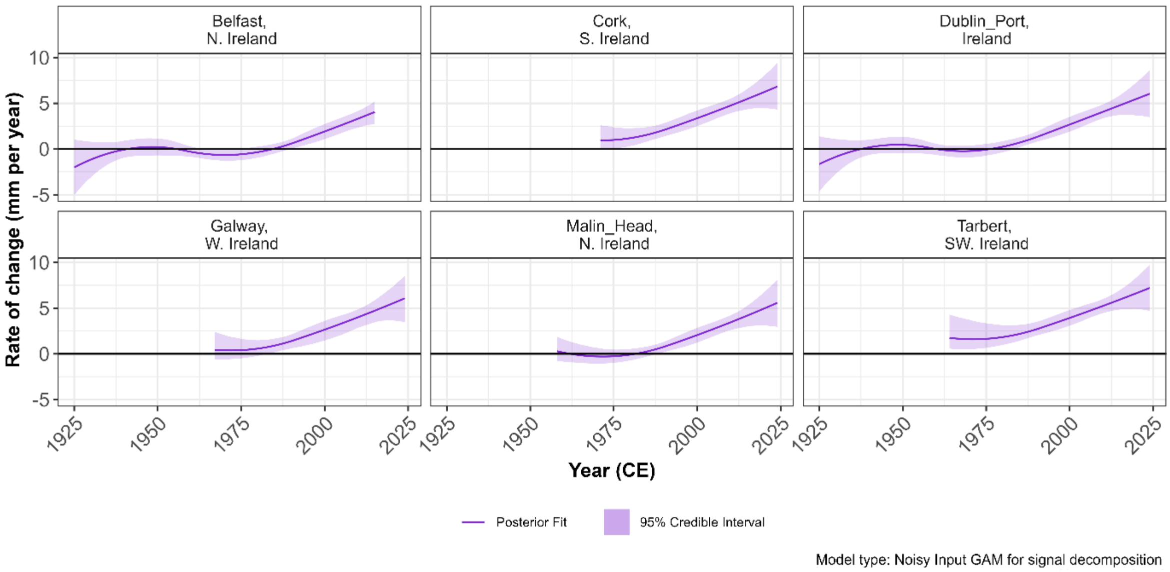


Figure 4.14: Modelled instantaneous sea-level rates across Irish tide-gauge sites (1925–2024). Shaded regions show the 95% credible interval of the posterior rate estimates. The figure highlights long-term trends and inter-site variability in the smoothed spatio-temporal rate field.

To examine GIA-adjusted instantaneous sea-level rates, the site-specific linear GIA component was removed from the NI-GAM posterior rate field (μ_pred_deriv) after model estimation. This produces a derived field in which the regional sea-level signal is retained, while vertical land motion from the Bradley_thick_71p510 GIA model is subtracted deterministically. Because the adjustment is applied directly to the posterior rate field, all sites share the same underlying temporal structure, with inter-site differences arising solely from the spatially constant GIA correction. The posterior uncertainty structure is preserved under the deterministic GIA adjustment, although the physical interpretation of the rate field changes.

Table 4.7 shows the NI-GAM posterior instantaneous RSL rates with deterministic GIA adjustment applied. The applied GIA corrections vary systematically across sites, ranging from −1.04 mm yr^{-1} in Belfast to +0.29 mm yr^{-1} in Cork, with intermediate values in Dublin Port (−0.59 mm yr^{-1}), Malin Head (−0.61 mm yr^{-1}), Galway (−0.17 mm yr^{-1}), and Tarbert (+0.06 mm yr^{-1}). Negative values reflect net glacial isostatic uplift, while positive values indicate subsidence. These adjustments shift the magnitude of site-level rates but do not alter the spatial variability structure of the posterior field.

Table 4.7: NI-GAM posterior-derived instantaneous RSL rates with deterministic post-estimation GIA adjustment applied using the Bradley_thick_71p510.

Site name	Period (time span)	Mean RSL rate (mm yr^{-1})	95% credible interval	GIA correction (mm yr^{-1})	GIA-adjusted rate (mm yr^{-1})
Belfast	1925–2015	0.40	0.07 – 0.74	−1.04	1.44
Cork	1971–2024	3.29	2.76 – 3.85	0.29	3.00
Dublin Port	1925–2024	1.30	0.97 – 1.63	−0.59	1.89
Galway	1967–2024	2.44	1.87 – 2.97	−0.17	2.61
Malin Head	1958–2024	1.59	1.15 – 2.01	−0.61	2.20
Tarbert	1964–2024	3.59	3.08 – 4.24	0.06	3.53

To enable fair comparison across sites, mean modelled instantaneous rates were calculated over the overlapping period 1971–present (Table 4.8). This temporal restriction ensures a consistent observational window across all sites, removing differences arising from unequal record lengths while preserving the underlying spatial structure of the modelled field.

Over this interval, site-level rates reflect the same regional temporal evolution, with differences arising from spatial variability in the sea-level signal and the deterministic adjustment applied post-estimation. Rates range from 1.22 mm yr^{-1} (95% CrI: 0.73–1.64) at Belfast to 3.84 mm yr^{-1} (95% CrI: 3.35–4.41) at Tarbert, with Cork also exhibiting elevated rates (3.29 mm yr^{-1}; 95% CrI: 2.76–3.85).

Following removal of the GIA component, site-level rates are shifted according to the spatially varying correction field, with Belfast increasing to 2.26 mm yr^{-1} and Dublin Port becoming more comparable to Cork (both ~3.0 mm yr^{-1}). Despite this adjustment, a clear spatial gradient remains, with the highest rates in the southwest (Cork and Tarbert).

Table 4.8: Comparison of mean modelled instantaneous sea-level rise rates (95% credible intervals) across Irish tide-gauge sites. Belfast record ends in 2015; rates are estimated over the full 1971–present posterior reconstruction window to ensure consistency across sites.

Site name	Period (time span)	Mean RSL rate (mm yr⁻¹)	95% credible interval	GIA correction (mm yr⁻¹)	GIA-adjusted rate (mm yr⁻¹)
Belfast	1971–present	1.22	0.73 – 1.64	−1.04	2.26
Cork	1971–present	3.29	2.76 – 3.85	0.29	3.00
Dublin Port	1971–present	2.49	2.06 – 2.96	−0.59	3.08
Galway	1971–present	2.59	1.98 – 3.13	−0.17	2.76
Malin Head	1971–present	1.99	1.47 – 2.47	−0.61	2.60
Tarbert	1971–present	3.84	3.35 – 4.41	0.06	3.78

The combined mean instantaneous RSL rate is summarised in Figure 4.15, representing the regional component of the NI-GAM decomposition. The model explicitly incorporates site-specific glacial isostatic adjustment (GIA) as a linear covariate within the NI-GAM formulation, and additional deterministic post-estimation adjustments are applied where GIA is removed from the posterior rate field for comparative analysis.

Over the full period 1925–2024, the mean modelled regional instantaneous RSL rate is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01). Estimated rates increase in the later period, rising from 1.20 mm yr^{-1} (95% CrI: 0.58–2.07) during 1925–2000 to 4.58 mm yr^{-1} (95% CrI: 3.34–5.57) during 2000–2024, consistent with a strengthening of the regional RSL signal over time. These estimates are derived from the posterior regional rate component (r_pred_deriv) of the model.

Integrating the posterior mean of this regional rate component over 1925–2024 yields a model-derived cumulative sea-level rise of approximately 20–23 cm.

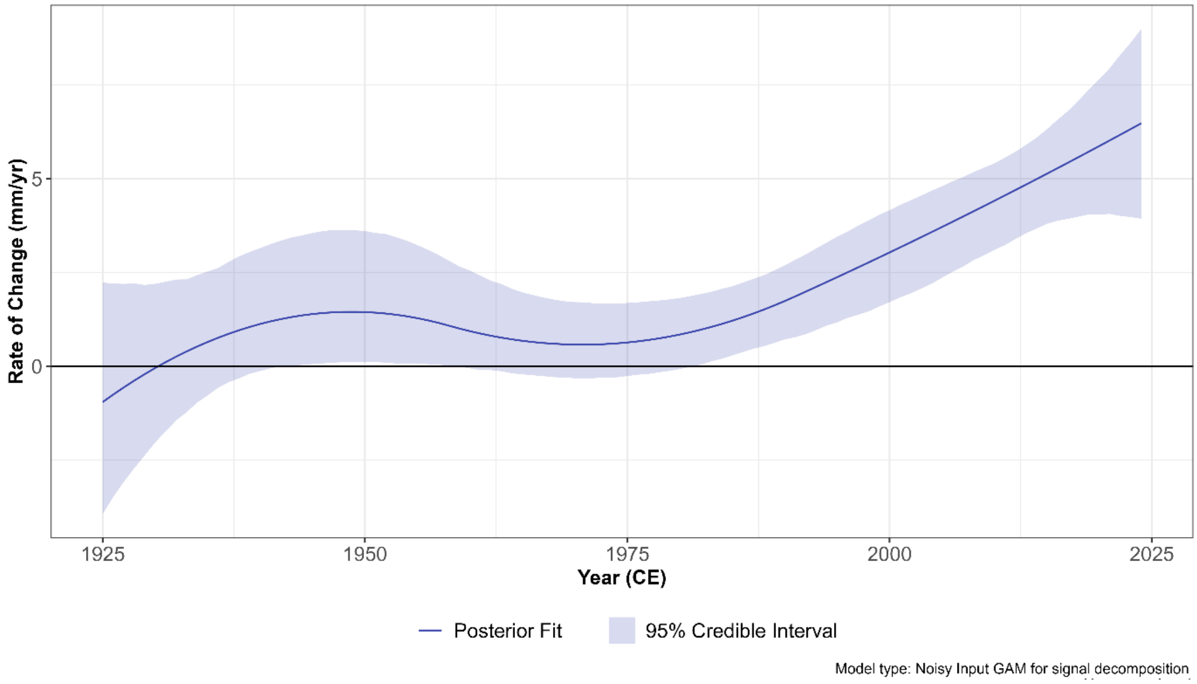


Figure 4.15: Smoothed regional sea-level rate (1925–2024) across Irish tide gauges, derived from the posterior regional rate component (r_pred_deriv) of the NI-GAM decomposition. Shaded areas indicate the 95% credible interval. The curve represents the modelled instantaneous RSL rate and is not based on raw annual observations. Site-specific glacial isostatic adjustment (GIA) is included as a linear covariate in the model fitting stage.

The regional sea-level reconstruction (regional_plot; Figure 4.16) shows the integrated evolution of sea level over time and exhibits a coherent long-term rise, consistent with the acceleration observed in the rate estimates.

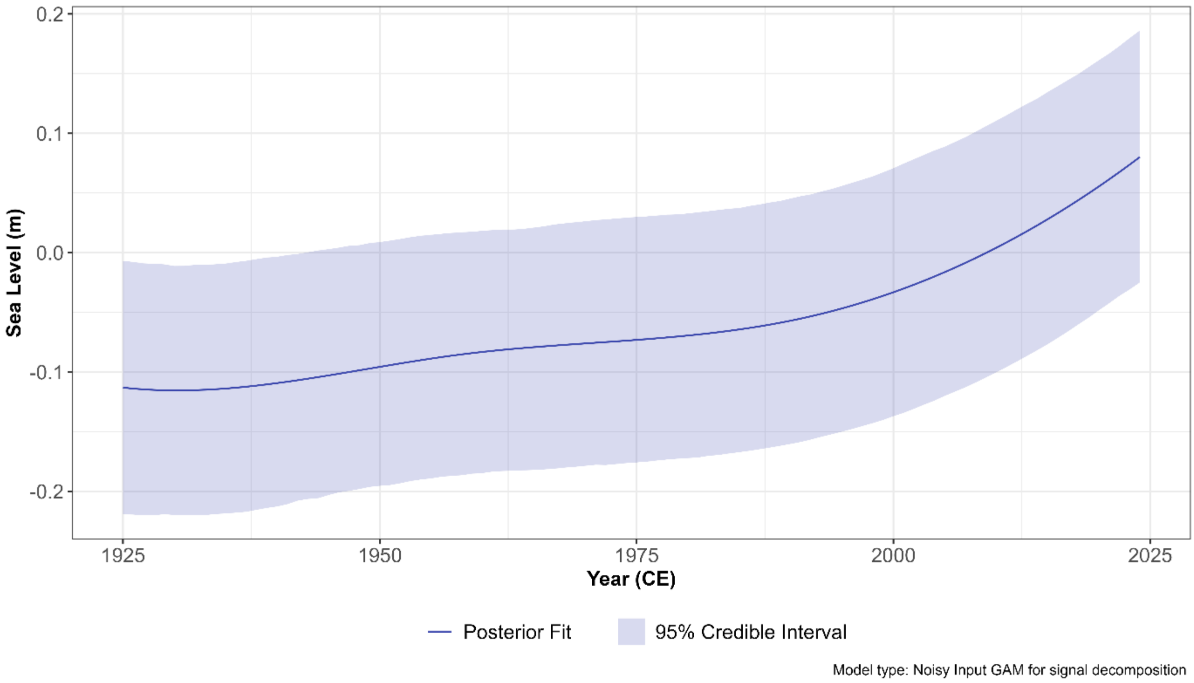


Figure 4.16: Smoothed regional sea-level curve (1925–2024) across Irish tide gauges. Shaded areas show the 95% credible interval. The curve represents the modelled regional sea-level reconstruction in level space (integrated from the posterior regional rate field), rather than raw annual observations, and reflects the regional sea-level signal with site-specific GIA accounted for within the model.

4.8 Discussion

The results highlight spatial and temporal variability in sea-level behaviour across Northern Ireland. Modelled instantaneous sea-level rates from the posterior are 1.59 mm yr^{-1} (95% CrI: 1.15–2.01) at Malin Head (1958–2024) and 0.40 mm yr^{-1} (95% CrI: 0.07–0.74) at Belfast (1925–2015). Modern modelled total instantaneous rates at Malin Head in 2024 reach 5.58 mm yr^{-1} (95% CrI: 2.95–8.11), while at Belfast in 2015 they reach 4.05 mm yr^{-1} (95% CrI: 2.72–5.20). It should be noted that these instantaneous rates are derived from the smoothed posterior and may slightly exaggerate peak values at the start and end of the record; this is reflected in the wider 95 % credible intervals in Figure 4.14, indicating increased uncertainty in these periods. Both substantially exceed their earlier-century rates of 0.34 mm yr^{-1} (95% CrI: −0.14 to 0.84) at Malin Head (1958–2000) and −0.12 mm yr^{-1} (95% CrI: −0.49 to 0.25) at Belfast (1925–2000) respectively. These differences indicate an increase in estimated rates in the post-2000 period relative to earlier decades. The higher rates reflect derivatives of the smoothed posterior rather than long-term averages. The IPCC AR6 projection tool reports total rates of 2.2 mm yr^{-1} (Malin Head) and 2.4 mm yr^{-1} (Belfast) for 2020 under SSP3-7.0 (NASA, 2025).

Differences between these values and our modelled rates likely reflect the differing reference periods and scenario-based nature of the projections. Our Malin Head rate (1.59 mm yr^{-1}, 1958–2024) is broadly consistent in magnitude with the IPCC estimate, indicating general agreement in regional sea-level change patterns.

To the east, Dublin Port exhibits a long-term instantaneous sea-level rate of ~1.30 mm yr^{-1} (1925–2024; 95% CrI: 0.97–1.63), while pre-2000 rates were lower, around 0.31 mm yr^{-1} (1925–2000; 95% CrI: −0.05 to 0.67), rising to 3.80 mm yr^{-1} (2000–2016; 95% CrI: 3.13–4.57), and reaching 6.05 mm yr^{-1} (2024; 95% CrI: 3.49–8.64) in the most recent year. These results are generally consistent with previous tide-gauge estimates for overlapping periods. For example, Shoari Nejad et al. (2022) report 1.1 mm yr^{-1} (95 % CI: 0.6–1.6 mm yr^{-1}) for 1953–2016 based on Bayesian linear regression–corrected data, whereas our mean rate is 1.41 mm yr^{-1} (1953–2016; 95% CrI: 1.15–1.67)—slightly higher, but both indicate an overall increase. Earlier analyses show modest and variable pre-2000 sea-level change around Dublin, with modelled rates of 0.29 mm yr^{-1} (1938–1961; 95% CrI: −0.41 to 0.97), declining to −0.10 mm yr^{-1} (1961–1980; 95% CrI: −0.70 to 0.44). These are broadly consistent with historical estimates of 0.6 mm yr^{-1} (1938–1961) and −0.3 mm yr^{-1} up to 1980 (Carter, 1982). Over 1938–1996, Woodworth et al. (1999) reported a long-term trend of 0.2 mm yr^{-1}, compared with our mean of 0.40 mm yr^{-1} (95% CrI: 0.10–0.69). Differences between studies are expected due to varying models, corrections, and data coverage; nevertheless, all indicate relatively little increase pre-2000, followed by pronounced acceleration post-2000. Palaeo-reconstructions using saltmarsh foraminifera indicate a similar century-scale rate since the early 19th century (1.6 ± 0.9 mm yr^{-1}; Roseby et al., 2023).

Across Ireland's south to west coasts, the highest modelled instantaneous sea-level rates are observed. Cork Harbour shows a long-term mean rise of 3.29 mm yr^{-1} (95% CrI: 2.76–3.85; 1971–2024), with instantaneous rates reaching Cork 6.84 mm yr^{-1} (95% CrI: 4.32–9.42) in 2024. These values exceed the longer-term historical linear trend of 2.2 mm yr^{-1} reported by Pugh et al. (2021) for 1842–2019, providing a robust baseline for comparison, corresponding to a cumulative rise of over 40 cm (Cubie, 2024). Tarbert similarly shows elevated rates, with a long-term modelled smoothed sea-level mean rate of 3.59 mm yr^{-1} (95% CrI: 3.08–4.24; 1964–2024) and recent smoothed rates reaching 7.21 mm yr^{-1} (95% CrI: 4.70–9.75). River discharge from the River Shannon may also influence the observed sea-level rates at Tarbert and Kilrush, as shown in studies of other estuarine systems (e.g., Piecuch et al., 2018). On the west coast, Galway Harbour exhibits a mean instantaneous sea-level rate of 2.44 mm yr^{-1} (95%

CrI: 1.87–2.97; 1967–2024), reflecting substantially higher rates in the 21st century, reaching Galway 6.08 mm yr^{-1} (95% CrI: 3.49–8.54) in 2024, consistent with the strong regional acceleration. In the absence of long historical records, it is difficult to accurately ascertain early-century rates for Cork, Tarbert, and Galway; however, the results indicate substantially lower rates prior to 2000, followed by marked acceleration post-2000.

Comparison of mean instantaneous rates across all sites over the overlapping period 1971–present revealed that Belfast had the lowest overall rate (1.22 mm yr^{-1}; 95% CrI: 0.73–1.64). Malin Head (1.99 mm yr^{-1}; 95% CrI: 1.47–2.47) and Dublin Port (2.49 mm yr^{-1}; 95% CrI: 2.06–2.96) exhibited intermediate rates, while higher values were observed in the west and southwest, with Galway at 2.59 mm yr^{-1} (95% CrI: 1.98–3.13), Cork at 3.29 mm yr^{-1} (95% CrI: 2.76–3.85), and Tarbert showing the highest rate at 3.84 mm yr^{-1} (95% CrI: 3.35–4.41).

The combined mean GIA-informed regional component across all tide-gauge sites is shown in Figure 4.15. Between 1925 and 2024, the mean modelled instantaneous sea-level rate was 2.30 mm yr^{-1} (95% CrI: 1.72–3.01), estimated from the posterior regional derivative within the NI-GAM framework with site-specific glacial isostatic adjustment (GIA) included as a covariate. The smoothed regional curve (Figure 4.15) indicates a clear acceleration in sea-level rise over the 1925–2024 period, with substantially higher rates in the post-2000 interval relative to the early twentieth century. This is consistent with the regional-scale acceleration identified in the NI-GAM posterior, where mean rates increase from approximately 1.20 mm yr^{-1} (95% CrI: 0.58–2.07 mm yr^{-1}) in the early period to 4.58 mm yr^{-1} (95% CrI: 3.34–5.57 mm yr^{-1}) in the post-2000 interval. This reflects changes in the time-varying regional rate component rather than cumulative RSL. The magnitude of long-term change implied by the integrated signal is not directly estimated here and should not be interpreted as a direct total sea-level rise without explicit temporal integration of the posterior rate field. These results are broadly consistent with global twentieth-century estimates of 10–25 cm (IPCC, 2021; Mu et al., 2025).

As noted previously, the ICE-5G Peltier and Bradley model families produce some of the largest GIA corrections across Ireland, with uplift rates approaching approximately −1.5 mm yr^{-1} at Malin Head and −1.26 mm yr^{-1} at Belfast in the ICE-5G configuration. These rates are larger than those produced by the selected Bradley_thick_71p510 model. However, the ICE-5G configuration was not adopted as the preferred model as it was not retained within the final model selection based on the inter-site performance criterion, and was included only within the full evaluation ensemble for comparison purposes.

Earlier tide-gauge studies reported near-zero to slightly negative RSL trends in northeastern Ireland, with site-specific estimates of approximately −0.16 mm yr^{-1} (Malin Head) and −0.20 mm yr^{-1} (Belfast) (Orford et al., 2006). The present results are broadly consistent with these findings in terms of magnitude and uncertainty, and with wider evidence indicating relative uplift in Northern Ireland, while southwestern Ireland experiences comparatively lower uplift or slight subsidence (Bradley et al., 2011; Bradley et al., 2023; Kirby et al., 2023).

GIA scenarios for southern and western Ireland are generally less pronounced, with many model configurations indicating slight subsidence or near-stable vertical land motion. Although the Bradley_thick_71p510 configuration and the Bradley model family more broadly produce a stronger north–southwest gradient than alternative model families such as ICE-6G or GLAC1D, this does not constitute evidence that these models provide the most accurate representation of Irish GIA. Rather, they may better express the spatial contrast between uplift in the north and comparatively lower uplift or subsidence in the south and west.

Similarly, although the older ICE-5G Peltier configurations are more dated and may be less reliable in a broader global context, they remain informative sensitivity tests because they also emphasise the north–southwest GIA gradient. Consequently, while ICE-5G was not selected within the final model selection, it is retained within the full ensemble as a sensitivity reference for regional-scale spatial variability in Irish glacial-isostatic adjustment.

For sensitivity testing, each candidate GIA model was independently supplied as the site-specific linear-rate covariate within the NI-GAM framework, and the full model was re-fitted prior to posterior extraction. Across all tested GIA configurations, posterior-derived long-term site-mean RSL rates (μ_pred_deriv) remained broadly consistent, with inter-model differences in site-specific long-term rates generally ≤0.2 mm yr^{-1}, indicating limited sensitivity of decadal-scale site-level trends to the choice of GIA forcing within the tested ensemble. This relative stability indicates that deterministic post-estimation removal of the linear GIA component primarily shifts the absolute magnitude of site-level rates without materially altering the underlying temporal structure of the NI-GAM posterior. While inter-site patterns and relative trends remain broadly consistent across GIA models, the choice of GIA forcing affects the absolute magnitude of the inferred regional mean rate. The regional component (r_pred_deriv) represents the posterior-estimated shared sea-level signal across all sites, conditioned on the specified GIA model within the NI-GAM framework. Across the tested configurations, the estimated regional mean instantaneous rate ranges from ~1.9 mm yr^{-1} (ICE-

6G_BC_hybrid_71p320, which produces the smallest changes to site-specific rates among the tested GIA models) to ~2.5 mm yr^{-1} (ICE-5G), with substantial overlap in 95% credible intervals. This indicates that the regional component exhibits greater sensitivity to GIA forcing than inter-site relative patterns, reflecting its role as the dominant shared signal in the model decomposition. The multi-model ensemble mean is ~2.2 mm yr^{-1}. Overall, the regional mean modelled instantaneous sea-level rise rate over 1925–2024 is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01). In a broader context, direct comparisons between Ireland and Great Britain are complicated by differing glacial histories. The thicker Celtic Ice Sheet over Britain drove stronger glacial isostatic adjustment, whereas Ireland's thinner ice cover produced smaller RSL changes (Shennan et al., 2018).

Hogarth et al. (2021) reconstructed long-term sea-level records for Great Britain using an extensively augmented and spatially clustered tide-gauge dataset, applying Glacial Isostatic Adjustment (GIA) corrections, and reported a post-1900 weighted linear rate of 2.12 mm yr^{-1}, with evidence of long-term acceleration from the 19th to 20th century. Our posterior mean estimate of ~2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01), derived using a NI-GAM framework with the Bradley_thick_71p510 GIA model, is broadly consistent in magnitude with these earlier estimates, although differences in modelling approach, temporal coverage, and GIA specification limit strict one-to-one comparability. Notably, estimates using ICE-6G BC_Hybrid_71p320 (~1.9 mm yr^{-1}) fall closer to the lower bound of this range and are of similar magnitude to ICE-6G_C-based corrected reconstructions reported in Hogarth et al. (2021).

The effect of GIA adjustment on instantaneous rates was examined by subtracting site-specific GIA corrections from the NI-GAM posterior rate field (μ_pred_deriv) after model estimation, producing a deterministic derived field in which the regional sea-level signal is retained while vertical land motion associated with the Bradley_thick_71p510 model is removed. This transformation preserves the temporal structure of the posterior rate field, with uncertainty inherited from the original NI-GAM output and not propagated through the GIA correction or any subsequent model re-estimation. As a result, the adjustment represents a deterministic post-estimation modification of the GIA contribution to the estimated sea-level rates.

Cross-validation of the NI-GAM model demonstrates that the smoothing and hierarchical borrowing of information produce well-calibrated reconstructions of relative sea-level time series, which underpin the derived instantaneous rate estimates. Predictive performance is consistent across sites, with 95% posterior predictive intervals effectively capturing observed variability, and site-specific coverage ranging from 0.931 to 1.000. Some variation is evident across sites (e.g. Belfast and Cork showing slightly lower coverage values), likely reflecting differences in observational uncertainty. Quantitative evaluation using 10-fold cross-validation shows low root-mean-squared errors (0.025–0.039 m), indicating strong predictive skill and minimal bias. The smoothing process may influence the representation of short-term variability during periods of rapid change (e.g. the 2000s–2010s), but the model still effectively captures regional and site-specific trends, even in records with temporal gaps.

Some uncertainty remains in the observational data. Errors in digitization can occur (McLoughlin et al., 2026a), and tide-gauge data may contain instrumentation errors (Gobron et al., 2019). While quality control reduces much of this noise, gaps in records—sometimes spanning several months or more—can still affect estimates. Atmospheric adjustments help reduce high-frequency variability but do not eliminate all uncertainty.

The reslr package produces robust regional estimates by integrating data from multiple sites (Upton et al., 2024). This hierarchical modelling approach allows sites with sparse records, such as Cork, Tarbert, and Galway, to benefit from information borrowed from neighbouring sites, resulting in continuous estimates even during periods of limited observations. A consequence of this strategy is that sites with short or incomplete records, such as Cork and Tarbert, may receive nearly identical instantaneous rates of rise during these intervals. While this reduces noise and increases the stability of the regional trend, it may smooth over real, site-specific variability. This approach highlights the ability to capture coherent regional trends, while emphasizing that caution is warranted when interpreting short-term or site-specific differences during periods of sparse data (Upton et al., 2024).

In 2024, posterior mean instantaneous rates from the derivative field (μ_pred_deriv) exceed ~5–7 mm yr^{-1} at most sites, including Dublin Port, Galway, Cork, and Tarbert. These values are derived from the NI-GAM posterior derivative field (μ_pred_deriv) and therefore represent modelled instantaneous rates rather than direct year-to-year changes in observed tide-gauge records. These elevated rates highlight the importance of exposure at vulnerable coastal locations, providing context for interpreting spatial differences in sea-level rates across Ireland. Belfast, along with Dublin, Cork, and Galway, faces significant potential impacts due to dense urban populations and exposure to storm surges and coastal flooding (Department of the Environment and Local Government, 2001; Paranunzio et al., 2022).

The southwest and west, including Cork, Tarbert, and Galway, are particularly vulnerable due to local subsidence and sparse observational data. Limited tide-gauge coverage, notably in the Shannon Estuary, introduces uncertainty in local sea-level trends, complicating risk assessments. Projected long-term average rates towards the end of the century are highest in the southwest (3.3–4.8 mm yr^{-1}) and lower in the northeast (2.2–3.7 mm yr^{-1}) (MWP, 2024). Enhanced tide-gauge monitoring would improve understanding of local variability and support adaptation planning, particularly considering the projected acceleration in global mean sea level (Wang et al., 2024).

4.9 Conclusions

A key objective of this study was to reconstruct historical mean sea-level (MSL) change across Ireland, with particular focus on the south and southwest, where long-term observations have been limited. Accurate assessment of MSL change ideally requires long, continuous records, and the hierarchical framework applied to Irish tide-gauge data provides robust reconstructions of both long-term trends and recent accelerations. By integrating archival and modern tide-gauge data, including Cork, Tarbert, and Galway, this study fills critical spatial gaps and situates Irish sea-level changes within a broader regional context, complementing previous studies in the UK.

The overall regional mean modelled instantaneous sea-level rate from 1925–2024 is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01). After accounting for GIA adjustment, site-level rates are slightly shifted but preserve the same spatial pattern. In 2024, posterior mean instantaneous rates from the NI-GAM derivative field (μ_pred_deriv) are elevated across Ireland, ranging from approximately 5.6 to 7.2 mm yr^{-1}, with the highest values consistently observed in the southwest (Cork, Tarbert, and Galway), indicating increased vulnerability to accelerated sea-level rise and coastal flooding. While the regional reconstruction provides robust island-wide trends, site-specific instantaneous rates should be interpreted with caution, as the smoothing framework does not fully resolve short-term variability at individual sites.

Adjustments for datums, atmospheric effects, seasonal cycles, and GIA (both within the NI-GAM formulation and in post-estimation sensitivity adjustments) were applied. Under the Bradley_thick_71p510 model, GIA-induced spatial differences are clearly resolved between northern and southern sites. However, alternative GIA model families produce differing estimates of vertical land motion, particularly in Northern Ireland. It should therefore be noted that this study adopts a single GIA configuration that provides the most consistent fit within the NI-GAM framework, rather than identifying a definitive “best” GIA model. This choice reduces inter-site discrepancies within the model but does not constitute a formal model selection assessment across GIA scenarios.

Cross-validation confirms the predictive performance of the regional reconstruction, demonstrating that even locations with shorter or sparse records can be reliably incorporated. Short-term variability at individual sites is smoothed, emphasizing the strength of the regional trend.

These findings highlight the vulnerability of Ireland’s coastal areas. Urban centres such as Cork and Dublin face heightened risk from rising seas and storm surges. Northern sites remain exposed to flooding in the context of accelerated sea-level rise across the island, particularly since the 2000s. The combination of accelerated sea-level rise, local subsidence, and urban exposure highlights the importance of targeted monitoring and adaptation planning.

Overall, this study demonstrates the value of integrating modern statistical frameworks with archival data. It provides a comprehensive assessment of sea-level trends across Ireland and strengthens the foundation for scientific understanding and evidence-based policy development. Future work will focus on extending this reconstruction to additional sites and refining corrections to improve regional understanding of both GIA contributions and implications for policy implementation in vulnerable areas. Past studies of mean sea level in Ireland reported relatively low rates of rise (Carter, 1982; Woodworth et al., 1999; Orford et al., 2006), and only recent individual site studies have shown rates of sea-level rise consistent with climate change-driven trends (Pugh et al., 2021; Shoari Nejad et al., 2022). This study synthesizes all available mean sea-level data across the island of Ireland, presenting for the first time a more geographically balanced view. This synthesis reveals a clear acceleration in sea-level rise since the early 2000s, with substantially higher recent instantaneous rates compared to the early twentieth century (approximately 4.6 mm yr^{-1} versus 1.2 mm yr^{-1}). The results indicate that Ireland now experiences rates of sea-level rise that are comparable to, or higher than, global averages, with the south and west being more vulnerable than the east and north. In the 21st century, with accelerating sea-level rise, Ireland’s heavily coastal population will need to adapt to the associated higher frequency of coastal flooding and inundation.

5. Discussion, future work, and concluding remarks

The final section revisits the key aims, objectives, and findings of the thesis, reviews outcomes from chapters 2–4, discusses its limitations, and outlines directions for future research.

5.1 Introduction

The primary aim of this research was to improve our understanding of mean sea-level change around Ireland—particularly along the west coast—by rescuing, digitising, and integrating archived paper tide-gauge records with existing datasets. The study also explored the feasibility of using students to assist in data digitisation, with the goal of developing a novel approach for error checking student-digitised tidal data. This approach could be applied not only to sea-level records but also to other types of environmental datasets, such as fluvial records, for training purposes. All digitised and retrieved data were quality-checked before being integrated into the mean sea-level change analysis.

The aims were addressed through the following four thesis objectives, as set out in Chapter 1:

Thesis Objective 1: Retrieving all available historical marigram archives of sea level along the east, north, south, and west coasts of Ireland to initiate the digitisation process (Chapters 2 and 4).

Thesis Objective 2: Advancing the methodology needed for the digitisation of historical marigrams (Chapter 2).

Thesis Objective 3: To integrate citizen science into college assignments, involving students in the digitisation of historical sea level records, with the goal of testing the feasibility and effectiveness of this approach (Chapter 3).

Thesis Objective 4: To contextualize the historical Irish mean sea level changes along the east and south coasts of Ireland and validate all digitised QC data with other published sea level data for similarities in trends and frequencies (Chapter 4).

This final chapter summarises the main research findings, discusses limitations, and identifies directions for further research.

5.2 Summary of the key research findings

5.2.1 Thesis Objective 1: Retrieving all available historical marigram archives of sea level along the east, north, south, and west coasts of Ireland to initiate the digitisation process (Chapters 2 and 4).

The goal of this objective was to retrieve all possible historical marigram archives of sea level along the east, south, and west coasts of Ireland to initiate the process of digitisation (Chapter 4). Despite extensive efforts spanning three years, no complete long-term datasets were obtained for the southwest of Ireland, where records often exceed 40 years in partial coverage. Multiple public bodies—including port authorities, the Port of Cork (Tivoli), the Office of Public Works (OPW), and the Electricity Supply Board (ESB)—were approached to access historical records. Collaboration with the OPW allowed an onsite visit in Headford, Galway, providing valuable access to archived datasets.

Engineers at the Port of Cork (Tivoli) facilitated access to all available tidal records, yielding datasets for the 1970s (1971–1974) and 1980s (1981–1984). Limited observations—only a couple of weeks at most—were also found from the 1960s, 1977–1978, and a single daily record from 1936. Reports suggested marigrams from the 1930s had existed but may have been lost in a 2000s flooding event when temporarily stored for archival purposes (Devoy, personal communication, 2024). Additional tidal data images from stations at Aghada, Passage West, Tivoli, Currabinny, Ballinacurra, and Monkstown were uncovered in the 1977 Cork Harbour Pollution Report (Vol. 8) (O'Sullivan, 1977); however, these records were brief, with the largest, Monkstown, containing only a few months of data suitable for digitisation.

Longer records were available for stations 24061 (Ferry Bridge, Maigue) and 23061 (Ferry Bridge, Feale), though examination revealed strong fluvial influence at both sites. At fluvially influenced sites, low-tide portions of the trace were often flattened, masking tidal minima and complicating extraction of true tidal amplitudes (Richards et al., 1993). Portions of the Maigue record displayed tidal characteristics, but extensive freshwater contributions and fluvial flats obscured the tidal signal, complicating digitisation and analysis. Some images were experimentally digitised using WebPlotDigitizer; however, with a week of data in a single trace, it was not feasible to digitise at hourly intervals. An alternative software, Un-Scan-IT, was tested where traces were clear and offered potential for digitising these types of records (UN-SCAN-IT Graph Digitizer, 2025, https://www.silkscientific.com/graph-digitizer.htm). While this tool was not used in the main research of this thesis, it proved useful for digitising certain high-quality week-long (or longer) traces where multiple traces did not overlap. Ultimately, the data from these sites were generally strongly influenced by fluvial inputs and were therefore discarded. Consultation with OPW engineers suggested that other long-term records may exist with the ESB, although their locations remain unknown. Attempts to contact the ESB regarding a 1960s Kilmokea dataset (Murphy et al., 2003) were unsuccessful.

A notable success was the recovery of a long dataset (>20 years) for Tarbert Island, Kerry, previously held by the ESB and now in the possession of the OPW, providing the first substantial tidal record for the southwest of Ireland. The Shannon Estuary water-level dataset described in Sheehan and Healy (2006) could not be obtained despite repeated attempts to access it and contact the authors, and was therefore excluded from the analysis. Based on available metadata and its strongly fluvial-influenced estuarine setting, its suitability for reconstructing regional sea-level trends is considered limited.

Additional data for Galway were obtained from NOC/BODC (BODC, 2025). Surveys from the late 1960s and early 1970s yielded four years of data (1967–1970) from Galway near Nimmos Pier. Although relatively short, this dataset was important given the scarcity of west coast records. The data were provided in Julian time and converted to standard datetime format, with no digitisation required.

Long-term records for the northeast of Ireland were available from the following sources: Malin Head (PSMSL), Belfast (Murdy et al., 2015), and Dublin Port (PSMSL and Shoari Nejad et al., 2022). All three stations provided records exceeding 50 years (Malin Head: 1958–present; Belfast: 1901/1902–2010; Dublin Port: 1923–present, including modern datasets; note that for Chapter 4, only records from 1925 onwards were used), offering a robust dataset for trend analysis in Chapter 4.

Modern data from the 2000s were obtained from MI and OPW; however, substantial gaps remained at stations in Galway, Cork, and Tarbert. Belfast records, which we used starting from 1925, ended in 2010, with the extension to 2015 being complemented by Bangor data (2011–2015). Malin Head, with additional Portrush data (1996–2003, 2015), produced a near-complete dataset when combined with MI and OPW records. Dublin Port (available digitised from 1938), complemented with Dún Laoghaire (1925–1933), Arklow (2003–2006) and Howth data (2007–2024), produced a near-complete dataset.

Despite gaps in records and some lost archives, the combined historical and modern datasets represent the most comprehensive compilation of Irish sea-level records to date, providing the first substantial tidal datasets for the southwest of Ireland. Together, these data offer a robust foundation for reconstructing mean sea-level changes across Ireland and evaluating long-term regional trends, while also illustrating the challenges inherent in historical data retrieval, digitisation, and quality assessment. Extending beyond Ireland, other regions worldwide, including India, similarly possess extensive historical tide and sea-level chart archives that could benefit from systematic digitisation and data rescue initiatives.

5.2.2 Thesis Objective 2: Advancing the methodology needed for the digitisation of historical marigrams (Chapter 2).

One of the key challenges addressed in this thesis was the accurate digitisation of historical sea-level marigrams. Many of these archival records exhibited physical issues such as bends, skewing, and paper distortion, which can compromise the accuracy of tidal data—often beyond the target precision of ±1 cm. In addition, some images were affected by blurring, overlapping traces, or faint ink, conditions under which automated digitisation techniques typically struggle to perform reliably. Chapter 2 outlines a novel methodological framework developed to overcome these challenges and ensure precise and reproducible digitisation of historical sea-level records.

The aims of the project were to: (i) digitise scanned marigrams at hourly intervals; (ii) identify sources of error within a 10 mm threshold by calculating offsets between the original and adjusted data; (iii) compare the unadjusted digitised data with the rectified (adjusted) data; and (iv) validate and contextualize the adjusted data through comparison with measurements from nearby sites.

All Dún Laoghaire archives were scanned using a high-resolution Metis scanner. The free, open-source software WebPlotDigitizer (https://automeris.io/) (Rohatgi, 2024) was used to digitise the data. The process began by recording each daily trace at hourly intervals. For each hour, the nearest foot-mark grid values on the marigram were digitised and compared with the actual (known) foot values to calculate offsets. These offsets were then applied to the digitised data, ensuring hourly measurements were accurate to within 1 cm.

Comparison between the original digitised and adjusted data showed yearly offsets ranging from –3.96 mm to 13.72 mm per year, with some images exceeding 20 mm. Applying these corrections brought the data to an accuracy within ±1 cm.

The historical marigrams often exhibited bends and skews on both sides, requiring the full grid to achieve precise digitisation. However, further investigation introduced a Reduced Grid Approach, where a single point at a selected foot interval in the middle of each hourly trace was used, adjusted to match the trace's offset for that hour. While this method can reduce digitisation time and achieve accuracy within ~1 cm, offsets at the top or bottom of traces may introduce small inaccuracies compared with the full-grid method.

However, scaling the data can significantly affect the accuracy of the final digitisation, making consistency essential. In the Dún Laoghaire data, thick lines represented foot intervals, and the top of each line was used as the reference for digitisation across all records. If the bottom of the line thickness had been used consistently, the resulting values would differ slightly. Using the top of each line as the reference minimised systematic offsets, which could otherwise approach or slightly exceed 1 cm, ensuring consistent accuracy throughout the dataset.

This approach was also important for human oversight when visualizing the images. In some cases, handwritten notes, pencil annotations on the sheets, broken clocks, or changes to the recording drum could result in duplicate dates, such as in November 1925. This included inspection of any available annotations on the marigrams, including marginal notes where present; however, reverse-side handwritten notes were not consistently available across the dataset. Human input helped identify and resolve these issues during digitisation.

Marigrams with predominantly poor-quality data were discarded, whereas usable traces within lower-quality images were retained. Traces with irregular shapes, abrupt changes, or inconsistent patterns were excluded, as these likely reflect measurement errors. Occasionally, traces continued onto a new marigram, causing offsets between consecutive records. In such cases, the final value of the previous marigram was used to maintain continuity, accounting for potential operational issues such as drum changes or calibration inconsistencies.

The dataset generated in this research is publicly available on Pangaea (https://doi.org/10.1594/PANGAEA.967078 ; McLoughlin et al., 2024b) and is organized into three main levels, along with a folder of grid values and a README file describing the contents.

1. Level 0 – Raw Images: Contains compressed marigram images organized by year (1925–1931). Each year has subfolders separating Good_Quality_Images and Poor_Quality_Images.

2. Level 1 – Digitised Data: Contains Excel files of hourly digitised heights (in feet relative to chart datum) for each year. These represent raw, unadjusted data.
3. Level 2 – Adjusted Data: Contains Excel files of hourly data corrected for offsets using the nearest foot interval, achieving an overall accuracy of 10 mm (1 cm).
4. Grid Values: Contains yearly Excel files detailing the recorded foot intervals, actual foot intervals, offsets, and datetime. This information underpins the accuracy of Level 2 Adjusted Data.

The final adjusted digitised data show that the M2 tidal amplitude in Dún Laoghaire Harbour, Dublin, ranged from 1.25 to 1.36 m, with phase lags between 323.1° and 327.4°. Daily mean sea level (MSL) values from the Dún Laoghaire records for the overlapping years (1925–1927 and 1931) exhibited very similar patterns to the Northern Ireland Belfast Harbour data, with nearly identical peaks and troughs. These data provide a valuable resource for further tidal analysis and more accurate historical estimates of sea-level rise.

This methodological approach demonstrates that, despite archival challenges, historical marigrams can be converted into high-quality datasets suitable for modern sea-level research. The workflow is also transferable to other digitisation software, such as WebPlotDigitizer (though the free version offers limited precision) and desktop-based applications like DataThief (2023), Engauge Digitizer (2023), and GetData Graph Digitizer (2023). In this study, several free and open-source tools—Engauge Digitizer, WebPlotDigitizer, and GetData Graph Digitizer—were evaluated for marigram digitisation. By generating precise hourly and daily records, the study provides essential data for reconstructing historical tidal regimes and validating contemporary models. It takes a total of six days to process one year of data: two to three days for digitising (excluding the digitisation of the underlying grid values for adjustment) and another three days for digitising the grid values for adjustments. The work underscores the importance of careful digitisation and rigorous quality control in linking historical observations with modern environmental science, enabling more reliable reconstructions of past sea-level variability.

5.2.3 Thesis Objective 3: To integrate citizen science into college assignments, involving students in the digitisation of historical sea level records, with the goal of testing the feasibility and effectiveness of this approach (Chapter 3).

The accurate digitisation of historical tidal records is a considerable challenge and requires training for external participants, such as students or citizen scientists. While the technical process, including grid adjustments and tracing tidal curves, is described in Chapter 2, Objective 3 focused on adapting these methods for students. Participants were given training instructions to ensure careful identification of dated traces and avoid confusion from overlapping lines. A robust error-checking protocol supported accurate data extraction.

Two previous student-led tidal data digitisation phases (i.e., distinct course projects) in climate and oceanography courses were examined. In 2023, postgraduate students in the Climate Change MSc programme worked with tidal records from Tivoli, Cork. Several students produced reliable results, whereas others faced challenges with scaling and interpreting the data, leading to inconsistencies. A similar undergraduate project, involving 54 students digitising tidal records from Dublin Port, found that only 22 datasets met the required quality standards.

A notable drawback was that much of the data produced also required manual correction of the historical records, and no robust error-checking protocol was employed. Following the lessons learned from the early phases, a robust error-checking protocol was deemed necessary, along with a training phase using clearer, more straightforward daily marigram traces. This approach allowed students to first grasp the principles and techniques of digitising daily traces before progressing to more complex historical images. In Phase 1 (2024–2025) of the undergraduate oceanography module, students worked with tidal data from Kilrush Harbour (2019–2021). These modern data were downloaded from the Irish Marine Institute's ERDDAP server and replotted to resemble a historical marigram with seven daily traces on a single image. Although artificial, these training datasets helped students practice identifying daily traces and correctly determining high and low tidal points. In GY310B Geography Research Workshops (Phase 2), the Dún Laoghaire Harbour data from 1925, from Chapter 2, were used. Training tidal datasets were created using real historical tidal records (McLoughlin et al., 2024a, 2024b; Phase 2A – Training). Students digitised both the training and historical tidal data (Phase 2B), which were derived from the same underlying dataset. Datasets deemed ‘Acceptable (Minor Revisions)’ were considered to meet the accuracy requirements for analysis.

Comparison of the student-digitised data with the verified reference dataset in Phase 1 showed that 63% of students produced datasets that met the requirements for accurate digitisation, allowing for minor omissions. Thirteen percent of submissions required resubmission, while the remainder needed revisions. A common source of error was students' failure to identify days with only three tidal turning points (highs and lows), where the fourth turning point occurred early on the following day's trace, rather than the typical two highs and two lows per day. In Phase 2, 69% of students produced digitised datasets that were deemed acceptable, requiring only minor revisions. In Phase 2B, this proportion decreased to 56%, likely due to the greater complexity of the real historical Dún Laoghaire images compared with the artificially generated training datasets used in the error-checking exercises. Common errors across all phases included incorrectly scaling the X and Y axes of the images, consistent misidentification or misdating of traces, and Excel formatting issues, such as incorrect date or datetime entries. Students who had previously completed Phase 1 exhibited slightly higher accuracy in Phase 2, with an average score of 13.28/15 (88.5%) compared to 12.5/15 (83.3%) for students without prior experience, indicating that prior training provided a modest advantage.

Student engagement in Phase 1 was evident from the questionnaire results, with 96% of respondents agreeing or strongly agreeing that the task helped them develop valuable skills related to the experimental digitisation of tidal data. Additionally, 90% agreed or strongly agreed that working with marigram images was clear and easy to follow. This activity also provided a significant learning opportunity to illustrate the imperfect nature of data and informed improvements to the visual aids and resources provided to students.

Student support was a key factor in the success of this research. Resources included tutorial videos, comprehensive data extraction manuals, color-coded marigram images, and prompt tutor assistance for questions. These materials were made available ahead of time, enabling students to receive immediate feedback and resolve issues as they worked through the tasks.

The research has resulted in several key outcomes. While these outcomes reflect student and citizen science participation, professional specialists would approach digitisation differently, relying on expertise and experience rather than structured training. Their approach generally yields higher initial accuracy and less reliance on supervised error-checking, providing a benchmark for evaluating student-led efforts: i) Systematic error-checking is essential to maintain high data quality. ii) A training method has been developed that is applicable to students, citizen scientists, and educators, and may also support future Machine Learning (ML) model development—a step currently limited by the complex visual nature of marigrams. By refining this approach and fostering collaboration among participants, future digitisation efforts can preserve high-quality historical tidal data and enhance understanding of sea-level trends and climate impacts. iii) Targeted training improves digitisation accuracy, thereby strengthening the foundation for producing reliable climate and weather data from historical archives, which is crucial for climate resilience research.

5.2.4 Thesis Objective 4: To contextualize the historical Irish mean sea level changes along the east and south coasts of Ireland and validate all digitised QC data with other published sea level data for similarities in trends and frequencies (Chapter 4).

As a significant and growing proportion of the world's population lives in close proximity to the coastline, understanding sea-level rise and coastal vulnerability is of paramount importance to society. In Ireland, this is particularly relevant, with approximately 40% of the population living within several kilometres of the coast (Wall et al., 2020). Long-term sea-level data are essential for quantifying sea-level change and identifying long-term trends. However, in the context of the island of Ireland, long-term sea-level records have historically been available primarily in the northeast, making comprehensive island-wide assessments challenging.

To date, no long-term study has examined mean sea-level change across the entire island of Ireland. Chapter 4 (McLoughlin et al., 2026b) addresses this research gap by integrating data from multiple sources, including newly gathered and digitised records from the southwest of Ireland, processed using appropriate and validated methodologies to ensure data accuracy (McLoughlin et al., 2024a). This includes the first long-term sea-level record for Tarbert (County Kerry), spanning approximately ~22 years from the 1960s to the 1980s, as well as data from Cork and Galway. An integrated statistical approach, applying all available tide-gauge sites within the reslr framework (Upton et al., 2024), yields an overall Ireland-scale mean instantaneous sea-level rise rate of approximately 2.30 mm yr^{-1} (1925–2024), derived from the posterior regional rate component (r_pred_deriv). This represents the spatially coherent sea-level signal shared across all sites within the NI-GAM decomposition.

Long-term instantaneous sea-level rates varied across Ireland. Site-specific instantaneous rates are derived from the full posterior instantaneous rate field (μ_pred_deriv) by averaging across spatial grid cells associated with each site. Belfast exhibited a lower mean rate of approximately 0.40 mm yr^{-1} (95% CrI: 0.07–0.74; 1925–2015), whereas Malin Head showed a higher mean rate of 1.59 mm yr^{-1} (95% CrI: 1.15–2.01; 1958–2024). Although Belfast experienced a lower rate, these results indicate that sea level in Northern Ireland is rising slightly rather than declining, broadly consistent with the low or near-zero rates reported by Orford et al. (2006). Differences between studies are expected due to methodological differences, longer and more complete observational records in the present analysis, and the use of a hierarchical spatio-temporal smoothing framework.

Dublin Port recorded a long-term mean instantaneous sea-level rate of around 1.30 mm yr^{-1} (95% CrI: 0.97–1.63), slightly higher than the 1.1 mm yr^{-1} reported by Shoari Nejad et al. (2022), and within the uncertainty range of Roseby et al. (2023), who reported 1.5 ± 0.9 mm yr^{-1} over the past two centuries. Previous analyses of Dublin tide-gauge records suggest low and variable sea-level trends through the mid-20th century, with differences largely attributable to methodological choices and data coverage. Despite this variability, there is broad agreement that sea-level rise remained modest prior to 2000 (Carter, 1982; Woodworth et al., 1999), followed by pronounced acceleration. Overall, rates at Belfast (1925–2000), Malin Head (1958–2000), and Dublin (1925–2000) were relatively small, further emphasizing the stability of sea-level rise before the 21st-century acceleration.

The south and west coasts of Ireland exhibit the highest long-term and instantaneous sea-level rise rates. Cork Harbour shows a long-term mean rate of approximately 3.29 mm yr^{-1} (95% CrI: 2.76–3.85), while Tarbert and Galway Harbour exhibit long-term rates of 3.59 mm yr^{-1} (95% CrI: 3.08–4.24) and 2.44 mm yr^{-1} (95% CrI: 1.87–2.97), respectively. Local factors, such as river discharge (e.g., the River Shannon), may also influence observed rates at estuarine locations such as Tarbert. Chapter 4 provides a spatially integrated estimate of mean sea-level change across the south and west of Ireland. Over the common comparison period (1971–2024), Cork shows a mean rate of 3.29 mm yr^{-1} (95% CrI: 2.76–3.85), while Tarbert shows a higher mean rate of 3.84 mm yr^{-1} (95% CrI: 3.35–4.41), reflecting sensitivity to the chosen temporal window. By comparison, Pugh et al. (2021) used a linear fit between 1842 and 2019 to estimate a rate of approximately 2.2 mm yr^{-1} for Cork sea-level change. This study confirms a higher rate and is consistent with a period of acceleration from the 1970s onwards, broadly comparable with earlier estimates.

Instantaneous rates show clear acceleration in the 2000s: Belfast reached 4.05 mm yr^{-1} in 2015, while all other sites exhibit elevated rates in 2024, with Malin Head at 5.58 mm yr^{-1}, Dublin Port at 6.05 mm yr^{-1}, Galway at 6.08 mm yr^{-1}, Cork at 6.84 mm yr^{-1}, and Tarbert at 7.21 mm yr^{-1}. These rates may be slightly exaggerated due to smoothing, with credible intervals widening towards the end of the model. Nevertheless, all rates are plausible within the bounds of the credible intervals, with caution advised for Belfast due to the poorest predictive performance. Overall, these rates are consistent with global studies, confirming the recent acceleration in sea-level rise.

The combined mean modelled instantaneous sea-level rate across Irish tide-gauge sites over 1925–2024 is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01), derived from the posterior regional component (r_pred_deriv) of the NI-GAM decomposition. This represents the dominant shared sea-level signal across all sites, and is broadly consistent with global estimates of total sea-level rise of approximately 10–25 cm over the 20th century (IPCC, 2021; Mu et al., 2025). The regional mean sea-level rate estimated in this study is broadly comparable to that reported for Great Britain by Hogarth et al. (2021), who derive a post-1900 weighted linear trend of 2.12 mm yr^{-1} (±0.02 mm yr^{-1}, 1σ) from a spatially clustered, GIA-adjusted tide-gauge reconstruction that incorporates ICE-6G-based corrections among other sensitivity configurations.

Across the tested GIA scenarios, the choice of glacial isostatic adjustment model has a limited effect on inter-site trends in the posterior instantaneous rate field (μ_pred_deriv), with differences typically ≤0.2 mm yr^{-1}. However, the absolute magnitude of the regional mean is moderately sensitive to the GIA formulation, with ensemble estimates ranging from approximately 1.9 mm yr^{-1} (ICE6G_BC_hybrid_71p320 configuration, which produces the smallest changes to site-specific rates among the tested GIA models) to ~2.5 mm yr^{-1} under ICE-5G sensitivity tests. The multi-model ensemble mean is ~2.2 mm yr^{-1}, and all estimates overlap within their 95% credible intervals, indicating broad consistency across model choices.

The Bradley_thick_71p510 family of models is retained as the preferred configuration based on inter-site consistency criteria within the NI-GAM framework. These variants, including Bradley_thick_Northsea1_71p510 and Bradley_thick_Northsea2_71p510, produce highly similar inter-site variability and preserve a consistent north–southwest gradient in glacial isostatic adjustment. In comparison, the Bradley model family generally emphasises stronger spatial contrasts between northern and southwestern Ireland than alternative model families such as ICE-6G and GLAC1D.

While ICE-5G produces larger uplift magnitudes towards Northern Ireland (up to ~−1.5 mm yr^{-1} in Malin Head), it is not adopted in the final reconstruction due to its older ice history and Earth rheology assumptions, and its more limited incorporation of modern geodetic constraints.

As a result, it is retained only as a sensitivity test rather than a preferred representation of glacial isostatic adjustment in the Irish context.

Overall, these rates are consistent with global studies, confirming the recent acceleration in sea-level rise. Such elevated rates, particularly along the southwest and west coasts, have direct implications for coastal vulnerability, with areas like Cork, Tarbert, and Galway at increased risk due to local subsidence, sparse observational coverage, and exposure to storm surges and flooding. Improved monitoring and risk assessment are essential to inform adaptation planning in these high-risk regions.

5.3 Limitations and considerations for future work

5.3.1 Considerations and limitations in historical data retrieval and digitisation

The interpretation of mean sea level and its tidal and non-tidal behaviour relies on long, high-frequency observational records. Hogarth et al. (2021) suggest that records of at least 40 years are required to robustly estimate trends in mean sea level. Shorter records can be informative for assessing mean sea-level change (Woodworth, 2018; Woodworth, 1999; Pugh et al., 2021), but they generally lack the temporal extent needed to detect changes in the rate of rise. While the data presented in this thesis represent a significant and innovative advance in data rescue efforts for Ireland, additional historical sea-level records may yet remain undiscovered. This thesis developed a novel approach to sea-level data rescue in collaboration with ICARUS Maynooth University, the Marine Institute (funding body), and Met Éireann (providing scanning equipment), substantially advancing the recovery of historical sea-level records in Ireland, although further work remains to be done.

A further challenge is that some datasets influenced by coastal processes are also strongly affected by fluvial dynamics. Long water-level records from the Limerick region, including Ardnacrusha (1949–2002), Ballycorey (1956–2002), Grangebridge (1954–2002), and Croom (1972–2002), are documented by Sheehan & Healy (2006). Despite numerous attempts, it was not possible to contact the authors to obtain access to these data. Geographic assessment, including proximity to the coast and comparison of tidal characteristics with nearby coastal stations, suggests that although these records may be useful for analysing long-term water-level variability, they are of limited value for detailed tidal or mean sea-level analysis due to strong fluvial influence. Consequently, these datasets were excluded from this study.

Datasets on local sea level are often constrained by missing records, gaps, and other limitations. Voortman & De Vos (2025) found that, across two global local sea-level datasets, only ~15%

of locations had sufficient data to reliably estimate rates of rise, with suitable records predominantly located in the Northern Hemisphere and with Latin America and Africa severely under-represented. The remaining ~85% of datasets were unsuitable due to missing records, limited temporal coverage, or insufficient data quality. Geographic coverage of the suitable datasets is particularly poor in Latin America and Africa. These findings highlight that many regions lack adequate and usable local sea-level records, underscoring that data availability and quality remain major challenges in global sea-level research. Such insights are broadly consistent with the findings of this thesis, as the availability of historical records throughout Ireland remained limited and geographically uneven, even after substantial searches were conducted. Nevertheless, additional historical records may yet emerge or be uncovered in the future, presenting important opportunities to expand and integrate the work presented in this study.

A methodology was developed in this thesis to achieve approximately 1 cm accuracy for tidal images (marigrams) digitised at hourly intervals (Chapter 2/McLoughlin et al., 2024a). The NUNIEAU toolkit facilitates the digitisation of marigrams, allowing for automated processing that speeds up digitisation and improves accuracy (Pons et al., 2016). Even with the more recent implementation of the predicted tide trace, challenges remain when tide gauges produce very faint or weak signals that deviate from the predicted tide. In contrast, the approach described by Chapter 2, which uses WebPlotDigitizer (Rohatgi, 2024), remains largely manual. This method is time-intensive and prone to error, often requiring at least three days to digitise the data and another three days to digitise the underlying grid for badly distorted images; prior practice or training could increase this time further. For less distorted images, the reduced grid method can shorten the process, but the combined effort for a year of data, including both digitisation and grid application, is still roughly four to five days. The key advantage of this manual approach is that every image is visually inspected, providing crucial insights into the data and necessary adjustments—an aspect that can be missed with fully automated methods, as was particularly important for the Tarbert dataset. Work undertaken in Germany has developed automated methods for detecting, classifying, and correcting tide gauge anomalies using statistical and machine learning techniques (Soltau et al., 2023). These approaches have been shown to improve data quality and reduce uncertainties in tide gauge records, while also improving processing efficiency through automated detection and classification of anomalies, including spikes, stuck sensors, and other irregularities in high-frequency data, while preserving environmental events such as surges or tsunamis. Despite these advances, careful visual inspection of historical records, as implemented in this thesis, remains crucial for older or lower-resolution marigrams, where automated methods may be less effective. There is also an opportunity for future work to implement some of these newly established methodologies for historical datasets.

Continuous work is being undertaken to improve quality control of tidal data (Lin-Ye et al., 2023). In this thesis, efforts focused on ensuring the accuracy of digitised historical sea-level records. Although these measures successfully validated the datasets used, there remain opportunities to integrate modern quality-control techniques, such as automated error detection and cross-validation with contemporaneous datasets, to further enhance the reliability of long-term sea-level reconstructions.

Tide gauge measurements, along with human observations, are inherently imperfect, introducing extra variability in the records due to changes or gaps in recording methods (Woodworth, 2017). Instrumental errors can result in inaccurate recordings (Haigh et al., 2009). For example, timing shifts in tide gauges often arise from malfunctions such as blockages in the stilling well or clock errors, which interfere with tidal measurements (Agnew, 1986). Historical observations sometimes used apparent or solar time rather than mean time, and in a modern context, these adjustments need to be corrected before harmonic analysis can be performed (e.g., Ray & Talke, 2019). Work undertaken in this thesis encountered many of these issues in datasets for Dún Laoghaire, Cork, and Tarbert in particular. While significant progress was made in resolving issues such as timing offsets and discarding data where incorrect measurements were made; uncertainties always remain. Accounting for both digitisation and timing offsets, a total uncertainty of 0.02 m was applied to the Cork and Tarbert datasets, with the methods for estimating and applying these corrections documented in Chapter 4. By improving the accuracy and accessibility of historical sea-level records, this research lays a foundation for both future scientific investigations and informed decision-making in coastal management and climate resilience efforts.

Most datasets remain affected by key limitations. For example, when only a month or more of data is available on a marigram, accurately digitising this information can be extremely challenging (Latapy et al., 2023), to the extent that even future machine learning approaches may struggle where the data are indistinguishable. Many datasets also contain large temporal gaps; while years with only partial data can still be used, they may fail to capture important seasonal variability and do not provide complete annual mean sea-level estimates. These limitations may slightly reduce the robustness of trend analyses, as gaps in data can overlook important seasonal variability, even though overall trends remain broadly reliable. Additional overall limitations should also be considered, including uneven geographical coverage of tide-gauge sites, instrumental or methodological uncertainties such as timing errors and stilling well issues, and non-tidal influences such as fluvial effects or local subsidence, all of which may further affect the interpretation of historical sea-level records.

5.3.2 Integration of citizen science in sea level data rescue

Various projects integrating the role of citizen science (including students) have been successful with historical data. Such as in early 2021, a pioneering citizen science project successfully recovered around 16,000 pages of historical tidal data from Liverpool and Hilbre Island, laying the groundwork for future machine-learning-assisted transcription of handwritten observations (Latapy et al., 2023). Over 5 million historical sub-daily sea-level pressure observations from 160 British and Irish locations (1919–1960), once forgotten, were rediscovered and are now available for detailed synoptic analyses and future reanalyses (Hawkins et al., 2023). While the role of citizen science through student involvement was explored in this thesis, it evolved primarily into a training and methodological exercise, reflecting the inherent complexity of tidal datasets rather than a large-scale student digitisation project.

Talke et al. (2018) successfully extended Boston's historical tide record (1825–2018) by 50 years using a citizen-science approach, with students at Portland State University and Tufts University digitising archival data into spreadsheets. Although automated scanning and optical character recognition, enhanced by machine learning, can accelerate data digitisation, these methods remain limited by changes in historical document formats and the variability of handwritten notes, particularly in older records (Matthews et al., 2021). This underscores the continued importance of careful manual inspection, as implemented in this thesis (Section 5.3.1), and highlights the valuable contribution of human input through citizen science. It also points to opportunities for developing more robust automated techniques in the future.

Online platforms like Zooniverse (https://www.zooniverse.org/) offer the tools and infrastructure needed to organize citizen science projects and aggregate the contributions of volunteers (Matthews et al., 2021). However, implementing such projects requires careful planning, particularly regarding the training and resources needed to prepare participants. As discussed in Chapter 3, the greatest efficiency can be achieved by initially focusing on the digitisation of high and low tidal points, although days with only three turning points can occasionally lead to misidentification. The training materials and visual aids described in Chapter 3 present an ideal opportunity to develop structured volunteer training, beginning with simplified datasets derived from tidal harmonics of real data. Once volunteers understand daily tidal patterns, they can progress to digitising more complex historical marigrams, such as those from Dún Laoghaire. Nonetheless, the extensive training required means that the module serves chiefly to develop methodological skills rather than produce large-scale digitised data. In the final phase, when students in the GY310B research workshops digitised actual marigrams, only 56% of Phase 2B submissions met the quality standard, compared with 69% in Phase 2A (training datasets) and 63% in Phase 1 (tidal point identification), highlighting the challenges of maintaining accuracy in real-world digitisation.

Maynooth University is keen to facilitate the digitisation of tidal records; however, due to the extensive training required, incorporating this into module assessments would likely require a full module or dedicated project. As outlined in Chapter 3, a training methodology has been developed that is applicable not only to students but also to citizen scientists and educators, and which could further support the development of machine learning models. This approach not only trains students in digitising complex tidal data but could also be extended to include experienced or retired citizen scientists. The Marine Institute has expressed interest in supporting a potential citizen science app for digitising these records, and similar initiatives may also be of interest to Met Éireann, representing a promising future direction for uncovering additional historical tidal archives and further extending Ireland's long-term sea-level record.

Building on these observations, several lessons emerged from integrating students into a citizen science approach. The tasks performed by students are assumed to reflect challenges faced by real-world citizen scientists working with tidal data. The study highlighted common errors, including digitization mistakes (e.g., point placement or calibration errors), misidentification of tidal points, and spreadsheet errors, illustrating the difficulties inherent in processing complex tidal datasets. Insights from the student survey indicate that providing structured templates, tailored instructions, and supportive tutorials can reduce errors and maintain engagement. Tidal data digitization benefits from prior training and is better suited to a long-term project rather than a single assessment. Overall, the findings from this study provide guidance for planning future long-term projects or citizen-science initiatives involving historical sea-level data.

5.3.3 Validation and contextualization of historical sea-level data

Haigh et al. (2023) emphasise that high-frequency, quality-controlled tide-gauge records are crucial in the analyses of mean sea level, extremes, and coastal risk, showing the importance of rigorous validation when extending historical datasets through digitisation. In this study, thorough quality checks were applied by analysing the M2 tidal constituent, including mean sea level (z_0), phase lags, and amplitudes. In addition, statistical outlier detection was undertaken to identify and remove anomalous values. Together, these procedures ensured that the resulting datasets met the high standards required for reliable sea-level analysis (UNESCO/IOC, 2020).

As such, this thesis provides an example of careful data processing, with extensive quality control applied throughout. Months in which approximately half of the data were missing were removed to avoid potential bias, along with individual days containing more than four hours of missing observations. The records were carefully datum-controlled and adjusted for atmospheric pressure to account for seasonal effects. All datum adjustments were applied consistently. Where better information was unavailable, nearby tide-gauge time series were plotted to identify outliers and potential datum shifts (Hogarth, 2014). However, despite these corrections, some limitations remained, particularly the presence of missing months in the historical records, as discussed earlier. These gaps may have had a minor influence on the atmospheric adjustment for certain years. The use of Copernicus Climate Change Service ERA5 data (Hersbach et al., 2023; Copernicus Climate Change Service, 2025) and NOAA's 20CRv3 dataset (Slivinski et al., 2019; NOAA PSL, 2025) enabled consistent atmospheric correction and seasonal cycle removal to be applied to the sea-level records using linear modelling. Despite these corrections, the overall relative sea-level trend for Ireland remained robust, yielding a regional mean rate of 2.43 mm yr^{-1} (r_pred_deriv). This differs by less than 0.15 mm yr^{-1} from the atmospherically adjusted estimate of 2.30 ± 0.29 mm yr^{-1}, indicating that the applied corrections had only a minor influence on the data prior to model fitting in reslr.

The data used in this study, while quality-checked where possible, have some limitations. Although the digitised records were produced at an hourly sampling interval and are well suited to tidal analyses such as mean sea-level change (Pugh et al., 2021), they are less capable of resolving short-duration, sharply peaked events. Analysis of ocean tides, storm surges, and extreme sea-level events requires data collected at higher temporal resolution (Woodworth et al., 2019). Previous work has shown that hourly tide-gauge data can underestimate storm-surge maxima, highlighting the limitations of low-frequency historical records for extreme sea-level analysis (Lee et al., 2009). Similar limitations were noted by Murdy et al. (2015) during the digitisation of historical Belfast Harbour tide-gauge records, which were mostly digitised at 10-minute intervals, except for the late 1980s–2000, when only hourly intervals were available.

In this study, it would have been technically possible to digitise Dún Laoghaire at 15-minute intervals and Tarbert at 10-minute intervals, due to the fine gridlines available between hourly marks. However, it was not possible to digitise the Cork records at sub-hourly intervals, as they were available only in coarse 1-hour blocks. Consequently, hourly intervals were considered the most practical and consistent choice across most datasets. Even using software to extract data at minute-level resolution from the daily traces would require correcting for bends, skews, and offsets in both the vertical and horizontal alignments. Recent work in tide prediction indicates that machine learning algorithms can effectively model complex water-level variations even with incomplete or coarse data (Granata & Di Nunno, 2021). This highlights the potential for artificial intelligence (AI) and machine learning (ML) approaches to complement and extend traditional digitisation workflows in future studies, particularly where historical records are incomplete or unevenly sampled.

Machine learning (ML) techniques, such as gated recurrent unit (GRU)-based recurrent neural networks, have been used to reconstruct incomplete tide-gauge records by learning relationships between regional sea level variability and proxy climate data, particularly upper-ocean temperature fields. This approach allows complex nonlinear dependencies to be captured and improves reconstructions of past coastal sea-level variability (Radin & Nieves, 2021; Nieves et al., 2021). While this goes beyond the research conducted in this thesis and uses different data records, it further highlights the potential for modern machine learning algorithms to be integrated into the validation and reconstruction of historical tide-gauge records.

Future work could focus on digitising additional historical tide-gauge records for under-represented sites in Ireland if they are uncovered, and on applying machine learning (ML) techniques to enhance the accuracy and efficiency of digitisation where possible. Improving the digitization efficiency and quality of historical records can greatly strengthen scientific research (World Meteorological Organization, 2024). This study highlights that careful validation, datum adjustment, and quality control are essential for historical sea-level data, and demonstrates the potential for artificial intelligence (AI) and machine learning (ML) methods to complement traditional digitisation approaches in future research.

5.3.4 Future Dataset Use

There is substantial potential for future research to build on both the data and findings presented in this study. Recent work on U.S. tide gauges (Piecuch et al., 2025) demonstrates that relying on a small subset of records can obscure long-term trends, whereas comprehensive analysis of all available long-term records reveals clear acceleration in relative sea level. This highlights the importance of complete, quality-controlled datasets for robust historical sea-level assessment—a principle directly applicable to the Irish tide-gauge records compiled here. Subsequent work could further assess the impacts of sea-level change across Ireland, with particular focus on the southwest, where observed rates of rise were highest, and within the modern tide-gauge network. The datasets compiled and quality-checked in this study (e.g., Murdy et al., 2015) provide a robust foundation for further analysis. These data could also be integrated with climate models or modern observational datasets to explore regional trends, and coastal risks. Future work may benefit from more integrated or nonlinear approaches to atmospheric correction, extending beyond the linear modelling applied here, which could further improve the representation of atmospheric forcing and enhance the accuracy of long-term sea-level estimates.

The hierarchical modelling approach used in Chapter 4 via the reslr package (Upton et al., 2024) provided robust regional estimates by integrating data from multiple sites. This enabled continuous trend estimation even for locations with sparse records, such as Cork, Tarbert, and Galway. While this increases the stability of regional trends, it can smooth over genuine site-specific variability, particularly during periods with limited observations. It should be noted that reslr can be sensitive to individual sites, and small adjustments to a site's data—such as minor corrections or rounding—can subtly influence estimated regional trends, typically affecting values only at the decimal level. Future work could build on these datasets and this approach by exploring alternative or complementary statistical methods. This would help further capture local tide-gauge variability, although the absence of long-term records may still present challenges.

The datum adjustments used from both the PSMSL and uncovered in this study were crucial for ensuring that the resulting time series were consistent and validated across different periods (Woodworth et al., 2012). However, uncertainties remain in the datum adjustments, particularly where historical records are sparse or incomplete and different nearby tide gauges are integrated. There is substantial potential to reduce datum uncertainties by leveraging modern geoid modelling. For instance, Huang et al. (2021) developed a hybrid gravimetric geoid for Taiwan and its islands, integrating multiple gravity datasets to produce a seamless vertical datum with centimetre-level accuracy. Applying similar approaches in Ireland could enhance historical tide-gauge datums for the data undertaken in this thesis, and support more precise sea-level reconstructions and coastal risk assessments. These datum-related uncertainties are distinct from, but complementary to, those associated with glacial isostatic adjustment.

The GIA contribution to sea-level estimates using the Bradley_thick_71p510 model is most pronounced in Northern Ireland, where spatial differences in glacial isostatic adjustment are largest. The ICE-5G Peltier model produces the greatest adjustment overall, increasing the regional mean to approximately ~2.5 mm yr^{-1} after GIA correction, particularly affecting northern sites. In contrast, the ICE-6G BC_Hybrid_71p320 model yields the smallest adjustment and the least spatial variability. The Bradley_thick_71p510 model yields the lowest spatial spread in the final model selection (excluding ICE-5G due to its potential limitations discussed previously) and is therefore adopted as the preferred GIA correction within the NI-GAM framework. These differences are small relative to the overall sea-level signal. The posterior regional mean instantaneous sea-level rate for Ireland (1925–2024) is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01), derived from the NI-GAM regional component (r_pred_deriv) using the Bradley_thick_71p510 configuration.

This estimate is broadly consistent with the post-1900 rate of 2.12 mm yr^{-1} reported by Hogarth et al. (2021), although differences in spatial coverage, temporal aggregation, and GIA specification (including their ICE-6G-based corrections) limit strict one-to-one comparability. Notably, estimates using ICE-6G BC_Hybrid_71p320 (~1.9 mm yr^{-1}) fall toward the lower end of this range and are comparable to ICE-6G-based reconstructions reported in Hogarth et al. (2021). Yearly GIA corrections provided by Bradley (personal communication, 2025) were applied to deterministically adjust instantaneous sea-level rates (μ_pred_deriv) at each site.

However, assuming a linear GIA may not fully capture complex vertical land motion, particularly during periods of accelerated ice-mass loss from the Greenland Ice Sheet (Briner et al., 2020; Frederikse et al., 2020; Sasgen et al., 2020), so some residual uncertainties in the instantaneous sea-level rates derived from the adjusted RSL series are likely. Future work assessing GIA uncertainties and exploring alternative models could help further validate the results from this dataset.

Andersen et al. (2015) demonstrate that integrating coarse-temporal satellite altimetry with high-frequency tide-gauge records can improve forecasts of high water and extreme events, capturing over 90% of high-water events in the North Sea and effectively representing tropical cyclone surges in northeast Australia. Although such an analysis is beyond the scope of this research and pertains to a different part of the world, it highlights potential avenues for applying the datasets derived and quality-checked in this study. There is potential to integrate these datasets with other records; however, satellite altimetry—ideally available from around 1993—could also serve as an independent quality-control measure, helping to validate tide-gauge data and identify potential inconsistencies or gaps, particularly for high-water or extreme events.

Furthermore, the sea-level datasets developed in this study could be directly integrated into coastal modelling frameworks to improve the representation of extreme events and regional water-level variability. For instance, wave and storm-surge projections, such as those produced by nested WAM-SWAN configurations (Kalayil Uthaman et al., 2024), require accurate boundary conditions for tides and mean sea level. In addition to wind-driven surges, wave setup can further elevate coastal water levels (Pugh & Woodworth, 2014), and this effect should be considered for extreme events on the west coast of Ireland. Incorporating the full tide-gauge records from Ireland (where applicable) could enhance the accuracy of simulations for significant wave heights, surges, and high-water events along the coast. This integration allows not only the validation of model outputs against observed sea levels but also provides a robust foundation for future projections under changing climate conditions (OPW & RPS 2023).

The availability of sea-level datasets for Ireland enables the investigation of issues such as potential subsidence (e.g., Cork and Dublin Port). This is particularly important when integrating data from multiple tide gauges across the country. Coastal vulnerability in Ireland varies regionally, driven by differences in relative sea-level rise, local subsidence, and protective infrastructure. The southwest and south coasts, including Cork, Tarbert, and the Shannon Estuary, are particularly at risk, with sea-level rise rates being the highest. Urbanised regions such as Dublin are also highly vulnerable due to land reclamation, port infrastructure, and dense populations. The datasets compiled in this study could also be used to investigate areas of potential subsidence, such as Dublin Port, and could be complemented with additional NTGN tide-gauge measurements not included in this study to support additional site-specific investigations of relative sea-level change at locations where detailed analysis may be particularly informative. Sparse tide-gauge coverage, particularly along the south and west coasts, continues to limit understanding of local coastal hazards, despite substantial data recovery. This underscores the need for enhanced monitoring to support flood-risk assessment and coastal adaptation planning (OPW & RPS, 2020b; Wang et al., 2024).

Future efforts to recover additional historical records could improve understanding of coastal vulnerability and open opportunities to apply artificial intelligence (AI) and machine learning (ML) techniques to enhance the accuracy and completeness of these datasets (Yang et al., 2024). The datum steps and techniques applied in this careful methodological approach may be useful for other locations where datum shifts are known or potentially occurring. The work undertaken in this thesis for understanding mean sea-level change is relevant and could potentially be integrated with other European studies (Hogarth et al., 2021) or even applied in a global context.

The availability of these datasets enables assessment of mean sea-level change around Ireland, including the southwest, where records were previously sparse. The recovery and digitisation of long-term tide-gauge data provides a foundation for integrating with projections such as UKCP18 (Palmer et al., 2018) and the IPCC AR6 tools (NASA, 2025) to support future coastal assessments.

Finally, based on the findings of this thesis, several recommendations for future work can be identified. These include: (1) prioritising the recovery of long-term tide-gauge records in data-sparse regions; (2) integrating manual digitisation approaches with emerging machine learning techniques to improve efficiency and scalability; and (3) using the recovered tide-gauge datasets to complement and validate future sea-level projections around Ireland's coast.

5.4. Concluding remarks

The research undertaken in this thesis makes a number of important contributions. Historical sea-level data rescue is transforming understanding of sea-level change around Ireland, which is crucial for assessing coastal vulnerability and identifying the areas most at risk. This work recovered, digitised, and quality-controlled archival tide-gauge records, integrating them with modern observations. These efforts improve understanding of long-term relative sea-level change at local and national scales.

A methodology was developed that demonstrates that historical paper marigrams can be digitised to centimetre-scale accuracy using transparent, reproducible workflows based on open-source software. Correction procedures were developed and applied to address image distortion and scaling uncertainty in the paper records. This enabled the recovery of reliable hourly sea-level data from Dún Laoghaire Harbour (1925–1931). Validation of M2 tidal characteristics (Amplitudes and Phase Lags) and comparing against historical and modern records from Dún Laoghaire tide-gauge confirms that the recovered data are robust and consistent with regional sea-level behaviour. The accurate digitisation of historical marigrams is time-intensive, highlighting the effort required to recover high-quality archival sea-level data and underscoring the scientific value of records that were previously inaccessible.

Recognising that data rescue at scale requires significant input with the potential for additional human capacity, this thesis also contributes a structured training framework for digitisation projects involving complex tidal data. While students did not contribute directly to the digitisation of the historical records, their participation in training exercises provided valuable insight into the challenges of working with complex tidal traces. By combining targeted instruction with systematic error checking, the training approach developed in this thesis familiarises students, citizen scientists, and educators with the digitisation workflow, enabling them to contribute meaningfully to high-quality data recovery. This framework not only improves digitisation accuracy but also addresses a key bottleneck in the development of machine-learning approaches for marigram analysis, which are currently constrained by the visual complexity of historical records. In doing so, the thesis strengthens the foundation for future collaborative and automated data-rescue efforts.

Perhaps most importantly, this work makes a significant contribution to the overall availability of tidal records for the South and West of Ireland. Data from the 1970s, 1980s, and early 2000s have now been made available for Cork, and data from 1964–1986 (with 1984–1986 of poorer quality) have also been digitised at high frequency with hourly intervals. These, combined with observations from modern stations, are important for improving our understanding of mean sea-level (MSL) change. The M2 tidal characteristics (Amplitudes and Phase Lags) have helped validate the data accuracy and identify potentially erroneous records.

Moreover, this work has enhanced the datasets for the South and West of Ireland and for many of Ireland's major tide-gauge sites, including Dublin Port, through the addition of Dún Laoghaire (1925–1933) and the validation of the Belfast dataset (1925–2010) (to be made available at: 10.5281/zenodo.17854748 upon publication of chapter 4). By integrating various sources of data, including the PSMSL, a significant understanding of MSL changes in Ireland at the national scale has been achieved. The reconstructed regional mean rate of relative sea-level rise for 1925–2024 is 2.30 ± 0.29 mm yr^{-1} (95% CrI: 1.72–3.01), while modelled instantaneous rates derived from the posterior derivative field (μ_pred_deriv) increase in the most recent years, ranging from approximately 5.6 to 7.2 mm yr^{-1}across sites with records extending to 2024. These rates may be slightly exaggerated due to smoothing, particularly for Belfast, but remain plausible within the bounds of the credible intervals. Adjustments were consistently applied for atmospheric forcing, seasonal cycles, datum offsets, and glacial isostatic adjustment. Sensitivity analyses show that the long-term trends remain robust to these corrections. The results show that Ireland now experiences rates of sea-level rise comparable to global averages, with the southwest emerging as a region of heightened vulnerability. Code for all major components of this study will be made available on GitHub (https://github.com/PatrickJMcLoughlin/Ireland-Sea-Level) upon publication.

These findings have important implications for coastal risk management and adaptation planning. Urban centres such as Cork and Dublin face compounded exposure due to rising sea levels, local subsidence, and dense infrastructure, while sparsely monitored coastlines remain at risk due to limited observational coverage. The datasets developed in this thesis provide a critical resource for improving flood-risk assessment and coastal modelling, and can be readily integrated with regional wave, surge, and climate-model frameworks to inform future projections.

Finally, this thesis demonstrates the value of combining historical data rescue, rigorous methods, and modern statistical modelling to improve understanding of sea-level change. By making previously inaccessible data usable and contextualising Irish sea-level trends regionally and globally, it provides a strong foundation for future research and policy development. As sea-level rise continues to accelerate through the 21st century, the approaches and datasets developed here will be essential for improving resilience to coastal flooding and guiding adaptation strategies in Ireland and beyond.

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Appendix: Authorship Declaration Forms

Maynooth University

Department of Geography

This form is to accompany the submission of a PhD that contains research reported in published or unpublished work. **Please include one copy of this form for each co-authored work.** This form along with the published work should, under normal circumstances, appear in an Appendix.

Authorship Declaration Form

Publication Details:

Thesis Chapter/Pages	Chapter 2
Publication title	**The accurate digitization of historical sea level records**
Publication status	Published
Type of publication	Peer-reviewed Journal Article
Publication citation	McCarthy, G.D., Nolan, G., Lawlor, R. & Hickey, K.(2024) The accurate digitization of historical sea level records. Geoscience Data Journal, 11, 790–805. https://doi.org/10.1002/gdj3.256

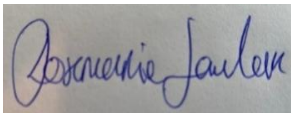
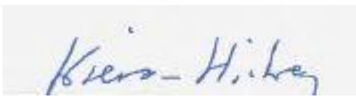
Nature/extent of my contribution to the work detailed above is as follows:

Nature/Extent of Contribution	**Lead author**
I wrote the full paper, digitised the data, and developed the methodology.	☒ Yes ☐ No

The following co-authors contributed to the work (all contributing co-authors):

Name	**Nature of contribution**
Gerard McCarthy	Provided access to the historical data; proofread and edited the draft; suggested validation improvements.
Glenn Nolan	Proofread and edited the draft; suggested validation improvements.
Rosemarie Lawlor	Provided helpful implementation suggestions and general advice.
Kieran Hickey	Edited the draft; suggested validation improvements.

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-author's contribution to this work

	Name	**Signature**	**Date**
Student	Patrick John McLoughlin		**29/05/2025**
Co-author 1	Gerard McCarthy		**29/06/2025**
Co-author 2	Glenn Nolan		**29/05/2025**
Co-author 3	Rosemarie Lawlor		**29/05/2025**
Co-author 4	Kieran Hickey		**29/05/2025**

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This form is to accompany the submission of a PhD that contains research reported in published or unpublished work. **Please include one copy of this form for each co-authored work.** This form along with the published work should, under normal circumstances, appear in an Appendix.

Authorship Declaration Form

Publication Details:

Thesis Chapter/Pages	Chapter 3
Publication title	Evaluating Student Involvement in Sea Level Data Rescue
Publication status	Under Review
Type of publication	Submitted manuscript for peer-reviewed journal article
Publication citation	McCarthy, G. D., Nolan, G., & Hickey, K. (2026). *Evaluating Student Involvement in Sea Level Data Rescue. Weather.* https://doi.org/10.1002/wea.7757

Nature/extent of my contribution to the work detailed above is as follows:

Nature/Extent of Contribution	**Lead author**
I wrote the full paper.	☒ Yes ☐ No

The following co-authors contributed to the work (all contributing co-authors):

Name	**Nature of contribution**
Gerard McCarthy	Provided access to and support for integrating the project into college assignments; proofread and edited the draft; suggested validation improvements.
Glenn Nolan	Proofread and edited the draft; suggested validation improvements.
Kieran Hickey	Edited the draft; suggested validation improvements.

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-author's contribution to this work

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Authorship Declaration Form

Publication Details:

Thesis Chapter/Pages	Chapter 4
Publication title	A Century of Mean Sea-Level Change in Ireland (1925-2024)
Publication status	Article submitted for review
Type of publication	Research Article
Publication citation	McLoughlin, P.J., Swan, L.D., Nolan, G., Hickey, K., Upton, M., Edwards, R. and McCarthy, G.D. (2026), A Century of Mean Sea-Level Change in Ireland (1925–2024). *EGUsphere* [preprint]. https://doi.org/10.5194/egusphere-2025-6404

Nature/extent of my contribution to the work detailed above is as follows:

Nature/Extent of Contribution	**Lead author**
I wrote the full paper. Application of quality control of data. Presentation of results.	☒ Yes ☐ No

The following co-authors contributed to the work (all contributing co-authors):

Name	**Nature of contribution**
Gerard McCarthy	Provided access to the historical data; proofread and edited the draft; suggested validation improvements.
Glenn Nolan	Proofread and edited the draft; suggested validation improvements.
Lionel Swan	Worked in the digitisation of Tarbert Dataset; Edited the draft.
Kieran Hickey	Edited the draft; suggested validation improvements.

Maeve Upton	Edited the draft; and helped in the data modelling.
Robin Edwards	Edited the draft; suggested validation improvements.

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-author's contribution to this work

	Name	**Signature**	**Date**
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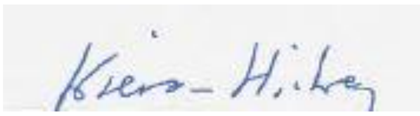
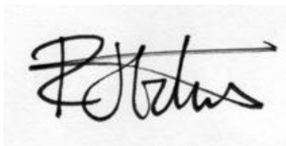
Co-author 1	Lionel Swan		**22/12/2025**
Co-author 2	Glenn Nolan		**06/01/2026**
Co-author 3	Kieran Hickey		**23/12/2025**
Co-author 4	Maeve Upton		**06/01/2026**
Co-author 5	Robin Edwards		**05/01/2026**
Co-author 6	Gerard McCarthy		**05/01/2026**