DETECTION OF TRANSIENT POLLUTION INCIDENTS IN RIVERS TO SUPPORT THE OBJECTIVE OF THE WATER FRAMEWORK DIRECTIVE IN THE CONTEXT OF INCREASING FREQUENCY AND INTENSITY OF RAINFALL EVENTS DUE TO CLIMATE CHANGE

Lisa Cronin, MSc., BSc. (Hons)

A thesis submitted in part fulfilment for the award of Doctor of Philosophy

School of Chemical Sciences

DUBLIN CITY UNIVERSITY

Supervisors: Professor Fiona Regan & Professor Frances Lucy,

Atlantic Technological University

August 2026

Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of PhD is entirely my own work, and that I have exercised reasonable care to ensure that the work is original and have conformed to the regulations on the use and declaration of Generative AI, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work. I hereby certify that no Generative Artificial Intelligence (Gen AI) tools have been used in the creation of the thesis.

Signed: *Lisa Cronin* ID No.: 20210048 Date: 25/08/2026

Acknowledgments

To my supervisors, Prof. Frances Lucy for her pragmatism and encouragement, and to Prof. Fiona Regan for her endless patience and support, and for giving me the opportunity to participate in the wonderful research group at DCU's Water Institute for which I am truly grateful.

To the Atlantic Technological University for supporting my research.

To Michael Quigley & Kathryn Ryan, Niall McAllister & Aisling Collins, for your generous access and for putting up with my frequent visits to your beautiful stretches of the Unshin and Owenmore Rivers.

To Cian Taylor, Ciprian Briciu-Burghina, Rachel Bracker, Una McCarthy and Anne Marie Frizelle for the many conversations about all things water, and for all your help and support.

To Diarmaid, Aoibheann & Lewis for putting up with my countless absences, and to Stephen without whom this research would not have been possible.

"If there is magic on the planet, it is contained in water."

Loren Eisley

Publications arising from this Thesis.

Peer-Reviewed Journal Articles

1. Cronin, L. *et al.* (2025) "An open-source workflow for identifying hydrodynamic water quality events in rivers by continuous water quality monitoring and time-series data processing using R and US EPA CANARY," *MethodsX*, 15, p. 103538. Available at: https://doi.org/10.1016/j.mex.2025.103538.

Author Contribution: Conceptualisation, Methodology, Software, Validation, Data curation, Writing – original draft, review & editing. Formal analysis, Software, Visualization, Investigation.

Manuscripts Submitted for Publication (Under Review)

1. Cronin, L., Taylor C.M., Lucy F.E., Regan F. (2026) "*Tracking the Frequency and Intensity of Riverine Hydrodynamic Water Quality Events under Climate-Driven Rainfall Change*" [Manuscript submitted for publication]. School of Chemical Sciences, Dublin City University.

Software and Workflow Publications

1. Cronin, L. and Taylor, C.M. (2025) "*Workflow for identifying water quality hydrodynamic events in time series data (V1.0.0)*". Zenodo. Available at: https://doi.org/10.5281/ZENODO.15358190

Author Contribution: Developing, writing, and implementing the R scripts, testing and debugging code. Drafting the initial workflow as well as refining the text.

Conference Papers & Proceedings

1. Cronin, L., Taylor C.M., Lucy F.E., Regan F. (2026) "*Remote hydrodynamic water quality event detection on rivers against a background of climate driven increased incidence and intensity of rainfall events"* [Oral Presentation]. Agriculture and Land Use in Ireland: Pathways to a Sustainable Future Conference, Tullamore, Ireland. Book of Abstracts: https://teagasc.ie/wp-content/uploads/uploads/media/website/environment/climate-action/climate-centre/Agriculture-and-Land-Use-in-Ireland-2026-Book-of-Abstracts.pdf

2. Cronin, L., Taylor C.M., Lucy F.E., Regan F. (2026) "*Temporary, off-grid, remote, hydrodynamic water quality event monitoring in rivers in the Northwest of Ireland in the context of more frequent and more intense rainfall events driven by climate change".* [Oral Presentation]. Annual Meeting Irish Freshwater Sciences Association, Dublin, Ireland. Book of Abstracts: https://freshwaterscience.ie/wp-content/uploads/2026/03/IFSA-2026-Book-of-Abstracts_FINAL.pdf

3. Cronin, L. et al. (2025) “Near real-time, water quality event monitoring in small rivers”, [Oral Presentation]. EGU General Assembly 2025. Vienna, Austria, 27 April–2 May. EGU25-10582 https://doi.org/10.5194/egusphere-egu25-10582
4. Cronin, L. et al. (2025) “*An open-source workflow for monitoring hydrodynamic events in small rivers using temporary continuous monitoring stations”*. [Oral Presentation]. 35th Irish Environmental Researchers Colloquium ‘One Health for a Sustainable Future’, Dublin, Ireland. Colloquium Proceedings: https://www.esaiweb.org/admin/php_scripts/classes/DownloadManager/download.php?fileId=333

5. Cronin, L., Regan, F., and Lucy, F. E. (2024) “*The role of effective freshwater protected areas in the restoration of freshwater biodiversity in the European Union”* [Oral Presentation]. 34th Irish Environmental Researchers Colloquium ‘Harvest to Harbour: Research from Soil to Sea’, Waterford, Ireland. [Oral Presentation]. Colloquium Proceedings: https://www.esaiweb.org/admin/php_scripts/classes/DownloadManager/download.php?fileId=289

6. Cronin, L., Regan, F., and Lucy, F. E. (2024) “*Comprehensive user tool to establish near real-time water quality hydrodynamic event monitoring stations”* [Poster Presentation]. An Fóram Uisce - The Water Forum Conference ‘Managing Ireland’s Water in a Changing Climate’, Tulllamore, Ireland https://thewaterforum.ie/app/uploads/2025/01/Conference-Report-final.pdf

7. Cronin, L., Regan, F., and Lucy, F. E. (2023) *“Detection of transient pollution events in an Irish river catchment in the context of increasing frequency and intensity of rainfall events due to climate change”*, [Oral Presentation]. EGU General Assembly 2023*, Vienna, Austria*, 24–28 Apr 2023, EGU23-15993 https://doi.org/10.5194/egusphere-egu23-15993

8. Cronin, L., Regan, F., and Lucy, F. E. (2022) *“Integrating Protected Area Management with River Basin Management Plans as a Measure to Address Diffuse Pollution*” [Oral Presentation]. International Water Association, Conference on Diffuse Pollution & Eutrophication (DIPCON) 2022, Istanbul, Turkey. https://iwadipcon2022.org/proceedings-book

Table of Contents

Declaration i
Acknowledgments ii
Publications arising from this Thesis. iv
List of Abbreviations xi
List of Tables xii
List of Figures xiv
Abstract xx
Chapter 1: Introduction 1
1.1 Introduction 1
1.2 Protected areas and their role in protecting against biodiversity loss and conserving high status waters under the Water Framework Directive. 2
1.2.1 Defining the Protected Area 4
1.3 Protected Area Coverage 4
1.3.1 Freshwaters and Protected Areas (PAs) 6
1.3.2 Protection afforded to freshwater habitats by PA designation. 6
1.3.3 Challenges for Freshwater Biodiversity 8
1.4 Protected Areas in Europe 10
1.4.1 Natura 2000 European Network of Protected Areas 10
1.4.2 Water Framework Directive (Directive 2000/60/EC) Protected Areas 11
1.4.3 National protected areas 11
1.4.4 River Protected Areas 12
1.4.5 Key Biodiversity Areas 12
1.5 Protected Area Designation in Europe 13
1.5.1 Governance and Management of Protected Areas in Europe 20
1.5.2 Protected areas and governance under the Water Framework Directive 32
1.6 Protected area designation and improving freshwater biodiversity. 34
1.6.1 Expanding Protected Area Coverage for Freshwater Biodiversity Conservation 35
1.6.2 Expanding the focus of freshwater conservation to broad range of aquatic habitats . 36
1.6.3 Effective expansion of PA network for freshwater biodiversity across the EU 38
1.6.3 Integrative, spatial approach to freshwater biodiversity conservation 41
1.7 Restoration of freshwater biodiversity in EU, the Biodiversity Strategy, the Water Framework Directive and the Nature Restoration Regulation. 42
1.8 High frequency monitoring & hydrodynamic event monitoring for freshwater biodiversity restoration 50
1.8.1 Sensors for High Frequency Water Quality Monitoring 50
1.8.2 High Frequency Monitoring of Surface Waters 50
1.8.3 Early Warning Systems and Event Monitoring 55

1.9 Conclusion 56
1.10 Research Aims and Objectives 59
Chapter 2: Methods 60
2.0 Introduction 61
2.1 Research Design 61
2.2 Literature Review Methodology 62
2.3 Catchment Characterisation Methodology 64
2.3.1 Desktop Assessment for Catchment Characterisation 64
2.3.2 Walkover Survey of Monitoring Locations 75
2.4 Water Quality Monitoring & Data Analysis Methodology 78
2.4.1 Hydrometric Stations in the Study Area 78
2.4.2 High Frequency (HF) Water Quality Monitoring Stations 80
2.4.2 In-stream Verification of High Frequency Data 83
2.5 HF Monitoring Sensor Deployment 84
2.5.1 River Owenmore Deployment 85
2.5.2 River Unshin Deployment 85
2.6 Data Management 86
2.6.1 Data Management Plan 86
2.6.2 Data Validation 86
2.6.3 Data Visualisation 87
2.6.4 Data outliers 88
2.6.5 Censored Data 89
2.7 Software for Monitoring and Analysis 90
2.7.1 High Frequency Data Collection and Storage 90
2.7.2 Data Processing and Analysis Software 90
2.8 Event Detection 91
2.8.1 Water Quality Event Detection 91
2.8.2 Hydrological Event Detection 91
2.9 Baseline Monitoring 92
2.9.1 Rainfall driven pollution event monitoring. 92
2.9.2 Continuous water quality monitoring versus discrete samples 93
2.9.3 Turbidity and Specific Conductivity Monitoring 93
2.9.4 Turbidity Monitoring 94
2.9.5 Specific Conductivity Monitoring 94
2.9.6 Challenges for temporary deployments 95
2.10 Objective of the Investigative Baseline Field Study 99
2.11 Results and Discussion for Baseline Monitoring 100
2.11.1 Trends for Turbidity and Specific Conductivity Data 100

2.11.2 Relationship between Discharge and Rainfall.....100
2.11.3 Relationship between Rainfall and Specific Conductivity.....101
2.11.4 Relationship between Turbidity and Rainfall.....102
2.11.5 Turbidity Trigger Value.....103
2.11.6 Event Detection.....104
2.12 Conclusion.....104
Chapter 3: Development of Open-Source Workflow for Hydrodynamic Water Quality Event Monitoring.....106
3.1 Introduction.....107
3.2 Aims and Objectives.....109
3.3 Materials and Methods.....109
3.3.1 Sensor Calibration.....109
3.3.2 Sensor Validation.....110
3.3.3 Sensor Deployment.....111
3.3.4 Sonde Water Quality Data.....112
3.3.5 Event Detection.....112
3.3.6 Data Management, data stewardship and reproducible research.....113
3.3.7 Significant change thresholds using R and the manual verification of potential water quality events.....115
3.3.8 Analysis by US EPA CANARY event detection software.....117
3.3.9 Matching between manually verified events and CANARY identified events.....118
3.4 Results and Discussion.....118
3.4.6 Identify CANARY Algorithm for optimum event detection.....118
3.4.2 R Code Validation.....119
3.4.3 Method Validation.....119
3.4.4 Availability of Code and Sample Data.....120
3.5 Conclusion.....120
3.6 Limitations.....121
Chapter 4: Tracking the Frequency and Intensity of Riverine Hydrodynamic Water Quality Events.122
4.1 Introduction.....123
4.1.1 Aims and Objectives.....127
4.2 Materials and Methods.....127
4.2.1 Study Area.....127
4.2.2 Data acquisition.....127
4.2.3 Data Analysis and Software.....129
4.2.4 Event Identification.....130
4.3 Results and discussion.....130
4.3.1 Characterisation of the Study Sites.....131

4.3.2 Examining if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters can adequately capture water quality variation over the range of river discharge at a hydrologically active period. 131
4.3.3 Characterisation of Streamflow on the River Owenmore and Stream Level on the River Unshin over the Study Period 134
4.3.4 Event Monitoring on the Owenmore and Unshin Rivers 137
4.3.5 Pairing of 5mm Rainfall, Streamflow and Water Quality Events on the Owenmore & Unshin Rivers 154
4.4 Strengths and Limitations of this approach to Event Monitoring 158
4.5 Conclusion 160
Chapter 5: Conclusion, Recommendations and Further Areas of Research 120
5.1 Conclusion 164
5.2 Limitations 168
5.3 Recommendations 169
5.4 Further Research 170
References 171
APPENDIX A: User Guide – Timeseries Water Quality Data Processing with R and EPA CANARY for Hydrodynamic Event Monitoring 1
Introduction 2
Cite the repository 2
Description 2
Getting Started 3
Dependencies 3
Installing the Software 3
Executing program (from RStudio) 5
Executing program (from Docker) 5
The Workflow 5
R Studio Projects 8
A1.0 Import Water Quality Data 8
A2.0 Data Integrity 18
A3.0 Visualisation of Water Quality Data 19
A4.0 Summary Statistics 27
A4.1 Save the edited dataframe to the working directory as .csv file 31
A4.2 Count no. of observations 32
A4.3 Record number of days and number of observations to an output file 32
A5.0 Define significant change thresholds for turbidity and highlight on plots to identify events. 32
A6.0 Manually Identify Potential Water Quality Events with the aid of interactive turbidity plot. 41
A7.0 Event Detection using EPA CANARY 42
A8.0 Compare manually identified Owenmore turbidity events to events identified by CANARY. 43

References 57
APPENDIX B: Data Management Plan, Sensor Calibration & In-stream Data Validation 60
B.1 Data Management Plan 1
B.1.1 Data description and collection or re-use of existing data 1
B.1.2 Data Documentation & Quality 2
B.1.2.1 Data Documentation 2
B.1.2.2 Metadata 3
B.1.2.3 Data Quality Control 3
B.1.2.4 Storage and backup during the research process 3
B.1.3 Data security and protection of sensitive data 3
B.1.3.1 Legal and ethical requirements, code of conduct 3
B.1.3.2 Management of other legal issues, such as IP rights and ownership. 3
B.1.4 Data sharing and long-term preservation 3
B.1.4.1 Software or Tools needed to access and use data? 4
B.1.5 Data management responsibilities and resources 4
B.2 Sensor Calibration 5
B2.1 Calibration of YSI 6600 Sensors 5
B2.2 Calibration of Field Meters for In-stream Data Validation when Deploying and Retrieving Sondes 17
B.3 In-stream Data Validation 22
APPENDIX C: CANARY Output Files 24
APPENDIX D: Logic for identifying full match and partial match between manually verified events and events identified by EPA CANARY 1
D.1: Workflow for Identifying Water Quality Hydrodynamic Events in Time Series Data 2
D.1.1: Logic for identifying full match and partial match between manually verified events and events identified by EPA CANARY event detection software. 2
APPENDIX E: Example of Match logic applied to an event Data File 4
Table E1: Example of Match logic applied to_Dat_ET0.89063alg_1.pdf. 1

List of Abbreviations

Abbreviation	Definition
BFI	Baseflow Index
BISE	Biodiversity Information System for Europe
CDDA	European inventory nationally designated protected areas
HF	High frequency
HFM	High frequency monitoring
IUCN	International Union for Conservation of Nature
OECM	Effective Area-Based Conservation Measures
PA	Protected Area
PCD	Physical Catchment Descriptors
SAC	Special area of conservation
SPA	Special protected area
WFD	Water Framework Directive

List of Tables

Table 1: National Protected Areas and competent authorities in EU-27 plus the United Kingdom. Based on data from Biodiversity Information System for Europe A [75,159]..... 22

Table 2: Comparing the Actions identified by Tickner [62] against the current situation in Europe (2023), the EU Biodiversity Strategy for 2030, the Water Framework Directive and the Nature Restoration Regulations..... 44

Table 3: Examples of International Studies using High Frequency Monitoring to Quantify the Input of Pollutants to Surface Waters. 52

Table 4: Special Areas of Conservation (SAC) [12] and Special Protected Areas (SPA) [129] in the Study Catchment..... 67

Table 5: Urban Wastewater Discharges in the Study Area. 70

Table 6: EPA Hydrometric Unit descriptors of flow and level percentile classification. 71

Table 7: Water Quality Data available from EPA for closest monitoring stations to the study sites. .. 73

Table 8: Typical Performance Specifications for the Temperature, Conductivity and Turbidity Sensors on the YSI 6600 EDS V2-2 sonde. 83

Table 9: Typical Performance Specifications for the Temperature, Conductivity and Turbidity handheld meters..... 84

Table 10: Open-Source Software used for data analysis in this research. 90

Table 11: Site and Data details for baseline monitoring on the Owenmore River. 92

Table 12: Training data sets for initial CANARY configuration at the study sites 112

Table 13: Data parameters and monitoring frequency imported for visualisation and event detection. 114

Table 14: Information for variables used in event identification, event pairing and plotting..... 129

Table 15: Rainfall Event Detection Parameters and Number of rainfall events identified for each event class..... 146

Table 16: Data sets for CANARY configuration in the literature. 148

Table 17: Optimum EPA CANARY configuration parameters for stations on the river Owenmore and River Unshin for semi-continuous water quality data at 15-minute interval over the period 05/10/2024 to 31/01/2025. 148

Table 18: Event detection for 5mm Rainfall, Streamflow, Stream Level and Water Quality on the Owenmore and Unshin Rivers. 151

Table 19: Pairing of 5mm rainfall events, baseflow separated (BFI A at α 0.980), daily streamflow events (eventMinima) with a 30th percentile threshold of quickflow and CANARY Turbidity Events on the Owenmore River from 01/10/2024 to 31/01/2025. 153

Table 20: Pairing of 5mm rainfall events, P90 stream level events and CANARY Turbidity Events on the Unshin River from 01/10/2024 to 31/01/2025. 154

Table 21: Pairing [300] of 5mm Rainfall, Streamflow and Water Quality (WQ) Events on the Owenmore & Unshin Rivers over the study period 01/10/2024 to 31/01/2025 155

List of Figures

Figure 1: Threats to Freshwater Biodiversity 9

Figure 2: International, regional, and national designations of protected areas in Europe (October 2023). 14

Figure 3:International protected area designations in Europe (October 2023). 15

Figure 4:Regional protected area designations in Europe (October 2023). 15

Figure 5: Percentage of total international, regional, and national protected area designations by country (October 2023). 16

Figure 6: Number of National Designation Categories for Protected Areas in EU-27 + UK (October 2023) (created using Bing Maps). 17

Figure 7: Number of Protected Areas in EU-27 + United Kingdom (October 2023) (created using Bing maps). 18

Figure 8: Increase in the number of sites and the cumulative area for nationally designated Protected Areas in Europe from 1800 to 2020 [149]. 19

Figure 9: Average proportion (%) of Freshwater Key Biodiversity Areas (KBAs) covered by protected areas in Europe in 2022. 20

Figure 10: Percentage overlap between terrestrial National PA designation and Natura 2000 Sites in EU-27 [75]. 31

Figure 11: (1) Hydrometric Area 35, Sligo Bay/Drowes catchment [308] and (2) River Owenmore and River Unshin. Map (2) created in QGIS (Version 3.42.1) using OpenStreetMap as a basemap. 66

Figure 12: Special Areas of Conservation (SAC) with surface water dependent habitats and Special Protection Areas (SPA) within the study area [313]. 68

Figure 13: River Waterbody WFD Status 2016-2021 for Rivers Unshin and Owenmore (gis.epa.ie). Map created in QGIS (Version 3.42.1) using OpenStreetMap as a basemap. 72

Figure 14: The Number of at-risk water bodies and the associated Water Quality Pressures in the Sligo Bay and Drowse Catchment [291]. 74
Figure 15: The number of as risk high ecological status objective waterbodies and the associated Water Quality Pressures in the Sligo Bay and Drowse Catchment [291]. 75
Figure 16: The harvesting of a conifer plantation adjacent to the River Unshin at Dowrea, Co. Sligo. 76
Figure 17: Land drainage works on the River Unshin downstream of Lisconny Bridge, Co. Sligo. A linear drainage channel (highlighted in red) is located in the mid-distance on the far bank of the river, starting at the telegraph pole and extending from the field towards the river at right angles to the riverbank. 77
Figure 18: River Unshin at Cartronduffy, Co. Sligo. The lack of a riparian buffer (highlighted in orange) can be seen in the mid distance on both sides of the river channel. A cattle access point on the right-hand riverbank immediately in front of the tree (highlighted in blue) is characterised by heavily poached ground and exposed bare soil extending to the water's edge. Localised bank erosion has undermined the root system of a riverside tree located on the right-hand bank, resulting in the collapse of a mature tree across the river channel (highlighted in red). 77
Figure 19: Hydrometric Station on the River Unshin at Ballygrania operated by the Office of Public Works [337]. 78
Figure 20: Hydrometric Station on the River Owenmore at Ballynacarrow operated by the Office of Public Works [338]. 79
Figure 21: Location of the water quality station (Owenmore WQ) and hydrometric station (Owenmore HydroM) on the River Owenmore and the location of the water quality station (Unshin WQ) and hydrometric station (Unshin HydroM) on the River Unshin. Map created in QGIS (Version 3.42.1) using OpenStreetMap as a basemap 79
Figure 22: River Unshin from the bridge at Ballygrania facing downstream. The hydrometric station is out of view to the left and the area to the right of the main channel (highlighted in red) floods from the river overflowing during high flows. 81

Figure 23: Deployment of the YSI 6600 EDS V2-2 Sonde at the study site showing (1) the frame used to house the sensor and (2) the deployment site on the Owenmore River at Ballynacarrow. 85
Figure 24: Deployment of the YSI 6600 EDS V2-2 Sonde on the Unshin River at the study site downstream of Markree Castle showing the recreational pontoon where the sonde was is attached, suspended in the water column. 86
Figure 25: Hyetograph - Hydrograph for the River Owenmore and River Unshin with river level used instead of discharge on the River Unshin due to the poor stage-discharge relationship caused by water retention at the R. Unshin gauging station during high flows [301] (R Studio). 88
Figure 26: Time series data for the Owenmore River at the study site in Ballynacarrow in October 2024 showing spikes in turbidity following rainfall during the period. 89
Figure 27:Sonde mounted in cage and deployed on the bed of the River Owenmore, during lower flow conditions on the left and fouling of sensor following a high flow event on the right following a three-week deployment period. 95
Figure 28: During a storm event significant debris accumulated on the purpose-built sonde support deployed on the bed of the Owenmore River. 96
Figure 29: Accumulation of algae on the anchor ropes and support cage for sonde mounted on the bed of the Owenmore River when deployed for just three weeks in summer season. 96
Figure 30: Algae attached to wiper of turbidity sensor on YSI 6600 sonde deployed in the Owenmore River in summer season. 97
Figure 31: Deployment location for the River Unshin under typical flow conditions. 98
Figure 32: River Unshin deployment location during very high flows showing flooding around the deployment pontoon highlighted by red circle. 98
Figure 33: River Unshin deployment pontoon following a severe storm event. 99
Figure 34: Cross correlation between rainfall and discharge on the River Owenmore. 101
Figure 35: Cross correlation between rainfall and Specific Conductivity on the River Owenmore.... 102
Figure 36: Cross correlation between rainfall and turbidity on the River Owenmore. 103

Figure 37: Protocol for data visualisation and training of the CANARY event detection system at individual water quality monitoring stations. 113
Figure 38: Sample of Data Visualisation for Turbidity 116
Figure 39: A - Water dependent protected areas in Ireland [Salmonid Rivers Regulations S.I. 293, Nutrient sensitive areas under Urban Wastewater Directive; SACs with water dependent habitats/species under Habitats Directive, SPAs with water dependent habitats/species under the Birds Directive, Drinking Water and Bathing Waters]. B – High WFD Status River Waterbodies 2019-2024 [485] 124
Figure 40: Change in the percentage of high ecological quality (macroinvertebrate) river sites in each survey period between 1987 and 2024 [16] 125
Figure 41: Workflow of the event detection method employed to identify hydrodynamic water quality events. 130
Figure 42: A -Flow duration curve (FDC) generated from high frequency discharge data on River Owenmore at Ballynacarrow [338] from May 2005 to May 2025 overlaid with semi-continuous specific conductivity data (blue dots) measured from 01/10/2024 to 31/01/2025 with a data interval of 15 minutes and B - Flow duration curve (FDC)generated from mean daily discharge data on River Owenmore at Ballynacarrow from 1955 to 2025 [338] overlaid with quarterly grab sample specific conductivity data 2007 to 2025 (green dot representing a daily sample) from the national river monitoring programme[518] 133
Figure 43: A - Hyetograph at Markree Weather Station, B - Hydrograph at hydrometric station 35001 on the Owenmore River at Ballynacarrow and C - Stream Level at hydrometric station 35003 on the Unshin River at Ballygrania, from 01/10/2024 to 31/01/2025 overlaid with percentiles where streamflow/level was equalled or exceeded for 95%, 30%, 10% and 5% of the time over the study period. 136

Figure 44: High frequency streamflow data from Nov 23 to Apr 25 at hydrometric station 35001 Ballynacarrow on the Owenmore River for the study period with the high frequency specific conductivity data overlaid where available. 138
Figure 45: Different baseflow filtering for streamflow data on River Owenmore at Ballynacarrow from 01/10/2024 to 31/01/2025. Streamflow is shown in solid blue with the different baseflow filters shown in the other colours, including BFI A at α 0.980 in red dashed line. and BFI A at α 0.950 in green dashed line. 139
Figure 46: Event extraction following baseflowA separation (α 0.980, passes (no. of times the digital filter is applied) = 3) by applying the event detection functions: peak over threshold, maxima, minima and the proportion of baseflow using hydroEvents package [522] on the River Owenmore streamflow data at Ballynacarrow from 01/10/2024 to 31/01/2025. 140
Figure 47: A -Extracted stream level events for the Owenmore River at Ballynacarrow ≥ threshold of the 90th percentile stream level (May 2005-May 2025) with an inter-event time of 6 days and B. -Extracted stream level events for the Unshin river at Ballygrania ≥ than a threshold of the 90th percentile stream level (Aug 2007 – Aug 2025) with an inter-event time of 6 days, both over the study period 01/10/2024 to 31/01/2025. 142
Figure 48: Monthly Rainfall Anomaly Index at Markree Weather Station from 8th May 2005 to 8th May 2025 with the study period November 2023 to April 2025 highlighted in red. 144
Figure 49: Extracted Rainfall events greater than a threshold of 5 mm of rain with an inter-event time (min.diff) of 1 timestep (day) for Markree weather station over the study period 01/10/2024 to 31/01/2025 with thresholds for 1 mm and 10 mm also highlighted. 145
Figure 50: Performance of the CANARY system for identifying potential water quality events on the Owenmore River at Ballynacarrow over the study period 01/10/2024 to 31/01/2025, with baseflow separated (BFI A at α 0.980) daily streamflow events identified using eventMinima with a 30th percentile threshold of quickflow and 5mm rainfall events. 149

Figure 51: Performance of the CANARY system for identifying potential water quality events on the Unshin river upstream of Ballygrania over the study period 01/10/2024 to 31/01/2025 with daily stream level events identified using eventMaxima with a threshold of 90th percentile of streamflow and 5mm rainfall events. 150

Figure 52: Schematic of the five event pairing algorithms implemented in function pairEvents. In this instance rainfall (blue) is matched to runoff (orange) but these algorithms can be used for any hydrologic data [522]..... 152

Figure 53: Event pairing using Type 5 pairing specification [300] on the Owenmore River at Ballynacarrow and the Unshin River upstream of Ballygrania over the study period. Paired events are indicated by the same colour and unpaired events are in black and highlighted using black circles A – rainfall events and Owenmore streamflow events, B - rainfall events and Unshin stream level events (Rainfall is plotted as vertical bars and streamflow/stream level as a line), C & D - rainfall events and EPA CANARY turbidity events (Rainfall is plotted as vertical bars and median turbidity as a line), E - streamflow events and EPA CANARY turbidity events, & F - Unshin stream level events and EPA CANARY turbidity events (median turbidity is plotted as vertical bars and streamflow/ stream level as a line). Rainfall events (eventPOT) with threshold of 5mm, water quality events were EPA CANARY detected turbidity events, Owenmore streamflow events were baseflow separated (BFI A at α 0.980) using eventMaxima at 30th percentile threshold of quickflow and Unshin stream level events were 90th percentile daily Unshin stream level (eventPOT). 157

Abstract

Detection of Transient Pollution Incidents in River Catchments to Support the Objective of the Water Framework Directive in the context of Increasing Frequency and Intensity of Rainfall Events due to Climate Change

Lisa Cronin

Over 25 years since the Water Framework Directive was adopted, water quality is in decline across the EU with little improvement since the 2010s. Freshwater ecosystems are highly susceptible to the impacts of this, particularly climate change due to the existing anthropogenic pressures on water quality.

Ireland remains one of the few remaining sanctuaries for high status waterbodies in Europe despite numbers dropping from 500 river sites in 1990s to just 30 sites in 2022, with diffuse pollution identified as a key pressure. There are significant gaps in how protected areas can be managed and monitored, to effectively meet the aquatic biodiversity and water quality requirements. To provide new insights and address this critical gap, this thesis aims to explore the water protection benefits of protected area designation and examine how to effectively monitor the impact of hydroclimatic events on a high-status river within a protected area study site, thereby contributing to a more comprehensive understanding of protection strategies for aquatic ecosystems.

The research produced a comprehensive, practical, protocol for high frequency water quality monitoring and event detection, tailored for both experts and non-experts, to encourage faster, more widespread adoption of high frequency monitoring by providing a structured, accessible framework that reduces implementation barriers. The protocol was tested and refined on a high-status river demonstrating the protocols' robustness and adaptability, but also highlighted the potential of short term, remote deployments to capture the variability in water quality over a comprehensive range of river discharge. Water quality events over the study period were matched to 86% of rainfall events, matched to 67% of streamflow events and 75% of stream level events demonstrating the impact of hydroclimatic events on these rivers, and the urgency of adopting event-based monitoring to mitigate any further drop in high-status waterbodies and reverse water quality declines.

Chapter 1: Introduction

1.1 Introduction

The planet is in the midst of a 'Triple Planetary Crisis' caused by climate change, biodiversity loss and pollution [1]. Freshwater ecosystems are highly susceptible to the impacts of the triple planetary crisis, particularly climate change due to the existing anthropogenic pressures on water quality and quantity, the direct impact of climate on water resources and the inability of most freshwater species to relocate to other habitats [2]

Water quality deterioration is one of the main drivers of freshwater biodiversity decline globally [3,4] due to habitat degradation and direct impact on aquatic species, compounded by climate change pressures [5].

The European Union has responded to the water and biodiversity crises through legally binding legislation and cross-sectoral strategies, with key actions under the European Water Resilience Strategy [6], Zero Pollution Action Plan [7] and the Nature Restoration Law [8], being underpinned by the EU Biodiversity Strategy for 2030 [9]. The EU also aligns its water policies with the United National Sustainable Development Goal 6, Clean Water and Sanitation and SDG 14, Life Below Water [10]. However, more than twenty five years since the enactment of the Water Framework Directive (WFD) [11] and thirty five years since the enactment of the Habitats Directive [12], European freshwater biodiversity recovery has come to a halt [13] and water quality is in decline [14]. Only 39.5 % of surface water bodies in Europe are in good ecological status or ecological potential [6] with only 14% of habitat assessments and 27% of non-bird species in 'good' conservation status in the EU [15]. Similarly, in Ireland, 52 % of surface waters are in good or high ecological status, a decline from previous assessments [16] while 90 % of Ireland's protected habitats are in 'unfavourable' conservation status, with 51 % showing deteriorating trends [17].

Under the WFD, the Habitats Directive, and the Birds Directive, protected areas are a key element of water, habitat and species management. However, protected areas are failing to protect freshwater biodiversity [18,19], which is an even greater challenge now due to climate change [20,21]. While much progress has been made on the regulatory and policy area, there are significant implementation gaps

in protected area designation [22] and data gaps for effective protection and management of designated sites [23]. Small rivers in protected areas frequently support sensitive habitats and species but bridging the data gaps to support conservation and restoration targets requires adopting newer monitoring strategies including high frequency monitoring to detect the impact of increasing frequency of hydroclimatic events on water quality [24]. Reference conditions are a key concept in the WFD [11] and it was the first instance reference conditions were used in EU policy or legislation [25]. Reference conditions for an ecological system are defined in the directive as the natural environmental conditions that exist when human influence is minimal or absent [11]. Water bodies at high ecological status provide reference conditions against which water status under WFD is assigned [26] and authors have argued that high status sites under the WFD be designated as PAs to mitigate the significant decline in high status sites [27]. Reference sites provide a baseline for comparison, with ecological status of a site under the WFD based on the degree of deviation from reference conditions. Therefore reference sites are a key benchmark for water quality, informing the target water quality aims for sites not achieving at least 'good status' and helping distinguish human impacts from natural changes [25].

This research explored the water protection benefits of protected area designation and studied how effectively monitoring the impact of hydroclimatic events on a high-status river within a protected area study site in the northwest of Ireland can inform better protection strategies.

1.2 Protected areas and their role in protecting against biodiversity loss and conserving high status waters under the Water Framework Directive.

Protected areas play an important role in addressing both climate change and biodiversity loss [28]. The designation of protected areas (PAs) is a mechanism that has been adopted worldwide, initially to preserve those areas perceived as being of high value to humans [29] and more recently to reverse losses in biodiversity [30]. The number of protected areas worldwide is increasing with 287,359 PAs covering 244 countries and territories [31] currently designated, compared to just over 230,000 PAs five years previously [32]. PAs are a key tool in conserving nature and reversing biodiversity decline [33–36] and a fundamental instrument for delivering biodiversity targets [33,37]. Protected areas are experiencing

increased pressure to deliver economic value, in conjunction with increased climate change and land-use pressures [38] and despite significant conservation activity, biodiversity improvements are not being realised [39]. Freshwater species are rarely the focus of area based approaches to conservation [40,41] with an assumption that terrestrial PAs afforded the same level of protection to freshwater ecosystems [42]. Only 10% of large global rivers are under protection [43] and the adoption of freshwater PAs for biodiversity conservation has been much slower than marine PAs [44,45]. PAs are disproportionally located at higher elevations [46] but lower elevation freshwater ecosystems contain higher number of species than upland areas with the majority of a river channel also occurring in lowland areas [47]. Worldwide, almost two-thirds of people are living downstream of protected areas [48] with half of all river systems have been significantly impacted by human activity, with the least impacted or most pristine areas of the world's surface and its river channel now only accounting for less than 14% of the total [49].

Climate change is a key driver of changes in biodiversity worldwide [50] and the impact of climate change is predicted to outstrip the effects of alterations in land use in the forthcoming decades with the sixth IPCC assessment report emphasising that restoration of biodiversity is key to mitigating the negative impacts of climate change [51].The EU aims to combat climate change, declines in biodiversity and environmental damage via the European Green Deal initiated in 2021 [52]. One of the key actions of the European Green Deal is the implementation of the EU Biodiversity Strategy to restore and protect nature across the EU [9]. The EU Biodiversity Strategy aims to restore at least 25,000 km of free-flowing rivers by 2030 by removing barriers and restoring floodplains and wetlands [9]. However, this in conflict with plans to construct 8,785 new hydropower plants across Europe with 33% of such plants planned for protected areas in the EU, predominantly in national parks and Natura 2000 sites [53]. This is in addition to the more than one million in-stream barriers already impacting European rivers [54]. There are areas of conflict between EU climate, energy and environmental law [55,56], and in the absence of a hierarchy in EU law it requires balancing trade-offs at a national level [57] with authors highlighting that EU policies on renewable energy are eroding nature protection [58,59].

Highlighting the urgency of the situation for freshwater conservation, it has been described it as a 'freshwater biodiversity crisis' [60,61] and an 'Emergency Recovery Plan' for freshwater biodiversity has been proposed [62]. Protection of inland waters has been found to be inconsistent globally, with 53% of countries, failing to meet the Convention on Biological Diversity (CBD) Aichi target 11 for 2020 of 17% for inland waters [63] and implementation reports frequently failing to adequately address the specific needs of aquatic PAs [64].

While the Aichi 2020 targets along with the Convention for Biological Diversity were focused on terrestrial area based targets [41], this has been rectified in the Kunming-Montreal Global Biodiversity Framework (KM-GBF) which distinctly recognises inland waters, aiming for their restoration in Target 2, and protection via systems of protected areas in Target 3 [37]. The key legislation in Europe for the restoration and protection of aquatic ecosystems are the WFD and the Nature Directives [65] which are now complemented by the Nature Restoration Regulations [66]. The urgency for freshwater conservation is highlighted by the plateau in freshwater biodiversity gains in Europe since the 2010s, despite the implementation of water quality improvement and restoration measures [13].

1.2.1 Defining the Protected Area

There is no single definition for protected areas, with over 1000 different expressions used around the globe [67–69]. The International Union for Conservation of Nature (IUCN) and the Convention for Biological Diversity (CBD) definitions of protected areas are the most commonly referenced definitions internationally [70], but not all protected areas are represented by these categories [71].

1.3 Protected Area Coverage

In terms of land area, protected areas are one of the most important categories of land use on the planet [67] and Europe has the largest number of protected areas in the world [72–74]. In the EU 26.4% of land and 12.1% of marine waters, covering more than 1840 species and more than 230 habitats are protected under EU law [75]. However, the high number of protected areas in Europe may be misleading as the size of those areas is relatively small compared to other regions, and underlines the fragmented nature of habitats in European protected areas [74,76] with 50% of protected areas in the EU being less

than 1 km² in size [75]. This is significant for freshwater conservation as fragmented and disconnected protected areas are particularly problematic for conservation of smaller more specialised aquatic species [77]. The EU has committed to developing a network of Green Infrastructure, ' a strategically planned network of natural and semi-natural areas' designed to deliver for a number of key EU policy objectives, including improving connectivity between sites in the Natura 2000 network [78].

The increase in protected areas has led to an expansion in the numbers, types and policies in protected areas with an overlap in many areas [79]. These overlaps may lead to an overestimation of the extent of protected areas [68] and approximately 25% of protected areas worldwide have more than one designation [79]. The overlaps are most common in terrestrial areas of Europe with 28.9% of PAs in the EU covered by national PAs and Natura 2000 [73]. Freshwater areas fall within terrestrial protected areas [80,81], with these freshwater areas generally only forming a small portion of the overall protected area which can diminish their relative importance for protected areas managers [82]. Freshwater ecosystems included in PA coverage globally is approximated to be between 11-21% depending on the methodology and dataset employed [83], with the fact that non-riparian freshwater PAs coverage still yet to be measured being highlighted [84].

The high population density in Europe brings environmental impacts on ecosystems [74] and has often resulted in the location of protected areas in remote areas, or areas of low commercial or agricultural value [46,85,86]. This can lead to Natura 2000 species present in lowland areas being unprotected [87] and can result in lowland aquatic ecosystems being the most endangered [88]. To address this issue, the Aichi Biodiversity Target No. 11 required conservation areas to be 'ecologically representative and well connected' and should 'include areas of particular importance for biodiversity and ecosystem services' [89]. While the Aichi target of protecting 10% of Europe's seas was met at the end of 2018 [90], and the Natura 2000 network exceeded the 17% terrestrial protected area target [91], overly focusing on the size of area protected can diminish the importance of protecting and improving biodiversity [33]. It has been argued that current area based targets are insufficient to protect biodiversity[92], and the EU aims to address this issue by establishing a coherent Trans-European Nature Network, covering at least 30%

of land and sea, with 10% of that area strictly protected to conserve areas of very high biodiversity value or potential [9].

The majority of Europe's biodiversity continues to decline with only 14% of European habitats having good conservation status, therefore the vast majority are at bad or poor status [15] with freshwater biodiversity being particularly impacted both in Europe [93,94] and globally [62,95]. Analysis of PAs for freshwater species in Europe highlights that only 7% of European sub basins are covered by existing PAs with low proportion of species distribution of 4% across all taxa [96].

1.3.1 Freshwaters and Protected Areas (PAs)

Freshwater regions while only comprising less than 1% of global area, account for around 10% of the world's species and even more significantly, account for approximately one-third of vertebrate species [97] with the greatest species diversity per unit area of any habitat [98]. Freshwater systems have been described as hotspots of diversity but also of human activity [97], and critical for human survival [99] with hotspots being a crucial component of conservation planning [100,101]. There is an absence of protected areas in the upper reaches of over 70% of the world's rivers by length, with most of the largest river basins having less than 10% of their areas protected [102] with freshwater protection in 53% of countries was less than the AICHI 11 target of 17% [63]. Key Biodiversity Areas (KBA) across terrestrial, freshwater and marine ecosystems are 'sites contributing significantly to the global persistence of biodiversity' [103], and they must be sufficiently large and interconnected to sustain viable populations of the species requiring protection [104].

1.3.2 Protection afforded to freshwater habitats by PA designation.

While freshwater ecosystems are most at risk, they form the smaller portion of protected areas [70], are often under-researched [95,105] and are valued more as a 'physical resource' rather than for their habitat value [106]. [107] underlines the lack of protection for headwaters, ponds, streams, ditches, swamps and floodplains, particularly in agricultural catchments with [108] demonstrating that springs within

protected areas are frequently exploited as sources of drinking water despite supporting unique macroinvertebrate communities.

In designating PAs, terrestrial species hotspots may not occur in the same areas as freshwater species hotspots. It was found that the majority of hotspots for mussel and fish biodiversity in the south-eastern USA did not fall within terrestrial protected areas [101] , with less than half of the freshwater species covered by the current terrestrial protected areas in the Western Ghats Hotspot [109]. The inability of the hotspot approach to recognise the linear interaction between streams, rivers and estuaries has been highlighted, along with the impact of areas a distance away from the PA, and that 'hotlines' rather than hotspots is more appropriate for river networks [110].

Although they form only a minor portion of terrestrial protected areas, it is argued that protecting freshwater habitats is critical to successfully supporting worldwide biodiversity [98], and the protection of freshwater areas should be prioritised [42]. Even for freshwaters that are protected, habitats including ponds and standing-water aquatic habitats are frequently excluded in freshwater PAs [107]. The significance of creating and assessing freshwater protected areas for "aquatic conservation" has been highlighted and how the practice of designating distinct parcels of protected areas within a continuous system such as a river, poses particular challenges for aquatic protected areas and provides limited, disjointed conservation[111]. This is despite the fact that many terrestrial species rely on these aquatic ecosystems, so adequate protection of freshwaters is therefore key to reducing biodiversity loss in numerous terrestrial species [82]. [112] determined that incidental and complete gaps, where target species or habitats are inadvertently included in a PA with different conservation targets e.g. forest PAs, or are completely unprotected, can be significant, particularly at national scales.

A bias towards terrestrial system research has led to disjointed knowledge of freshwater biodiversity [113] and even when freshwater systems fall within terrestrial protected areas, management strategies are often concentrated on terrestrial species [62,113]. It has been highlighted that conservation strategies for terrestrial protected areas are unsatisfactory for freshwater systems and their distinct requirements [41], however it has been argued that the decline of some aquatic species may be linked not only to changes in the aquatic habitat, but also to changes in the terrestrial habitat bordering that

waterbody [114] including land use changes, eutrophication, invasive species and hydrological disturbances [115]. Despite the limitations of PAs for freshwater biodiversity conservation, they have been shown to be very effective and important for floodplain habitat protection, particularly due to the dramatic decrease in the number of floodplain habitats across Europe [116]

A novel approach to freshwater protection has been adopted in New Zealand, 'ownership by river' whereby the Te Awa Tupua (Whanganui) River has been granted legal personhood and it speaks and acts via a representative body which protects the river and must act in the river's best interests [117]. This nature held property rights approach has not been adopted in Europe as yet and has some limitations, but such property rights act as an additional conservation measure to protected areas and may positively influence public awareness and policy around freshwater conservation [118].

1.3.3 Challenges for Freshwater Biodiversity

Numerous authors have identified and described the threats and challenges to freshwater diversity [19,61,63,81,99,119,120]. As outlined in Figure 1, five categories of threats to freshwater biodiversity have been defined including traditional pressures such as water pollution, habitat modification and alien invasive species [119], with a comparison of marine PAs and freshwater PAs also identifying 6 categories including poverty and illegal fishing [121]. Dudgeon's 5 categories were expanded to comprise 12 emerging and enduring threats including climate change, infectious diseases, emerging contaminants and microplastics [99]. The European Environment Agency has identified the greatest threats to aquatic and water dependent ecosystems as changes in the physical environment and natural flows along with diffuse pollution sources [6]. However, authors have advised against ranking threats to biodiversity as such rankings oversimplify multiple threats and only provide partial information as they do not consider the intensity of the threat, the sensitivity of various species and the adaptative capacities of different aquatic ecosystems [122].

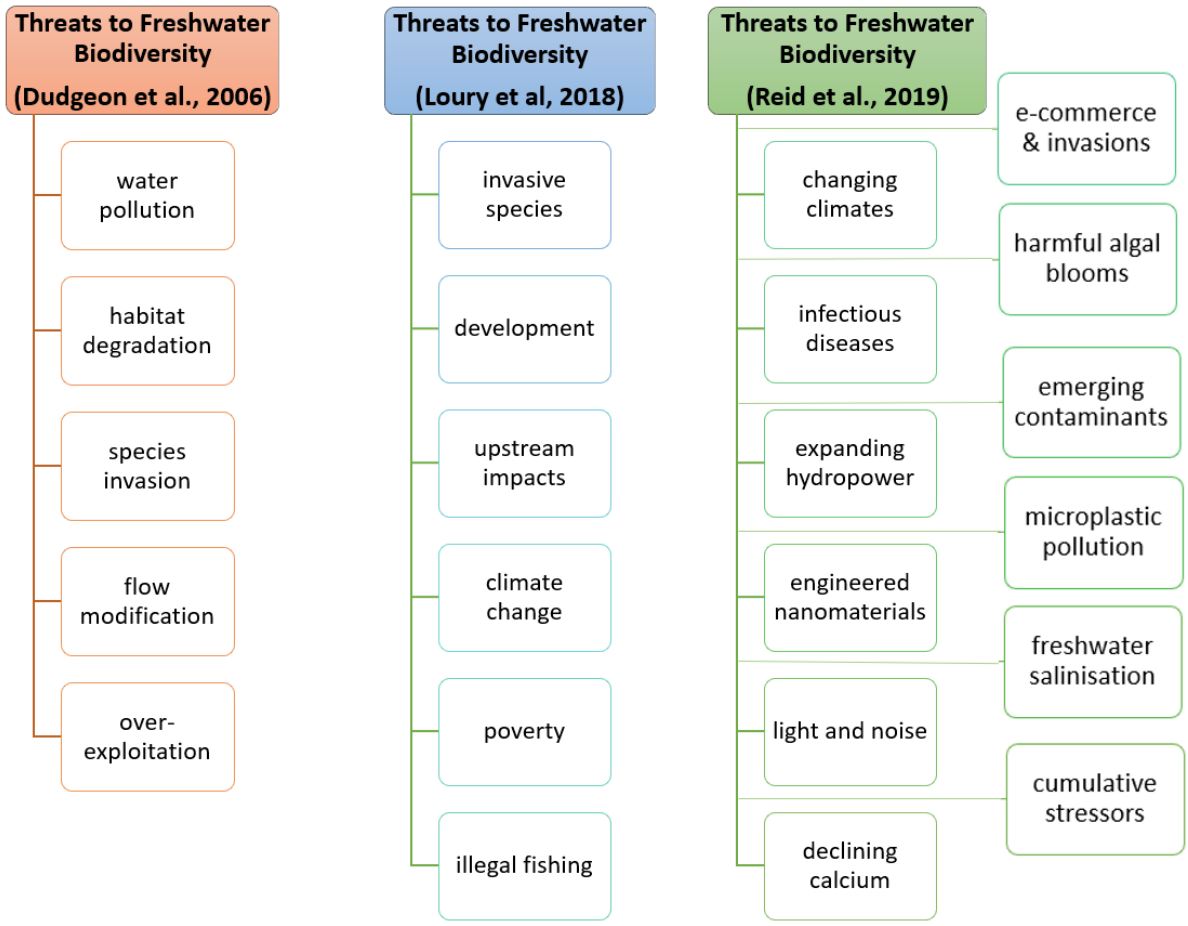


Figure 1: Threats to Freshwater Biodiversity

Quality freshwaters are key to supporting freshwater biodiversity with the main pressures on freshwaters in protected areas identified as alien invasive species, inadequate catchment management and pollution [123]. It has been calculated that 63% of freshwater resources coming from protected areas are subject to moderate levels of threat due to human activity [48] with the connectivity of freshwaters ecosystems being a particular advantage to invasive species [121].

Our current position for biodiversity has been described as a 'brief window of opportunity' to address the decline in freshwater systems [62]. While much focus has been paid to the impact of climate change on ecosystems [99,121] and the increased threats to freshwater due to the Anthropocene [99], authors have warned against complacency in addressing threats that are more immediate for freshwaters such as dams, habitat loss and pollution [124].

1.4 Protected Areas in Europe

1.4.1 Natura 2000 European Network of Protected Areas

Despite the large number of protected areas worldwide, there are minimal numbers of 'coordinated networks of protected areas aiming at continental-scale conservation' [125]. In addition to nationally designed protected areas, the European Union created the Natura 2000 network to safeguard biodiversity and the 'Nature Directives' provide the collective legislative framework for that network in Europe [126]. The Natura 2000 network is a coordinated conservation network [126,127] as it operates across the 27 EU member states and is the largest such network globally [125–128]. The Nature Directives provide for the creation of PAs, Special Protected Areas (SPAs) classified under the Birds Directive which protects rare, vulnerable, or migratory birds and their breeding or roosting sites [129], and Special Areas of Conservation (SACs) designated under the Habitats Directive which protects a broader range of rare or endangered wildlife habitats, plants, and non-bird animal species. [12]. Both form part of the European Union's Natura 2000 network. The EU is a contracting party to the Convention on the Conservation of European wildlife and natural habitats (Bern Convention), and the SACs and SPAs are the EU member states contribution to the Emerald Network [130].

By the end of 2021, the Natura 2000 network consisted of over 27,000 sites covering 18.6% of the EU land territory [131], and its implementation significantly increased biological knowledge of European habitats and species [127]. The network is a cornerstone of EU biodiversity conservation strategy [39,73,74,125] and forms part of the EU's strategy to halt biodiversity decline and meet the targets of the EU Biodiversity Strategy for 2030 [9]. However despite the large scale of Natura 2000, only a limited amount of freshwater species are protected under the Habitats Directive with many range restricted and highly endangered aquatic species not included [132]. Although European lakes are adequately covered by the Natura 2000 network at waterbody level, terrestrial areas surrounding those waterbodies have much lower protection including buffer zones around waterbodies has been highlighted [133]. Notwithstanding the limitations of the Natura 2000 network for freshwater conservation, significantly higher levels of PA coverage of rivers exists in EU member states then non-EU member states in neighbouring Balkan countries [134].

1.4.2 Water Framework Directive (Directive 2000/60/EC) Protected Areas

The WFD specifically provides for protected areas where such areas require 'special protection under specific Community legislation for the protection of their surface water and groundwater or for the conservation of habitats and species directly depending on water' [11]. The WFD identifies five categories of protected areas listed under Annex IV including SACs under the Habitats directive & SPAs under the Birds Directive, designated areas for drinking water abstraction, designated areas for economically significant aquatic species, recreational waters including bathing waters, and nutrient sensitive areas (nitrate vulnerable zones and urban wastewater sensitive areas). Drinking Water PAs which are water bodies identified under WFD Article 7(1) are the only category of WFD PAs that are solely designated by the WFD legislation [135]. Annex IV of the WFD also makes specific mention of the Natura 2000 sites, so therefore WFD PA applies to all Natura 2000 sites that contain water-dependent habitats and species. Under Article 6, member states are obliged to monitor such protected areas [11] and were required to achieve compliance with any objectives or standards in protected areas by 2015. Where a waterbody occurs within a Natura 2000 site then both the WFD status objectives along with the requirement to maintain or restore the site to favourable conservation status must be considered, with Article 4.2 of the WFD requiring that the more stringent of the objectives shall apply [11] In principle it is the WFD objective of the restoration of good ecological status that prevails, but all the objectives of the WFD and the Nature Directives must be achieved by member states [136]. In addition, that the management of water bodies at catchment level under the WFD provides the opportunity for extending the protection of PAs beyond the defined spatial boundaries of those PAs [18].

Data on WFD protected areas is available via the Water Information System for Europe (WISE) PA data set [137]. The data source varies depending on the relevant legislation under which the data is being reported to the European Commission by each member state.

1.4.3 National protected areas

National protected areas in Europe cover a broad range of designation types, assigned under national legislation to areas of land and to water bodies with some of the most common designations including national parks, nature reserves and wilderness areas [138]. The long history of protected areas in Europe

has generated a diverse range of PA types [76] with over 400 designation categories across Europe [75]. The different designation types reflect different management authorities and varying level of protection [139].

1.4.4 River Protected Areas

Globally, 1.9 million kilometres or 16% of river length occurs within PAs with 1.7 million kilometres of free flowing rivers or 17% of free flowing river length occurring within PAs [140]. Of the larger river basins in the EU, those with a high level of protection for free-flowing kilometres include the Rhine and the Danube, with Poland and Germany having more than 40% of free-flowing kilometres within PAs. However, for European long (>500Km) free flowing rivers, the majority of which are in Western Russia, only 7% are in PAs compared to 25% of long non free flowing rivers occurring within PAs.

Europe's first Wild River National Park, the Vjosa Wild River National Park which flows freely for 272km from its source to the Adriatic coast, was designated on 15 March 2023 and protects the entire river length and 4 of its tributaries. The Albanian and Greek governments engaged to create the Aoös -Vjosa transboundary park to protect the river from source to sea [141]. The Vjosa Wild River National Park PA consists of 400 km of waterway with over 1000 species of flora and fauna, 300 cultural monuments and 1 UNESCO Cultural World Heritage site [142]. Under the EU Nature Restoration Law and the Biodiversity Strategy for 2030, the EU set a target to restore at least 25,000 km of free flowing river and in the U.S. Five EU countries, Finland, France, Slovenia, Spain and Sweden along with two other European countries, Norway and Iceland have national legal provisions protecting the free-flowing character of rivers with proposals for similar in North Macedonia, Montenegro and Portugal [143]. Only two larger rivers are fully protected from source to sea, the Kalixälv in Sweden and the Torneälv in Finland and Sweden and while only short sections are protected in some cases, they were found to be 'remarkably successful in safeguarding the protection aims of free flowing character and preventing hydropower development [143].

1.4.5 Key Biodiversity Areas

Key Biodiversity Areas (KBA) across terrestrial, freshwater and marine ecosystems are 'sites contributing significantly to the global persistence of biodiversity' [103] and they must be sufficiently

large and interconnected to sustain viable populations of the species requiring protection [104]. KBAs are legally designated PAs but are an inexpensive, standardised approach to scientifically identify sites areas based on the presence of trigger species that are critically important for the persistence of biodiversity [144]. An advantage of KBAs is that they can mitigate some of the shortfalls for freshwater biodiversity in terrestrial PAs [81]. The IUCN developed a methodology for identifying freshwater KBIs to determine priority areas for freshwater conservation which is based on catchment boundaries, therefore which facilitating easy integration into River Basin Management Plans [143]. In Europe, since 2000 there was more than a 50% increase in the proportion of freshwater KBAs covered by designated PAs, from 40% in 2000 up to 63.3% in 2021 [145].

KBAs have been used as an important tool to prioritise sites for PA designation, with research demonstrating that KBAs were more exposed to the impact of future climate and land-use projections in Mediterranean countries (9 within the EU) than lower value sites for biodiversity [146]. [147] used a variety of freshwater species and the KBA criteria, to apply a spatial conservation strategy approach for identifying a network of Critical Catchments of freshwater biodiversity in Europe. They highlighted the 'spatial mismatch' between freshwater biodiversity and PAs in Europe, with 94% of the Critical Catchments identified having only 30% spatial overlap with PAs. Using spatial prioritisation, they identified the key areas for freshwater biodiversity conservation comprising 17% of the area of Europe, primarily occurring in southern and eastern Europe.

1.5 Protected Area Designation in Europe

The categorisation of PAs is determined by the administrative and political scale that they are designated and in turn managed, ranging from global treaties, EU directives, national legislation and local level authorities [75]. Examples of international PAs in Europe include UNESCO world heritage sites and the Natura 2000 network, of regional PAs includes Danubeparks and European Geoparks Network, and of national protected areas include national parks [139] . The Biodiversity Information System for Europe (BISE) provides data on the numbers and area coverage of protected areas [75]and the World Database on Protected Areas provides details on the number and type of designations. The European inventory of nationally designated protected areas (CDDA) maintained by the European Environment

Agency, details information on PAs including their designation type, and provides information from 38 European member countries of Eionet to the World Database of Protected areas [149].

The World Database on PAs provides the best source of data, however there is a lack of a complete database for PAs and this is further complicated by areas with no legal designation but which in effect act as protected areas [150]. For the purpose of this review, the data used was from the BISE [75] and the World Database on Protected Areas . According to the database, in Europe (62 countries) there are 427 categories of international, regional and national protected areas [151] as outlined in Figure 2: International, regional, and national designations of protected areas in Europe (October 2023).

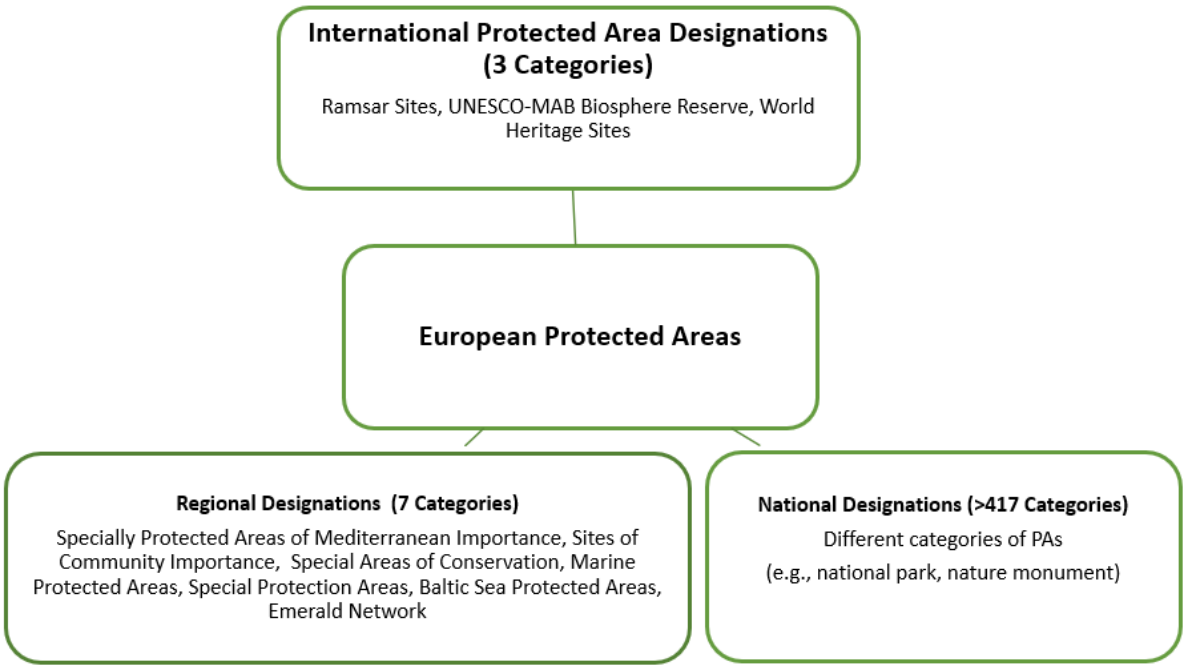


Figure 2: International, regional, and national designations of protected areas in Europe (October 2023).

International designations account for only 1353 (0.77%) of the total number of protected sites with almost 80% of these being Ramsar sites (Figure 3).

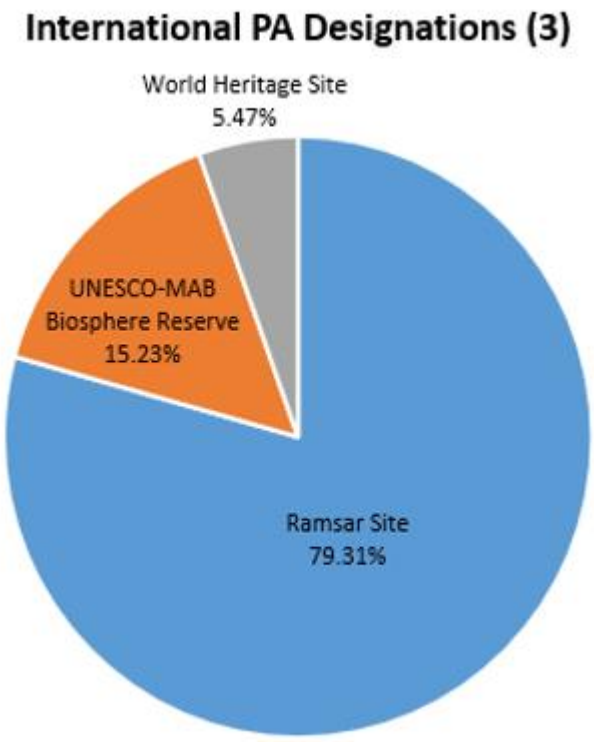


Figure 3:International protected area designations in Europe (October 2023).

Regional designated PAs account for 30,838 (17.47%) of sites and greater than 60% of these PAs are designated special areas of conservation under the Habitats Directive (Figure 4).

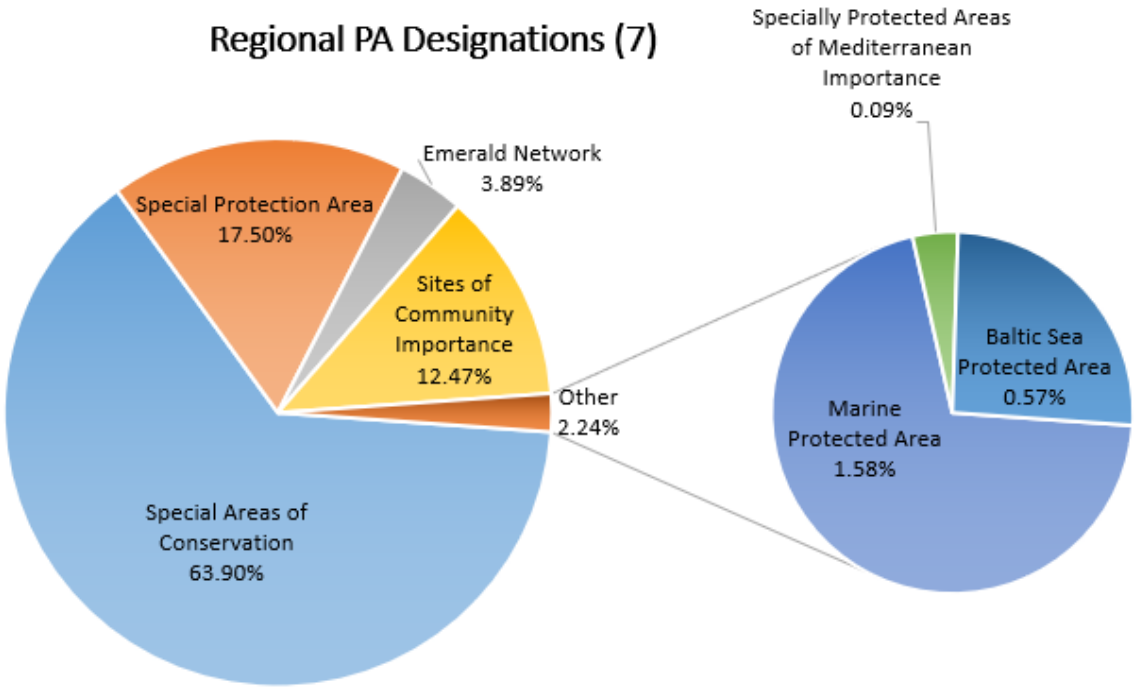


Figure 4:Regional protected area designations in Europe (October 2023).

The proportion of international, regional, and national protected area designations of the total in the EU-27 + UK countries varies significantly, with Estonia having the largest proportion of national PAs at 96.7% of its total, followed by the UK at 95.6%. Italy has the largest proportion of regional PAs at 76% of its total PAs, closely followed by Ireland at 75%. Most countries had less than 2% international PAs of their total designations with the Netherlands having the largest proportion at almost 10% of its total PAs followed by Portugal at 8.3 % (Figure 5).

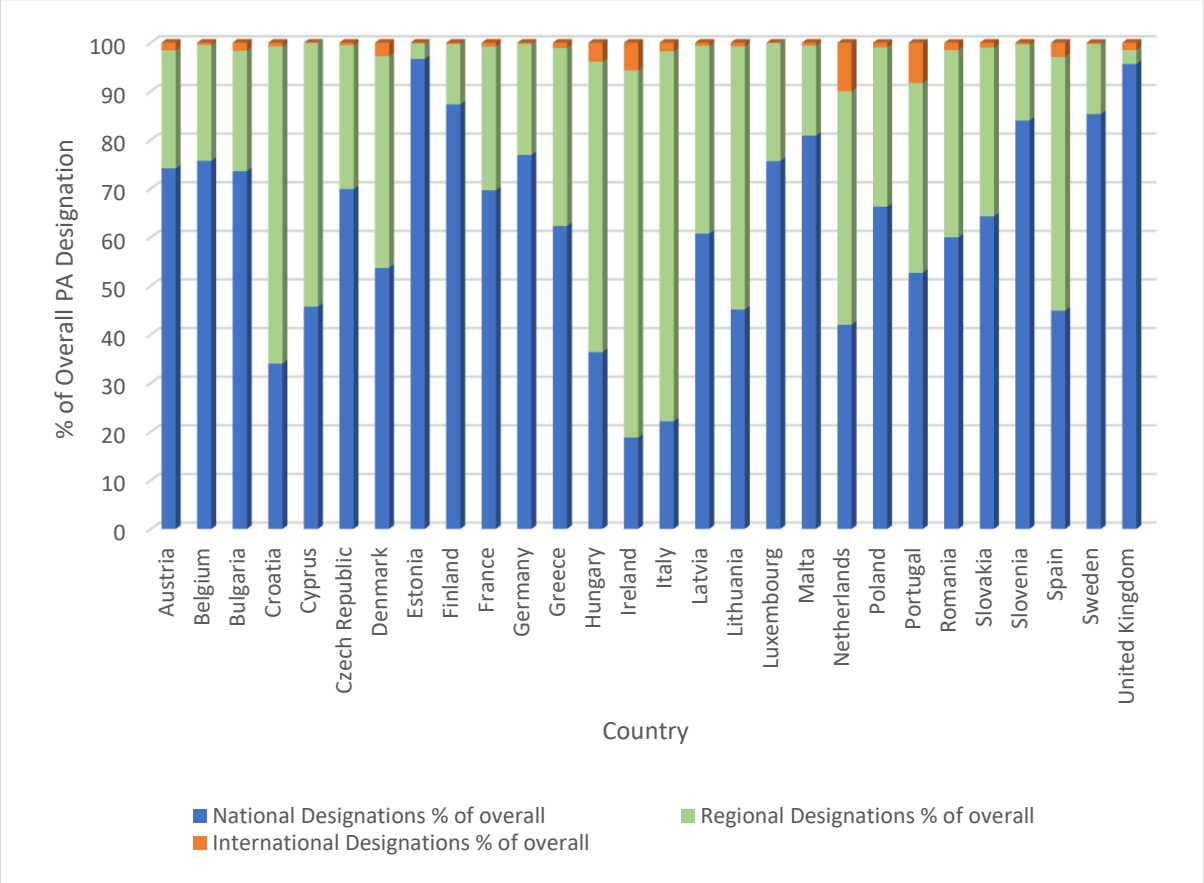


Figure 5: Percentage of total international, regional, and national protected area designations by country (October 2023).

The vast majority of protected sites in Europe are national protected areas accounting for 144,373 of sites (81.77%) with over 400 categories, 328 of those categories in EU-27 + UK [151]. The number of national PA designation categories varies from 1 category in Ireland to 43 categories in Spain with a median of 9 categories across the EU-27 + UK (Figure 6).

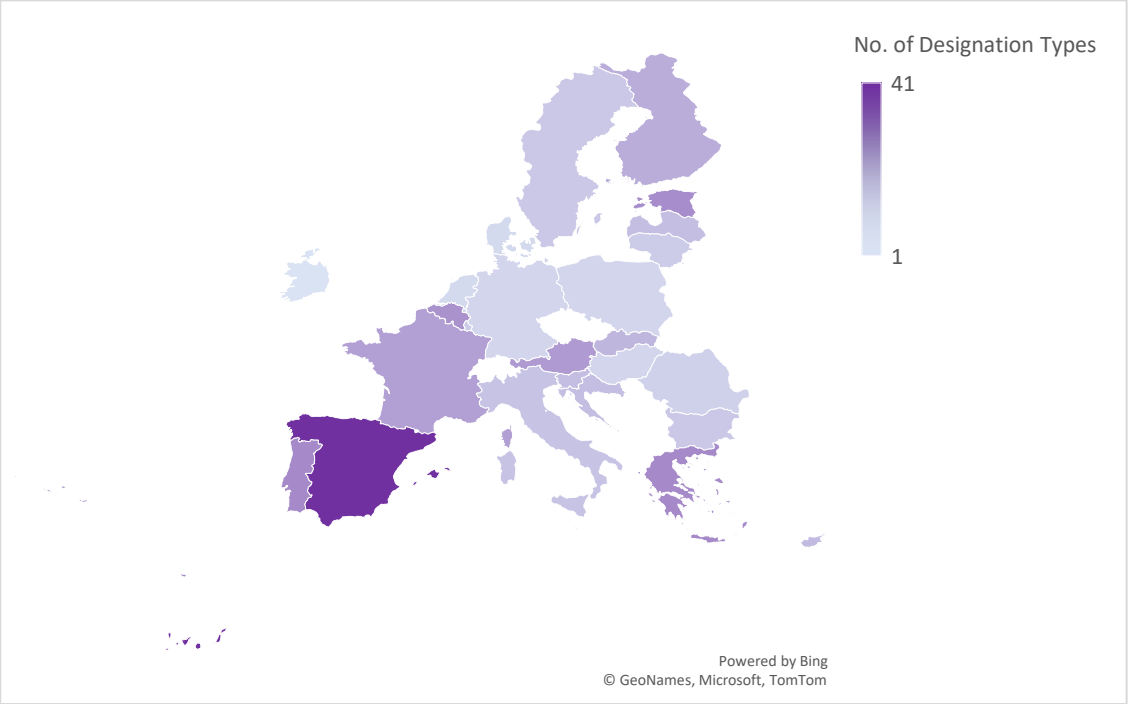


Figure 6: Number of National Designation Categories for Protected Areas in EU-27 + UK (October 2023) (created using Bing Maps).

Similarly, the numbers of national PAs vary considerably between European countries with just 59 in Cyprus compared to over 27,000 in Sweden, with a median of 998 national PAs across the EU-27 + UK. Differences in the numbers of protected areas across countries ae associated with differences in total land area, level of affluence, land ownership and habitat variety [152] as highlighted in Figure 7.

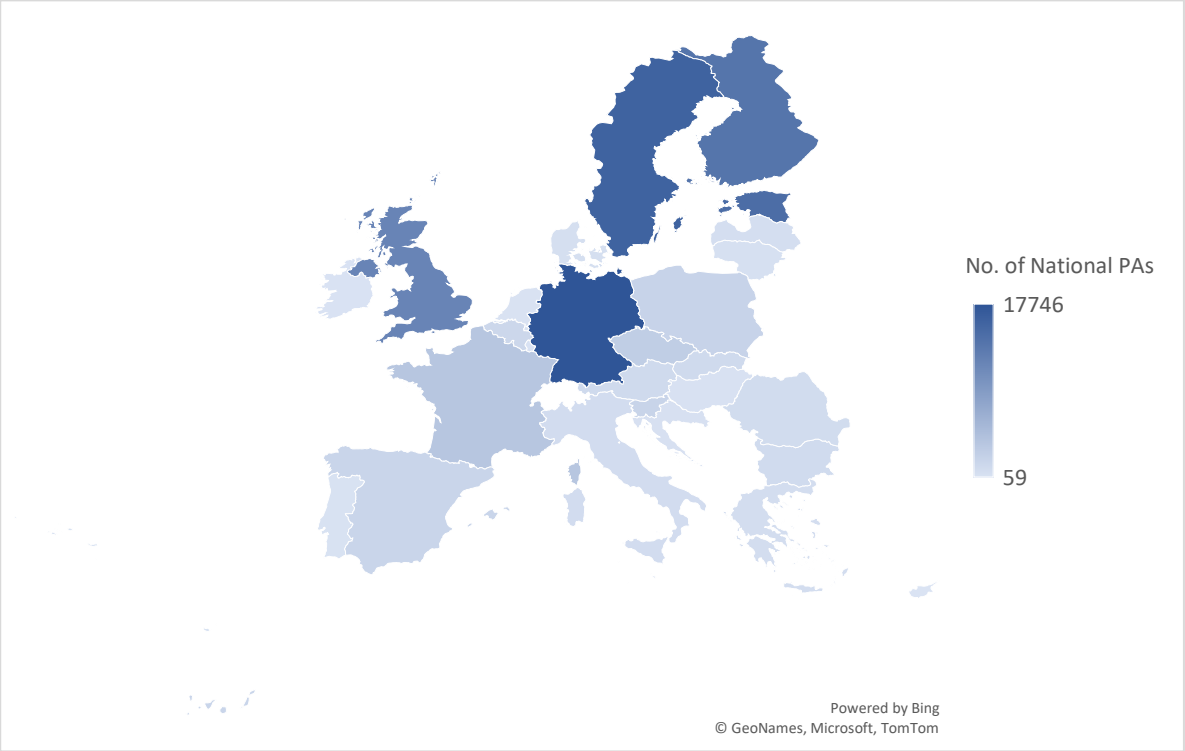


Figure 7: Number of Protected Areas in EU-27 + United Kingdom (October 2023) (created using Bing maps).

The designation of protected areas has increased significantly over the last 50 years [102] with more than 80% of protected areas created since 1962 [38]. Despite the slow pace of designations in the late 1990s [153], the establishment of EU's Natura 2000 network has significantly increased the protected area coverage [154] (Figure 8). The total number of protected areas globally stands at 257,889 with 158,450 (61.4%) of those in Europe [138]. The EU Nature Restoration Law [8] strengthens protection within existing PAs areas through strict legal frameworks and extends restoration, protection, and non-deterioration obligations beyond protected areas, encouraging the expansion of protected areas and connectivity between PAs across the EU. However, it does allow limited, controlled derogations for major public interest projects (especially energy and defence).

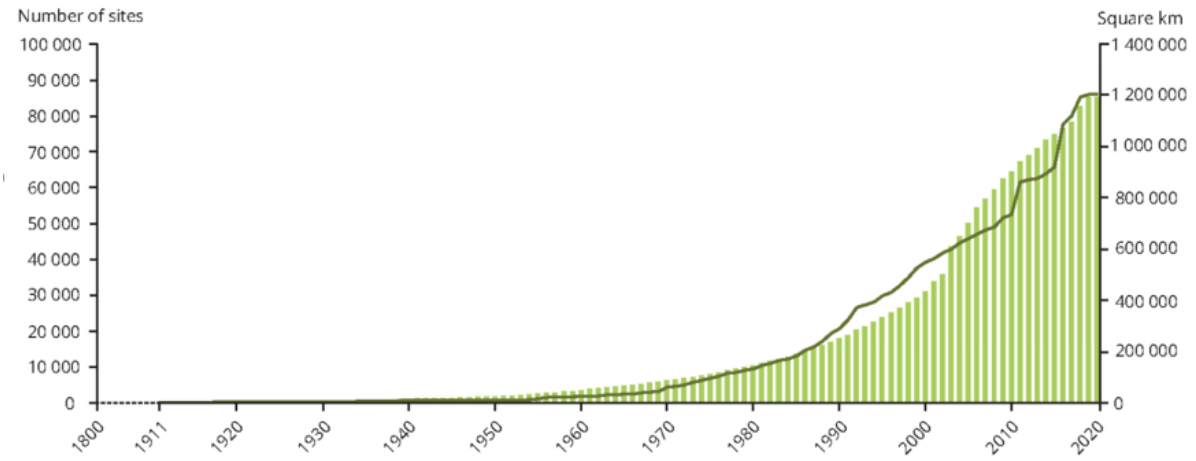


Figure 8: Increase in the number of sites and the cumulative area for nationally designated Protected Areas in Europe from 1800 to 2020 [149].

While the drivers for PA designation in the EU may be policy, legislative or convention driven (EEA and European Commission, 2023), other factors including an area being identified as a key biodiversity area (KBA) can influence designation [155]. Worldwide there are 16,333 KBAs with Europe having 4,862 KBAs covering an area of 1,565,283 km^2 and 1,082 trigger species. Freshwater KBA's make up just over 28% of the overall KBAs in Europe covering 26.5% of the KBA area and consisting of up to 40% of the trigger species. However, the average proportion (%) of freshwater KBAs covered by protected areas in Europe has remained largely static since the early 2000s, with 11 EU countries having over 90% of freshwater KBAs covered by PAs in 2022, and Cyprus and Luxembourg having less than 40% coverage (Figure 9) [156]. The Water Framework Directive was enacted in 2000 with a focus on the implementation of this directive as the primary tool to restore water quality across EU [11].

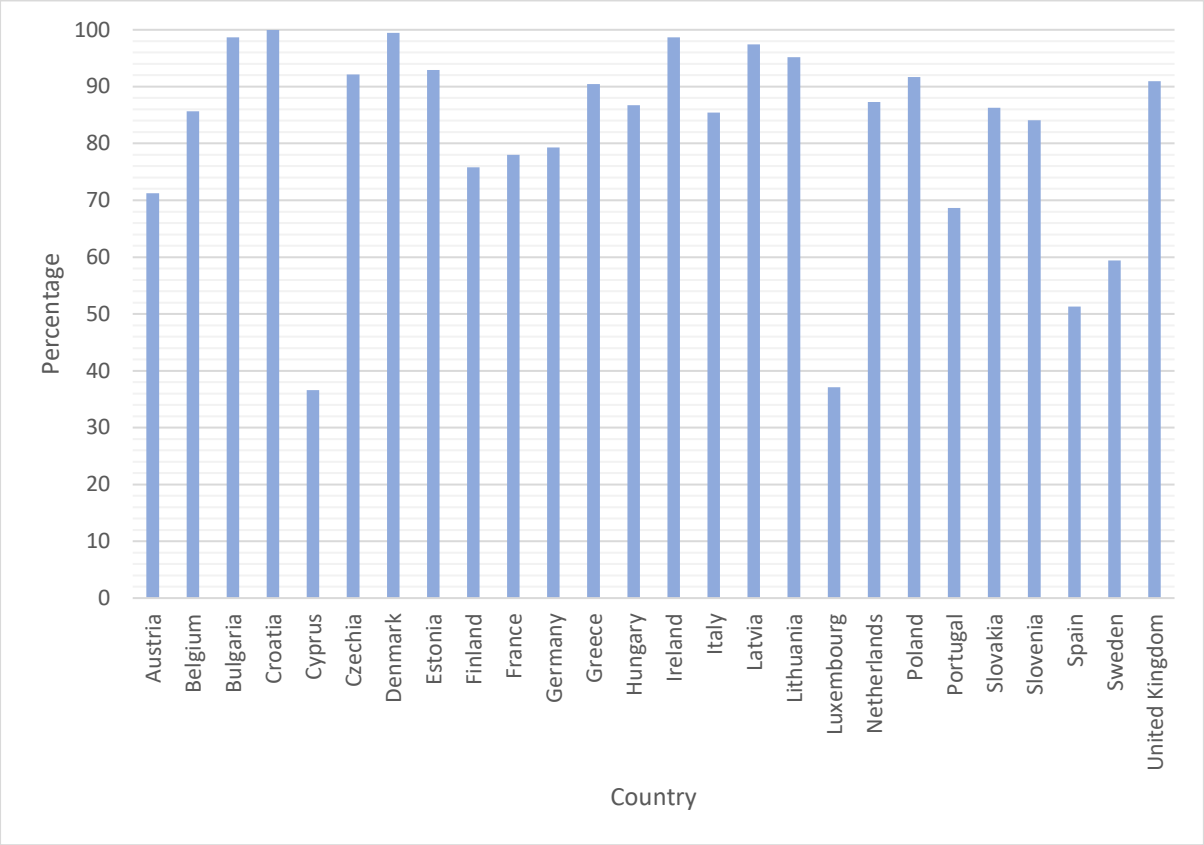


Figure 9: Average proportion (%) of Freshwater Key Biodiversity Areas (KBAs) covered by protected areas in Europe in 2022.

1.5.1 Governance and Management of Protected Areas in Europe

There are a wide variety of agencies involved in protected area governance [157] . Although the types of governance in protected areas can be quite diverse [158], there are 4 categories of protected areas recognised by the International Union for Conservation of Nature (IUCN) and the Convention for Biological Diversity (CBD), Governance by government, Shared governance, Private governance, and Governance by indigenous peoples and local communities [157].The World Database for Protected Areas reports information on Governance type and management authority for each PA, but for many National PAs on the database the management authority is 'not reported' [159]. The extensive history of protected areas in Europe has resulted in diverse approaches to both PA designation and PA management across the different countries [76]. The author could find no single repository for information on the competent authorities for protected areas, either for the EU member states or worldwide. The author searched the World Database for PAs and searched government agency

websites for information on competent authors for EU-27 + UK countries. In the absence of information from the database and website, information on agencies involved in protected area management in the EU was gathered via correspondence with government departments, via academics and via government websites, and is detailed in Table 1 under ‘reference’.

Table 1: National Protected Areas and competent authorities in EU-27 plus the United Kingdom. Based on data from Biodiversity Information System for Europe A [75,159].

Country	(a)[1]	(b)[2]	(c)[3]	No. of National Designation Types[B]	No. of National PAs Designated [B]	% Overlap between terrestrial National PA Designation and Natura 2000 Sites[A]	Agencies involved in management of Protected Areas	Reference
Austria	1668	29.2	0	17	1237	38.2	Nine Federal Provinces	Umweltbundesamt /Environment Agency Austria (2021) Email to Lisa Cronin, 14 Mar.
Belgium	2256	15.55	38.06	19	1708	23.5	Three Institutions Flanders: INBO - Research Institute Nature and Forest Brussels: Brussels Environment Wallonia: SPW Agriculture, Resources naturelles et Environnement	Nationaal Knooppunt EMA & EIONET/NFP Belgium (2021) Email to Lisa Cronin, 15 Mar.
Bulgaria	1430	41.04	8.11	7	1052	21.5	Directorates, operating under the ministry of Environment, manage and administer the National Parks with the Executive Agency for Environment providing guidance on ecological monitoring and environmental quality.	Parks, Reserves, and other Protected Areas in Bulgaria. Available at: http://www.parks.it/world/BG/Eindex.html (Accessed: 30 Mar 2021)

[1] (a) Total Protected Areas [A]

[2] (b) Land Cover for PA (% of total land area) [A]

[3] (c) Marine Cover for PA (% of total marine and coastal area)[A]

Croatia	1200	38.51	8.99	9	408	32.0	Ministry of Economy and Sustainable development oversees and funds public institutions responsible for the management of protected areas and Institute for Environment and Nature within the Ministry provides centralized oversight and expertise.	Republike Hrvatska Ministarstvo gospodarstva I održivog razvoja/ Republic of Croatia Ministry of Economy & Sustainable Development (2021) Email to Lisa Cronin, 15 Mar.
Cyprus	129	38.72	8.62	10	59	41.2	Department of Environment, Department of Forests, Department of Fisheries and Marine Research, Game Fund	Department of Environment, Ministry of Agriculture, Rural Development and Environment (2021) Email to Lisa Cronin, 18 Mar.
Czechia	3899	22.17	0	7	2725	44.0	Nature Conservation Agency of the Czech Republic, Regional authorities, Contracting Parties for Contractually Protected Areas.	Agentura Ochrany Přírody a Krajiny ČR/ Nature Conservation Agency of the Czech Republic (2021) Email to Lisa Cronin, 15 Mar.
Denmark	1088	16.97	18.32	3	584	30.4	Danish Environmental Protection Agency has the primary responsibility for designation and protection.	Miljøministeriet Miljøstyrelsen/Ministry of Environment Denmark (2021) Email to Lisa Cronin, 15 Mar.
Estonia	18947	21.41	18.78	20	18315	84.7	Estonian Environmental Board designates protected areas and compiles area-based rules and management plans.	Keskkonnaministeerium/Republic of Estonia Ministry of Environment (2021) Email to Lisa Cronin, 15 Mar.
Finland	17801	13.4	11.99	14	15544	74.2	State-owned land: Metsähallitus under the Ministry of the Environment. Privately owned Protected Areas: Landowner, ELY Centre & Metsähallitus.	Ympäristöhallinto/Finish Ministry of the Environment (2020) Protected Areas. Available at https://www.ymparisto.fi/en-US/Nature/Protected_areas (Accessed 16 Mar 2021)
France	6085	28.4	49.82	17	4238	18.4	The Ministry of Environment (Ministry of Ecological Transition).	Ministère de l'Ecologie/Ministry of Ecology, CGDD / SDES (2021) Email to Lisa Cronin, 15 Mar.
Germany	23207	37.59	45.46	4	17851	25.4	Federal States designate and manage terrestrial protected areas, large scale protected areas by special agencies e.g. Park Administrations for each National Park and Biosphere Reserve. Nature Parks are managed by Park	Umweltbundesamt Deutschland/ German Environment Agency (2021) Email to Lisa Cronin, 15 Mar.

							Administrations and smaller protected areas managed by County Districts (Landkreis).	
Greece	1289	35.22	4.52	21	803	28.1	36 Protected Areas Management Bodies (2018) cover the PA network in Greece, supervised by the Minister of Environment and Energy. The Natural Environment and Climate Change Agency implement the policy set by the Ministry of Environment and Energy for the management of protected areas and the conservation of biodiversity. The small percentage of nationally designated PAs areas outside the Natura 2000 network are managed by the relevant Decentralised Administration.	NHMC (2018) Life Natura Themis. Available at http://www.lifethemis.eu/en/content/new-law-management-bodies-protected-areas (Accessed 7 Sept 2021)
Hungary	896	22.6	0	4	326	37.5	Under the Ministry of Agriculture, Department of National Parks and Landscape Protection, 10 national park directorates are responsible for the protection, development, maintenance, and presentation of the nationally important PAs. Locally important PAs are under the responsibility of the local government.	Nemzeti Parki és Tájvéd/ Department of National Parks and Landscape Protection (2021) Email to Lisa Cronin, 15 Mar.
Ireland	825	14.43	2.33	1	155	1.34	The National Parks & Wildlife Service (NPWS) is responsible for the designation of conservation sites in Ireland.	National Parks and Wildlife Service Available at https://www.npws.ie/protected-sites (Accessed 15 Mar 2021)
Italy	3348	21.58	10.61	8	875	37.9	National parks and marine fall under the Italian Ministry for the Environment and the Protection of Land and Sea, regional parks under various regional administrations,	Federparchi, Italian Federation of Parks and Natural Reserves (2022) Available at http://www.federparchi.it/ (Accessed 15 Mar 2021)

							reserves under the Italian Ministry for Agricultural Policy, and others which are under provincial or municipal administrations.	
Latvia	1123	18.18	16.04	9	682	63.5	Strict nature reserves, national parks and biosphere reserves are established by the Saeima (Parliament of the Republic of Latvia). Protected landscape areas, nature reserves, nature parks, protected sea territories and nature monuments are established by the Cabinet of Ministers. Nature reserves, nature parks and nature monuments of local significance may be established by local governments. Management of protected territories is coordinated by the Ministry of Environmental Protection and Regional Development. Nature Conservation Agency manage protected areas established by the Saeima and Cabinet, Local governments may also manage protected areas. Specific associations and foundations implement measures necessary in a PA.	Dabas Aizsardzības Departamenta/Department of Nature Protection (2021) Email to Lisa Cronin, 22 Mar.
Lithuania	1061	17.08	25.59	6	479	63.3	Government establishes state protected areas. Management and monitoring by State Service for Protected Areas (SSPA). Department of Cultural Heritage under the Ministry of Culture is responsible for cultural heritage sites.	Aplinkos Apsaugos Agentura/Lithuanian Environmental Protection Agency (2021) Email to Lisa Cronin, 15 Mar.

Luxembourg	271	55.8	0	6	205	48.1	The Administration de la Nature et des Forêts is responsible for management and monitoring of protected areas.	Administration de la nature et des forêts/Administration for Nature and Forests (2021) Email to Lisa Cronin, 14 Sept.
Malta	335	30.64	7.44	16	271	48.5	Lead agency for designation, protection, monitoring and management of protected areas is the Environment and Resources Authority (ERA). The ERA delegates implementation to stakeholders via management agreements.	Environment & Resources Authority (2021) Email to Lisa Cronin, 22 Sept.
Netherlands	462	22.47	26.86	3	194	57.3	Ministry of Agriculture, Nature and Food Quality responsible for the designation of Natura 2000 sites and the 12 Provincial Administrations responsible for management of N2000 and the other protected areas mostly National Nature Network (NNN) and areas of national parks not part of NNN or N2000. Rijkswaterstaat (national water agency) is responsible for the management and the nature monitoring for the large waterbodies	Ministerie van Landbouw, Natuur en Voedselkwaliteit /Ministry of Agriculture, Nature and Food Quality (2021) Email to Lisa Cronin, 7 Apr.
Poland	3109	39.57	22.57	4	2061	31.0	National parks are managed by the director of the national park and national park management. Designation of landscape parks and protected landscape area is carried out by resolution of the voivodeship council, and managed by the director of the landscape park, appointed by the voivodship board (local government authority). Nature monuments, documentation sites, ecological sites and nature and	Departament Ochrony Przyrody/ Department of Nature Conservation (2021) Email to Lisa Cronin, 15 Mar.

							landscape areas are appointed by municipal councils, and the municipal government is also responsible for managing these areas. Designation and protection of Nature reserves and Natura 2000 sites is the responsibility of the regional environmental protection directors and the General Director of Environmental Protection who also have a decisive influence on planning, spatial and implementation of projects in all protected areas.	
Portugal	469	22.91	16.9	21	247	33.0	Instituto da Conservação da Natureza e Florestas (ICNF) responsible for designation monitoring and managing protected areas, including marine protected areas.	Agencia Portuguesa do Ambiente/ Portuguese Environment Agency (2021) Email to Lisa Cronin, 15 Mar.
Romania	1574	24.52	23.1	6	944	20.2	Designation is by local authorities (for local protected areas), by the Ministry for Environment (for sites for community importance - Natura 2000 sites SCI), by Romania Government (for natural and natural parks, natural reserve and natural monuments, Natura 2000 sites SPA) or by the Romanian Parliament (for international protected areas). Management is by National Agency for Protected Areas (ANANP), some natural and national parks by the National Company for Forestry (ROMSILVA), and for Danube Delta Biosphere Reserve with the Administration of the Danube Delta Biosphere Reserve.	Ioja, C. (2021) Email to Lisa Cronin 3 Sept.

Slovakia	1969	37.59	0	11	1266	42.4	The Ministry for Environment manages and controls state agencies responsible for protected areas. The State Nature Protection of the Slovak Republic Authority has national competence for nature and landscape protection and works alongside other agencies including the Inspectorate, District Offices, State Veterinary and Food Administration and the Nature Guards.	Žoncová, M. (2021) Email to Lisa Cronin 9 Sept
Slovenia	2267	40.44	2.32	9	1904	93.3	Protected areas are designated by the state, one of the municipalities or the state and the municipality together. All major and some of the smaller ones are managed by state or municipal public institutes, concessionaires or managers. Supervision of compliance with the prescribed regimes is performed by nature conservation and voluntary supervisors.	Kus Veenvliet, J. (2021). Email to Lisa Cronin 9 Oct
Spain	4119	28.12	12.79	43	1849	50	Ministry of Agriculture Food and Environment is responsible for the declaration, planning and management of protected spaces located in marine areas under national sovereignty or jurisdiction, provided that there is no ecological continuity of the marine ecosystem with a natural land area subject to protection. In turn, the Autonomous Communities are responsible for the declaration, planning and management of protected areas in their territorial scope, as well as in	Ministerio para la Transcion Ecologica y el Reto Demografico/ Ministry for Ecological Transition and Demographic Challenge Available at: https://www.miteco.gob.es/es/biodiversidad/temas/espacios-protegidos/default.aspx (Accessed 21 Mar 2021)

							marine waters when, for the latter, in each case there is such ecological continuity.	
Sweden	31801	15.43	15.82	15	27137	85.6	The responsible organisation for the National Parks, Natures Reserves, nature conservation areas, animal and plant protection areas, cultural reserves, water protection areas, natural monuments, biotype protection areas, Natura 2000 SPA/SCI/SAC & landscape image protection areas is the Swedish Environmental Protection Agency. The Swedish Forest Agency is responsible for forest habitat protection areas.	Naturvårdsverket / Swedish Environmental Protection Agency 2021. Email to Lisa Cronin 6 Sept.
United Kingdom (Non-EU-27)	10902	27.77	44.06	18	10426	Not available	National Governments, Department for Environment, Food and Rural Affairs (DEFRA), Joint Nature Conservation Committee (JNCC) which is umbrella body for four national agencies Natural England, the Countryside Council for Wales, Scottish National Heritage and the Council for Nature Conservation and the Countryside, Local authorities and Marine Management Organisation	Dept. of Agriculture, Environment and Rural Affairs, Protected Areas. Available at: https://www.daera-ni.gov.uk/landing-pages/protected-areas. (Accessed 26Mar 2021)

Data from 21 EU-27 + UK countries reveals that protected area (PA) designation and management involve a fragmented array of national, regional, and municipal agencies (Table 1). This institutional fragmentation, combined with decentralised governance, poses severe challenges for freshwater biodiversity conservation [160]. Because freshwater ecosystems rely heavily on lateral and longitudinal connectivity [161], managing them across fragmented jurisdictions often results in a lack of cohesive strategy.

For example, delegating conservation duties to regional authorities in countries like Austria [162] and Italy [163] has created significant discrepancies and a lack of national standards. In contrast, stronger central oversight in Germany and Spain has fostered better cross-border coherence [164]. Furthermore, national reporting frameworks remain inadequate for coherent planning, and a lack of formal structures severely hinders vital cross-border cooperation [164,165].

To bridge these gaps, a systematic, continental-scale approach to policy instruments such as the EU Green Infrastructure Network, is necessary to efficiently improve PA connectivity. A Green Infrastructure Network would be multifunctional in nature with areas for protection jointly selected to meet multiple objectives [166] with a higher priority assigned to areas providing the greatest value for multiple ecosystem services [167]. A Green Infrastructure Network would enhancing the capacity of existing PAs to provide protection under the predicted land use and climate changes by connecting existing Natura 2000 sites [166]. However, considerable investment is required for implementation [168] and additional areas of agriculture and forestry and further policy development will be necessary [166]. This type of approach is further complicated by massive spatial discrepancies across the EU; for instance, the overlap between national PA designations and Natura 2000 sites plummets from 93.3% in Slovenia to a mere 1.3% in Ireland (Figure 10). Standardising spatial prioritisation across member states is essential to resolve these coverage gaps and safeguard interconnected aquatic ecosystems [133].

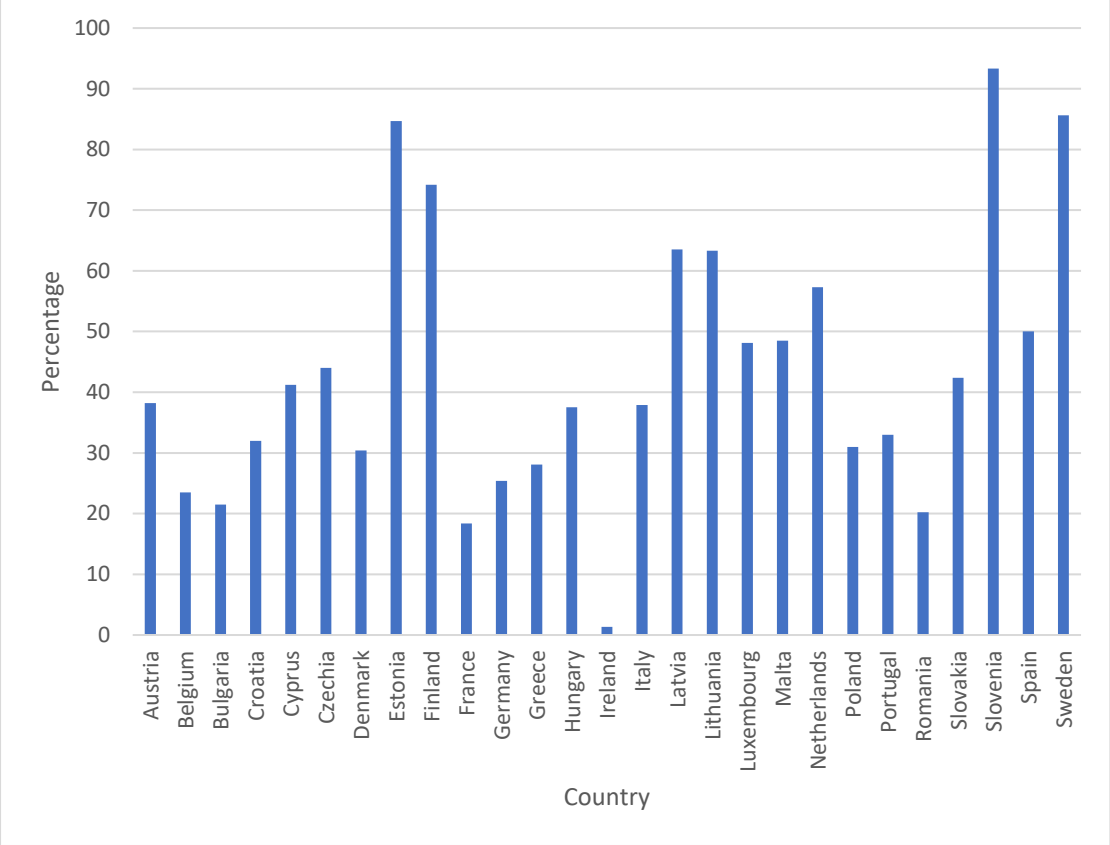


Figure 10: Percentage overlap between terrestrial National PA designation and Natura 2000 Sites in EU-27 [75].

Some areas in Europe are covered by 5 or more designations and it's argued that such overlaps may lead to ambiguity in governance [79]. Multiple designations can bring many benefits including greater levels of research and may in fact bolster protection[69] although it is argued that multiple designations do not guarantee 'cumulative protection effect' [169].

The Natura 2000 network, established under the Nature Directives has no single management strategy as EU directives are not directly applicable, therefore while member states are bound by the terms of a directive, they can choose the manner in which the directive will be transposed into national law [170]. This illustrates the complexity of the current way in which PAs are managed across the EU and the absence of a single, systematic approach to PA management even within the EU Natura 2000 network.

1.5.2 Protected areas and governance under the Water Framework Directive

The WFD specifically provides for protected areas where such areas require 'special protection under specific Community legislation for the protection of their surface water and groundwater or for the conservation of habitats and species directly depending on water' [11]. The WFD identifies five different categories of protected areas listed under Annex IV,

1. Drinking Water Abstraction,
2. Economically Significant Species,
3. Recreational Waters,
4. Nutrient-Sensitive Areas and
5. Habitats and Species Protection [11].

The WFD makes specific mention of the Natura 2000 sites with member states obliged to monitor such protected areas [11]. There is a direct relationship between the WFD and the Nature Directives via Articles 1, 4, and 11 along with Annex IV and Annex VI of the WFD [171].

The WFD entered the 3rd and final Management Cycle in January 2021 [11], and similarly to freshwater biodiversity, while monitoring has advanced, water quality is deteriorating [14]. Article 8 of the WFD requires the monitoring of protected areas along with surface water status and ground water status [11]. Although it includes monitoring protected areas defined under the Directive, specific supplementary monitoring for water dependent habitat and species is not always included, and consequently suitable intervention measures to protect such species including appropriate Environmental Quality Standards are not identified [172]. Article 4(1) of the WFD requires that where multiple objectives apply to a water body i.e., for surface waters, for groundwater or for protected areas, then the most rigorous objectives shall apply [11]. There is good consensus between the objectives of the WFD and the Nature Directives, and the WFD implementation must respect the obligations of the Nature Directives [173]. In addition, according to Annex VI of the WFD, programmes of measures to restore water quality must consider the Nature directives and water bodies that fall under both WFD and Natures directive must be integrated into the programme of measures for the WFD. However Article 4 of the WFD also allows for exemptions from deadlines or exemptions to meet environmental

objectives to balance strict environmental goals with social and economic needs allowing member states to extend deadlines, permit temporary deterioration, set lower targets where unfair social or economic hard may be caused [11]. It has been argued that such exemptions weaken the implementation of the directive and can impede the achievement of good status [174] with Germany claiming exemptions for 82% of surface water bodies and 36% of groundwater bodies [175]. Conversely, exemptions can provide a mechanism for balancing the competing interests of environmental, social and economic sustainability [176]. Conflict may also arise where restoration of aquatic habitats can threaten protected species currently occupying the altered habitat [65]. It has been recommended that high status sites under the water framework directive be designated as PAs to help reverse the significant decline in high status sites, as they argue the requirements for high status waters and protected aquatic areas are broadly comparable [27]. However, analysis carried examining freshwater ecological quality within Natura 2000 sites in Greece, concluded that sites within protected areas were as likely to fail to achieve 'good status' under the WFD as sites outside protected areas [177]. In addition, implementation of the WFD is centred on larger rivers with catchment areas greater than 10 km^2 and larger lakes with surface area greater than 50 ha, to the exclusion of smaller water bodies including ponds and headwater streams [107].

The integration of the WFD and Nature directives was examined in ten case studies across Europe and highlighted the importance of integrating the objectives for both directives at the outset of river restoration projects [136] with greater synergies than differences identified in the legislation, however collaboration between the agencies involved is necessary for successful outcomes [173]. In Ireland, restoration of freshwater pearl mussel to favourable conservation status was only possible by adopting a sub-basin management plan approach for the freshwater pearl mussel catchments rather than individual Habitats Directive management plans for the PAs, with pressure specific measures produced to deliver for the objectives of both the WFD and the Habitats Directive. Similarly in France, an integrated monitoring strategy was implemented to achieve the objectives of both the WFD and

the Habitats Directive improving cost effectiveness, reducing resources required and more effective monitoring of a larger number of sites [136].

1.6 Protected area designation and improving freshwater biodiversity.

It's important to note that the protection of freshwater areas is seldom conceived specifically for protecting freshwater biodiversity [120,178] and many authors advocate for designating protected area status specifically for freshwater systems [119,179]. The Natura 2000 network was found to deliver inadequate coverage for freshwater species in the Iberian Peninsula [180] and similarly it was found that a network of river protected areas in Spain was ineffective to protect aquatic biodiversity [181]. In an examination of the benefit of PAs for freshwater species, it was observed that both positive and negative impacts occurred, however it was highlighted that these studies examined the differences in biodiversity between protected and non-protected areas and not the performance of the protected area over time. The authors highlighted that PAs can result in improvements to:

- fish abundance,
- fish size,
- biodiversity,
- water quality,
- help control invasive species.

However their effectiveness for freshwater species can be constrained by the following resulting in mixed evidence for conservation success [182]:

- connectivity,
- cross-boundary threats,
- time lags,
- limitations in the PA design.

A systematic review found that for the 75 global case studies examined, just 51% of protected areas (73% in tropical and subtropical rivers) were effective for conserving freshwater biodiversity, and that protecting freshwaters is complex with no single reason identified as the primary cause for lack of effectiveness [19]. Protection of the whole aquatic habitat was found to be a key factor in

sustaining global freshwater biodiversity, with aquatic connectivity highlighted as particularly important along with the need to reduce and manage anthropogenic pressures and invasive species [19].

It has been argued that applying protected areas concepts designed for terrestrial areas to freshwater systems is challenging and that a conceptual framework for freshwaters protected areas is required [43]. Aquatic connectivity has been identified as the single most important factor why terrestrial protected areas are ineffective for protecting freshwater systems, with designing for connectivity doubling the conservation of aquatic species [42]. Aquatic connectivity enhances the conservation of aquatic species by allowing organisms to move between different habitats for feeding, for breeding and for migration [183] and overall aquatic ecosystem functioning[184]. Connected rivers, wetlands and floodplains supports genetic diversity and population resilience of freshwater species including fish [185]. Connectivity also allows PAs to act as refuges, allowing mobile species to move to deeper or cooler waters during droughts or extreme heat [186]. This is supported by other studies that argue connectivity and upstream water quality are necessary for conserving biodiversity [101,187] and that while 'linearity and continuity of river systems' add complexity, they are crucial to the design of freshwater protected areas [111].

1.6.1 Expanding Protected Area Coverage for Freshwater Biodiversity Conservation

Conserving areas of very high biodiversity value or potential and meeting the 30% PA coverage of land and sea target including 10% of strictly protected PAs across the EU will require expanding the existing PA network [9], alongside the urgent need to improve representation of freshwater species in the existing and expanded Natura 2000 network [132]. Networks of PAs for freshwater biodiversity should provide comprehensive, adequate, representative, and efficient conservation of target aquatic habitats and species [188]. The importance of identifying areas of greatest vulnerability to loss of biodiversity has been highlighted, particularly for aquatic ecosystems, and how aquatic plant species should be used as bioindicators for assessing vulnerability [189].

1.6.1.1 Challenges to expanding the PA Network

There is inadequate biodiversity data for aquatic habitats with the lack of biodiversity data for wetlands at a landscape scale highlighted as a significant challenge for their effective conservation [45,119]. Systematic assessments of ichthyofauna on waterbodies is required to identify changes in species composition, identify rare species and non-Natura 2000 species requiring protection to inform designation of new or expanded PAs [87]. Filling gaps in freshwater biodiversity protection in Europe necessitates expanding the number of species under protection beyond those listed in Habitats directive and increasing the number of subcatchments covered by Natura 2000 to conserve aquatic species with very restricted ranges that are inadequately represented in Natura 2000 sites [132]. Such identified gaps could be used to inform the designation of strictly protected areas to 10% of overall PA coverage under the Biodiversity strategy for 2030 [9]. The static nature of typical freshwater conservation plans is a significant limitation when the aim is to protect a dynamic ecosystem where the location of pressures and their severity can vary requiring temporal scheduling of protection e.g., during migration season [190]. The designation of climate refugia and their integration into the Natura 2000 network is required to mitigate against dynamic threats including climate change [5]. Threats from outside the PA network are also recognised and while the EU Biodiversity Strategy target of 30% PA cover with 10% under strict PAs is realisable, additional research is required into the alternative design of PA networks taking into account land use and ownership, and the development of PA corridors in conjunction with systematic implementation of policies including the Common Agricultural Policy [191].

1.6.2 Expanding the focus of freshwater conservation to broad range of aquatic habitats

Aquatic species frequently migrate and move between different aquatic habitats to feed and complete their lifecycle[107], therefore expanding protection of suitable aquatic habitats must consider not only connectivity between aquatic habitats' but also the importance of ponds and other still waters for effective freshwater biodiversity conservation [192].

1.6.2.1 Shallow Aquatic Habitats, Ponds and Artificial Water Bodies

Shallow freshwater aquatic areas provide very important habitats at critical life stages for semi-aquatic species [193,194] and are of considerable value for foraging by breeding birds along with providing shelter and camouflage against predators [195].

The importance of ponds for regional aquatic biodiversity has been demonstrated and despite ponds having the smallest catchment size in a study area, they contained the highest number of species and the highest index of species rarity [196]. This is because ponds provide a variety of habitats therefore supporting a greater number of species across a region and also because they experience different climatic events and disturbances making each pond habitat unique, it results in difference species communities across a region [197]. The importance of protecting ponds at the landscape scale has been emphasised with a particular focus on protecting sites of high ecological uniqueness, particularly with the expansion of urban areas [198]. Incorporating local contribution to beta diversity metrics into spatial planning for conservation to identify sites of ecological uniqueness and sites of high taxonomic richness is crucial when expanding the spatial network of aquatic PAs in urban areas [198]. The regional variation in ecological uniqueness and taxonomic richness occurring in ponds has been highlighted [198]

The importance of artificial ponds for aquatic biodiversity and ecologist informed design of artificial ponds including on golf courses has been highlighted [199]. Notwithstanding the importance of pond habitats, [107] reported that over 60% of ponds in an area in Northwest England had disappeared between the late 1800s and early 1990s with river restoration schemes rarely including ponds and floodplains. There is significant potential for pond habitats to expand the PA coverage of freshwaters, particularly in agricultural areas where de-intensified small catchments would provide areas of high aquatic biodiversity [196]. Large scale wetland PAs along field margins along with small natural or manmade field ponds could mitigate many of the impacts of intense agriculture on aquatic biodiversity [200,201]. High quality ditches, while not natural habitats and often occurring in drained wetlands, can provide important refuges for species that were once widespread in that area. [202]

1.6.2.2 Riparian buffers

Riparian zones infrequently inform the design of PAs but are often indirectly included in PAs due to the presence of endangered species or the river flows through a PA [203]. However, deliberately protecting and restoring riparian buffers along waterbodies combined with headwater conservation and minimal land use disturbance is very important for maintaining freshwater biodiversity [204].

1.6.2.3 Headwaters

Existing PAs often neglect freshwater species with restricted distributions including fish and freshwater molluscs [96] with the crucial importance of prioritising headwaters, forested areas and small coastal subcatchments for freshwater fish conservation when designating PAs demonstrated [205].

1.6.2.4 Effective Area-Based Conservation Measures (OECMs)

The majority, 76.5% of unprotected KBAs occurred within or partly within, other effective area-based conservation measures (OECMs), highlighting their importance for KBAs but also for the expansion of PA networks [206]. Similarly, in small freshwater ecosystems, informal voluntary no-access riparian PAs as operated by angling clubs, can improve habitat quality, fish abundance, riparian vegetation, and abundance of sensitive songbirds [207].

1.6.3 Effective expansion of PA network for freshwater biodiversity across the EU

1.6.3.1 IUCN Categories

IUCN categories evaluate and organise species into nine distinct categories based on their risk of extinction, ranging from fully secure to lost and provides a framework that allows for comparisons between PAs [67]. They are increasingly used for developing and conducting conservation despite being initially designed as a tool for reporting purposes [208]. However, [209] found that the IUCN category assigned to a PA had no impact on the effectiveness of the PA, which is also supported by other research [210,211] and IUCN categories do not provide clear direction on how biodiversity should be prioritised alongside other goals [212].

1.6.3.2 More restrictive management of PAs

Modelling illustrated that more restrictive management of the existing protected areas to IUCN categories I or II, could deliver equivalent benefits to biodiversity as expanding the current terrestrial protected network area from 22% to 31% [213]. This is an important consideration in areas like Europe where some regions do not have enough natural area left to increase the protected area network [214] to meet the requirement of 30% coverage of PAs in EU [9]. Such restrictive management, better design and supervision [18] and a move away from biodiversity targets and towards more effective implementation is a better approach to deliver positive outcomes for biodiversity in the post Aichi, Kunming-Montreal Global Biodiversity Framework [215].

1.6.3.3 Strictly Protected PAs

It has been argued that targets are required to focus on areas of significant biodiversity and to realise ecological representation [216], with a target of 10% or one third of strictly protected PAs across the EU focused on areas of high biodiversity value [9]. However, caution is advised against the hasty designation of new protected areas unless measures to ensure their success are concurrently implemented [217] with authors advising against proceeding with designating strictly protected areas under the EU Biodiversity Strategy for 2030 until investment by governments delivers the high quality biodiversity data required to inform such designations [218].

1.6.3.4 Incorporating unique aspects of freshwater systems

To identify catchments requiring urgent protection, three key catchment characteristics of irreplaceability, condition and vulnerability should be considered for effective freshwater conservation [219]. Protecting microhabitats for fish breeding sites in rivers is required to counteract isolated microhabitats created by dams and other barriers [220]. Integrating invertebrate multi-taxa, expert opinion and GIS to generate spatial-distribution maps for prioritising areas for conservation both within and outside existing PAs is required [221].

1.6.3.5 Ecological corridors and connectivity between upper and lower catchment areas

Expanding the PA network for river ecosystems should focus on identifying priority areas for protection in upper catchments and restoring temporal, lateral and longitudinal connectivity in upstream areas to lower catchment PAs [161]. In addition, population connectivity and the effects of migration should inform the design of PA networks providing a geometrical perspective to species movement [222]. The importance of identifying areas of greatest importance for fish spawning and focusing efforts on improving connectivity to these areas first has been highlighted [223], in addition to the potential of rivers to deliver the spatial connections required to provide regional landscape connectivity between PAs [134]. To mitigate the impact of dams and other barriers on freshwater ecosystems, the importance of having adequate stretches of suitable aquatic habitat either already in place or restored prior to restoring modified flow regimes is highlighted, as without it restoring flow can actually reduce biodiversity [224]. Regional governments in Spain have expanded the coverage of the PA network and have linked PAs by designating rivers and wetlands as ecological corridors [225].

1.6.3.6 PA Networks and Area Based Targets for Biodiversity

The existence of protected area networks however, does not guarantee conservation and biodiversity [121,217]. The high population density in Europe brings environmental impacts on ecosystems [74] and has often resulted in the location of protected areas in remote areas or areas of low commercial value [46,85]. In order to address this issue, the Aichi Biodiversity Target No. 11 required conservation areas to be 'ecologically representative' [226] and should 'include areas of particular importance for biodiversity and ecosystem services' [29]. While the Aichi target of protecting 10% of Europe's seas was met at the end of 2018 [90] and the Natura 2000 network has exceeded the 17% terrestrial protected area target [91], overly focusing on the size of area protected can diminish the importance of conserving and improving biodiversity [33]. However, the current area-based targets are insufficient to protect biodiversity [92] with the majority of Europe's biodiversity continuing to decline. Only 14% of European

habitats having good conservation status, therefore the vast majority are at bad or poor status [15] with freshwater biodiversity being particularly impacted both in Europe [93,94] and globally [62,94,95].

Protected areas' status and the size of protected areas was demonstrated not to provide greater biological diversity and that land use and anthropogenic changes have a significant impact on biological quality [227]. Regardless of the limitations of PAs, they provide the last remaining sanctuaries for many species [228].

1.6.4 Integrative, spatial approach to freshwater biodiversity conservation

The EU advocates for an integrated spatial planning approach involving stakeholders to develop a Trans-European Network for Green Infrastructure [229]. Because aquatic species rely on predictable movement patterns [230], spatial planning is essential to protect critical habitats across all life stages, including spawning and migration corridors [231]. Utilising geographic information science helps determine priority conservation areas within complex aquatic systems [189]. Furthermore, an integrated regional approach over local catchment planning offers lower costs, requires less overall conservation area, and minimises scale-based priorities [232]. For lotic systems, incorporating connectivity indices is vital to prioritize biodiversity during PA expansions [161].

To bridge ecological theory and practice, an Integrative Freshwater Ecology and Biodiversity Conservation approach shifts focus from single species to broader strategies [233]. This framework accounts for biotic and abiotic factors, human well-being, and life-stage-specific habitat deficiencies alongside seasonal and temporal variability. Abiotic factors include hydrology, geomorphology and temperature with biotic factors include species composition and physiological adaptations [234]. Integrating bioindicators, genetic tools, and biomarkers is crucial for monitoring stress, especially as climate change shifts species distributions. When expanding PAs, using the appropriate spatial scale is critical; while whole catchments are ideal [235], designating sub-catchments of 100–200 km² effectively secures necessary lateral (between the main channel and adjacent floodplains, wetlands and riparian zones) and longitudinal (upstream to downstream flow) connectivity [219]. Ultimately, the

spatial distribution of threatened and endangered species must drive PA designations, translating into quantifiable, area-based targets to curb biodiversity loss [86].

1.6.4.1 Flexible PA Designation for freshwaters and Aquatic Refuges

The need for adaptability in freshwater PAs so they can deliver for freshwater biodiversity has been highlighted, avoiding the need to designate large freshwater areas such as whole catchments to effectively respond to dynamic threats and multiple stressors [190]. Similarly, flexibility in PA designation and 'a multi-zoning structure of different management regimes' for PAs under Natura 2000 is required, with PAs containing rare or threatened species designated as strictly protected while areas providing connectivity and other services are less strictly protected [43,132]. A review of PA designation recommendations under climate change found that protecting a limited number of large areas rather than multiple small areas was preferable and that existing protected area coverage can be enhanced by the addition of temporary protected areas [236]. Equally, complementing existing PAs by identifying priority aquatic refuges in intermittent streams can strengthen strategies for climate change adaptation for freshwater species, and the effectiveness of such refuge PAs should be assessed with the PA network and revised and updated as required [237]. The European Commission issued guidance on Natura 2000 and climate change outlining how Natura 2000 protected sites can be adapted for climate change by integrating climate considerations into conservation planning, using flexible EU nature laws, and focusing on resilience, restoration, and habitat connectivity [238].

1.7 Restoration of freshwater biodiversity in EU, the Biodiversity Strategy, the Water Framework Directive and the Nature Restoration Regulation.

It must be recognised that while freshwater PAs are a tool in reducing biodiversity decline, the designation of such areas does not guarantee biodiversity [239]. 'Protected areas do not manage themselves' [240] and they do not address the fundamental external causes of biodiversity decline [121]. While the EU has legal frameworks, strategies and action plans to protect nature and restore habitats and species, the ecological effectiveness of protected areas, including the Natura 2000 network, is

dependent on the activities that are permitted within those areas and land use outside those areas [241]. It is also dependent on the successful implementation of conservation legislation and the European Commission has taken legal action against member states via the European Court of Justice for failing to meet the requirements of the Habitats Directive [242].

Many of the significant threats facing freshwater ecosystem conservation including invasive species, pollution, fragmentation and climate change [243] are similar to those identified for river basins across Europe under the WFD [244]. The WFD has been described as a pioneering piece of environmental legislation as it adopted an ecosystem approach to water protection [245] and similarly the EU Nature Restoration law is the first law of this type at a continent scale that includes legally binding targets to restore degraded ecosystems and underpins the EU's ambitious Biodiversity Strategy to 2030 [246].
Six priority actions for the restoration of freshwater biodiversity were identified[62] and Table 2 sets out these priority actions against the current situation in Europe examining how well the EU is positioned to respond to these actions under the EU Biodiversity Strategy for 2030 , the EU WFD, and the EU Nature Restoration Regulation.

Table 2: Comparing the Actions identified by Tickner [62] against the current situation in Europe (2023), the EU Biodiversity Strategy for 2030, the Water Framework Directive and the Nature Restoration Regulations.

Action No.	Priority Action for the restoration of freshwater biodiversity [62]	Situation in Europe (2023)	EU Biodiversity Strategy for 2030 [9]	Provision under the WFD (2000/60/EC) [11]	Provision under Nature Restoration Regulation[66]
1	Accelerate implementation of environmental flows	For surface water bodies hydromorphological pressures affect 40%, hydrological alterations affect 7% and abstractions are significant pressure for 7% of surface water bodies. 95% of original floodplain area converted to other uses. [247]	"Member State authorities should review water abstraction, and impoundment permits to implement ecological flows in order to achieve good status or potential of all surface waters and good status of all groundwater by 2027 at the latest, as required by the Water Framework Directive"	Environmental flows not specifically referred to in WFD but to achieve good ecological status "ecologically appropriate hydrological regimes are necessary to meet this status" [248]	No specific mention.
2	Improve water quality to sustain aquatic life.	40% of surface waters are at good ecological status, [249] 38% are at good chemical status [250]	"The Commission will promote the goal of zero pollution from nitrogen and phosphorus flows from fertilisers through reducing nutrient losses by at least 50%" via the development of "an Integrated Nutrient Management Action Plan in 2022". "Farm to fork strategy will address the reduction in the use and risk of pesticides and support wider implementation of Integrated Pest Management" via "environmental risk assessment of pesticides". "The Commission will develop a set of indicators for the progressive reduction of pollution and will establish baselines to help monitor progress".	"to improve the protection of Community waters in terms of quantity and quality" WFD [11].	No specific mention of water quality but 'this proposal complements the Water Framework Directive by drawing up restoration targets and other specific requirements for rivers and floodplains. Moreover, this proposal's non-deterioration requirement matches the Directive's existing requirement to take measures to prevent the deterioration of the status of all water bodies

			"The pressure from plastics is notably addressed through the implementation of the European Strategy for Plastics and the new Circular Economy Action Plan"		
3	Protect and restore critical habitats	Conservation status of habitats at EU level; 81% of habitats at poor or bad conservation status, 9% of habitats show improving trends, >33% habitats continuing to deteriorate. [251].	Section 2.2 An EU Nature Restoration Plan: restoring ecosystems across land and sea, 2.2.7 Restoring freshwater ecosystems which includes restoring the natural function of rivers in order to achieve the objective of the WFD. Large scale river and floodplain restoration can contribute significantly to the restoration of freshwater ecosystems. Build a coherent Trans-European Nature Network EU Nature Restoration Plan" At least 30% of the land and 30% of the sea should be protected in the EU. "At least one third of protected areas – representing 10% of EU land and 10% of EU sea – should be strictly protected". "Effectively manage all protected areas, defining clear conservation objectives and measures, and monitoring them appropriately". Legally binding EU nature restoration targets Commission will request Member States to ensure no deterioration in conservation trends and status of all protected habitats and species by 2030. "Member States will have to ensure that at least 30% of species and habitats not	"to protect aquatic ecosystems, and terrestrial ecosystems and wetlands directly depending on them" WFD [11]	Legally binding restoration targets that can be measured and monitored are included across a wide range of ecosystems both inside and outside Natura 2000 network.

			currently in favourable status are in that category or show a strong positive trend".		
4	Manage exploitation of freshwater species and riverine aggregates.	Key pressures for species and habitats under Nature Directives (Art. 12 & 17), exploitation of species; exploitation of freshwater fish and shellfish harvesting 7% of pressures, other impacts from freshwater aquaculture 4.9% [252]	"At least one third of protected areas – representing 10% of EU land and 10% of EU sea – should be strictly protected". "Effectively manage all protected areas, defining clear conservation objectives and measures, and monitoring them appropriately". Legally binding EU nature restoration targets. Commission will request Member States to ensure no deterioration in conservation trends and status of all protected habitats and species by 2030. "Member States will have to ensure that at least 30% of species and habitats not currently in favourable status are in that category or show a strong positive trend".	Exploitation of freshwater species and riverine aggregates not specifically referred to but "composition and abundance" of aquatic flora, benthic invertebrate fauna, fish, phytoplankton form part of the quality elements for the classification of ecological status. [11]	No specific mention.
5	Prevent and control non-native species invasions in freshwater habitats.	756 freshwater species are alien or suspected alien in European inland waters [253]	"Manage established invasive alien species and decrease the number of Red List species they threaten by 50% "	Non-native species invasions not specifically referred to in WFD. Introduction of invasive alien species (IAS) is included as example of biological pressure in EU WFD guidance document [254].	No specific mention
6	Safeguard and restore freshwater connectivity	>500,000 recorded barriers and estimated to be >1M barriers [255]	"At least 25,000 km of rivers will be restored into free-flowing rivers by 2030 through the removal of primarily obsolete barriers and the restoration of floodplains and wetlands."	Under Annex 5 (1) Surface water status quality elements, 1.1.1. River continuity forms part of the classification for ecological status.	Under Article 7, Restoration of the natural connectivity of rivers and natural functions of the related Floodplains. Member states shall identify and remove the barriers to the natural

			Ecological corridors to be set up to prevent genetic isolation and create a coherent and resilient Trans-European Nature Network. For the target of returning at least 10% of agricultural area under high-diversity landscape features. “Member States will need to translate the 10% EU target to a lower geographical scale to ensure connectivity among habitats”.		longitudinal and lateral connectivity of surface waters and improve the function of floodplains. “Member States should primarily address obsolete barriers”.

In terms of how well the EU is positioned to respond to the Priority Actions for the restoration of freshwater biodiversity [62] detailed in Table 2, for actions 1 and 2, 'accelerate implementation of environmental flows and improve water quality to sustain aquatic life' the EU Biodiversity Strategy to 2030 has identified clear strategies and goals to deliver on these targets and has committed to developing indicators to alleviate pollution. The EU action plan 'Towards Zero Pollution for Air, Water and Soil' was developed so that pollution prevention is included in all applicable EU policies [7]. The Nature Restoration Regulations also require non-deterioration in conservation trends or in the status of protected species and habitats which corresponds to the WFD requirement for non-deterioration in status of water bodies thereby providing clear obligation on member states to maintain and improve conditions to sustain freshwater biodiversity. For action 3, 'protect and restore critical habitats', one of the limitations of the EU biodiversity strategy for 2020 [256] was the lack of specific mention of freshwater in the increase of terrestrial and marine PAs coverage to 30%, but this has been rectified in the EU Biodiversity Strategy for 2030 under section 2.2.7 restoring freshwater ecosystems. This action is also provided for in the WFD, and habitat restoration has been very significantly strengthened by legally binding restoration targets for ecosystems in the EU Nature Restoration Regulations. In contrast, for action 4 'manage exploitation of freshwater species and riverine aggregates' there is no specific mention of measures for either in the EU Biodiversity Strategy for 2030, nor is it specifically provided for in the WFD. This is despite the extraction of riverine aggregates being associated with a number of alterations to freshwater ecological structure and biodiversity [257,258]. However, the extension of strictly protected areas to 10% of EU land under the Nature Restoration Regulation could provide relief for these pressures. Legally binding restoration targets for ecosystems in the EU Nature Restoration Regulations provides for the prevention of unsustainable exploitation of freshwater species and riverine aggregates, and the European Commission 2030 Biodiversity Strategy has committed to better implementation and enforcement of legislation to protect biodiversity in the EU [9]. For action 5 'Prevent and control non-native species invasions in freshwater habitats', the EU Biodiversity Strategy requires that alien invasive species (IAS) be managed so as to reduce the pressure

on Red List species by 50%. There is no specific mention of IAS in the WFD or in the Nature Restoration Regulation [8] but the regulation 'aims to complement existing environmental policy' including the existing Invasive Alien Species (IAS) Regulation which aims to prevent, detect, eradicate and manage IAS [259]. Finally, for action 6 'Safeguard and restore freshwater connectivity' this action is comprehensively covered by the EU Biodiversity Strategy and by the Nature Restoration Regulation and is provided for under the WFD. Crucially, a specific target in the EU Biodiversity Strategy to restore 25,000km of EU rivers to free flowing by 2030, will drive this restoration to support freshwater biodiversity with the strategy specifically mentioning the establishment of ecological corridors and connectivity among habitats. The Nature Restoration Regulation requires member states to identify and remove barriers to connectivity and improve floodplain function with an initial focus on obsolete barrier removal. The specific restoration target aims to restore an estimated one eight of river connectivity in the EU, although the full extent of barriers numbers is not clear with research carried out in Europe and the US indicate that existing barrier records underestimate the number of barriers by approx. 61% in Europe [54] and the number of dams in by over 80% the US [260].

The EU is very well placed to address freshwater biodiversity loss, both in terms of policy and appropriate legislation with clear strategies and goals to restore biodiversity, a requirement for non-deterioration in conservation or water quality trends, a network of protected areas that can be expanded and refined, and a new focus on freshwater biodiversity. Limitations of the EU Biodiversity Strategy to 2020 and legislation for freshwater biodiversity restoration was recognised and addressed with 'restoring freshwater ecosystems' in the Biodiversity Strategy to 2030, the legally binding restoration targets for ecosystems in the EU Nature Restoration Regulations and pollution prevention included in all relevant EU policies via the 'Towards Zero Pollution for Air, Water and Soil' action plan. These policies and legislation provide mechanisms by which all 6 Priority Action for the restoration of freshwater biodiversity [62] can be effectively addressed across the EU. These legally binding targets along with monitoring and reporting is expected to deliver consistent action on ecosystem restoration, and better joint action by member states across the EU [66].

1.8 High frequency monitoring & hydrodynamic event monitoring for freshwater biodiversity restoration

1.8.1 Sensors for High Frequency Water Quality Monitoring

A wide range of sensors are available for water quality monitoring [261]. Water quality sensors convert a 'physical parameter into equivalent measurable electrical quantity' and are deployed to collect data for a defined point of a water body [262]. Early developments in high frequency monitoring included turbidity sensors [263], followed by optical sensors for nitrate [264] for dissolved organic carbon [265] and in-situ bankside analysers to measure nutrients including phosphorus[266] and isotopes of oxygen and hydrogen to track catchment flow pathways during storm events [267].

A recent systematic literature review examining the most commonly monitored parameters for water quality identified pH as being the most common, followed by turbidity, dissolved oxygen, electrical conductivity, total dissolved solids, water depth/level, oxidation reduction potential, ammonia and salinity [268]. However, the use of HF monitoring is dominated by water quality research projects [24] despite the lack of sufficient monitoring to identify causes of degradation highlighted as a key challenge for implementation of the Water Framework Directive [245]. The most common matrix where water quality sensors were deployed was found to be in rivers/lakes/seas and springs, followed by aquaculture/fish farming and in laboratories [268].

1.8.2 High Frequency Monitoring of Surface Waters

Ireland retains one of the highest levels of high ecological status (HES) water bodies in the EU with a total of 17.6% of water bodies at high status. Comparable number of HES waterbodies are only found in Alpine areas of Austria (20%), Finland (16%) Sweden (12%) with very few left in the UK (3%), Germany (0.1%) and Poland (0.5%) [250]. Despite Ireland having one of the highest proportions of water bodies remaining in good or high status in the EU, there has been a sharp decline in the percentage at highest water quality status. Highest water status water bodies in Ireland with a score of Q5 dropped from 13.4% in the 1990s to just 1.1% of monitored river stations in 2024 with diffuse agricultural pollution a key pressure [16]. High-frequency monitoring (HFM) using in-situ sensors has transformed

freshwater quality assessment [24]. Traditional grab sampling methods (e.g., monthly or bi-monthly laboratory analysis) severely lack the temporal resolution required to capture the rapid, dynamic changes occurring within protected aquatic ecosystems [269,270]. In the context of PA management and compliance with frameworks including the EU WFD, HFM is no longer just a research tool, it is a management necessity. Traditional sampling schedules routinely miss ephemeral, short-lived pollution events [271]. Incidents such as agricultural runoff, combined sewer overflows, or sudden industrial discharges can severely impact a river's ecological status and kill sensitive species within hours, yet completely dissipate before the next monthly grab sample [272]. Continuous sensors (measuring parameters like turbidity, dissolved oxygen, pH, temperature, and conductivity) log data at minutes-long intervals, capturing the exact onset, peak, and duration of these transient events [272]. Climate change has drastically altered hydrological regimes, increasing the frequency and intensity of extreme rainfall [24]. Intense storms trigger massive pulses of diffuse pollution (e.g., sediment, nitrates, phosphorus) into protected waters via surface runoff. High-frequency sensors allow water managers to track how catchment systems respond in real-time to specific storm hydrographs, bridging the gap between ecological theory and actual field practice [24,233].

To provide an overview of the international evidence of the use of high frequency monitoring on surface water bodies, studies from different countries are presented in Table 3. Given the breath of the literature in this field, the table highlights examples that demonstrate variation in the sensors employed, the monitoring intervals and the geographical context. It also highlights similarities and differences in the parameters measured and the difficulties encountered with such monitoring.

Table 3: Examples of International Studies using High Frequency Monitoring to Quantify the Input of Pollutants to Surface Waters.

Author	Year	Country	Nature of the Research	Equipment Used	Monitoring Frequency (min.)	General Outcomes	Any Notable Difficulties
Cassidy et al. [273]	2011	Ireland	To evaluate sampling and load estimation for phosphorus in rivers.	Dr. Lange Sigmatax & Phosphax for phosphorus, OTT Thalimedes water level recorder, Starflow area-velocity meter, OTT Nautilaus electromagnetic flowmeter, Streampro ADCP for stream discharge & velocity	20	Weekly, daily, storm-event triggered and random sample sets failed to accurately estimate the annual loads particularly for runoff related events.	Requires regular service and maintenance requirements. Excessive sediment preventing sample delivery to analysers.
Minaudo et al. [274]	2017	Ireland & France	To estimate phosphorus (P) concentrations at a sub-hourly time step for estimating loads in rivers.	Automatic gauging station PONSEL TU-NA Turbidity Sensor Hydrolab HL4 Turbidity Sensor Hach Solitax Turbidity Sensor, ISCO 612 Autosampler for phosphorus, Hach Phosphax-Sigma for phosphorus.	10 (France) 15 (Ireland)	Turbidity and discharge can be used to help predict reliable estimates of phosphorus exports.	Sampling bias during successive storms where first storm is always monitored by autosampler but miss the following storms.
Jones et al [275]	2019	USA	To quantify the effects of livestock concentration on stream nitrate levels.	Automatic gauging station, Hach Nitratax sc plus nitrate sensor.	15	Higher stream nitrate in the two watersheds where livestock concentration was greatest.	None described.
Kämäri et al. [276]	2020	Finland	To explore the possibility of using turbidity as a surrogate for phosphorus	s::can UV-Vis spectrophotometer for turbidity & nitrate,	30	Stronger relationship between in situ measured turbidity and particulate phosphorus than between turbidity and total phosphorus and	Interruption to continuous measurement as sensor needed to be removed during

						stronger relationships in larger catchments.	ice clearing period to prevent damage.
Yu et al. [277]	2021	Netherlands	To improve understanding of the mechanisms controlling temporal nutrient patterns in an urban catchment.	Sigmatax & Phosphax sigma auto analyzer for total phosphorus, Amtax for NH_4-N & a Filtrax automatic sampler, HACH Solitax t-line sc for turbidity, CTD-Diver for electrical conductivity and water temperature. Nitratax for NO_3.	5 (turbidity, EC, and water temperature), 10 (NH_4-N), 20 (total phosphorus)	Nitrogen and phosphorus dynamics are seasonal with groundwater a significant influence. Most phosphorus is released in winter.	Nitratax NO_3 data consistently showed drift and was unreliable, possibly due to accumulation of biofilm & precipitation of iron oxide at the site.
Haddadchi et al. [278]	2023	New Zealand	To quantify riverbank erosion and its contribution to channel suspended sediment exports and budgets.	LiDARUSA Snoopy A-Series mobile LiDAR unit equipped with a Velodyne HDL-32E LiDAR scanner. Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU). Acoustic Doppler Current Profiler (ADCP) for flow gaugings.	5	A sediment budget for a 5.5-km-long study reach of the lower Ōreti River was established.	Semi-permanent markers are required to validate the alignment of point clouds in the river channel where there is an absence of man-made structures.
Elfferich et al. [279]	2024	U.K.	To understand the lowest measurement frequency that can fully capture variation in different parameters & to investigate bias in grab sampling at different times.	Automatic gauging station, Hydrolab MS5, YSI 6600 V2, YSI EXO2 to measure dissolved oxygen, turbidity, pH, conductivity, water temperature (different sensors at individual sites measuring same parameters). Sea-Bird SUNA v2 and HACH Nitratax for nitrate.	15, 30 & 60 depending on the monitoring station	Most parameters required a four-hourly data frequency to adequately capture the variation.	The minimum temporal frequency is not static but can vary per season and per year and is catchment dependent.

				Sea-bird ECO-FL & YSI 6600 V2 for Chlorophyll a. HACH Sigmatax SC & Phosphax for phosphorus. Sea-Bird ECO-CDOM for Chromophoric or Dissolved Organic Matter.			
Li et al.	2024	China	To identify the impact of storms on abstraction reservoir water quality, on reservoir thermal stratification and on water turbidity.	Niskin Water Harvester for sample collection. YSI EXO2 multiparameter probe for water temperature, dissolved oxygen, electrical conductivity, pH, turbidity, oxidation reduction potential & chlorophyll-a. BRAN+LUEBBE Auto Analyzer III for Total phosphorus, total dissolved phosphorus, PO_4^{3-}, Total nitrogen, total dissolved nitrogen, NO_3-N, NO_2-N, and NH_4^+-N.	5	Rainstorms caused runoff resulting in high turbidity, particulate phosphorus, and organic matter and disrupts the stratification of the reservoir water.	None described.
Leite Costa et al. [280]	2026	French Guiana	To establish high-frequency baseline for a data-poor tropical river estuary.	HOBO data loggers (models U20L-01, U24-001 and U26-001) & NKE WiMo multiparameter probes for temperature, salinity and dissolved oxygen.	10	Extreme storm event analysis revealed frequent hyposalinity and hypoxia with HF monitoring improving the detection of climate sensitive events.	HOBO loggers were replaced monthly to minimise biofouling. HOBO loggers were replaced with NKE WiMo multiparameter probes to reduce complexity of deployment.

As shown in Table 3, high frequency monitoring has been used to estimate high frequency baseline data, to evaluate sampling frequencies and load estimation for sediment & nutrients, to gain insights into the mechanisms controlling temporal nutrient patterns, to examine the suitability of surrogate parameters and to identify the impact of storms on reservoir water quality. Monitoring frequencies varied from 1 to 60-minute intervals depending on the objective of the study. Maintenance requirements, excessive sediment, interruptions to continuous monitoring, sensor drift, biofouling and inter-annual, inter-seasonal, and catchment differences all highlighted as notable difficulties in high frequency monitoring programmes. The commonality in all these studies was that only high frequency data can provide the level of data necessary to capture temporal variability, short term fluctuations, episodic events and temporal patterns that provide a more comprehensive understanding of processes occurring at catchment scale [24,272]

The WFD requires member states to achieve and maintain "good ecological and chemical status" for surface waters. Relying strictly on discontinuous data risks misclassifying water bodies, leading to ineffective River Basin Management Plans (RBMPs). Continuous data provides a mechanistic understanding of biogeochemical cycles, allowing regulatory agencies to identify specific anthropogenic pressures and accurately evaluate if mitigation measures are working [281]. Because freshwater protected areas are defined by lateral and longitudinal connectivity, a pollution incident upstream quickly compromises habitats downstream. HFM serves as an early-warning system, giving conservationists a window of opportunity to respond to pollution spikes before they penetrate deep into vulnerable nature reserves or protected sub-catchments [280].

1.8.3 Early Warning Systems and Event Monitoring

Surface waters can be subject to rapid changes in water quality due to intentional, accidental or natural contamination from a myriad of sources including point discharges and storm events [282,283]. Early warning and event monitoring systems typically comprise instrument technology to detect changes in water quality, analysis tools and response mechanisms [284]. Research in the area of early warning and event monitoring systems gained significant momentum in the early 2000s leading to a

rapid expansion of the evidence base particularly for drinking water supplies [282,284–286]. Events occur when sensor data exceed allowable thresholds [287], and optimised detection seeks to maximise true positives while minimising false alarms [288]. Monitoring to detect drinking-water contamination events was a key driver for the development and adoption of event detection software systems [286,289,290], with many commercial event systems available [291] and used for monitoring events in different water types.

Climate change is driving increased frequency and intensity of heavy rain events [292] with changing weather patterns altering the type and dynamics of water pollutant movements [293,294]. However, the impacts of these increasingly frequent and intense hydroclimatic extremes on surface water quality, and the mechanisms driving these responses remain poorly understood [295]. The effects of extreme weather events on water quality can persist for up to ten years following an event, with the employment of high technology innovation a key metric to mitigating the significant impacts of these events [296].

1.9 Conclusion

Protected areas play a critical role in addressing both climate change and biodiversity loss and is a mechanism that has been adopted worldwide for conservation with the expansion of PAs under the EU Biodiversity Strategy 2030. There is a close association between protected areas and the establishment of reference conditions as often such areas exhibit the natural or near-natural environmental conditions that exist when human influence is minimal or absent.

The vast majority of protected sites in Europe are national protected areas accounting for 144,373 of sites (81.77%) with over 400 categories, 328 of those categories in the EU-27 + UK. The proportion of international, regional, and national protected area designations of the total in the EU-27 + UK countries varies significantly, with Estonia having the largest proportion of national PAs at 96.7%, Italy has the largest proportion of regional PAs at 76%, and most countries had less than 2% international PAs of their total designations with the Netherlands having the largest at almost 10%. Similarly, the

numbers of national PAs vary considerably between European countries with just 59 in Cyprus compared to over 27,000 in Sweden, with a median of 998 national PAs across the EU-27 + UK. The average proportion (%) of freshwater KBAs covered by protected areas in Europe has remained largely static since the early 2000s, with freshwater KBA's making up just over 28% of the overall KBAs in Europe covering 26.5% of the KBA area and consisting of up to 40% of the trigger species. In addition, there is significant overlap between nationally designated PA sites and Natura 2000 sites, varying from 93.3% in Slovenia to just 1.3% of overlap in Ireland.

This review highlights the complexity of PA designation across the EU with many different administrative and associated management models. In reviewing the literature, no single repository for information on the competent authorities for protected areas could be found, either for the EU member states or worldwide. For 21 of the EU-27 + UK countries, information on agencies involved in protected area management in the EU was gathered via correspondence with government departments, with academics and via government websites. This information has been summarised and compiled for the first time in this review.

Comparing the Actions identified by Tickner [62] against the current situation in Europe (2023), the EU Biodiversity Strategy for 2030, the WFD and the Nature Restoration Regulations found that for actions 1 and 2 'accelerate implementation of environmental flows and improve water quality to sustain aquatic life', action 3, 'protect and restore critical habitats', action 5 'prevent and control non-native species invasions in freshwater habitats' and action 6 'safeguard and restore freshwater connectivity' the EU legislative and policy frameworks provide clear strategies and goals to deliver on these actions. In contrast, for action 4 'manage exploitation of freshwater species and riverine aggregates', there is currently no specific provision for this within EU strategies or policy instruments but the extension of strictly protected areas to 10% of EU land under the Nature Restoration Regulation could provide relief for these pressures. However, there is therefore a significant gap in terms of how PAs can be managed and monitored to effectively meet the aquatic biodiversity and water quality requirements.

The recent fitness check of the WFD confirms it provides high level of protection for European water bodies, however insufficient implementation was identified as a key failure in its implementation [297]. The lack of sufficient monitoring to identify causes of degradation has been highlighted as a key challenge for implementation of the Water Framework Directive [245] and high frequency monitoring can help to bridge the monitoring gap.

While Ireland retains one of the highest levels of high ecological status (HES) water bodies in the EU [250] there has been a sharp decline in the percentage at highest water quality status over the last thirty years with diffuse agricultural pollution identified as a key pressure [16]. Water Quality is key to supporting the recovery of freshwater biodiversity across Europe [13] and current monitoring methods for monitoring under the WFD severely lack the temporal resolution required to capture the rapid, dynamic changes occurring within protected aquatic ecosystems [269,270].

Climate change has drastically altered hydrological regimes and is driving increased frequency and intensity of extreme rainfall [24]. Changing weather patterns alter the type and dynamics of water pollutant movements [293,294] into protected waters via surface runoff. High-frequency sensors allow scientists to track a catchment's response in real-time to specific storm hydrographs, bridging the gap between ecological theory and actual field practice [24,233]. High frequency monitoring (HFM) serves as an early-warning system, providing a window of opportunity to respond to pollution spikes [280]. HFM is a necessary tool for tracking the impact of diffuse agricultural pollution sources and pathways [272,281,298,299] which are a key pressure on the highest status waterbodies [16]. Event detection systems facilitate the upscaling of high frequency monitoring on vulnerable water bodies by focusing monitoring efforts and resources when water quality impacts are occurring [288,300].

1.10 Research Aims and Objectives

The aim of this research is to examine protected area designation focusing on freshwaters and to demonstrate the value of high frequency monitoring for detecting transient pollution events in small rivers to support the objective of the WFD in the context of increasing frequency and intensity of rainfall events due to climate change. The specific objectives are to:

1 Conduct a literature review to examine protected areas and their designation as an instrument for protecting water quality and aquatic biodiversity in Europe.

2 Develop a practical, flexible and reproducible monitoring workflow for temporary, remote, off-grid monitoring of water quality events in small rivers.

3 Examine if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters could adequately capture water quality variation over the range of river discharge at a hydrologically active period.

4 Deploy and test the temporary, remote, off-grid event monitoring system in a high-status river located within a protected area to determine if it can identify hydrodynamic driven water quality events.

To address these objectives, the thesis is structured as follows. Building on the research problem outlined in the introduction, Chapter 1 reviews the existing literature to synthesise current knowledge of PA designation as an instrument for protecting water quality and aquatic biodiversity. Chapter 2 outlines the methods used in this research, detailing the study design, data collection, and analytical approaches employed to address the research objectives. Chapter 3 details the practical, flexible and reproducible methodological framework for detecting water quality events on small rivers. Chapter 4 examines the ability of a short-term deployment to adequately capture the frequency and intensity of hydrodynamic events at the river monitoring stations. Chapter 5 discusses the conclusion of this research, the recommendations, and further study.

Chapter 2: Methods

2.0 Introduction

2.1 Research Design

Chapter 1 critically reviewed the literature on protected areas for freshwaters identifying key limitations in existing approaches to the protection of high-status water bodies. In particular, the review highlighted the significant gap in terms of how PAs can be managed and monitored to effectively meet the aquatic biodiversity and water quality requirements.

This chapter outlines the methodological approach used to address the research aims of this thesis with a mixed-methods design adopted, combining a qualitative and quantitative approach. The qualitative component was applied to the literature review, where a structured and interpretive approach was used to examine protected areas and their designation in Europe, their Importance for high-quality surface waters, to identify the key threats and challenges for protected areas and examine how well the EU is positioned to respond to the freshwater biodiversity crisis. This enabled the synthesis of current knowledge and the identification of the numbers and types of protected areas across the EU and how they're designated, common challenges for the protection of freshwater biodiversity and the regulatory provision to address freshwater biodiversity decline. A qualitative approach to the literature review was adopted to allow for thematic synthesis rather than a purely descriptive or critical summary.

The quantitative component focused on the development of a detailed workflow to aid the deployment of high frequency, remote, off-grid water quality sensors, the identification of potential water quality events, and the analysis of water quality data to evaluate the value of short-term, temporary, deployments to assess the impact of rainfall and streamflow events on water quality. This approach provided measurable and objective insight into patterns and trends in water quality in a high-status river within a protected area. The workflow developed is a comprehensive guide covering all aspects of high frequency river monitoring from deployment to data interpretation. By integrating qualitative insights from the literature with quantitative analysis of water quality data, this study provides a comprehensive understanding of both the perceived challenges for high status rivers within

protected areas and the measurement of environmental conditions to monitor and protect these important water bodies.

2.2 Literature Review Methodology

A web-based search (article title, abstract and keywords) of scientific literature via Scopus and Web of Science core collection databases was carried out. The search was designed to identify literature related to challenges associated with freshwater and aquatic protected areas, as well as broader water governance issues. It retrieved documents that either focus directly on designated protected areas—such as aquatic or freshwater protected areas, Natura 2000 sites, Special Areas of Conservation, or conservation areas—within freshwater contexts (including rivers, lakes, and surface waters), or address topics like water quality or freshwater and aquatic biodiversity in combination with governance, management, or the WFD and Challenges. The search of the Web of Science database returned 4217 articles including 501 review articles, and the search of the Scopus database returned 4249 articles including 515 review articles. The results of Scopus and Web of Science searches were exported in RIS format and subsequently imported into Covidence software for screening. Duplicate records (n = 221) were automatically identified, manually verified and removed. Titles and abstracts of 796 review articles were then manually screened against predefined inclusion and exclusion criteria. The inclusion criteria for this review were designed to capture literature that addresses challenges in freshwater and aquatic protected areas, as well as broader water governance contexts. Studies were included if they focused on freshwater environments such as rivers, lakes, wetlands, or other surface waters, and either examined designated protected areas (e.g., freshwater protected areas, Natura 2000 sites, Special Areas of Conservation, or similar conservation areas) or explored wider issues related to water governance, management, policy or challenges. Eligible studies also needed to engage with themes such as water quality or freshwater and aquatic biodiversity in combination with governance structures, management practices, or the WFD. The exclusion criteria were applied to remove studies that did not align with the focus of the review including articles on

the marine environments or terrestrial ecosystems without a clear freshwater component. Given the substantial volume of literature (~ 4000 records) and the presence of substantial existing reviews in this area as the challenges affecting protected areas, water quality and freshwater biodiversity have been well documented, a review of reviews was carried out. The aim of this study was not to examine individual challenges for each topic in detail, but to explore synergies and relationships between them and therefore a higher-level approach was required. Studies meeting the criteria proceeded to full-text review and Covidence software was used to manage duplicate articles between the Web of Science and Scopus searches, and to manage the manual screening process. References of the included articles were also scanned to identify and include pertinent studies for freshwater.

In addition to the academic databases, targeted searches were performed on official publications and reports from relevant European and international organisations, including European Commission (EUR-Lex, European Commission website), European Environment Agency (EEA) publications database, European Parliament (official reports and resolutions), Biodiversity Information Centre for Europe and United Nations Environment Programme (UNEP) publications and reports. For each organisation, specific searches were conducted using their official websites and publication databases. Search terms included: "protected areas," "conservation," "biodiversity," and "Europe," combined with the organisation's name.

The author could find no single repository for information on the competent authorities for protected areas, either for the EU member states or worldwide. For 21 of the EU-27 + UK countries, information on agencies involved in protected area management in the EU was gathered via correspondence with government departments, with academics and via government websites. Summarised details of this correspondence including the name of organisation/person contacted and the date of reply was captured in Table 1.

There were limitations to this approach as the search was conducted in English and therefore excluded sources published in other languages. The scope of the search terms used may have excluded other relevant articles where freshwaters are classified under terrestrial protected areas. In addition, the

review of reviews is dependent on the quality of reviews and nuances from primary studies may be overlooked.

2.3 Catchment Characterisation Methodology

2.3.1 Desktop Assessment for Catchment Characterisation

The first step in the water quality monitoring section of this study was a desktop assessment to collect and review all available information prior to site selection and sensor deployment. This provided data for catchment characterisation including identifying land use, discharge points including wastewater treatment plants and sensitive receptors including drinking water sources and conservation areas. It provided initial understanding of river status and informed the identification of potential monitoring locations and what water quality pressures in this catchment could be contributing to water quality events.

2.3.1.1 Historical Datasets

There are a number of historical datasets available which were used to inform this research:

a) River level and flow records

   Observed level and flow records for the River Owenmore and level records only for the River Unshin obtained from gauged locations administered by the Office of Public Works (OPW; http://waterlevel.ie/). Due to water retention at the R. Unshin gauging station during high flows, no site-specific discharge relationship is available to convert level to flow [301].

b) Rainfall data

   Observed rainfall data obtained from the automatic weather station at Markree administered by Met Éireann (https://www.met.ie/climate/available-data/historical-data)

c) Water quality data

   Historical water quality data obtained from the Environmental Protection Agency administered by the EPA Catchments Unit (https://www.catchments.ie/data/#/?_k=0hudur).

The desktop assessment fulfilled a number of objectives including identifying:

- appropriate hydrometric and meteorological stations within the catchment.
- suitable monitoring locations in terms of adjacent national water quality monitoring stations, adjacent hydrometric stations, adequate security for monitoring equipment, suitable all-season access and permissions from landowners.
- water quality pressures in the catchment.

2.3.1.2 Catchment Characterisation

"Catchments are coherent, topographically-based features, defined by the natural hydrology and hydrogeology, with water in continuous connection over ground and underground from the highest areas along the topographic divide to the lowest areas alongside rivers" [302]. Surveillance monitoring of water bodies in catchments or sub catchments within river basin districts (RBD) is a requirement under the WFD to ensure shared and coordinated management of water bodies across national boundaries [11]. The character of a catchment has a significant influence on water quality as an area's geology, soils and land use all significantly impact on water quality [303] with pollutants such as phosphorus and sediment influenced by the stream and the catchment characteristics [304,305].

The Sligo Bay and Drowes Catchment was the location for the study sites in this research (Figure 11). It is located in the North West of Ireland covering an area of 1,603 square kilometres [306], with 13 sub catchments, comprising of 70 rivers, 18 lakes, 6 transitional, 6 coastal and 43 groundwater bodies [307]. In terms of water quality pressures, for rivers in this catchment, the most significant pressures are nutrient overload, which is impacting 22 waterbodies, followed by morphological issues, organic pollution, sediment, hydrological issues and chemical pollution. These pressure are predominantly associated with agricultural, forestry, hydromorphological (mainly channelisation) and urban wastewater activities [307].

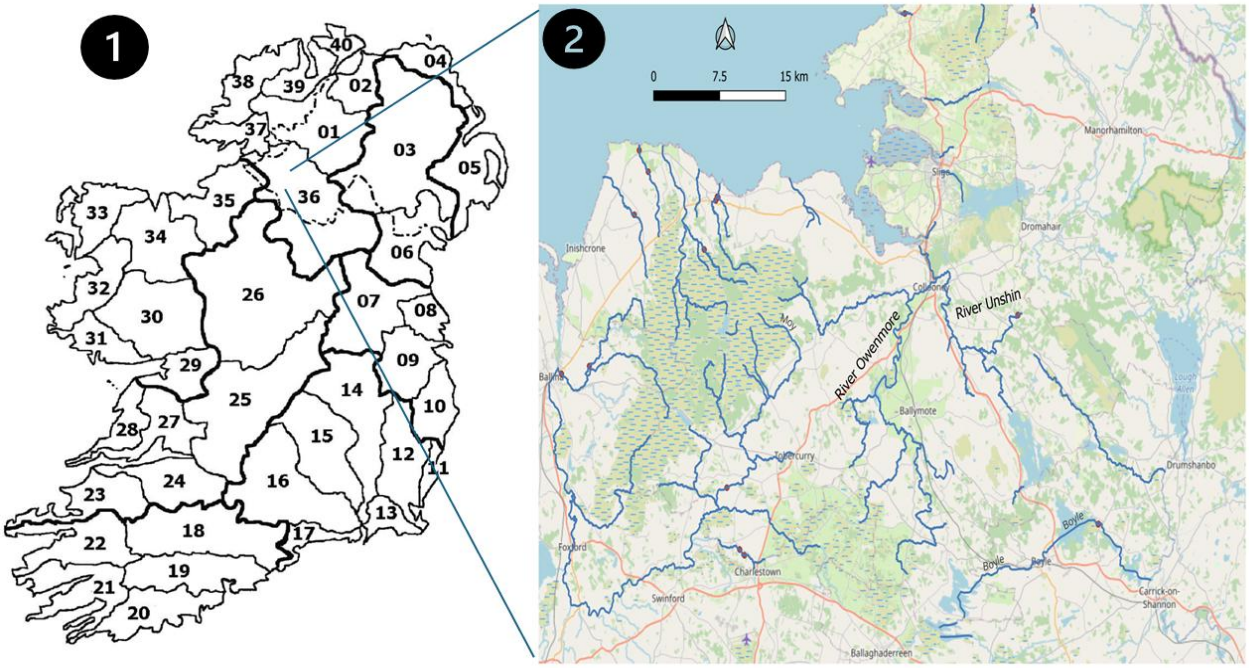


Figure 11: (1) Hydrometric Area 35, Sligo Bay/Drowes catchment [308] and (2) River Owenmore and River Unshin. Map (2) created in QGIS (Version 3.42.1) using OpenStreetMap as a basemap.

2.3.1.3 Rivers Unshin and Owenmore Sub-catchments

The monitoring locations for this study within the Sligo Bay/Drowes area were on the rivers Owenmore and Unshin located to the South of Sligo town (Figure 11). The Owenmore catchment covers an area of 65,000 ha and is divided into three main tributaries, the river Owenmore located in the centre and north of the catchment, the river Unshin located northwest of Lough Arrow and the river Owenbeg (not included in this research study) is a fast-flowing river subject to spates which flows east. Of note is the varied characteristics of the three rivers, the largest of which is the Owenmore (52km in length) pH neutral, mostly slow moving and flat, the Unshin (23 km in length) which rises in Lough Arrow, also quite slow moving but alkaline due to base-rich karst groundwater with a couple of steep sections, and the Owenbeg (23km), an acid mountain river with peatland in the upper reaches [309]. The Owenbeg and Owenmore unite upstream of Collooney with the Unshin joining 3 km downstream to form the Ballysadare river which travels a further 4 km to enter the sea at Ballysadare Bay [310]. The total length of the stream and river channels for the Owenmore subcatchment is 312km

and for the Unshin subcatchment is 211km. There is over 50% first order streams in each river with 165km of first order streams in the Owenmore and 129km of first order streams in the Unshin [309].

2.3.1.4 Special Areas of Conservation (SACs) and Special Protected Areas

EU Member States are required to establish a Natura 2000 network of sites under the EU Habitats Directive (92/43/EEC) [12] and the EU Birds Directive (79/409/EEC) [129]. In Ireland, the Natura 2000 network is composed of specials areas of conservation (SACs), candidate SACs, and Special Protection Areas. In the study area there are four SACs (Figure 12) with surface water dependent habitats (Table 4).

Table 4: Special Areas of Conservation (SAC) [12] and Special Protected Areas (SPA) [129] in the Study Catchment.

Name of PA	SAC	SPA	Size (ha)	Relevance for the Study Sites
Lough Arrow	√		1457.5	upstream of the river Unshin monitoring station
Lough Arrow		√	1337.9	upstream of the river Unshin monitoring station
Unshin	√		916.6	location for river Unshin monitoring station
Templehouse & Cloonacleigha Loughs	√		492.6	upstream of the Owenmore station
Ballysadare Bay	√		2144.6	downstream of both monitoring stations
Ballysadare Bay		√	2129	downstream of both monitoring stations

The importance of the River Unshin as a high quality river is highlighted by its description as one of the most pristine rivers in Ireland and a rarity at European level [311] due to the presence of internationally important aquatic vegetation [309], its status as a benchmark or reference site for floating reed-mats [312], with those species being supported by good quality water supported by significant inputs of groundwater [311].

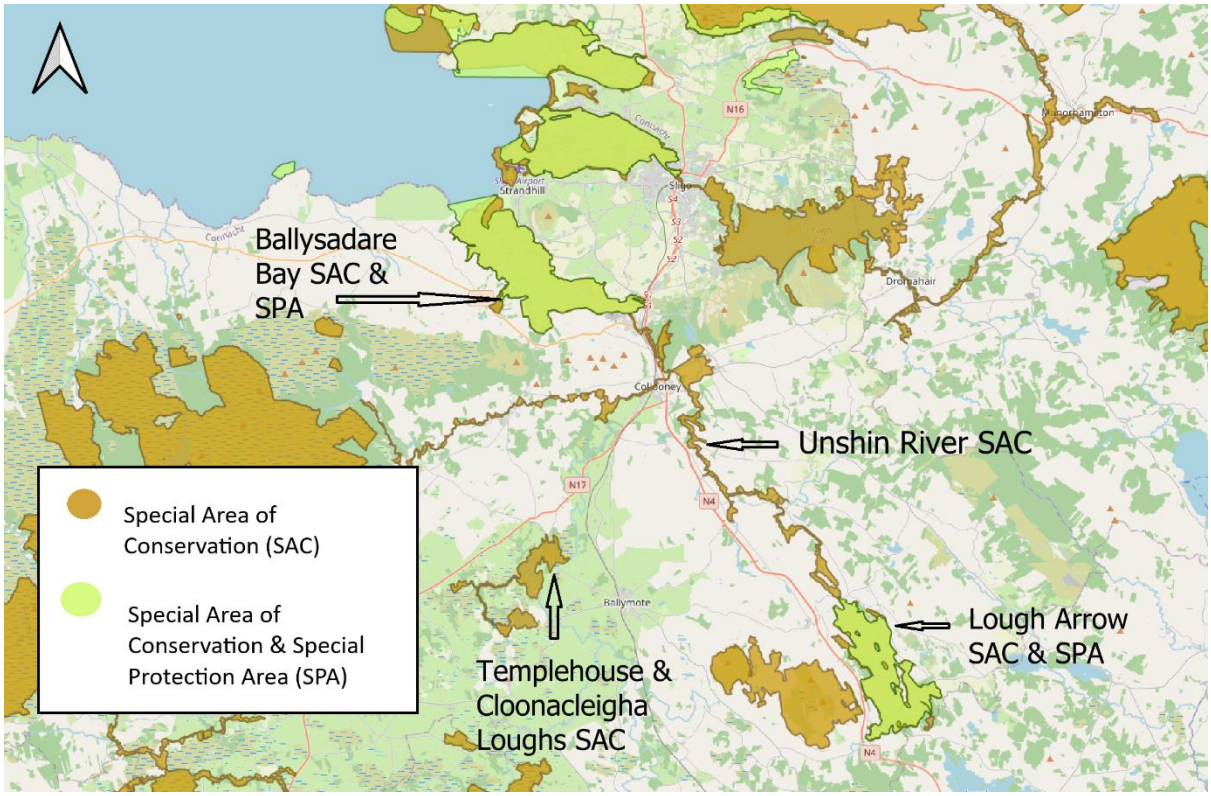


Figure 12: Special Areas of Conservation (SAC) with surface water dependent habitats and Special Protection Areas (SPA) within the study area [313].

2.3.1.5 Physical Catchment Descriptors (PCD)

Catchment descriptors describe and measure physical and climatological characteristics of a catchment [314] and PCDs are used for estimating flood frequency and the impact of land use on river water quality or quantity. Climate driven changes in individual catchments will be affected by the topography, the plant species that are present, the geology and by human induced modifications [315]. The sensitivity of 206 Irish catchments to change in low flows associated with climate change (changes in annual mean rainfall and changes in seasonality of rainfall) was examined and five catchment sensitivity types were identified with hydrometric stations on the Owenbeg river and Ballysadare river included in the analysis [292]. High runoff coefficient was identified as an indicator that catchments may be more sensitive to increases in seasonal amplitude. The Ballysadare station was categorised as catchment sensitivity type (e) which are generally 'low lying and possess greater natural storage to offset reduced summer precipitation' and will be less affected by seasonal changes in rainfall due to

climate change. The station on the Owenbeg was categorised as catchment sensitivity type (b) which have 'generally poor natural storage' and will be most sensitive to seasonal changes in rainfall [292].

The WFD acknowledges the importance of hydromorphology to support aquatic flora and fauna with hydromorphology comprising one of the quality elements for surface water status along with biological elements and chemical & physiochemical elements. The hydromorphological elements include the hydrological regime and the morphological conditions [11]. Hydromorphology has a significant indirect impact on stream invertebrates and hydromorphological modifications affect both the stream substrate and the concentration of organic matter and nutrients at site scale [316]. Hydromorphological pressures are one of the most frequently identified pressures on surface waters, affecting almost 40% of surface waters in the EU with 'altered habitats' the most commonly reported [247]. Physical alterations of the channel, bed, shore or the riparian zone affected 60% of such impacted water bodies with agriculture and flood protection being the main drivers. Extreme weather impact on river hydromorphology with respect to river flow, changes to sediment dynamics and river channels [317,318]. Arterial drainage was carried out on both the Owenmore and Unshin subcatchments with the majority of drainage works carried out on the Owenmore and only limited works carried out on the Unshin. Deepening of some sections of the Owenmore channel was carried out in 1927-1936 resulting in significant lowering of the Cloonacleigha and Templehouse lakes [309].

Land use impacts both on hydromorphological and chemical characteristics of streams and indirectly on the ecological status of streams [316]. Land use in the study area is predominantly agricultural with some urban areas including Gorteen (pop. 393), Ballymote (pop. 1549), Ballinacarrow (pop. 202), Collooney (pop. 1610) [319]. There are several urban wastewater discharges (Table 5) associated with settlements in the catchment.

Table 5: Urban Wastewater Discharges in the Study Area.

Agglomeration	Population Equivalent	Primary Discharge	Storm Water Overflow	Discharge to River Unshin	Discharge to River Owenmore
Ballinafad	<500	√		√	
Castlebaldwin	<500	√		√	
Riverstown	<500	√		√	
Ballinacarrow	<500	√	√		√
Ballymote	3000	√	√√		√
Culfadda	<500	√	√		√
Collooney	3100	√	√√		√
Gurteen	<500	√	√		√

(The number of √ corresponds to the number of discharges)

2.3.1.6 Weather Station

There are 20 automated weather observing stations in Ireland operated by Met Éireann [320]. Daily total and high frequency (15-minute interval) rainfall data is available from 2005 to the present from for a weather station located within the catchment at Markree. The national weather station at Markree is located 35 m above sea level and 7.3 km inland from the coast [321] and is adjacent to the water quality monitoring station on the Unshin river. A 'tipping bucket' which tips when 0.1 or 0.2mm of rain falls with the number of tips counted, is used to measure rainfall. Rainfall in the west of Ireland averages between 1000 and 1400 mm/annually.[322]. In examining meteorological indicators of climate change in Ireland, precipitation indicators were used to measure the intensity, frequency and duration of storm events. The indicators used included the number of precipitation events above the 90th percentile to identify extreme precipitation events [323]. This analysis is location specific and therefore takes into account, the local climate.

2.3.1.7 Flow & Level Data

Water level recorders at gauging stations on the Rivers Unshin and Owenmore are operated by the OPW. These record the water level at 15-minute intervals, and a site-specific-discharge relationship developed by the OPW to convert water level to flow rate. The EPA Hydrometric Unit use the descriptions of flow and level percentile classification [324] as detailed in Table 6.

Table 6: EPA Hydrometric Unit descriptors of flow and level percentile classification.

Flow/Level Descriptor	Percentile Classification	Description
Particularly high	>10%tile exceedance	Monthly level or flow occurs 10% of the time
Above normal	>30%tile <10%tile exceedance	Monthly level or flow occurs 20% of the time
Normal	>70%tile <30%tile exceedance	Monthly level or flow occurs 40% of the time
Below normal	>95%tile <70%tile exceedance	Monthly level or flow occurs 20% of the time
Particularly low	<95%tile exceedance	Monthly level or flow occurs 5% of the time

Due to water retention at the R. Unshin gauging station during high flows, no site-specific discharge relationship is available to convert level to flow at Ballygrania [301]. The discharge at a point in a river is calculated from the relationship between water level height (stage) and volumetric flow (discharge) at each gauging station. Multiple flow measurements are taken at different level heights in the river from low flow to flood flows to develop a rating curve [325]. However, water level at this hydrometric station is continuously recorded, and this data was used to pair stream level and water quality events as detailed in Chapter 4.

2.3.1.8 Water Quality in the Catchment

The Sligo Bay & Drowes Catchment has 100 surface water bodies, and the River Unshin is one of just 14 water bodies in this catchment with a 'high ecological status' (HSO) objective' with 71% of these HSO waterbodies located within a PA. It is only one of just 6 waterbodies (43%) meeting the high-status environmental objective under the WFD for this catchment [307]. However, in the first River Basin Management Plan (RBMP) cycle (2010-2015) the Unshin water quality status dropped to 'Good' status

and as a result was included as an 'area for action' in the second WFD planning cycle [307]. The cause of this drop was not identified but unknown pressures are the second most common pressure affecting at risk surface water bodies in the catchment generally, and also the second most common pressure affecting at risk high ecological status water bodies [307] as detailed in Figure 15. It recovered in the 2013-2018 monitoring period and has met the high status objective since [291]. Water quality status of the Rivers Unshin and Owenmore (WFD Status 2016-2021) varies from poor to high status (Figure 13) across the sub-catchments for both rivers.

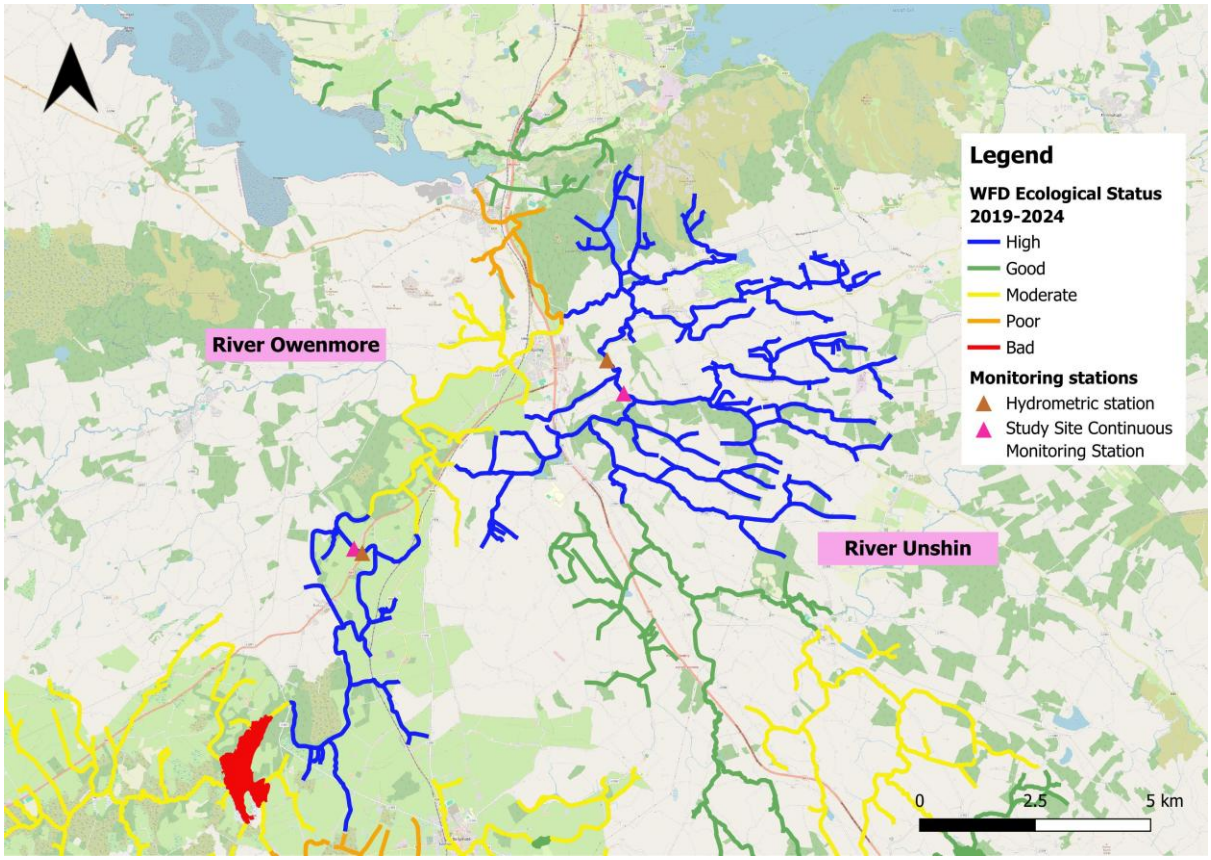


Figure 13: River Waterbody WFD Status 2016-2021 for Rivers Unshin and Owenmore (gis.epa.ie). Map created in QGIS (Version 3.42.1) using OpenStreetMap as a basemap.

Urban wastewater, agriculture, industry and unknown anthropogenic are identified as the most significant pressures within the catchment [307].

Water Quality Data for the study area was sourced from EPA catchments website [327] with results available from 2007 to the present (Table 7). The EPA implement a national river monitoring

programme consisting of 2429 river water bodies for surveillance (179 rivers) and operational (2250 rivers) monitoring with biology monitored every three river and grab samples for defined physical and chemical parameters monitored several times per year [328]

Table 7: Water Quality Data available from EPA for closest monitoring stations to the study sites.

Water Body	Sub catchment	Station Code	Station Name	Sample type & Frequency	Parameters Monitored
OWENMORE (SLIGO)_060	35_5 Owenmore (Sligo)_SC_020	RS35O060500	Templehouse Br (d/s)	Grab sample. 4 samples /annum from 2007 – 2015 5/annum from 2016	Alkalinity-total (mg/l as $CaCO_3$) Dissolved Oxygen (% Saturation) ortho-Phosphate (mg/l as P) Temperature (°C) Total Oxidised Nitrogen (mg/l as N) Total Hardness (mg/l as $CaCO_3$) True Colour (Hazen) Ammonia-Total (mg/l as N) Total BOD - 5 days (mg/l) Chloride (mg/l) Conductivity (µS/cm) Nitrate & Nitrite (mg/l as N) pH
UNSHIN_050	35_2 Owenmore (Sligo)_SC_030	RS35U010600	Bridge u/s Ballisodare River		

This water quality data was compared against data generated from this research in Chapter 4 to examine if high frequency monitoring and event monitoring has significant advantages in terms of data capture for water quality assessment over the national grab sample-based monitoring programmes.

2.3.1.9 Water Quality Pressures in the Catchment

For the Sligo Bay and Drowse catchment, the significant water quality pressures driving the risk of not meeting at least good status in the Water Framework Directive are agriculture, hydromorphology and unknown pressures (i.e. water quality pressures where the source has yet to be identified) [291] as highlighted in Figure 15. These pressures are a result of nutrient pollution, altered habitat and organic

pollution on surface waters [14,291,294]. This is reflective of water quality pressures across Europe with agricultural land use identified as a primary driver of aquatic risks to surface waters across the EU [14,250,330].

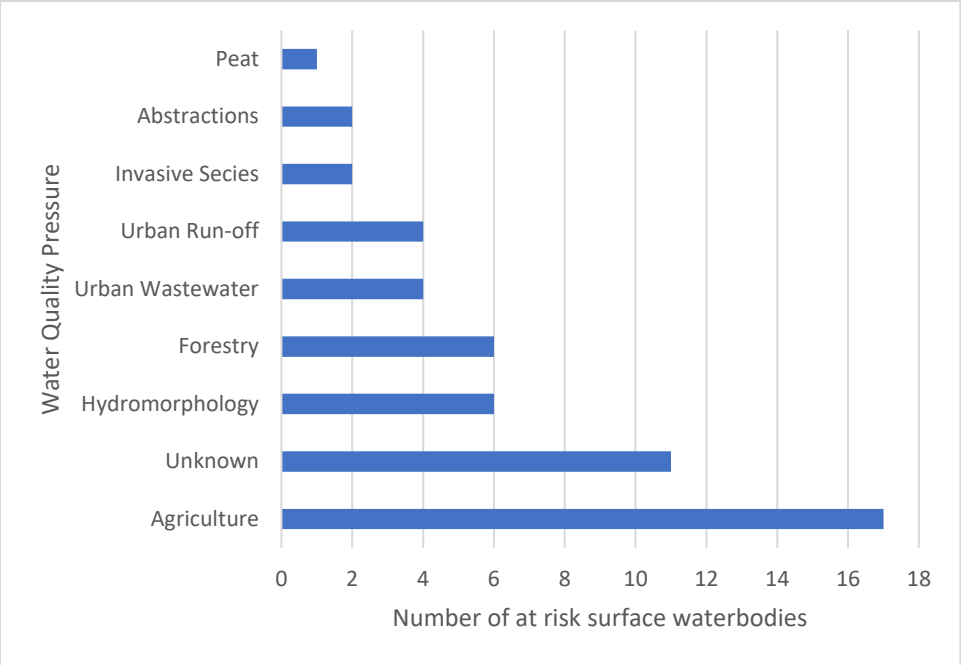


Figure 14: The Number of at-risk water bodies and the associated Water Quality Pressures in the Sligo Bay and Drowse Catchment [291].

Agriculture is the primary water quality pressure in the catchment overall but hydromorphology is the primary pressure for high ecological status objective waterbodies [326,331] as highlighted in Figure 15. There is a strong association between agricultural land use and hydromorphological alteration of freshwaters [330,332–334].

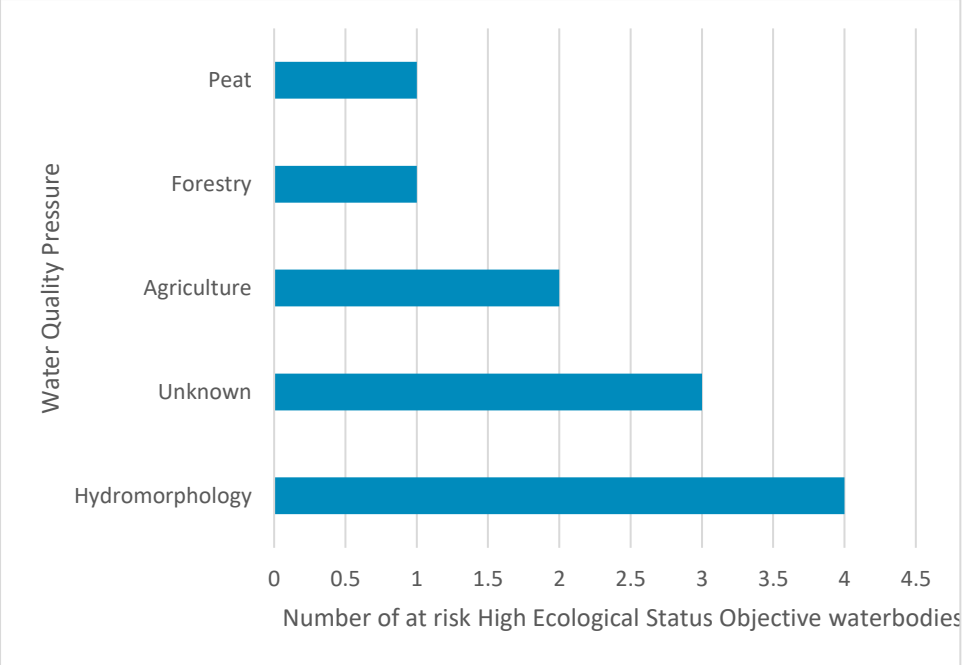


Figure 15: The number of as risk high ecological status objective waterbodies and the associated Water Quality Pressures in the Sligo Bay and Drowse Catchment [291].

For the Owenmore river, the water quality pressures are agriculture, forestry and urban runoff, hydromorphology, unknown pressures and invasive species with nutrients identified as a pressure in one area of the river Unshin [307]. Hydromorphological changes including dams, weirs and dredging directly impact aquatic habitats required to support fish, plants and aquatic insect populations [335], whereas land use impacts water quality due to the input of point source and diffuse source pollutants [336].

2.3.2 Walkover Survey of Monitoring Locations.

Following the desktop assessment a walkover survey was carried out to ensure that the monitoring plan was suitable, feasible and appropriately tailored to the specific conditions of the river monitoring stations thereby assuring the quality of the monitoring data. The primary purpose of the walkover survey was to:

- ground truth the desktop data.
- assess site conditions.

- identify any potential risks and issues.
- refine the sampling strategy.
- support baseline data collection.

The on-site inspection confirmed the accuracy of the desktop study on land use, hydrological features and water quality pressures. The current physical conditions of the river and surrounding land was observed including river morphology, bank stability, vegetation cover, animal access and signs or erosion or sedimentation. Photographic evidence of the primary water quality pressures was also gathered including forestry harvesting (Figure 16), hydromorphological pressure due to land drainage works (Figure 17) and direct animal access due to lack of riparian buffer resulting in bank instability, soil erosion and lack of root support causing tree to topple into the river (Figure 18).



Figure 16: The harvesting of a conifer plantation adjacent to the River Unshin at Dowrea, Co. Sligo.



Figure 17: Land drainage works on the River Unshin downstream of Lisconny Bridge, Co. Sligo. A linear drainage channel (highlighted in red) is located in the mid-distance on the far bank of the river, starting at the telegraph pole and extending from the field towards the river at right angles to the riverbank.



Figure 18: River Unshin at Cartronduffy, Co. Sligo. The lack of a riparian buffer (highlighted in orange) can be seen in the mid distance on both sides of the river channel. A cattle access point on the right-hand riverbank immediately in front of the tree (highlighted in blue) is characterised by heavily poached ground and exposed bare soil extending to the water's edge. Localised bank erosion has undermined the root system of a riverside tree located on the right-hand bank, resulting in the collapse of a mature tree across the river channel (highlighted in red).

2.3.2.1 Risk Assessment

A site-specific risk assessment was carried out as part of the walkover survey to identify potential hazards including swift currents, unstable banks, and contaminated water, and to plan safe access and egress from the monitoring sites. Systematically evaluating risks before the monitoring programme commences allows for appropriate safety measures, suitable protective equipment to be selected and implemented and allows for emergency planning thereby minimising the likelihood of accidents or injuries.

2.4 Water Quality Monitoring & Data Analysis Methodology

2.4.1 Hydrometric Stations in the Study Area

The gauged location on the River Unshin is hydrometric station 35003 at Ballygrania (Figure 19), and due to retention downstream of this station during high flows it is not possible to calculate flow from the observed water levels due to censoring of the data at high water levels [306].



Figure 19: Hydrometric Station on the River Unshin at Ballygrania operated by the Office of Public Works [337].

The gauged location on the River Owenmore is hydrometric station 35001 at Ballynacarrow (Figure 20). Both level (m) and discharge data (cubic meter per second) are available at this station [338].



Figure 20: Hydrometric Station on the River Owenmore at Ballynacarrow operated by the Office of Public Works [338].

There is one automated hydrometric station managed by the office of public works on the river Unshin and one on the river Owenmore (Figure 21) and the location of these stations influenced the location of water quality monitoring stations in this study, as the water quality data measured was analysed in conjunction with hydrometric and rainfall data.



Figure 21: Location of the water quality station (Owenmore WQ) and hydrometric station (Owenmore HydroM) on the River Owenmore and the location of the water quality station (Unshin WQ) and hydrometric station (Unshin HydroM) on the River Unshin. Map created in QGIS (Version 3.42.1) using OpenStreetMap as a basemap

2.4.1.4 Flow Duration Curve

A flow duration curve (FDC) is a cumulative probability graph used in hydrology to show the percentage of time a specific river or streamflow is equalled or exceeded over a given period. The shape of an FDC reveals the underlying hydrology and geology of a catchment with a steep slope indicating a flashy stream and flat slope indicating a stable stream with consistent, sustained baseflow (groundwater fed) [339,340]. FDCs are widely used in hydrology to model streamflow in ungauged catchments [341–343], for estimating environmental flows [344,345] and quantifying the hydrological impacts of climate change [346,347]. Discharge data from the OPW [338] was used to create a flow duration curve for the River Owenmore for analysis detailed in Chapter 4 but this was not possible for the river Unshin due to the lack of flow data. As a consequence of water retention at the R. Unshin gauging station during high flows, no site-specific discharge relationship is available to convert level data to flow data at this hydrometric station [301].

2.4.2 High Frequency (HF) Water Quality Monitoring Stations

Two monitoring locations were selected in the Sligo Bay and Drowse catchment (hydrometric area 35), one on the river Owenmore, a moderate status water body and a second location on the river Unshin, a high-status water body (Figure 21). Both locations met the criteria for a remote, off grid, sensor deployment site in terms of proximity to national water quality monitoring stations, hydrometric stations and had the necessary, security, all season access, and landowner permissions. The primary focus of this study was a monitoring strategy for significant water quality pressures on a high-status waterbody within a PA, to strengthen the study design and aid interpretation, concurrent monitoring of a moderate-status river within the same catchment was carried out. This provided a comparative baseline, enabling the differentiation of natural variability from anthropogenic pressures, testing the sensitivity of the high-frequency monitoring approach, and demonstrating how water quality parameters differ across the ecological status classes. Comparative analysis with a moderate-

status river helps interpret high-status stability and resilience, as high-status systems are expected to exhibit lower variability in key pollutants and faster recovery following disturbance events, while differences between the two can reveal subtle pressures that may otherwise go undetected.

2.4.2.5 Unshin river HF monitoring station

The Unshin river location was selected as an example of a river with a high-status objective under the water framework directive. The national water quality monitoring station RS35U010500 with historical data available from 2007 to 2023 along with the hydrometric station 35003 at Ballygrania was located 1300 m downstream of the study site (Figure 21). The reason why the study site was located upstream of the national monitoring station is due to attenuation at Ballygrania during periods of high flow as the Unshin river is restricted from entering the larger flow of the Owenmore River at the confluence. This attenuation causes a slowdown in the flow of the Unshin, flooding of the floodplain at Ballygrania and rapid settlement of solids and turbidity and evidence of this could be seen in the walkover survey (Figure 22). This would result in measured values at this point not always representing the true turbidity and suspended sediment values in the river channel. The Unshin flows through a predominantly agricultural catchment, has some small upstream villages including Castlebaldwin (pop. 107), Riverstown (pop. 334) and Ballygawley (population 310) [319].



Figure 22: River Unshin from the bridge at Ballygrania facing downstream. The hydrometric station is out of view to the left and the area to the right of the main channel (highlighted in red) floods from the river overflowing during high flows.

2.4.2.6 Owenmore HF Monitoring Station

The Owenmore River is classified a moderate status water body and has maintained this status throughout the three cycles of RBMPs. The national water quality monitoring station RS35O060600 with historical data available from 2007 to 2023 along with the hydrometric station 35001 Ballynacarrow is located 200 m upstream of the study site. The site walkover raised concerns about security at the hydrometric station, so the sensor was located 200m downstream to a more secure location. The land use in the area is predominantly agricultural but also contains upstream urban areas including Gorteen (pop. 393), Ballymote (pop. 1549), Ballinacarrow (pop. 202), Collooney (pop. 1610) [319]. Templehouse Lake is located upstream of the study site and was prioritised as an area for action to improve water quality in 2021 under the RBMP 2022-2027 and is the only water body in this catchment at 'Bad' status [326] (Figure 21).

2.4.2.7 Multiparameter sondes

A multiparameter sonde (Model YSI 6600 EDS V2-2, YSI Inc., Ohio, USA) was deployed at each of the high frequency monitoring stations on the River Owenmore at Ballinacarrow and on the River Unshin upstream of Ballygrania bridge. The parameters measured were temperature, specific conductivity, and turbidity. The turbidity sensor included a mechanical wiper to minimise biofouling and the measurement interval was every 15 minutes. This sonde has an internal battery (8 x C alkaline cells) with a battery life of up to 75 days at 15-minute sampling intervals and stores up to 150,000 readings The deployed sensors were inspected fortnightly and calibrated monthly as per the manufacturer's instructions with calibration data in Appendix B2.1.

2.4.1.8 Performance Specification for the Sensors on YSI Sonde

The performance specification for the HF sensors used in this study are detailed in Table 8. Sensors were calibrated as per manufacturers recommendations prior to deployment (Appendix B2.1).

Table 8: Typical Performance Specifications for the Temperature, Conductivity and Turbidity Sensors on the YSI 6600 EDS V2-2 sonde.

Sensor	Model	Measurement Unit	Specification	
Conductivity †	YSI 6560	µS/cm	Range	0 to 100 mS/cm
			Resolution	0.001 to 0.1 mS/cm (range-dependent)
			Accuracy	±0.5% of reading + 0.001 mS/cm
Temperature	YSI6560	°C	Range	-5 to +45°C
			Resolution	0.01°
			Accuracy	±0.15°C
Turbidity	YSI 6136	nephelometric turbidity units (NTU).	Range	0 to 1,000 NTU
			Resolution	0.1 NTU
			Accuracy	±5% of reading or 2 NTU, whichever is greater

† Report outputs of specific conductivity (conductivity corrected to 25° C). These values are automatically calculated from conductivity according to algorithms found in Standard Methods for the Examination of Water and Wastewater (ed 1989).

2.4.2 In-stream Verification of High Frequency Data

The high frequency sensor data was verified with in-steam spot measurements using handheld meters to enhance overall data reliability and accuracy of the water quality data. In-stream spot measurements were taken by measuring turbidity, specific conductivity and temperature when the sensors were deployed and retrieved. HACH HQ Series Portable Meter was used to measure water temperature and specific conductivity and HACH 2100Q was used to measure in stream turbidity. In-stream validation data is presented in Appendix B3.

2.4.2.8 Performance Specification for the handheld meters

The performance specification for the handheld meters used for verifying the HF sensor data used in this study are detailed in Table 9. Hand-held meters were calibrated as per manufacturers recommendations prior to deployment with calibration data presented in Appendix B2.2.

Table 9: Typical Performance Specifications for the Temperature, Conductivity and Turbidity handheld meters.

Parameter	Model	Measurement Unit	Specification	
Conductivity †	Intellical Conductivity Probe	µS/cm	Range	0.01 to 200 mS/cm
			Resolution	0.0 to 0.1 mS/cm (range-dependent)
			Accuracy	± 0.5% of reading + 0.001 mS/cm
Temperature	Intellical Conductivity Probe	°C	Range	-10 to +110 °C
			Resolution	Not stated
			Accuracy	±0.3 °C
Turbidity	HACH 2100Q	nephelometric turbidity units (NTU).	Range	0 to 1,000 NTU
			Resolution	± 1% of reading or 0.01 NTU, whichever is greater
			Accuracy	± 2% of reading plus stray light

2.5 HF Monitoring Sensor Deployment

A multiparameter YSI-6600 V2 sonde was deployed at each of the high frequency monitoring stations on the River Owenmore at Ballinacarrow and on the River Unshin upstream of Ballygrania bridge. The deployment method varied between the two sites.

2.5.1 River Owenmore Deployment

A purpose-built steel frame was used to house the YSI 6600 EDS V2-2 sensor (YSI Inc., Ohio, US.), sited mid-stream in the Owenmore River, fixed to the stream bed via metal prongs with the steel frame attached to a tree on the riverbank via rope. This allowed for the sensor to be submerged during variable river flows as the river level rises and falls in response to rainfall (Figure 23).



Figure 23: Deployment of the YSI 6600 EDS V2-2 Sonde at the study site showing (1) the frame used to house the sensor and (2) the deployment site on the Owenmore River at Ballynacarrow.

2.5.2 River Unshin Deployment

On the Unshin river, permission was obtained from the landowner to mount the YSI 6600 EDS V2-2 sensor on the side of the pontoon floating in the river (Figure 24). The pontoon was mounted on steel poles and rises and falls with the river level which allowed the sensor to remain suspended in the water column at all times. The sensor was hung on the side of the pontoon under the water level using marine rope and stainless-steel carabiners and the length of rope was adjustable to ensure the sonde remained above the riverbed in very low flow conditions.



Figure 24: Deployment of the YSI 6600 EDS V2-2 Sonde on the Unshin River at the study site downstream of Markree Castle showing the recreational pontoon where the sonde was is attached, suspended in the water column.

2.6 Data Management

For water quality monitoring there are two components to data management, a data management plan and validation of the data collected during the research.

2.6.1 Data Management Plan

A data management plan is a core component of research projects [348] and provides for data security and the opportunity for data sharing [349]. The standard six stages of data life cycle; creating, processing, analysing, preserving, giving access and re-using [350] was applied to the data collection protocols and data quality in this research with the data management plan detailed in Appendix B.

2.6.2 Data Validation

Data validation is a process to decide whether data collected is fit for purpose [351] and involves a thorough review of data quality [352]. Water quality data commonly includes missing results, censored results, outliers [352] and is subject to errors that are random (unpredictable variations causing repeated measurements to fluctuate around the true value [353]) and are systematic (constant bias causing measurements to be persistently high or lower than the true value[353]) [354]. Water quality data requires

expertise in judging whether data points are erroneous and should be removed [352] as data validation is primarily a subjective process [354].

2.6.3 Data Visualisation

The high frequency data series were exported from YSI sonde via EcoWatch® software to a laptop as a .csv file. The data was then plotted in R Studio initially before any further analysis was carried out as shown in Figure 25 and Figure 26. This allowed for data visualisation to examine properties of the time series data, to visually identify any relationships and to detect any unusual data or 'outliers'. A hyetograph (rainfall versus time) and a hydrograph (streamflow/discharge versus time) are commonly plotted in hydrology with the convention to plot an inverted hyetograph the most common presentation in hydrology [355]. The hyetograph – hydrograph curve shows the cause and effect relationship between rainfall and runoff and how the catchment responds in terms of river flow [356]. Figure 25 shows the hyetograph - hydrograph for the River Owenmore and River Unshin with river level used instead of discharge on the River Unshin due to the poor stage-discharge relationship caused by water retention at the R. Unshin gauging station during high flows. It shows the response of both rivers to rainfall and highlights how both rivers exhibit a similar response time to rainfall events. The graphs also display the flow/level percentiles with the P5 exceeded 95% of the time and the P95 only exceeded 5% of the time.

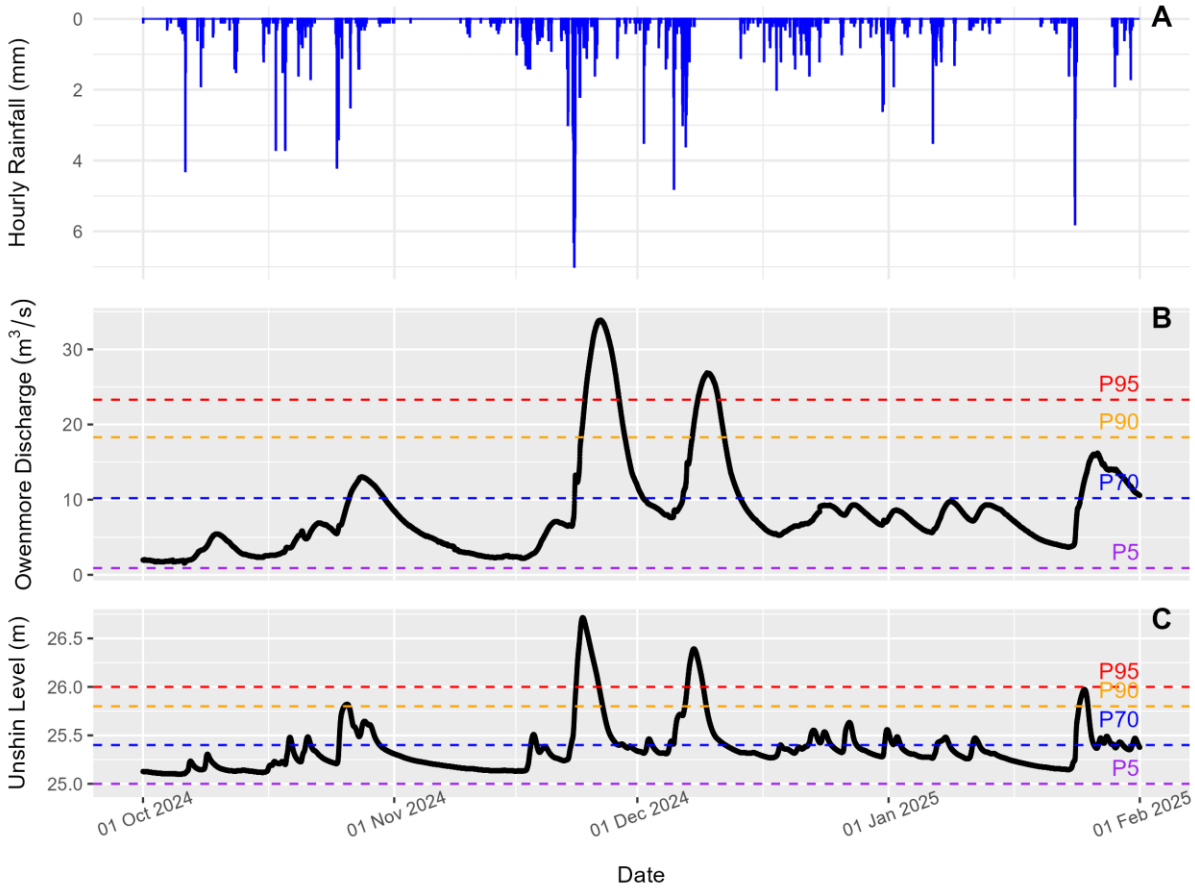


Figure 25: Hyetograph - Hydrograph for the River Owenmore and River Unshin with river level used instead of discharge on the River Unshin due to the poor stage-discharge relationship caused by water retention at the R. Unshin gauging station during high flows [301] (R Studio).

2.6.4 Data outliers

The presence of data values that are significantly larger or smaller than the baseline is commonly encountered with water quality data [352]. Figure 26 demonstrates increased turbidity values during periods of rainfall and also occasional peaks in turbidity when there is little or no rainfall. Point source discharges can increase river turbidity by introducing suspended solids and other particulate matter and reducing water clarity [357,358]. All potential outliers are examined in the context of other data points collected at that time along with hydrometric and rainfall data before a decision is made to include or exclude that data point.

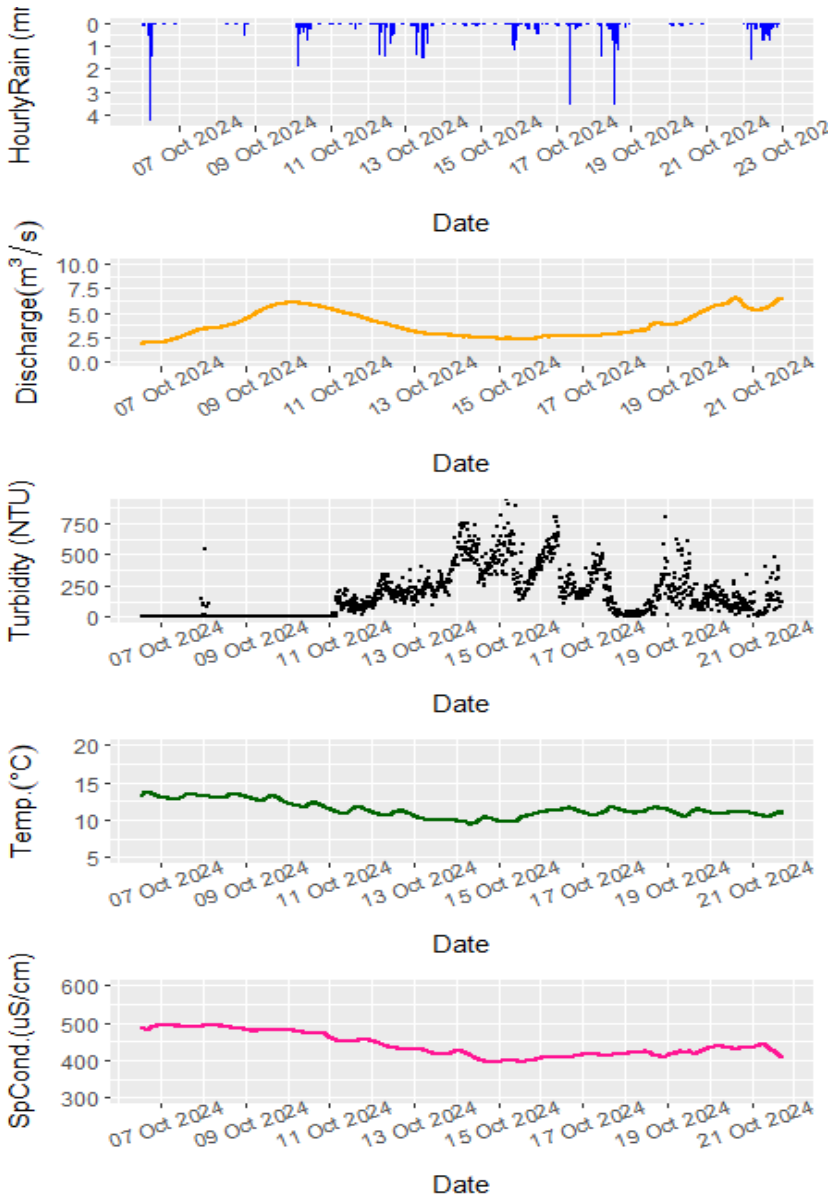


Figure 26: Time series data for the Owenmore River at the study site in Ballynacarrow in October 2024 showing spikes in turbidity following rainfall during the period.

2.6.5 Censored Data

Censored data occurs where the level of a substances detected in a sample is less than the less than the detection limit of the sensor or laboratory method employed [359] often recorded as “non-detected” A number of methods have been developed for evaluating censored data with maximum likelihood estimation and regression on order statistics commonly used to manage censored data in datasets

while avoiding introducing excessive bias [360]. Baseline monitoring was carried out to evaluate if the data collection method was sensitive enough to detect significant changes in temperature, specific conductivity and turbidity e.g. during a pollution event to verify if spikes in data trends were below or close to the sensor limits as detailed in Section 2.12.

2.7 Software for Monitoring and Analysis

2.7.1 High Frequency Data Collection and Storage

The YSI 6600 sonde features a built-in battery and internal memory allowing it to function as a standalone datalogger for continuous water quality monitoring requiring no external power supply. It can store up to 150,00 individual data readings for up to 75 days.

The EcoWatch® for Windows® software is a dedicated PC application for interfacing with the YSI 6-series sondes. The software allows the user to download the internally logged data to a laptop/PC as .csv file and to calibrate the sensors.

2.7.2 Data Processing and Analysis Software

Open source software was used in this study as open source software in research ensures transparency, drives reproducibility and removes the cost and restrictive licensing barriers to accessing software tools [361]. Once data was downloaded from the sonde the following open-source tools (Table 10) were used for processing and analysis:

Table 10: Open-Source Software used for data analysis in this research.

Software Tool	Purpose
R [362]	Data visualisation Data Analysis
US EPA CANARY [363]	Water quality event detection
R package 'hydroEvents' [300]	Baseflow separation Event pairing

2.8 Event Detection

2.8.1 Water Quality Event Detection

US EPA CANARY event detection system was employed in this study to differentiate between typically background water quality trends and changes in water quality due to pollution or other events. US EPA CANARY, originally developed for drinking-water contamination [364,365], is suitable for diverse time-series applications including water distribution [366] water reuse [367], water runoff [368] and surface waters [288,291]. CANARY parameters are refined on a station specific basis [369] using historical data in offline mode [364], and the associated Linear Prediction Coefficient Filter (LPCF) method employed in this study, yields low false positives and detects single-signal events effectively [288,291,365]. The LPCF is an adaptive digital-filtering method that predicts the next data value as a weighted average of recent observations using linearly estimated coefficients that minimize bias and variance, flagging observations as outliers when their prediction errors exceed a specified threshold. Water Quality data exported from the sondes was imported into US EPA CANARY software for event detection with further information detailed in Chapter 3.

2.8.2 Hydrological Event Detection

Baseflow separation is typically performed prior to rainfall-runoff event detection. Baseflow separation isolates slow-moving groundwater from the total streamflow hydrograph, leaving only the quickflow (surface runoff). This process allows hydrologists to detect true event peaks, and accurately quantify storm volumes [370]. The hydroEvents R package [300] was used in this research and employs variants of the one-parameter recursive digital filter [371],—'baseflowA()' [372] and 'baseflowB()' [373] for baseflow separation.

The hydroEvents R package provides multiple strategies for event identification and event pairing. It was used to identify rainfall events and was also used for pairing rainfall with flow events, rainfall with water quality events and flow events with further information detailed in Chapter 3.

2.9 Baseline Monitoring

Baseline data for water quality, flow, weather and other parameters is frequently used to establish if developments are affecting water quality [374], to regulate inputs to surface waters and cumulative effects assessments [375], identify catchments sensitive to fluvial flooding [292] and to examine impact of climate change on catchments [376]. Rainfall events have been found to impact baseline water quality [329] by increasing surface water organic matter [377], pesticides turbidity and phosphorus [378] and by causing nutrient fluxes to exceed annual average mass loads [329].

The desktop assessment identified that the primary water quality pressures in the study catchment are associated with diffuse pollution. Baseline monitoring was carried out to inform the appropriate method of event detection. The purpose of the baseline monitoring for this research was to study the relationship between rainfall, flow and turbidity and to identify trigger levels for turbidity based on high frequency turbidity data. Data was collected from October 2022 to March 2023 during baseflow and stormflow conditions for the River Owenmore (Table 11).

Table 11: Site and Data details for baseline monitoring on the Owenmore River.

River	**Site Name**	**Precipitation (mm) Frequency[1]**	**Discharge (m^3) Frequency2**	**Turbidity (NTU) Frequency[3]**
Owenmore	Ballynacarrow	1 hour	15 min	15 min

[1]Source: Met Eireann, [2]Source: OPW (waterlevel.ie), [3]Source: Data from deployed YSI sonde.

2.9.1 Rainfall driven pollution event monitoring.

Rainfall is a significant driver of pollution into water bodies including organic and inorganic chemicals [379], sediment and nutrients [380,381] and is a key driver of diffuse pollution from agriculture, particularly sediment loss [381]. Both hydrology and water quality are particularly exposed to short duration rainfall events following prolonged drought [382]. With the increasing variability of hydroclimatic conditions worldwide due to climate change, long time series water quality data is crucial and 'networks of measurement probes' continuously monitoring across catchments are required, in addition to the

longstanding water quality monitoring stations [24,272,279,383]. Rainfall data from Met Eireann was analysed with water quality data at the study sites to identify any association between rainfall events and water quality events with further details in Chapter 4.

2.9.2 Continuous water quality monitoring versus discrete samples

High temporal resolution datasets are needed to address the multiple threats currently facing water quality around the world [329,384–386]. Currently, the Irish national river monitoring programme operated by the EPA relies on long term discrete samples for physical and chemical analysis taken several times per annum, and supplemented by biological monitoring every 3 years [387].

To investigate if continuous monitoring had significant advantages in terms of data capture for water quality assessment over the current national grab-sample based monitoring programme data, high frequency data gathered during the study was analysed against the historical EPA grab sampling data at the Owenmore national monitoring station.

2.9.3 Turbidity and Specific Conductivity Monitoring

Turbidity and conductivity sensors on the YSI 6600 EDS V2-2 sonde were used to measure water quality at 15-minute intervals. Service and calibration of the sensors was carried out off site in the laboratory as per the manufacturer's instructions. Data was downloaded to a laptop using EcoWatch Lite software and sensors were cleaned, inspected for damage, water intrusion, battery life and adequate data storage memory. Calibration for turbidity was via a two-point calibration with deionised water and 126 NTU standard (part no. 607300) and for conductivity was via a single point calibration with 1413 µS/cm standard as per manufacturer's instructions. Prior to deployment the sensors were allowed to run in water to check that the sensors were logging and values were stable. Site visits were carried out every 2-4 weeks and sondes were removed from the water, inspected, cleaned with values verified at deployment against a portable turbidity meter and a portable conductivity meter with a calibration criterion of ± 10% of the measured value. Differences in

measured values can be indicative of sensor fouling or calibration drift requiring sensor maintenance or recalibration to rectify.

2.9.4 Turbidity Monitoring

Turbidity has been used as an indicator of water quality in rivers [388] as it is a rapid indicator reflecting the amount of sediment in the water with low turbidity generally indicative of good water quality and high turbidity frequently associated with erosion. runoff from land and pollution inputs [357,388]. Increased turbidity is associated with extreme precipitation and discharge events [389] and also with intense agricultural land use [390] Some pollutants including phosphorus are significantly correlated with suspended solids [304,391] and solids have been estimated from turbidity measurements [392]. Turbidity has been used to monitor fine sediment transport in rivers due to storms [393], as a proxy for suspended solids [394] and to detect metal transport in rivers [395], to assess pollutant loads in combined sewers [396] and to detect hydrophobic organic pollutants [397].

2.9.5 Specific Conductivity Monitoring

Specific conductivity measures a water sample's ability to conduct electrical current, primarily influenced by the concentration of dissolved ions such as salts, acids, bases, and other inorganic chemicals. It is expressed in microsiemens per centimeter (µS/cm) or millisiemens per centimeter (mS/cm) High specific conductivity values generally indicate increased total dissolved solids which can result from pollution sources such as industrial effluents, sewage, agricultural runoff, and mining activities. [398]. Changes in specific conductivity can signal the introduction of pollutants including industrial wastewaters [288,399], acid mine drainage [400,401] and septic tank pollution [402] into water bodies, making it a quick and cost-effective preliminary assessment tool [403]. While specific conductivity alone cannot specify the type or source of pollution, it serves as a valuable, rapid indicator of overall water quality and potential pollution levels and has been used for modelling nitrate in groundwaters [399,404] and as a water pollution indicator in a number of studies [288,405].

2.9.6 Challenges for temporary deployments

Deployments of water quality sondes in temporary monitoring locations presents several challenges including power supply limitations resulting in a reliance on internal batteries or external bankside batteries or solar panels. Automatic transmission of sonde data was not employed in this study but is subject to reliable data transmission which can be challenging in remote or inaccessible locations. Biofouling and sensor fouling also occurs with temporary deployments with significant amounts of solids being transported in high flow events (Figure 27Figure 27).



Figure 27:Sonde mounted in cage and deployed on the bed of the River Owenmore, during lower flow conditions on the left and fouling of sensor following a high flow event on the right following a three-week deployment period.

Severe storms can result in the transport of large amounts of vegetative debris downstream during the event with material becoming entrapped sonde supports mounted on the riverbed (Figure 28). Access to sondes during high flows is also restricted due to high water depth.



Figure 28: During a storm event significant debris accumulated on the purpose-built sonde support deployed on the bed of the Owenmore River.

Summer conditions also bring challenges as warmer air and water temperatures resulting in algal growth and algal attachment over a short length of time, particularly in water bodies where nutrient enrichment is a water quality pressure (Figure 29).



Figure 29: Accumulation of algae on the anchor ropes and support cage for sonde mounted on the bed of the Owenmore River when deployed for just three weeks in summer season.

Fouling can also impact sensor measurement even when wiper technologies are in place to prevent biofouling and remove debris from the senor measurement window (Figure 30).



Figure 30: Algae attached to wiper of turbidity sensor on YSI 6600 sonde deployed in the Owenmore River in summer season.

Temporary deployments lack the hard infrastructure used to keep sensors in the same position, covered by streamflow providing easy access so careful consideration must be given to the most appropriate deployment method. For this study two different deployment methods were used to match the local site conditions. Environmental conditions may also have a greater impact on temporary deployments. The deployment on the pontoon on the river Unshin provided easy, ready access over most of the study period (Figure 31)



Figure 31: Deployment location for the River Unshin under typical flow conditions.

However, during very high flows the area around the pontoon flooded rendering the location inaccessible (Figure 32).



Figure 32: River Unshin deployment location during very high flows showing flooding around the deployment pontoon highlighted by red circle.

In a severe storm, one side of the pontoon was lifted off the steel support pole and damaged by the force of the river water flowing past the pontoon requiring remounting before the sonde could be retrieved and repairs before the sonde could be redeployed Figure 33.



Figure 33: River Unshin deployment pontoon following a severe storm event.

With increased frequency and intensity of hydrodynamic events occurring resulting in the decline of water quality [295], such deployments are critical in tracking the impact of such events on water quality, however the careful planning of off-grid monitoring programmes to prepare and adapt to such deployment challenges is required.

2.10 Objective of the Investigative Baseline Field Study

The aim of the investigative field studies was to gather baseline data to identify the suitability of the parameters being monitored and to identify if high frequency monitoring for stream turbidity and specific conductivity trend data could be used for water quality event monitoring during precipitation events.

The core objectives of the baseline study were to:

1. Evaluate the performance of the sensors over the deployment period, examining sensor accuracy and precision over time at the deployment location both under baseline and elevated conditions.
2. Carry out baseline monitoring assessment to establish if a relationship exists between rainfall, flow and turbidity and specific conductivity on the river Owenmore by deploying a high frequency turbidity sensor over a period of months and analysing that data against rainfall data and flow data using R Studio.
3. Identify 'trigger levels for turbidity' where there was an increase in the background turbidity level.

2.11 Results and Discussion for Baseline Monitoring

2.11.1 Trends for Turbidity and Specific Conductivity Data

There was minimal drift in sensor response during deployment, and the wiper maintained a clear measurement window on the turbidity sensor with minimal biofouling on the specific conductivity sensor. The sensors accurately detected turbidity and specific conductivity across the measured range from typical background levels to elevated levels during rainfall events. Specific conductivity readings remained stable without excessive noise or fluctuating spikes in the data. Turbidity data exhibited more noise than the specific conductivity data with some fluctuating spikes evident, however turbidity readings did return to baseline with stable readings during baseline conditions. Both turbidity and showed good agreement with readings from the handheld meters.

2.11.2 Relationship between Discharge and Rainfall

The cross-correlation function between rainfall and river discharge is shown in Figure 34 and was used to examine the temporal relationship between rainfall inputs and the corresponding discharge response. Cross correlation analysis is commonly used in hydrology to identify catchment response times and assess rainfall runoff relationships [406]. Positive lag values indicate that changes in river discharge occur after rainfall events. River Discharge at the Owenmore study site was found to be

positively correlated to rainfall with a lag of 0 hours indicating that the river responds very quickly to rainfall events with an immediate effect on discharge (Figure 34). This suggests and immediate hydrological response of the catchment to rainfall, likely reflecting rapid runoff generation and efficient flow routing of rainfall inputs to the river channel.

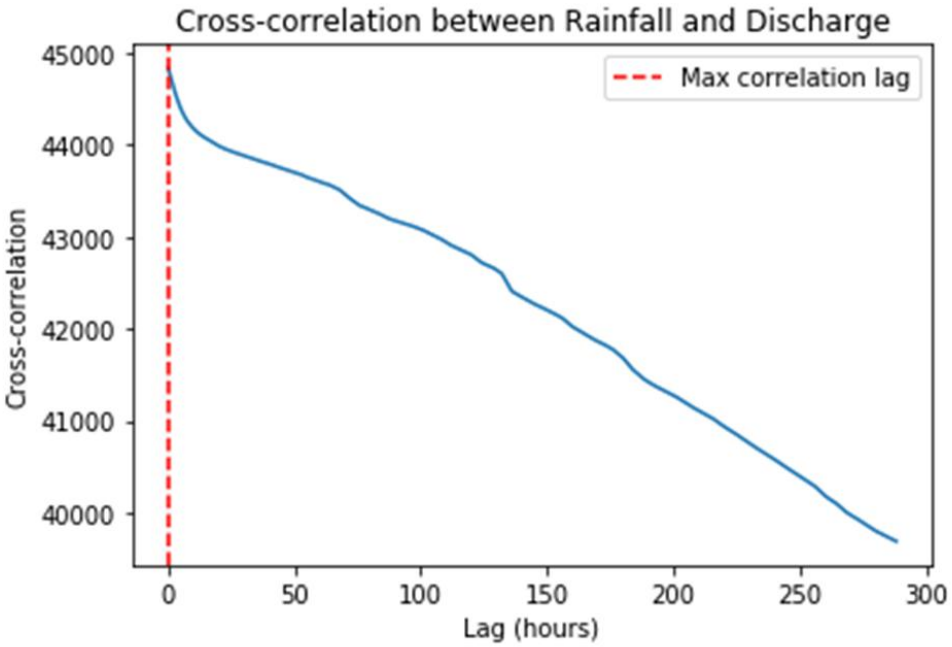


Figure 34: Cross correlation between rainfall and discharge on the River Owenmore.

2.11.3 Relationship between Rainfall and Specific Conductivity

The cross-correlation function between rainfall and specific conductivity to examine the temporal relationship between rainfall events and variations in specific conductivity. Rainfall and specific conductivity had a positive linear relationship. Specific conductivity had a moderate positive correlation with rainfall (0.34) but a lag of 288 hours (12 days) (Figure 35). This lag time suggests that changes in specific conductivity followed rainfall events after a substantial delay. This indicates that the effect of rainfall on specific conductivity were not immediate and were likely mediated through slower hydrological processes such as groundwater recharge, subsurface flow pathways or catchment storage effects [407].

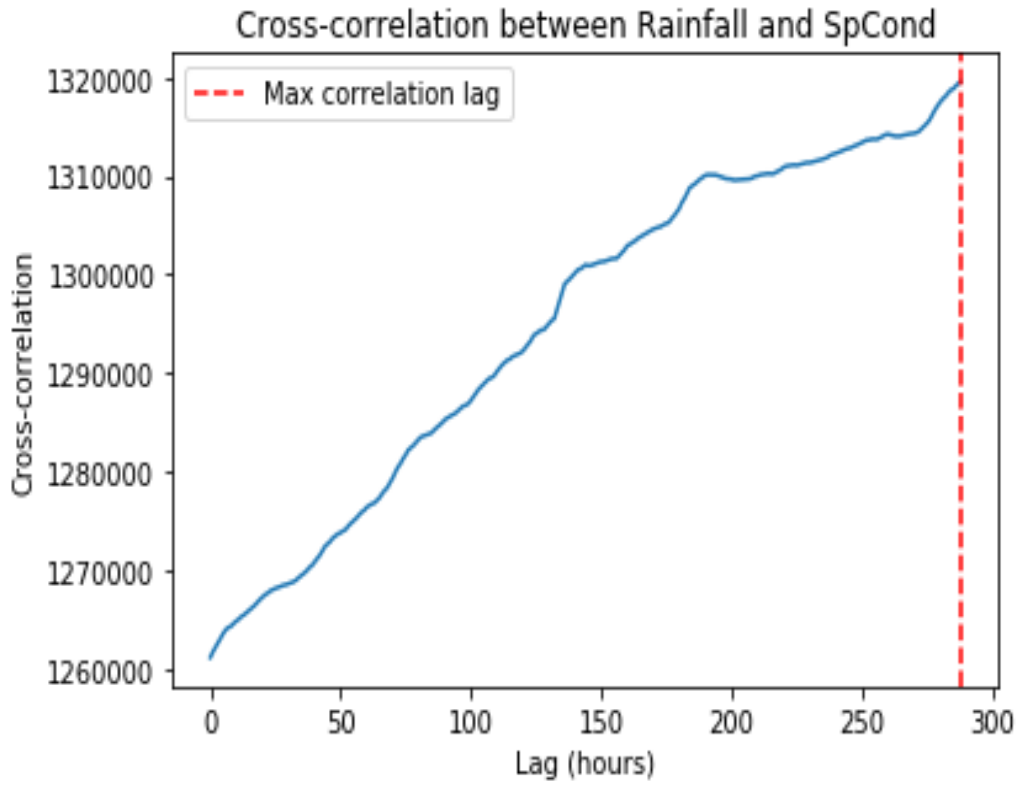


Figure 35: Cross correlation between rainfall and Specific Conductivity on the River Owenmore.

2.11.4 Relationship between Turbidity and Rainfall

Turbidity was found to be weakly positively correlated with rainfall with a lag of 185 hours (8 days) and a correlation of 0.11 (Figure 36). The relationship between rainfall and turbidity as a surrogate for solids transport is complex and highly variable, depending on multiple environmental and hydrological factors and can vary significantly between multiple rainfall events at the same monitoring station [408–410]. This raises a number of questions that require further investigation, does the length of the lag depend on the event type or intensity? Further monitoring and analysis were carried out with the aim of characterising storm events for rainfall and turbidity at these study sites and is detailed in Chapter 4.

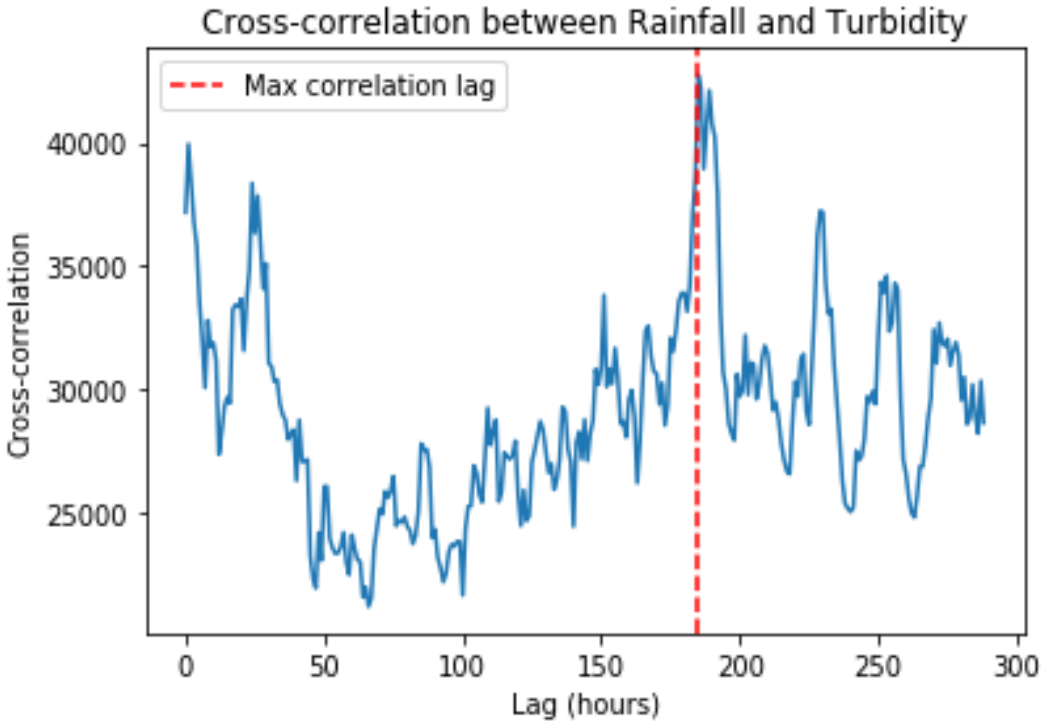


Figure 36: Cross correlation between rainfall and turbidity on the River Owenmore.

2.11.5 Turbidity Trigger Value

Turbidity trigger values are used in a number of different water quality applications including harbour dredging activities [411], for the treatment of surface waters for drinking water supply [412] and indicator trigger values for classifying New Zealand rivers and streams [413] with trigger values indicating 'potential risk' to water quality at a site [414].

To identify a turbidity trigger value to identify potential pollutant events, outlier detection analysis was carried out. Tukey's Fences method is used for outlier detection in water quality data [415,416] and is suitable for data that do not follow a normal distribution which is typical of water quality data [417,418]. Tukey Fence's Method is based on the third interquartile range with measurements identified as potential outliers where any value falls above the high potential outliers calculated by Q3 + 1.5*IQR [419] The Tukey Fences' method identified a turbidity threshold value of 13 NTU and the 95th percentile analysis identified a turbidity trigger value of 17.7 NTU over the monitoring period at the Owenmore site.

2.11.6 Event Detection

Following the results of the baseline study and the noise associated with the turbidity data further research was carried out to identify suitable open source, event detection software that had been applied to detecting events in surface water. EPA CANARY was identified as such a system and tested in the next stage of this research. While a number of different open-source event detection software systems were identified, CANARY was identified as a suitable option as it developed by the US EPA and had extensive training material and user manuals available, had been used in numerous other studies and the software was maintained by the US EPA unlike other software identified which were associated with PhD or other shorter term studies, had limited training material/ user manuals associated with them and were not being maintained or updated.

2.12 Conclusion

Against a backdrop of increasing complexity in water quality monitoring and a lack of improvement in water quality, this investigative field work aimed to gather data to identify if high frequency, remote monitoring for stream turbidity could be used to capture water quality changes during precipitation events.

Baseline trend monitoring for turbidity carried out in the study area showed that discharge is positively correlated to rainfall with a lag of 0 hours indicating that the river Owenmore responds very quickly to rainfall events with an immediate effect on discharge. While peaks in turbidity occurred, turbidity was weakly positively correlated with rainfall with a lag of 185 hours (8 days) and a correlation of 0.11. Specific conductivity had a moderate positive correlation with rainfall (0.34) but a lag of 288 hours (12 days).

The method chosen for this study was selected due to its appropriateness for monitoring the water quality pressures identified for the rivers in this study [307] being associated with diffuse sources of pollution [420–422] and it's use in previous studies [288,367,368]. This is however, the first instance of US EPA CANARY event detection being used to analyse water quality events in rivers in conjunction with analysing corresponding rainfall and discharge data.

Building on the results from the baseline monitoring, the following Chapter 3 presents the method development and optimisation for site specific event monitoring at these river stations with Chapter 4 demonstrating the ability of this method to track the frequency and intensity of hydrodynamic water quality events in the study catchment.

Chapter 3: Development of Open-Source Workflow for Hydrodynamic Water Quality Event Monitoring

3.1 Introduction

Chapter 2 outlined the methodological approach used to address the research aims of this thesis. This chapter builds on the baseline monitoring carried out in Chapter 2 and details the practical, flexible and reproducible, open-source workflow and associated step by step detailed user guide for monitoring water quality and identifying hydrodynamic water quality events in small rivers using high frequency monitoring.

Protected areas provide reference sites with minimal disturbance, allowing scientists to establish and monitor baseline water quality and aquatic biodiversity. These benchmarks are essential for detecting changes, assessing the impact of human activities outside protected zones, and setting conservation targets. The WFD specifically provides for protected areas where such areas require 'special protection under specific Community legislation for the protection of their surface water and groundwater or for the conservation of habitats and species directly depending on water' [11]. Aquatic species are sustained by good water quality and water quality deterioration is one of the main drivers of freshwater biodiversity decline globally [3,4] which is compounded by climate change pressures [5].

Optimising the design of water quality monitoring programmes can maximise the likelihood of detecting pollution events and also decrease the time to detection of such pollution events [423] but the rapid pace at which monitoring tools for water quality parameters are developing poses difficulties for the adoption of such tools by water resource managers in addition to the varying monitoring requirements and land use and regulatory requirements between different water bodies [424].

Higher water quality standard requirements combined with increased water quality pressures are resulting in a growing demand for innovative and effective pollutant detection which has led the development of autonomous, remote sensors which can provide continuous, in-situ quality data [425]. Such in situ deployed sensors can provide baseline data, data for modelling and early warning alarms in the event of declining water quality [426]. In-situ sensors have been developed for monitoring many water quality parameters including phosphorus [427–430] , turbidity [431–433], nitrogen [434–436], and multi parameter sensors including pharmaceuticals and heavy metals [437].

However, high discharge events and low analyte concentrations can pose a challenge for in-situ monitoring of some nutrients when compared to standard laboratory analysis [438]. A review of online and in-situ water quality monitoring highlighted the need for greater in field deployment of sensors to evaluate the reproducibility and precision of these methods and their suitability for regulatory compliance monitoring [439]. It has been argued that an integrated framework of in situ-monitoring and remote sensing alongside data analytics is required for an ideal catchment observation system [440].

Despite awareness of new and innovative technologies, it has been found that statutory bodies responsible for freshwater monitoring are less likely to use these technologies and that adequate funding, training and method guidelines are urgently required to accelerate the uptake of such technologies [441].

Identifying effective freshwater protection and restoration measures to protect and restore high status waterbodies requires adequate data and high frequency monitoring to facilitate rapid, real time strategic adaptation for the delivery of water quality improvements [442] with more data required to determine specific water quality pressures [14,443]. Numerous studies have demonstrated the value of high frequency, continuous water quality monitoring for evaluating surface waters [272,444–446].

High frequency water quality monitoring requires 'robust deployment, maintenance, and data management protocols' [281] along with 'practical guidelines' [24], and the challenges for citizen scientists and non-experts in sharing metadata and analyzing millions of water quality data points has been highlighted [447]. Furthermore, many researchers are not software engineers or formally trained in coding [448] with code errors and the inability to reproduce analyses frequently encountered, even where datasets and code were published [449,450].

To enable and ensure the replicability and traceability of scientific research, the datasets and the data analysis for the corresponding scientific publication must be made publicly available [451]. Github, a widely used cloud-based platform where developers store, manage, and collaborate on software code provides a robust framework for managing and tracking scientific research activities and facilitates knowledge transfer [452]. It is one of the most commonly used platforms for academic research [453] and

improves the dissemination of research articles [454]. Originally Github was primarily associated with software developers and programmers but it's use has extended into many fields including the field based biology [455] and research laboratories [456]

3.2 Aims and Objectives

The aim of this work was to develop a practical, flexible and reproducible, open-source workflow for monitoring water quality and identifying hydrodynamic water quality events in small rivers using high frequency monitoring. This aim was achieved via the following objectives; (1) describing suitable deployment arrangements for water quality sondes using two temporary monitoring sites with different site characteristics: (2) detailing suitable data collection and data validation method for high frequency water quality data; (3) developing and detailing a concise, reproducible, open-source workflow detailing the use of R, R markdown and US EPA CANARY software for data import, data cleaning, data visualisation, data integrity; (4) describing how a site-specific CANARY event system configuration can be constructed for the detection of potential water quality events.

3.3 Materials and Methods

3.3.1 Sensor Calibration

One of the objectives of continuous, high frequency monitoring is to collect the most accurate and complete datasets for monitoring purposes [457]. Service and calibration of the sensors was carried out off site in the laboratory as per manufacturer's instructions with calibration data in Tables B2 and B3 in Appendix B. Data was downloaded to a laptop using EcoWatch Lite software and sensors were cleaned, inspected for damage, water intrusion, battery life and adequate data storage memory. Calibration for turbidity was via a two-point calibration with deionized water and 126 NTU standard (part no. 607300), and for conductivity using 1413µS/cm standard conductivity calibration solution as per manufacturer's instructions. Prior to deployment the sensors were allowed to run in stream water to check that the sensor was logging, and turbidity, conductivity and temperature values were consistent. Site visits were carried out every 2-4 weeks for sonde maintenance. Cleaning of sensors

was carried out using a soft-bristle brush to remove debris from the outside of the sensors, wiping with a damp towel and then rinsing with deionized water. The frequency of sensor maintenance and appropriate service intervals is determined by the rate of sensor fouling, and this rate depends on the monitoring location, the sensor type, hydrological conditions and the time of year [24]. Fouling was not found to be a particular issue at either site in the autumn, winter and spring but during the summer months there was significant accumulation of filamentous algae on the frame and anchor ropes at the Owenmore site. Weekly sensor maintenance inspections were carried out on the Owenmore site during low flow periods to examine for biofouling as demonstrated in Figure 29 and also immediately following storm events to examine for sensor deployment position and debris build up as demonstrated in Figure 28.

3.3.2 Sensor Validation

3.3.2.1 Data Validation

Instrument checks to verify the operation of the sondes and to monitor sensor drift were carried out on site. River turbidity, specific conductivity and temperature were measured using calibrated field meters with calibration data in Table B4 in Appendix B. Portable, calibrated sensors were used to collect field measurements at the time of sensor deployment and retrieval with data in Table B5 in Appendix B. Measurements were taken adjacent to the deployed instruments to provide an independent assessment of sensor performance under in-situ conditions. These observations were compared with the deployed sensor data. A portable turbidity meter (HACH 2100Q Portable Turbidimeter), and a portable conductivity/temperature meter (HACH HQ series Conductivity) with a calibration criterion of ± 10% of the measured value for specific conductivity and temperature and ± 20% or within 1.0 NTU for turbidity. It is the relative change in turbidity, specific conductivity and temperature and not the absolute values that were of interest in this study as it is the relative change in data values of a parameters from the baseline that is used by US EPA CANARY for event

identification. Following retrieval from the field, sensors were checked for drift by measuring the same calibration standards used during the initial pre-deployment calibration (Table B6 in Appendix B). Post -deployment responses were compared with known standard values. Differences between pre- and post-deployment measurements were used to quantify sensor drift and assess sensor performance throughout the monitoring period [458]. Significant drift was not detected in the datasets and the wiper system on the turbidity sensors (YSI 6136) was found to be effective at maintaining a clean window. Differences in measured turbidity between different sensors has previously been identified as an issue for turbidity monitoring [459] so the same turbidity sensors were used throughout this study.

3.3.3 Sensor Deployment

A YSI 6600 EDS V2-2 sonde (YSI Inc., Ohio, USA) was deployed at each of two river sites in the northwest of Ireland to continuously measure temperature (YSI6560), specific conductivity (YSI 6560), and turbidity (nephelometer YSI 6136, including a mechanical wiper to minimize biofouling). Three signals were used for event detection which was in line with similar previous studies as detailed later in Table 16. Samples were taken every 15 minutes to monitor changes in these parameters over the study period. There was no permanent infrastructure associated with these temporary monitoring stations with power provided via internal batteries in the sondes. The sondes were initially deployed for a short, non-continuous test period from Nov 2022 to Jul 2023 for training the CANARY software (Table 12). The purpose of the initial deployment was to assess the suitability of the deployment methods and locations. The sondes were deployed in November 2022 as the highest levels of rainfall occur in December and January for most areas in Ireland [460]. Analysis of climate long term averages show that annual average rainfall in Ireland has increased from 1961-1990 and 1991-2020, with the greatest increases of 6-12% occurring in the west and north of Ireland [461].

Table 12: Training data sets for initial CANARY configuration at the study sites

Configuration Variables and Parameters	River Unshin Dataset	River Owenmore Dataset
Matrix	Surface water (river)	Surface water (river)
Data Range (not continuous)	26/11/2022 to 07/07/2023	26/11/2022 to 21/07/2023
Monitoring location coordinates	54.175332, -8.462728	54.144790, -8.551777
Number of Sensor Signals tested	3	3
Monitoring Frequency (min)	15	15
No. of timesteps per dataset	15,860	17,040

The method of deployment differed between the sites, with the sonde for the Owenmore River housed in a purpose-built steel frame, deployed mid width on the bed of the river (Section 2.11.1) and for the Unshin deployed on the side of a privately owned recreational pontoon floating in the river (Section 2.11.2).

3.3.4 Sonde Water Quality Data

The data collected by each YSI sonde was stored on an internal sonde memory as a .txt file and downloaded by the operator to a laptop at regular intervals via EcoWatch Lite v1.0.5.15 software (YSI Inc., Ohio, USA). The interval between measurements was set to 15 minutes. The .txt files were imported to R as per the workflow for water quality data processing for event detection. Prior to deployment, the sensors were allowed to run in water to check sensor operation and any 'Start/Stop', or 'Out of the Water' edits were made after the data was imported into R. This ensures transparency in data manipulation and the rationale for each manipulation is recorded in the code thereby improving reproducibility [462].

3.3.5 Event Detection

Hydrological event detection is a critical component of water resource management, flood forecasting, and environmental monitoring [463,464]. Land use along with catchment and climatic characteristics are strongly related to trends in water quality [465] with the analysis of time series data

revealing underlying patterns, trends and anomalies [466–468]. In this study, water quality event detection was carried out using data collected by the sondes and the use of US EPA CANARY event detection software.

3.3.6 Data Management, data stewardship and reproducible research.

The workflow presented for event detection is a nine-step process as outlined in Figure 37. Each step in the workflow is comprehensively detailed in Appendix A.

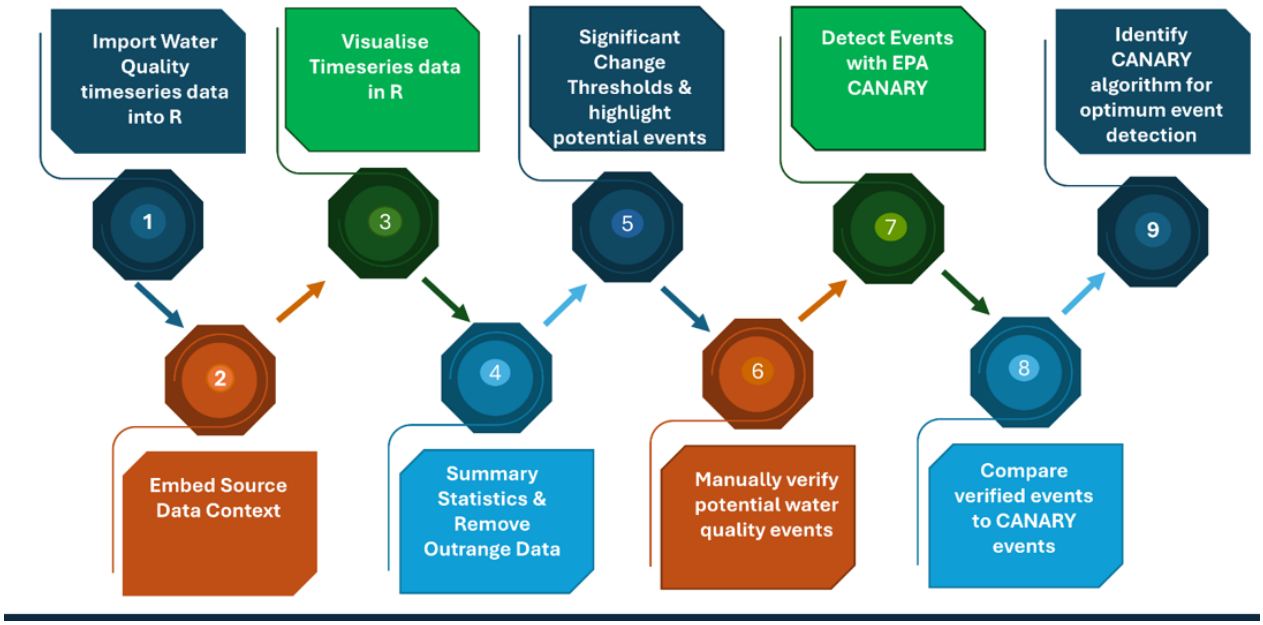


Figure 37: Protocol for data visualisation and training of the CANARY event detection system at individual water quality monitoring stations.

To minimise the issues associated with non-reproducible code, the workflow incorporated best practice in:

- Data management: processing of the data in R Studio v2024.04.2+764 [362] was done in accordance with the model of Import, Tidy, a loop of Transform, Visualize, and Model, followed by Communicate [469].
- Data Stewardship: the source context of the data was embedded in the data imported to R using variable labels to ensure the integrity of the data persisted once imported [470].
- Reproducible research: creating fully computationally reproducible research requires a workflow that manages the primary causes of non-reproducibility, and to this aim the method

described in this research incorporated the four pillars of reproducibility; version control, dynamic document generation, dependency tracking and software management [471].

3.3.6.1 Data Management

The data management model applied was a systematic approach to data analysis and informed Steps 1 to 4 of the workflow. Water quality data (Table 13) was imported (into R), tidied (each column is a variable and each row an observation), transformed (remove out of water data and out of sensor range data) and visualised prior to event detection [469]. These steps included presenting a concise overview of the datasets in summary statistics tables, removing 'out of the water' data when the sonde was operating prior to deployment and removing 'out-range' data where values measured were outside the sensor range. The results of analysis on a data file alongside the relevant code were recorded using R markdown, and presented alongside a detailed user guide published on Github in Appendix A [472].

Table 13: Data parameters and monitoring frequency imported for visualisation and event detection.

River	**Site Name**	**Turbidity (NTU) [YSI 6136] Frequency [A]**	**Temperature (° C) [YSI 6560] Frequency[A]**	**Specific conductivity (µS/cm) [YSI 6560] Frequency[A]**
Unshin	Upstream of Ballygrania	15 min	15 min	15 min
Owenmore (Sligo)	Ballynacarrow	15 min	15 min	15 min

[A] Source: Data from deployed YSI 6600 sondes.

3.3.6.2 Data Stewardship

One of the challenges with increasing numbers of large datasets and the secondary use of data is data stewardship [473]. To preserve the integrity of data collected these types of studies, Step 2 of the workflow included embedding the source data context via variable labels in R studio [470] detailing the location and sensor details for water quality monitoring.

3.3.6.3 Reproducible research

In water research, errors in computer code and the inability to reproduce analysis despite the code and the dataset being published, is common [449,474] with most errors being preventable if good coding practices were employed [450]. To minimize issues with non-reproducibility, the workflow in this research followed recommendations for research reproducibility using code [449,450,462] and a detailed user guide consisting of code alongside the output of analysis was developed. The four key components employed for reproducible software including R [471] incorporated in this workflow included:

- Git – for version control (git and RStudio were integrated via GitHub).
- renv – for managing R package dependencies.
- Docker – to manage the software environment.
- R markdown - for dynamic document generation.

An additional step of using an R project file, which places all project files in a single directory, [475] and a standard folder management structure, consisting of 'Data', 'Scripts' and 'Output_Files' directories was also employed for each step in R studio.

3.3.7 Significant change thresholds using R and the manual verification of potential water quality events.

There are inherent challenges associated with high frequency water quality data including biofouling, calibration errors, spikes and sensor drift with anomalies or outliers associated with water quality events requiring validation to confirm true anomalies and minimise false positives [476]. Semi-automated validation approaches serve as a bridge between fully automated detection systems and manual expert analysis, aiming to improve the accuracy and reliability of event identification with methods often involving initial automated screening followed by manual verification [288,477,478]. Data collected from YSI sensors (YSI Inc., Ohio, USA) was processed in Rstudio [479] as per Steps 1 to 6 of the workflow. This facilitated visualisation of the turbidity, conductivity and temperature data with the identification of significant change thresholds for turbidity used to aid the manual verification of

potential water quality events. Significant change thresholds were identified using Tukey Fences test for outliers with outliers defined as greater than or equal to the upper bound of the calculated Tukey fence. The output of the significant change threshold (SCT) plot was exported as .csv files and timesteps where the turbidity value exceeded the SCT for turbidity assigned a value of 1 for true, or 0 for false.

Turbidity values obtained at the monitoring sites examined did not show a diurnal trend, and baseline levels for turbidity at both sites were low. Turbidity has been used to monitor fine sediment transport in rivers due to storms [480], as a proxy for suspended solids [481] and to detect metal transport in rivers [395]. Patterns of significant peaks in turbidity were observed in the datasets (Figure 38).

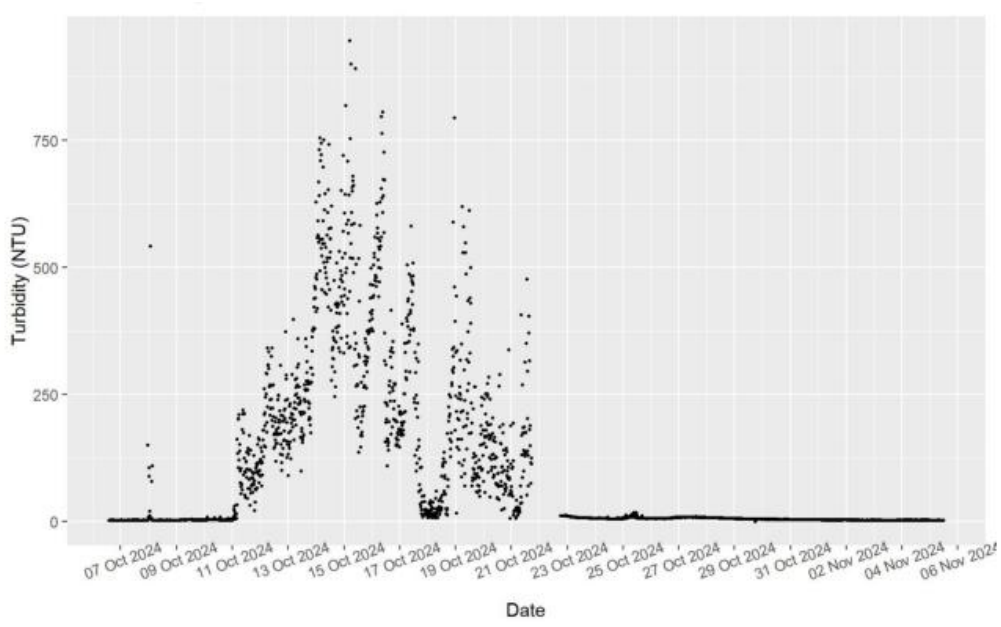


Figure 38: Sample of Data Visualisation for Turbidity

Similar to previous studies, the analyst then manually verified values that exceeded the SCT for turbidity by visually scanning the turbidity plots and editing the .csv file [288]. Values either side of the values exceeding the SCT may also be identified as potential events by the analyst by visual inspection.

3.3.8 Analysis by US EPA CANARY event detection software.

Event identification was carried out as per Step 7 in the workflow by processing 'training data' (Table 13) through the CANARY event detection system which uses algorithms to identify user defined 'outlier' datapoints in time series water quality data, whilst striving to minimize the detection of 'false alarms' [286]. CANARY adopts a two-stage approach when detecting events with the CANARY algorithms processing the water quality data at each time step. In the first stage, the future water quality value is predicted and in the second stage is it compared to the observed value. The residual is the difference between the predicted and the observed which determines whether the water quality value is expected or an outlier [286]. The linear prediction–correction filter (LPCF) algorithm, the most commonly used CANARY algorithm for predicting water quality anomalies [291] was used in CANARY to produce an alarm when at least one of the sensor signals deviated from the baseline for a required time period [288,367,368]. The binomial event discriminator (BED) setting, user defined settings in the LPCF algorithm optimised during the training of CANARY, determines how many outliers are required over a specified time period to qualify as an event [286]. When enough user defined outliers occur, an alarm is triggered, and CANARY identifies the water quality profile as a probable event [286].

Problems with turbidity measurements including random spikes have been well documented [482]. However, this BED feature of CANARY which filters out random spikes overcomes one of the most significant challenges with continuous monitoring, especially for turbidity, where short lived signal spikes, caused by air for example, may lead to false positives and are not indicative of a water quality event. The data files processed in CANARY and the output files for the CANARY event detection are available in the '07 EPA CANARY Event Detection' folder [472] and details for the CANARY output files are provided in Appendix C1.

3.3.9 Matching between manually verified events and CANARY identified events.

For Step 8 of the workflow, the approach used in previous research was used to match events and identify the most suitable CANARY algorithm for the data [288]. Matching events was carried out by manually verifying changes in the turbidity trend of the data. R code was used to automatically compare CANARY alarms to the manually identified events for each of the 96 algorithms used to train CANARY. Matches were classified as either a full match or a partial match. An Exact match is when the start and end timestamp for an event in CANARY matches the start and end timestamp of the manually identified event file. A Partial event match is where the start or end time of an event in CANARY overlaps with a manually identified event or vice versa. One of the challenges of applying the approach used in previous research is that the detail of the logic used for matching events was not published. The author was contacted for clarification and the logic for identifying full and partial matches between manually verified events and EPA CANARY identified events [483]. is provided in the Appendix D together with an example of the match logic applied to a dataset (Appendix E). One of the limitations of this approach is that manually verification by the analyst requires familiarity with screening time series datasets, it is labour intensive, can be difficult to replicate, and analysts may have difficulty in detecting subtle patterns and changes.

3.4 Results and Discussion

3.4.6 Identify CANARY Algorithm for optimum event detection.

The optimum CANARY algorithm for event detection, Step 9 of the workflow, was identified by comparing the number of potential water quality events identified by CANARY to the number of manually verified water quality events [288]. The Dat_Files directory contains each of the CANARY algorithm output files matched to the manually verified events file. An example of how matching can be verified by the user is included in 'Example of match logic applied to _Dat_For_OW061024_051124C_LPCF_BED6_ET0.89063alg_1' in Appendix E. The output file ‘algo scores’ summarises the number of full and partial matches for each CANARY algorithm and assigns a percent agreement to the total number of verified events. This can be used to identify the most

suitable algorithm for the particular monitoring station based on the data provided to 'train' CANARY. The algorithm with the highest percentage of matches is chosen as the algorithm with the most suitable parameters for detecting potential water quality events at that monitoring station. Adequate data points covering a range of events over a time period, is required to train CANARY and identify the most suitable algorithm. The optimum time period required depends on the frequency of events and the variability in event profiles at each monitoring station.

3.4.2 R Code Validation

The code written by the corresponding author (who is not formally trained in coding) was validated to identify code errors, to optimise code for efficiency and scalability, to maintain consistency in code across the workflow and to identify any potential issues. The code was initially written to process a single dataset at a time. Due to the large number of CANARY files to be matched, the code was amended to automate this processing which also involved standardising filename conventions and standardising file paths to directories. The code was edited to provide a more efficient approach to joining data frames and was also reviewed and edited for the use of R packages for functions that can be easily replicated using base R.

3.4.3 Method Validation

Results for the river Unshin and Owenmore data processed through the workflow are comparable with the results of previous studies [288,291,367]. CANARY generated alarms for all 47 of the manually identified events for the river Owenmore turbidity data i.e. 100% agreement and 38 of the 39 manually identified events i.e. 97% agreement for the river Unshin turbidity data, compared to 94% agreement in another surface water study [288]. There were no exact matches (i.e. identical start time and end time) between the CANARY events and the manually identified events, so all matches were partial matches. Different algorithm configurations for each of the Owenmore and Unshin monitoring stations were identified for optimum event identification at those sites. This is an advantage of the US EPA CANARY event detection software as locations in a river system often respond differently to

storm events [484]. The authors recognise the importance of validating these results using larger datasets and plan to undertake further research using expanded datasets and monitoring locations.

3.4.4 Availability of Code and Sample Data

The source code used for visualisation and data analysis is publicly available on GitHub [472] along with a README file describing how to reproduce the results. The repository contains data, an interactive R markdown file with code and results of analysis, so users can apply the workflow directly to their own datasets. The repository is structured as per the nine-step protocol for data visualization and training of the CANARY event detection system detailed in Figure 37 and detailed in the user guide. All materials are freely accessible under the MIT license.

3.5 Conclusion

The aim of this research was to develop a comprehensive, reproducible, practical, open-source workflow for high frequency water quality monitoring suitable for multiple users. This method describes all steps in the process detailing the use of R, R markdown and US EPA CANARY software for data import, data cleaning, data visualization, data integrity, along with site-specific CANARY event system configuration for the detection of potential water quality events. Application of this method to two, temporary, remote monitoring stations in a single catchment demonstrated the ability of US EPA CANARY to successfully identify 100% (n 47) and 97% (n 39) of the manually identified turbidity events. It is the first instance of a published water quality event detection method detailing every step from deployment, sensor calibration, validation, data analysis matched to rainfall and discharge/stream level.

High frequency water quality monitoring can provide timely data for real-time strategic adaptation, for the identification of significant water quality pressures and for the identification of appropriate water quality improvement measures in surface waters, but comprehensive, practical protocols such

as the method presented here are required to accelerate the adoption of high frequency water quality monitoring and realize its full potential.

3.6 Limitations

The method described is for hydrodynamic water quality event monitoring in small rivers and alternative deployment methods may be required in larger rivers or other waterbodies. Access to sensors for calibration, maintenance and recovery back to the laboratory following hydrodynamic events can be challenging due to flooding, high water levels and the lifting of pontoons from anchor points as occurred in this research. The processing of data for event detection as described in this method is the same regardless of the deployment method. The frequency of sensor maintenance and appropriate service interval is site and sensor specific and must be determined for each deployment. Characterisation of event length at individual river stations is required to optimise the event timeout parameter in configuring CANARY and the amount of data required to 'train' the CANARY system will depend on the profile of water quality events at each monitoring station.

Chapter 4: Tracking the Frequency and Intensity of Riverine Hydrodynamic Water Quality Events

4.1 Introduction

Building on the method established in Chapter 3, this chapter applies that event detection method at the two monitoring sites in this research study, focusing specifically on the identification of water quality events on these rivers. In doing so this chapter contributes to the overall objective of this thesis which aims to identify hydrodynamic driven water quality events in a high-status river located within a PA, and evaluate if short term, temporary deployments can adequately capture water quality variation over the range of river discharge. This chapter begins by Examining the ability of short-term deployments to adequately capture water quality variability, followed by analysing the data captured for water quality, rainfall and streamflow/stream level events and concludes with pairing of those events to understand the drivers of water quality events in both rivers.

Water bodies within PAs often require higher water quality than outside PAs and measures to protect them are part of the programme of measures to achieve the objectives of the WFD. Furthermore, under Article 8 of the WFD, specific monitoring programmes tailored to legislation under which the PA was designated must be implemented [11]. The overlap between areas designated to protect water dependent species (Figure 39 A) and high-status river waterbodies in Ireland (Figure 39 B) highlights the importance for effective monitoring of these waterbodies to support freshwater biodiversity restoration.

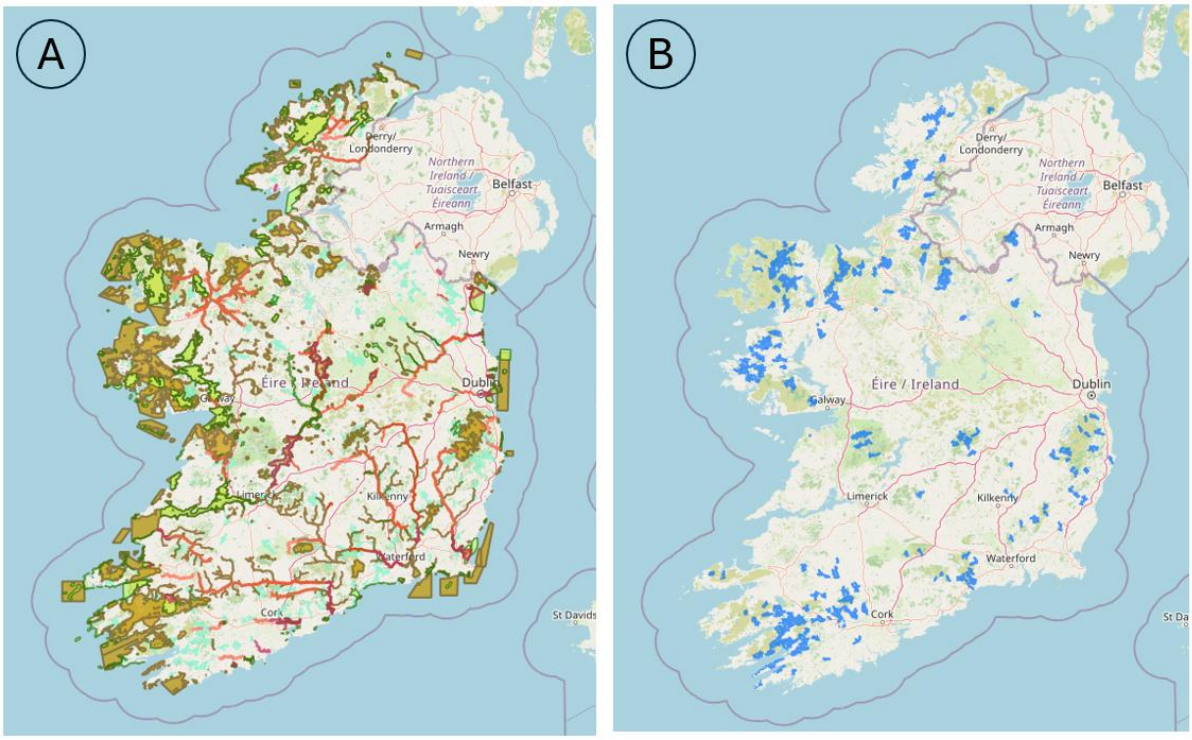


Figure 39: A - Water dependent protected areas in Ireland [Salmonid Rivers Regulations S.I. 293, Nutrient sensitive areas under Urban Wastewater Directive; SACs with water dependent habitats/species under Habitats Directive, SPAs with water dependent habitats/species under the Birds Directive, Drinking Water and Bathing Waters]. B – High WFD Status River Waterbodies 2019-2024 [485].

Despite considerable improvements to the legislative framework for protecting and restoring waterbodies in the EU over the past 35 years, there has been a very significant decline in the percentage of high ecological quality (macroinvertebrate) river sites in Ireland from 13.4% in the 1990s to just 1.1% in 2024 [16] (Figure 40).

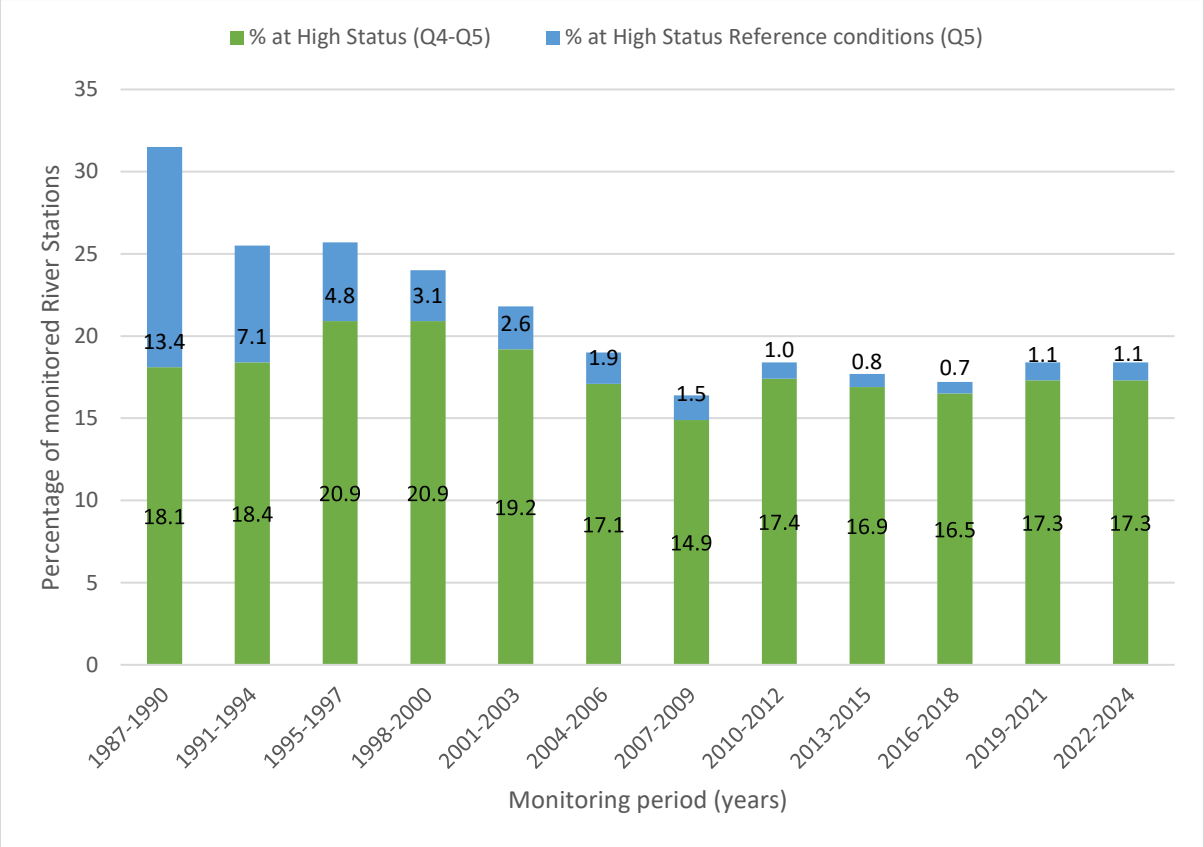


Figure 40: Change in the percentage of high ecological quality (macroinvertebrate) river sites in each survey period between 1987 and 2024 [16].

Notwithstanding a modest improvement from a low of 0.7% in 2018 to 1.1% in 2021, which corresponded to the implementation of the Blue Dot Catchment intervention programme in Ireland [486], the rate of recovery is very slow for Q5 sites, with the impacts of climate driven changes on freshwater species contributing to the halting of freshwater biodiversity recovery across Europe since the 2010s [13].

In Europe, there is greater monitoring of large urban rivers than of headwaters (first order streams) draining agricultural areas or semi-natural catchments [487]. Ireland's network of 84,800 km of river channel is dominated (75%) by first and second order streams [488] with high status waterbodies predominantly located in the upper reaches of catchments and are primarily composed of lower order streams [27]. In an increasing trend of rainfall events due to climate change [489] only a few Irish catchments have permanent, multi-parameter, HF monitoring stations [490]. This is mirrored globally,

with high frequency monitoring primary focused on individual rivers and catchments operated by research groups rather than integrated into routine water quality monitoring [281].

Critical source areas, those areas that contribute a disproportionately high amount of contaminants to a waterbody [491], often show episodic pollutant losses requiring high-frequency (HF) monitoring [492], which can resolve gaps in low-resolution programmes, especially during targeted times or rainfall events [493]. Diffuse agricultural pollution remains a major barrier to achieving "good status" [247] and detecting short-term changes under RBMP cycles requires increasing sampling frequency and investment [492]. HF or continuous in situ monitoring, characterises hydrological responses to diurnal cycles, and informs optimal sampling frequencies [444]. HF monitoring is also key for assessing climate-change impacts [272,494,495] and for robust water quality model calibration [496], particularly for estimating pollutant transport of suspended solids and phosphorus loads during rainfall events [270,497]. Winter precipitation and streamflow are projected to increase in the west of Ireland [489,498] under climate change, with HF monitoring particularly valuable to inform climate-driven projections in landscapes dominated by agriculture and high rainfall [272].

Irish hydrology is strongly influenced by fractured bedrock aquifers and multiple flow pathways [499]. Rapid pollutant mobilisation often precedes peak discharge [500], requiring differentiation between surface-water and groundwater-driven streamflow [499]. In agricultural catchments, quickflow, the rapidly responding runoff segment of the discharge curve [501] can contribute up to 50% of event-based phosphorus loads, despite comprising <10% of total flow [502] which emphasises the need to monitor and manage this pathway [502–504]. Baseflow separation is a standard process of separating a stream's total discharge hydrograph into baseflow (groundwater contribution) and quickflow (surface runoff) components and reveals the relative contributions of different water sources to streamflow. The Baseflow Index (BFI) is calculated as a ratio of total baseflow to total streamflow over a given period [505]. Reliable BFI estimation requires conceptual models of subsurface flow [506], and consideration of spatiotemporal variability [507], with aquifer class (the ability to store, transmit and yield groundwater)

influencing BFI values [499]. Integrated approaches to BFI estimation using hydrochemical and isotopic analysis [499,502] offer higher reliability but were beyond the scope of this study.

4.1.1 Aims and Objectives

The aim of this study was to examine if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters could adequately capture water quality variation over the range of river discharge at a hydrologically active period, and if such monitoring could track the frequency and intensity of hydrodynamic water quality events at the two river stations on the Owenmore and Unshin rivers. This aim was achieved by plotting water quality data on a flow duration curve for both high frequency and grab sample monitoring and by deploying and testing the remote, off-grid monitoring system detailed in Chapter 3 in a high-status river located within a protected area to determine if it could identify hydrodynamic driven water quality events.

4.2 Materials and Methods

4.2.1 Study Area

Following on from the baseline monitoring detailed in chapter 2 and based on the event detection method detailed in Chapter 3, two YSI 6600 sensors were deployed on Unshin River and the Owenmore River as per Section 2.11 in Chapter 2 to track the frequency and intensity of riverine hydrodynamic water quality events.

4.2.2 Data acquisition

4.2.2.1 Hydrometric Data

High frequency hydrometric data available (15-minute interval) from the Office of Public Works (OPW) from long-term water level recorders at gauging stations (Section 2.4.3) on both the River Unshin and the River Owenmore were used in this study.

4.2.2.2 Rainfall data

High frequency rainfall data (15-minute interval) from the Met Éireann national weather station at Markree which is located within the study catchment (Section 2.4.1.4) was used for this analysis.

4.2.2.2.1 Rainfall Anomaly Index

The rainfall anomaly index, RAI [508] was plotted for rainfall at Markree weather station to examine how the magnitude and severity of precipitation during the study period compared to the long-term average (May 2005 to May 2025) with positive RAI values indicating above average rainfall and negative values indicating below average rainfall.

4.2.2.3 Water Quality Data

Time series data used for this study was semi-continuous with a data interval of 15 minutes and extended from 01/10/2024 to 31/01/2025 which corresponded to the start of the hydrological new year [509], including the months of December and January when the highest levels of rainfall occur for most areas of Ireland [460].

Turbidity was used as the water quality indicator parameter in this research supported by temperature and specific conductivity and were measured using YSI 6600 EDS V2-2 sonde (YSI Inc, Ohio, USA). Increased levels of turbidity in rivers has been associated with rainfall intensity and surface runoff from adjacent agricultural land [283,510,511] and also because conductivity and turbidity show faster responses to changes in streamflow than other water quality parameters [512].

Details on the variables used for water quality event detection on the Owenmore and Unshin Rivers is detailed in Table 14.

.

Table 14: Information for variables used in event identification, event pairing and plotting.

Parameter	River Owenmore			River Unshin		
	Data Range	No. Missing Observations	Total # Observations for Study Period	Data Range	No. Missing Observations	Number of Observations
Turbidity (NTU) *	06/10/2024 to 24/01/2025	27.2 % (n = 3059)	11,233	05/10/2024 to 31/01/2025	19.1 % (n = 2143)	11,229
Specific Cond (µS/cm) *	06/10/2024 to 24/01/2025	27.2 % (n = 3059)	11,233	05/10/2024 to 31/01/2025	19.1% (n = 2143)	11,229
Temperature (°C) *	06/10/2024 to 24/01/2025	27.2 % (n = 3059)	11,233	05/10/2024 to 31/01/2025	19.1% (n = 2143)	11,229
Hourly Rainfall (mm) **	01/10/2024 to 31/01/2025	3.5% (n = 102)	2951	01/10/2024 to 31/01/2025	3.5% (n = 102)	2951
Daily Rainfall (mm) **	01/10/2024 to 31/01/2025	4.1 % (n= 5)	123	01/10/2024 to 31/01/2025	4.1 % (n= 5)	123
15 min Streamflow (cumec)	01/10/2024 to 31/01/2025	0.19% (n = 22)	11808	NA	NA	NA
Mean Daily discharge (cumec)	01/10/2024 to 31/01/2025	0	123	NA	NA	NA
Stream level[+] (m)	01/10/2024 to 31/01/2025	1.0% (n = 117)	11808	01/10/2024 to 31/01/2025	0.05% (n = 6)	11808

** Missing data due to sondes removed for service, calibration & maintenance. ** Markree weather station located within the study catchment was used for rainfall data for both rivers. [+] Stream level used for river Unshin as stream flow unavailable due to the poor stage-discharge relationship* [301].

4.2.3 Data Analysis and Software

Data collected from YSI sensors (YSI Inc., Ohio, USA) was processed in RStudio [479] which facilitated the visualisation of the water quality data, with the identification of significant change thresholds for turbidity used to aid the manual verification of potential water quality events. Event identification was carried out by processing the data through the CANARY event detection system which uses algorithms to identify user defined 'outlier' datapoints in time series water quality data, whilst striving to minimise the detection of 'false alarms' [363]. Detailed methodology for the processing of water quality

data in this study is detailed in Chapter 3 and summarised in Figure 41 and is based on the screening of 96 different configurations of the CANARY event detection algorithm in the offline-mode [288].

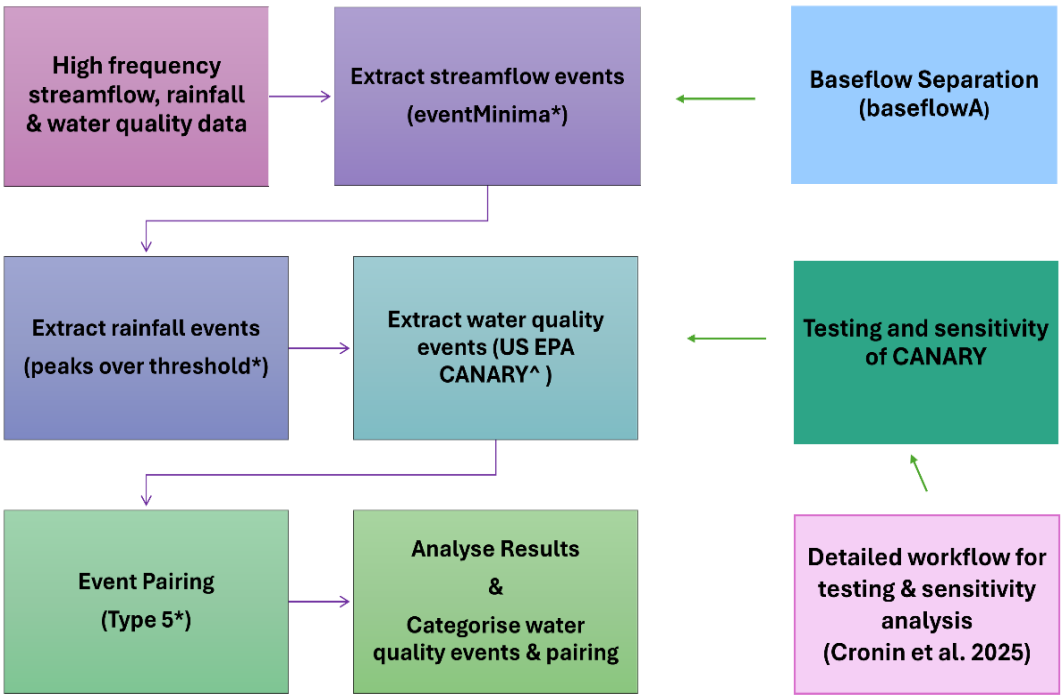


Figure 41: Workflow of the event detection method employed to identify hydrodynamic water quality events.

The method outlined in Chapter 3 was further refined in this study, with 120 different configurations of the CANARY algorithm tested and the sensitivity and precision determined to identify the optimum algorithm which maximised the $F1_{score}$ [513]. The 'hydroEvents' R package [300] was then used to identify hydrologic events, and to pair the rainfall, streamflow and water quality events.

4.2.4 Event Identification

Identification of water quality, streamflow and precipitation events was carried out to evaluate the ability of US EPA CANARY to identify possible water quality (WQ) events on these rivers, to compare those WQ events to streamflow and precipitation events, and to pair events from multiple time series.

4.3 Results and discussion

The aim of this study was to examine if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters could adequately capture water quality variation over the range of river discharge at a hydrologically active period with the results positively confirming the value of

such monitoring. Further investigations assessed whether the same short-term, high-frequency (HF) monitoring approach could identify hydrodynamic events as a key driver of water quality (WQ) changes over a four-month hydrologically active period. Results showed that 80% of WQ events in the Owenmore River and 90% in the Unshin River were associated with rainfall and streamflow events.

4.3.1 Characterisation of the Study Sites

Land use within the catchment was predominantly characterised by low-intensity livestock agriculture, with urban development limited to small towns and villages. Land use in the catchment aligns well with water quality pressures identified in the desktop assessment (Section 2.4.1.7). Both monitoring locations were situated in areas classified as locally and regionally important aquifers. Groundwater vulnerability in these areas was generally low to moderate, with some localised zones of higher vulnerability [485].

4.3.2 Examining if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters can adequately capture water quality variation over the range of river discharge at a hydrologically active period.

This analysis was carried out to address objective 3 of this thesis to examine if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters could adequately capture water quality variation over the range of river discharge at a hydrologically active period. Flow duration curves are one of the primary methods used to summarise a rivers hydrological characteristics [514], and plots the relationship between the streamflow magnitude and the percentage of time a flow is equalled or exceeded over a defined time period for a particular stream gauge [515]. A flow duration curve (FDC) constructed with streamflow data from May 2005 to May 2025 for the Owenmore River using the R package '*hydroTSM*' [516] and combined with water quality data, was plotted to examine if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters could adequately capture water quality variation over the range of river discharge

at a hydrologically active period. High frequency (15-minute interval) semi-continuous specific conductivity data measured from 06/10/2024 to 24/01/2024 was overlaid on this FDC for high frequency discharge data (15 min interval) on the river Owenmore at Ballynacarrow (Figure 42 A). Specific conductivity was used for comparing HF and grab sampling as turbidity is not monitored under the national river monitoring programme. The high frequency data was plotted with the mean daily discharge data as a cumulative frequency curve on the River Owenmore at Ballynacarrow from 1955 to 2025 and overlaid with quarterly grab sample specific conductivity data (n = 67) from the EPAs national river monitoring programme between 2007 to 2025 (Figure 42 B). The national river monitoring programme caried out by the Environmental Protection Agency focuses on the main river channels with quarterly grab samples for chemical analysis used to inform water quality status, and to monitor the effectiveness of measures implemented under the river basin management plans [517]. This analysis could not be carried out on the River Unshin due to a lack of streamflow data.

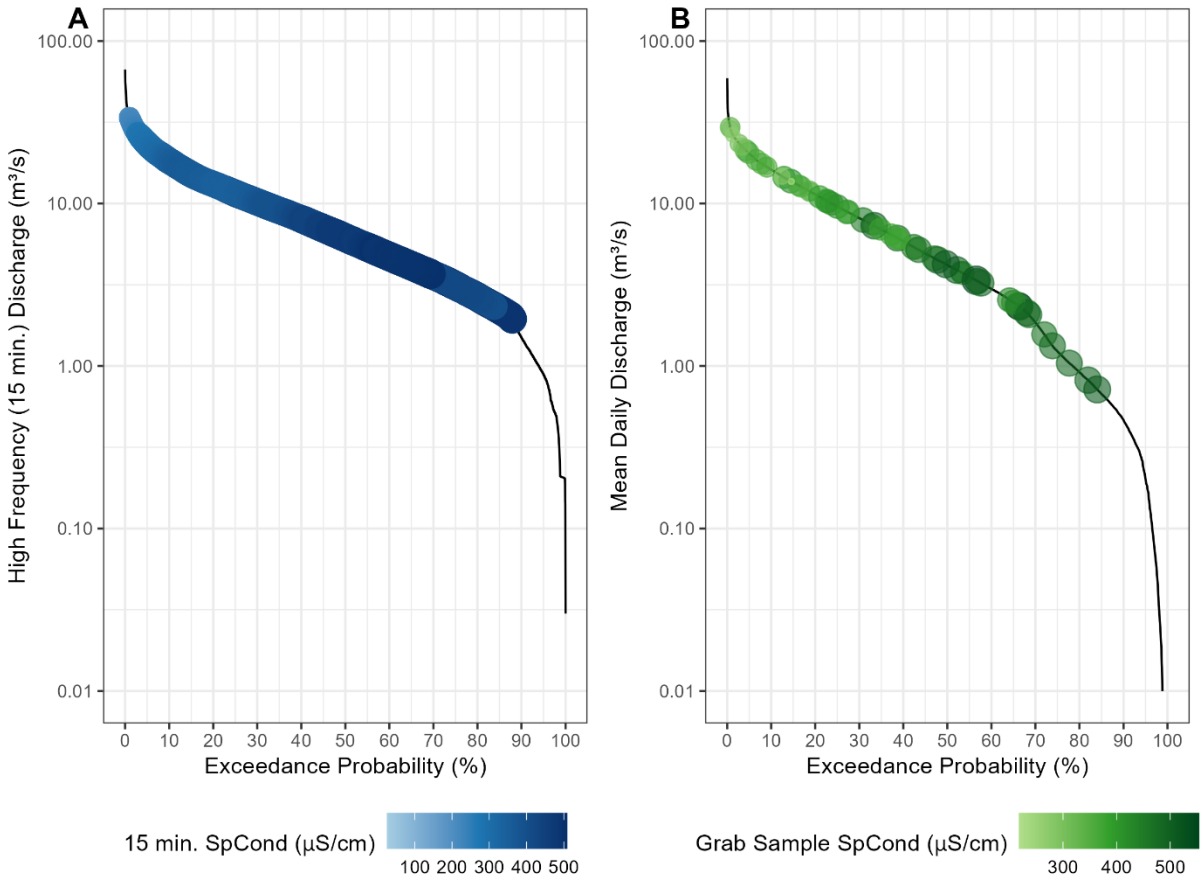


Figure 42: A -Flow duration curve (FDC) generated from high frequency discharge data on River Owenmore at Ballynacarrow [338] from May 2005 to May 2025 overlaid with semi-continuous specific conductivity data (blue dots) measured from 01/10/2024 to 31/01/2025 with a data interval of 15 minutes and B - Flow duration curve (FDC)generated from mean daily discharge data on River Owenmore at Ballynacarrow from 1955 to 2025 [338] overlaid with quarterly grab sample specific conductivity data 2007 to 2025 (green dot representing a daily sample) from the national river monitoring programme[518].

The plots highlight that the short deployment period compared well to the grab sampling for this parameter and was adequate to capture most flow conditions and associated water quality on the river Owenmore at Ballynacarrow from moderate flows to the high flow events. The flow duration curve highlights that flows are sustained at low flows (flows exceeded 90% of the time), which indicates a persistent baseflow which maintains river levels with a steady, reliable discharge of groundwater. This aligns with the groundwater classification for this area as locally and regionally important aquifers. The high frequency semi-continuous monitoring over a four-month period

captured a broader range of specific conductivity values at the lower range with the quarterly grab samples over the eighteen-year period capturing more high range values. Both curves show lower specific conductivity data predominating at higher flows consistent with a dilution effect. The short deployment period for the high-frequency monitoring did not capture low flow conditions (Figure 42), but this was expected as the aim was to monitor during a hydrologically active period with deployment during the autumn and winter when rainfall is typically highest. However, high flow conditions at this monitoring station were well represented over the short deployment period. These findings supports previous research on the value of high frequency monitoring [270,519] and demonstrates that even short periods of semicontinuous water quality monitoring on this river can provide as much insight into the variability of the water quality parameter measured over the range of river discharge at a hydrologically active period, compared to quarterly measurements conducted over decades.

4.3.3 Characterisation of Streamflow on the River Owenmore and Stream Level on the River Unshin over the Study Period

Over the study period, there were four streamflow peaks on the Owenmore River at Ballynacarrow (station 35001) significantly above the 70th percentile (P70) defined as 'above normal' flow [324]. Percentiles were calculated from the flow and level records from 2005 to 2025. Two of these streamflow peaks were above P90 and P95 which are 'particularly high' flows with peaks in streamflow corresponding with peaks in rainfall (Figure 43). Streamflow data is not available for the Unshin river due to the poor stage-discharge relationship between level and flow at hydrometric station 35003 Ballygrania [301] so in the absence of any other automated hydrometric station on this river, stream level at this site level was examined. The River Unshin is restricted from entering the larger flow of the River Owenmore at the confluence which causes attenuation at Ballygrania during periods of high flow. This attenuation causes a slowdown in the flow of the Unshin, flooding of the floodplain at Ballygrania and rapid settlement of solids and turbidity. Therefore, values measured at the hydrometric station do not always representing the true turbidity and suspended sediment values in the river channel, which is why the water quality monitoring station was located upstream of the hydrometric station.

For the time period of interest, there were four peaks in stream level in the River Unshin greater than the 70th percentile. Censoring of the data at the upper values due to flooding below the hydrometric station results in underestimating the 70th percentile as the data lacks the true variation at the higher values. At the 90th percentile (P90) there were 4 stream level peaks above this threshold with two of these stream level peaks above P95 which are classified as 'particularly high' levels [324]. Peaks in stream level ≥ P90 on the Unshin corresponded with peaks in rainfall and also corresponded with peaks in streamflow ≥P70 on the Owenmore River (Figure 43).

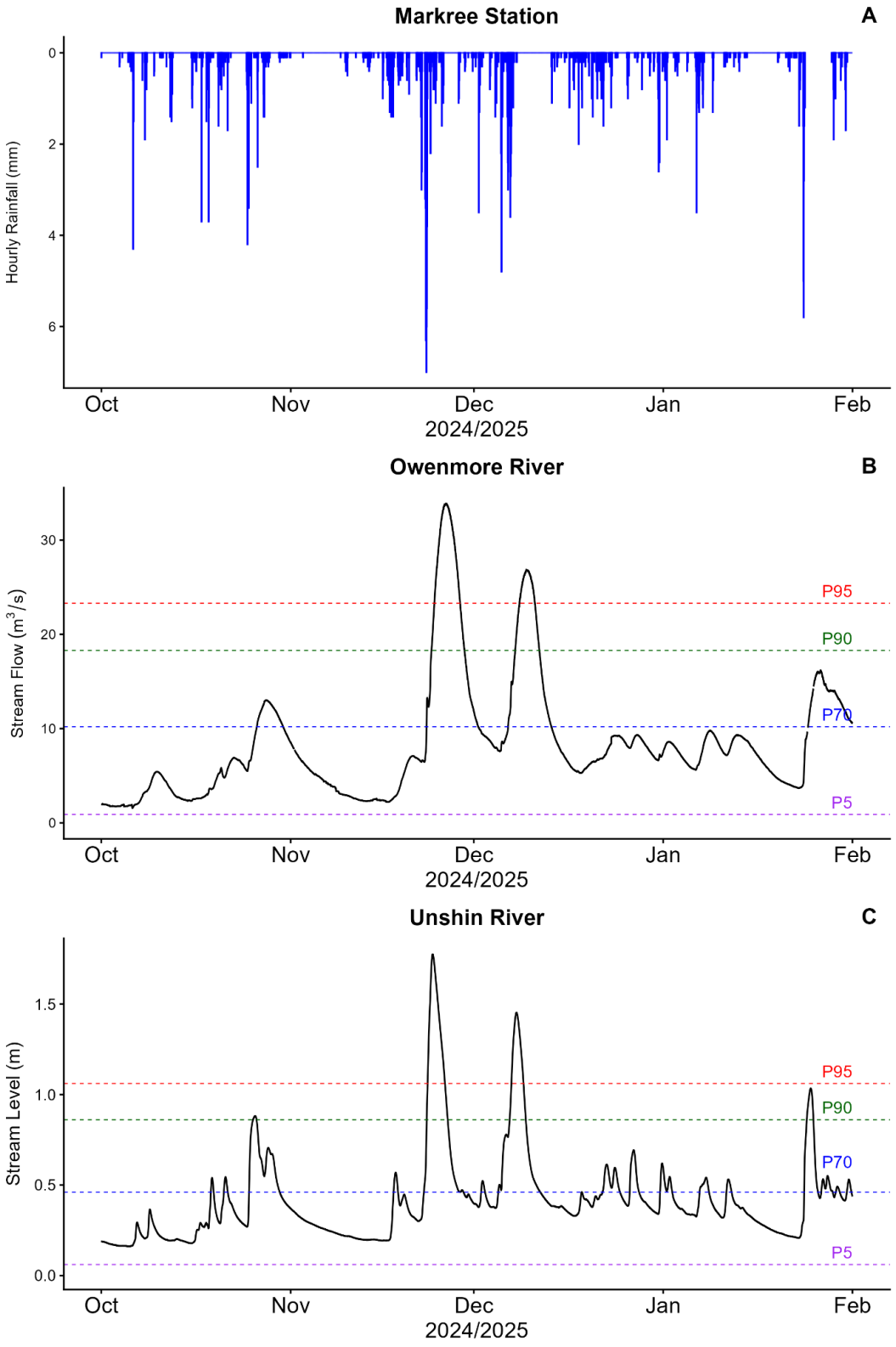


Figure 43: A - Hyetograph at Markree Weather Station, B - Hydrograph at hydrometric station 35001 on the Owenmore River at Ballynacarrow and C - Stream Level at hydrometric station 35003 on the Unshin River at Ballygrania, from 01/10/2024 to 31/01/2025 overlaid with percentiles where streamflow/level was equalled or exceeded for 95%, 30%, 10% and 5% of the time over the study period.

4.3.4 Event Monitoring on the Owenmore and Unshin Rivers

4.3.4.1 Streamflow and Stream level Events

The hydroEvents package [300] provided functions for detecting and analysing hydrological events in the flow data. The baseflow component is the sustained groundwater contribution to the streamflow and can be distinguished from quick surface runoff or 'quickflow' with a baseflow separation algorithm applied to the streamflow data to estimate the baseflow component [370].

4.3.4.1.1 Identifying Streamflow Events

Following baseflow separation, four different event detection functions in the hydroEvents package were employed to identify streamflow events on the Owenmore River; detected peaks (maxima) via '*eventMaxima'*, detected troughs (minima) via '*eventMinima*', detected high flow events via peak over threshold '*eventPOT*', and baseflow dominated periods via '*eventBaseflow*' to extract events in the streamflow data which provided insights into the flow regime and event characteristics.

4.3.4.1.1.1 Baseflow Separation

Baseflow cannot be measured directly so two different algorithms, baseflowA and baseflowB were tested for separating baseflow, the portion of streamflow sustained between rain events, fed by groundwater. The method employs a filter parameter α, which controls the sensitivity of the separation, and is a measure of baseflow recession. In the present work, α was varied for α 0.925, α 0.950 and α 0.980 for both BaseflowA and BaseflowB algorithms with lower values of α retaining a greater proportion of the flow as baseflow [300].

Sensitivity analysis, to verify baseflow periods was carried out by testing different values for alpha, the filter parameter (Figure 45) combined with a visual assessment and validation of specific conductivity data (Figure 44) by overlaying high frequency discharge data in blue on high frequency specific conductivity data in red from November 2023 to April 2025.

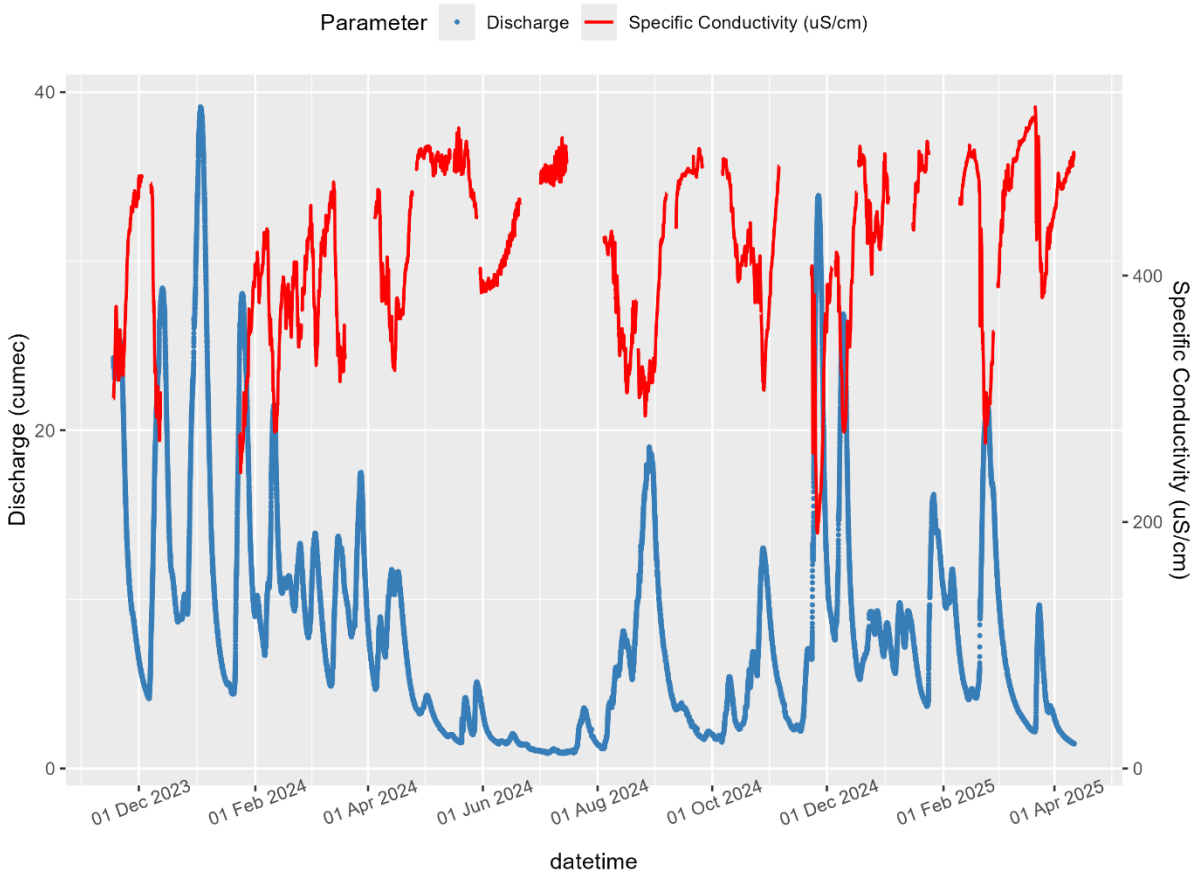


Figure 44: High frequency streamflow data from Nov 23 to Apr 25 at hydrometric station 35001 Ballynacarrow on the Owenmore River for the study period with the high frequency specific conductivity data overlaid where available.

Daily flow data is commonly used for baseflow separation as it reduces data noise, matches standard regional water models [520,520] and requires much less computing power than high frequency data. Baseflow typically has higher and more stable conductivity compared to quickflow which exhibits lower or more variable conductivity. While the various baseflow separation algorithms all converged at the lowest flows over the period, the specific conductivity shows a mixed pattern with high specific conductivity values at low flow periods but also high conductivity values at elevated flows indicating mixed sources of dissolved solids which may include point source pollutants (Figure 44).Variations in specific conductivity can reflect varying contributions of groundwater, interflow, bank return waters and soil water [407]with stormwater transporting substantial dissolved ion loads accumulated in soils and land surface leading to elevated specific conductivity during storm events [521]. The high frequency conductivity data was used to evaluate the suitability of different α values for the recursive digital

filter baseflow separation. Periods of elevated baseflow typically correspond with higher specific conductivity data. This analysis pointed to the algorithm and filter parameter (α) of BFI A at α 0.980 with this value for α being selected by identifying baseflow separation that most closely aligned to groundwater dominated flow conditions [407]. While the applications of an integrated approach to determining BFI values is required to establish reliable BFI value [499,502], it was outside the scope of this research and BFI A at α 0.980 was used for streamflow event extraction.

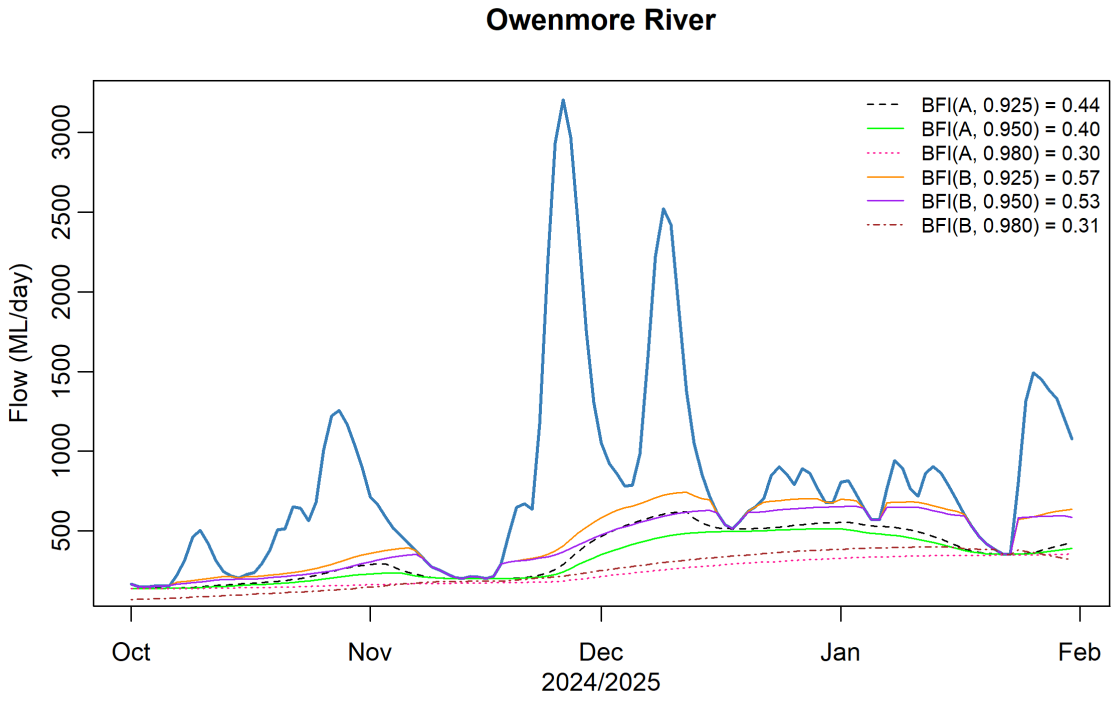


Figure 45: Different baseflow filtering for streamflow data on River Owenmore at Ballynacarrow from 01/10/2024 to 31/01/2025. Streamflow is shown in solid blue with the different baseflow filters shown in the other colours, including BFI A at α 0.980 in red dashed line. and BFI A at α 0.950 in green dashed line.

3.4.4 Extraction of Streamflow Events

Following baseflow separation (BFI A at α 0.980), four different event detection functions [300] were employed to identify streamflow events on the Owenmore River. Over the study period, four flow

events were detected using eventPoT, four events using *eventMaxima*, five flow events were detected using *eventBaseflow* with 6 flow events detected using *eventMinima* with *eventMinima* used for subsequent pairing of events. The original flow data was overlaid with events highlighted for each event detection function (Figure 46).

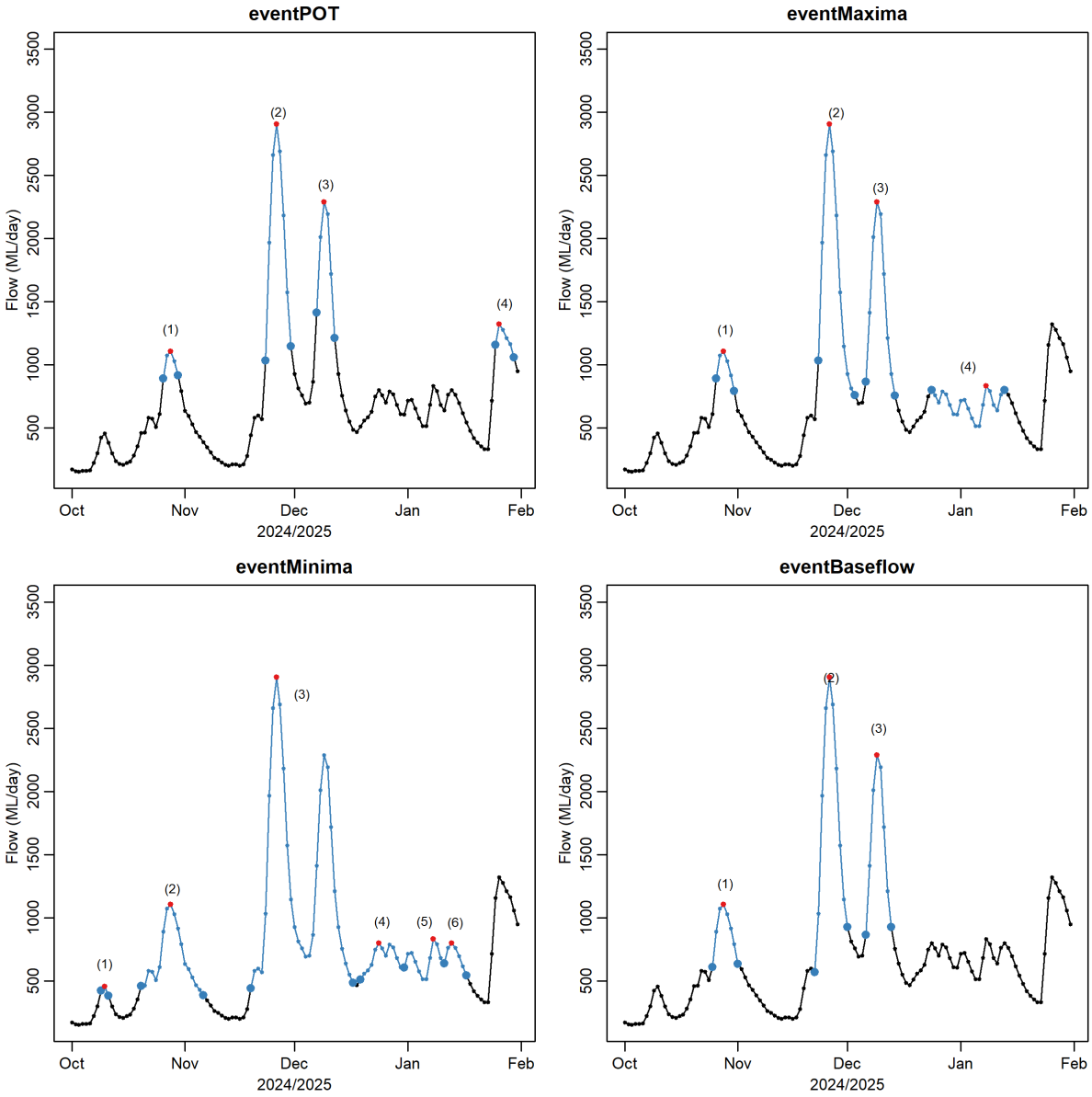


Figure 46: Event extraction following baseflowA separation (α 0.980, passes (no. of times the digital filter is applied) = 3) by applying the event detection functions: peak over threshold, maxima, minima and the proportion of baseflow using hydroEvents package [522] on the River Owenmore streamflow data at Ballynacarrow from 01/10/2024 to 31/01/2025.

The characteristics of the hydrograph data at this station (May 2005 to May 2025) were analysed to determine appropriate detection parameters tailored to the data's natural variability. Potential events were identified based on event separation employing delta.y and delta.x with a threshold then applied as a filter. For parameter delta.y, the minimum allowable difference in value between a peak and its neighbouring trough or valley typical event amplitudes were captured for this streamflow timeseries, via the median of peak to trough rises for periods of streamflow greater than the 70th percentile. For delta.x, the minimum time steps between adjacent peaks to consider them as separate events, a minimum separation between events was set by measuring the time differences between peaks for this streamflow timeseries and selecting the lower quartile as a typical minimum separation. The 70th percentile of streamflow is defined as above normal for streamflow [324] so the threshold, the minimum value that the data must exceed, was set at the 70th percentile of quick flow.

4.3.4.1.2 Stream Level Events

4.3.4.1.2.1 Identifying Stream level Events

A 'peak over threshold' approach was used to identify stream level events on the river Unshin at Ballygrania hydrometric station due to the lack of associated streamflow data because of the poor stage-discharge relationship [301]. While periods of stream level above the 70th percentile are defined as 'above normal' for streamflow [324], the water attenuation downstream of the gauging station on the River Unshin during periods of high flow impacts peaks discharge. This results in a reduction in the magnitude of the maximum discharge, delays in peak flows and broadening of the hydrograph. Therefore the 70th percentile of the daily water level record calculated on the Unshin is likely to be an underestimate of the actual water level equalled or exceeded 70% of the time.

4.3.4.1.2.2 Extraction of Stream Level Events

To facilitate comparison between the sites, stream level events were also identified on the River Owenmore (Figure 47) and compared to streamflow events identified on the River Unshin. Due to censoring of the data at the upper values because of flooding below the hydrometric station and the resultant underestimation of the 70th percentile on the River Unshin, stream level events ≥ the 90th

percentile (for level data from 08/05/2005 to 07/05/2025) with minimum separation time of 1 day were examined to identify medium to high level events on the Unshin. Four stream level events were identified on the River Unshin, and three stream level events were identified on the River Owenmore greater than or equal to the 90th percentile over the study period.

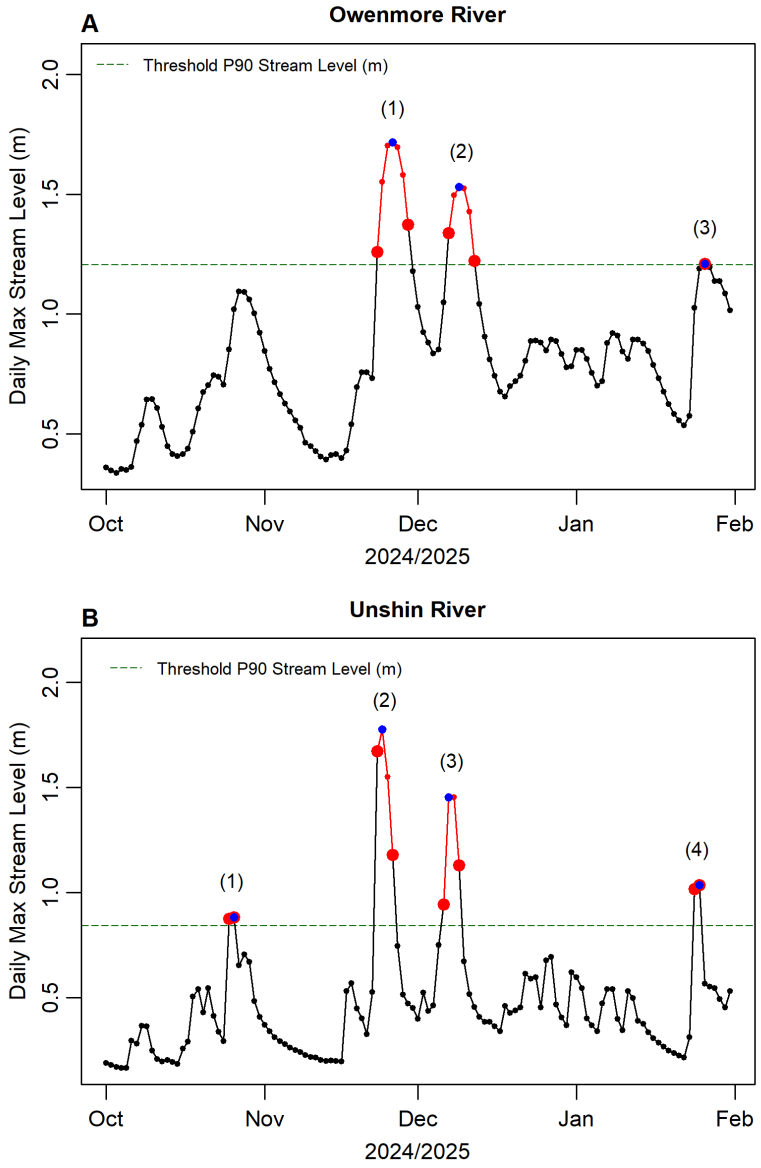


Figure 47: A -Extracted stream level events for the Owenmore River at Ballynacarrow ≥ threshold of the 90th percentile stream level (May 2005-May 2025) with an inter-event time of 6 days and B. - Extracted stream level events for the Unshin river at Ballygrania ≥ than a threshold of the 90th percentile stream level (Aug 2007 – Aug 2025) with an inter-event time of 6 days, both over the study period 01/10/2024 to 31/01/2025.

4.3.4.2 Precipitation Events

The method implemented in hydroEvents package for identifying precipitation events was the 'peaks over threshold' approach with data over a defined threshold highlighted as events, with a user defined number of time steps between events [300]. Daily rainfall was used to identify precipitation events in this study with a threshold of 5 mm of rainfall and separation time of 1 day (1 timestep) of zero rainfall between events applied [523].

4.3.4.2.1 Characterisation of Rainfall over the Study Period

The climate in the study area is temperate oceanic with rainfall in the west of Ireland averaging between 1000 and 1400 mm [499]. Long term average annual rainfall at Markree weather station is 1212.1 mm with long term annual average air temperature of 9.2 ^{o}C [322]. River flow is heavily influenced by antecedent conditions so to contextualise the short-term rainfall and flow observations over the study period, a monthly rainfall anomaly index from May 2005 to May 2025 was plotted. There is significant variation in rainfall at Markree weather station, but the pattern of positive and negative RAI values is broadly similar to the long-term data series (Figure 48).

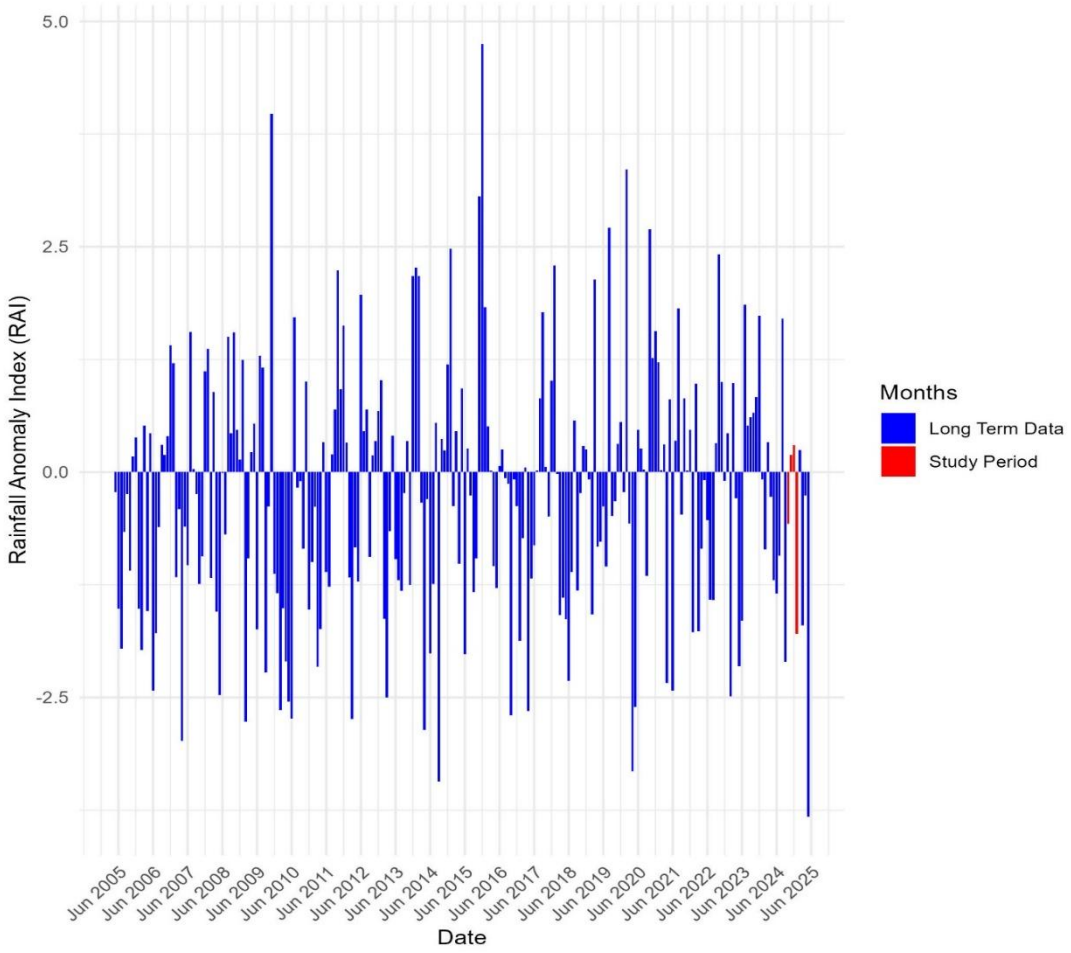


Figure 48: Monthly Rainfall Anomaly Index at Markree Weather Station from 8th May 2005 to 8th May 2025 with the study period November 2023 to April 2025 highlighted in red.

4.3.4.2.2 Extraction of Precipitation Events

There was a gap in the rainfall data from 24/01/2025 to the 29/01/2025 representing 3.3% of the daily data so the total rainfall for January 2025 is underestimated. The total rainfall over the 4-month study period was at least 359.4 mm, with a mean daily rainfall of 3 mm. For rainfall analysis, an event is often defined as rainfall greater than or equal to 1mm of rain with at least 1 timestep (in this case 1 day) between precipitation events for them to be defined as separate events [523]. Studies of long term extreme precipitation indices in Ireland have included counts of the number of days/annum when precipitation is ≥ 5mm (R5mm), ≥ 10mm (R10mm) and ≥ 20mm (R20mm) [498]. Over the study period, 79% of the 118 rainfall observations had rainfall >0 mm, with 49% of observations >1mm. Increasing trends in R5mm precipitation has been observed at stations in the north and northwest of Ireland [498]

so for this study the event extraction and pairing focused on the more significant 5mm and 10mm rainfall events (Figure 49).

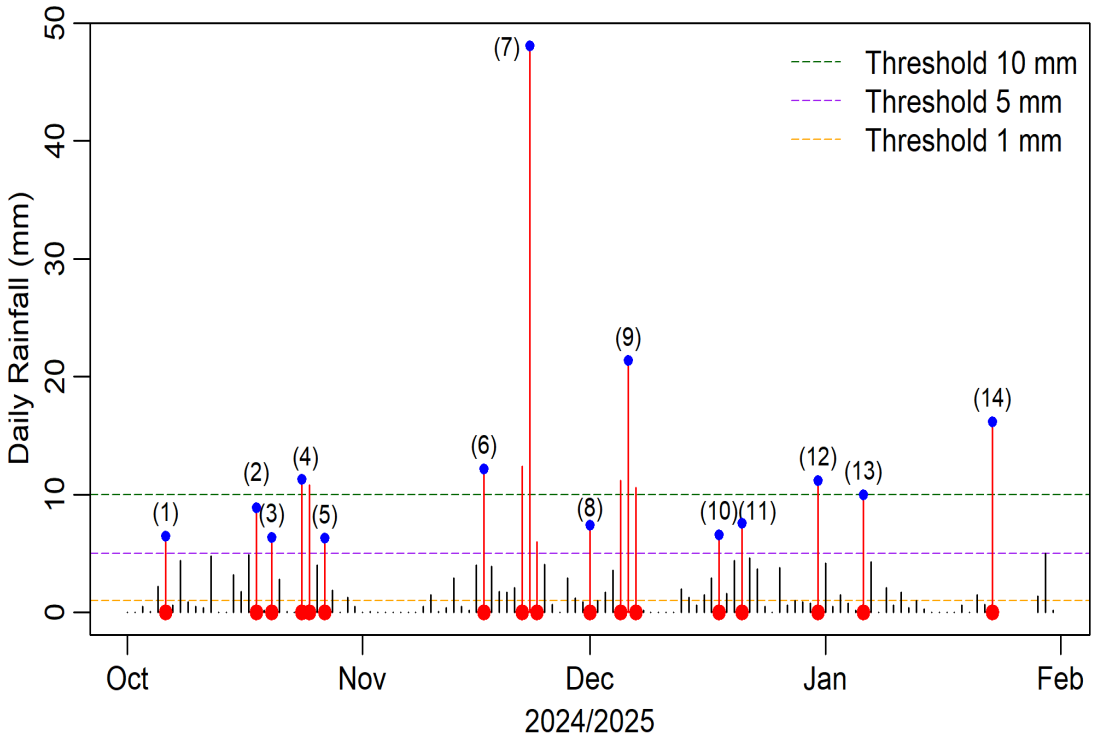


Figure 49: Extracted Rainfall events greater than a threshold of 5 mm of rain with an inter-event time (min.diff) of 1 timestep (day) for Markree weather station over the study period 01/10/2024 to 31/01/2025 with thresholds for 1 mm and 10 mm also highlighted.

There were only 2 events identified at ≥20 mm over the study period (Table 15).

Table 15: Rainfall Event Detection Parameters and Number of rainfall events identified for each event class.

Parameter	Precipitation Index	Event class	Event definition (mm rain)	Event separation	Number of Events
Rainfall (mm)	N/A	Wet day /light rain	> 1mm	>1 day	23
	R5mm *	Moderate rain	> 5mm	>1 day	14
	R10mm *	Very wet day /heavy rain	> 10mm	>1 day	6
	R20mm	Very heavy rain	>20mm	>1 day	2
	90th percentile ** (2005-2025)	Extreme	9.8mm	>1 day	7

*[498] **[323].

4.3.4.3 Water Quality Events

There were breaks in water quality data collection due to regular sensor maintenance and calibration, with a total of 8,174 observations on the Owenmore and 9086 observations on the Unshin between 01/10/2024 and 31/01/2025 [https://doi.org/10.5281/zenodo.19445108]. Frequently encountered problems with turbidity sensors are well documented including sensor fouling, drift, changes in other variables and random spikes due to lens obstruction [524] and the importance of reporting metadata for turbidity sensor manufacturer and model along with deployment arrangements has been highlighted [525]. The quality of sensor data is key to the effective performance of any event detection system [526] and details on sensor deployment, turbidity sensor metadata, sensor calibration and data validation contained in Chapter 2.

The CANARY event detection software [363] uses statistical and mathematical algorithms to identify user defined outlier datapoints in time series drinking water quality data, whilst minimising the number of 'false alarms' detected. Similar to the approach adopted for surface waters [288] the linear prediction coefficient filter (LPCF) algorithm was used for CANARY event detection in this research. Performance of the CANARY algorithm was measured by comparing CANARY-detected events to those manually verified as being real events, by inspection of the turbidity data. Further information on this approach

is described in previous work [527]. The performance metric used to determine the quality of event detection was the $F1_{score}$ as this allowed easy optimisation of both sensitivity (ability to detect water quality events) and precision (number of detected events which are real), at the same time. The water quality data, as described in Table 14 was visualised using ggplot2 [528] in R [362] and plotted with rainfall, streamflow and stream level

4.3.4.3.1 Testing and Sensitivity Analysis of the CANARY Model

The objective of the CANARY model testing and sensitivity analysis was to determine the configuration parameters that yield the most effective event detection for the specific monitoring site [365]. Building on the initial optimisation detailed in Chapter 3, turbidity data was used to manually validate detected events. Optimisation seeks to maximise true event detection while minimising false alarms [288], and is achieved by systematically refining CANARY's configuration settings. Accordingly, both sensitivity and precision were evaluated [513]. The overarching design principle guiding parameter selection is that genuine water quality events should not be missed. To facilitate the optimisation of both sensitivity and precision at the same time, the usual convention was followed by calculating their harmonic mean, the $F1_{score}$:

$$F1_{score} = 2 \times \frac{Sensitivity \times Precision}{Sensitivity + Precision}$$

The optimisation process involved finding the selection of CANARY parameters which maximised the $F1_{score}$.

The parameters are determined via testing water quality data [364] in the offline mode of CANARY with refinement of parameters conventionally carried out separately for each monitoring station [369]. The number of timesteps and time interval used for CANARY configuration and water quality event identification used in this study along with details for other studies are detailed in Table 16.

Table 16: Data sets for CANARY configuration in the literature.

Author	Matrix	Interval time (min)	Timeframe	No. of Days	No. of datasets	No. of timesteps/ Dataset*
This study	Surface Water	15	06/10/24 – 24/01/25 05/10/24 – 31/01/25	93 100	2	8,175^ 9,086^^
Burkhardt et al. [288]	Surface Water	15	09/05/14 – 31/03/16	692	2	66,432
Nafsin & Li [291]	Surface Water	10	June – July 2018 June – July 2019 June – July 2020	183	1	26,352
Leow et al. [367]	Reuse Water	0.5	N/A	114	1	328,320*
Kertesz et al. [368]	Urban Runoff	1	18/02/13 – 01/06/13	104	1	149,760*
Murray and Haxton [364]	Drinking Water	2	08/07 - 07/08	31	3	22,230
Murray and Haxton [364]	Drinking Water	2	01/03 – 09/04	39	2	28,082

^ River Owenmore. ^^ River Unshin. * Where not stated, calculated by multiplying days x interval.

The optimum CANARY algorithm configurations for the River Owenmore and the River Unshin over the study period differed (Table 17) highlighting the importance of site-specific configuration.

Table 17: Optimum EPA CANARY configuration parameters for stations on the river Owenmore and River Unshin for semi-continuous water quality data at 15-minute interval over the period 05/10/2024 to 31/01/2025.

River Station	BED^ window	History window	Outlier threshold	Event threshold	Event detection sensitivity	Precision	$F1_{score}$
Owenmore at Ballynacarrow	10	48	1.0	0.99903	1	0.32	0.48
Unshin upstream of Ballygrania	6	24	2.0	0.89063	1	0.43	0.60

^Binomial Event Discriminator

The higher $F1_{score}$ at the Unshin site indicates a better balance between capturing true positives and avoiding false positives but at both sites the CANARY algorithms had sensitivity of 1 where all 'real' water quality events were captured by CANARY.

4.3.4.3.2 Extraction of Water Quality Events

Extraction of water quality events was carried out by running the data through CANARY for the optimum CANARY configuration at that monitoring station. There were 20 potential water quality events identified on the river Owenmore over the study period with 13 of these events overlapping with the 7 manually verified turbidity events (Figure 50). The CANARY event detection system was originally designed for drinking water supplies and has an event timeout parameter which was set to 36 timesteps to resets the event alarm system, however, longer events that occur on river systems can therefore time out, resulting in multiple alarms for the same event. Further training and refinement of the CANARY algorithm with larger datasets could be carried out to examine if this performance could be improved.

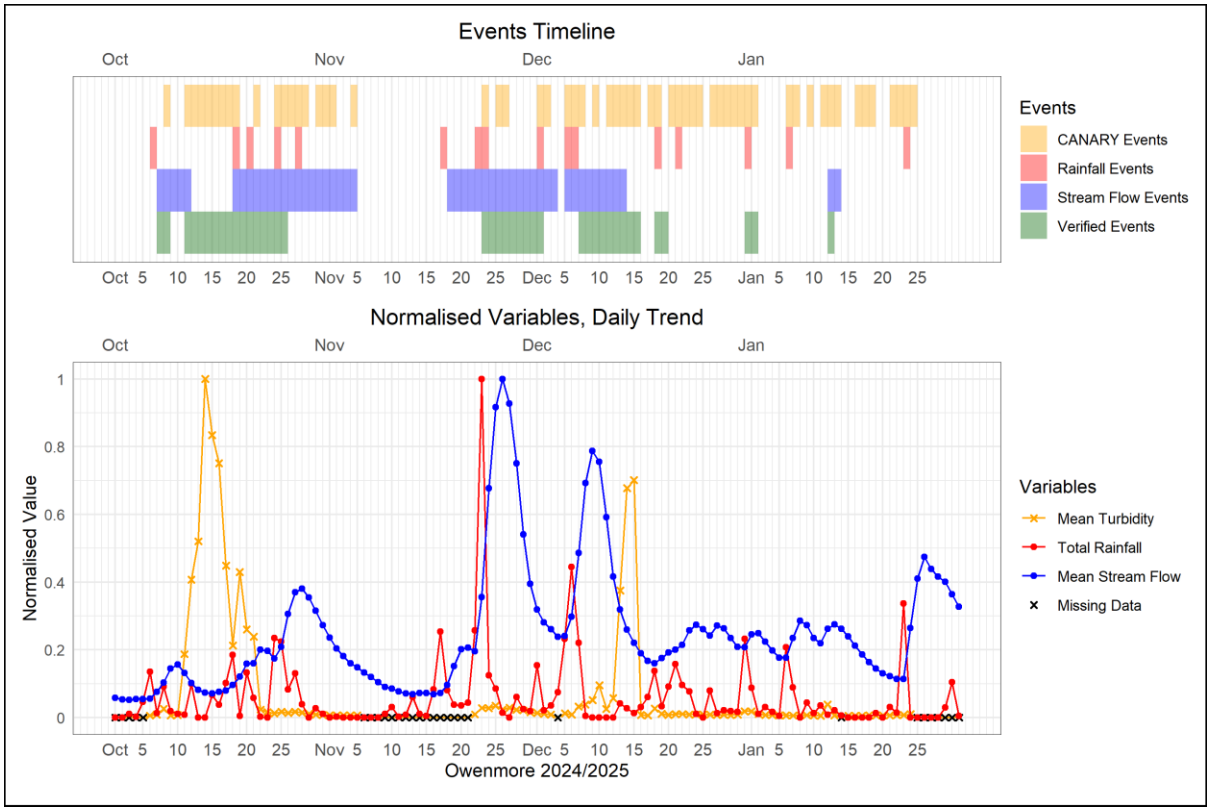


Figure 50: Performance of the CANARY system for identifying potential water quality events on the Owenmore River at Ballynacarrow over the study period 01/10/2024 to 31/01/2025, with baseflow separated (BFI A at α 0.980) daily streamflow events identified using eventMinima with a 30th percentile threshold of quickflow and 5mm rainfall events.

There were 17 potential water quality events identified on the river Unshin over the study period with 9 of these events overlapping with the 10 manually verified turbidity events (Figure 51) and one CANARY event overlapping two manually verified events.

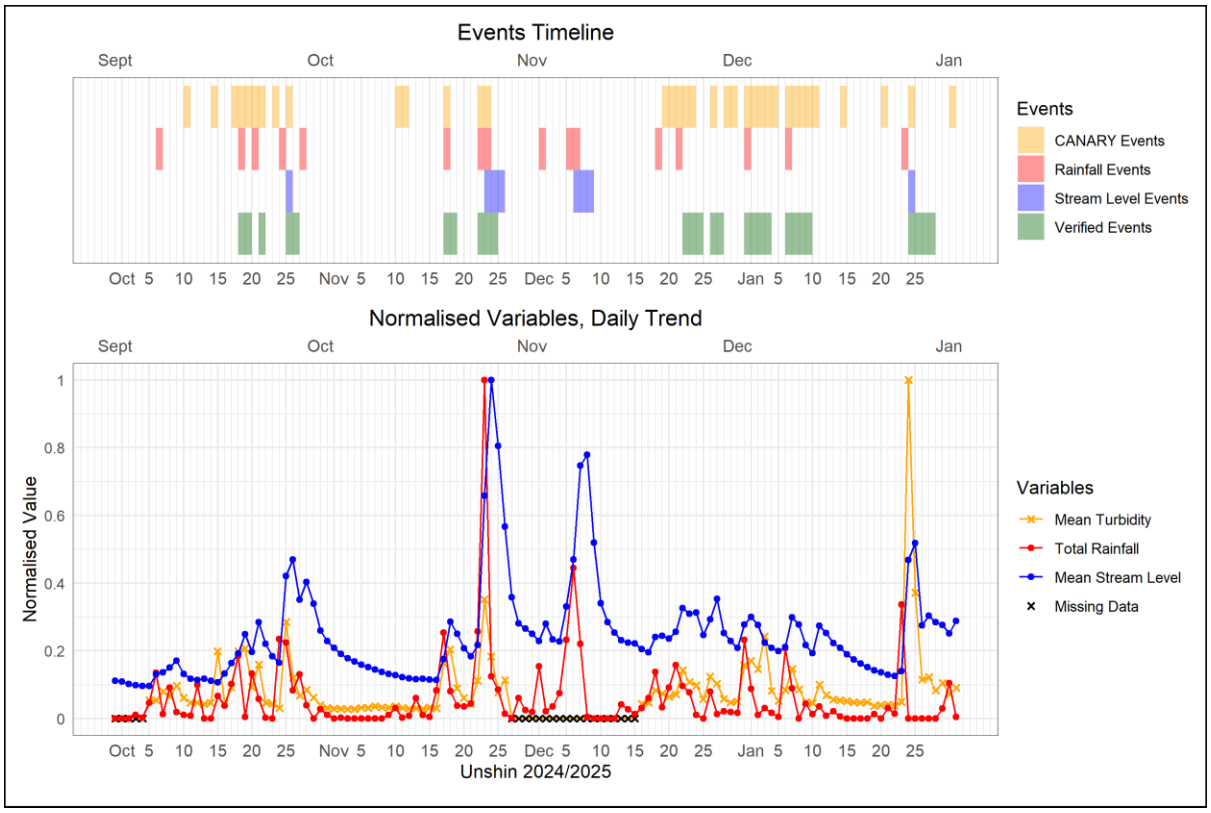


Figure 51: Performance of the CANARY system for identifying potential water quality events on the Unshin river upstream of Ballygrania over the study period 01/10/2024 to 31/01/2025 with daily stream level events identified using eventMaxima with a threshold of 90th percentile of streamflow and 5mm rainfall events.

Overall, there were a higher number of water quality events identified on the Owenmore River than on the Unshin (Table 18), with baseflow separation prior to identifying the streamflow events returning higher number of events (n=6) than without separation (n=4) as the inclusion of baseflow may mask smaller quickflow peaks.

Table 18: Event detection for 5mm Rainfall, Streamflow, Stream Level and Water Quality on the Owenmore and Unshin Rivers.

Parameter	Event Definition	Event ID Method [300]^ or US EPA CANARY ^^	Number of Events on Owenmore River	Number of Events on Unshin River
Rainfall	Rainfall events ≥ 5mm	eventPOT ^	14	14
Streamflow	Streamflow events - baseflow separated (BFI A at α 0.980) daily streamflow events (eventMinima) with a 30th percentile threshold of quickflow.	event Minima ^	6	N/A
Stream Level	Stream Level Events ≥ 90th percentile	eventPOT ^	3	4
Turbidity	Detected by US EPA CANARY	Details in Table 5 ^^	20	17

4.3.4.3.3 Pairing of Events, Rainfall to Streamflow/Stream level and CANARY events.

Event pairing between rainfall and streamflow is commonly used to understand and model catchment behaviour [300,529]. The streamflow response to rainfall is complex and varies with catchment characteristics and hydro-meteorological conditions [530] with event-based analysis helping to isolate responses to individual storms [531] and identify pollutant transfer pathways [293,532,533].

The event pairing algorithm requires a maximum lag to represent catchment response time with the lag time acting in the manner of a search window for the matching process. The lag between the rainfall threshold exceedance and the streamflow peak (Qp) was calculated from observed data over an extended time period (01/05/2023–30/04/2025), following the approach of previous work [504]. First, the data series was analysed to pinpoint occasions when >1mm of rainfall occurred following at least five consecutive dry days. For each of those occasions, the time difference between the onset of rainfall and the streamflow inflection point was calculated.

The average of those time differences yielded a mean lag of 5.1 days (4.1–6.1 days uncertainty).

A maximum lag of 6 days was therefore adopted as it represents the longest expected time between the rainfall trigger and the corresponding streamflow peak.

The hydroEvents package [300] was used to pair events to five different specification types (Type 1 to 5), with the type argument in *pairEvents()* controlling how the algorithm defines paired events. The difference in the five different pairing types is illustrated in Figure 52 [522].

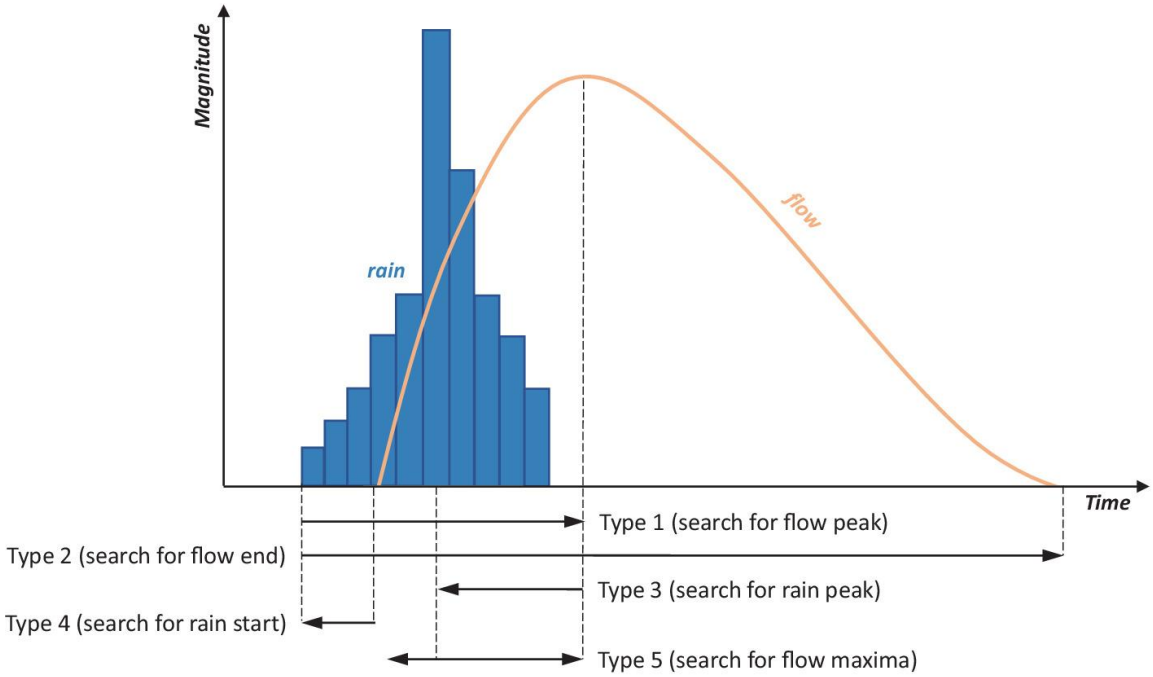


Figure 52: Schematic of the five event pairing algorithms implemented in function pairEvents. In this instance rainfall (blue) is matched to runoff (orange) but these algorithms can be used for any hydrologic data [522].

For all event pairings examined across both sites, Type 5 was found to return the highest total number of pairs and was the pairing type specification used for this study. Type 5 is the most flexible in event matching and searches bidirectionally from rainfall or streamflow/stream level peak or water quality peak to find peaks within the lag window. It captures a broader set of related events and is useful for screening events. Pairing was also extended to rainfall–water quality and streamflow-water quality events in this study. Outputs consisted of matched event tables for rainfall (events.P), streamflow (events.Q) and turbidity data (events.CANARY), with NA returned where no match occurred (Table 19).

Table 19: Pairing of 5mm rainfall events, baseflow separated (BFI A at α 0.980), daily streamflow events (eventMinima) with a 30th percentile threshold of quickflow and CANARY Turbidity Events on the Owenmore River from 01/10/2024 to 31/01/2025.

Pairing 5mm rainfall and Owenmore qf_Min_res streamflow events

Rain Threshold	Pairing Type	# Rainfall Events	# qf_Min_res Events	# Paired Events
5mm Rainfall, min.diff = 1	Type 1	14	6	7
5mm Rainfall, min.diff = 1	Type 2	14	6	1
5mm Rainfall, min.diff = 1	Type 3	14	6	6
5mm Rainfall, min.diff = 1	Type 4	14	6	6
5mm Rainfall, min.diff = 1	Type 5	14	6	8

Pairing 5mm Rainfall events to Owenmore CANARY Water Quality events

Rain Threshold	Pairing Type	# P Events	# CANARY Turbidity Events	# Paired Events
5mm Rainfall, min.diff = 1	Type 1	14	20	10
5mm Rainfall, min.diff = 1	Type 2	14	20	7
5mm Rainfall, min.diff = 1	Type 3	14	20	13
5mm Rainfall, min.diff = 1	Type 4	14	20	13
5mm Rainfall, min.diff = 1	Type 5	14	20	12

Pairing_qf_Min_res streamflow events to Owenmore CANARY Water Quality events

Owenmore Streamflow Threshold	Pairing Type	# qf_Min_res Events	# CANARY Turbidity Events	# Paired Events
qf_event_Minima_delta.y_81_delta.x_8	Type 1	6	20	4
qf_event_Minima_delta.y_81_delta.x_8	Type 2	6	20	4
qf_event_Minima_delta.y_81_delta.x_8	Type 3	6	20	6
qf_event_Minima_delta.y_81_delta.x_8	Type 4	6	20	5
qf_event_Minima_delta.y_81_delta.x_8	Type 5	6	20	4

The function plotPairs() was then used to create a dual-variable event plots displaying the continuous time series of both variables with paired events highlighted by same colour in the two time-series. The same workflow was applied for rainfall, streamflow, and stream-level pairing with CANARY events (Table 20).

Table 20: Pairing of 5mm rainfall events, P90 stream level events and CANARY Turbidity Events on the Unshin River from 01/10/2024 to 31/01/2025.

Pairing 5mm rainfall and Unshin P90 stream level events

Rain Threshold	Pairing Type	# Rainfall Events	# P90 Streamflow Events	# Paired Events
5mm Rainfall, min.diff = 1	Type 1	14	4	6
5mm Rainfall, min.diff = 1	Type 2	14	4	5
5mm Rainfall, min.diff = 1	Type 3	14	4	4
5mm Rainfall, min.diff = 1	Type 4	14	4	4
5mm Rainfall, min.diff = 1	Type 5	14	4	7

Pairing 5 mm Rainfall events to Unshin CANARY Water Quality events

Rain Threshold	Pairing Type	# P Events	# CANARY Turbidity Events	# Paired Events
5mm Rainfall, min.diff = 1	Type 1	14	17	11
5mm Rainfall, min.diff = 1	Type 2	14	17	11
5mm Rainfall, min.diff = 1	Type 3	14	17	12
5mm Rainfall, min.diff = 1	Type 4	14	17	12
5mm Rainfall, min.diff = 1	Type 5	14	17	12

Pairing P90 Unshin Stream level Events to Unshin CANARY Water Quality events

Unshin Stream level Threshold	Pairing Type	# Stream Level Events	# CANARY Turbidity Events	# Paired Events
90th Percentile	Type 1	4	17	2
90th Percentile	Type 2	4	17	2
90th Percentile	Type 3	4	17	2
90th Percentile	Type 4	4	17	2
90th Percentile	Type 5	4	17	3

4.3.5 Pairing of 5mm Rainfall, Streamflow and Water Quality Events on the Owenmore & Unshin Rivers

To examine if water quality events were associated with hydrodynamic events driven by rainfall or streamflow/ stream level events, event pairing [300] between water quality events and rainfall, streamflow (quickflow component) and stream level was carried out. Both the Owenmore and Unshin

rivers are groundwater fed which often leads to stable, less flashy responses to rainfall with lakes upstream of the monitoring stations also slowing the rainfall response. This can reduce the likelihood of pairing where the specification types are searching based on peaks that occur close together in time (Type 1 to 3) with the Type 4 and 5 pairings matching based on whether the peaks align or their time windows overlap. Type 4 and Type 5 pairings were found to have an increased likelihood of pairing the hydrological events with the CANARY water quality events identified at these sites. Similarly to streamflow response, if rainfall events are diffuse or prolonged, (79% of the 118 rainfall observations over the study period had rainfall >0 mm, with 49% of observations >1mm), multiple rainfall events may overlap the streamflow and turbidity peaks with multiple CANARY turbidity events found to overlap the rainfall and streamflow events in this study.

Over the study period, 12 from 14 (86 %) of the rainfall events and 4 from 6 (67 %) of the streamflow (quickflow component) events were paired to water quality events (n=20) on the Owenmore River. Similar patterns of rainfall and stream level response were observed on the Unshin River with pairings of 12 from 14 (86 %) of the rainfall events and 3 from 4 (75 %) of the stream level events paired to water quality events (n=17) (Table 21).

Table 21: Pairing [300] of 5mm Rainfall, Streamflow and Water Quality (WQ) Events on the Owenmore & Unshin Rivers over the study period 01/10/2024 to 31/01/2025

River	# ≥ 5 mm Rainfall Events (*eventPOT)*	# Streamflow ^ /Stream level Events ^^	# Turbidity WQ Events (*EPA CANARY)*	# Pairings between Rainfall & Streamflow Events	# Pairings between Rainfall & WQ Events	# Pairings between Streamflow^*/ Stream level^^** Events & WQ events
Owenmore ^	14	6	20	8	12	4
Unshin ^^	14	4	17	7	12	3

*BFI A at α 0.980 using eventMaxima at 30th percentile threshold of quickflow. **90th percentile daily Unshin stream level (eventMaxima).

These pairings indicate that the majority of water quality events observed on these rivers were associated with rainfall and subsequent increases in streamflow/ stream level. Plotting of paired events highlights the event pairings over the time series with paired events indicated by the same colour and unpaired events in black and highlighted using black circles (Figure 53). Baseline turbidity levels on the Owenmore are typically less than 4 NTU and less than 3 NTU on the Unshin River with turbidity levels during events rising very significantly to several hundred NTU on the Owenmore and an order of magnitude lower on the Unshin. This is unsurprising as the Owenmore has moderate water quality status whereas the Unshin is a high-status objective waterbody [534].

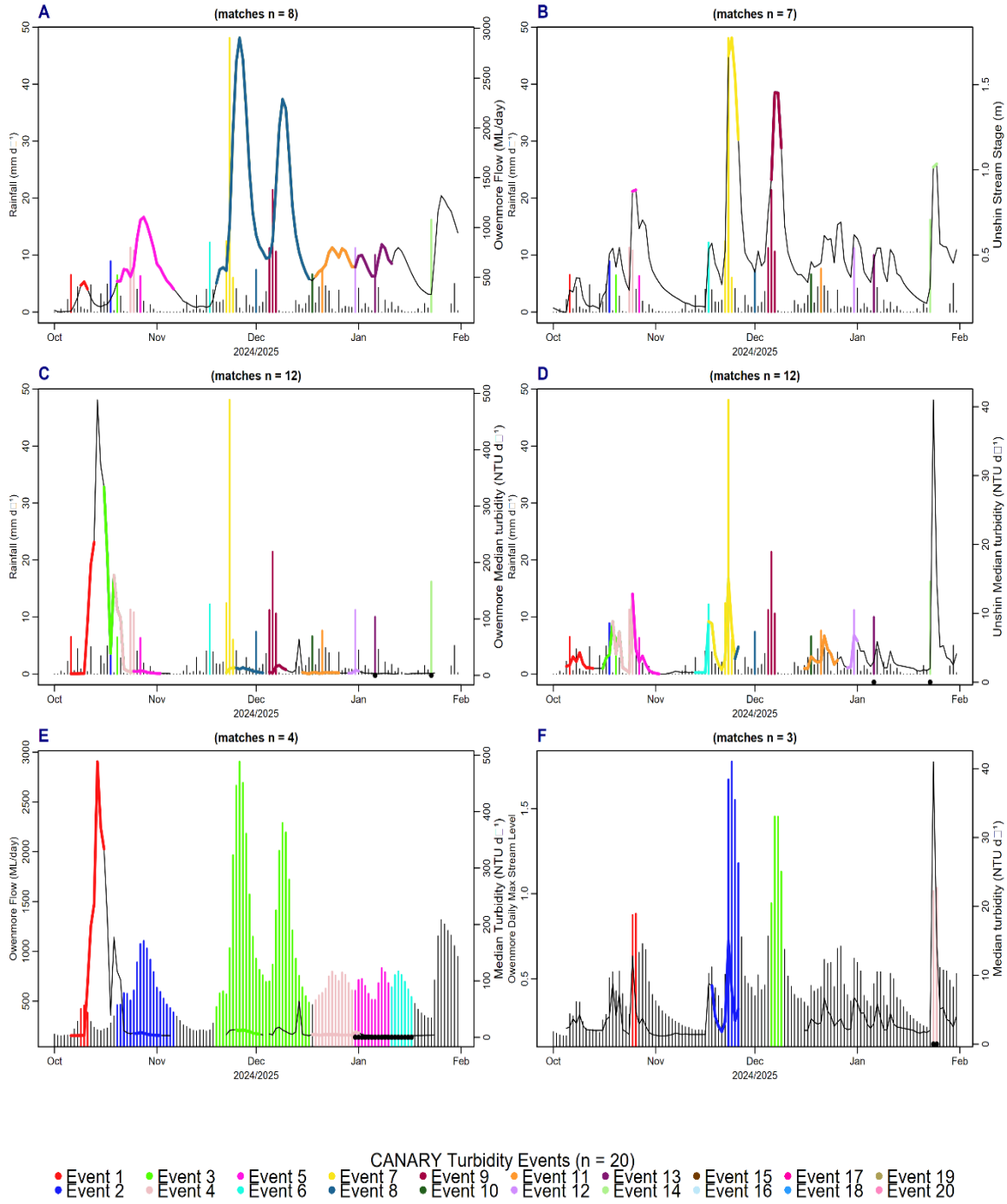


Figure 53: Event pairing using Type 5 pairing specification [300] on the Owenmore River at Ballynacarrow and the Unshin River upstream of Ballygrania over the study period. Paired events are indicated by the same colour and unpaired events are in black and highlighted using black circles A – rainfall events and Owenmore streamflow events, B - rainfall events and Unshin stream level events (Rainfall is plotted as vertical bars and streamflow/stream level as a line), C & D - rainfall events and EPA CANARY turbidity events (Rainfall is plotted as vertical bars and median turbidity as a line), E - streamflow events and EPA

CANARY turbidity events, & F - Unshin stream level events and EPA CANARY turbidity events (median turbidity is plotted as vertical bars and streamflow/ stream level as a line). Rainfall events (eventPOT) with threshold of 5mm, water quality events were EPA CANARY detected turbidity events, Owenmore streamflow events were baseflow separated (BFI A at α 0.980) using eventMaxima at 30th percentile threshold of quickflow and Unshin stream level events were 90th percentile daily Unshin stream level (eventPOT).

However, the monitoring does show that episodic water quality events are occurring on the Unshin river. Previously, water quality status dropped from 'High' to 'Good' in the 2010-2015 monitoring period returning to 'High' status again in 2016 and the Unshin currently has unidentified significant water quality pressure for nutrients in one area [534]. High status river water quality sites are increasingly rare in Europe and are a priority for protection as they support sensitive aquatic species including salmon, trout and freshwater pearl mussels with good water quality a key supporting factor [535].

The River Owenmore had more water quality events that were not linked to rainfall or streamflow compared to the River Unshin. The Owenmore is affected by multiple pressures, including agriculture, forestry, urban runoff, hydromorphological changes, and urban wastewater, contributing nutrients and sediments through both diffuse and point sources. In contrast, the Unshin River is a high-status waterbody with only one area identified as 'at risk' of not meeting environmental objectives under the WFD. The main pressures are unknown, although nutrients have been identified as a key water quality issue [534]. Non paired events could be indicative of points sources or other activities in the catchment, or the requirement for greater testing and sensitivity analysis of the CANARY model with larger data sets.

Overall, these results indicate that for the study period, hydrodynamic events were a key driver of water quality events across both the Owenmore and Unshin river stations in this catchment.

4.4 Strengths and Limitations of this approach to Event Monitoring

Building on previous studies using CANARY to identify potential water quality events [288,291,367,368] this research is the first application of this method for remote monitoring of hydrodynamic water quality events paired to rainfall and streamflow events. Previous research has demonstrated that individual

rivers respond differently to hydrodynamic events, demonstrating different lag times and flow pathways for different pollutants across different hydrodynamic events [502–504]. However, evaluating an effective methods for strategic monitoring of such events was one of the aims of this research, with investment in such HF monitoring systems [492] fundamental to mitigating the pressure on water quality due to the impacts of increased frequency of climate driven, hydrodynamic water quality events [295,536,537].

This approach offers a novel and flexible framework for identifying hydrodynamically driven water quality events. A strength lies in the site-specific configuration of the CANARY system, which is tailored to individual monitoring stations to optimise event detection. By maximising true positives while minimising false alarms, the method improves the reliability of event identification compared to more generic monitoring approaches. This targeted configuration represents a significant advancement in applying high-frequency monitoring to complex river systems.

Another important innovation is the remote deployment setup, which removes the need for permanent bankside infrastructure and dedicated power supply. As a result, the approach enables efficient baseline surveys at multiple stations within a catchment, helping to identify critical source areas for pollutant export and locations most sensitive to hydrodynamic pressures, all with relatively low infrastructure investment and minimising the significant resources associated with long term, high frequency monitoring stations.

The approach also provides strong temporal insights by enabling the tracking and characterisation of hydrodynamic events in terms of both frequency and intensity. This creates opportunities to detect trends over time and supports the development and evaluation of climate mitigation and adaptation measures. In addition, the data generated can guide the strategic placement of complementary monitoring technologies, such as automatic or passive samplers, to further investigate the impacts of these events on water quality.

This work highlights that spatial variability studies involving testing and sensitivity analysis of the CANARY model from earlier research [472], allows for site specific training of the model to widely

differing river stations. A longer term or inter-annual water quality dynamics study would be valuable. A study of multiple river stations, monitoring multiple parameters in various catchments over longer periods would provide even further understanding of hydrodynamic water quality event monitoring.

4.5 Conclusion

HF semi-continuous monitoring for turbidity, temperature and specific conductivity was implemented on the River Owenmore and the River Unshin over a four-month hydrologically active period between October 2024 and January 2025. The water quality data was supported by rainfall [322] and hydrometric data [338] at the monitoring stations. While turbidity data was used to track water quality events as detailed in chapter 3, turbidity or suspended solids are not monitored in the EPA national river monitoring programme [518] so specific conductivity was used instead. High frequency specific conductivity data monitored over the four month period was plotted on the flow duration curve, and compared to quarterly grab sample data for 2007 to 2025 at the same site from the EPAs national river monitoring programme [518] demonstrating that the short deployment was adequate to capture most flow conditions and associated water quality on the river Owenmore at Ballynacarrow from moderate flows to the high flow events.

To examine if the high frequency water quality data monitored over the four months could track the frequency and intensity of hydrodynamic water quality events, the water quality data was processed to identify water quality events, and the corresponding rainfall and streamflow/stream level data were analysed to identify potential rainfall and streamflow events. Following event extraction, the different event types were paired to each other so events from multiple time series could be matched to identify instances of when rainfall events or streamflow/ stream level events occurred within the same time window as potential water quality events. The event analysis carried out from October 2024 to January 2025 on the Owenmore River paired 12 from 14 (86 %) of the rainfall events and 4 from 6 (67 %) of the streamflow (quickflow component) to water quality events (n=20). Similar patterns of rainfall and stream level response were observed over the same period on the Unshin River with pairings of 12 from 14 (86 %) of the rainfall events and 3 from 4 (75 %) of the stream level events paired to water

quality events (n=17). More water quality events were detected on the Owenmore which reflects its lower water quality status then the Unshin. However, the number of water quality events on the high-status river over a short 4-month period was not insignificant and suggests that the water quality pressures identified may be linked to hydrodynamic events.

This is the first instance of the use of EPA CANARY event detection system with remote, off-grid, semi-continuous deployments of water quality sensors, combined with pairing water quality and rainfall/streamflow events for evaluating the frequency and intensity of hydrodynamic events on river water quality. Permanent installations across such a large network are impractical, making remote, temporary, off-grid HF deployments advantageous due to their flexibility, and ease of redeployment to other locations.

Chapter 5: Conclusion, Recommendations and Further Areas of Research

5.1 Conclusion

Water quality deterioration is one of the main drivers of freshwater biodiversity decline globally [3,4] which is compounded by climate change pressures [5]. Biodiversity is in crisis and is the 'ultimate conservation challenge' [119] with freshwater biodiversity being most acutely impacted. The EU has responded to freshwater biodiversity crisis through legally binding legislation and cross-sectoral strategies, but 25 years since the Water Framework Directive was adopted [538] and 35 years since the Habitat's Directive was adopted [12], only 39.5 % of surface water bodies in Europe are in good ecological status [6] with only 14% of habitat assessments are in 'good' conservation status [131]. Gains made in reversing biodiversity decline and restoring water quality in Europe have plateaued, due to the direct impact of climate change on aquatic ecosystems [539]. This lack of improvement in water quality and biodiversity reflects the complexity in controlling pollution from a myriad of sources which varies significantly, both spatially and temporally [540]. There is a dearth in research linking climate change and water quality due to their complexity, with climate studied on an international and national level whereas water quality is most commonly studied on a regional or local level, despite climate change impacting on freshwater systems regionally and locally. While current water quality monitoring programmes are providing valuable information in terms of water quality status and pressures [541], targeted monitoring at increased frequency is required for evidence-based decisions on appropriate management measures to protect and restore water quality [542].

In this thesis, the primary aim was to examine protected area designation focusing on freshwaters and to demonstrate the value of high frequency monitoring for detecting transient pollution events in small rivers to support the objective of the WFD in the context of increasing frequency and intensity of rainfall events due to climate change. To achieve this, the research was structured around specific objectives including 1) reviewing the literature to examine PA designation for freshwaters, 2) developing a practical, reproducible workflow for water quality event monitoring in small rivers, 3) examine if short term deployments of high frequency monitoring can adequately capture water quality variability, and 4) deploy and test the event monitoring system within a protected area to

determine it can identify hydrodynamic driven water quality events. The following conclusion synthesises the findings in relation to the aim and objectives, highlights the contribution of this research to the gaps in knowledge in this area and identifies potential directions for future research.

The first objective of this study was to conduct a literature review to examine protected areas and their designation as an instrument for protecting water quality and aquatic biodiversity in Europe. Evidence from the literature review demonstrates that across the EU, countries and regions have different mechanisms for identifying and designating PAs, resulting in multiple different names and types of PAs, a diversity of governance arrangements, and in some instances multiple governance types within a PA boundary. It demonstrates the large numbers of agencies involved in PA management with the vast majority of PAs in Europe being national PAs with over 400 different categories and overlaps in many areas designated as PAs. This review has identified a number of challenges to expanding the PA network including gaps in biodiversity data for aquatic species particularly those with restricted ranges, the need for more dynamic PA designation and conservation plans, and a lack of information on alternative PA network design. The EU has the largest network of PAs in the world with the establishment of Natura 2000 but Even for the Natura 2000 network there is no single management strategy across the EU to deliver effective management for these PAs, and the lack of integration between PA agencies has been identified as a key weakness in the effective management of PAs. There are striking differences in the designation of SACs among different regions in the same country and poor integration of biodiversity conservation into territorial plans, with the delegation of conservation management from state to regional and autonomous provinces leading to significant divergence in implementation, even within a single EU member state. The establishment and implementation of interconnected Natura 2000 sites across member state borders is crucial for biodiversity restoration, however, at national level existing structures and procedures are insufficient to promote cross-border cooperation and integration, with only limited efforts taking place at the local level. This is particularly challenging for freshwater biodiversity conservation, as freshwater species occur across a broad range of different PA designation types due to the longitudinal and lateral

connectivity of freshwaters especially as PAs are rarely designed with freshwater conservation in mind.

The second objective aimed to develop a practical, flexible and reproducible monitoring workflow for temporary, remote, off-grid monitoring of water quality events in small rivers. Integrated frameworks of in-situ monitoring alongside data analytics is necessary for effective catchment management [543]. The rapid pace and increasing complexity of water quality monitoring tools pose difficulties for adoption by water resource managers and limits the realisation of such technologies to deliver water quality improvements [424]. Data gaps for water quality and aquatic biodiversity were identified in the literature as a key challenge for delivering freshwater recovery and as diffuse pollution is a key water quality pressure for waterbodies across the EU, this protocol provides for not only high frequency monitoring but also for water quality event detection. High frequency (HF) monitoring is necessary for identifying diffuse pollutant sources but 'robust deployment, maintenance, and data management protocols' [281] along with 'practical guidelines' [24] are required to accelerate the adoption of HF monitoring, especially among statutory agencies [441]. The workflow and step by step user guide provide extensive guidance on the specific requirements for HF monitoring, provide comprehensive technical information to allow non-experts plan and execute high frequency monitoring for events but also to manage large timeseries datasets, to analyse the data and match the water quality data to hydrodynamic drivers of diffuse pollution in their specific catchment. Initially the aim was to develop a workflow as a high-level overview outlining the sequence of tasks or activities for remote water quality event detection using EPA CANARY. However, through experience attempting to execute code published by other researchers, it was recognised that a detailed step-by-step user guide was essential to facilitate wider adoption of the workflow to make it more accessible and easier to implement and to troubleshoot.

Code errors and the inability to reproduce analyses has been highlighted as a common issue, even where datasets and code were published [449,450] but avoidable if good code practices are employed [450]. This workflow was specifically designed for reproducibility and incorporated the four key components

for reproducible software [471] to overcome this problem. Alongside the code, a detailed user guide was produced which included the output of analysis so non experts can follow each stage of the analysis using the sample data provided before applying to their own data. Practical, method guidelines are urgently required to accelerate the uptake of new and innovative water monitoring tools [441] to effectively identify specific water quality pressures [14,443] and this workflow and detailed user guide fill a gap in translating available technologies into core components of monitoring systems and their integration into monitoring programmes.

The third objective focused on examining if short term, temporary, remote, semi-continuous monitoring of routine water quality parameters could adequately capture water quality variation over the range of river discharge at a hydrologically active period. This was achieved by plotting high frequency specific conductivity data from the 4-month study period on a flow duration curve for the river Owenmore and comparing this to grab sample specific conductivity data over an 18-year period also plotted on a flow duration curve. The findings indicate that the short deployment period compared well to the grab sampling for this parameter and was adequate to capture most flow conditions and associated water quality on the river Owenmore at Ballynacarrow from moderate flows to the high flow events. This suggests that short term deployments over hydrologically active periods could provide key insights into water quality dynamics particularly at a time of increasing hydrodynamic events due to climate change. This is very practical option to realise the benefits of high frequency monitoring without the significant costs, resourcing and infrastructure requirements associated with permanent high frequency monitoring stations.

Finally, the fourth objective builds on the event detection framework and applied it in the field to test and evaluate the water quality event protocol. The study found that from October 2024 to January 2025 on the Owenmore River, 86 % of the rainfall events (n=12), 67 % (n = 6) of the streamflow (quickflow component) were paired to water quality events (n=20). Similar patterns of rainfall and stream level response were observed over the same period on the Unshin River with 86 % of the rainfall events 75 % (n=4) of the stream level events paired to water quality events (n=17). These

findings confirm that episodic events are occurring in the catchment and diffuse source pressures are occurring more frequently in the Owenmore than on the Unshin which is consistent with their water quality status. The monitoring does revel the frequency and intensity of the riverine response to rainfall events and could be used to differentiate between point source and diffuse source pressures when tracked and paired to rainfall and discharge response. This is the first instance of the use of EPA CANARY event detection system with remote, off-grid, semi-continuous deployments of water quality sensors, combined with pairing water quality and rainfall/streamflow events for evaluating the frequency and intensity of hydrodynamic events on river water quality.

This may be the last window of opportunity to reverse biodiversity decline in the EU and the European Union is planning to spend at least €20 billion per year to 2030 to restore biodiversity [9]. The Nature Restoration Law echoes the lofty ambitions of the WFD and the Habitat's Directive but expanding PAs without examining and reforming PA designation will not reverse biodiversity decline. A step change is required in our approach to leveraging the full potential benefit of PAs to protect and restore water quality and aquatic biodiversity and requires improved governance which is intrinsically tied to designation and improved monitoring to fill the data gaps. This research filled a gap in knowledge on PA designation, a crucial first step in protecting reference sites and hotspots of biodiversity but also the type of which determines the governance structure and effectiveness of conservation. The field monitoring highlighted the value of short-term deployments to fill some of those data gaps with the monitoring framework and workflow turning available technologies and innovative approaches to event detection into real world operational tools, that can be integrated with rainfall and discharge data to deliver tangible findings to inform water quality restoration programmes.

5.2 Limitations

i. This study was confined to two river stations in the one catchment in the Northwest of Ireland. However, while this is the first instance of CANARY event detection system being used on surface waters with water quality events paired to rainfall and discharge events, both the CANARY system and the pairing of events have been successfully used in other water bodies.

ii. Similarly, the short-term deployment data monitoring for specific conductivity and comparison to the long-term grab samples was carried out at one monitoring station and needs to be evaluated for rivers with different water quality and hydrological characteristics.

iii. The study was carried out over one hydrodynamically active winter season, and an all- season performance would need to be determined.

iv. Not all waterbodies are suitable for temporary deployments due to security issues or local site factors, however high-status water bodies are predominantly located in first and order streams in more remote areas and with active community involvement, security issues are greatly reduced.

5.3 Recommendations

i. Due to the scale of the current crisis for freshwater biodiversity, the management model for PAs must rapidly move from a largely local/national model to an integrated, strategic regional model.

ii. The monitoring and management of freshwater PAs in the EU should be integrated with the River Basin Management Plans. Such an approach would provide a mechanism for setting cohesive targets to effectively deliver at least 'favourable conservation status' for freshwater PAs alongside at least 'good ecological status/potential' for water bodies.

iii. The development of integrated monitoring and management programmes focusing on freshwater habitats and species. This common framework approach also allows for co-management of protected areas by conservation and water quality specialists and would facilitate knowledge transfer between agencies across Europe.

iv. Specific provision should be made under the EU Biodiversity Strategy for 2030 to manage the exploitation of freshwater species and riverine aggregates.

v. The availability of hydrometric data and the installation/upgrading of existing hydrometric stations should be prioritised to protect and restore the remaining high status objective water bodies.

5.4 Further Research

i. Data from longer deployment periods could be compared to the short-term data to evaluate how well the short-term deployment characterises the water quality variability.

ii. The application of this approach should be applied to other waterbodies to assess and compare its performance.

iii. Other water quality parameters should be used with this approach with the water quality parameter matched to the particular pressures for the waterbody of interest.

References

1. United Nations. Alongside Pandemic, World Faces 'Triple Planetary Emergency', Secretary-General Tells World Forum for Democracy, Citing Climate, Nature, Pollution Crises | UN Press. UN Meeting Coverage and Press Releases. November 16, 2020. Accessed July 11, 2023. https://press.un.org/en/2020/sgsm20422.doc.htm

2. Woodward G, Perkins DM, Brown LE. Climate change and freshwater ecosystems: impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2010;365(1549):2093-2106. doi:10.1098/rstb.2010.0055

3. Mazor T, Doropoulos C, Schwarzmueller F, Gladish DW, Kumaran N, Merkel K, Di Marco M, Gagic V. Global mismatch of policy and research on drivers of biodiversity loss. *Nat Ecol Evol*. 2018;2(7):7. doi:10.1038/s41559-018-0563-x

4. Williams-Subiza EA, Epele LB. Drivers of biodiversity loss in freshwater environments: A bibliometric analysis of the recent literature. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2021;31(9):9. doi:10.1002/aqc.3627

5. Basen T, Chucholl C, Oexle S, Ros A, Brinker A. Suitability of Natura 2000 sites for threatened freshwater species under projected climate change. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2022;32(12):1872-1887. doi:10.1002/aqc.3899

6. EEA. *Europe's State of Water 2024: The Need for Improved Water Resilience*. European Environment Agency; 2024:108. Accessed June 16, 2025. https://www.eea.europa.eu/en/analysis/publications/europes-state-of-water-2024

7. European Commission. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Pathway to a Healthy Planet for All EU Action Plan: "Towards Zero Pollution for Air, Water and Soil."* 2021. Accessed April 11, 2026. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0400&qid=1623311742827

8. European Commission. The EU Nature Restoration Law. June 22, 2022. Accessed June 25, 2022. https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-law_en

9. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Biodiversity Strategy for 2030, Bringing Nature Back into Our Lives*. European Commission; 2020:22. https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF

10. United Nations. Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs. Sustainable Development. 2023. Accessed November 21, 2023. https://sdgs.un.org/2030agenda

11. European Commission. *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy*. 2000:1-72. Accessed June 16, 2025. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

12. The Council of the European Communities. *Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora*. Vol 206. 1992. Accessed August 13, 2023. http://data.europa.eu/eli/dir/1992/43/oj/eng

13. Haase P, Bowler DE, Baker NJ, Bonada N, Domisch S, Garcia Marquez JR, Heino J, Hering D, Jähnig SC, Schmidt-Kloiber A, Stubbington R, Altermatt F, Álvarez-Cabria M, Amatulli G, Angeler DG, Archambaud-Suard G, Jorrín IA, Aspin T, Azpiroz I, Bañares I, Ortiz JB, Bodin CL, Bonacina L, Bottarin R, Cañedo-Argüelles M, Csabai Z, Datry T, de Eyto E, Dohet A, Dörflinger G, Drohan E, Eikland KA, England J, Eriksen TE, Evtimova V, Feio MJ, Ferréol M, Floury M, Forcellini M, Forio MAE, Fornaroli R, Friberg N, Fruget JF, Georgieva G, Goethals P, Graça MAS, Graf W, House A, Huttunen KL, Jensen TC, Johnson RK, Jones JI, Kiesel J, Kuglerová L, Larrañaga A, Leitner P, L'Hoste L, Lizée MH, Lorenz AW, Maire A, Arnaiz JAM, McKie BG, Millán A, Monteith D, Muotka T, Murphy JF, Ozolins D, Paavola R, Paril P, Peñas FJ, Pilotto F, Polášek M, Rasmussen JJ, Rubio M, Sánchez-Fernández D, Sandin L, Schäfer RB, Scotti A, Shen LQ, Skuja A, Stoll S, Straka M, Timm H, Tyufekchieva VG, Tziortzis I, Uzunov Y, van der Lee GH, Vannevel R, Varadinova E, Várbíró G, Velle G, Verdonschot PFM, Verdonschot RCM, Vidinova Y, Wiberg-Larsen P, Welti EAR. The recovery of European freshwater biodiversity has come to a halt. *Nature*. 2023;620(7974):7974. doi:10.1038/s41586-023-06400-1

14. Wolfram J, Stehle S, Bub S, Petschick LL, Schulz R. Water quality and ecological risks in European surface waters – Monitoring improves while water quality decreases. *Environment International*. 2021;152:106479. doi:10.1016/j.envint.2021.106479

15. European Environment Agency. *State of Nature in the EU*. 2020:142. Accessed July 21, 2022. https://www.eea.europa.eu/publications/state-of-nature-in-the-eu-2020

16. Feeley H, McGonigley C, Bradley C, Smith J, Tierney D, Wilkes R, Stephens A, O'Connell O, Brown S, Treacy P, McAleer E. *Water Quality in Ireland 2019-2024*. Environmental Protection Agency; 2025:112. https://doi.org/10.1016/j.scitotenv.2015.03.076

17. NPWS. *The Status of EU Protected Habitats and Species in Ireland*. National Parks ans Wildlife Service; 2025:98. Accessed December 31, 2025. https://assets.gov.ie/static/documents/1b52a57d/The_Status_of_EU_Protected_Habitats_and_Species_in_Ireland.pdf

18. Hermoso V, Abell R, Linke S, Boon P. The role of protected areas for freshwater biodiversity conservation: challenges and opportunities in a rapidly changing world. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2016;26(S1):3-11. doi:https://doi.org/10.1002/aqc.2681

19. Acreman M, Hughes KA, Arthington AH, Tickner D, Dueñas MA. Protected areas and freshwater biodiversity: a novel systematic review distils eight lessons for effective conservation. *Conservation Letters*. 2019;13(1):e12684. doi:https://doi.org/10.1111/conl.12684

20. Heino J, Virkkala R, Toivonen H. Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. *Biological Reviews*. 2009;84(1):1. doi:10.1111/j.1469-185X.2008.00060.x

21. Markovic D, Carrizo S, Freyhof J, Cid N, Lengyel S, Scholz M, Kasperdius H, Darwall W. Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs. *Diversity and Distributions*. 2014;20(9):9. doi:10.1111/ddi.12232

22. Ranius T, Widenfalk LA, Seedre M, Lindman L, Felton A, Hämäläinen A, Filyushkina A, Öckinger E. Protected area designation and management in a world of climate change: A review of recommendations. *Ambio*. 2023;52(1):1. doi:10.1007/s13280-022-01779-z

23. Hoffmann S. Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. *Biodivers Conserv*. 2022;31(2):325-352. doi:10.1007/s10531-021-02340-2

24. Rozemeijer J, Jordan P, Hooijboer A, Kronvang B, Glendell M, Hensley R, Rinke K, Stutter M, Bieroza M, Turner R, Mellander PE, Thorburn P, Cassidy R, Appels J, Ouwerkerk K, Rode M. Best practice in high-frequency water quality monitoring for improved management and assessment; a novel decision workflow. *Environ Monit Assess*. 2025;197(4):353. doi:10.1007/s10661-025-13795-z

25. Bouleau G, Pont D. Did you say reference conditions? Ecological and socio-economic perspectives on the European Water Framework Directive. *Environmental Science & Policy*. 2015;47:32-41. doi:10.1016/j.envsci.2014.10.012

26. Wallin M, Wiederholm T, Johnson R. *Guidance on Establishing Reference Conditions and Ecological Status Class Boundaries for Inland Surface Waters*. Publication Office of the EU; 2003:93.

27. White B, Moorkens E, Irvine K, Glasgow G, Chuanigh E. Management strategies for the protection of high status water bodies under the water framework directive. *Biology & Environment Proceedings of the Royal Irish Academy*. 2014;114B:129-142. doi:10.3318/BIOE.2014.25

28. Lopoukhine N, Crawhall N, Dudley N, Figgis P, Karibuhoye C, Laffoley D, Londoño J, MacKinnon K, Sandwith T. Protected areas: Providing natural solutions to 21st Century challenges. *Sapiens*. 2012;5:116-131.

29. Watson JEM, Dudley N, Segan DB, Hockings M. The performance and potential of protected areas. *Nature*. 2014;515(7525):7525. doi:10.1038/nature13947

30. Geldmann J, Coad L, Barnes MD, Craigie ID, Woodley S, Balmford A, Brooks TM, Hockings M, Knights K, Mascia MB, McRae L, Burgess ND. A global analysis of management capacity and ecological outcomes in terrestrial protected areas. *Conservation Letters*. 2018;11(3):e12434. doi:10.1111/conl.12434

31. UNEP-WCMC. October 2023 update of the WDPA and WD-OECM. Protected Planet. October 2023. Accessed October 7, 2023. https://www.protectedplanet.net/en/resources/october-2023-update-of-the-wdpa-and-wd-oecm

32. UNEP World Conservation Monitoring Centre. *2018 United Nations List of Protected Areas: Supplement on Protected Area Management Effectiveness.* UNEP-WCMC: Cambridge, UK; 2018.

33. Hoffmann S, Beierkuhnlein C, Field R, Provenzale A, Chiarucci A. Uniqueness of Protected Areas for Conservation Strategies in the European Union. *Scientific Reports*. 2018;8(1):1. doi:10.1038/s41598-018-24390-3

34. Kremen C, Merenlender AM. Landscapes that work for biodiversity and people. *Science*. 2018;362(6412). doi:10.1126/science.aau6020

35. Thieme M, Khrystenko D, Qin S, Golden Kroner R, Lehner B, Pack S, Zarfl C, Shahbol N, Mascia M. Dams and protected areas: Quantifying thespatial and temporal extent of global dam construction within protected areas. *Conservation Letters*. 2020;13:e12719. doi:10.1111/conl.12719

36. Zafra-Calvo N, Geldmann J. Protected areas to deliver biodiversity need management effectiveness and equity. *Global Ecology and Conservation*. 2020;22:e01026. doi:10.1016/j.gecco.2020.e01026

37. CBD. COP15: Final text of Kunming-Montreal Global Biodiversity Framework. Convention on Biological Diversity. December 22, 2022. Accessed December 23, 2022. https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222

38. Jones-Walters L, Čivić K. European protected areas: Past, present and future. *Journal for Nature Conservation*. 2013;21(2):122-124. doi:10.1016/j.jnc.2012.11.006

39. Hermoso V, Morán-Ordóñez A, Canessa S, Brotons L. Realising the potential of Natura 2000 to achieve EU conservation goals as 2020 approaches. *Scientific Reports*. 2019;9. doi:10.1038/s41598-019-52625-4

40. Holland RA, Darwall WRT, Smith KG. Conservation priorities for freshwater biodiversity: The Key Biodiversity Area approach refined and tested for continental Africa. *Biological Conservation*. 2012;148(1):167-179. doi:10.1016/j.biocon.2012.01.016

41. Higgins J, Zablocki J, Newsock A, Krolopp A, Tabas P, Salama M. Durable Freshwater Protection: A Framework for Establishing and Maintaining Long-Term Protection for Freshwater Ecosystems and the Values They Sustain. *Sustainability*. 2021;13(4):4. doi:10.3390/su13041950

42. Leal CG, Lennox GD, Ferraz SFB, Ferreira J, Gardner TA, Thomson JR, Berenguer E, Lees AC, Hughes RM, Nally RM, Aragão LEOC, Brito JG de, Castello L, Garrett RD, Hamada N, Juen L, Leitão RP, Louzada J, Morello TF, Moura NG, Nessimian JL, Oliveira-Junior JMB, Oliveira VHF, Oliveira VC de, Parry L, Pompeu PS, Solar RRC, Zuanon J, Barlow J. Integrated terrestrial-freshwater planning doubles conservation of tropical aquatic species. *Science*. 2020;370(6512):117-121. doi:10.1126/science.aba7580

43. Abell R, Allan JD, Lehner B. Unlocking the potential of protected areas for freshwaters. *Biological Conservation*. 2007;134(1):48-63. doi:10.1016/j.biocon.2006.08.017

44. Crivelli A. The role of protected areas in freshwater fish conservation. *Conservation of Freshwater Fishes: Options for the Future*. Published online January 1, 2002:373-388.

45. Suski CD, Cooke SJ. Conservation of Aquatic Resources through the Use of Freshwater Protected Areas: Opportunities and Challenges. *Biodivers Conserv*. 2007;16(7):2015-2029. doi:10.1007/s10531-006-9060-7

46. Joppa L, Pfaff A. High and Far: Biases in the Location of Protected Areas. *PloS one*. 2009;4:e8273. doi:10.1371/journal.pone.0008273

47. Rodriguez-Iturbe I, Muneepeerakul R, Bertuzzo E, Levin SA, Rinaldo A. River networks as ecological corridors: A complex systems perspective for integrating hydrologic, geomorphologic, and ecologic dynamics. *Water Resources Research*. 2009;45(1). doi:10.1029/2008WR007124

48. Harrison IJ, Green PA, Farrell TA, Juffe-Bignoli D, Sáenz L, Vörösmarty CJ. Protected areas and freshwater provisioning: a global assessment of freshwater provision, threats and management strategies to support human water security. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2016;26(S1):103-120. doi:10.1002/aqc.2652

49. Su G, Logez M, Xu J, Tao S, Villéger S, Brosse S. Human impacts on global freshwater fish biodiversity. *Science*. 2021;371(6531):835-838. doi:10.1126/science.abd3369

50. IPBES. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Zenodo; 2019. doi:10.5281/zenodo.6417333

51. IPCC. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. The Intergovernmental Panel on Climate Change; 2023:115. Accessed November 20, 2023. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

52. European Commission. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal*. 2019. Accessed August 12, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

53. Schwarz U. *Hydropower Pressure on European Rivers: The Story in Numbers*. WWF, RiverWatch, EuroNatur, GEOTA; 2019:40. Accessed August 8, 2023. https://balkanrivers.net/sites/default/files/European%20Hydropower%20report%202019_w.pdf

54. Belletti B, Garcia de Leaniz C, Jones J, Bizzi S, Börger L, Segura G, Castelletti A, van de Bund W, Aarestrup K, Barry J, Belka K, Berkhuysen A, Birnie-Gauvin K, Bussettini M, Carolli M, Consuegra S, Dopico E, Feierfeil T, Fernández S, Fernandez Garrido P, Garcia-Vazquez E, Garrido S, Giannico G, Gough P, Jepsen N, Jones PE, Kemp P, Kerr J, King J, Łapińska M, Lázaro G, Lucas MC, Marcello L, Martin P, McGinnity P, O'Hanley J, Olivo del Amo R, Parasiewicz P, Pusch M, Rincon G, Rodriguez C, Royte J, Schneider CT, Tummers JS, Vallesi S, Vowles A, Verspoor E, Wanningen H, Wantzen KM, Wildman L, Zalewski M. More than one million barriers fragment Europe's rivers. *Nature*. 2020;588(7838):7838. doi:10.1038/s41586-020-3005-2

55. Durá-Alemañ CJ, Moleón M, Pérez-García JM, Serrano D, Sánchez-Zapata JA. Climate change and energy crisis drive an unprecedented EU environmental law regression. *Conservation Letters*. 2023;16(3):e12958. doi:10.1111/conl.12958

56. Berg Grimstad A, Nasiritousi N, Glass J, Karlsson M. Governing environmental complexity: Exploring coherence across EU climate and biodiversity strategies. *Ambio*. Published online July 26, 2026:1-14. doi:10.1007/s13280-026-02449-0

57. Huhta K, Soininen N, Vesa S. The ecological sustainability of the energy transition in EU law: pro et contra hydropower. *Journal of Energy & Natural Resources Law*. 2025;43(1):29-45. doi:10.1080/02646811.2024.2331886

58. Rehbein JA, Watson J, Lane J, Sonter L, Venter O, Atkinson S, Allan J. Renewable energy development threatens many globally important biodiversity areas. *Global Change Biology*. 2020;26:3040-3051. doi:10.1111/gcb.15067

59. Hennenberg KJ, Böttcher H, Bradshaw CJA. Revised European Union renewable-energy policies erode nature protection. *Nat Ecol Evol*. 2018;2(10):1519-1520. doi:10.1038/s41559-018-0659-3

60. Harrison I, Abell R, Darwall W, Thieme M, Tickner D, Timboe I. The freshwater biodiversity crisis. *Science*. 2018;362:1369.1-1369. doi:10.1126/science.aav9242

61. Albert JS, Destouni G, Duke-Sylvester SM, Magurran AE, Oberdorff T, Reis RE, Winemiller KO, Ripple WJ. Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio*. 2021;50(1):85-94. doi:10.1007/s13280-020-01318-8

62. Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, Cooke SJ, Dalton J, Darwall W, Edwards G, Harrison I, Hughes K, Jones T, Leclère D, Lynch AJ, Leonard P, McClain ME, Muruven D, Olden JD, Ormerod SJ, Robinson J, Tharme RE, Thieme M, Tockner K, Wright M, Young L. Bending the Curve of Global Freshwater Biodiversity Loss: An Emergency Recovery Plan. *BioScience*. 2020;70(4):330-342. doi:10.1093/biosci/biaa002

63. Bastin L, Gorelick N, Saura S, Bertzky B, Dubois G, Fortin MJ, Pekel JF. Inland surface waters in protected areas globally: Current coverage and 30-year trends. *PLOS ONE*. 2019;14(1):e0210496. doi:10.1371/journal.pone.0210496

64. Juffe-Bignoli D, Harrison I, Butchart S, Flitcroft R, Hermoso V, Jonas H, Lukasiewicz A, Thieme M, Turak E, Bingham H, Dalton J, Darwall W, Deguignet M, Dudley N, Gardner R, Higgins J, Kumar R, Linke S, Milton G, van Soesbergen A. Achieving Aichi Biodiversity Target 11 to improve the performance of protected areas and conserve freshwater biodiversity: Elements needed to meet a global target for protected areas. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2016;26:133-151. doi:10.1002/aqc.2638

65. Weigelhofer G, Feldbacher E, Trauner D, Pölz E, Hein T, Funk A. Integrating Conflicting Goals of the EC Water Framework Directive and the EC Habitats Directives Into Floodplain Restoration Schemes. *Frontiers in Environmental Science*. 2020;8:225. doi:10.3389/fenvs.2020.538139

66. European Parliament & Council of EU. *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Nature Restoration*. 2022:80. Accessed October 16, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0304

67. Chape S, Harrison J, Spalding M, Lysenko I. Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2005;360(1454):443-455. doi:10.1098/rstb.2004.1592

68. Jenkins C, Joppa L. Expansion of the global terrestrial protected area system. *Biological Conservation*. 2009;142:2166-2174. doi:10.1016/j.biocon.2009.04.016

69. Schéré CM, Dawson TP, Schreckenberg K. Multiple conservation designations: what impact on the effectiveness of marine protected areas in the Irish Sea? *International Journal of Sustainable Development & World Ecology*. 2020;27(7):596-610. doi:10.1080/13504509.2019.1706058

70. Juffe-Bignoli D, Burgess N, Bingham H, Belle E, Lima M, Deguignet M, Bertzky B, Milam AN, Martínez-López J, Lewis E, Eassom A, Wicander S, Geldmann J, van Soesbergen A, Arnell A, O'Connor B, Park S, Shi Y, Danks F, Kingston N. *Protected Planet Report 2014*. United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC); 2014.

71. Gardner CJ. IUCN management categories fail to represent new, multiple-use protected areas in Madagascar. *Oryx*. 2011;45(3):336-346. doi:10.1017/S0030605310001808

72. Araújo MB, Alagador D, Cabeza M, Nogués-Bravo D, Thuiller W. Climate change threatens European conservation areas. *Ecology Letters*. 2011;14(5):484-492. doi:https://doi.org/10.1111/j.1461-0248.2011.01610.x

73. Maiorano L, Amori G, Montemaggiori A, Rondinini C, Santini L, Saura S, Boitani L. On how much biodiversity is covered in Europe by national protected areas and by the Natura 2000 network: insights from terrestrial vertebrates. *Conservation Biology*. 2015;29(4):986-995. doi:https://doi.org/10.1111/cobi.12535

74. Friedrichs M, Hermoso V, Bremerich V, Langhans SD. Evaluation of habitat protection under the European Natura 2000 conservation network – The example for Germany. *PLOS ONE*. 2018;13(12):e0208264. doi:10.1371/journal.pone.0208264

75. European Commission, European Environment Agency. BISE - Biodiversity Information System for Europe. 2023. Accessed October 18, 2021. https://biodiversity.europa.eu/

76. Underwood E, Ashcroft R, Kettunen M, McConville A, Tucker G. *Protected Area Approaches in the EU*. Institute for European Environmental Policy, London/Brussels; 2014:146.

77. Arthington AH, Dulvy NK, Gladstone W, Winfield IJ. Fish conservation in freshwater and marine realms: status, threats and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2016;26(5):838-857. doi:https://doi.org/10.1002/aqc.2712

78. European Commission. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Green Infrastructure (GI) — Enhancing Europe's Natural Capital*. 2013:11. Accessed November 10, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0249

79. Deguignet M, Arnell A, Juffe-Bignoli D, Shi Y, Bingham H, MacSharry B, Kingston N. Measuring the extent of overlaps in protected area designations. *PLOS ONE*. 2017;12(11):e0188681. doi:10.1371/journal.pone.0188681

80. Jordaan MS, Chakona A, van der Colff D. Protected Areas and Endemic Freshwater Fishes of the Cape Fold Ecoregion: Missing the Boat for Fish Conservation? *Front Environ Sci*. 2020;8. doi:10.3389/fenvs.2020.502042

81. Nogueira JG, Teixeira A, Varandas S, Lopes-Lima M, Sousa R. Assessment of a terrestrial protected area for the conservation of freshwater biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2021;31(3):520-530. doi:https://doi.org/10.1002/aqc.3502

82. Pittock J, Finlayson M, Arthington AH, Roux D, Matthews JH, Biggs H, Froend R, Harrison E, Blom E, Flitcroft R. *Managing Freshwater, River, Wetland and Estuarine Protected Areas*. ANU Press; 2015. https://www.jstor.org/stable/j.ctt1657v5d.26

83. Protected Planet. Protected area coverage of freshwater ecosystems. Protected Planet. October 8, 2023. Accessed October 8, 2023. https://www.protectedplanet.net/en/news-and-stories/protected-area-coverage-of-freshwater-ecosystems

84. van Rees CB, Waylen KA, Schmidt-Kloiber A, Thackeray SJ, Kalinkat G, Martens K, Domisch S, Lillebø AI, Hermoso V, Grossart HP, Schinegger R, Decleer K, Adriaens T, Denys L, Jarić I, Janse JH, Monaghan MT, De Wever A, Geijzendorffer I, Adamescu MC, Jähnig SC. Safeguarding freshwater life beyond 2020: Recommendations for the new global biodiversity framework from the European experience. *Conservation Letters*. 2021;14(1):e12771. doi:10.1111/conl.12771

85. Margules CR, Pressey RL. Systematic conservation planning. *Nature*. 2000;405(6783):243-253. doi:10.1038/35012251

86. Nobel A, Lizin S, Malina R. What drives the designation of protected areas? Accounting for spatial dependence using a composite marginal likelihood approach. *Ecological Economics*. 2023;205:107732. doi:10.1016/j.ecolecon.2022.107732

87. Nagy AA, Erős N, Imecs I, Bóné G, Fülöp A, Pap PL. Distribution and diversity of fishes and lampreys in Transylvania (Romania): a complete survey and suggestions for new protected areas. *ZooKeys*. 2023;1166:351-373. doi:10.3897/zookeys.1166.102854

88. West DW, Leathwick JR, Dean-Speirs TL. Approaches to the selection of a network of freshwater ecosystems within New Zealand for conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2019;29(9):1574-1586. doi:10.1002/aqc.3060

89. CBD. DECISION ADOPTED BY THE CONFERENCE OF THE PARTIES TO THE CONVENTION ON BIOLOGICAL DIVERSITY AT ITS TENTH MEETING X/2. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. Published online October 29, 2010. Accessed April 10, 2021. https://www.cbd.int/doc/decisions/cop-10/cop-10-dec-02-en.pdf

90. European Commission. European Union meets target of conserving 10% of Europe's seas by 2020. European Commission - European Commission. October 29, 2018. Accessed July 21, 2022. https://ec.europa.eu/info/news/european-union-meets-target-conserving-10-europes-seas-2020-2018-oct-29_en

91. European Environment Agency. Natura 2000 sites designated under the EU Habitats and Birds Directives. February 7, 2022. Accessed July 21, 2022. https://www.eea.europa.eu/ims/natura-2000-sites-designated-under

92. Baillie J, Zhang YP. Space for nature. *Science*. 2018;361(6407):1051-1051. doi:10.1126/science.aau1397

93. Deinet S, Scott-Gatty K, Rotton H, Twardek WM, Marconi V, McRae L, Baumgartner LJ, Brink K, Claussen JE, Cooke SJ, Darwall W, Eriksson BK, Garcia de Leaniz C, Hogan Z, Royte J, Silva LGM, Thieme ML, Tickner D, Waldman J, Wanningen H, Weyl OLF, Berkhuysen A. *The Living Planet Index (LPI) for Migratory Freshwater Fish: Technical Report*. World Fish Migration Foundation; 2020.

94. Neubauer TA, Hauffe T, Silvestro D, Schauer J, Kadolsky D, Wesselingh FP, Harzhauser M, Wilke T. Current extinction rate in European freshwater gastropods greatly exceeds that of the late Cretaceous mass extinction. *Commun Earth Environ*. 2021;2(1):1-7. doi:10.1038/s43247-021-00167-x

95. He F, Zarfl C, Bremerich V, David JNW, Hogan Z, Kalinkat G, Tockner K, Jähnig SC. The global decline of freshwater megafauna. *Global Change Biology*. 2019;25(11):3883-3892. doi:https://doi.org/10.1111/gcb.14753

96. Tsavdaridou AI, Doxa A, Mazaris AD. Towards achieving a twenty-fold increase in the coverage of freshwater species distributions within protected areas in Europe. *Biological Conservation*. 2023;285:110233. doi:10.1016/j.biocon.2023.110233

97. Strayer DL, Dudgeon D. Freshwater biodiversity conservation: recent progress and future challenges. *jnbs*. 2010;29(1):344-358. doi:10.1899/08-171.1

98. Finlayson M, Arthington A, Pittock J. *Freshwater Ecosystems in Protected Areas: Conservation and Management (1st Ed.)*. Routledge; 2017.

99. Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol Rev Camb Philos Soc*. 2019;94(3):849-873. doi:10.1111/brv.12480

100. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. *Nature*. 2000;403(6772):6772. doi:10.1038/35002501

101. Walters AD, Brown MA, Cerbie GM, Williams MG, Banta JA, Williams LR, Ford NB, Berg DJ. Do hotspots fall within protected areas? A Geographic Approach to Planning analysis of regional freshwater biodiversity. *Freshwater Biology*. 2019;64(11):2046-2056. doi:https://doi.org/10.1111/fwb.13394

102. Abell R, Lehner B, Thieme M, Linke S. Looking Beyond the Fenceline: Assessing Protection Gaps for the World's Rivers. *Conservation Letters*. 2016;10. doi:10.1111/conl.12312

103. IUCN. Key Biodiversity Areas. 2023. Accessed October 11, 2023. https://www.iucn.org/our-work/region/mediterranean/our-work/biodiversity-knowledge-and-action/key-biodiversity-areas

104. Bibby C. Selecting Areas for Conservation. In: *Conservation Science and Action*. 2009:176-201. doi:10.1002/9781444313499.ch9

105. Maasri A, Jähnig SC, Adamescu MC, Adrian R, Baigun C, Baird DJ, Batista-Morales A, Bonada N, Brown LE, Cai Q, Campos-Silva JV, Clausnitzer V, Contreras-MacBeath T, Cooke SJ, Datry T, Delacámara G, De Meester L, Dijkstra KDB, Do VT, Domisch S, Dudgeon D, Erös T, Freitag H, Freyhof J, Friedrich J, Friedrichs-Manthey M, Geist J, Gessner MO, Goethals P, Gollock M, Gordon C, Grossart HP, Gulemvuga G, Gutiérrez-Fonseca PE, Haase P, Hering D, Hahn HJ, Hawkins CP, He F, Heino J, Hermoso V, Hogan Z, Hölker F, Jeschke JM, Jiang M, Johnson RK, Kalinkat G, Karimov BK, Kasangaki A, Kimirei IA, Kohlmann B, Kuemmerlen M, Kuiper JJ, Kupilas B, Langhans SD, Lansdown R, Leese F, Magbanua FS, Matsuzaki S ichiro S, Monaghan MT, Mumladze L, Muzon J, Mvogo Ndongo PA, Nejstgaard JC, Nikitina O, Ochs C, Odume ON, Opperman JJ, Patricio H, Pauls SU, Raghavan R, Ramírez A, Rashni B, Ross-Gillespie V, Samways MJ, Schäfer RB, Schmidt-Kloiber A, Seehausen O, Shah DN, Sharma S, Soininen J, Sommerwerk N, Stockwell JD, Suhling F, Tachamo Shah RD, Tharme RE, Thorp JH, Tickner D, Tockner K, Tonkin JD, Valle M, Vitule J, Volk M, Wang D, Wolter C, Worischka S. A global agenda for advancing freshwater biodiversity research. *Ecology Letters*. 2022;25(2):255-263. doi:10.1111/ele.13931

106. Flitcroft R, Cooperman MS, Harrison IJ, Juffe-Bignoli D, Boon PJ. Theory and practice to conserve freshwater biodiversity in the Anthropocene. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2019;29(7):1013-1021. doi:https://doi.org/10.1002/aqc.3187

107. Sayer CD. Conservation of aquatic landscapes: ponds, lakes, and rivers as integrated systems. *WIREs Water*. 2014;1(6):573-585. doi:10.1002/wat2.1045

108. Cíbik J, Beracko P, Bulánková E, Čiamporová Zaťovičová Z, Gregušová K, Kodada J, Krno I, Mišíková Elexová E, Navara T, Rogánska A, Derka T. Are springs hotspots of benthic invertebrate diversity? Biodiversity and conservation priority of rheocrene springs in the karst landscape. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2022;32(5):843-858. doi:10.1002/aqc.3802

109. Raghavan R, Das S, Nameer PO, Bijukumar A, Dahanukar N. Protected areas and imperilled endemic freshwater biodiversity in the Western Ghats Hotspot. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2016;26(S1):78-90. doi:https://doi.org/10.1002/aqc.2653

110. Décamps H. River networks as biodiversity hotlines. *Comptes Rendus Biologies*. 2011;334(5):420-434. doi:10.1016/j.crvi.2011.03.002

111. Loury EK, Ainsley SM. Identifying Indicators to Evaluate Community-Managed Freshwater Protected Areas in the Lower Mekong Basin: A Review of Marine and Freshwater Examples. *Water*. 2020;12(12):12. doi:10.3390/w12123530

112. Mu Y, Li X, Guo Y, Liang C, Bai J, Linke S, Cui B. Using climatic-geomorphological surrogates to identify complete and incidental freshwater conservation gaps within large river basins in China. *Global Ecology and Conservation*. 2021;30:e01744. doi:10.1016/j.gecco.2021.e01744

113. Darwall W, Holland R, Smith K, Allen D, Wright E, Katarya V, Pollock C, Shi Y, Clausnitzer V, Cumberlidge N, Cuttelod A, Dijkstra K, Diop M, García N, Seddon M, Skelton P, Snoeks J, Tweddle D, Ví JC, Levin D. Implications of bias in conservation research and investment for freshwater species. *Conservation Letters*. 2011;4. doi:10.1111/j.1755-263X.2011.00202.x

114. Dolný A, Harabiš F, Mižičová H. Home Range, Movement, and Distribution Patterns of the Threatened Dragonfly Sympetrum depressiusculum (Odonata: Libellulidae): A Thousand Times Greater Territory to Protect? *PLOS ONE*. 2014;9(7):e100408. doi:10.1371/journal.pone.0100408

115. Janse JH, Kuiper JJ, Weijters MJ, Westerbeek EP, Jeuken MHJL, Bakkenes M, Alkemade R, Mooij WM, Verhoeven JTA. GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. *Environmental Science & Policy*. 2015;48:99-114. doi:10.1016/j.envsci.2014.12.007

116. Erős T, Petrovszki J, Mórocz A. Planning for sustainability: Historical data and remote sensing-based analyses aid landscape design in one of the largest remnant European floodplains. *Landscape and Urban Planning*. 2023;238:104837. doi:10.1016/j.landurbplan.2023.104837

117. The Parliament of New Zealand. *Te Awa Tupua (Whanganui River Claims Settlement) Act 2017*. 2022. Accessed September 14, 2023. https://www.legislation.govt.nz/act/public/2017/0007/latest/whole.html#DLM6830855

118. De Vries-Stotijn A, Van Ham I, Bastmeijer K. Protection through property: from private to river-held rights. *Water International*. 2019;44(6-7):736-751. doi:10.1080/02508060.2019.1641882

119. Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA. Freshwater biodiversity: importance,

threats, status and conservation challenges. *Biol Rev Camb Philos Soc*. 2006;81(2):163-182. doi:10.1017/S1464793105006950

120. Britton AW, Day JJ, Doble CJ, Ngatunga BP, Kemp KM, Carbone C, Murrell DJ. Terrestrial-focused protected areas are effective for conservation of freshwater fish diversity in Lake Tanganyika. *Biological Conservation*. 2017;212:120-129. doi:10.1016/j.biocon.2017.06.001

121. Loury EK, Ainsley S, Bower S, Chuenpagdee R, Farrell T, Guthrie AG, Heng S, Lunn Z, Mamun A, Oyanedel R, Rocliffe S, Satumanatpan S, Cooke S. Salty stories, fresh spaces: Lessons for aquatic protected areas from marine and freshwater experiences. Published online 2018. doi:10.1002/AQC.2868

122. Bellard C, Marino C, Courchamp F. Ranking threats to biodiversity and why it doesn't matter. *Nat Commun*. 2022;13(1):2616. doi:10.1038/s41467-022-30339-y

123. Acreman M, Hughes KA, Arthington AH, Tickner D, Dueñas MA. Protected areas and freshwater biodiversity: a novel systematic review distils eight lessons for effective conservation. *Conservation Letters*. 2019;13(1):1. doi:https://doi.org/10.1111/conl.12684

124. Dudgeon D. Multiple threats imperil freshwater biodiversity in the Anthropocene. *Current Biology*. 2019;29(19):R960-R967. doi:10.1016/j.cub.2019.08.002

125. Blicharska M, Orlikowska E, Roberge JM, Grodzińska-Jurczak M. Contribution of social science to large scale biodiversity conservation: A review of research about the Natura 2000 network. *Biological Conservation*. 2016;199:110-122. doi:10.1016/j.biocon.2016.05.007

126. Orlikowska EH, Roberge JM, Blicharska M, Mikusiński G. Gaps in ecological research on the world's largest internationally coordinated network of protected areas: A review of Natura 2000. *Biological Conservation*. 2016;200:216-227. doi:10.1016/j.biocon.2016.06.015

127. Kati V, Hovardas T, Dieterich M, Ibisch PL, Mihok B, Selva N. The challenge of implementing the European network of protected areas Natura 2000. *Conservation Biology*. 2015;29(1):260-270. doi:https://doi.org/10.1111/cobi.12366

128. Campagnaro T, Sitzia T, Bridgewater P, Evans D, Ellis E. Half Earth or Whole Earth: What Can Natura 2000 Teach Us? *BioScience*. 2019;69. doi:10.1093/biosci/biy153

129. The Council of the European Communities. *Council Directive of 2 April 1979 on the Conservation of Wild Birds (79/409/EEC)*. 2008. Accessed August 13, 2023. http://data.europa.eu/eli/dir/1979/409/2008-12-23/eng

130. Council of Europe. Emerald Network of Areas of Special Conservation Interest - Convention on the Conservation of European Wildlife and Natural Habitats - www.coe.int. Convention on the Conservation of European Wildlife and Natural Habitats. 2023. Accessed October 8, 2023. https://www.coe.int/en/web/bern-convention/emerald-network

131. European Environment Agency. Natura 2000 Barometer. October 6, 2022. Accessed October 9, 2023. https://www.eea.europa.eu/data-and-maps/dashboards/natura-2000-barometer

132. Hermoso V, Filipe AF, Segurado P, Beja P. Filling gaps in a large reserve network to address freshwater conservation needs. *Journal of Environmental Management*. 2015;161:358-365. doi:10.1016/j.jenvman.2015.07.023

133. Tsavdaridou AI, Moustaka-Gouni M, Katsiapi M, Mazaris AD. Gaps in the protection of European lakes. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2019;29(10):1726-1734. doi:10.1002/aqc.3218

134. Papazekou M, Tsavdaridou AI, Almpanidou V, Mazaris AD. A river-based approach in reconstructing connectivity among protected areas: Insights and challenges from the Balkan region. *Journal for Nature Conservation*. 2022;67:126182. doi:10.1016/j.jnc.2022.126182

135. Néry F. *WISE WFD Protected Area Spatial Data Set Technical Report*. European Environment Agency; 2021:13. Accessed October 11, 2023. https://sdi.eea.europa.eu/data/40e6624e-cd58-4183-8a5d-61795100b133?dir=undefined&path=%2Fdocs&openfile=563339

136. Schmedtje, Kremer. *Links between the Water Framework Directive and Nature Directives, Frequently Asked Questions*. European Commission; 2011:31. Accessed February 24, 2022. https://ec.europa.eu/environment/nature/natura2000/management/docs/FAQ-WFD%20final.pdf

137. European Environment Agency. WISE WFD Protected Areas under the Water Framework Directive. European Environment Agency Datahub. June 26, 2023. Accessed September 11, 2023. https://www.eea.europa.eu/en/datahub/datahubitem-view/06c3dcab-77bd-462b-b19e-32ac72d9155d

138. UNEP-WCMC and IUCN. Protected Planet - Discover the world's protected areas. Protected Planet. October 10, 2023. Accessed October 10, 2023. https://www.protectedplanet.net/en

139. European Environment Agency. *Protected Areas in Europe :An Overview.* Publications Office; 2012. Accessed October 18, 2021. https://data.europa.eu/doi/10.2800/55955

140. Opperman J, Shahbol N, Maynard J, Grill G, Higgins J, Tracey D, Thieme M. Safeguarding Free-Flowing Rivers: The Global Extent of Free-Flowing Rivers in Protected Areas. *Sustainability*. 2021;13:2805. doi:10.3390/su13052805

141. IUCN. Vjosa, one of our last wild rivers, becomes Europe's first Wild River National Park - Press release. March 15, 2023. Accessed October 9, 2023. https://www.iucn.org/press-release/202303/vjosa-one-our-last-wild-rivers-becomes-europes-first-wild-river-national-park

142. Ministry of Tourism and Environment of Albania. Vjosa Wild River National Park. Vjosa National Park. 2023. Accessed October 9, 2023. https://www.vjosanationalpark.al/

143. Schäfer T. Legal Protection Schemes for Free-Flowing Rivers in Europe: An Overview. *Sustainability*. 2021;13(11):11. doi:10.3390/su13116423

144. IUCN. *A Global Standard for the Identification of Key Biodiversity Areas*. nternational Union for Conservation of Nature; 2016:46. https://portals.iucn.org/library/sites/library/files/documents/2016-048.pdf

145. Our World in Data. Share of freshwater Key Biodiversity Areas that are protected. Source data, BirdLife International, International Union for Conservation of Nature and United Nations Environment Programme. Our World in Data. 2023. Accessed October 14, 2023. https://ourworldindata.org/grapher/proportion-of-important-sites-for-freshwater-biodiversity-covered-by-protected-areas?tab=chart

146. Verniest F, Galewski T, Julliard R, Guelmami A, Le Viol I. Coupling future climate and land-use projections reveals where to strengthen the protection of Mediterranean Key Biodiversity Areas. *Conservation Science and Practice*. 2022;4(11):e12807. doi:10.1111/csp2.12807

147. Carrizo SF, Lengyel S, Kapusi F, Szabolcs M, Kasperidus HD, Scholz M, Markovic D, Freyhof J, Cid N, Cardoso AC, Darwall W. Critical catchments for freshwater biodiversity conservation in Europe: identification, prioritisation and gap analysis. *Journal of Applied Ecology*. 2017;54(4):1209-1218. doi:10.1111/1365-2664.12842

148. UNEP-WCMC and IUCN. Protected Planet - Discover the world's protected areas. Protected Planet. October 10, 2023. Accessed October 10, 2023. https://www.protectedplanet.net/en

149. EEA. The European inventory of Nationally designated areas. Datahub Nationally Designated Areas. August 11, 2026. Accessed August 19, 2026. https://www.eea.europa.eu/en/datahub/datahubitem-view/f60cec02-6494-4d08-b12d-17a37012cb28

150. Gaston KJ, Jackson SF, Nagy A, Cantú-Salazar L, Johnson M. Protected Areas in Europe. *Annals of the New York Academy of Sciences*. 2008;1134(1):97-119. doi:https://doi.org/10.1196/annals.1439.006

151. UNEP-WCMC. Protected Area Profile for Europe from the World Database on Protected Areas, October 2023. Protected Planet. 2023. Accessed October 10, 2023. https://www.protectedplanet.net/region/EU

152. Bakar A, Suratman MN. *Protected Areas, National Parks and Sustainable Future*. BoD – Books on Demand; 2020.

153. European Commission. Nature protection: Commission establishes largest ever list of protected areas in the EU. European Commission - European Commission. December 8, 2004. Accessed October 18, 2021. https://ec.europa.eu/commission/presscorner/detail/en/IP_04_1449

154. Moreno-Saiz JC, Albertos B, Ruiz-Molero E, Mateo RG. The European Union can afford greater ambition in the conservation of its threatened plants. *Biological Conservation*. 2021;261:109231. doi:10.1016/j.biocon.2021.109231

155. UNEP. Key biodiversity areas and biodiversity conservation targets. Published online May 1, 2018. Accessed October 15, 2023. https://www.cbd.int/doc/c/f608/8caf/71b9bcd5f00870cc5cf39b66/sbstta-22-inf-37-en.pdf

156. KeyBiodiversityAreas.org. KBA Data from KBA Global Dataset. September 2023. Accessed October 11, 2023. https://www.keybiodiversityareas.org/kba-data

157. Borrini-Feyerabend, Dudley N, Jaeger T, Lassen B, Pathak Broome N, Phillips A, Sandwith T. *Governance of Protected Areas: From Understanding to Action. Best Practice Protected Area Guidelines Series No. 20, Gland, Switzerland: IUCN. Xvi + 124pp.* 2013.

158. Nolan M, Rodriguez A, Rajaobelinirina JE, Hugu S, Bocchino C. Enhancing the diversity, quality and vitality of governance of protected and conserved areas. Published online 2014. Accessed August 30, 2021. https://www.academia.edu/25012090/Enhancing_the_diversity_quality_and_vitality_of_governance_of_protected_and_conserved_areas

159. UNEP-WCMC. Protected Area Profile by country from the World Database on Protected Areas, October 2023. Protected Planet. 2023. Accessed October 10, 2023. https://www.protectedplanet.net/country

160. Kingsford RT, Biggs HC, Pollard SR. Strategic Adaptive Management in freshwater protected areas and their rivers. *Biological Conservation*. 2011;144(4):4. doi:10.1016/j.biocon.2010.09.022

161. Rivers-Moore N, Mantel S, Ramulifo P, Dallas H. A disconnectivity index for improving choices in managing protected areas for rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2016;26(S1):29-38. doi:10.1002/aqc.2661

162. Opermanis O, MacSharry B, Evans D, Sipkova Z. Is the connectivity of the Natura 2000 network better across internal or external administrative borders? *Biological Conservation*. 2013;166:170-174. doi:10.1016/j.biocon.2013.06.019

163. Lai S. Hindrances to Effective Implementation of the Habitats Directive in Italy: Regional Differences in Designating Special Areas of Conservation. *Sustainability*. 2020;12(6):6. doi:10.3390/su12062335

164. European Court of Auditors. *More Efforts Needed to Implement the Natura 2000 Network to Its Full Potential (Pursuant to Article 287(4), Second Subparagraph, TFEU).* 2020:63. Accessed November 11, 2023. http://www.eca.europa.eu/en/publications/sr17_1

165. Robinson JL, Fordyce JA, Parker CR. Conservation of aquatic insect species across a protected area network: null model reveals shortfalls of biogeographical knowledge. *J Insect Conserv*. 2016;20(4):565-581. doi:10.1007/s10841-016-9889-3

166. Hermoso V, Morán-Ordóñez A, Lanzas M, Brotons L. Designing a network of green infrastructure for the EU. *Landscape and Urban Planning*. 2020;196:103732. doi:10.1016/j.landurbplan.2019.103732

167. Margules CR, Pressey RL. Systematic conservation planning. *Nature*. 2000;405(6783):6783. doi:10.1038/35012251

168. Maes J, Barbosa A, Baranzelli C, Zulian G, Batista e Silva F, Vandecasteele I, Hiederer R, Liquete C, Paracchini ML, Mubareka S, Jacobs-Crisioni C, Castillo CP, Lavalle C. More green infrastructure is required to maintain ecosystem services under current trends in land-use change in Europe. *Landscape Ecol*. 2015;30(3):517-534. doi:10.1007/s10980-014-0083-2

169. Coetzer KL, Witkowski ETF, Erasmus BFN. Reviewing Biosphere Reserves globally: effective conservation action or bureaucratic label? *Biological Reviews*. 2014;89(1):82-104. doi:10.1111/brv.12044

170. Publications Office of the EU. National transposition - EUR-Lex. Eur-Lex Access to European Union Law. 2023. Accessed October 15, 2023. https://eur-lex.europa.eu/collection/n-law/mne.html

171. Hödl E. Legislative Framework for River Ecosystem Management on International and European Level. In: Schmutz S, Sendzimir J, eds. *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future*. Aquatic Ecology Series. Springer International Publishing; 2018:325-345. doi:10.1007/978-3-319-73250-3_17

172. Mayes E, Codling I. WATER FRAMEWORK DIRECTIVE AND RELATED MONITORING PROGRAMMES. *Biology and Environment: Proceedings of the Royal Irish Academy*. 2009;109B(3):321-344.

173. Janauer GA, Albrecht J, Stratmann L. Synergies and Conflicts Between Water Framework Directive and Natura 2000: Legal Requirements, Technical Guidance and Experiences from Practice. In: Ignar S, Grygoruk M, eds. *Wetlands and Water Framework Directive: Protection, Management and Climate Change*. GeoPlanet: Earth and Planetary Sciences. Springer International Publishing; 2015:9-29. doi:10.1007/978-3-319-13764-3_2

174. Boeuf B, Fritsch O, Martin-Ortega J. Undermining European Environmental Policy Goals? The EU Water Framework Directive and the Politics of Exemptions. *Water*. 2016;8(9):9. doi:10.3390/w8090388

175. Richter S, Völker J, Borchardt D, Mohaupt V. The Water Framework Directive as an approach for Integrated Water Resources Management: Results from the experiences in Germany on implementation, and future perspectives. *Environmental earth sciences*. 2013;69:719-728. doi:10.1007/s12665-013-2399-7

176. Starke JR, Van Rijswick HFMW. Exemptions of the EU Water Framework Directive Deterioration Ban: Comparing Implementation Approaches in Lower Saxony and The Netherlands. *Sustainability*. 2021;13(2):2. doi:10.3390/su13020930

177. Stefanidis K, Oikonomou A, Stoumboudi M, Dimitriou E, Skoulikidis NT. Do Water Bodies Show Better Ecological Status in Natura 2000 Protected Areas Than Non-Protected Ones?—The Case of Greece. *Water*. 2021;13(21):21. doi:10.3390/w13213007

178. Nieto C, Ovando XMC, Loyola R, Izquierdo A, Romero F, Molineri C, Rodríguez J, Martín PR, Fernández H, Manzo V, Miranda MJ. The role of macroinvertebrates for conservation of freshwater systems. *Ecology and Evolution*. 2017;7(14):5502-5513. doi:10.1002/ece3.3101

179. Chessman BC. Do protected areas benefit freshwater species? A broad-scale assessment for fish in Australia's Murray–Darling Basin. *Journal of Applied Ecology*. 2013;50(4):969-976. doi:10.1111/1365-2664.12104

180. Hermoso V, Filipe AF, Segurado P, Beja P. Effectiveness of a large reserve network in protecting freshwater biodiversity: a test for the Iberian Peninsula. *Freshwater Biology*. 2015;60(4):698-710. doi:10.1111/fwb.12519

181. Cañedo-Argüelles M, Hermoso V, Herrera-Grao T, Barquín J, Bonada N. Freshwater conservation planning informed and validated by public participation: The Ebro catchment, Spain, as a case study. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2019;29(8):1253-1267. doi:https://doi.org/10.1002/aqc.3108

182. Adams VM, Setterfield SA, Douglas MM, Kennard MJ, Ferdinands K. Measuring benefits of protected area management: trends across realms and research gaps for freshwater systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2015;370(1681):20140274. doi:10.1098/rstb.2014.0274

183. Choy M, Lawrie D, Edge CB. Measuring 30 years of improvements to aquatic connectivity in the Greater Toronto Area. *Aquatic Ecosystem Health & Management*. 2018;21(3):342-351. doi:10.1080/14634988.2018.1497400

184. Dias BS, Frisk MG, Jordaan A. Opening the tap: Increased riverine connectivity strengthens marine food web pathways. *PLOS ONE*. 2019;14(5):e0217008. doi:10.1371/journal.pone.0217008

185. Schofield KA, Alexander LC, Ridley CE, Vanderhoof MK, Fritz KM, Autrey BC, DeMeester JE, Kepner WG, Lane CR, Leibowitz SG, Pollard AI. Biota Connect Aquatic Habitats throughout Freshwater Ecosystem Mosaics. *JAWRA Journal of the American Water Resources Association*. 2018;54(2):372-399. doi:10.1111/1752-1688.12634

186. Chardon V, Euzen C, Schmitt L. Functional river restoration as a lever for adapting to climate change from an interdisciplinary emblematic showcase on the Upper Rhine. *Journal of Environmental Management*. 2025;393:127151. doi:10.1016/j.jenvman.2025.127151

187. Pârvulescu L, Iorgu EI, Zaharia C, Ion MC, Satmari A, Krapal AM, Popa OP, Miok K, Petrescu I, Popa LO. The future of endangered crayfish in light of protected areas and habitat fragmentation. *Sci Rep*. 2020;10(1):1. doi:10.1038/s41598-020-71915-w

188. Linke S, Turak E, Nel J. Freshwater conservation planning: The case for systematic approaches. *Freshwater Biology*. 2010;56:6-20. doi:10.1111/j.1365-2427.2010.02456.x

189. Rodríguez-Merino A, García-Murillo P, Fernández-Zamudio R. Combining multicriteria decision analysis and GIS to assess vulnerability within a protected area: An objective methodology for managing complex and fragile systems. *Ecological Indicators*. 2020;108:105738. doi:10.1016/j.ecolind.2019.105738

190. Linke S, Hermoso V, Januchowski-Hartley S. Toward process-based conservation prioritizations for freshwater ecosystems. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2019;29(7):1149-1160. doi:10.1002/aqc.3162

191. Staccione A, Brown C, Arneth A, Rounsevell M, Hrast Essenfelder A, Seo B, Mysiak J. Exploring the effects of protected area networks on the European land system. *Journal of Environmental Management*. 2023;337:117741. doi:10.1016/j.jenvman.2023.117741

192. Zealand AM, Jeffries MJ. The distribution of pond snail communities across a landscape: separating out the influence of spatial position from local habitat quality for ponds in south-east Northumberland, UK. *Hydrobiologia*. 2009;632(1):177-187. doi:10.1007/s10750-009-9837-2

193. Watson J, McAllister K, Pierce D. Home Ranges, Movements, and Habitat Selection of Oregon Spotted Frogs (Rana pretiosa). *Journal of Herpetology*. 2009;37:292-300. doi:10.1670/0022-1511(2003)037[0292:HRMAHS]2.0.CO;2

194. Smaniotto N, Moreira L, Rivas J, Strüssmann C. Home range size, movement, and habitat use of yellow anacondas (Eunectes notaeus). *Salamandra*. 2020;56:159-167.

195. Hancock MH, Robson HJ, Smith TD, Douse A. Spatial and temporal patterns of foraging activity by breeding Common Scoters (Melanitta nigra) in Scotland. 2019;96.

196. Davies BR, Biggs J, Williams PJ, Lee JT, Thompson S. A comparison of the catchment sizes of rivers, streams, ponds, ditches and lakes: implications for protecting aquatic biodiversity in an agricultural landscape. *Hydrobiologia*. 2008;597(1):7-17. doi:10.1007/s10750-007-9227-6

197. Davies B, Biggs J, Williams P, Whitfield M, Nicolet P, Sear D, Bray S, Maund S. Comparative biodiversity of aquatic habitats in the European agricultural landscape. *Agriculture, Ecosystems & Environment*. 2008;125(1):1-8. doi:10.1016/j.agee.2007.10.006

198. Hill MJ, White JC, Biggs J, Briers RA, Gledhill D, Ledger ME, Thornhill I, Wood PJ, Hassall C. Local contributions to beta diversity in urban pond networks: Implications for biodiversity conservation and management. *Diversity and Distributions*. 2021;27(5):887-900. doi:10.1111/ddi.13239

199. Colding J, Lundberg J, Lundberg S, Andersson E. Golf Courses and Wetland Fauna. *Ecological Applications*. 2009;19(6):1481-1491.

200. Fang WT, Cheng BY, Shih SS, Chou JY, Otte ML. Modeling driving forces of avian diversity in a spatial configuration surrounded by farm ponds. *Paddy Water Environ*. 2016;14(1):185-197. doi:10.1007/s10333-015-0489-8

201. Schiesari L, Saito V, Ferreira J, Freitas L, Goebbels A, Leite J, Oliveira J, Pelinson R, Querido B, Carmo J, Espíndola E, Guedes-Munin N, Montagner C, Rossetto R, Taniwaki R, Martinelli L. Community reorganization stabilizes freshwater ecosystems in intensively managed agricultural fields. *Journal of Applied Ecology*. 2023;60:1-13. doi:10.1111/1365-2664.14423

202. Clarke SJ. Conserving freshwater biodiversity: The value, status and management of high quality ditch systems. *Journal for Nature Conservation*. 2015;24:93-100. doi:https://doi.org/10.1016/j.jnc.2014.10.003

203. González E, Felipe-Lucia MR, Bourgeois B, Boz B, Nilsson C, Palmer G, Sher AA. Integrative conservation of riparian zones. *Biological Conservation*. 2017;211:20-29. doi:10.1016/j.biocon.2016.10.035

204. Ekness P, Randhir T. Effects of Riparian Areas, Stream Order, and Land Use Disturbance on Watershed-Scale Habitat Potential: An Ecohydrologic Approach to Policy1. *JAWRA Journal of the American Water Resources Association*. 2007;43(6):1468-1482. doi:10.1111/j.1752-1688.2007.00102.x

205. Maire A, Laffaille P, Maire JF, Buisson L. Identification of Priority Areas for the Conservation of Stream Fish Assemblages: Implications for River Management in France. *River Research and Applications*. 2017;33(4):524-537. doi:10.1002/rra.3107

206. Donald PF, Buchanan GM, Balmford A, Bingham H, Couturier AR, de la Rosa Jr. GE, Gacheru P, Herzog SK, Jathar G, Kingston N, Marnewick D, Maurer G, Reaney L, Shmygaleva T, Sklyarenko S, Stevens CMD, Butchart SHM. The prevalence, characteristics and effectiveness of Aichi Target 11's "other effective area-based conservation measures" (OECMs) in Key Biodiversity Areas. *Conservation Letters*. 2019;12(5):e12659. doi:10.1111/conl.12659

207. Nikolaus R, Matern S, Schafft M, Maday A, Wolter C, Klefoth T, Arlinghaus R. Influence of protected riparian areas on habitat structure and biodiversity in and at small lakes managed by recreational fisheries. *Fisheries Research*. 2022;256:106476. doi:10.1016/j.fishres.2022.106476

208. Dudley N, Parrish J, Redford K, Stolton S. The revised IUCN protected area management categories: The debate and ways forward. *Oryx*. 2010;44. doi:10.1017/S0030605310000566

209. Elleason M, Guan Z, Deng Y, Jiang A, Goodale E, Mammides C. Strictly protected areas are not necessarily more effective than areas in which multiple human uses are permitted. *Ambio*. 2021;50(5):1058-1073. doi:10.1007/s13280-020-01426-5

210. Leroux S, Krawchuk M, Schmiegelow F, Cumming S, Lisgo K, Anderson L, Petkova M. Global protected areas and IUCN designations: Do the categories match the conditions? *Biological Conservation*. 2010;143:609-616. doi:10.1016/j.biocon.2009.11.018

211. Jones KR, Venter O, Fuller RA, Allan JR, Maxwell SL, Negret PJ, Watson JEM. One-third of global protected land is under intense human pressure. *Science*. 2018;360(6390):788-791. doi:10.1126/science.aap9565

212. Muñoz L, Hausner VH. What Do the IUCN Categories Really Protect? A Case Study of the Alpine Regions in Spain. *Sustainability*. 2013;5(6):6. doi:10.3390/su5062367

213. Gray CL, Hill SLL, Newbold T, Hudson LN, Börger L, Contu S, Hoskins AJ, Ferrier S, Purvis A, Scharlemann JPW. Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature Communications*. 2016;7(1):1. doi:10.1038/ncomms12306

214. Müller A, Schneider UA, Jantke K. Evaluating and expanding the European Union's protected-area network toward potential post-2020 coverage targets. *Conservation Biology*. 2020;34(3):654-665. doi:https://doi.org/10.1111/cobi.13479

215. Phang SC, Failler P, Bridgewater P. Addressing the implementation challenge of the global biodiversity framework. *Biodivers Conserv*. 2020;29(9):3061-3066. doi:10.1007/s10531-020-02009-2

216. Watson J, Darling E, Venter O, Maron M, Walston J, Possingham H, Dudley N, Hockings M, Barnes M, Brooks T. Bolder science needed now for protected areas. *Conservation biology : the journal of the Society for Conservation Biology*. 2015;30. doi:10.1111/cobi.12645

217. Geldmann J, Manica A, Burgess ND, Coad L, Balmford A. A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *PNAS*. 2019;116(46):23209-23215. doi:10.1073/pnas.1908221116

218. Miu IV, Rozylowicz L, Popescu VD, Anastasiu P. Identification of areas of very high biodiversity value to achieve the EU Biodiversity Strategy for 2030 key commitments. *PeerJ*. 2020;8:e10067. doi:10.7717/peerj.10067

219. Linke S, Pressey RL, Bailey RC, Norris RH. Management options for river conservation planning: condition and conservation re-visited. *Freshwater Biology*. 2007;52(5):918-938. doi:10.1111/j.1365-2427.2006.01690.x

220. Yadav P, Kumar A, Hussain SA, Gupta SK. Evaluation of the effect of longitudinal connectivity in population genetic structure of endangered golden mahseer, Tor putitora (Cyprinidae), in Himalayan rivers: Implications for its conservation. *PLOS ONE*. 2020;15(6):e0234377. doi:10.1371/journal.pone.0234377

221. Gobbi M, Riservato E, Bragalanti N, Lencioni V. An expert-based approach to invertebrate conservation: Identification of priority areas in central-eastern Alps. *Journal for Nature Conservation*. 2012;20(5):274-279. doi:10.1016/j.jnc.2012.05.003

222. Gimenez L. Incoporating the geometry of Dispersal and migration to understand spatial patterns of species distributions. *Ecography*. 2018;42. doi:10.1111/ecog.03493

223. Davies P, Britton JR, Nunn AD, Dodd JR, Bainger C, Velterop R, Bolland JD. Cumulative impacts of habitat fragmentation and the environmental factors affecting upstream migration in the threatened sea lamprey, Petromyzon marinus. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2021;31(9):2560-2574. doi:10.1002/aqc.3625

224. Karatayev VA, Burlakova LE, Karatayev AY, Yang L, Miller T. Advection exacerbates population decline from habitat loss: maintaining threatened taxa while restoring natural river flow regimes. *Oecologia*. 2020;193(3):773-785. doi:10.1007/s00442-020-04706-9

225. Sánchez-Fernández D, Baquero RA, Velasco L, Aranda A, Nicola GG. Assessing the role of the aquatic Natura 2000 network to protect both freshwater European species of community interest and threatened species in a Mediterranean region. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 2021;31(7):1901-1911. doi:10.1002/aqc.3540

226. Dudley N, Parish J. *Closing the Gap Creating Ecologically Representative Protected Area Systems*. 2006. Accessed March 14, 2021. https://www.cbd.int/doc/publications/cbd-ts-24.pdf

227. Mancini L, Formichetti P, Anselmo A, Tancioni L, Marchini S, Sorace A. Biological quality of running waters in protected areas: The influence of size and land use. *Biodiversity and Conservation*. 2005;14:351-364. doi:10.1007/s10531-004-5355-8

228. Joppa L, Baillie J, Robinson J. *Protected Areas. Are They Safeguarding Biodiversity?* Wiley-Blackwell; 2016. https://www.researchgate.net/publication/318404691_Protected_Areas_Are_they_safeguarding_biodiversity

229. The European Parliament. *European Parliament Resolution of 15 November 2017 on an Action Plan for Nature, People and the Economy (2017/2819(RSP))*. 2017:6. Accessed November 10, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017IP0441

230. Binder TR, Marsden JE, Riley SC, Johnson JE, Johnson NS, He J, Ebener M, Holbrook CM, Bergstedt RA, Bronte CR, Hayden TA, Krueger CC. Movement patterns and spatial segregation of two populations of lake trout Salvelinus namaycush in Lake Huron. *Journal of Great Lakes Research*. 2017;43(3):108-118. doi:10.1016/j.jglr.2017.03.023

231. Cañas CM, Pine III WE. Documentation of the temporal and spatial patterns of pimelodidae catfish spawning and larvae dispersion in the madre de Dios River (Peru): Insights for conservation in the Andean-Amazon headwaters. *River Research and Applications*. 2011;27(5):602-611. doi:10.1002/rra.1377

232. Brumm KJ, Hanks RD, Baldwin RF, Peoples BK. A scale-linked conservation planning framework for freshwater ecosystems. *Landsc Ecol*. 2022;37(10):10. doi:10.1007/s10980-022-01505-w

233. Geist J. Integrative freshwater ecology and biodiversity conservation. *Ecological Indicators*. 2011;11(6):1507-1516. doi:10.1016/j.ecolind.2011.04.002

234. Zalewski M. Chapter 4 - The role of abiotic and biotic factors in regulating ecosystem processes. In: Zalewski M, Wolanski E, Elliott M, Richmond RH, eds. *Transdisciplinary Ecohydrology*. Ecohydrology from Catchment to Coast. Elsevier; 2026:59-70. doi:10.1016/B978-0-443-41596-8.00008-X

235. Nel JL, Reyers B, Roux DJ, Cowling RM. Expanding protected areas beyond their terrestrial comfort zone: Identifying spatial options for river conservation. *Biological Conservation*. 2009;142(8):1605-1616. doi:10.1016/j.biocon.2009.02.031

236. Ranius T, Widenfalk LA, Seedre M, Lindman L, Felton A, Hämäläinen A, Filyushkina A, Öckinger E. Protected area designation and management in a world of climate change: A review of recommendations. *Ambio*. 2023;52(1):68-80. doi:10.1007/s13280-022-01779-z

237. Yu S, Rose P, Bond N, Stuart, Bunn S, Kennard M. Identifying priority aquatic refuges to sustain freshwater biodiversity in intermittent streams in eastern Australia. *Aquatic Conservation Marine and Freshwater Ecosystems*. 2022;32. doi:10.1002/aqc.3871

238. European Commission. *ANNEX to the Communication to the Commission Approval of the Content of a Draft Commission Notice on the Guidance on Natura 2000 and Climate Change*. European Commission; 2026:120. Accessed March 30, 2026. https://environment.ec.europa.eu/document/download/208a9b47-653e-45da-9b22-2bffcbcc38a8_en?filename=C_2026_2031_1_EN_annexe_acte_autonome_cp_part1_v4.pdf

239. Baldwin RF, Beazley KF. Emerging Paradigms for Biodiversity and Protected Areas. *Land*. 2019;8(3):3. doi:10.3390/land8030043

240. Dudley N, Mulongoy KJ, Cohen S, Stolton S, Barber CV, Gidda S. Towards Effective Protected Area Systems An Action Guide to Implement the Convention on Biological Diversity Programme of Work on Protected Areas. *Technical Series*. 2005;No. 18, 108 pages.

241. Davis M, Naumann S, McFarland K, Graf A, Evans D. *Literature Review - The Ecological Effectiveness of the Natura 2000 Network*. 2014. doi:10.13140/RG.2.1.4358.9288

242. Paavola J. Protected Areas Governance and Justice: Theory and the European Union's Habitats Directive. *Environmental Sciences*. 2004;1:59-77. doi:10.1076/evms.1.1.59.23763

243. Cooke SJ, Harrison I, Thieme ML, Landsman SJ, Birnie-Gauvin K, Raghavan R, Creed IF, Pritchard G, Ricciardi A, Hanna DEL. Is it a new day for freshwater biodiversity? Reflections on outcomes of the Kunming-Montreal Global Biodiversity Framework. *PLOS Sustainability and Transformation*. 2023;2(5):e0000065. doi:10.1371/journal.pstr.0000065

244. European Commission. *REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on the Implementation of the Water Framework Directive (2000/60/EC), the Environmental Quality Standards Directive (2008/105/EC Amended by Directive 2013/39/EU) and the Floods Directive (2007/60/EC) Implementation of Planned Programmes of Measures, New Priority Substances, Preliminary Flood Risk Assessments and Areas of Potential Significant Flood Risk*. 2021:18. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0970

245. Carvalho L, Mackay EB, Cardoso AC, Baattrup-Pedersen A, Birk S, Blackstock KL, Borics G, Borja A, Feld CK, Ferreira MT, Globevnik L, Grizzetti B, Hendry S, Hering D, Kelly M, Langaas S, Meissner K, Panagopoulos Y, Penning E, Rouillard J, Sabater S, Schmedtje U, Spears BM, Venohr M, van de Bund W, Solheim AL. Protecting and restoring Europe's waters: An analysis of the future development needs of the Water Framework Directive. *Science of The Total Environment*. 2019;658:1228-1238. doi:10.1016/j.scitotenv.2018.12.255

246. European Commission. New Nature Restoration Law boosts biodiversity and climate action across Europe. European Climate, Infrastructure and Environment Executive Agency. July 12,

2023. Accessed October 9, 2023. https://cinea.ec.europa.eu/news-events/news/new-nature-restoration-law-boosts-biodiversity-and-climate-action-across-europe-2023-07-12_en

247. Kristensen P, Whalley C, Nery F, Christiansen T, Schmedtje U, Solheim A, Austnes K, Kampa E, Rouillard J, Prchalová H, Klančnik K, Völker J, Peterlin M, Fribourg-Blanc B, Prins T, Kodes V, Persson J, Baltas E, Bariamis G. *European Waters -- Assessment of Status and Pressures 2018*. European Environment Agency; 2018. Accessed June 16, 2025. https://www.eea.europa.eu/en/analysis/publications/state-of-water

248. Acreman MC, Ferguson AJD. Environmental flows and the European Water Framework Directive. *Freshwater Biology*. 2010;55(1):32-48. doi:10.1111/j.1365-2427.2009.02181.x

249. EEA. Ecological status of surface waters in Europe. Indicators. November 18, 2021. Accessed October 11, 2023. https://www.eea.europa.eu/ims/ecological-status-of-surface-waters

250. EEA. European waters -- Assessment of status and pressures 2018 — European Environment Agency. 2018. Accessed June 13, 2022. https://www.eea.europa.eu/publications/state-of-water

251. EEA. Habitats and species: latest status and trends. April 4, 2023. Accessed October 11, 2023. https://www.eea.europa.eu/en/topics/at-a-glance/nature/state-of-nature-in-europe-a-health-check/habitats-and-species-latest-status-and-trends

252. EEA. Habitats and species: main pressures and threats. June 2, 2023. Accessed October 11, 2023. https://www.eea.europa.eu/en/topics/at-a-glance/nature/state-of-nature-in-europe-a-health-check/habitats-and-species-main-pressures-and-threats

253. Nunes A, Tricarico E, Panov V, Cardoso A, Katsanevakis S. Pathways and gateways of freshwater invasions in Europe. *Aquatic Invasions*. 2015;10:359-370. doi:10.3391/ai.2015.10.4.01

254. European Commission, Directorate-General for the Environment. *Analysis of Pressures and Impacts No 3. No 3.* OPOCE; 2003. Accessed September 14, 2021. http://bookshop.europa.eu/uri?target=EUB:NOTICE:KH5103180:EN:HTML

255. AMBER Consortium. The AMBER Barrier Atlas. A Pan-European database of artificial instream barriers. Version 1. 2020. Accessed October 11, 2023. https://amber.international/european-barrier-atlas/

256. European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Our life insurance, our natural capital: an EU biodiversity strategy to 2020 COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Our life insurance, our natural capital: an EU biodiversity strategy to 2020. May 3, 2011. Accessed October 17, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52011DC0244

257. Koehnken L, Rintoul MS, Goichot M, Tickner D, Loftus AC, Acreman MC. Impacts of riverine sand mining on freshwater ecosystems: A review of the scientific evidence and guidance for future research. *River Research and Applications*. 2020;36(3):362-370. doi:https://doi.org/10.1002/rra.3586

258. Leal Filho W, Hunt J, Lingos A, Platje J, Vieira LW, Will M, Gavriletea MD. The Unsustainable Use of Sand: Reporting on a Global Problem. *Sustainability*. 2021;13(6):6. doi:10.3390/su13063356

259. European Parliament and Council of the EU. *Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the Prevention and Management of the Introduction and Spread of Invasive Alien Species*. Vol 317. 2014. Accessed July 24, 2022. http://data.europa.eu/eli/reg/2014/1143/oj/eng

260. Buchanan BP, Sethi SA, Cuppett S, Lung M, Jackman G, Zarri L, Duvall E, Dietrich J, Sullivan P, Dominitz A, Archibald JA, Flecker A, Rahm BG. A machine learning approach to identify barriers in stream networks demonstrates high prevalence of unmapped riverine dams. *Journal of Environmental Management*. 2022;302:113952. doi:10.1016/j.jenvman.2021.113952

261. O'Grady J, Burghina CB, Regan F. Catchment-Based Water Monitoring Using a Hierarchy of Sensor Types. In: Di Mauro A, Scozzari A, Soldovieri F, eds. *Instrumentation and Measurement Technologies for Water Cycle Management*. Springer International Publishing; 2022:341-362. doi:10.1007/978-3-031-08262-7_14

262. Geetha S, Gouthami S. Internet of things enabled real time water quality monitoring system. *Smart Water*. 2017;2(1):1. doi:10.1186/s40713-017-0005-y

263. Evans JG, Wass PD, Hodgson P. Integrated continuous water quality monitoring for the LOIS river syndromme. *Science of The Total Environment*. 1997;194-195:111-118. doi:10.1016/S0048-9697(96)05387-9

264. Chapin TP, Caffrey JM, Jannasch HW, Coletti LJ, Haskins JC, Johnson KS. Nitrate sources and sinks in Elkhorn Slough, California: Results from long-term continuous in situ nitrate analyzers. *Estuaries*. 2004;27(5):882-894. doi:10.1007/BF02912049

265. Jones TD, Chappell NA, Tych W. First Dynamic Model of Dissolved Organic Carbon Derived Directly from High-Frequency Observations through Contiguous Storms. *Environ Sci Technol*. 2014;48(22):13289-13297. doi:10.1021/es503506m

266. Jordan P, Arnscheidt A, McGrogan H, McCormick S. Characterising phosphorus transfers in rural catchments using a continuous bank-side analyser. *Hydrology and Earth System Sciences*. 2007;11(1):372-381. doi:10.5194/hess-11-372-2007

267. von Freyberg J, Studer B, Kirchner JW. A lab in the field: high-frequency analysis of water quality and stable isotopes in stream water and precipitation. *Hydrology and Earth System Sciences*. 2017;21(3):1721-1739. doi:10.5194/hess-21-1721-2017

268. de Camargo ET, Spanhol FA, Slongo JS, da Silva MVR, Pazinato J, de Lima Lobo AV, Coutinho FR, Pfrimer FWD, Lindino CA, Oyamada MS, Martins LD. Low-Cost Water Quality Sensors for IoT: A Systematic Review. *Sensors*. 2023;23(9):4424. doi:10.3390/s23094424

269. Leigh C, Kandanaarachchi S, McGree JM, Hyndman RJ, Alsibai O, Mengersen K, Peterson EE. Predicting sediment and nutrient concentrations from high-frequency water-quality data. Duan W, ed. *PLoS ONE*. 2019;14(8):e0215503. doi:10.1371/journal.pone.0215503

270. Piniewski M, Marcinkowski P, Koskiaho J, Tattari S. The effect of sampling frequency and strategy on water quality modelling driven by high-frequency monitoring data in a boreal catchment. *Journal of Hydrology*. 2019;579:124186. doi:10.1016/j.jhydrol.2019.124186

271. Madrid Y, Zayas ZP. Water sampling: Traditional methods and new approaches in water sampling strategy. *TrAC Trends in Analytical Chemistry*. 2007;26(4):293-299. doi:10.1016/j.trac.2007.01.002

272. Jennings E, Eyto E, Dillane M, Mellander PE, Regan F, Wilkes R, O'Neill M, Briciu C, Antunes P, Jordan P, Arnscheidt J, Linnane S, Mccarthy V, McElarney Y, Huallacháin D, Rolston A, Wynne C. Using High Frequency In-Situ Monitoring to Gain New Insights into Irish Aquatic Systems. *Biology and Environment: Proceedings of the Royal Irish Academy*. 2022;122B:201-221. doi:10.1353/bae.2022.0014

273. Cassidy R, Jordan P. Limitations of instantaneous water quality sampling in surface-water catchments: Comparison with near-continuous phosphorus time-series data. *Journal of Hydrology*. 2011;405(1):182-193. doi:10.1016/j.jhydrol.2011.05.020

274. Minaudo C, Dupas R, Gascuel-Odoux C, Fovet O, Mellander PE, Jordan P, Shore M, Moatar F. Nonlinear empirical modeling to estimate phosphorus exports using continuous records of turbidity and discharge. *Water Resources Research*. 2017;53(9):7590-7606. doi:10.1002/2017WR020590

275. Jones CS, Drake CW, Hruby CE, Schilling KE, Wolter CF. Livestock manure driving stream nitrate. *Ambio*. 2019;48(10):1143-1153. doi:10.1007/s13280-018-1137-5

276. Kämäri M, Tarvainen M, Kotamäki N, Tattari S. High-frequency measured turbidity as a surrogate for phosphorus in boreal zone rivers: appropriate options and critical situations. *Environ Monit Assess*. 2020;192(6):366. doi:10.1007/s10661-020-08335-w

277. Yu L, Rozemeijer JC, Broers HP, van Breukelen BM, Middelburg JJ, Ouboter M, van der Velde Y. Drivers of nitrogen and phosphorus dynamics in a groundwater-fed urban catchment revealed by high-frequency monitoring. *Hydrology and Earth System Sciences*. 2021;25(1):69-87. doi:10.5194/hess-25-69-2021

278. Haddadchi A, Bind J, Hoyle J, Hicks M. Quantifying the contribution of bank erosion to a suspended sediment budget using boat-mounted LiDAR and high-frequency suspended sediment monitoring. *Earth Surface Processes and Landforms*. 2023;48(14):2920-2938. doi:10.1002/esp.5667

279. Elfferich I, Bagshaw EA, Perkins RG, Johnes PJ, Yates CA, Lloyd CEM, Bowes MJ, Halliday SJ. Interpretation of river water quality data is strongly controlled by measurement time and frequency. *Science of The Total Environment*. 2024;954:176626. doi:10.1016/j.scitotenv.2024.176626

280. Leite Costa I, Foulquier V, Blanchard F, Rousseau Y, Tagliarolo M. High-frequency monitoring reveals recurrent extreme events in a tropical estuary. *Continental Shelf Research*. 2026;298:105655. doi:10.1016/j.csr.2026.105655

281. Bieroza M, Acharya S, Benisch J, ter Borg RN, Hallberg L, Negri C, Pruitt A, Pucher M, Saavedra F, Staniszewska K, van't Veen SGM, Vincent A, Winter C, Basu NB, Jarvie HP, Kirchner JW. Advances in Catchment Science, Hydrochemistry, and Aquatic Ecology Enabled by High-Frequency Water Quality Measurements. *Environ Sci Technol*. 2023;57(12):4701-4719. doi:10.1021/acs.est.2c07798

282. Gullick RW, Grayman WM, Deininger RA, Males RM. Design of Early Warning Monitoring Systems for Source Waters. *Journal AWWA*. 2003;95(11):58-72. doi:10.1002/j.1551-8833.2003.tb10493.x

283. Lu Y, Chen J, Xu Q, Han Z, Peart M, Ng CN, Lee FYS, Hau BCH, Law WWY. Spatiotemporal variations of river water turbidity in responding to rainstorm-streamflow processes and farming activities in a mountainous catchment, Lai Chi Wo, Hong Kong, China. *Science of The Total Environment*. 2023;863:160759. doi:10.1016/j.scitotenv.2022.160759

284. Grayman WM, Deininger RA, Males RM, Foundation AR. *Design of Early Warning and Predictive Source-Water Monitoring Systems*. American Water Works Association; 2001.

285. Burchard-Levine A, Liu S, Vince F. Drinking Water Source Contamination Early Warning System and Modelling in China: A Review. *International Journal of Environmental Pollution and Remediation (IJEPR)*. 2012;1(1):13-19.

286. Hart DB, McKenna SA. User's Manual for CANARY. Published online 2012. Accessed November 22, 2025. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1005VE2.TXT

287. Hou D, He H, Huang P, Zhang G, Loaiciga H. Detection of water-quality contamination events based on multi-sensor fusion using an extented Dempster–Shafer method. *Meas Sci Technol*. 2013;24(5):055801. doi:10.1088/0957-0233/24/5/055801

288. Burkhardt JB, Sahoo D, Hammond B, Long M, Haxton T, Murray R. Near real-time event detection for watershed monitoring with CANARY. *Environmental Science: Advances*. 2022;1(2):170-181. doi:10.1039/D2VA00014H

289. Storey MV, van der Gaag B, Burns BP. Advances in on-line drinking water quality monitoring and early warning systems. *Water Research*. 2011;45(2):741-747. doi:10.1016/j.watres.2010.08.049

290. Dejus S, Nescerecka A, Juhna T. ON-LINE DRINKING WATER CONTAMINATION EVENT DETECTION METHODS. *Environment Technology Resources Proceedings of the International Scientific and Practical Conference*. 2017;1:77. doi:10.17770/etr2017vol1.2627

291. Nafsin N, Li J. Using canary event detection software for water quality analysis in milwaukee river. *Journal of Hydro-environment Research*. 2021;38. doi:10.1016/j.jher.2021.06.003

292. Broderick C, Murphy C. *Identification of Climate Sensitive Catchments: Water REsources and Climate Change Adaptation*. Irish Water; 2020:109. Accessed July 8, 2023. https://www.water.ie/about/research-and-innovation/CRU-Report-Identification-of-Climate-Sensitive-Catchments-Water-Reso....pdf

293. Ezzati G, Collins AL, Pulley S, Galloway J, Hawtree D, Mellander P. Impacts of changing weather patterns on the dynamics of water pollutants in agricultural catchments: Insights from 11-year high temporal resolution data analysis. *Journal of Hydrology*. 2024;644:132122. doi:10.1016/j.jhydrol.2024.132122

294. Gander MJ. Climate change and the water quality threats posed by the emerging contaminants per- and polyfluoroalkyl substances (PFAS) and microplastics. *Water International*. 2025;50(3-4):306-328. doi:10.1080/02508060.2022.2120255

295. van Vliet MTH, Thorslund J, Strokal M, Hofstra N, Flörke M, Ehalt Macedo H, Nkwasa A, Tang T, Kaushal SS, Kumar R, van Griensven A, Bouwman L, Mosley LM. Global river water quality under climate change and hydroclimatic extremes. *Nat Rev Earth Environ*. 2023;4(10):10. doi:10.1038/s43017-023-00472-3

296. Zou XY, Peng XY, Zhao X, Chang CP. The impact of extreme weather events on water quality: international evidence. *Natural Hazards*. 2022;115. doi:10.1007/s11069-022-05548-9

297. Hervé-Fournereau N. Beyond the 2019 Fitness Check of the Water Framework Directive: Designing the Future of European Water Law. In: *Research Handbook on EU Environmental Law*. Edward Elgar Publishing; 2020:280-295. Accessed August 25, 2026. https://www.elgaronline.com/edcollchap/edcoll/9781788970662/9781788970662.00029.xml

298. Mellander PE, Lynch MB, Galloway J, Žurovec O, McCormack M, O'Neill M, Hawtree D, Burgess E. Benchmarking a decade of holistic agro-environmental studies within the Agricultural Catchments Programme. *Irish Journal of Agricultural and Food Research*. 2022;61:201-217. doi:10.15212/ijafr-2020-0145

299. Meyer AM, Fuenfrocken E, Kautenburger R, Cairault A, Beck HP. Detecting pollutant sources and pathways: High-frequency automated online monitoring in a small rural French/German transborder catchment. *Journal of Environmental Management*. 2021;290:112619. doi:10.1016/j.jenvman.2021.112619

300. Wasko C, Guo D. Understanding event runoff coefficient variability across Australia using the hydroEvents R package. *Hydrological Processes*. 2022;36(4):e14563. doi:10.1002/hyp.14563

301. Office of Public Works. Station Info Ballygrania. waterlevel.ie/hydro-data. November 22, 2025. Accessed November 9, 2025. https://waterlevel.ie/hydro-data/#/overview/stations/station/11808/Ballygrania/stationInfo

302. EPA Ecology Unit. The Catchment Services Concept - A means of connecting and progressing Water Framework Directive and biodiversity requirements in the context of 'Sustainable Intensification' of agriculture, and climate change. Catchments.ie. May 26, 2017. Accessed August 13, 2023. https://www.catchments.ie/catchment-services-concept-means-connecting-progressing-water-framework-directive-biodiversity-requirements-context-sustainable-intensification-agricult/

303. Environmental Protection Agency. *Water Quality in 2022. An Indicators Report*. 2023:31. Accessed May 12, 2023. https://www.epa.ie/publications/monitoring--assessment/freshwater--marine/Water-Quality-2022-Indicator-Report-Web.pdf

304. Sandström S, Futter M, Kyllmar K, Bishop K, O'Connell D, Djodjic F. Particulate phosphorus and suspended solids losses from small agricultural catchments: Links to stream and catchment characteristics. *Science of The Total Environment*. 2019;711:134616. doi:10.1016/j.scitotenv.2019.134616

305. Sandström S, Futter MN, O'Connell DW, Lannergård EE, Rakovic J, Kyllmar K, Gill LW, Djodjic F. Variability in fluvial suspended and streambed sediment phosphorus fractions among small agricultural streams. *Journal of Environmental Quality*. 2021;50(3):612-626. doi:10.1002/jeq2.20210

306. Office of Public Works. *Western CFRAM Unit of Management 35 - Sligo Bay/Drowes Hydrology Report*. Office of Public Works; 2015:279. Accessed November 22, 2025. https://www.floodinfo.ie/publications/?a=648

307. EPA. *3rd Cycle Draft Sligo Bay & Drowes Catchment Report (HA 35)*. Catchment Science & Management Unit, Environmental Protection Agency; 2021:47. Accessed May 31, 2022. https://www.google.ie/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiZ0-GWoN__AhWMg1wKHdB_DjoQFnoECA4QAQ&url=https%3A%2F%2Fcatchments.ie%2Fwp-content%2Ffiles%2Fcatchmentassessments%2F35%2520Sligo%2520Bay%2520%26%2520Drowse%2520Catchment%2520Summary%2520WFD%2520Cycle%25203.pdf&usg=AOvVaw0ixSzrE0Y5ybVWFy6GLPjY&opi=89978449

308. Murray D, Langton P, O' Connor JP, Ashe PJ. Distribution Records of Irish Chironomidae (Diptera): Part 2 - Orthocladiinae. *Bulletin of the Irish Biogeographical Society*. 2014;(No. 38). Accessed August 23, 2026. https://www.researchgate.net/publication/268872406_DISTRIBUTION_RECORDS_OF_IRISH_CHIRONOMIDAE_DIPTERA_PART_2_-_ORTHOCLADIINAE

309. Goodwillie R, Buckley P, Douglas C. *Owenmore River, Proposed Arterial Drainage Environmental Impact Assessment, Botanical and Ornithological Surveys.* National Parks & Wildlife Service, Office of Public Works; 1992:201. Accessed November 22, 2025. https://www.npws.ie/sites/default/files/publications/pdf/Goodwillie_1992_Owenmore_River.pdf

310. Inland Fisheries Ireland. *Sampling Fish for the Water Framework Directive*. Inland Fisheries Ireland; 2010:79. Accessed May 26, 2022. http://www.wfdfish.ie/wp-content/uploads/2011/11/WRBD_rivers_report_2010.pdf

311. National Parks & Wildlife Service. *Unshin River SAC Site Synopsis, Site Code: 001898*. Dept. of Arts Heritage & the Gaeltacht; 2016:2. Accessed May 28, 2022. https://www.npws.ie/sites/default/files/protected-sites/synopsis/SY001898.pdf

312. Raven PJ, Holmes NTH, Dawson PJA, Everard M, Fozzard IR, Rouen KJ. *River Habitat Quality the Physical Character of Rivers and Streams in the UK and Isle of Man*. Environment Agency; 1998:96. Accessed May 26, 2022. https://www.riverhabitatsurvey.org/wp-content/uploads/2012/07/RHS.pdf

313. EPA. Special Area of Conservation (SAC) and Special Protected Area (SPA). Published online 2026. Accessed August 23, 2026. https://gis.epa.ie/EPAMaps/

314. DEFRA, Environment Agency. URBEXT2000 – A new FEH catchment descriptor Calculation, dissemination and application. Published online March 2007. Accessed May 25, 2022. https://assets.publishing.service.gov.uk/media/602bb59de90e070556671419/URBEXT2000_-_A_new_FEH_catchment_descriptor_-_SID5_summary.pdf

315. O'Briain R. Climate change and European rivers: An eco-hydromorphological perspective. *Ecohydrology*. 2019;12(5):e2099. doi:10.1002/eco.2099

316. Villeneuve B, Piffady J, Valette L, Souchon Y, Usseglio-Polatera P. Direct and indirect effects of multiple stressors on stream invertebrates across watershed, reach and site scales: A structural equation modelling better informing on hydromorphological impacts. *Science of The Total Environment*. 2018;612:660-671. doi:10.1016/j.scitotenv.2017.08.197

317. Whitehead P, Butterfield D, Wade A. *Potential Impacts of Climate Change on River Water Quality*. Environment Agency; 2008:115.

318. Yilmaz S, Chaudhary A, Kanda R. Impacts of Extreme Weather Events on Hydromorphology of UK Rivers. *Turkish Journal of Water Science and Management*. 2021;5:116-156. doi:10.31807/tjwsm.819574

319. Sligo County Council. *Sligo County Development Plan 2017-2023*. Development Planning Unit, Sligo County Council; 2017. Accessed July 1, 2023. https://www.sligococo.ie/cdp/

320. Met Éireann. Weather Observing Stations - Met Éireann - The Irish Meteorological Service. 2023. Accessed July 14, 2023. https://www.met.ie/climate/weather-observing-stations

321. Mckeown M, Potito A, Hickey K. The long-term temperature record from Markree Observatory, County Sligo, from 1842 to 2011. *Irish Geography*. 2013;45. doi:10.1080/00750778.2013.830871

322. Met Eireann. Rainfall - Met Éireann - The Irish Meteorological Service. 2025. Accessed November 22, 2025. https://www.met.ie/climate/what-we-measure/rainfall

323. McElwain L, Sweeney J. *Key Meteorological Indicators of Climate Change in Ireland*. Environmental Protection Agency; 2007:40.

324. EPA. Hydrology Summary Bulletin - July 2025. Environmental Protection Agency Hydrology Bulletin. July 2025. Accessed August 31, 2025. https://www.epa.ie/publications/monitoring--assessment/freshwater--marine/hydrology-bulletin/hydrology-bulletin/hydrology-summary-bulletin---july-2025.php

325. Boiten W. *Hydrometry: IHE Delft Lecture Note Series*. CRC Press; 2020.

326. EPA Catchments Unit. *Cycle 3 HA 35 Sligo Bay & Drowes Catchment Report*. Environmental Protection Agency, Ireland; 2024. Accessed June 1, 2024. https://catchments.ie/wp-content/files/catchmentassessments/35%20Sligo%20Bay%20&%20Drowse%20Catchment%20Summary%20WFD%20Cycle%203.pdf

327. EPA Catchments. Catchments.ie. Catchments.ie. June 30, 2023. Accessed June 30, 2023. https://www.catchments.ie/data/

328. EPA. *Ireland's National Water Quality Monitoring Programme 2022–2027*. Environmental Protection Agency; 2023:32. https://www.epa.ie/publications/monitoring--assessment/freshwater--marine/EPA_WFD_MonitoringProgramme_2022_2027.pdf

329. Mellander PE, Jordan P. Charting a perfect storm of water quality pressures. *Science of The Total Environment*. 2021;787:147576. doi:10.1016/j.scitotenv.2021.147576

330. Schürings C, Globevnik L, Lemm JU, Psomas A, Snoj L, Hering D, Birk S. River ecological status is shaped by agricultural land use intensity across Europe. *Water Research*. 2024;251:121136. doi:10.1016/j.watres.2024.121136

331. Dept. of Housing, Local Government & Heritage. *Third Cycle Draft River Basin Management Plan 2022-2027 - Consultation Report*. 2022:84. https://www.gov.ie/en/department-of-housing-local-government-and-heritage/publications/third-cycle-draft-river-basin-management-plan-2022-2027-consultation-report/

332. Elosegi A, Díez J, Mutz M. Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. *Hydrobiologia*. 2010;657(1):199-215. doi:10.1007/s10750-009-0083-4

333. Chang C, Hu E, Xue X, Li J, Du D, Yang F, Li M. Hydro-morphology and water quality jointly shape the structure and network stability of the plankton community in multi-tributary river basins. *Journal of Hydrology*. 2024;643:131945. doi:10.1016/j.jhydrol.2024.131945

334. Vilenica M, Vidaković Maoduš I, Mihaljević Z. The Impact of Hydromorphological Alterations on Mayfly Assemblages of a Mid-Sized Lowland River in South-Eastern Europe. *Insects*. 2022;13(5):436. doi:10.3390/insects13050436

335. Elosegi A, Díez J, Mutz M. Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. *Hydrobiologia*. 2010;657(1):199-215. doi:10.1007/s10750-009-0083-4

336. Locke KA. Impacts of land use/land cover on water quality: A contemporary review for researchers and policymakers. *Water Quality Research Journal*. 2024;59(2):89-106. doi:10.2166/wqrj.2024.002

337. OPW. Complete high-res data for Ballygrania. Published online 2025. Accessed November 22, 2025. https://waterlevel.ie/hydro-data/#/overview/Waterlevel/station/11808/Ballygrania/Waterlevel?period=P7D

338. OPW. Complete high-res data for Ballynacarrow. Published online 2025. Accessed November 8, 2025. https://waterlevel.ie/hydro-data/#/overview/Waterlevel/station/11806/Ballynacarrow/Qdownload

339. Vogel RM, Fennessey NM. Flow Duration Curves Ii: A Review of Applications in Water Resources Planning. *JAWRA Journal of the American Water Resources Association*. 1995;31(6):1029-1039. doi:10.1111/j.1752-1688.1995.tb03419.x

340. Langat PK, Kumar L, Koech R, Ghosh MK. Hydro-Morphological Characteristics Using Flow Duration Curve, Historical Data and Remote Sensing: Effects of Land Use and Climate. *Water*. 2019;11(2):309. doi:10.3390/w11020309

341. MOHAMOUD YM. Prediction of daily flow duration curves and streamflow for ungauged catchments using regional flow duration curves. *Hydrological Sciences Journal*. 2008;53(4):706-724. doi:10.1623/hysj.53.4.706

342. Ridolfi E, Kumar H, Bárdossy A. A methodology to estimate flow duration curves at partially ungauged basins. *Hydrology and Earth System Sciences*. 2020;24(4):2043-2060. doi:10.5194/hess-24-2043-2020

343. Santos AC, Portela MM, Rinaldo A, Schaefli B. Analytical flow duration curves for summer streamflow in Switzerland. *Hydrology and Earth System Sciences*. 2018;22(4):2377-2389. doi:10.5194/hess-22-2377-2018

344. Karimi S, Salarijazi M, Ghorbani K, Heydari M. Comparative assessment of environmental flow using hydrological methods of low flow indexes, Smakhtin, Tennant and flow duration curve. *Acta Geophys*. 2021;69(1):285-293. doi:10.1007/s11600-021-00539-z

345. Guo X, Xu L, Su L, Deng Y, Yang C. Comparing Flow Duration Curves and Discharge Hydrographs to Assess Eco-flows. *Water Resour Manage*. 2021;35(14):4681-4693. doi:10.1007/s11269-021-02890-8

346. Kwakye SO, Bárdossy A. Quantification of the hydrological consequences of climate change in a typical West African catchment using flow duration curves. *Journal of Water and Climate Change*. 2021;13(1):26-42. doi:10.2166/wcc.2021.147

347. Lane R, Kay A. (PDF) Climate Change Impact on the Magnitude and Timing of Hydrological Extremes Across Great Britain. *Frontiers in Water*. Published online August 11, 2026. doi:10.3389/frwa.2021.684982

348. Vitale CH, Moulaison Sandy H. Data Management Plans A Review. *DESIDOC Jl Lib Info Technol*. 2019;39(06):322-328. doi:10.14429/djlit.39.06.15086

349. Michener WK. Ten Simple Rules for Creating a Good Data Management Plan. *PLOS Computational Biology*. 2015;11(10):e1004525. doi:10.1371/journal.pcbi.1004525

350. Ball A. *Review of Data Management Lifecycle Models*. University of Bath; 2012. https://purehost.bath.ac.uk/ws/portalfiles/portal/206543/redm1rep120110ab10.pdf

351. van der Loo MPJ, de Jonge E. Data Validation. In: *Wiley StatsRef: Statistics Reference Online*. John Wiley & Sons, Ltd; 2020:1-7. doi:10.1002/9781118445112.stat08255

352. Rangeti I, Dzwairo B, Barratt GJ, Otieno FAO. *Validity and Errors in Water Quality Data — A Review*. IntechOpen; 2015. doi:10.5772/59059

353. Broekaert JAC. Daniel C. Harris: Quantitative chemical analysis, 9th ed. *Anal Bioanal Chem*. 2015;407(30):8943-8944. doi:10.1007/s00216-015-9059-6

354. Clemens F, Lepot M, Blumensaat F, Leutnant D, GRUBER G. Data validation and data quality assessment. In: 2021:327-390. doi:10.2166/9781789060119_0327

355. Singh VP. *Chow's Handbook of Applied Hydrology*. 2nd ed. McGraw Hill; 2016. https://www.researchgate.net/publication/306097368_Chow's_Handbook_of_Applied_Hydrology

356. Dingman SL. *Physical Hydrology: Third Edition*. Waveland Press; 2015.

357. Bright C, Horton S, Mager S. Clarifying the waters: the use of turbidity for suspended sediment monitoring in New Zealand | Request PDF. *Journal of Hydrology (NZ)*. Published online 2020:18.

358. Lenhart CF, Brooks KN, Heneley D, Magner JA. Spatial and temporal variation in suspended sediment, organic matter, and turbidity in a Minnesota prairie river: implications for TMDLs. *Environ Monit Assess*. 2010;165(1):435-447. doi:10.1007/s10661-009-0957-y

359. Wang D, Singhasemanon N, Goh KS. Statistical Considerations for Interpreting Censored and Intermittent Surface Water Monitoring Data. In: *Pesticides in Surface Water: Monitoring, Modeling, Risk Assessment, and Management*. Vol 1308. ACS Symposium Series. American Chemical Society; 2019:365-376. doi:10.1021/bk-2019-1308.ch018

360. Helsel D. *Statistics for Censored Environmental Data Using Minitab and R*. 2012. doi:10.1002/9781118162729

361. Heron M, Hanson VL, Ricketts I. Open source and accessibility: advantages and limitations. *J Interact Sci*. 2013;1(1):2. doi:10.1186/2194-0827-1-2

362. R Core Team. R: A Language and Environment for Statistical Computing (v4.4.1 on Windows 11x64 (build 22631). Published online 2024. Accessed November 22, 2025. https://www.R-project.org/

363. Hart, Haxton. CANARY-EDS. Published online 2020. Accessed June 16, 2025. https://github.com/USEPA/CANARY

364. Murray, Haxton. *Water Quality Event Detection Systems for Drinking Water Contamination Warning Systems*. US EPA Office of Research & Development; 2010:85. https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=496189&Lab=NHSRC

365. US EPA. *Configuring Online Monitoring Event Detection Systems*. US EPA Office of Research & Development; 2014:71. Accessed April 17, 2024. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHSRC&dirEntryId=287299

366. Gleeson K, Husband S, Gaffney J, Boxall J. Algorithms to mimic human interpretation of turbidity events from drinking water distribution systems. *Journal of Hydroinformatics*. 2023;26(1):143-161. doi:10.2166/hydro.2023.159

367. Leow A, Burkhardt J, Iii WEP, Zimmerman B, Brinkman NE, Turner A, Murray R, Sorial G, Garland J. Application of the CANARY event detection software for real-time performance monitoring of decentralized water reuse systems. *Environ Sci: Water Res Technol*. 2017;3(2):224-234. doi:10.1039/C6EW00226A

368. Kertesz R, Burkhardt J, Panguluri S. Real-Time Analysis of Moisture and Flow Data to Describe Wet Weather Response in a Permeable Pavement Parking Lot. Published online May 30, 2014:985-1000. doi:10.1061/9780784413548.099

369. Haxton T, Murray R, Hagar J, Allgeier S, Umberg K, Cafferky S, Hart D, Hollister S, McKenna S. Canary Training Tutorials. Published online 2013. https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=516747

370. Duncan HP. Baseflow separation – A practical approach. *Journal of Hydrology*. 2019;575:308-313. doi:10.1016/j.jhydrol.2019.05.040

371. Lyne V, Hollick M. Stochastic time-variable rainfall-runoff modelling. In: *Proceedings Ofthe Hydrology and Water Resources Symposium*. No. 79/10. Institution of Engineers National Conference Publication; 1979:4. https://onlinelibrary.wiley.com/action/getFTRLinkout?url=http%3A%2F%2Fscholar.google.com%2Fscholar_lookup%3Fhl%3Den%26publication_year%3D1979%26author%3DV%2BLyne%26author%3DM%2BHollick%26title%3DStochastic%2Btime%25E2%2580%2590variable%2Brainfall%25E2%2580%2590runoff%2Bmodelling&doi=10.1002%2Fhyp.14563&linkType=gs&linkLocation=Reference&linkSource=FULL_TEXT

372. Fuka WDR, Stenhuis JA, Archibald MT, Easton ZM. EcoHydRology: A Community Modeling Foundation for Eco-Hydrology. Published online 2019. Accessed September 21, 2025. https://rdrr.io/cran/EcoHydRology/

373. Ladson T. A standard approach to baseflow separation using the Lyne and Hollick filter. *Australian Journal of Water Resources*. 2013;17:25-34. doi:10.7158/W12-028.2013.17.1

374. Pappas S, Shaw DP, Shrimpton L, Strachan S, Trainor K, Yeow A. *Baseline Surface Water Quality in the Petitot River Basin and Surrounding Watersheds : Examining Potential Impacts of Shale Gas Development in the Horn River Basin, British Columbia*. Environment and Climate Change Canada; 2019:105. https://publications.gc.ca/collections/collection_2019/eccc/En84-147-2017-eng.pdf

375. Mac Donald D, Zajdlik B, Sinclair J. *DRAFT Guidelines for Developing Baseline Water Quality Monitoring Programs in the Northwest Territories*. The Mackenzie Valley Land and Water Board; 2018:43. https://wlwb.ca/sites/default/files/mvlwb/DraftGuidelines/draft%20guidelines%20for%20developing%20baseline%20water%20quality%20programs%20in%20the%20Northwest%20Territories%20-%20May%202018.pdf

376. Meresa H, Donegan S, Golian S, Murphy C. Simulated Changes in Seasonal and Low Flows with Climate Change for Irish Catchments. *Water*. 2022;14(10):10. doi:10.3390/w14101556

377. Delpla I, Jones T, Monteith D, Hughes D, Baurès E, Jung AV, Thomas O, Freeman C. Response to heavy rain events on water quality in different environments. *Journal of Environmental Quality*. 2015;In press.

378. Rostami S, He J, Hassan QK. Riverine Water Quality Response to Precipitation and Its Change. *Environments*. 2018;5(1):1. doi:10.3390/environments5010008

379. Peñalver R, Jacobs MR, Hegarty S, Regan F. Assessment of anthropogenic pollution by monitoring occurrence and distribution of chemicals in the river Liffey in Dublin. *Environ Sci Pollut Res*. 2021;28(38):53754-53766. doi:10.1007/s11356-021-14508-y

380. Fong CR, Gaynus CJ, Carpenter RC. Extreme rainfall events pulse substantial nutrients and sediments from terrestrial to nearshore coastal communities: a case study from French Polynesia. *Sci Rep*. 2020;10(1):1. doi:10.1038/s41598-020-59807-5

381. Zhang Y, Granger SJ, Semenov MA, Upadhayay HR, Collins AL. Diffuse water pollution during recent extreme wet-weather in the UK: Environmental damage costs and insight into the future? *Journal of Cleaner Production*. 2022;338:130633. doi:10.1016/j.jclepro.2022.130633

382. Qiu J, Shen Z, Leng G, Wei G. Synergistic effect of drought and rainfall events of different patterns on watershed systems. *Sci Rep*. 2021;11(1):1. doi:10.1038/s41598-021-97574-z

383. Burt T p., Howden N j. k., Worrall F. On the importance of very long-term water quality records. *WIREs Water*. 2014;1(1):41-48. doi:10.1002/wat2.1001

384. O'Grady J, Briciu C, Regan F. Catchment-Based Water Monitoring Using a Hierarchy of Sensor Types. In: *Springer Water*. 2022:341-362. doi:10.1007/978-3-031-08262-7_14

385. Reljić M, Romić M, Romić D, Gilja G, Mornar V, Ondrasek G, Bubalo Kovačić M, Zovko M. Advanced Continuous Monitoring System—Tools for Water Resource Management and Decision Support System in Salt Affected Delta. *Agriculture*. 2023;13(2):2. doi:10.3390/agriculture13020369

386. Saleh T, Stanley M. *Real-Time Water Quality Monitoring: Benefits for Decision Making*. International Institute for Sustainable Development; 2023:26. Accessed August 16, 2023. https://www.iisd.org/publications/report/real-time-water-quality-monitoring

387. EPA Catchments. Areas for Action. Catchments.ie. 2023. Accessed July 27, 2023. https://www.catchments.ie/data/

388. Huey GM, Meyer ML. Turbidity as an Indicator of Water Quality in Diverse Watersheds of the Upper Pecos River Basin. *Water*. 2010;2(2):2. doi:10.3390/w2020273

389. Ralston DK, Yellen B, Woodruff JD, Fernald S. Turbidity Hysteresis in an Estuary and Tidal River Following an Extreme Discharge Event. *Geophysical Research Letters*. 2020;47(15):e2020GL088005. doi:10.1029/2020GL088005

390. Atwell AK, Bouldin JL. Effects of Agricultural Intensity on Nutrient and Sediment Contributions within the Cache River Watershed, Arkansas. *Water*. 2022;14(16):2528. doi:10.3390/w14162528

391. Harrington S, Harrington J. Dissolved and particulate nutrient transport dynamics of a small Irish catchment: the River Owenabue. *Hydrology and Earth System Sciences*. 2014;18. doi:10.5194/hess-18-2191-2014

392. Ulén B, Geranmayeh P, Blomberg M, Bieroza M. Seasonal variation in nutrient retention in a free water surface constructed wetland monitored with flow-proportional sampling and optical sensors. *Ecological Engineering*. 2019;139:105588. doi:10.1016/j.ecoleng.2019.105588

393. Smith BPG, Naden PS, Leeks GJL, Wass PD. The influence of storm events on fine sediment transport, erosion and deposition within a reach of the River Swale, Yorkshire, UK. *Science of The Total Environment*. 2003;314-316:451-474. doi:10.1016/S0048-9697(03)00068-8

394. Leigh C, Kandanaarachchi S, McGree JM, Hyndman RJ, Alsibai O, Mengersen K, Peterson EE. Predicting sediment and nutrient concentrations from high-frequency water-quality data. *PLOS ONE*. 2019;14(8):e0215503. doi:10.1371/journal.pone.0215503

395. Nasrabadi T, Ruegner H, Sirdari ZZ, Schwientek M, Grathwohl P. Using total suspended solids (TSS) and turbidity as proxies for evaluation of metal transport in river water. *Applied Geochemistry*. 2016;68:1-9. doi:10.1016/j.apgeochem.2016.03.003

396. Lacour C, Joannis C, Chebbo G. Assessment of annual pollutant loads in combined sewers from continuous turbidity measurements: Sensitivity to calibration data. *Water Research*. 2009;43(8):2179-2190. doi:10.1016/j.watres.2009.02.017

397. Rügner H, Schwientek M, Beckingham B, Kuch B, Grathwohl P. Turbidity as a proxy for total suspended solids (TSS) and particle facilitated pollutant transport in catchments. *Environ Earth Sci*. 2013;69(2):373-380. doi:10.1007/s12665-013-2307-1

398. APHA. *Standard Methods for the Examination of Water and Wastewater*. 23rd ed. American Public Health Association; 2017.

399. Wu T, Zhu G, Zhu M, Xu H, Zhang Y, Qin B. Use of conductivity to indicate long-term changes in pollution processes in Lake Taihu, a large shallow lake. *Environ Sci Pollut Res*. 2020;27(17):21376-21385. doi:10.1007/s11356-020-08590-x

400. Galván L, Olías M, Cánovas CR, Torres E, Ayora C, Nieto JM, Sarmiento AM. Refining the estimation of metal loads dissolved in acid mine drainage by continuous monitoring of specific conductivity and water level. *Applied Geochemistry*. 2012;27(10):1932-1943. doi:10.1016/j.apgeochem.2012.07.011

401. Smith J, Sheridan C, van Dyk L, Harding KG. Critical evaluation of the chemical composition of acid mine drainage for the development of statistical correlations linking electrical conductivity with acid mine drainage concentrations. *Environmental Advances*. 2022;8:100241. doi:10.1016/j.envadv.2022.100241

402. Georgakakos CB, Richards PL, Walter MT. Tracing Septic Pollution Sources Using Synthetic DNA Tracers: Proof of Concept. *Air, Soil and Water Research*. 2019;12:1178622119863794. doi:10.1177/1178622119863794

403. Chusov AN, Bondarenko EA, Andrianova MJ. Study of Electric Conductivity of Urban Stream Water Polluted with Municipal Effluents. *Applied Mechanics and Materials*. 2014;641-642:1172-1175. doi:10.4028/www.scientific.net/AMM.641-642.1172

404. Zhang D, Wang P, Cui R, Yang H, Li G, Chen A, Wang H. Electrical conductivity and dissolved oxygen as predictors of nitrate concentrations in shallow groundwater in Erhai Lake region. *Science of The Total Environment*. 2022;802:149879. doi:10.1016/j.scitotenv.2021.149879

405. Rusydi AF. Correlation between conductivity and total dissolved solid in various type of water: A review. *IOP Conf Ser: Earth Environ Sci*. 2018;118(1):012019. doi:10.1088/1755-1315/118/1/012019

406. Henry T, Doyle E, Lehnhart-Barnett H, Wall C. This old river keeps rolling: characterising natural solutions to baseflow maintenance and flood mitigation in a catchment in the Burren, Co Clare, Ireland. *Natural Hazards*. 2026;122(13):524. doi:10.1007/s11069-026-08207-5

407. Cartwright I, Miller MP. Temporal and spatial variations in river specific conductivity: Implications for understanding sources of river water and hydrograph separations. *Journal of Hydrology*. 2021;593:125895. doi:10.1016/j.jhydrol.2020.125895

408. Göransson G, Larson M, Bendz D. Variation in turbidity with precipitation and flow in a regulated river system - River Göta Älv, SW Sweden. *Hydrology and Earth System Sciences Discussions*. 2013;10:255-293. doi:10.5194/hessd-10-255-2013

409. Ortiz-Lopez C, Torres A, Bouchard C, Rodriguez M. A methodology for integrating time-lagged rainfall and river flow data into machine learning models to improve prediction of quality parameters of raw water supplying a treatment plant. *Journal of Hydroinformatics*. 2023;25(6):2406-2426. doi:10.2166/hydro.2023.122

410. Nakkazi MT, Nkwasa A, Martínez AB, van Griensven A. Linking land use and precipitation changes to water quality changes in Lake Victoria using earth observation data. *Environ Monit Assess*. 2024;196(11):1104. doi:10.1007/s10661-024-13261-2

411. Fox DR. *Turbidity Triggers for Lyttleton Port Company's Channel Deepening Project*. Environmetrics Australia; 2018:53. Accessed September 5, 2023. https://www.lpc.co.nz/wp-content/uploads/2020/04/Turbidity_Triggers.pdf

412. US EPA. *Guidance Manual for Compliance with the Surface Water Treatment Rules: Turbidity Provisions*. US Environmental Protection Agency; 2020:144. Accessed September 5, 2023.

https://www.epa.gov/sites/default/files/2020-06/documents/swtr_turbidity_gm_final_508.pdf

413. Mcdowell R, Snelder T, Booker D, Cox N, Wilcock R. Establishment of reference or baseline conditions of chemical indicators in New Zealand streams and rivers relative to present condition. *Marine and Freshwater Research*. 2012;64. doi:10.1071/MF12153

414. Australian and New Zealand Environment and Conservation Council. *Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Volume 1 The Guidelines*. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand; 2000.

415. Karim MR, Syeed MMM, Rahman A, Ayaz Rabbani K, Fatema K, Khan RH, Hossain MS, Uddin MF. A Comprehensive Dataset of Surface Water Quality Spanning 1940-2023 for Empirical and ML Adopted Research. *Sci Data*. 2025;12(1):391. doi:10.1038/s41597-025-04715-4

416. Liu S, Wang P, Huang Q, Gabysheva OI, Li Z, Zhang J, Kazak ES, Liu Y, Bazarzhapov TZ, Shpakova RN, Gabyshev VA, Pozdniakov SP, Frolova NL. A database of water chemistry in eastern Siberian rivers. *Sci Data*. 2022;9(1):737. doi:10.1038/s41597-022-01844-y

417. Helsel DR, Hirsch RM, Ryberg KR, Archfield SA, Gilroy EJ. *Statistical Methods in Water Resources*. U.S. Geological Survey; 2020. doi:10.3133/tm4A3

418. Fu L, You-GanWang. Statistical Tools for Analyzing Water Quality Data. In: *Water Quality Monitoring and Assessment*. IntechOpen; 2012. doi:10.5772/35228

419. Tukey JW. *Exploratory Data Analysis*. Vol 2. First. Addison-wesley Reading, MA; 1977.

420. Harvey GL, Moorhouse TP, Clifford NJ, Henshaw AJ, Johnson MF, Macdonald DW, Reid I, Rice SP. Evaluating the role of invasive aquatic species as drivers of fine sediment-related river management problems: The case of the signal crayfish (Pacifastacus leniusculus). *Progress in Physical Geography: Earth and Environment*. 2011;35(4):517-533. doi:10.1177/0309133311409092

421. Greenwood P, Kuhn NJ. Does the invasive plant, Impatiens glandulifera, promote soil erosion along the riparian zone? An investigation on a small watercourse in northwest Switzerland. *J Soils Sediments*. 2014;14(3):637-650. doi:10.1007/s11368-013-0825-9

422. Gavrilaș S, Burescu FL, Chereji BD, Munteanu FD. The Impact of Anthropogenic Activities on the Catchment's Water Quality Parameters. *Water*. 2025;17(12):1791. doi:10.3390/w17121791

423. Zhu X, Yue Y, Wong PWH, Zhang Y, Ding H. Designing an Optimized Water Quality Monitoring Network with Reserved Monitoring Locations. *Water*. 2019;11(4):4. doi:10.3390/w11040713

424. Behmel S, Damour M, Ludwig R, Rodriguez MJ. Water quality monitoring strategies — A review and future perspectives. *Science of The Total Environment*. 2016;571:1312-1329. doi:10.1016/j.scitotenv.2016.06.235

425. Donohoe A, Diamond D, McCaul M. 2 - Emerging technologies for autonomous in-situ monitoring of water quality. In: Johnson S, ed. *Monitoring Environmental Contaminants*. Environmental Contaminants. Elsevier; 2021:19-55. doi:10.1016/B978-0-444-64335-3.00001-3

426. Power S, Free L, Briciu Burghina CC, Richards C, Clinton R, Regan F. A Low-cost Novel Optical Sensor for In Situ Water Quality Monitoring. In: 2023. Accessed September 6, 2023. https://doras.dcu.ie/28308/

427. Panther JG, Teasdale PR, Bennett WW, Welsh DT, Zhao H. Titanium Dioxide-Based DGT Technique for In Situ Measurement of Dissolved Reactive Phosphorus in Fresh and Marine Waters. *Environ Sci Technol*. 2010;44(24):9419-9424. doi:10.1021/es1027713

428. Li W, Lee LY, Yung LYL, He Y, Ong CN. Combination of in Situ Preconcentration and On-Site Analysis for Phosphate Monitoring in Fresh Waters. *Anal Chem*. 2014;86(15):7658-7665. doi:10.1021/ac5015386

429. Taylor E, Bonner J, Nelson R, Fuller C, Kirkey W, Cappelli S. Development of an in-situ total phosphorus analyzer. In: 2015. doi:10.23919/OCEANS.2015.7404384

430. Vaughan MCH, Bowden WB, Shanley JB, Vermilyea A, Wemple B, Schroth AW. Using in situ UV-Visible spectrophotometer sensors to quantify riverine phosphorus partitioning and concentration at a high frequency. *Limnol Oceanogr Methods*. 2018;16(12):840-855. doi:10.1002/lom3.10287

431. Droujko J, Molnar P. Open-source, low-cost, in-situ turbidity sensor for river network monitoring. *Sci Rep*. 2022;12(1):1. doi:10.1038/s41598-022-14228-4

432. Sanchez R, Groc M, Vuillemin R, Pujo-Pay M, Raimbault V. Development of a Frugal, In Situ Sensor Implementing a Ratiometric Method for Continuous Monitoring of Turbidity in Natural Waters. *Sensors*. 2023;23(4):4. doi:10.3390/s23041897

433. Vu CT, Zahrani AA, Duan L, Wu T. A Glass-Fiber-Optic Turbidity Sensor for Real-Time In Situ Water Quality Monitoring. *Sensors*. 2023;23(16):16. doi:10.3390/s23167271

434. Lin B, Xu J, Lin K, Li M, Lu M. Low-Cost Automatic Sensor for in Situ Colorimetric Detection of Phosphate and Nitrite in Agricultural Water. *ACS Sens*. 2018;3(12):2541-2549. doi:10.1021/acssensors.8b00781

435. Nightingale AM, Hassan S ul, Warren BM, Makris K, Evans GWH, Papadopoulou E, Coleman S, Niu X. A Droplet Microfluidic-Based Sensor for Simultaneous in Situ Monitoring of Nitrate and Nitrite in Natural Waters. *Environ Sci Technol*. 2019;53(16):9677-9685. doi:10.1021/acs.est.9b01032

436. Mahmud MAP, Ejeian F, Azadi S, Myers M, Pejcic B, Abbassi R, Razmjou A, Asadnia M. Recent progress in sensing nitrate, nitrite, phosphate, and ammonium in aquatic environment. *Chemosphere*. 2020;259:127492. doi:10.1016/j.chemosphere.2020.127492

437. Alam AU, Clyne D, Jin H, Hu NX, Deen MJ. Fully Integrated, Simple, and Low-Cost Electrochemical Sensor Array for in Situ Water Quality Monitoring. *ACS Sens*. 2020;5(2):412-422. doi:10.1021/acssensors.9b02095

438. Granger SJ, Qunicke JA, Harris P, Collins AL, Blackwell MS. Comparison of high frequency, in-situ water quality analysers and sensors with conventional water sample collection and laboratory analyses: phosphorus and nitrogen species. *Hydrology and Earth System Sciences Discussions*. Published online January 26, 2018:1-33. doi:10.5194/hess-2017-684

439. Silva GM e, Campos DF, Brasil JAT, Tremblay M, Mendiondo EM, Ghiglieno F. Advances in Technological Research for Online and In Situ Water Quality Monitoring—A Review. *Sustainability*. 2022;14(9):9. doi:10.3390/su14095059

440. O'Grady J, Zhang D, O'Connor N, Regan F. A comprehensive review of catchment water quality monitoring using a tiered framework of integrated sensing technologies. *Science of The Total Environment*. 2021;765:142766. doi:10.1016/j.scitotenv.2020.142766

441. Westerhoff R, McDowell R, Brasington J, Hamer M, Muraoka K, Alavi M, Muirhead R, Lovett A, Ruru I, Miller B, Hudson N, Lehmann M, Herpe M, King J, Moreau M, Ausseil O. Towards implementation of robust monitoring technologies alongside freshwater improvement policy in Aotearoa New Zealand. *Environmental Science & Policy*. 2022;132:1-12. doi:10.1016/j.envsci.2022.01.020

442. Glavan M, Železnikar Š, Velthof G, Boekhold S, Langaas S, Pintar M. How to Enhance the Role of Science in European Union Policy Making and Implementation: The Case of Agricultural Impacts on Drinking Water Quality. *Water*. 2019;11(3):3. doi:10.3390/w11030492

443. du Plessis A. Persistent degradation: Global water quality challenges and required actions. *One Earth*. 2022;5(2):129-131. doi:10.1016/j.oneear.2022.01.005

444. Coraggio E, Han D, Gronow C, Tryfonas T. Water Quality Sampling Frequency Analysis of Surface Freshwater: A Case Study on Bristol Floating Harbour. *Frontiers in Sustainable Cities*. 2022;3. Accessed July 25, 2023. https://www.frontiersin.org/articles/10.3389/frsc.2021.791595

445. Khamis K, Bradley C, Stevens R, Hannah DM. Continuous field estimation of dissolved organic carbon concentration and biochemical oxygen demand using dual-wavelength fluorescence, turbidity and temperature. *Hydrological Processes*. 2017;31(3):540-555. doi:10.1002/hyp.11040

446. ONeill M, Briciu C, Jennings E, Antunes P, Huallacháin D, Kelly-Quinn M, O'Sullivan M, Regan F. Influence of a cattle access point on temporal changes in stream turbidity. *Irish Journal of Agricultural and Food Research*. Published online January 20, 2023. doi:10.15212/ijafr-2022-0109

447. Oviedo-Vargas D, Peipoch M, Ensign SH, Bressler D, Arscott DB, Jackson JK. Advancing freshwater science with sensor data collected by community scientists. *Frontiers in Ecology and the Environment*. 2024;22(6):e2748. doi:10.1002/fee.2748

448. Filazzola A, Lortie C. A call for clean code to effectively communicate science. *Methods in Ecology and Evolution*. 2022;13(10):2119-2128. doi:10.1111/2041-210X.13961

449. Stagge JH, Rosenberg DE, Abdallah AM, Akbar H, Attallah NA, James R. Assessing data availability and research reproducibility in hydrology and water resources. *Sci Data*. 2019;6(1):190030. doi:10.1038/sdata.2019.30

450. Trisovic A, Lau MK, Pasquier T, Crosas M. A large-scale study on research code quality and execution. *Sci Data*. 2022;9(1):60. doi:10.1038/s41597-022-01143-6

451. Perez-Riverol Y, Gatto L, Wang R, Sachsenberg T, Uszkoreit J, Leprevost F da V, Fufezan C, Ternent T, Eglen SJ, Katz DS, Pollard TJ, Konovalov A, Flight RM, Blin K, Vizcaíno JA. Ten Simple

Rules for Taking Advantage of Git and GitHub. *PLoS Comput Biol*. 2016;12(7):e1004947. doi:10.1371/journal.pcbi.1004947

452. Chen KY, Toro-Moreno M, Subramaniam AR. GitHub enables collaborative and reproducible laboratory research. *PLoS Biol*. 2025;23(2):e3003029. doi:10.1371/journal.pbio.3003029

453. Wattanakriengkrai S, Chinthanet B, Hata H, Kula RG, Treude C, Guo J, Matsumoto K. GitHub repositories with links to academic papers: Public access, traceability, and evolution. *Journal of Systems and Software*. 2022;183:111117. doi:10.1016/j.jss.2021.111117

454. Kang D, Kang T, Jang J. Papers with code or without code? Impact of GitHub repository usability on the diffusion of machine learning research. *Information Processing & Management*. 2023;60(6):103477. doi:10.1016/j.ipm.2023.103477

455. Braga PHP, Hébert K, Hudgins EJ, Scott ER, Edwards BPM, Sánchez Reyes LL, Grainger MJ, Foroughirad V, Hillemann F, Binley AD, Brookson CB, Gaynor KM, Shafiei Sabet S, Güncan A, Weierbach H, Gomes DGE, Crystal-Ornelas R. Not just for programmers: How GitHub can accelerate collaborative and reproducible research in ecology and evolution. *Methods in Ecology and Evolution*. 2023;14(6):1364-1380. doi:10.1111/2041-210X.14108

456. Scroggie KR, Burrell-Sander KJ, Rutledge PJ, Motion A. GitHub as an open electronic laboratory notebook for real-time sharing of knowledge and collaboration. *Digital Discovery*. 2023;2(4):1188-1196. doi:10.1039/D3DD00032J

457. Hoppe K. *Continuous Monitoring Water Quality Standard Operating Procedures*. State of Maine Department of Environmental Protection; 2023:50. Accessed June 16, 2025. https://www.maine.gov/dep/water/monitoring/Continuous%20Monitoring%20SOP%202023.pdf

458. Wagner R, Mattraw H, Ritz G, Smith B. *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting*. U.S. Geological Survey & U.S. Dept. of the Interior; 2006:51. Accessed June 16, 2025. https://pubs.usgs.gov/publication/tm1D3

459. Rymszewicz A, O'Sullivan JJ, Bruen M, Turner JN, Lawler DM, Conroy E, Kelly-Quinn M. Measurement differences between turbidity instruments, and their implications for suspended sediment concentration and load calculations: A sensor inter-comparison study. *Journal of Environmental Management*. 2017;199:99-108. doi:10.1016/j.jenvman.2017.05.017

460. Nolan P. *Ensemble of Regional Climate Model Projections for Ireland: 2008-FS-CC-m*. Environmental Protection Agency; 2015.

461. Coonan B, Curley M, Ryan C. *Long-Term Rainfall Averages for Ireland 1991-2020*. Met Éireann; 2024:32. Accessed June 16, 2025. https://www.tara.tcd.ie/handle/2262/108693

462. Sandve GK, Nekrutenko A, Taylor J, Hovig E. Ten Simple Rules for Reproducible Computational Research. *PLOS Computational Biology*. 2013;9(10):e1003285. doi:10.1371/journal.pcbi.1003285

463. Chang FJ, Guo S. Advances in Hydrologic Forecasts and Water Resources Management. *Water*. 2020;12(6):6. doi:10.3390/w12061819

464. Heathwaite AL, Bieroza M. Fingerprinting hydrological and biogeochemical drivers of freshwater quality. *Hydrological Processes*. 2021;35(1):e13973. doi:10.1002/hyp.13973

465. McDowell RW, McNeill SJ, Drewry JJ, Law R, Stevenson B. Difficulties in using land use pressure and soil quality indicators to predict water quality. *Science of The Total Environment*. 2024;935:173445. doi:10.1016/j.scitotenv.2024.173445

466. Gentilucci M, Djouohou SI, Barbieri M, Hamed Y, Pambianchi G. Trend Analysis of Streamflows in Relation to Precipitation: A Case Study in Central Italy. *Water*. 2023;15(8):8. doi:10.3390/w15081586

467. Gupta N, Yadav S, Chaudhary N. Time Series Analysis and Forecasting of Water Quality Parameters along Yamuna River in Delhi. *Procedia Computer Science*. 2024;235:3191-3206. doi:10.1016/j.procs.2024.04.302

468. Lange H, Hauhs M. Complexity Analysis of Environmental Time Series. *Entropy*. 2025;27(4):4. doi:10.3390/e27040381

469. Wickham H, Grolemund G. *R for Data Science: Import, Tidy, Transform, Visualize, and Model*. 1st ed. O'Reilly Media; 2017. Accessed June 16, 2025. https://www.amazon.co.uk/R-Data-Science-Garrett-Grolemund/dp/1491910399

470. Pileggi S. Context-is-king. In: *What They Forgot To Teach You About R*. 2024. Accessed June 16, 2025. https://posit.co/blog/talks-and-workshops-from-posit-conf-2024/

471. Peikert A, van Lissa CJ, Brandmaier AM. Reproducible Research in R: A Tutorial on How to Do the Same Thing More Than Once. *Psych*. 2021;3(4):4. doi:10.3390/psych3040053

472. Cronin L, Taylor CM. Workflow for identifying water quality hydrodynamic events in time series data (V1.0.0). Published online May 7, 2025. doi:10.5281/ZENODO.15358190 (Accessed: 2025-06-16)

473. Arend D, Psaroudakis D, Memon JA, Rey-Mazón E, Schüler D, Szymanski JJ, Scholz U, Junker A, Lange M. From data to knowledge – big data needs stewardship, a plant phenomics perspective. *The Plant Journal*. 2022;111(2):335-347. doi:10.1111/tpj.15804

474. Hutton C, Wagener T, Freer J, Han D, Duffy C, Arheimer B. Most computational hydrology is not reproducible, so is it really science? *Water Resources Research*. 2016;52(10):7548-7555. doi:10.1002/2016WR019285

475. Siraji MA, Rahman M. Primer on Reproducible Research in R: Enhancing Transparency and Scientific Rigor. *Clocks Sleep*. 2023;6(1):1-10. doi:10.3390/clockssleep6010001

476. Santos-Fernandez E, Ver Hoef JM, Peterson EE, McGree J, Villa CA, Leigh C, Turner R, Roberts C, Mengersen K. Unsupervised Anomaly Detection in Spatio-Temporal Stream Network Sensor Data. *Water Resources Research*. 2024;60(11):e2023WR035707. doi:10.1029/2023WR035707

477. Herrera J, Carrion D, Bresciani M, Bratic G. SEMI-AUTOMATED PRODUCTION AND FILTERING OF SATELLITE DERIVED WATER QUALITY PARAMETERS. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. 2022;XLIII-B3-2022:1019-1026. doi:10.5194/isprs-archives-XLIII-B3-2022-1019-2022

478. Sowrav SFF, Debsarma SK, Das MK, Ibtehal KM, Rahman M, Hridita NT, Broty AA, Hoque MSA. Developing a semi-automated technique of surface water quality analysis using GEE and machine learning: A case study for Sundarbans. *Heliyon*. 2025;11(3):e42404. doi:10.1016/j.heliyon.2025.e42404

479. Posit team. RStudio: Integrated Development Environment for R. Published online 2024. Accessed June 16, 2025. https://posit.co/products/open-source/rstudio/

480. Smith B, Naden P, Leeks G, Wass P. The influence of storm events on fine sediment transport, erosion and deposition within a reach of the River Swale, Yorkshire, UK. *Science of The Total Environment*. 2003;s 314–316:451-474. doi:10.1016/S0048-9697(03)00068-8

481. Leigh C, Kandanaarachchi S, McGree JM, Hyndman RJ, Alsibai O, Mengersen K, Peterson EE. Predicting sediment and nutrient concentrations from high-frequency water-quality data. *PLOS ONE*. 2019;14(8):e0215503. doi:10.1371/journal.pone.0215503

482. Yousif M, Burdett H, Wellen C, Mandal S, Arabian G, Smith D, Sorichetti RJ. An innovative approach to correct data from in-situ turbidity sensors for surface water monitoring. *Environmental Modelling & Software*. 2022;155:105461. doi:10.1016/j.envsoft.2022.105461

483. Burkhardt J. Details for Event Matching for Near real time event detection for watershed monitoring with CANARY, Email to Lisa Cronin. Published online December 6, 2024.

484. Whitehead PG, Wade AJ, Butterfield D. Potential impacts of climate change on water quality and ecology in six UK rivers. *Hydrology Research*. 2009;40(2-3):113-122. doi:10.2166/nh.2009.078

485. EPA. EPA Geoportal. 2025. Accessed November 22, 2025. https://gis.epa.ie/

486. McConigley C, White B. Blue Dot Catchments – working to let life thrive in some of our wildest waters. Catchments.ie. December 10, 2020. Accessed April 12, 2023. https://www.catchments.ie/blue-dot-catchments-working-to-let-life-thrive-in-some-of-our-wildest-waters/

487. Wynants M, Hallberg L, Prischl LA, Livsey J, Bieroza M. Trends and purposes of European river monitoring and restoration. *Environmental Science & Policy*. 2025;170:104130. doi:10.1016/j.envsci.2025.104130

488. McGarrigle M. Assessment of small water bodies in Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy*. 2014;114B(3):119-128.

489. Steele-Dunne S, Lynch P, McGrath R, Semmler T, Wang S, Hanafin J, Nolan P. The impacts of climate change on hydrology in Ireland. *Journal of Hydrology*. 2008;356(1):28-45. doi:10.1016/j.jhydrol.2008.03.025

490. Fealy RM, Buckley C, Mechan S, Melland A, Mellander PE, Shortle G, Wall D, Jordan P. The Irish Agricultural Catchments Programme: catchment selection using spatial multi-criteria decision analysis. *Soil Use and Management*. 2010;26(3):225-236. doi:10.1111/j.1475-2743.2010.00291.x

491. McDowell R, Kleinman PJA, Haygarth P, McGrath JM, Smith D, Heathwaite L, Iho A, Schoumans O, Nash D. A review of the development and implementation of the critical source area

concept: A reflection of Andrew Sharpley's role in improving water quality. *Journal of Environmental Quality*. 2025;54(4):807-826. doi:10.1002/jeq2.20551

492. McDowell RW, Noble A, Kittridge M, Ausseil O, Doscher C, Hamilton DP. Monitoring to detect changes in water quality to meet policy objectives. *Sci Rep*. 2024;14(1):1914. doi:10.1038/s41598-024-52512-7

493. Torres C, Gitau MW, Paredes-Cuervo D, Engel B. Evaluation of sampling frequency impact on the accuracy of water quality status as determined considering different water quality monitoring objectives. *Environ Monit Assess*. 2022;194(7):489. doi:10.1007/s10661-022-10169-7

494. Moraetis D, Efstathiou D, Stamati F, Tzoraki O, Nikolaidis NP, Schnoor JL, Vozinakis K. High-frequency monitoring for the identification of hydrological and bio-geochemical processes in a Mediterranean river basin. *Journal of Hydrology*. 2010;389(1-2):127-136. doi:10.1016/j.jhydrol.2010.05.037

495. Burns DA, Pellerin BA, Miller MP, Capel PD, Tesoriero AJ, Duncan JM. Monitoring the riverine pulse: Applying high-frequency nitrate data to advance integrative understanding of biogeochemical and hydrological processes. *WIREs Water*. 2019;6(4):4. doi:10.1002/wat2.1348

496. Adams R, Quinn PF, Perks M, Barber NJ, Jonczyk J, Owen GJ. Simulating high frequency water quality monitoring data using a catchment runoff attenuation flux tool (CRAFT). *Science of The Total Environment*. 2016;572:1622-1635. doi:10.1016/j.scitotenv.2016.01.045

497. Adams R, Quinn PF, Bowes MJ. The Catchment Runoff Attenuation Flux Tool, a minimum information requirement nutrient pollution model. *Hydrology and Earth System Sciences*. Published online 2015. doi:10.5194/hess-19-1641-2015

498. Ryan C, Curley M, Walsh S, Murphy C. Long-term trends in extreme precipitation indices in Ireland. *International Journal of Climatology*. 2022;42(7):4040-4061. doi:10.1002/joc.7475

499. O'Brien RJ, Misstear BD, Gill LW, Deakin JL, Flynn R. Developing an integrated hydrograph separation and lumped modelling approach to quantifying hydrological pathways in Irish river catchments. *Journal of Hydrology*. 2013;486:259-270. doi:10.1016/j.jhydrol.2013.01.034

500. Lefrancq M, Jadas-Hécart A, La Jeunesse I, Landry D, Payraudeau S. High frequency monitoring of pesticides in runoff water to improve understanding of their transport and environmental impacts. *Science of The Total Environment*. 2017;587-588:75-86. doi:10.1016/j.scitotenv.2017.02.022

501. Reitz M, Sanford WE. Estimating quick-flow runoff at the monthly timescale for the conterminous United States. *Journal of Hydrology*. 2019;573:841-854. doi:10.1016/j.jhydrol.2019.04.010

502. Mellander PE, Melland AR, Jordan P, Wall DP, Murphy PNC, Shortle G. Quantifying nutrient transfer pathways in agricultural catchments using high temporal resolution data. *Environmental Science & Policy*. 2012;24:44-57. doi:10.1016/j.envsci.2012.06.004

503. Lloyd CEM, Freer JE, Johnes PJ, Collins AL. Using hysteresis analysis of high-resolution water quality monitoring data, including uncertainty, to infer controls on nutrient and sediment transfer in catchments. *Science of The Total Environment*. 2016;543:388-404. doi:10.1016/j.scitotenv.2015.11.028

504. Adams R, Quinn P, Barber N, Burke S. Identifying Flow Pathways for Phosphorus Transport Using Observed Event Forensics and the CRAFT (Catchment Runoff Attenuation Flux Tool). *Water*. 2020;12(4):1081. doi:10.3390/w12041081

505. Ladson AR, Brown R, Neal B, Nathan R. A Standard Approach to Baseflow Separation Using The Lyne and Hollick Filter. *Australasian Journal of Water Resources*. 2013;17(1):25-34. doi:10.7158/13241583.2013.11465417

506. Fitzsimons IBDRM and VP. Estimating groundwater recharge in fractured bedrock aquifers in Ireland. In: *Groundwater in Fractured Rocks*. CRC Press; 2007.

507. Mao B, Wang X, Jia S, Liu Z. Multi-methods to investigate the baseflow: Insight from watershed scale spatiotemporal variety perspective. *Ecological Indicators*. 2024;158:111573. doi:10.1016/j.ecolind.2024.111573

508. Van Rooy MP. A RAINFALL ANOMALLY INDEX INDEPENDENT OF TIME AND SPACE, NOTOS. *WEATHER BUREAU SOUTH AFRICA Year*. 1965;14:43-48.

509. Murphy A. *Drought Summary 8th June 2020*. Climate Services Met Éireann; 2020:3. https://www.met.ie/cms/assets/uploads/2020/06/DroughtSummaryJune20.pdf

510. Wenng H, Barneveld R, Bechmann M, Marttila H, Krogstad T, Skarbøvik E. Sediment transport dynamics in small agricultural catchments in a cold climate: A case study from Norway. *Agriculture, Ecosystems & Environment*. 2021;317:107484. doi:10.1016/j.agee.2021.107484

511. Upadhayay HR, Zhang Y, Granger SJ, Micale M, Collins AL. Prolonged heavy rainfall and land use drive catchment sediment source dynamics: Appraisal using multiple biotracers. *Water Research*. 2022;216:118348. doi:10.1016/j.watres.2022.118348

512. Ross C, Petzold H, Penner A, Ali G. Comparison of sampling strategies for monitoring water quality in mesoscale Canadian Prairie watersheds. *Environ Monit Assess*. 2015;187(7):395. doi:10.1007/s10661-015-4637-9

513. Nallakaruppan MK, Gangadevi E, Shri ML, Balusamy B, Bhattacharya S, Selvarajan S. Reliable water quality prediction and parametric analysis using explainable AI models. *Sci Rep*. 2024;14(1):7520. doi:10.1038/s41598-024-56775-y

514. Westerberg I, Guerrero JL, Younger P, Beven K, Seibert J, Halldin S, Freer J, Xu CY. Calibration of hydrologic models using flow-duration curves. *Hydrology and Earth System Sciences*. 2011;15:2205-2227. doi:10.5194/hess-15-2205-2011

515. Vogel RM, Fennessey NM. Flow-Duration Curves. I: New Interpretation and Confidence Intervals. *Journal of Water Resources Planning and Management*. 1994;120(4):485-504. doi:10.1061/(ASCE)0733-9496(1994)120:4(485)

516. Zambrano-Bigiarini M. hydroTSM: Time Series Management and Analysis for Hydrological Modelling. R package. Published online 2025. :https://CRAN.R-project.org/package=hydroTSM

517. EPA. *Ireland's National Water Quality Monitoring Programme 2022 - 2027*. Environmental Protection Agency; 2023:32. Accessed August 2, 2026. https://www.epa.ie/publications/monitoring--assessment/freshwater--marine/irelands-national-water-quality-monitoring-programme-20222027.php

518. EPA Catchments Unit. Catchment Data. Catchments.ie. December 2, 2025. Accessed September 19, 2025. https://www.catchments.ie/data/

519. Marcé R, George G, Buscarinu P, Deidda M, Dunalska J, de Eyto E, Flaim G, Grossart HP, Istvanovics V, Lenhardt M, Moreno-Ostos E, Obrador B, Ostrovsky I, Pierson DC, Potužák J, Poikane S, Rinke K, Rodríguez-Mozaz S, Staehr PA, Šumberová K, Waajen G, Weyhenmeyer GA, Weathers KC, Zion M, Ibelings BW, Jennings E. Automatic High Frequency Monitoring for Improved Lake and Reservoir Management. *Environ Sci Technol*. 2016;50(20):10780-10794. doi:10.1021/acs.est.6b01604

520. Lin Y, Wang D, Mei Y, Zhu J, Wu H, Wang S, Xu Z, Shamseldin AY, Anagnostou EN. Symbolic regression-based regionalization of baseflow separation parameter using catchment-scale characteristics. *Hydrol Earth Syst Sci*. 2026;30(11):3425-3438. doi:10.5194/hess-30-3425-2026

521. Zarnaghsh A, Husic A. An index for inferring dominant transport pathways of solutes and sediment: Assessing land use impacts with high-frequency conductivity and turbidity sensor data. *Science of The Total Environment*. 2023;894:164931. doi:10.1016/j.scitotenv.2023.164931

522. Wasko C, Guo D. hydroEvents: Extract Event Statistics in Hydrologic Time Series. Published online February 12, 2025. Accessed August 20, 2025. https://cran.r-project.org/web/packages/hydroEvents/index.html

523. Wasko C, Nathan R. Influence of changes in rainfall and soil moisture on trends in flooding. *Journal of Hydrology*. 2019;575:432-441. doi:10.1016/j.jhydrol.2019.05.054

524. Tomperi J, Isokangas A, Tuuttila T, Paavola M. Functionality of turbidity measurement under changing water quality and environmental conditions. *Environ Technol*. 2022;43(7):1093-1101. doi:10.1080/09593330.2020.1815860

525. Rymszewicz A, O'Sullivan JJ, Bruen M, Turner JN, Lawler DM, Conroy E, Kelly-Quinn M. Measurement differences between turbidity instruments, and their implications for suspended sediment concentration and load calculations: A sensor inter-comparison study. *Journal of Environmental Management*. 2017;199:99-108. doi:10.1016/j.jenvman.2017.05.017

526. Riss G, Romano M, Memon FA, Kapelan Z. Detection of water quality failure events at treatment works using a hybrid two-stage method with CUSUM and random forest algorithms. *Water Supply*. 2021;21(6):3011-3026. doi:10.2166/ws.2021.062

527. Cronin L, Taylor CM, Briciu Burghina C, Lucy FE, Regan F. An open-source workflow for identifying hydrodynamic water quality events in rivers by continuous water quality monitoring and time-series data processing using R and US EPA CANARY. *MethodsX*. 2025;15:103538. doi:10.1016/j.mex.2025.103538

528. Wickham H, Chang W, Henry L, Pedersen TL, Takahashi K, Wilke C, Woo K, Yutani H, Dunnington D, Brand T van den, Posit, PBC. ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics (v 3.5.2). Published online April 9, 2025. Accessed November 22, 2025. https://cran.r-project.org/web/packages/ggplot2/index.html

529. Mohammadpour Khoie MM, Guo D, Wasko C. Improving the consistency of hydrologic event identification. *Environmental Modelling & Software*. 2025;191:106521. doi:10.1016/j.envsoft.2025.106521

530. Beven K. Uniqueness of place and the presentation of hydrological processes. *Hydrology and Earth System Sciences*. 2000;4. doi:10.5194/hess-4-203-2000

531. Fischer S, Schumann A. Spatio-temporal consideration of the impact of flood event types on flood statistic. *Stoch Environ Res Risk Assess*. 2020;34(9):1331-1351. doi:10.1007/s00477-019-01690-2

532. Minaudo C, Dupas R, Gascuel-Odoux C, Roubeix V, Danis PA, Moatar F. Seasonal and event-based concentration-discharge relationships to identify catchment controls on nutrient export regimes. *Advances in Water Resources*. 2019;131:103379. doi:10.1016/j.advwatres.2019.103379

533. Vale SS, Dymond JR. Interpreting nested storm event suspended sediment-discharge hysteresis relationships at large catchment scales. *Hydrological Processes*. 2020;34(2):420-440. doi:10.1002/hyp.13595

534. EPA. *Cycle 3 HA 35 Sligo Bay & Drowes Catchment Report*. Environmentla Protection Agency; 2024:14. Accessed October 15, 2024. https://catchments.ie/wp-content/files/catchmentassessments/35%20Sligo%20Bay%20&%20Drowse%20Catchment%20Summary%20WFD%20Cycle%203.pdf

535. EPA. *Water Quality in 2023 An Indicators Report*. Environmental Protection Agency; 2024:24. Accessed June 16, 2024. https://www.epa.ie/publications/monitoring--assessment/freshwater--marine/EPA-Water-Quality-Indicator-Report-2023-web-11June2024.pdf

536. Abily M, Acuña V, Gernjak W, Rodríguez-Roda I, Poch M, Corominas L. Climate change impact on EU rivers' dilution capacity and ecological status. *Water Research*. 2021;199:117166. doi:10.1016/j.watres.2021.117166

537. Graham DJ, Bierkens MFP, van Vliet MTH. Impacts of droughts and heatwaves on river water quality worldwide. *Journal of Hydrology*. 2024;629:130590. doi:10.1016/j.jhydrol.2023.130590

538. EU. *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy*. Vol 327. 2000. Accessed November 22, 2025. http://data.europa.eu/eli/dir/2000/60/oj/eng

539. Haase P, Pauls SU, Schindehütte K, Sundermann A. First audit of macroinvertebrate samples from an EU Water Framework Directive monitoring program: human error greatly lowers precision of assessment results. *jnbs*. 2010;29(4):1279-1291. doi:10.1899/09-183.1

540. OECD. Diffuse Pollution, Degraded Waters: Emerging Policy Solutions | READ online. oecd-ilibrary.org. 2017. Accessed June 13, 2022. https://read.oecd-ilibrary.org/environment/diffuse-pollution-degraded-waters_9789264269064-en

541. EEA. Habitats and species: latest status and trends. April 4, 2023. Accessed October 11, 2023. https://www.eea.europa.eu/en/topics/at-a-glance/nature/state-of-nature-in-europe-a-health-check/habitats-and-species-latest-status-and-trends

542. Chapman DV, Sullivan T. The role of water quality monitoring in the sustainable use of ambient waters. *One Earth*. 2022;5(2):132-137. doi:10.1016/j.oneear.2022.01.008

543. O'Grady J, Zhang D, O'Connor N, Regan F. A comprehensive review of catchment water quality monitoring using a tiered framework of integrated sensing technologies. *Science of The Total Environment*. 2021;765:142766. doi:10.1016/j.scitotenv.2020.142766

APPENDIX A: User Guide – Timeseries Water Quality Data Processing with R and EPA CANARY for Hydrodynamic Event Monitoring

This User guide and the supporting R code and data are published on Github at

https://github.com/LCroninATU/Workflow-for-identifying-water-quality-hydrodynamic-events-in-time-series-data

User Guide - Timeseries Water Quality Data Processing with R and EPA CANARY for Hydrodynamic Event Monitoring

A full functional water quality project written in R showing a simple step-by-step workflow for processing time series data from a water quality sensor and how to use that data for the identification of potential water quality events.

Authors: Lisa Cronin, Cian Taylor

2025-04-25

For the supporting code and data: https://github.com/LCroninATU/Workflow-for-identifying-water-quality-hydrodynamic-events-in-time-series-data

Please contact me with questions by email Lisa.cronin@atu.ie. For more information on projects being carried out at DCU Water Institute https://dcuwater.ie/ led by Prof. Fiona Regan



Introduction

This guide is based on and designed to be used in conjunction with the R markdown file available on github at https://github.com/LCroninATU/Workflow-for-identifying-waterhttps://github.com/LCroninATU/Workflow-for-identifying-water-quality-hydrodynamic-events-in-time-series-dataquality-hydrodynamic-events-in-time-series-data . The markdown file contains a detailed description of the workflow, the R code and output files from that R code, and from the EPA CANARY event detection software.

Cite the repository

If you use this software in your work, please cite it using the following metadata. Lisa Cronin and Cian Taylor (2025) "LCroninATU/Workflow-for-identifying-water-qualityhydrodynamic-events-in-time-series-data: V1.0.0".
DOI: https://doi.org/10.5281/zenodo.15358190

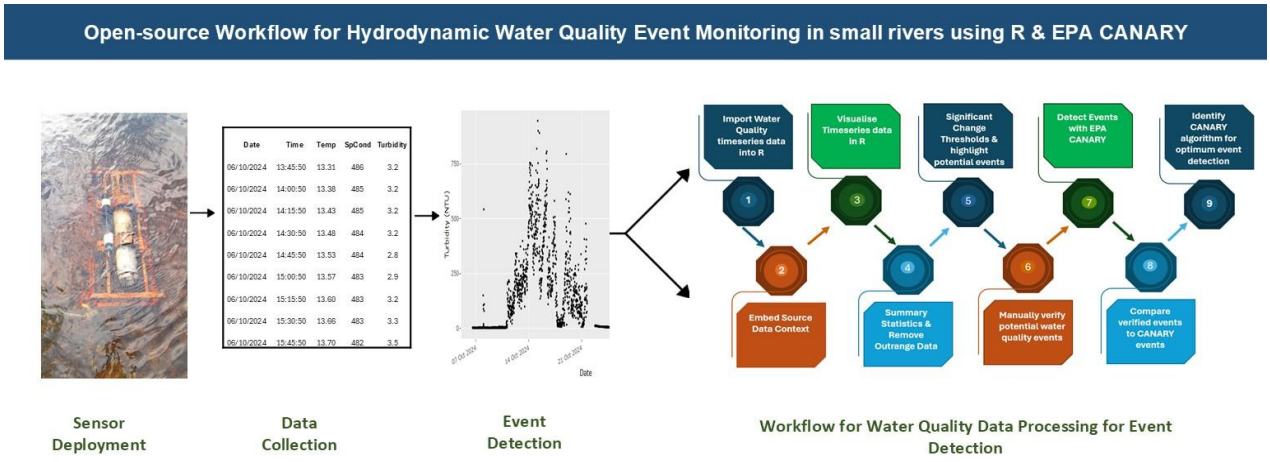
Description

This project contains a concise, reproducible, open-source workflow detailing the use of R, R markdown and EPA CANARY event detection software and was designed for catchment scientists, researchers and those working in on stream hydrochemistry, diffuse pollution or any EU Water Framework Directive water quality projects who require a simple, detailed workflow that can be easily replicated requiring minimum expertise in R. One of the primary objectives of this project was to provide simple code that non-coders can follow and to produce outputs at each step of the workflow so the user can validate the code for their data. This project includes a sample data file and a detailed markdown so you can take the sample file provided through each step of the workflow, prior to applying the code to your own data.

Each part of this project is simple sample code which details how to do the following:

- import time series data,
- clean the data,

- visualize the data,
- maintain data integrity,
- manually identify potential water quality events,
- match those events to the output of EPA CANARY event detection software,
- identify the most suitable configuration of EPA CANARY for that particular water quality monitoring station.



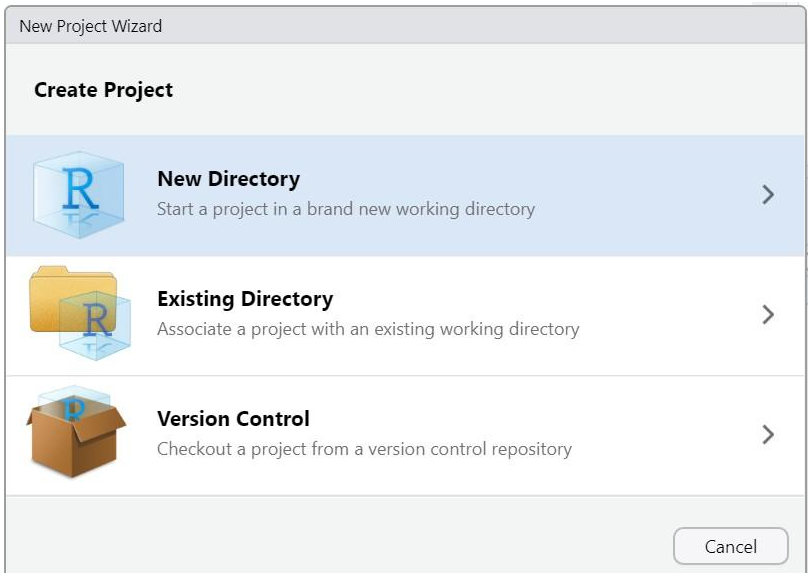
Getting Started

Dependencies

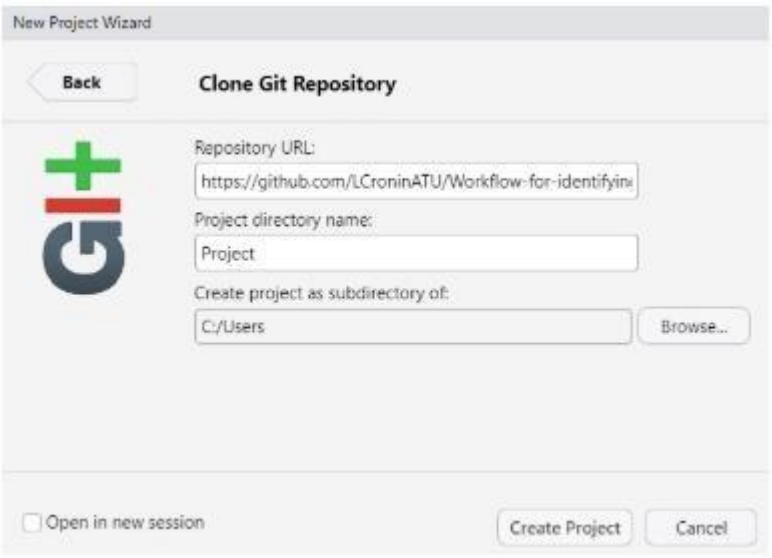
- Needs recent install of R and Rstudio.
- Dependencies are managed through the renv package which was created by RStudio developers specifically for this purpose. The "renv" package will create a package library which is specific to this project. Thus, you can ensure that you have the correct version of all required packages (those used in the original build). Outside of the project, you can use or install whatever package versions you prefer, those inside the project space will not be affected.

Installing the Software

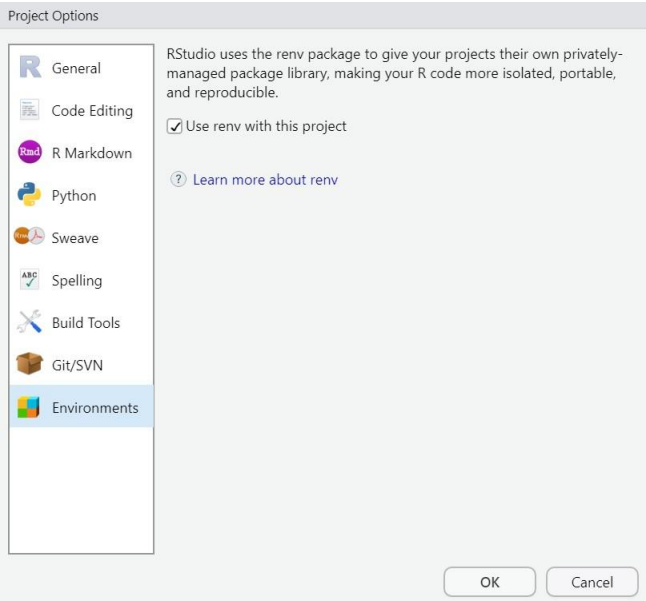
- Install R and Rstudio latest versions.
- Install the "renv" package by typing install.packages("renv") in the R console.
- You need to have a github account and a local install of git on your machine.
- Open a git BASH (start the "git BASH app") and introduce yourself to git. This will allow Rstudio to connect successfully to github.
- Open RStudio and create a New Rstudio Project.
- Select the option to install from "Version Control".



- Select "git".
- In the dialog box that follows, fill the first two boxes in as shown below:



- In the third box, browse to the folder on your local machine where you want to install the project.
- Select "Create Project"
- Ensure that "renv" is enabled for the project as follows:
    - In Rstudio click on "Tools" menu, followed by "Project Options".
    - Select "Environments" from the list of icons on the left of the dialog box.
    - Ensure the box beside "Use renv with this project" is ticked as shown:



- Now check that the correct versions of all required packages are installed by running the command renv::status(), from the R console. You will see a list of any dependency issues.
- To resolve any dependency issues, type the command renv::restore(). The correct version of every required dependent package will now install.
- At this point you should be able to execute any of the scripts or RMd documents within any directory.

Executing program (from RStudio)

- Follow the step-by-step instructions, the code and the output of the code in the 'Workflow for Hydrodynamic Event Detection' markdown file.
- The scripts are also available but the markdown file is the place to start for users who are new to R.

Executing program (from Docker)

- In the event that you want to run the package from docker, follow the setup steps described above in order to create a copy of the repository on your local machine.
- Then follow the steps outline here.

The Workflow

- Open the Project file, Project Workflow for detecting Hydrodynamic Water Quality Events (extension R Project) followed by the Workflow-for-Hydrodynamic-Event-Detection (extension RMD file).
  There is also a Workflow-for-Hydrodynamic-Event-Detection HTML file which can be a helpful read along user guide for those new to R. It is too large to open in GitHub so must be downloaded to your web browser.

Help

More information on reusing other people's code in your project https://docs.github.com/en/get-started/learning-to-code/reusing-other-peoples-code-in-your-projects

How to tweak this project for your own use

We would encourage you to clone this project from Github and rename this project to use for your own data.

Contents

R Studio Projects

A1.0 Import Water Quality Data

A1.1 Load the packages

A1.2 The working Directory

A1.2 Set the time zone (no daylight saving)

A1.3 Import the data file

A1.4 Tidy the data and format the imported water quality data

A1.5 Combine the files into a single dataframe

A2.0 Data Integrity

A3.0 Visualisation of Water Quality Data

A4.0 Summary Statistics

A5.0 Define significant change thresholds for turbidity and highlight on plots to identify events

A6.0 Manually Identify Potential Water Quality Events with the aid of the interactive turbidity plot.

A7.0 Event Detection using EPA CANARY

A8.0 Compare manually identified Owenmore turbidity events to events identified by CANARY 9.0

Compare the Owenmore CANARY files to the manually identified events to identify the most suitable CANARY algorithm.

References

R Studio Projects

R Studio uses projects to store all the data, R scripts, output files including figures, tables etc associated with each individual project in one place.

There is a project file associated with this project called 'Project Workflow for detecting Hydrodynamic Water Quality Events'. You must double click on this file to open this project *prior* to running the code. Otherwise, the code may not run correctly.

A1.0 Import Water Quality Data

One of the first steps in processing data is importing the data into R.

A1.1 Load the packages

You may need to install some of the packages before loading them. Go to the output pane on the bottom right of the screen, go to packages, install, enter the name of the package under packages and click install. You may be asked to enter 'Y' in the console to confirm the installation.

for working with tabular data library(data.table) *### for data wrangling* library(dplyr) *### for working with dates & times* library(lubridate) *### for labelling of variables* library(labelled) *### breaks and labels for axes and legends on graphs* library(scales) *### for data visualisation* library(ggplot2) *### tidy ways to summarise, visualise, and manipulate missing data* library(naniar) *### for creating interactive web-based graphs* library(plotly) *### for combining multiple plots into a single figure* library(cowplot) *### for arranging graphical elements* library(grid) *### to arrange multiple grid-based plots* library(gridExtra) *### for publication quality tables* library(stargazer) *### to make working with strings as easy as possible* library(stringr) *### tool to tidu up messy datasets* library(tidyr) *### to import, organize, manipulate, and visualise data* library(tidyverse)

A1.2 The working Directory

This is the location on your pc which r will use for reading and writing files. R operates a working directory where it looks for files that you want to load and where it saves files you request R to save. This working directory is displayed at the top of the console window. The

'here' package sets the top level of the project folder. It's very important to open the project file as described previously **before** trying to run any code to avoid problems with files and the working directory.

```
library(here)  # for file referencing
```

1.2 Set the timezone (no daylight saving)

```
Sys.setenv(TZ='UTC')
Sys.timezone()
## [1] "UTC"
```

A1.3 Import the data file.

There are two options in this workflow to import the data files, either as individual files or loading multiple files together. Two csv files have been provided as an example, OW061024 and OW221024. OW refers to the name of the river where the sonde was deployed, in this case the Owenmore River, Sligo, and 061024 is the date the sonde was deployed in the river.

Option 1: Import a single .csv data file and specify the variables to be loaded.

In this case 'Date', 'Time', 'Temp', 'SpCond' and 'Turbid+'. Watch out for spaces in column names in some .txt files when specifying the variable name, it must match exactly. **Note: For these files, only data for temperature, specific conductivity and turbidity are valid as only these sensors were calibrated.**

```
OW061024<-fread("01_ImportYSI_Data/Data/OW061024.txt",skip=1, header=T,select = c("
OW221024<-fread("01_ImportYSI_Data/Data/OW221024.txt",skip=1, header=T,select = c("
```

Display the structure and properties of the imported file.

```
# Display the structure of the imported file str(OW061024)
## Classes 'data.table' and 'data.frame':   1466 obs. of  5 variables:
## $      Date: chr  "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...
```

```
## $    Time  : chr  "12:30:50" "12:45:50" "13:00:50" "13:15:50" ...
## $  Temp    : chr  "13.04" "13.09" "14.50" "15.76" ...
## $ SpCond   : chr  "265" "264" "6" "5" ...
## $ Turbid+  : chr  "1.2" "1.6" "0.7" "0.8" ... ##  - attr(*, ".internal.selfref")=<externalptr>
str(OW221024)
## Classes 'data.table' and 'data.frame':   1354 obs. of  5 variables:
## $      Date: chr  "22/10/2024" "22/10/2024" "22/10/2024" "22/10/2024" ...
## $    Time  : chr  "10:30:50" "10:45:50" "11:00:50" "11:15:50" ...
## $  Temp    : chr  "12.59" "12.47" "12.37" "12.27" ...
## $ SpCond   : chr  "278" "265" "266" "266" ...
## $ Turbid+  : chr  "0.2" "0.4" "0.3" "0.3" ...
##  - attr(*, ".internal.selfref")=<externalptr>
# Display the class or the properties of the imported file, this affects how the im
class(OW061024)
## [1] "data.table" "data.frame"
class(OW221024)
## [1] "data.table" "data.frame"
```

Option 2: Import Multiple Files into R & bind them together.

Alternative option for importing files is to import the entire file and subset for the variables of interest. **Note: For these files, only data for temperature, specific conductivity and turbidity are valid as only these sensors were calibrated.**

```
# Import the data file
OW061024<-fread("01_ImportYSI_Data/Data/OW061024.txt",skip=1, header=T,)[-1:-2]
OW221024<-fread("01_ImportYSI_Data/Data/OW221024.txt",skip=1, header=T)[-1:-2]
str(OW061024)
## Classes 'data.table' and 'data.frame':   1466 obs. of  15 variables:
## $      Date: chr  "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...
## $    Time  : chr  "12:30:50" "12:45:50" "13:00:50" "13:15:50" ...
```

```
## $ Temp    : chr  "13.04" "13.09" "14.50" "15.76" ...
## $ SpCond   : chr  "265" "264" "6" "5" ...
## $ Cond    : chr  "0.204" "0.204" "0.005" "0.004" ...
## $ TDS    : chr  "0.172" "0.172" "0.004" "0.003" ...
## $ Sal    : chr  "0.13" "0.13" "0.00" "0.00" ...
## $ Press   : chr  "14.287" "14.286" "14.282" "14.281" ...
## $ Depth   : chr  "-0.265" "-0.266" "-0.268" "-0.270" ...
## $ pH    : chr  "5.17" "5.08" "5.16" "4.53" ...
## $ pH   : chr  "59.3" "62.5" "59.8" "81.7" ...
## $ Chl    : chr  "0.9" "1.2" "0.2" "0.1" ...
## $ Chl    : chr  "0.2" "0.3" "0.0" "0.0" ...
## $ Turbid+  : chr  "1.2" "1.6" "0.7" "0.8" ...
## $ Battery  : chr  "11.7" "11.7" "11.7" "11.7" ... ##  - attr(*, ".internal.selfref")=<externalptr>
str(OW221024)
## Classes 'data.table' and 'data.frame':   1354 obs. of  15 variables:
## $ Date: chr  "22/10/2024" "22/10/2024" "22/10/2024" "22/10/2024" ...
## $ Time  : chr  "10:30:50" "10:45:50" "11:00:50" "11:15:50" ...
## $ Temp    : chr  "12.59" "12.47" "12.37" "12.27" ...
## $ SpCond   : chr  "278" "265" "266" "266" ...
## $ Cond    : chr  "0.212" "0.202" "0.202" "0.202" ...
## $ TDS    : chr  "0.181" "0.173" "0.173" "0.173" ...
## $ Sal    : chr  "0.13" "0.13" "0.13" "0.13" ...
## $ Press   : chr  "14.750" "14.756" "14.759" "14.761" ...
## $ Depth   : chr  "0.062" "0.066" "0.068" "0.069" ...
## $ pH    : chr  "6.23" "6.34" "6.42" "6.42" ...
## $ pH   : chr  "23.1" "19.5" "16.7" "16.8" ...
```

$ Chl : chr "0.8" "0.2" "0.4" "0.6" ...

$ Chl : chr "0.2" "0.1" "0.1" "0.1" ...

$ Turbid+ : chr "0.2" "0.4" "0.3" "0.3" ...

$ Battery : chr "11.3" "11.3" "11.3" "11.4" ... ## - attr(*,

".internal.selfref")=<externalptr> class(OW061024) ## [1] "data.table" "data.frame"

class(OW221024)

[1] "data.table" "data.frame"

Display the column names, this provides the exact column name (including any spaces!) when choosing columns of interest and then drop any unwanted variables by entering NULL against these.

 # Display the column names colnames(OW061024)
[1] " Date" " Time" " Temp" "SpCond" " Cond"

[6] " TDS" " Sal" " Press" " Depth" " pH" ## [11] " pH" " Chl" " Chl"

"Turbid+" "Battery"

colnames(OW221024)

[1] " Date" " Time" " Temp" "SpCond" " Cond"

[6] " TDS" " Sal" " Press" " Depth" " pH"

[11] " pH" " Chl" " Chl" "Turbid+" "Battery"

 # Subset for the variables of interest in OW061024 by dropping each column not requ
OW061024$` Cond`<-NULL

OW061024$` TDS`<-NULL

OW061024$` Sal`<-NULL

OW061024$` Press`<-NULL

OW061024$` Depth`<-NULL

OW061024$` pH`<-NULL

OW061024$` pH`<-NULL

```
OW061024$`  Chl`<-NULL

OW061024$"  Chl"<-NULL

OW061024$Battery<-NULL

# Subset for the variables of interest in OW221024 by dropping each column not requ
OW221024$` Cond`<-NULL

OW221024$`  TDS`<-NULL

OW221024$`   Sal`<-NULL

OW221024$`  Press`<-NULL

OW221024$`  Depth`<-NULL

OW221024$`   pH`<-NULL

OW221024$`    pH`<-NULL

OW221024$`  Chl`<-NULL

OW221024$"  Chl"<-NULL

OW221024$Battery<-NULL

# View the dataframe to see what variables have been retained (Note there is a numb
str(OW061024)
```

```
## Classes 'data.table' and 'data.frame':   1466 obs. of  5 variables:

## $      Date: chr  "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...

## $    Time  : chr  "12:30:50" "12:45:50" "13:00:50" "13:15:50" ...

## $  Temp    : chr  "13.04" "13.09" "14.50" "15.76" ...

## $ SpCond    : chr  "265" "264" "6" "5" ...

## $ Turbid+   : chr  "1.2" "1.6" "0.7" "0.8" ... ##  - attr(*, ".internal.selfref")=<externalptr>

str(OW221024)

## Classes 'data.table' and 'data.frame':   1354 obs. of  5 variables:

## $      Date: chr  "22/10/2024" "22/10/2024" "22/10/2024" "22/10/2024" ...

## $    Time  : chr  "10:30:50" "10:45:50" "11:00:50" "11:15:50" ...

## $  Temp    : chr  "12.59" "12.47" "12.37" "12.27" ...
```

$ SpCond : chr "278" "265" "266" "266" ...

$ Turbid+ : chr "0.2" "0.4" "0.3" "0.3" ...

- attr(*, ".internal.selfref")=<externalptr>

A1.4 Tidy the data and format the imported water quality data.

#Combine date and time columns to form DateTime & change from chr to as.POSIXct (as
OW061024$DateTime<-with(OW061024, dmy(OW061024$` Date`) + hms(OW061024$` Ti

OW221024$DateTime<-with(OW221024, dmy(OW221024$` Date`) + hms(OW221024$` Ti

str(OW061024)

Classes 'data.table' and 'data.frame': 1466 obs. of 6 variables:

$ Date: chr "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...

$ Time : chr "12:30:50" "12:45:50" "13:00:50" "13:15:50" ...

$ Temp : chr "13.04" "13.09" "14.50" "15.76" ...

$ SpCond : chr "265" "264" "6" "5" ...

$ Turbid+ : chr "1.2" "1.6" "0.7" "0.8" ...

$ DateTime : POSIXct, format: "2024-10-06 12:30:50" "2024-10-06 12:45:50" ... ## - attr(*,

".internal.selfref")=<externalptr>

str(OW221024)

Classes 'data.table' and 'data.frame': 1354 obs. of 6 variables:

$ Date: chr "22/10/2024" "22/10/2024" "22/10/2024" "22/10/2024" ...

$ Time : chr "10:30:50" "10:45:50" "11:00:50" "11:15:50" ...

$ Temp : chr "12.59" "12.47" "12.37" "12.27" ...

$ SpCond : chr "278" "265" "266" "266" ...

$ Turbid+ : chr "0.2" "0.4" "0.3" "0.3" ...

$ DateTime : POSIXct, format: "2024-10-22 10:30:50" "2024-10-22 10:45:50" ... ## - attr(*,

".internal.selfref")=<externalptr>

 # Rename the column names
OW061024<-setnames(OW061024, "Turbid+", "Turbidity")

OW061024<-setnames(OW061024," Temp", "Temp") *# this removes the space in fro.*

OW221024<-setnames(OW221024, "Turbid+", "Turbidity") OW221024<-

setnames(OW221024," Temp", "Temp") colnames(OW061024)

[1] " Date" " Time" "Temp" "SpCond" "Turbidity" ## [6] "DateTime"

colnames(OW221024)

[1] " Date" " Time" "Temp" "SpCond"

"Turbidity" ## [6] "DateTime"

 # Change variable format from chr to numeric str(OW061024)
Classes 'data.table' and 'data.frame': 1466 obs. of 6 variables:

$ Date: chr "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...

$ Time : chr "12:30:50" "12:45:50" "13:00:50" "13:15:50" ...

$ Temp : chr "13.04" "13.09" "14.50" "15.76" ...

$ SpCond : chr "265" "264" "6" "5" ...

$ Turbidity : chr "1.2" "1.6" "0.7" "0.8" ...

$ DateTime : POSIXct, format: "2024-10-06 12:30:50" "2024-10-06 12:45:50" ... ## - attr(*,

".internal.selfref")=<externalptr>

str(OW221024)

Classes 'data.table' and 'data.frame': 1354 obs. of 6 variables:

$ Date: chr "22/10/2024" "22/10/2024" "22/10/2024" "22/10/2024" ...

$ Time : chr "10:30:50" "10:45:50" "11:00:50" "11:15:50" ...

$ Temp : chr "12.59" "12.47" "12.37" "12.27" ...

$ SpCond : chr "278" "265" "266" "266" ...

$ Turbidity : chr "0.2" "0.4" "0.3" "0.3" ...

$ DateTime : POSIXct, format: "2024-10-22 10:30:50" "2024-10-22 10:45:50"

... ## - attr(*, ".internal.selfref")=<externalptr>

```
OW061024$SpCond<-as.numeric((OW061024$SpCond))

OW061024$`Temp`<-as.numeric((OW061024$Temp))

OW061024$Turbidity<-as.numeric((OW061024$Turbidity))

OW221024$SpCond<-as.numeric((OW221024$SpCond))

OW221024$`Temp`<-as.numeric((OW221024$Temp))

OW221024$Turbidity<-as.numeric((OW221024$Turbidity))

# Change variable format from chr to numeric # View the structure after the format changes
str(OW061024)
```

Classes 'data.table' and 'data.frame': 1466 obs. of 6 variables:

$ Date: chr "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...

$ Time : chr "12:30:50" "12:45:50" "13:00:50" "13:15:50" ...

$ Temp : num 13 13.1 14.5 15.8 16.4 ...

$ SpCond : num 265 264 6 5 6 486 485 485 484 484 ...

$ Turbidity : num 1.2 1.6 0.7 0.8 1.8 3.2 3.2 3.2 3.2 2.8 ...

$ DateTime : POSIXct, format: "2024-10-06 12:30:50" "2024-10-06 12:45:50" ... ## - attr(*,

".internal.selfref")=<externalptr>

```
str(OW221024)
```

Classes 'data.table' and 'data.frame': 1354 obs. of 6 variables:

$ Date: chr "22/10/2024" "22/10/2024" "22/10/2024" "22/10/2024" ...

$ Time : chr "10:30:50" "10:45:50" "11:00:50" "11:15:50" ...

$ Temp : num 12.6 12.5 12.4 12.3 12.1 ...

$ SpCond : num 278 265 266 266 263 265 267 268 267 267 ...

$ Turbidity : num 0.2 0.4 0.3 0.3 1.7 2.4 1.7 1.5 1.7 1.7 ...

$ DateTime : POSIXct, format: "2024-10-22 10:30:50" "2024-10-22 10:45:50"

... ## - attr(*, ".internal.selfref")=<externalptr>

Review imported file and if required, remove out-of-the-water-edits i.e. data before sensor was deployed in the river if sensor is running before being deployed, and data after sensor is removed from the river. Often the sensor will be put into operation to check everything is logging before being deployed in the water.

 # When importing multiple files together you will need to do this for each file imp OW061024 <-
OW061024 %>% filter(DateTime > ymd_hms('2024-10-06 13:40:00'))
 # and after removed from river
OW061024 <- OW061024 %>% filter(DateTime < ymd_hms('2024-10-21 17:20:00'))

OW221024 <- OW221024 %>% filter(DateTime > ymd_hms('2024-10-22

17:45:50')) *# and after removed from river.*

OW221024 <- OW221024 %>% filter(DateTime < ymd_hms('2024-11-05 11:46:50'))

 # and similarly, if the sensor was checked in situ during deployment

---

A1.5 Combine the files into a single dataframe.

To process the data as one file for visualization and event detection, the files need to be joined together.

 # Bind OW061024 and OW221024 to form new object OWCombined
OWCombined<- bind_rows(OW061024,OW221024)

A2.0 Data Integrity

A2.1 Embed source data context for data integrity by adding variable labels.

To ensure the integrity of the data persists once imported into R, it is very useful to embed the source data context in the datafile. Embed the source data context by adding variable labels to the sensor data. In this case the site name and sensor details are embedded.

```
OWCombined<-OWCombined|>   labelled::set_variable_labels(     DateTime = "Measurement
Date and Time of River Owenmore, Sligo ",
   Temp = "Temperature (degC) YSI6600EDSV2_2 6560 Conductivity_Temp. Probe",
   SpCond = "Specific Conductance uScm-1 YSI6600EDSV2-2 6560 Conductivity_Temp. Pr
Turbidity = "Turbidity (NTU) - YSI_6600_EDS_V2-2 - 6136 Turbidity Probe"
 )
# To view the variable labels # A new tab opens displaying the combined dataframe.
View(OWCombined)
```

```
##         Date     Time  Temp SpCond Turbidity           DateTime
##       <char>   <char> <num>  <num>     <num>           <POSc>
## 1: 06/10/2024 13:45:50 13.31    486       3.2 2024-10-06 13:45:50
## 2: 06/10/2024 14:00:50 13.38    485       3.2 2024-10-06 14:00:50
## 3: 06/10/2024 14:15:50 13.43    485       3.2 2024-10-06 14:15:50
## 4: 06/10/2024 14:30:50 13.48    484       3.2 2024-10-06 14:30:50
## 5: 06/10/2024 14:45:50 13.53    484       2.8 2024-10-06 14:45:50
## 6: 06/10/2024 15:00:50 13.57    483       2.9 2024-10-06 15:00:50
```

A2.2 Export the tidyied datafile as a .csv file and as .rds file to working directory.

Note the data labels are lost when exporting the files as .csv but are maintained when exported as .rds file. This file is used for visualisation and event detection.

 # Export the cleaned datafile as .csv to the working directory #

write.table(OWCombined,"./02_Embed_Source_Data_Context/Output_Files/OW061024_051

124

 # save the file as RData (useful if importing into R again)
saveRDS(OWCombined, file =

"./02_Embed_Source_Data_Context/Output_Files/OW061024_05

A3.0 Visualisation of Water Quality Data

A3.1 Load the cleaned datasets into R studio

Load the YSI Sonde Dataset for the River Owenmore at Ballynacarrow
OW061024_051124C<readRDS('./02_Embed_Source_Data_Context/Output_Files/OW061024_

051 str(OW061024_051124C)

Classes 'data.table' and 'data.frame': 2775 obs. of 6 variables:

$ Date: chr "06/10/2024" "06/10/2024" "06/10/2024" "06/10/2024" ...

$ Time : chr "13:45:50" "14:00:50" "14:15:50" "14:30:50" ...

$ Temp : num 13.3 13.4 13.4 13.5 13.5 ... ## ..- attr(*, "label")= chr "Temperature

(degC) YSI6600EDSV2_2 6560 Conductivity ## $ SpCond : num 486 485 485 484 484 483 483

483 482 482 ...

..- attr(*, "label")= chr "Specific Conductance uScm-1 YSI6600EDSV2-2 6560 Con ## $

Turbidity : num 3.2 3.2 3.2 3.2 2.8 2.9 3.2 3.3 3.5 3.2 ...

..- attr(*, "label")= chr "Turbidity (NTU) - YSI_6600_EDS_V2-2 - 6136 Turbidit

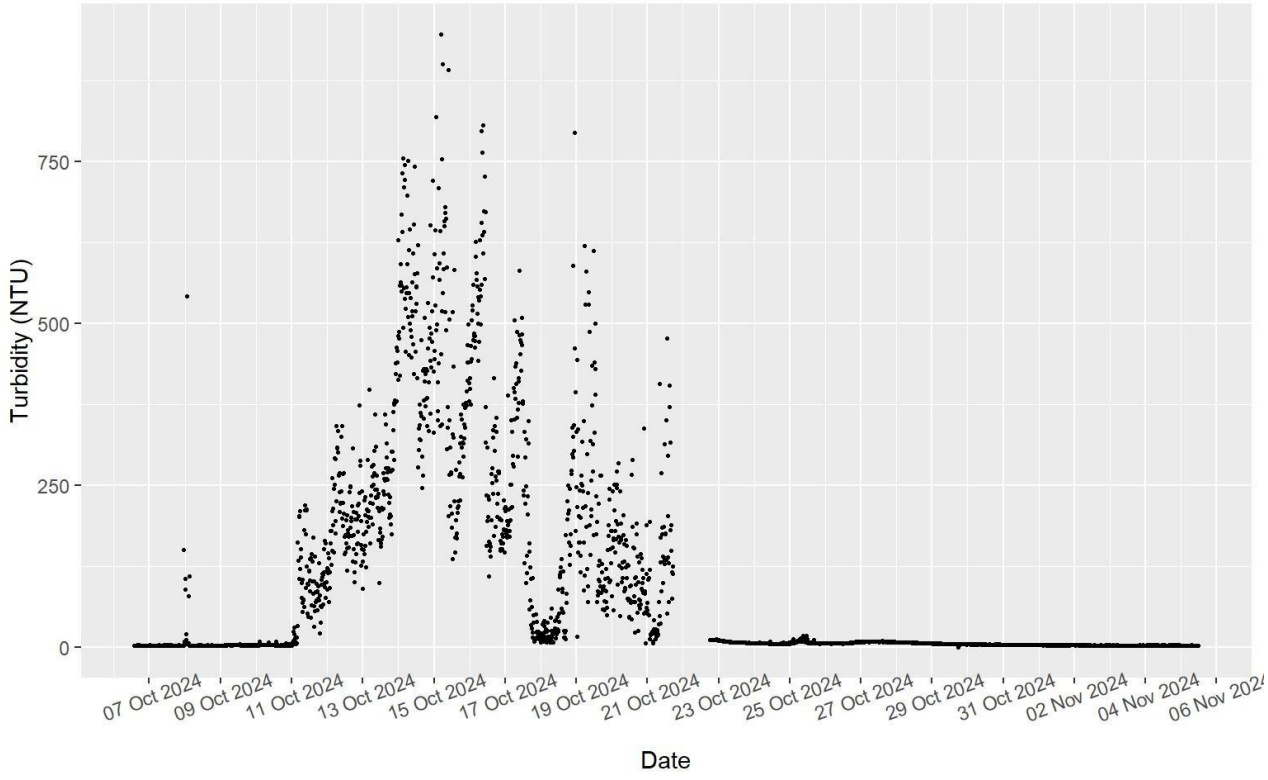
$ DateTime : POSIXct, format: "2024-10-06 13:45:50" "2024-10-06 14:00:50" ... ## -

attr(*, ".internal.selfref")=<externalptr>

A3.2 Visualise the Data using ggplot2 and ggplotly

Data is visualised which aids in understanding the data. There are two types of plots created: 1. Static plots which appear as an image can be viewed in the Plots tab and 2. Interactive plots where can be viewed in the viewer tab. With interactive plots, you can hover over specific data points and the value will be displayed, you can zoom in on an area of a plot by click and drag with the mouse and zoom out completely by double clicking. Video resources are available online for ggplotly if you want to learn more.

A3.2.1 Plot the Turbidity data ggplot(OW061024_051124C,aes(DateTime, Turbidity))+ geom_point(size=0.5)+ xlab("Date")+ ylab("Turbidity (NTU)")+ scale_x_datetime(labels = date_format("%d %b %Y"), breaks = date_breaks("2 days"))+ theme(axis.text.x = element_text(angle = 20))

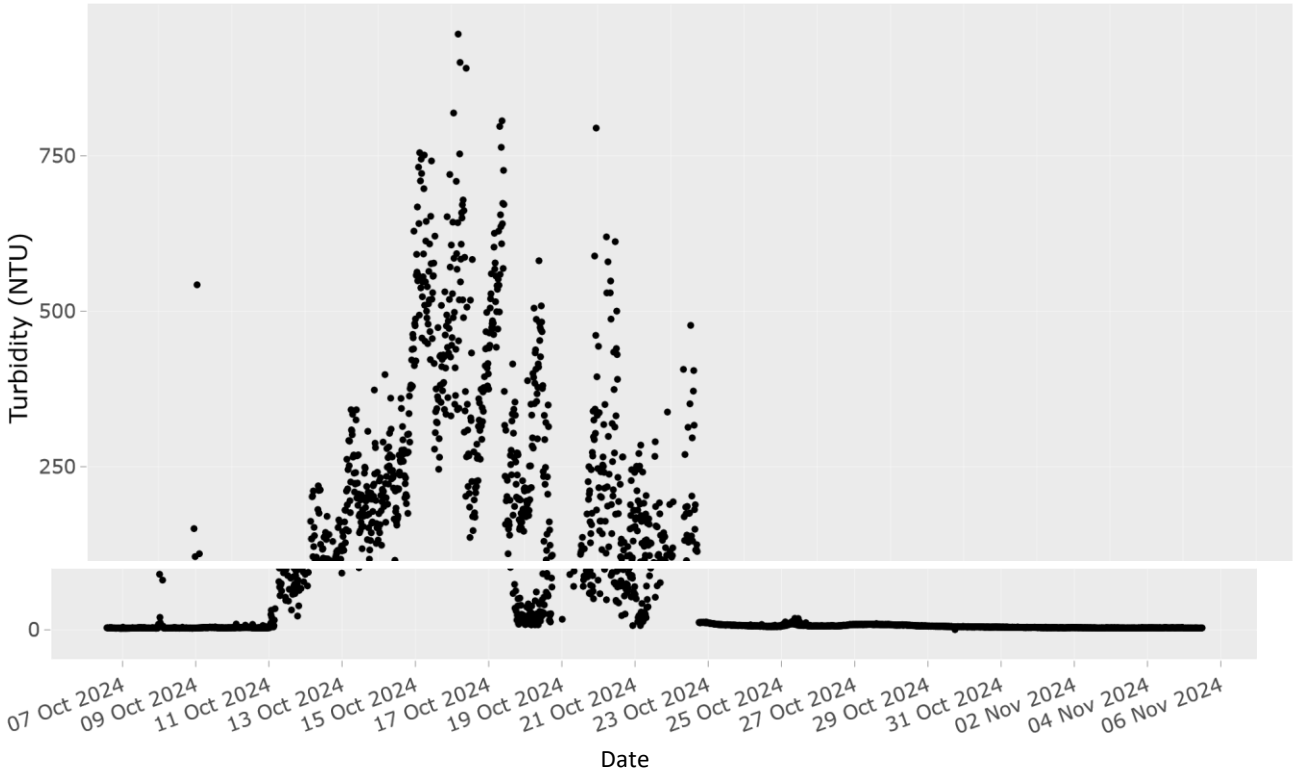


Name the object Turbidity Plot for specific Data file OW061024_051124C_Turbidity_Plot<ggplot(OW061024_051124C,aes(DateTime, Turbidity))+ geom_point(size=0.5)+ xlab("Date")+ ylab("Turbidity (NTU)")+ scale_x_datetime(labels = date_format("%d %b %Y"), breaks = date_breaks("2 days"))+ theme(axis.text.x = element_text(angle = 20))

Plot an interactive turbidity plot using plotly.

IntTurbidity_Plot<-ggplotly(OW061024_051124C_Turbidity_Plot)

IntTurbidity_Plot

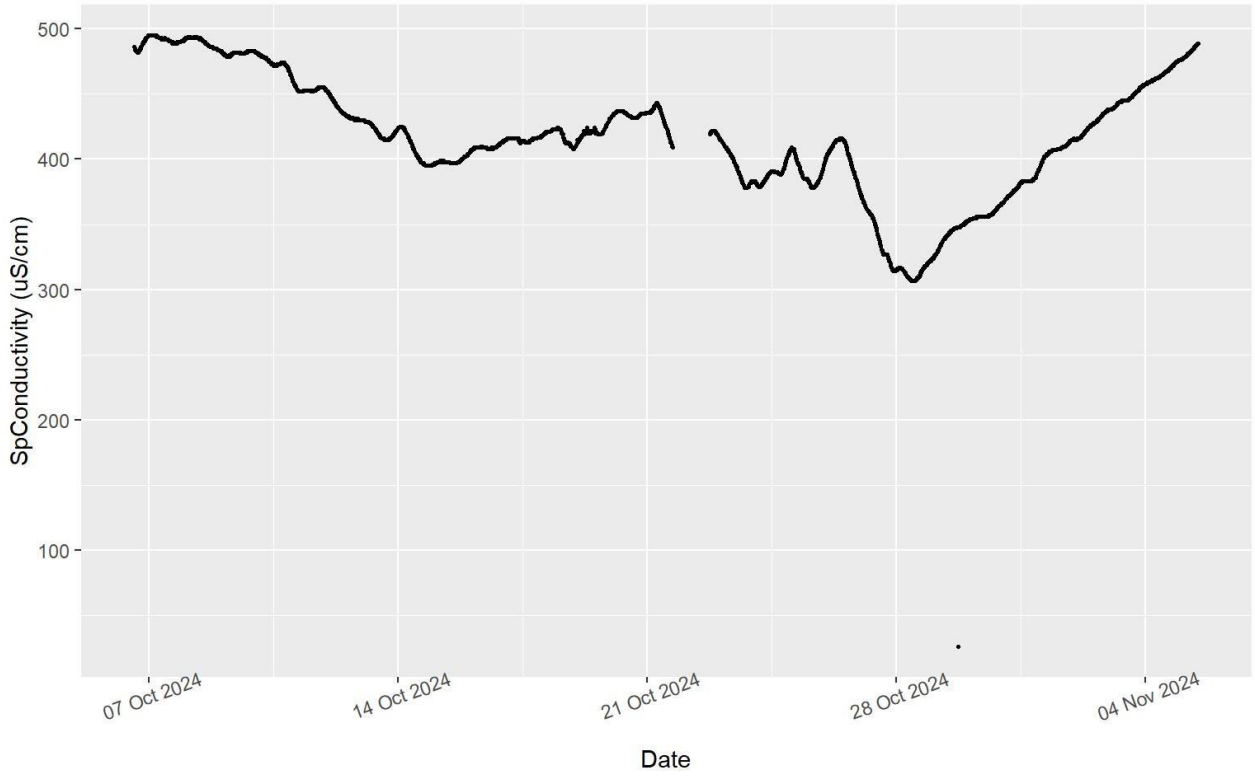


A3.2.2 Plot the Specific Conductance data

ggplot(OW061024_051124C,aes(DateTime, SpCond))+geom_point(size=0.5)+

xlab("Date")+ylab("SpConductivity (uS/cm)")+ scale_x_datetime(labels = date_format("%d %b

%Y"))+ theme(axis.text.x = element_text(angle = 20))



 # Name the object SpCond for specific data file

OW061024_051124C_SpCond_Plot<ggplot(OW061024_051124C,aes(DateTime,

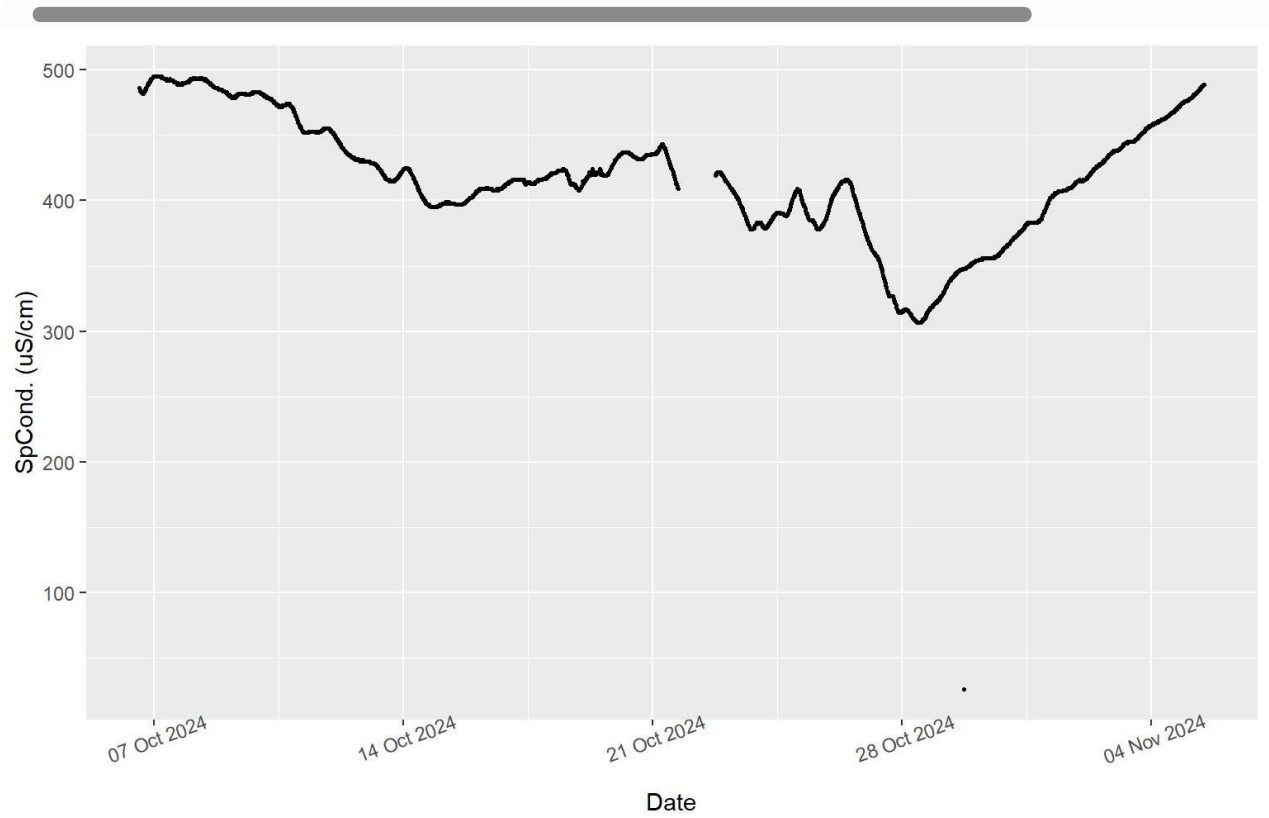
SpCond))+geom_p xlab("Date")+ylab("SpCond.

(uS/cm)")+ scale_x_datetime(labels = date_format("%d %b %Y"))+

theme(axis.text.x =

element_text(angle = 20))

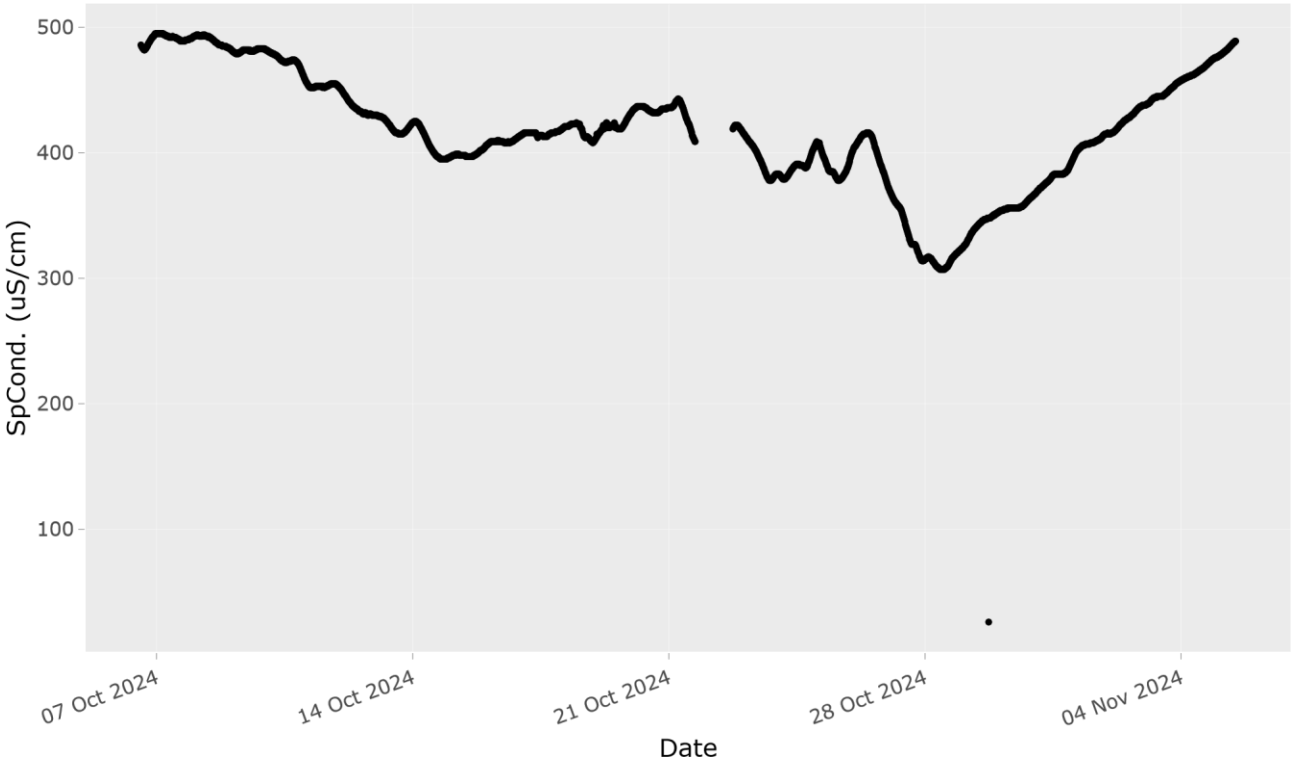
OW061024_051124C_SpCond_Plot



Interactive plot for specific conductance using plotly

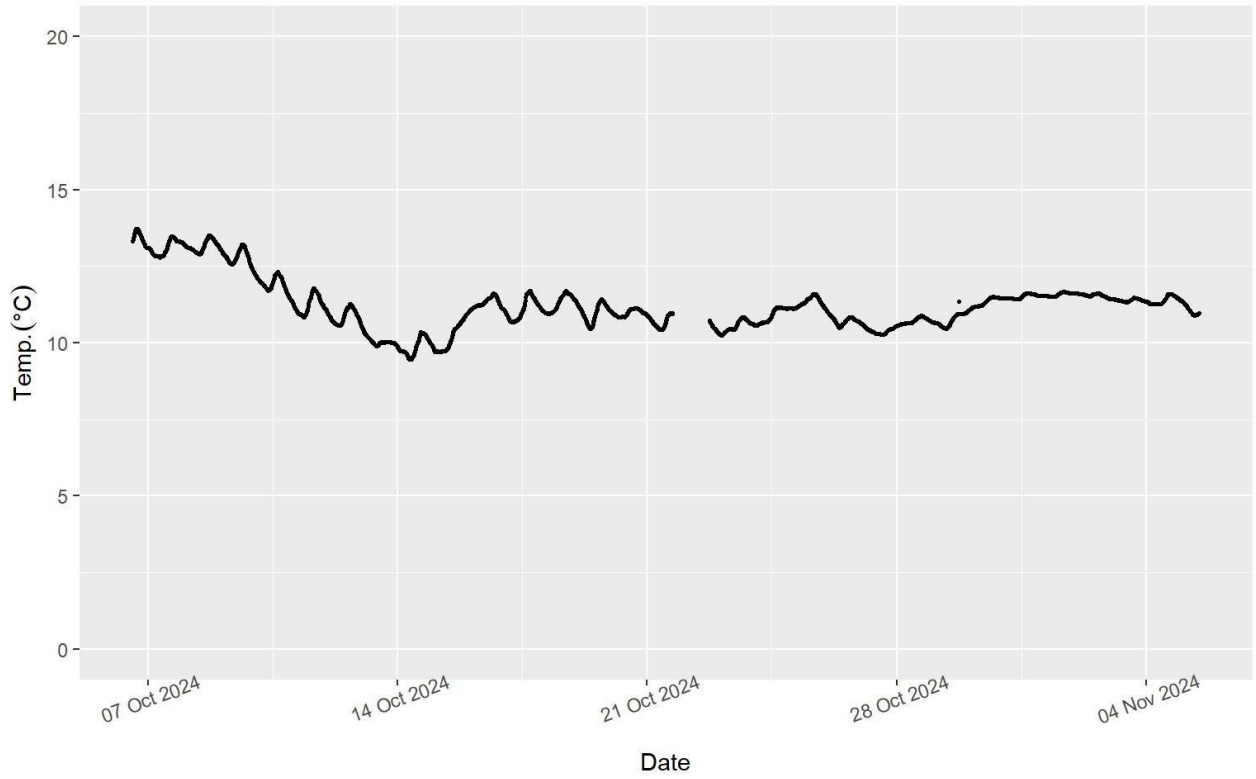
IntSpCond_Plot<-ggplotly(OW061024_051124C_SpCond_Plot)

IntSpCond_Plot



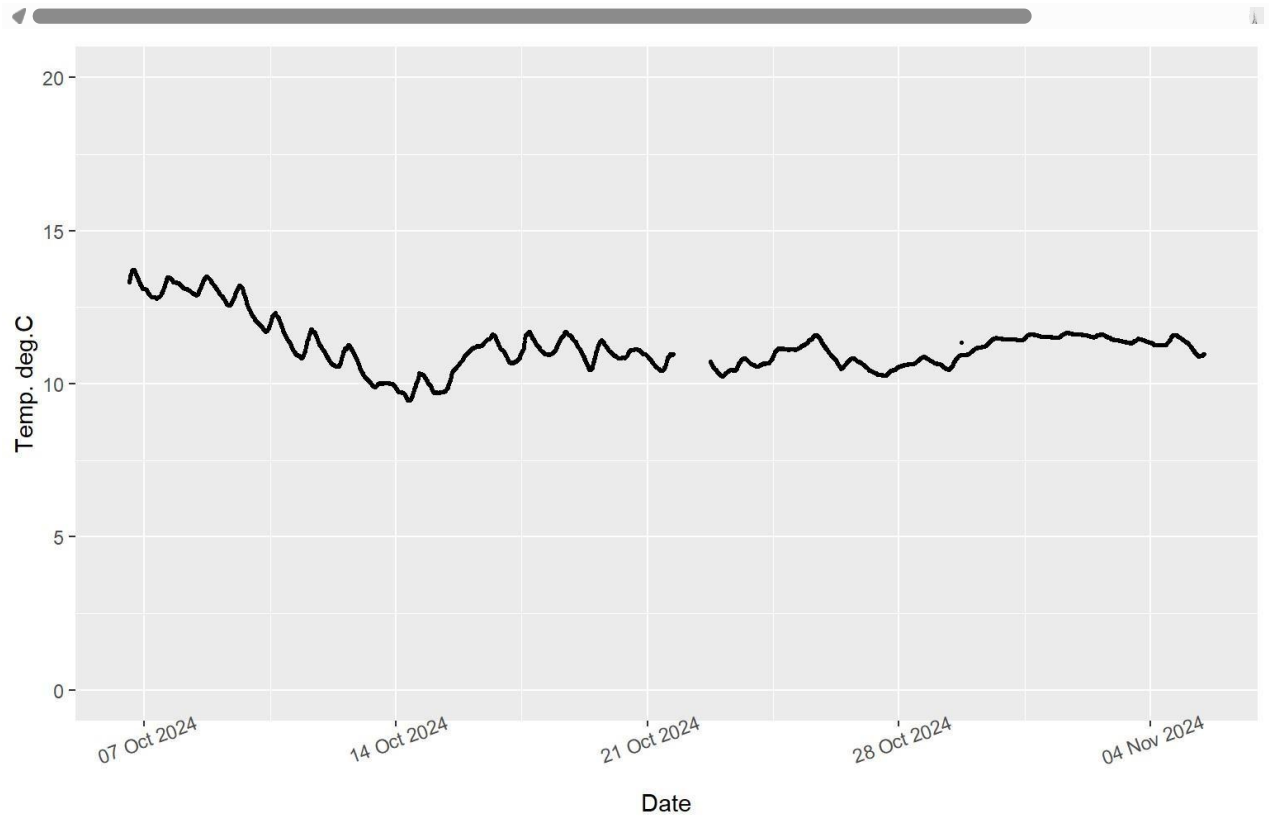
A3.2.3 Plot the Temperature Data

```
OW061024_051124C_Temp_Plot<-ggplot(OW061024_051124C, aes(DateTime,Temp)) +
geom_poi   xlab("Date") + ylab(bquote(Temp. ("\u00B0C")))+   scale_x_datetime(labels =
date_format("%d %b %Y"))+   theme(axis.text.x = element_text(angle = 20))+   ylim(0, 20)
OW061024_051124C_Temp_Plot
```



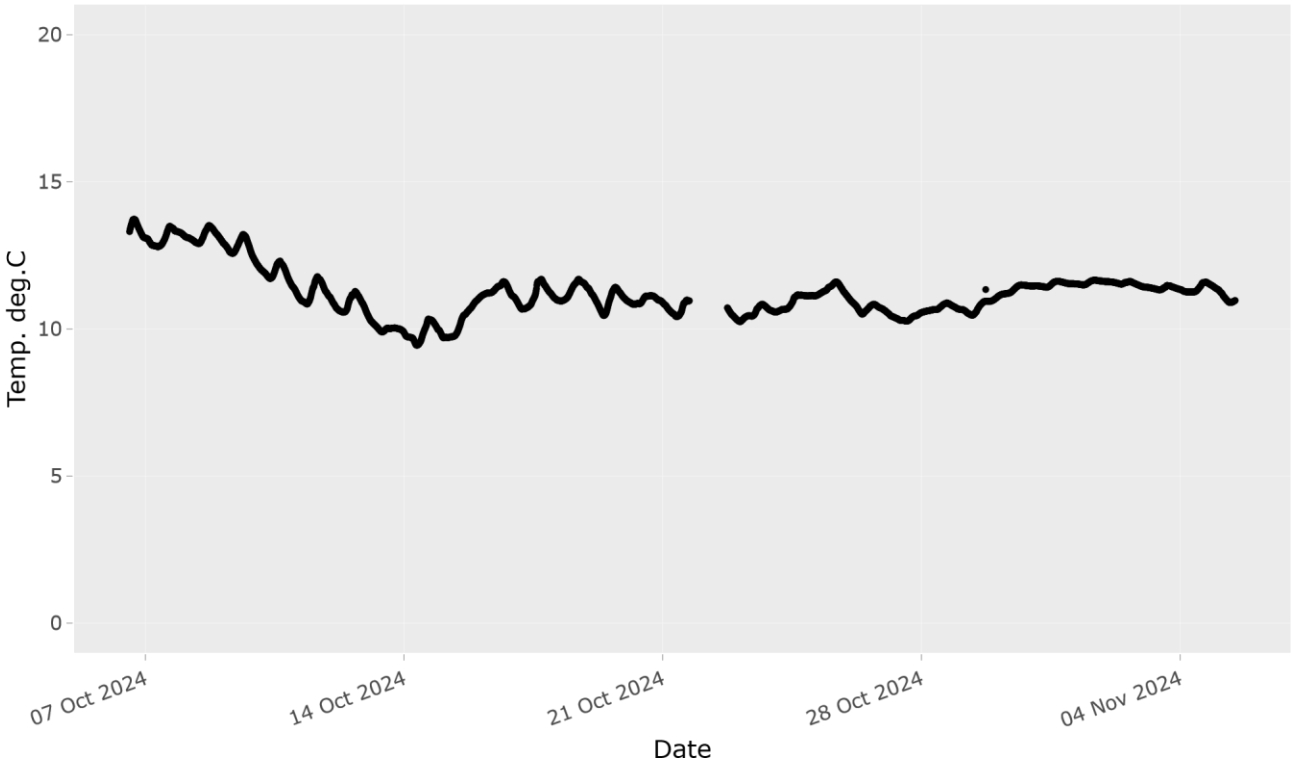
Plot the interactive temperature plot using plotly (plotly won't plot with customised symbols used for units, in this case the text 'degrees celsius' is used for the y axis label))

```
OW061024_051124C_Temp_PlotV1<-ggplot(OW061024_051124C, aes(DateTime,Temp)) +
geom_p   xlab("Date") + ylab("Temp. deg.C")+   scale_x_datetime(labels = date_format("%d %b
%Y"))+   theme(axis.text.x = element_text(angle = 20))+   ylim(0, 20)
OW061024_051124C_Temp_PlotV1
```



IntTemp_Plot<-ggplotly(OW061024_051124C_Temp_PlotV1)

IntTemp_Plot

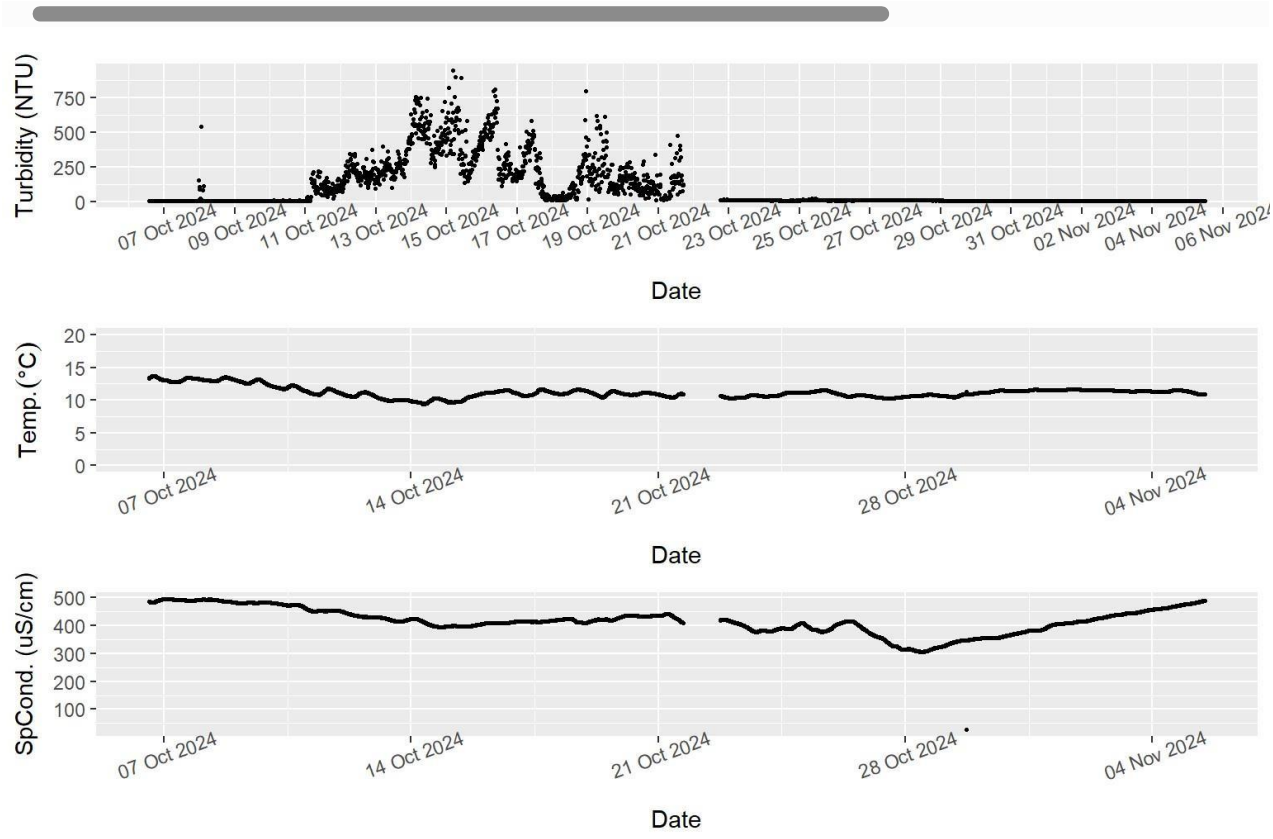


A3.2.4 Plot the water quality data together in one plot

You can zoom in on a plot using zoom in the Plots tab. Arrange all plots in one column and align by xaxis

Comb_OW061024_051124C<-plot_grid(OW061024_051124C_Turbidity_Plot, OW061024_051124C_Temp_Plot, OW061024_051124C_S

Comb_OW061024_051124C



 # To include a title on the plot

Comb_OW061024_051124CV1<-grid.arrange(OW061024_051124C_Turbidity_Plot, OW061024_051124C_Temp_Plot, OW061024_051124C_SpCon

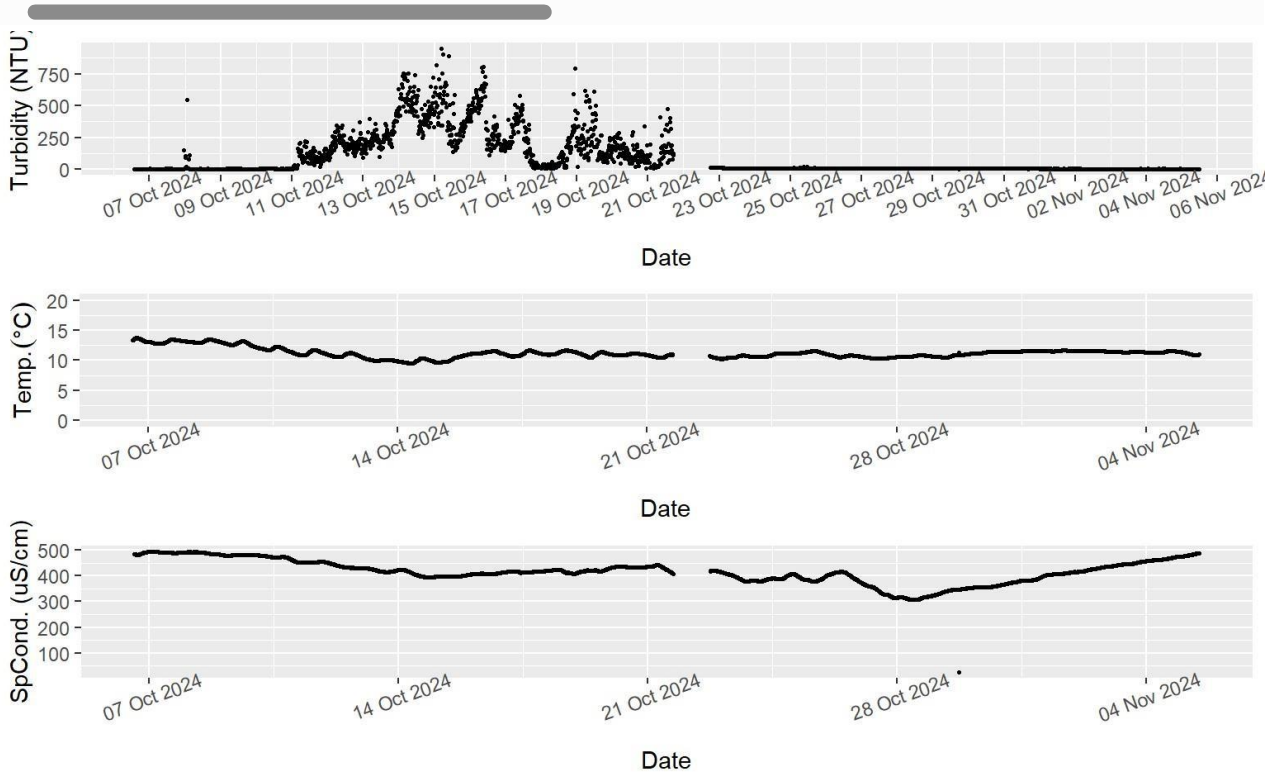


Figure 1: River Owenmore at Ballynacarrow

A3.3 Save the Combined Plots

```
ggsave(here("./03_Data_Visualisation_of_TimeSeries_Data/Output_Files", "Comb_OW0610
```

```
## Saving 8 x 5 in image
```

A4.0 Summary Statistics

A4.1 Check for any missing values as it interferes with computing summary statistics and further analysis.

```
colSums(is.na(OW061024_051124C))
```

```
##      Date      Time      Temp    SpCond  Turbidity   DateTime
##         0         0         0         0         0         0
```

 # Find and count any missing values # number of missing values

which(is.na(OW061024_051124C$Turbidity)) ## integer(0)

which(is.na(OW061024_051124C$SpCond)) ## integer(0)

which(is.na(OW061024_051124C$Temp)) ## integer(0)

 # location of missing values (if any) print("Position of missing values ") ## [1] "Position of missing values "

which(is.na(OW061024_051124C)) ## integer(0)

A4.2 Screen for datapoints outside the measurement range of the sensors. The measurement range varies from sensor to sensor so it's important to refer to the measurement range for the particular sensors used.

Specific Conductance

 # Identify where SpCond <0 uS/cm
OW061024_051124C_SpCond_lo<-OW061024_051124C$SpCond<0 *#count the number of TRUE, FALSE, and NA values in vector turbidity <0. If count o*
summary(OW061024_051124C_SpCond_lo)

Mode FALSE

logical 2775

 # Identify where SpCond>100,000 uS/cm
OW061024_051124C_SpCond_hi<-OW061024_051124C$SpCond>100000 *#count TRUE, FALSE, and NA values in vector turbidity >1000* summary(OW061024_051124C_SpCond_hi) ## Mode FALSE

logical 2775

Export SpCond_OutRange Values to pdf file pdf("04 Summary Statistics in R & Remove Outrange data/Output_Files/OW061024_051124

summary(OW061024_051124C_SpCond_lo)

Mode FALSE ## logical 2775 summary(OW061024_051124C_SpCond_hi)

Mode FALSE ## logical 2775

dev.off

function (which = dev.cur())

{

if (which == 1) ## stop("cannot shut down device 1 (the null device)")

.External(C_devoff, as.integer(which))

dev.cur()

}

<bytecode: 0x000001b12689b7e8>

<environment: namespace:grDevices>

 # in this case there are no values outside the measurement range so the pdf file is

Turbidity - YSI 6136 Turbidity Sensor Range 0 to 1000 NTU

 # Identify where turbidity <0 NTU identify_rows_turbidity_lo<-
OW061024_051124C$Turbidity<0 *#count TRUE, FALSE, and NA values in vector turbidity <0*

summary(identify_rows_turbidity_lo)

Mode FALSE

logical 2775

 # Identify where turbidity >1000NTU identify_rows_turbidity_hi<-
OW061024_051124C$Turbidity>1000 *#count TRUE, FALSE, and NA values in vector turbidity >1000* summary(identify_rows_turbidity_hi)
##

Mode

FALSE ##

logical

2775

 # If turbidity in the file is >1000NTU create a subset dataframe with these values.

subset(OW061024_051124C, Turbidity>1000)

Empty data.table (0 rows and 6 cols): Date, Time,Temp,SpCond,Turbidity,

A4.3 Replace All Data Points outside the Measuring Range of Sensor with NA and create new dataframe

Replace all turbidity values greater than sensor measuring range (>1000 NTU) with NA

OW061024_051124C_NoOutRange<- replace_with_na_at(OW061024_051124C, "Turbidity", ~ .

Replace all turbidity values less than the measuring range (<0 NTU) with NA

OW061024_051124C_NoOutRange<- replace_with_na_at(OW061024_051124C_NoOutRange, "Turb

Check datapoints have been replaced (both greater than and less than the measuring range)

identify_rows_turbidity_hi<-OW061024_051124C_NoOutRange$Turbidity>1000

summary(identify_rows_turbidity_hi)

Mode FALSE ## logical 2775 identify_rows_turbidity_lo<-

OW061024_051124C_NoOutRange$Turbidity<0

summary(identify_rows_turbidity_lo)

Mode FALSE

logical 2775

A4.1 Save the edited dataframe to the working directory as .csv file

here::here() ## [1] "C:/Repos/Workflow-for-identifying-potential-water-quality-eventsusing-time

```
write.csv(OW061024_051124C_NoOutRange, "04 Summary Statistics in R & Remove Outrang
```

A4.4 Summary Statistics

Produce a summary statistics table

```
df1<-as.data.frame(OW061024_051124C_NoOutRange)
data_summary<-stargazer(df1, type="text", title="River Owenmore, Sligo  06/10/24 to
covariate.labels = c("Temperature (deg.C)", "Specific Condu
summary.stat=c("n","mean", "sd","min", "median","max"),                    style="ajps",
out="04 Summary Statistics in R & Remove Outrange data/Outp
```

```
##
## River Owenmore, Sligo 06/10/24 to 05/11/24 (non-continuous)
## ---------------------------------------------------------------
## Statistic                    N   Mean  St. Dev. Min Median  Max
## ---------------------------------------------------------------
## Temperature (deg.C)         2775 11.2    0.9    9.4  11.1  13.7
## Specific Conductance (uS/cm) 2775 417.8   46.1   26   416    495
## Turbidity (NTU)             2775 93.1   158.9   0.3  6.9   945.8
## ---------------------------------------------------------------
```

Count the number of days when monitoring was carried out

n_distinct(OW061024_051124C_NoOutRange$` Date`) ## [1] 31 CountDays<-

n_distinct(OW061024_051124C_NoOutRange$` Date`)

CountDays

[1] 31

A4.2 Count no. of observations

NumberRowsOW061024_051124C<-nrow(OW061024_051124C_NoOutRange)

NumberRowsOW061024_051124C

[1] 2775

A4.3 Record number of days and number of observations to an output file

sink("04 Summary Statistics in R & Remove Outrange data/Output_Files/OW061024_05112

CountDays NumberRowsOW061024_051124C sink()

A5.0 Define significant change thresholds for turbidity and highlight on plots to identify events.

A5.1 Identification of Significant Change Thresholds for Turbidity

The turbidity timeseries data needs to be visually inspected to identify potential water quality events where there is a significant change in the turbidity from the baseline. To facilitate the visual identification (using ggplot2) of events from significant increases in water turbidity, a turbidity threshold value is calculated for water quality at the site. Sections of the plot greater than this turbidity threshold are highlighted and the data from this plot exported to a csv file. This csv file is used by the analyst to record the manually verified events and subsequently compared to the potential water quality events identified by the CANARY software.

A5.2 Visualise the data

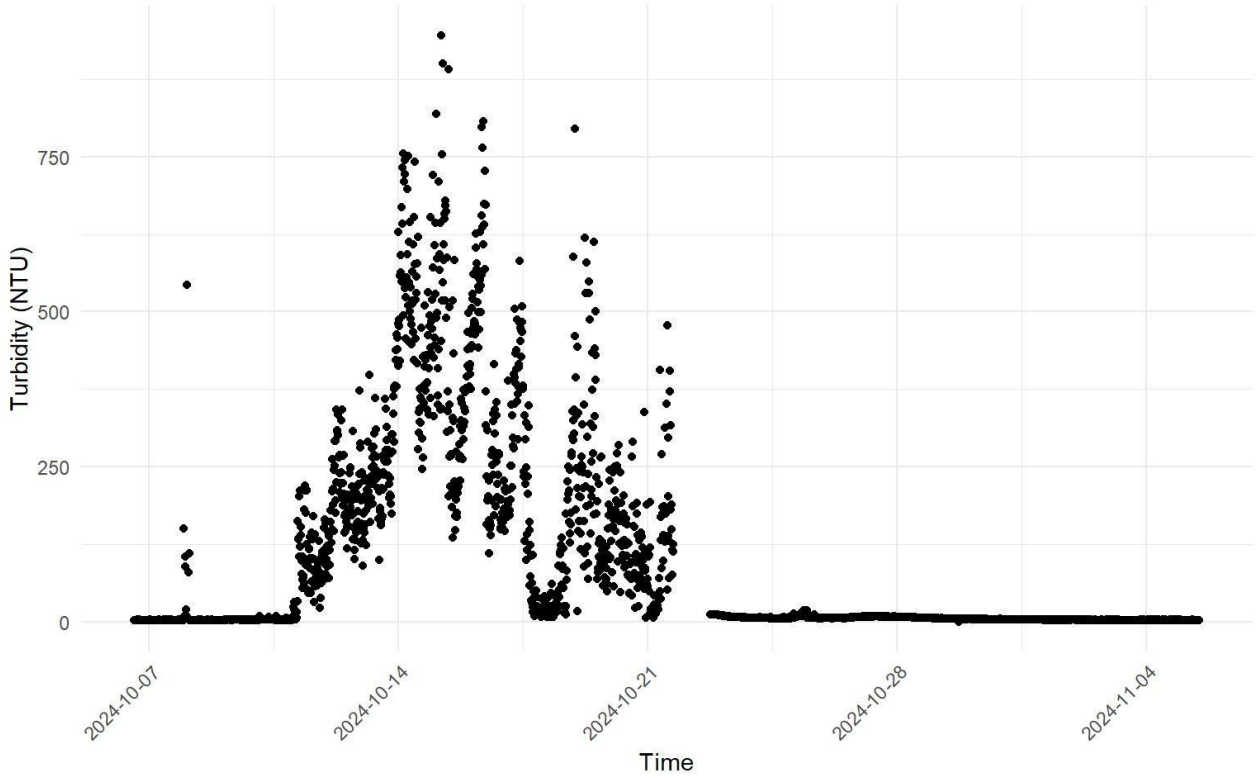
Plot the turbidity data and remove NA values (Not Available data or missing values) as these affect how the code runs.

OW061024_051124C_Turbidity_Plot <- ggplot(OW061024_051124C_NoOutRange, aes(x =

Date geom_point(na.rm = TRUE)+ scale_x_datetime(date_breaks = "1 week")+ labs(x =

"Time", y = "Turbidity (NTU)") + theme_minimal()+ theme(axis.text.x =

element_text(angle = 45, hjust = 1)) OW061024_051124C_Turbidity_Plot



Save the plot to the working directory.

Save the OW061024_051124C_NoOutRange_Turbidity_Plot to a pdf document pdf("05 SCT

and highlight areas on plot for events/Output_Files/OW061024_051124C_Tu

print(OW061024_051124C_Turbidity_Plot) dev.off()

png

2

Plot an interactive turbidity plot.

Can be used to zoom in on areas of interest using the zoom function above the plot when examining potential water quality events.

```
OW061024_051124C_IntTurbPlot<- ggplotly(OW061024_051124C_Turbidity_Plot)

OW061024_051124C_NoOutRange

##           Date     Time  Temp SpCond Turbidity          DateTime

##         <char>   <char> <num>  <num>     <num>            <POSc>

##    1: 06/10/2024 13:45:50 13.31    486       3.2 2024-10-06 13:45:50

##    2: 06/10/2024 14:00:50 13.38    485       3.2 2024-10-06 14:00:50

##    3: 06/10/2024 14:15:50 13.43    485       3.2 2024-10-06 14:15:50

##    4: 06/10/2024 14:30:50 13.48    484       3.2 2024-10-06 14:30:50

##    5: 06/10/2024 14:45:50 13.53    484       2.8 2024-10-06 14:45:50

##   ---

## 2771: 05/11/2024 10:45:51 10.94    488       3.1 2024-11-05

10:45:51 ## 2772: 05/11/2024 11:00:51 10.95    488       3.1 2024-

11-05 11:00:51

## 2773: 05/11/2024 11:15:51 10.95    489       2.9 2024-11-05 11:15:51

## 2774: 05/11/2024 11:30:51 10.96    489       3.0 2024-11-05 11:30:51

## 2775: 05/11/2024 11:45:50 10.97    489       3.1 2024-11-05 11:45:50
```

A5.3 Significant Change Threshold & Highlight potential water quality events on turbidity plots

This may be helpful for those unfamiliar with viewing time series plots. A statistical test, Tukey Fences test for outliers is used to identify potential turbidity outliers in the data, 26ccurring26 those high turbidity values 26ccurring at the upper range of the data as these can indicate possible water quality events. The identified outliers will be highlighted in red on the plot and an interactive plot of turbidity values is plotted. This allows the analyst to manually verify possible turbidity events which can be used for the initial CANARY configuration (training).

A5.3.1 Tukey Fences test for outliers

Compute Inter Quartile Range (IQR) of the turbidity data. These values are displayed under 'Values' in the environment.

quantile(OW061024_051124C_NoOutRange$Turbidity, 0.25, na.rm=TRUE)

25%

3.5

Q1<-quantile(OW061024_051124C_NoOutRange$Turbidity, 0.25,

na.rm=TRUE) quantile(OW061024_051124C_NoOutRange$Turbidity, 0.75,

na.rm=TRUE) ## 75%

135.6

Q3<- quantile(OW061024_051124C_NoOutRange$Turbidity, 0.75,

na.rm=TRUE) IQR<-Q3-Q1 print(IQR) ## 75% ## 132.1 multiplier <- 1.5

The upper bound and lower bound are the values of interest in terms of turbidity outliers
Calculate the Lower bound turbidity value
Q1-(IQR * multiplier)

25% ## -194.65

lower_bound<-Q1-(IQR

* multiplier)

Calculate the upper bound turbidity value
Q3 + (IQR*multiplier)

upper_bound<-Q3 + (IQR*multiplier)

A5.3.2 Identify where the turbidity is likely to be an outlier.

An outlier is >/= upper bound in Tukey Fences. Create a new variable (column) called 'Alarm

Classify' where values are categorised as 1 (True) i.e. >/= upper bound or 0 (False) i.e. </=

upper bound.

Identify where Turbidity >/= upper bound (Turbidity Threshold Value) and in a new variable (column) called Event Alarm, classify as 1 (true) or 0 (false)

```
OW061024_051124C_TurbEvent<-OW061024_051124C_NoOutRange %>%

mutate(Possible_Owenmor   Turbidity > upper_bound, true = 1, false = 0))

head(OW061024_051124C_TurbEvent, 10)
```

```
##         Date     Time  Temp SpCond Turbidity           DateTime

##       <char>   <char> <num>  <num>    <num>           <POSc>

##  1: 06/10/2024 13:45:50 13.31    486      3.2 2024-10-06 13:45:50

##  2: 06/10/2024 14:00:50 13.38    485      3.2 2024-10-06 14:00:50

##  3: 06/10/2024 14:15:50 13.43    485      3.2 2024-10-06 14:15:50

##  4: 06/10/2024 14:30:50 13.48    484      3.2 2024-10-06 14:30:50

##  5: 06/10/2024 14:45:50 13.53    484      2.8 2024-10-06 14:45:50

##  6: 06/10/2024 15:00:50 13.57    483      2.9 2024-10-06 15:00:50

##  7: 06/10/2024 15:15:50 13.60    483      3.2 2024-10-06 15:15:50

##  8: 06/10/2024 15:30:50 13.66    483      3.3 2024-10-06 15:30:50

##  9: 06/10/2024 15:45:50 13.70    482      3.5 2024-10-06 15:45:50 ## 10: 06/10/2024

16:00:50 13.72    482      3.2 2024-10-06 16:00:50

##    Possible_Owenmore_Event_Alarm

##                        <num>

##  1:                        0

##  2:                        0

##  3:                        0

##  4:                        0

##  5:                        0

##  6:                        0

##  7:                        0

##  8:                        0
```

```
## 9:                    0 ## 10:                    0

str(OW061024_051124C_TurbEvent)

## Classes 'data.table' and 'data.frame':   2775 obs. of  7 variables:

## $       Date                : chr  "06/10/2024" "06/10/2024" "06/10/2024" "0 ##  $      Time
: chr  "13:45:50" "14:00:50" "14:15:50" "14:30:5 ##  $ Temp                      : num  13.3 13.4
13.4 13.5 13.5 ...
##   ..- attr(*, "label")= chr "Temperature (degC) YSI6600EDSV2_2 6560 Conductivity ##  $

SpCond                  : num  486 485 485 484 484 483 483 483 482 482 .

##   ..- attr(*, "label")= chr "Specific Conductance uScm-1 YSI6600EDSV2-2 6560 Con ##  $

Turbidity               : num  3.2 3.2 3.2 3.2 2.8 2.9 3.2 3.3 3.5 3.2 .

##  $ DateTime              : POSIXct, format: "2024-10-06 13:45:50" "2024-1 ##  $

Possible_Owenmore_Event_Alarm: num  0 0 0 0 0 0 0 0 0 0 ...

##  - attr(*, ".internal.selfref")=<externalptr>
```

A5.3.3 Count the number of observations where the turbidity >/= upper bound and express as a percentage of the total number of turbidity values in the data frame.

Count the number of True (1) values i.e. where turbidity >/= upper bound

```
print(Number_True_values<-length(which(OW061024_051124C_TurbEvent
$Possible_Owenmor
```

```
## [1] 275
```

Count the number of observations (i.e. number of values for each parameter in the data frame. This is also the number of rows in the dataframe.)

```
print(Number_observations<-nrow(OW061024_051124C_NoOutRange))
## [1] 2775
```

Calculate the percentage of values in dataframe where turbidity >/= upper bound

print(Percentage_turb_upperbound<-(Number_True_values/Number_observations)*100) ##

[1] 9.90991

A5.3.4 Export as .csv file the observations where Turbidity >/= upper bound. This file contains the observations suspected of being a possible turbidity water quality event.

Export OW061024_051124C_NoOutRange_TurbEvent as a .csv file
OW061024_051124C_TurbEvent$DateTime<format(OW061024_051124C_TurbEvent$DateTim

e) #

write.csv(OW061024_051124C_TurbEvent, "05 SCT and highlight areas on plot for event

A5.3.5 Highlight significant change turbidity thresholds in red on plots

The code for this section is edited for this dataframe (Edward, 2024)

To help with visualising the turbidity values >/= upper bound (>/= Turbidity Threshold) on a plot, these values are highlighted on the plot as red lines.

Owenmore_Turbidity_Threshold_Plot<- ggplot(OW061024_051124C_NoOutRange, aes(x =

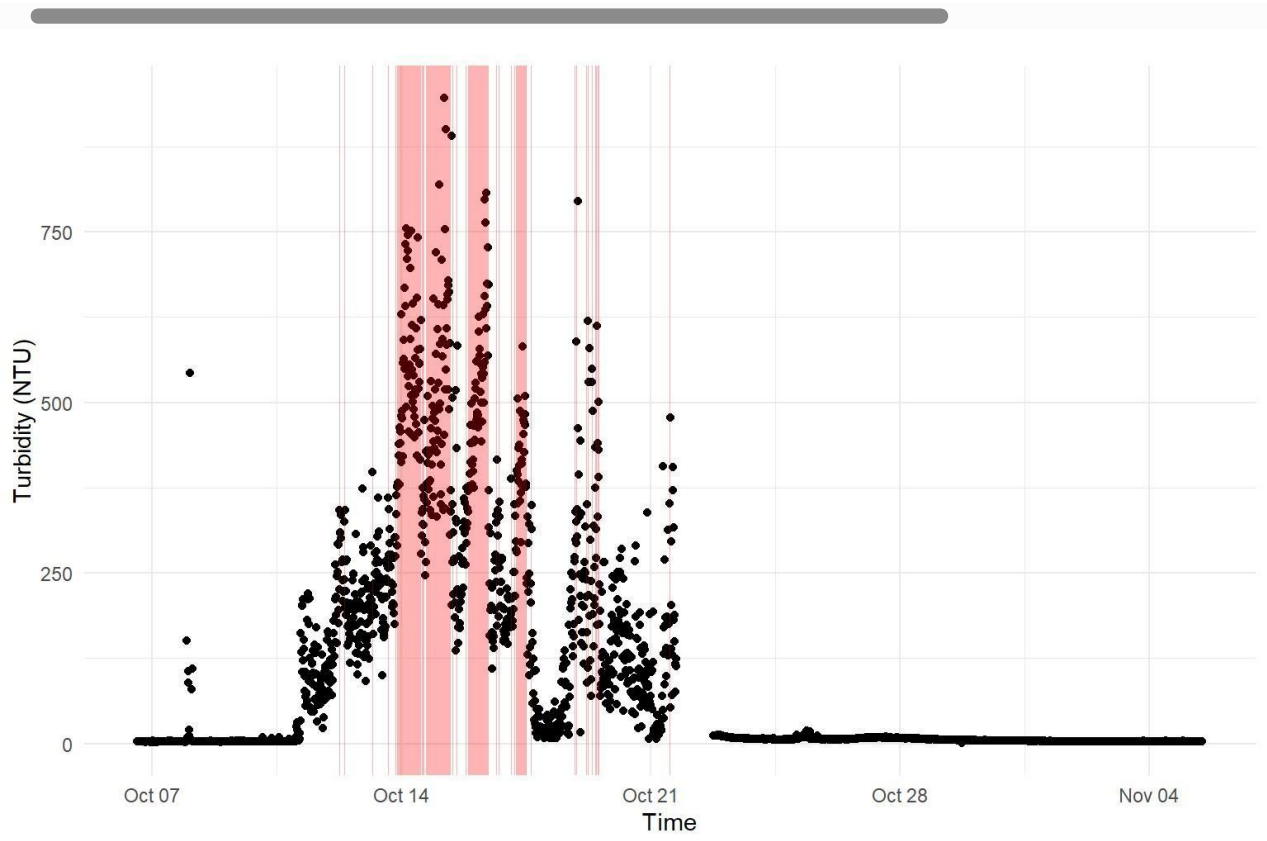
Dat geom_point(na.rm = TRUE)+ geom_rect(data =

subset(OW061024_051124C_NoOutRange, Turbidity >=upper_bound),

aes(xmin = DateTime-450, xmax = DateTime+450, ymin = -Inf, ymax = Inf), fill = "red",

alpha = 0.3) + labs(x = "Time", y = "Turbidity (NTU)") + theme_minimal()

Owenmore_Turbidity_Threshold_Plot



A5.3.6 Interactive plot with highlighted areas on plot where turbidity is greater than the turbidity threshold value.

Interactive plots are very useful for interrogating data and this interactive plot may aid in the identification of probable turbidity events for users unfamiliar with time series datasets.

Users can zoom in and out of the plots. Use magnifying glass icon to open the plot full screen and click and drag the mouse to zoom in on an area, double click to zoom back out. The code for this section is edited for this dataframe (Kat, 2024).

Plot an interactive plot for turbidity with turbidity values >/= upper bound (>/= Turbidity Threshold) highlighted on the plot as red lines.

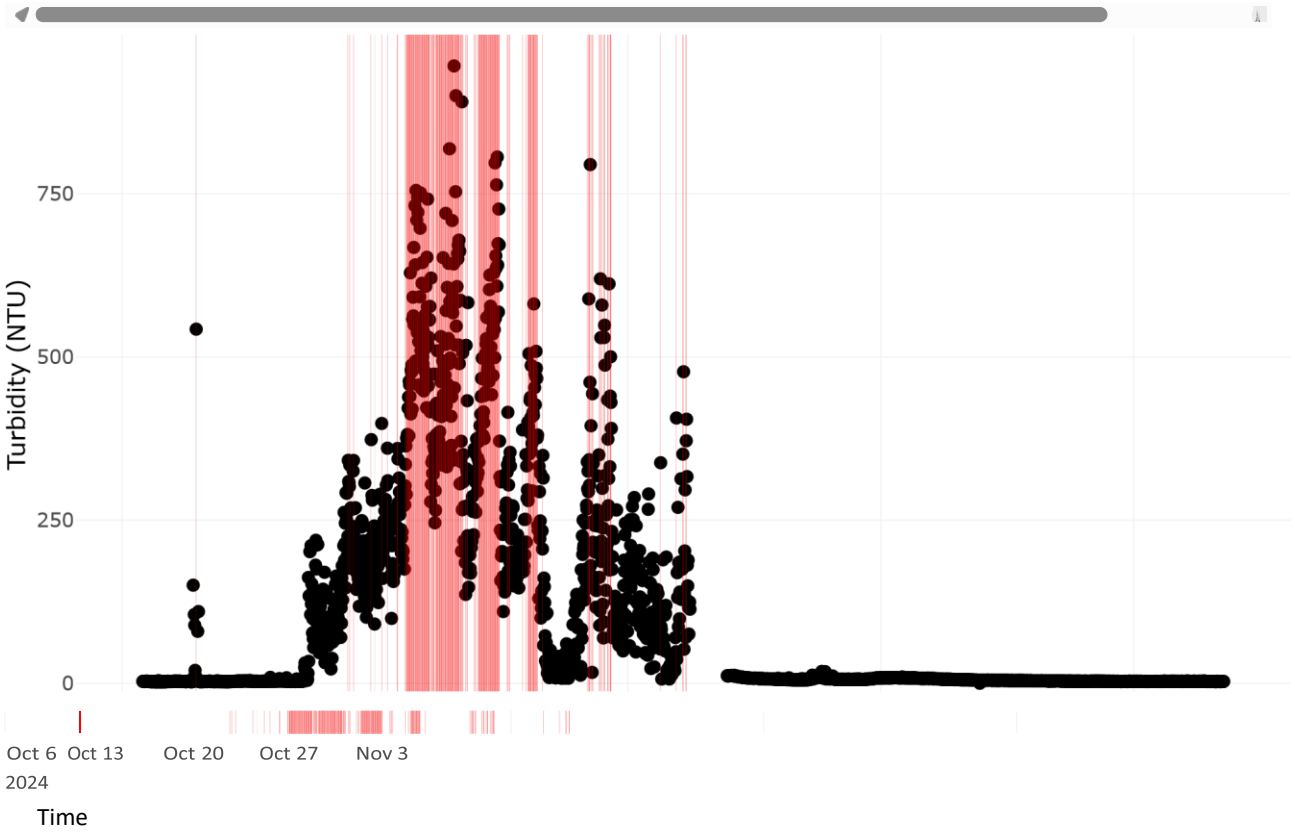
```
Fixer <- function(plt) {

  plt <- plotly_build(plt)            # make sure entire plot built   lapply(1:length(plt$x$data), \(k) {   # go through each trace (layer)     plt$x$data[[k]]$x <<- as.POSIXct(plt$x$data[[k]]$x) # update x-axis data type   })   plt } tSpan <- function(gplt) {  # gplt: ggplot graph to be made into a ggplotly
#  - assuming one x-axis within gplt
  #  - assuming geom_rect called 2nd in gplt
```

 # 2 here, because geom_rect was called 2nd --- get data from plot dta <- data.frame(ggplot_build(gplt)$data[[2]][c("xmin", "xmax", "fill", "alpha") mutate(xmin = as.POSIXct(xmin), xmax = as.POSIXct(xmax)) shps <- map(1:nrow(dta), \(k) { *# create data used in geom_rect*

list(type = "rect", xref = "x", yref = "paper", *# define shape, use x axis, no* x0 = dta$xmin[k],

x1 = dta$xmax[k], *# where on x* y0 = 0, y1 = 1, *# where on plot (versus y)* *# update aesthetics* fillcolor = dta$fill[1], opacity = dta$alpha[1], line = list(width = 0)) }) ggplotly(gplt) %>% *# pre xaxis for dates* layout(xaxis = list(tickmode = "auto", type = "date", autorange = T), shapes = NA) %>% *# remove migration garbage* fixer() %>% *# fix dates – make them dates again* layout(shapes = shps) *# add new shapes* } tSpan(Owenmore_Turbidity_Threshold_Plot)



A6.0 Manually Identify Potential Water Quality Events with the aid of interactive turbidity plot.

A6.1 Manually identify potential water quality events.

The analyst manually identifies potential water quality events by visual inspection i.e. looking at changes in the trend in the turbidity plot.

The highlighted areas on the interactive turbidity plot for events can be used as an aid to this manually identification as they highlight values where the Turbidity value is >/= upper bound of the Tukey Fences test for outliers. The highlighted data points are recorded in the 'Possible_Owenmore_Event_Alarm'column of the file 'OW061024_051124C_NoOutRange_TurbEvent' file and turbidity values at each timestep are recorded as either (true) if the Turbidity value >/= upper bound of the Tukey Fences test for outliers, or 0 (false) if not.

The highlighted areas can help identify potential events by drawing our attention to that area of the plot. However, data points either side of these highlighted areas may also indicate events and it is for the analyst viewing the data to determine whether a datapoint is a potential outlier by following the procedure outlined below.

The file 'OW061024_051124C_NoOutRange_TurbEvent' was copied by the analyst and renamed 'OW061024_051124C_NoOutRange_ManVer_TurbEvent.csv'. Note there is a gap in this data set between 21/10/2024 17:15:00 and 22/10/2024 18:00:00 when the sonde was removed from the river to the laboratory for service and calibration. An additional column 'Verified_OW_Event_Alarm' is manually added by the analyst to 'OW061024_051124C_NoOutRange_ManVer_TurbEvent.csv' file. The analyst manually records at each timestep whether they think the turbidity value is a potential alarm by inserting either 1 (true) or 0 (false) into 'Verified_OW_Event_Alarm' column based on visually examining the interactive turbidity plot in R which is produced in step 5.3.6 Interactive plot with highlighted areas on plot where turbidity is greater than the turbidity threshold value. The analyst may

identify values either side of the highlighted areas on the plot as potential events and should insert 1 (true) at each timestep where this occurs. Once completed by the analyst, the 'OW061024_051124C_NoOutRange_ManVer_TurbEvent.csv' file is saved in the Man_Ver_Alarm folder in '06 Manually Identify Potential Water Quality Events/Output_Files' folder.

A7.0 Event Detection using EPA CANARY

The software used for event detection was EPA CANARY-EDS. It is available on GitHub https://github.com/USEPA/CANARY (https://github.com/USEPA/CANARY) and includes links to download the software, and a comprehensive CANARY user manual, a quick start guide and tutorials to practice running the code. The EPA CANARY software will need to be downloaded and the OW061024_051124C_NoOutRange.csv file run through the CANARY software. The water quality parameters analysed in EPA CANARY were Temperature, Specific Conductivity and Turbidity.

Four parameters in CANARY were varied to train the EPA CANARY software to identify probable water quality events in the dataset, with the aim of minimising the likelihood of false alarms. The parameters were history window, outlier threshold, BED window and event threshold. These parameters in CANARY were varied as per the method used in monitoring the Smith Branch watershed, Columbia, United States with the method to vary these parameters described in Section 3.2 CANARY event detection software and detailed in Table 3 (Burkhardt *et al.*, 2022). Rainfall events were not filtered for the analysis on the sample file from the Owenmore River, Ireland.

The output for step 7 event Detection using EPA CANARY is saved in 07 EPA CANARY Event Detection

Folder consisting of 96 .csv output files in six different folders. Once the data file

OW061024_051124C_NoOutRange was processed in CANARY the output from the CANARY Data files for each algorithm were graphed monthly with probability and then converted to .csv files in CANARY.

A8.0 Compare manually identified Owenmore turbidity events to events identified by CANARY.

This section of the code combines the manually identified events by the user with the output for each of the 96 algorithm files produced by CANARY into one dataframe, creating 96 new .csv files. The files are saved into six directories (folders) in the same file format as the CANARY output with the file name structure: sitedate_algorithm type_algorithm details_algorithm number. These files are saved in the directory associated with that data which is specified by the user by amending the code for the identifier in section 8.12. In this example, the data to be processed was placed in the directory called Data1 and the identifier set as follows #data_set_identifier<-“Data1/”. Where multiple datasets are to be processed the user places each dataset in its own directory, e.g. Data1, Data2, Data3 etc and updates the code for data_set_identifier when running each dataset. The code automatically creates a directory in Output_Files for each dataset specified and ran through the code e.g. Output_Files/Data1, Output_Files/Data2 etc.

The output for step 8 comparing manually identified and CANARY events is saved in 08 Manually compare events to CANARY events/Output_files.

A8.1 Specify the directory where the “manually verified event data” in located.

A8.1.1 The path for this directory should be given relative to the project directory.

```
# Set the top directory for this step
ManVer_file_top_directory<-"06 Manually Identify Potential Water Quality Events/Out
```

A8.1.2 This identifier is used to select the “manually verified event dataset” to be processed.

```
data_set_identifier<-"Data1/"
```

Sets up the full path to the “manually verified event data”.

```
ManVer_file_directory<-paste0(ManVer_file_top_directory,data_set_identifier)

(ManVer_file<list.files(ManVer_file_directory,pattern='ManVer_TurbEvent'))

## [1] "OW061024_051124C_ManVer_TurbEvent.csv"

ManVer_file_full_path<-paste0(ManVer_file_directory,ManVer_file)
```

A8.2 Load the “manually verified event data” and format the dataframe.

Load the “manually verified event data”.

```
ManVer_TurbEvent<-fread(ManVer_file_full_path,header=T,stringsAsFactors = F, select

str(ManVer_TurbEvent)

## Classes 'data.table' and 'data.frame':   2775 obs. of  3 variables:

##  $ DateTime            : chr  "06/10/2024 13:45" "06/10/2024 14:00" "06/10/20 ##  $ Turbidity

: num  3.2 3.2 3.2 3.2 2.8 2.9 3.2 3.3 3.5 3.2 ...

##  $ Verified_OW_Event_Alarm: int  0 0 0 0 0 0 0 0 0 0 ...

##  - attr(*, ".internal.selfref")=<externalptr>
```

Change DateTime from chr to Date (as.POSIXct stores both a date and time with an associated time zone)

```
ManVer_TurbEvent$DateTime<-as.POSIXct(ManVer_TurbEvent$DateTime, format =

"%d/%m/%Y str(ManVer_TurbEvent)

## Classes 'data.table' and 'data.frame':   2775 obs. of  3 variables:

##  $ DateTime            : POSIXct, format: "2024-10-06 13:45:00" "2024-10-06 1 ##  $ Turbidity

: num  3.2 3.2 3.2 3.2 2.8 2.9 3.2 3.3 3.5 3.2 ...

##  $ Verified_OW_Event_Alarm: int  0 0 0 0 0 0 0 0 0 0 ...
```

- attr(*, ".internal.selfref")=<externalptr>

Rename to TIME_STEP to match the Owenmore CANARY File

ManVer_TurbEvent<- ManVer_TurbEvent%>% rename(TIME_STEP = DateTime)

A8.3 Get list of directory names in the folder “07 EPA CANARY Event Detection”

Each directory is associated with a different configuration of CANARY.
Within each directory are output files generated by various versions of the algorithm. The path for top_dir should be given relative to the project directory.

output_file_top_directory<-"07 EPA CANARY Event Detection/Output_Files/"

output_file_full_path<-paste0(output_file_top_directory,data_set_identifier)

List directories but not sub-directories.
(directory_list<-list.dirs(output_file_full_path,recursive=FALSE))

[1] "07 EPA CANARY Event

Detection/Output_Files/Data1/Owenmore_LPCF_BED10_ET0.98

[2] "07 EPA CANARY Event

Detection/Output_Files/Data1/Owenmore_LPCF_BED10_ET0.99

[3] "07 EPA CANARY Event

Detection/Output_Files/Data1/Owenmore_LPCF_BED6_ET0.890

[4] "07 EPA CANARY Event

Detection/Output_Files/Data1/Owenmore_LPCF_BED6_ET0.984

[5] "07 EPA CANARY Event

Detection/Output_Files/Data1/Owenmore_LPCF_BED8_ET0.964

[6] "07 EPA CANARY Event

Detection/Output_Files/Data1/Owenmore_LPCF_BED8_ET0.996

ID_String<-vector(mode="character",length=length(directory_list)) for (i in

1:length(directory_list)){

```
 ID_String[i]<-paste0("_L",sub(".*_L","",directory_list[i]))

}
```

A8.4 Load the Owenmore CANARY file from 07 EPA CANARY

Event Detection Folder

```
# Now, step through each folder and locate the csv files for each algorithm. # Loop over the
directories for (i in 1:length(directory_list)){    # List all files in each parent directory, in turn.
(files_list<-list.files(directory_list[i],pattern='alg'))   #list all files in sp

alg_ver<vector(mode="character",length=length(files_list)) # initialise two

char   Output_filename_string<-

vector(mode="character",length=length(files_list)) # Loop through each file

in the files_list    for (j in 1:length(files_list)){            # Put together the

input filename and directory it is in.

   input_filename_string<-paste0(directory_list[i],'/',files_list[j])

   # Read each of the "CANARY Event Detection" data files into a dataframe called
Input_Data<-fread(input_filename_string, header=T, stringsAsFactors = F,                    select =

c("TIME_STEP","P_Event"))

      # Put together string name for output file.
      # First get the "algorithm version from each filename.
   # It's found by taking the part of the filename after the word "details" withou          alg_ver[j]<-
str_sub(sub(".*details-","",files_list[j]), end=-5)       # Setup the output filename.
#(output_filename_string<-paste0("CANARYOwenmore",ID_String[i],alg_ver))

   #str(Input_Data)

   #Change TIME_STEP from chr to Date
   Input_Data$TIME_STEP<-as.POSIXct(Input_Data$TIME_STEP, format = "%d/%m/%Y %H:%M


   # Change any negative values in CANARYOwenmoreAlg1 P_Event to absolute values t
   Input_Data$`P_Event`<-abs(Input_Data$`P_Event`)
```

```
   # A column containing the "manually verified event data" is added to the "CANAR     #... data frame called "Combined Data".

   Combined_Data<-merge(Input_Data,ManVer_TurbEvent,by="TIME_STEP")


   #(which(is.na(Input_Data), arr.ind=TRUE))

   # View the first few rows and the structure of the combined dataframe
   #head(Combined_Data)
   #str(Combined_Data)
      # Export this data table as.csv file     here() # indicates the working directory
Combined_Data$TIME_STEP<-format(Combined_Data$TIME_STEP) # this prevents 00:00:


      # Now setup directory and filename for saving the combined data file.

   Output_directory_string<-paste0("08 Manually compare events to CANARY events/Ou

   Output_subdirectory_string<-paste0("Output_Files_",ID_String[i],"/")

   Output_directory_string_complete<-paste0(Output_directory_string,Output_subdire


   # Extract the location and date range information from the "manually verified e     # i.e, take the first part of the filename before the "_ManVer_TurbEvents...."

   Location_and_Date_Range_ID_String<-sub("\\_M.*","",ManVer_file)


   Output_filename_string[j]<-paste0(Location_and_Date_Range_ID_String,ID_String[i


   (Output_file_path_and_name<-paste0(Output_directory_string,Output_subdirectory_        if

(!dir.exists(Output_directory_string_complete)) dir.create(Output_directory_

write.csv(Combined_Data,Output_file_path_and_name, row.names=FALSE)    if (j==1){    #

Only print this message once per processed directory.

   cat("Writing data to file:\n",Output_file_path_and_name,"\n")}   }

}

## Writing data to file:
```

08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files__LP

Writing data to file:

08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files__LP

Writing data to file:

08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files__LP

Writing data to file:

08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files__LP

Writing data to file:

08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files__LP

Writing data to file:

08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files__LP

A9.0 Compare the Owenmore CANARY files to the manually identified events to identify the most suitable CANARY algorithm.

This is the last step in the workflow where the events identified are compared in order to identify the most suitable algorithm for that particular site based on the data provided to 'train' CANARY. This workflow used changes in the turbidity signal to identify potential water quality events at these two river stations as the turbidity values for the monitoring sites examined did not show a diurnal trend and baseline levels for turbidity at both sites was low. The identification of full and partial matches was carried out by analysing the output of step 8 where the output files of CANARY for each algorithm file were combined with manually identified event file. Events were classified as FULL or PARTIAL matches depending on whether the event time start timestep or time end timestep matched fully or partially.A description of the logic detailing how full and partial matches were classified is available in the Supplementary Material directory. Using the classification for matches the combined files

(output for step 8) were analysed for matches by looping over each file to find where time steps either fully or partially matched for identified events. This was done in a step-by-step fashion to allow the user to verify that this code is correctly matching events for their data. The logic for how the files were matched is contained in the 'Code Logic for Finding Matches between manually verified events and EPA events' in the supplementary material folder.

Determine the number of matches and identify the most suitable CANARY algorithm.

A9.1 Identify the folder for processing

Here, enter the directory containing the folders for processing
top_directory<-paste0("08 Manually compare events to CANARY events/Output_Files/",d #

List directories but not sub-directories.

(directory_list<-list.dirs(top_directory,recursive=FALSE))

[1] "08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files

[2] "08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files

[3] "08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files

[4] "08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files

[5] "08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files

[6] "08 Manually compare events to CANARY events/Output_Files/Data1/Output_Files

 # Only take the directory names which include the string "Output_Files"
directory_list<directory_list[grepl("Output_Files",directory_list)] *# Set up dataframe for output.*
Algorithm_Scores<-data.frame(algorithm=character(),FULL_MATCH=integer(),PARTIAL_MAT

A9.2 Loop over all the directories for processing.

```
for (k in 1:length(directory_list)){   # List all files in each parent directory, in
turn. # Only consider filenames that have the string 'alg' in them.

 (files_list<-list.files(directory_list[k],pattern='alg')) # Loop over all the files in the current
directory.   for (j in 1:length(files_list)){        # Put together the directory path and filename
for the current
file to be proce     input_filename_string<-paste0(directory_list[k],'/',files_list[j])

dat<read.csv(input_filename_string, header=T, stringsAsFactors = F) # loading


   # Compare the Owenmore Turb Events to CANARY algorithm to determine the number
# The method requires an extra row at the top and bottom of the dataframe.     # Add row of
0s at start of dataframe.      dat<-rbind(0,dat)        # Add row of 0s at end of dataframe.
dat<-rbind(dat,0)        #Initialise variables to 0
   dat<-cbind(dat,Ver_Alarm_Start=0,Ver_Alarm_End=0)        #Initialise variables to 0     dat<-

cbind(dat,CANARYTurb_Alarm_Start=0,CANARYTurb_Alarm_End=0)        #Initialise variables to

999

   dat<-cbind(dat, FULL_MATCH=999,PARTIAL_MATCH=999)




   # Before doing the match, check for any na values in the dataframe, there          # if NA is
present the code returns where NA occurs in the dataframe.      dat[which(rowSums(is.na(dat[,-
1]))>0),]

   ## Also, ensure that there is a least 1 alarm present in the ##"Verified_OW_Event_A

contains_one<-any(dat$Verified_OW_Event_Alarm==1) if(!contains_one){  stop("There are no

Verified Alarms in the data, nothing to do!")

}

      # Any records containing NA values should be checked and must be removed for th

   # The code will iterate over rows of the dataframe starting from row 2
   # This loop locates the start and end point for each Verified alarm and labels     # Also, this
loop locates the start and end point for each CANARY alarm and lab          for (i in
2:nrow(dat)){
    # Checks if the value in Verified_OW_Event_Alarm of the previous row (i-1) is       # the alarm
has commenced and 1 is placed in Ver_Alarm_Start which marks the       if
```

```
((dat$Verified_OW_Event_Alarm[i-1]==0) & (dat$Verified_OW_Event_Alarm[i]==

{dat$Ver_Alarm_Start[i]<-1}


    # Checks if the value in Verified_OW_Event_Alarm of the previous row (i-1) is      # the alarm has finished and 1 is placed in Ver_Alarm_End which marks the end      if ((dat$Verified_OW_Event_Alarm[i-1]==1) & (dat$Verified_OW_Event_Alarm[i]==

{dat$Ver_Alarm_End[i-1]<-1}


    # As above for P_Event
    #if ((dat$P_Event[i-1]==0.00000) & (dat$P_Event[i]==1.000000))
#{dat$CANARYTurb_Alarm_Start[i]<-1}      if ((dat$P_Event[i-1]<1) &
(dat$P_Event[i]==1.000000))     {dat$CANARYTurb_Alarm_Start[i]<-1}          if

((dat$P_Event[i1]==1) & (dat$P_Event[i]<1))      {dat$CANARYTurb_Alarm_End[i-1]<-1}


  }



  # locate the indices for the start and end points of each CANARY Alarm
  CANARYTurb_Alarm_Start_Indices<-grep(1,dat$CANARYTurb_Alarm_Start)

CANARYTurb_Alarm_End_Indices<-grep(1,dat$CANARYTurb_Alarm_End)


  # locate the indices for the start and points of each Verified Alarm
  Ver_Alarm_Start_Indices<-grep(1,dat$Ver_Alarm_Start)

  Ver_Alarm_End_Indices<-grep(1,dat$Ver_Alarm_End)


  # ALL CASES    # This only runs if "CANARY" has found at least one alarm.
if(length(CANARYTurb_Alarm_Start_Indices)>0){ # checks for any start indices in      for (m
in 1:length(Ver_Alarm_Start_Indices)){  # This loop iterates over each

Ver_Alarm_Chunk_Length<-(Ver_Alarm_End_Indices[m]-Ver_Alarm_Start_Indices[m

CANARY_TEST_Chunk1<-dat$P_Event[(Ver_Alarm_Start_Indices[m]):(Ver_Alarm_End
```

```
      CANARY_Alarm_ON_Chunk1_Length<-sum(CANARY_TEST_Chunk1)              if
(Ver_Alarm_Chunk_Length==CANARY_Alarm_ON_Chunk1_Length)      {       # Now extend
the CANARY test Chunk by 1 step above and below.

        # If FULL_MATCH, then sum(CANARY test chunk) will not change.
        CANARY_TEST_Chunk2<-dat$P_Event[(Ver_Alarm_Start_Indices[m]-1):(Ver_Alarm
CANARY_Alarm_ON_Chunk2_Length<-sum(CANARY_TEST_Chunk2)                  if
(CANARY_Alarm_ON_Chunk1_Length==CANARY_Alarm_ON_Chunk2_Length)
{dat$FULL_MATCH[Ver_Alarm_End_Indices[m]]<-"TRUE"}                  else
{dat$PARTIAL_MATCH[Ver_Alarm_End_Indices[m]]<-"TRUE"}
      }
                else if (CANARY_Alarm_ON_Chunk1_Length>=1){
dat$PARTIAL_MATCH[Ver_Alarm_End_Indices[m]]<-"TRUE"       }

    }
  }

  (count_FULL_MATCH <- length(which(dat$FULL_MATCH == "TRUE")))
  (count_PARTIAL_MATCH <- length(which(dat$PARTIAL_MATCH == "TRUE")))
  (count_TOTAL_MATCH<-count_FULL_MATCH+count_PARTIAL_MATCH)
     # Count the number of actual alarms.
  Num_Ver_Alarms<-
sum(dat$Ver_Alarm_Start==1)       # Count
the number of CANARY alarms.

  Num_CANARY_Alarms<-sum(dat$CANARYTurb_Alarm_Start==1)

  # Calculate the % Agreement between CANARY and Ver Alarms
Percent_CANARY_Agreement_to_TOTAL_Verified_Events<round((count_TOTAL
```

```
_MATCH/Num                              current_row_for_output<-list(files_list[j],
count_FULL_MATCH, count_PARTIAL_MAT
  Algorithm_Scores[nrow(Algorithm_Scores) + 1,] <- current_row_for_output


  # Ensure that a folder is available to receive the output data/    # "data_set_identifer" will be
used as the folder name.       if (!dir.exists(paste0('09 ID CANARY Algorithm for turbidity
events/Output_File
    dat_out_directory<-paste0('09 ID CANARY Algorithm for turbidity events/Output_F       #

Save Current dat to file, for troubleshoot or testing as required.

  if    (!dir.exists(dat_out_directory))    dir.create(dat_out_directory,    recursive    =    F
write.csv(dat,(paste0(dat_out_directory,'/Dat_For_',files_list[j])), row.names=    if (j==1){    #
Only print this message once per processed directory.          cat("Writing data to
file:\n",(paste0(dat_out_directory,'/Dat_For_',files_list[


}
}
## Writing data to file:

##  09 ID CANARY Algorithm for turbidity events/Output_Files/Data1/Dat_Files/Dat_Fo ##

Writing data to file: ##  09 ID CANARY Algorithm for turbidity

events/Output_Files/Data1/Dat_Files/Dat_Fo ## Writing data to file: ##  09 ID CANARY

Algorithm for turbidity events/Output_Files/Data1/Dat_Files/Dat_Fo ## Writing data to file:

##  09 ID CANARY Algorithm for turbidity events/Output_Files/Data1/Dat_Files/Dat_Fo ##

Writing data to file:

##  09 ID CANARY Algorithm for turbidity events/Output_Files/Data1/Dat_Files/Dat_Fo ##

Writing data to file: ##  09 ID CANARY Algorithm for turbidity

events/Output_Files/Data1/Dat_Files/Dat_Fo

dat$TIME_STEP<-format(dat$TIME_STEP) # this prevents 00:00:00 being removed from Ti
Location_and_Date_Range_ID_String<-paste0(sub("\\_L.*","",files_list[1]),"_")

Filename_and_path_for_algorithm_scores<-paste0("09 ID CANARY Algorithm for turbidit

write.csv(Algorithm_Scores,Filename_and_path_for_algorithm_scores, row.names=FALSE)
```

A9.3 Output files for comparing the CANARY files to the manually identified events and identify the most suitable CANARY algorithm.

The output for step 9 identifying the best CANARY algorithm for turbidity events is saved in 09 ID CANARY Algorithm for turbidity events/Output_Files. It consists of two outputs, a Dat_Files directory containing 96 files and an 'Algo_scores files.

A9.3.1 The Dat_Files directory

The Dat_Files directory contains each of the CANARY alorithm output files matched to the manually verified events file. In addition, for the sample data provided with this workflow, an example of how matching could be verified by the user is included in the file 'Match_highlighted_for_Dat_For_OW061024_051124C_LPCF_BED6_ET0.89063alg_1' in the supplementary material folder.

head(dat)

```
##          TIME_STEP P_Event Turbidity Verified_OW_Event_Alarm Ver_Alarm_Start
## 1 0                   0      0.0                 0           0
## 2 2024-10-06 13:45:00      0      3.2                 0           0
## 3 2024-10-06 14:00:00      0      3.2                 0           0
## 4 2024-10-06 14:15:00      0      3.2                 0           0
## 5 2024-10-06 14:30:00      0      3.2                 0           0
## 6 2024-10-06 14:45:00      0      2.8                 0           0
##   Ver_Alarm_End CANARYTurb_Alarm_Start CANARYTurb_Alarm_End FULL_MATCH
## 1           0                  0               0      999
## 2           0                  0
0       999 ## 3           0                  0
0       999
## 4           0                  0               0      999
## 5           0                  0               0      999
## 6           0                  0               0      999
##   PARTIAL_MATCH
## 1         999
#
#
2
```

9
9
9
#
#
3

9
9
9
4 999
5 999
6 999

A9.3.2 Algo scores file

The algo scores file summarises the number of full and partial matches for each CANARY algorithm and assigns a percent agreement to the total number of verified events. This can be used to identify the most suitable algorithm for the particular monitoring station based on the data provided to 'train' CANARY. It should be noted that adequate data covering a range of events over a time period is required to train CANARY and identify the most suitable algorithm. The optimum time period will depend on the frequency of events and the variability in event profiles for each monitoring station.

For this short dataset all algorithms show 100% identification of events i.e. they all identified the 4 manually identified events so more data would be required to distinguish the most suitable algorithm for this monitoring location.

head(Algorithm_Scores)

algorithm FULL_MATCH PARTIAL_MATCH

1 OW061024_051124C_LPCF_BED10_ET0.98926alg_1.csv 0 4

2 OW061024_051124C_LPCF_BED10_ET0.98926alg_10.csv 0 4

3 OW061024_051124C_LPCF_BED10_ET0.98926alg_11.csv 0 4

4 OW061024_051124C_LPCF_BED10_ET0.98926alg_12.csv 0 4

5 OW061024_051124C_LPCF_BED10_ET0.98926alg_13.csv 0 4

6 OW061024_051124C_LPCF_BED10_ET0.98926alg_14.csv 0 4

TOTAL_MATCH Total_CANARY_Events Total_Verified_Events

1 4 112 4

2 4 38 4

3 4 36 4

4 4 26 4

5 4 34 4

6 4 15 4

Percent_CANARY_Agreement_to_TOTAL_Verified_Events

1 100

2

100 ## 3

100

4 100

5 100

6 100

References

Auguie, B. and Antonov, A. (2017) ‘gridExtra: Miscellaneous Functions for "Grid" Graphics’. Available at: https://cran.r-project.org/web/packages/gridExtra/index.html (https://cran.rproject.org/web/packages/gridExtra/index.html) (Accessed: 28 April 2025).

Barrett, T. *et al.* (2024) ‘Data.table: Extension of ’data.frame’’. Available at: https://cran.rproject.org/web/packages/data.table/index.html (https://cran.rproject.org/web/packages/data.table/index.html) (Accessed: 14 February 2025).

Burkhardt, J.B. *et al.* (2022) ‘Near real-time event detection for watershed monitoring with CANARY’, *Environmental Science: Advances*, 1(2), pp. 170–181. Available at: https://doi.org/10.1039/D2VA00014H (https://doi.org/10.1039/D2VA00014H).

Edward, [https://stackoverflow.com/users/7514527/edward] (2024) ‘Highlight areas in a time series when y is greater than a threshold value and a range of values’. Stackoverflow. Available at: https://stackoverflow.com/questions/78469527/highlight-area-in-a-time-series-when-y-ishttps://stackoverflow.com/questions/78469527/highlight-area-in-a-time-series-when-y-is-greater-than-a-threshold-value-and-a-rgreaterthan-a-threshold-value-and-a-r (https://stackoverflow.com/questions/78469527/highlight-area-in-atime-series-when-y-ishttps://stackoverflow.com/questions/78469527/highlight-area-in-a-time-series-when-y-is-greater-than-a-threshold-value-and-a-rgreater-than-a-threshold-value-and-a-r).

Hlavac, M. (2022) ‘Stargazer: Well-Formatted Regression and Summary Statistics Tables’. Available at: https://cran.r-project.org/web/packages/stargazer/index.html (https://cran.rproject.org/web/packages/stargazer/index.html) (Accessed: 28 April 2025). Kat, [https://stackoverflow.com/users/5329073/kat] (2024) ‘Highlight areas of interactive time

series plotly plot where y is greater than defined threshold and annotate them'. Stackoverflow. Available at: https://stackoverflow.com/questions/78761758/highlighthttps://stackoverflow.com/questions/78761758/highlight-areas-of-interactive-time-series-plotly-plot-where-y-is-greater-than-dareas-of-interactive-time-series-plotly-plotwhere-y-is-greater-than-d (https://stackoverflow.com/questions/78761758/highlight-areas-ofinteractive-time-serieshttps://stackoverflow.com/questions/78761758/highlight-areas-of-interactive-time-series-plotly-plot-where-y-is-greater-than-dplotly-plot-where-y-is-greater-than-d).

Larmarange, J. *et al.* (2025) 'Labelled: Manipulating Labelled Data'. Available at: https://cran.rproject.org/web/packages/labelled/index.html (https://cran.rproject.org/web/packages/labelled/index.html) (Accessed: 16 February 2025).

Müller, K. and Bryan, J. (2020) 'Here: A Simpler Way to Find Your Files'. Available at: https://cran.rproject.org/web/packages/here/index.html (https://cran.rproject.org/web/packages/here/index.html) (Accessed: 14 February 2025).

Sievert, C. *et al.* (2024) 'Plotly: Create Interactive Web Graphics via 'plotly.js''. Available at: https://cran.rproject.org/web/packages/plotly/index.html (https://cran.rproject.org/web/packages/plotly/index.html) (Accessed: 14 February 2025).

Spinu, V. *et al.* (2024) 'Lubridate: Make Dealing with Dates a Little Easier'. Available at: https://cran.rproject.org/web/packages/lubridate/index.html (https://cran.rproject.org/web/packages/lubridate/index.html) (Accessed: 14 February 2025).

Team, R.C. (2024) 'R: A Language and Environment for Statistical Computing'. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/ (https://www.Rproject.org/).

Tierney, N. *et al.* (2024) 'Naniar: Data Structures, Summaries, and Visualisations for Missing Data'. Available at: https://cran.r-project.org/web/packages/naniar/index.html

(https://cran.rproject.org/web/packages/naniar/index.html) (Accessed: 28 April 2025).

Wickham, H., François, R., *et al.* (2023) 'Dplyr: A Grammar of Data Manipulation'. Available at: https://cran.r-project.org/web/packages/dplyr/index.html (https://cran.rproject.org/web/packages/dplyr/index.html) (Accessed: 14 February 2025).

Wickham, H., Pedersen, T.L., *et al.* (2023) 'Scales: Scale Functions for Visualization'. Available at: https://cran.r-project.org/web/packages/scales/index.html (https://cran.rproject.org/web/packages/scales/index.html) (Accessed: 14 February 2025).

Wickham, H., Chang, W., *et al.* (2024) 'ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics'. Available at: https://cran.rhttps://cran.r-project.org/web/packages/ggplot2/index.htmlproject.org/web/packages/ggplot2/index.html (https://cran.rproject.org/web/packages/ggplot2/index.html) (Accessed: 14 February 2025).

Wickham, H., Vaughan, D., *et al.* (2024) 'Tidyr: Tidy Messy Data'. Available at: https://cran.rproject.org/web/packages/tidyr/index.html (https://cran.rproject.org/web/packages/tidyr/index.html) (Accessed: 14 February 2025).

Wickham, H. and RStudio (2023) 'Tidyverse: Easily Install and Load the 'Tidyverse''. Available at: https://cran.r-project.org/web/packages/tidyverse/index.html (https://cran.rproject.org/web/packages/tidyverse/index.html) (Accessed: 14 February 2025).

Wickham, H., Software, P. and PBC (2023) 'Stringr: Simple, Consistent Wrappers for Common String Operations'. Available at: https://cran.r-project.org/web/packages/stringr/index.html (https://cran.rproject.org/web/packages/stringr/index.html) (Accessed: 28 April 2025).

Wilke, C.O. (2024) 'Cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2''. Available at: https://cran.r-project.org/web/packages/cowplot/index.html (https://cran.rproject.org/web/packages/cowplot/index.html) (Accessed: 28 April 2025).

APPENDIX B: Data Management Plan, Sensor Calibration & In-stream Data Validation

B.1 Data Management Plan

B.1.1 Data description and collection or re-use of existing data

New data will be managed as outlined in table 1 with existing data being managed as outlined in table 2.

B.1.1.1 New Data

TableB1: Management of New Data

Research Area	Data Type	Data Source	Data Format	Data Provenance	File Naming Convention
Baseline monitoring	Water quality Data – turbidity every 15 minutes	Multiparameter sonde (Model YSI 6600 EDS V2-2, YSI Inc., Ohio, USA)	Data collected is stored on internal sonde memory and downloaded every month via EcoWatch Lite as CSV files.	Quality assurance as methodology	River.Date E.g. UN010123 or OW010123
Event Monitoring	Water quality – turbidity, conductivity and temperature collected every 15 minutes	Multiparameter sonde (Model YSI 6600 EDS V2-2, YSI Inc., Ohio, USA)	Data collected is stored on internal sonde memory and downloaded every month via EcoWatch Lite as CSV files.	Quality assurance as per methodology	River.Date E.g. UN010123 or OW010123
Verification Monitoring	Water quality – grab sample to validate HF monitoring. pH, conductivity, temperature, dissolved oxygen, turbidity		PDF and MS Excel	laboratory is accredited by INAB to SO/IEC 17025	As per laboratory format.

TableB2: Reuse of Existing Data

Data Type	Data Source	Source Detail	Data Format	Data Provenance
Protected Areas	Dept. of Housing, Local Government and Heritage	Data is publicly available from: https://www.npws.ie/protected-sites	pdf	Recorded and validated by NPWS
Land Use Impacts	EPA	Data is publicly available from: Uisce Eireann AER Reports: https://epawebapp.epa.ie/terminalfour/wwda/index.jsp?disclaimer=yes&Submit=Continue Catchment Assessments: https://www.catchments.ie/data/#/?_k=nyo28u	pdf	Recorded and validated by data source
Water Quality	EPA	Data is publicly available from: https://www.catchments.ie/data/#/?_k=0hudur	CSV files	Recorded and validated by data source
Hydrometric Data	OPW	Data is publicly available from: http://waterlevel.ie/	CSV files	Recorded and validated by data source
Meteorological Data - rainfall	Met Eireann	Data is publicly available from: https://www.met.ie/climate/available-data/historical-data	csv files	Recorded and validated by data source

B.1.2 Data Documentation & Quality

B.1.2.1 Data Documentation

A spreadsheet documenting all data files, including primary and secondary data will be maintained. Project details will also be included as a file. The spreadsheet is formatted as below.

Format	Name	Size in KB	Description	Data Collection Method
Pdf, csv, etc	As outlined in Table 1		Site where data was collected, units of measurement (if not included in the column header)	Specific to each data type.

B.1.2.2 Metadata

File format, file size and methodology of data collection will be captured on the spreadsheet and files will be organised by the date the data was collected.

Data will be organised in folders according to data type (e.g. station & hydrometric data, with individual files for each date data is collected).

B.1.2.3 Data Quality Control

Calibration of instrumentation, repeated samples and measurements is carried out as outlined in the methodology.

B.1.2.4 Storage and backup during the research process

Data is stored on the DCU google drive and backed up to the ATU One Drive and to an external hard drive. Backups will be performed weekly.

B.1.3 Data security and protection of sensitive data

No personal or sensitive data will be collected during this research and data will be openly accessible once the project is complete. Data protection policies GDPR do not apply to this data.

B.1.3.1 Legal and ethical requirements, code of conduct

No personal data is being processed in this research.

B.1.3.2 Management of other legal issues, such as IP rights and ownership.

No IP associated with this research.

B.1.4 Data sharing and long-term preservation

Data will be published and openly accessible once project is complete.

B.1.4.1 Software or Tools needed to access and use data?

R Studio used for data analysis

B.1.5 Data management responsibilities and resources

Researcher Lisa Cronin responsible for data management, then passed to Prof. Fiona Regan

B.2 Sensor Calibration

B2.1 Calibration of YSI 6600 Sensors

B2.1.1 Calibration of YSI 6600 Sensor at Owenmore River Site

Table B2: Calibration data for YSI 6600 sensors on the Owenmore River at Ballynacarrow over the study period.

Date/Time	06/10/2024		Sonde	YSI 6600 0001A910	
Checked by	L. Cronin		Location	River Owenmore	
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	24.78	**Calibrate**	24.65
Specific Conductivity (µS/cm)	0		7 @ 24.78 ºC		5 @ 24.65 ºC
	1413		1381 @ 24.88 ºC		1412 @ 24.72 ºC
Turbidity (NTU)	0		-0.6		0.1
	126		123.2		126.1
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range	
Conductivity cell constant	4.7477	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.94954	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.05095	
Maintenance Record	**Task**		**Comment**

Date/Time	22/10/2024		Sonde	YSI 6600 0001A910		
Checked by	L. Cronin		Location	River Owenmore		
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**	
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	23.28	**Calibrate**	23.44	
Specific Conductance (µS/cm)	0		8 @ 23.28 ºC		5 @ 23.44 ºC	
	1413		1336 @ 23.15 ºC		1418 @ 22.92 ºC	
Turbidity (NTU)	0		0.5		0.0	
	126		127.2		125.5	
Comments						

YSI CALIBRATION DETAILS

Parameter	value	acceptable range	
Conductivity cell constant	4.74757	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.949514	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.050947	
Maintenance Record	**Task**		**Comment**

Date/Time	06/11/2024		Sonde	YSI 6600 0001A910		
Checked by	L. Cronin		Location	River Owenmore		
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**	
Temperature (ºC) (sonde)	N/A	**Clean so**	23.66	**Calibrat**	23.45	

Specific Conductivity (µS/cm)	0		7 @ 23.66 °C		6 @ 23.45 °C
	1413		1431 @ 23.83 °C		1415 @ 23.63 °C
Turbidity (NTU)	0		0.5		0
	126		124.8		125.9
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range	
Conductivity cell constant	4.95325	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.99065	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.896646	
Maintenance Record	**Task**		**Comment**

Date/Time	22/11/2024		Sonde	YSI 6600 0001A910	
Checked by	L. Cronin		Location	River Owenmore	
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	23.05	**Calibrate**	22.93
Specific Conductance (µS/cm)	0		7 @ 23.05 °C		6 @ 22.93 °C
	1413		1418 @ 22.94 °C		1414 @ 22.82 °C
Turbidity (NTU)	0		-0.7		-0.2
	126		123.1		126

Comments	

YSI CALIBRATION DETAILS

Parameter	value	acceptable range	
Conductivity cell constant	4.92804	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.985609	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.183151	
Maintenance Record	**Task**		**Comment**

Date/Time	04/12/2024		Sonde	YSI 6600 0001A910		
Checked by	L. Cronin		Location	River Owenmore		
Parameter	**Standard Used**		**Before Calibration Reading**			**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	22.68		**Calibrate**	22.58
Specific Conductivity (µS/cm) @ ºC	0		6 @ 23.88			6 @ 23.69
	1413		1414 @ 22.68 ºC			1413 @ 22.58 ºC
Turbidity (NTU)	0		0.2			0
	126		130.7			126
Comments						

YSI CALIBRATION DETAILS

Parameter	value	acceptable range

Conductivity cell constant	4.9238	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.98476	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.365769	
Maintenance Record	**Task**		**Comment**

Date/Time	17/12/2024		Sonde	YSI 6600 0001A910	
Checked by	L. Cronin		Location	River Owenmore	
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	25.05	**Calibrate**	24.92
Specific Conductance (µS/cm) @ ºC	0		7 @ 24.98		5 @ 24.76
	1413		1378 @ 24.75 ºC		1415 @ 24.68 ºC
Turbidity (NTU)	0		0.2		0
	126		125.5		125.7
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range
Conductivity cell constant	5.04795	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	1.009589	Between 0.91 & 1.09

Turbidity 6136	Offset	1.693981	
Maintenance Record	**Task**		**Comment:** Pontoon at Markree repaired on 15/12/24

Date/Time	03/01/2025		Sonde	YSI 6600 0001A910	
Checked by	L. Cronin		Location	River Owenmore	
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	25.11	**Calibrate**	24.88
Specific Conductivity (µS/cm) @ ºC	0		8 @ 25.09		5 @ 24.92
	1413		1443 @ 25.11 ºC		1416 @ 24.88 ºC
Turbidity (NTU)	0		-0.6		0
	126		131.4		125
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range	
Conductivity cell constant	4.94309	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.988619	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.153552	
Maintenance Record	**Task**		**Comment**

Date/Time	15/01/2025		Sonde	YSI 6600 0001A910
Checked by	L. Cronin		Location	River Owenmore

Parameter	Standard Used		Before Calibration Reading		After Calibration Reading
Temperature (ºC) (sonde)	N/A	Clean Sonde	24.22	Calibrate	24.06
Specific Conductance (µS/cm)	0		7 @ 23.96		6 @ 23.80
	1413		1424 @ 23.95 ºC		1415 @ 23.82 ºC
Turbidity (NTU)	0		-0.1		0
	126		120.8		125.7
Comments					

YSI CALIBRATION DETAILS			
Parameter	value	acceptable range	
Conductivity cell constant	4.90435	5.0 ± 0.45 & not more than ±0.1 from historical record	
Conductivity gain	0.980871	Between 0.91 & 1.09	
Turbidity 6136	Offset	1.57946	
Maintenance Record	**Task**		**Comment**

B2.1.2 Calibration of YSI 6600 Sensor at Unshin River Site

Table B3: Calibration data for YSI 6600 sensors on the Unshin River at Markree over the study period.

Date/Time	05/10/2024		Sonde	YSI 6600 00019595	
Checked by	L. Cronin		Location	River Unshin	
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	23.44	**Calibrate**	23.26
Specific Conductivity (µS/cm) @ ºC	0		8 @ 24.38		7 @ 24.22
	1413		1326 @ 23.37 ºC		1408 @ 23.10 ºC
Turbidity (NTU)	0		0.7		0.2
	126		125.6		126.3
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range
Conductivity cell constant	4.84266	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	0.968532	Between 0.91 & 1.09
Turbidity 6136	Offset	2.00671
Maintenance Record	**Task**	**Comment**

Date/Time	22/10/2024		Sonde	YSI 6600 00019595

Checked by	L. Cronin		Location	River Unshin	
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	25.1	**Calibrate**	25.08
Specific Conductance (µS/cm) @ ºC	0		7 @ 25.13 ºC		7 @ 24.99
	1413		1391 @ 25.06 ºC		1416 @ 25.0
Turbidity (NTU)	0		0.8		0
	126		125.2		125.5
Comments					

YSI CALIBRATION DETAILS

Parameter	**value**	**acceptable range**
Conductivity cell constant	4.842665	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	0.968533	Between 0.91 & 1.09
Turbidity 6136	**Offset**	2.7185
Maintenance Record	**Task**	**Comment**

Date/Time	06/11/2024		Sonde		YSI 6600 00019595
Checked by	L. Cronin		Location		River Unshin
Parameter	**Standard Used**		**Before Calibration**		**After Calibration**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	24.22	**Calibrate**	24.36
Specific Conductivity (µS/cm) @ ºC	0		8 @ 24.36		7 @ 23.97
	1413		1442 @ 24.21 ºC		1388 @ 24.50 ºC

Turbidity (NTU)	0		-0.2		-0.1
	126		124.6		126
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range
Conductivity cell constant	4.82107	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	0.964214	Between 0.91 & 1.09
Turbidity 6136	Offset	2.5769
Maintenance Record	**Task**	**Comment**

Date/Time	16/12/2024		Sonde		YSI 6600 00019595
Checked by	L. Cronin		Location		River Unshin
Parameter	**Standard Used**		**Before Calibration**		**After Calibration**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	24.08	**Calibrate**	24.22
Specific Conductance (µS/cm) @ ºC	0		7 @ 23.95		7 @ 24.13
	1413		1454 @ 23.98 ºC		XX ºC
Turbidity (NTU)	0		-0.2		0.1
	126		125.8		126.2
Comments	Pontoon repaired following severe storm				

YSI CALIBRATION DETAILS

Parameter	value	acceptable range
Conductivity cell constant	4.68607	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	0.937213	Between 0.91 & 1.09

Turbidity 6136	Offset	2.35824
Maintenance Record	**Task**	**Comment**

Date/Time	03/01/2025		Sonde		YSI 6600 00019595
Checked by	L. Cronin		Location		River Unshin
Parameter	**Standard Used**		**Before Calibration Reading**		**After Calibration Reading**
Temperature (ºC) (sonde)	N/A	**Clean Sonde**	24.28	**Calibrate**	24.33
Specific Conductivity (µS/cm) @ ºC	0		7 @ 23.83		6 @ 24.11
	1413		1376 @ 23.7ºC		1410 @ 24.21 ºC
Turbidity (NTU)	0		0		0.3
	126		126.4		125.3
Comments					

YSI CALIBRATION DETAILS

Parameter	value	acceptable range
Conductivity cell constant	4.89327	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	0.978655	Between 0.91 & 1.09
Turbidity 6136	Offset	2.31889
Maintenance Record	**Task**	**Comment**

Date/Time	18/01/2025		Sonde	YSI 6600 00019595
Checked by	L. Cronin		Location	River Unshin

Parameter	Standard Used		Before Calibration Reading		After Calibration Reading
Temperature (ºC) (sonde)	N/A	Clean Sonde		Calibrate	
Specific Conductance (µS/cm) @ ºC	0		7 @ 23.95		6 @ 24.15
	1413		1432 @ 23.68 ºC		1413 @ 23.93 ºC
Turbidity (NTU)	0		0.5		0
	126		122		125.7
Comments	Some larger solids present, and a lot of debris in water following storm				

YSI CALIBRATION DETAILS

Parameter	value	acceptable range
Conductivity cell constant	4.8289	5.0 ± 0.45 & not more than ±0.1 from historical record
Conductivity gain	0.96578	Between 0.91 & 1.09
Turbidity 6136	Offset	2.75585
Maintenance Record	**Task**	**Comment**

B2.2 Calibration of Field Meters for In-stream Data Validation when Deploying and Retrieving Sondes

Calibration of field meters was carried out as per manufacturers recommendations prior to deployment and retrieval of sondes from the Owenmore and Unshin rivers.

Table B4: Calibration data for field meters used for instream measurements on the Owenmore and Unshin Rivers over the Study Period.

Date	05/10/2024	**Deployment**	√	**Removal**	**X**	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope**	**Offset**	**Cell Const K**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	98.50%	0.00	N/A		100	14.7	999	N/A		N/A			
Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.388		N/A			1430	25.6	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		760	99	19.9	10.2
Comments																

Date	21/10/2024	**Deployment**	**X**	**Removal**	√	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	101.1	0.00	N/A		100	13.6	1009	N/A		N/A			
Specific Conductance (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.385		N/A					N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		763	100	20.5	10.1
Comments																

Date	22/10/2024	**Deployment**	√	**Removal**	**X**	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	99.6	0.00	N/A		100	10.3	1021	N/A		N/A			

Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.387		N/A		1429	25.6	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A		N/A		769	100	20.0	10.1
Comments															

Date	05/11/2024	**Deployment**	**X**	**Removal**	√	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	98.6	0.00	N/A		100	12.3	NR	N/A		N/A			
Specific Conductance (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.39		N/A			1409	24.8	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		771	99	20.0	10.3
Comments																

Date	06/11/2024	**Deployment**	√	**Removal**	**X**	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	98.9	0.00	N/A		100	12.3	1021	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-55.0	4.80	0.9999		N/A			N/A		N/A			
Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.391		N/A			1430	25.6	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		787	99	20.2	10.2
Comments																

Date	22/11/2024	**Deployment**	√	**Removal**	**X**	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset (mV)**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	100.7	0.00	N/A		100	8.2	1005	N/A		N/A			

pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-54.9	8.90	0.9999		N/A		N/A		N/A		
Specific Conductance (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.385		N/A		1423	25.3	N/A		
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A		N/A		783	101	19.9	10.1
Comments														

Date	26/11/2024	**Deployment**	**X**	**Removal**	√	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset (mV)**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	101.8	0.00	N/A		100	14.6	1008	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-56.9	8.00	1.0000		N/A			N/A		N/A			
Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.388		N/A			1413	25.6	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		808	105	19.9	10.2
Comments																

Date	03/12/2024	**Deployment**	**X**	**Removal**	√	**Checked by:**	L. Cronin	**Dissolved Oxygen**			**Sp. Conductivity**		**Standards Turbidity (NTU)**			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	99.0	0.00	N/A		100	18.3	1016	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-55.6	6.60	0.9999		N/A			N/A		N/A			
Specific Conductance (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.386		N/A			1397	24.4	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		748	96	19.6	9.88
Comments																

Date	16/12/2024	**Deployment**	√	**Removal**	**X**	**Checked by:**	L. Cronin	**Dissolved Oxygen**	**Sp. Conductivity**	**Standards Turbidity (NTU)**

Parameter	Meter	Probe	Standard Used	Slope (%)	Offset	Cell Const K/ R^2	Calibrate	DO (%)	Temp	hPa	1413 uS/cm std	Temp oC	800	100	20	10
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	101.7	0.00	N/A		100	11.8	1021	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-54.9	3.50	0.9999		N/A			N/A		N/A			
Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.385		N/A			1424	25.4	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		764	96	19.8	9.8
Comments																

Date	23/12/2026	Deployment		Removal		Checked by:	L. Cronin	Dissolved Oxygen			Sp. Conductivity		Standards Turbidity (NTU)			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	101.6	0.00	N/A		100	19.3	1018	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-55.0	0.00	0.9998		N/A			N/A		N/A			
Specific Conductance (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.377		N/A			1437	25.9	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		748	99	19.2	10
Comments																

Date	02/01/2025	Deployment	√	Removal	X	Checked by:	L. Cronin	Dissolved Oxygen			Sp. Conductivity		Standards Turbidity (NTU)			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	103.1	0.00	N/A		100	14.2	1022	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-54.5	-0.70	0.9999		N/A			N/A		N/A			
Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.383		N/A			1404	24.6	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		761	99	19.2	9.92
Comments																

Date	15/01/2025	Deployment	√	Removal	X	Checked by:	L. Cronin	Dissolved Oxygen			Sp. Conductivity		Standards Turbidity (NTU)			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	101.5	0.00	N/A		100	22.9	1024	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-54.3	-2.10	0.9996		N/A			N/A		N/A			
Specific Conductance (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.388		N/A			1436	25.8	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		745	98	18.9	9.67
Comments																

Date	18/01/2025	Deployment	X	Removal	√	Checked by:	L. Cronin	Dissolved Oxygen			Sp. Conductivity		Standards Turbidity (NTU)			
Parameter	**Meter**	**Probe**	**Standard Used**	**Slope (%)**	**Offset**	**Cell Const K/ R^2**	**Calibrate**	**DO (%)**	**Temp**	**hPa**	**1413 uS/cm std**	**Temp oC**	**800**	**100**	**20**	**10**
Dissolved Oxygen (% & mg/l)	HACH HQ30d	LOD0101	N/A	102.5	0.00	N/A		100	10.9	1016	N/A		N/A			
pH	HACH HQ30d	Intellical	buffer 4, 7 & 10	-53.4	-1.70	0.9995		N/A			N/A		N/A			
Specific Conductivity (µS/cm)	HACH HQ30d	Intellical	1413	N/A	N/A	0.388		N/A			1461	26.7	N/A			
Turbidity (NTU)	HACH 2100Q	N/A	10 - 800	N/A	N/A	N/A		N/A			N/A		768	98	19.7	10.2
Comments																

B.3 In-stream Data Validation

In stream data validation was carried out by measuring temperature, specific conductivity and turbidity using field instruments when the sondes were deployed and retrieved. The field measurements and YSI sensor measurements were assessed against the criteria in Table B1 [458].

Table B5: Agreement Criteria for in-situ YSI Sensor measurements and field measurements

Parameter	Agreement Criteria
Sp.conductivity	±5 uS or ±3% of measured value, whichever is greater
Temperature	±0.5 deg. C
Turbidity	±0.5 NTU or ±5% of measured value, whichever is greater

Table B6: YSI 6600 in-stream measurements and handheld meter in-stream measurements on the Owenmore River over the Study Period.

															YSI Drift Check		
Filename	Deploy	Remove	Date	Time	YSI Temp	YSI SpCond	YSI Turbidity	HACH pH	HACH Temp	HACH SpCond	HACH DO	HACH DO %	x̄ HACH Turbidity	HACH Turb 1	HACH Turb 2	HACH Turb 3	126 NTU	DI H2O Turb	1413uS/cm
OW061024	1		06/10/2024	13:45	13.31	486	3.2	NR	13.7	491	11.32	113.9	3.20	3.18	3.19	3.22			
		1	21/10/2024	17:20	10.95	409	113.7	NR	10.5	411	9.69	89.4	32.50	32.4	32.8	32.3			
OW221024	1		22/10/2024	17:55	10.72	419	11.9	8.23	11.1	403	9.58	86.3	NR	NR	NR	NR			
			05/11/2024	10:45	10.97	489	3.1	8.01	11.3	467	8.35	NR	3.54	3.6	3.55	3.48			
OW221124	1		22/11/2024	17:00	4.58	406	5	8.14	4.8	389	10.83	86.0	4.64	4.61	4.6	4.71			
		1	03/12/2024	11:30	7.24	407	5.3	8.07	7.5	411	9.94	83.3	5.34	5.37	5.27	5.37	122.6	0.3	1410 @23.4C
OW051224	1		05/12/2024	13:00	7.33	411	8.3	8.05	7.8	400	10.08	87.8	6.60	6.64	6.51	6.65			
		1	16/12/2024	17:15	7.44	468	4	8.24	7.8	467	10.37	92.7	3.7	3.72	3.87	3.7			
OW171224	1		17/12/2024	17:05	7.97	492	3.2	8.33	8.4	494	10.79	92.2	3.68	3.41	3.83	3.79			
		1	02/01/2025	15:35	7.09	462	4.5	8.30	7.3	448	10.99	90.6	5.00	5.01	4.97	5.03	127.1	0.3	1421 @ 24.73

OW030125	1		03/01/2025	14:10	6.29	440	4.2	8.25	6.6	432	10.62	86.9	4.59	4.55	4.83	4.4			
		1	13/01/2025	14:05	5.69	434	3.2	8.27	6.1	419	11.16	93.3	2.85	2.79	2.81	2.95	118.8	0.4	1401 @ 24.59C
OW150125	1		15/01/2025	14:20	7.61	441	3.1	8.27	7.5	427	10.61	92.2	3.18	3.11	3.18	3.25			
		1	24/01/2025	00:45	5.86	498	5.7	NR	NR	NR	NR	NR	NR	NR	NR	NR			

Table B7: YSI 6600 in-stream measurements and handheld meter in-stream measurements on the Unshin River over the Study Period.

																YSI Drift Check		
Filename	**Deploy**	**Remove**	**Date**	**Time**	**YSI Temp**	**YSI SpCond**	**YSI Turbidity**	**HACH pH**	**HACH Temp**	**HACH SpCond**	**HACH DO**	**HACH DO %**	**HACH Turbidity**	**HACH Turb 1**	**HACH Turb 2**	**HACH Turb 3**	**126 NTU**	**DI NTU**	**1413uS/cm**
UN051024	1		05/10/2024	19:10	12.93	390	2	NR	13.3	384	9.77	95.3	2.49	2.5	2.45	2.52			
		1	21/10/2024	17:45	10.99	335	6.1	NR	11.5	323	10.28	95.3	6.57	6.45	6.3	6.95			
UN221024	1		22/10/2024	17:10	10.54	405	2.3	8.19	10.9	388	10.68	96.8	2.64	2.49	2.58	2.86			
		1	05/11/2024	11:05	10.54	446	1.8	8.27	11	429	10.04	NR	2.56	2.59	2.37	2.73			
UN061124	1		06/11/2024	12:20	11.38	433	1	8.26	11.8	428	9.83	91.5	1.32	1.26	1.25	1.46			
		1	26/11/2024	09:45	6.12	398	2.9	7.96	6.4	384	10.45	84.5	3.61	3.63	3.31	3.88	121.4	0.7	1418 @ 24.28C
UN161224	1		16/12/2024	15:25	7.97	384	1.1	8.28	8.1	382	11.14	95.9	1.36	1.3	1.39	1.39			
		1	02/01/2025	16:00	5.63	388	7.3	8.23	6	391	12.22	96.7	7.42	7.12	7.68	7.46	123.8	0.5	1140 @ 25.48
UN030125	1		03/01/2025	13:40	4.99	428	2.6	8.24	5.4	415	12.02	96.4	3.17	3.17	3.17	3.18			
		1	18/01/2025	15:30	7.06	426	2.5	8.43	7.4	411	11.73	98.9	2.59	2.88	2.29	2.6	121.5	0.6	NT
UN190125	1		18/01/2025	17:00	7.19	422	1.7	8.37	7.7	418	11.83	99.2	1.83	2.17	2.2	1.13			
		1	03/02/2025	15:40	7.28	424	2.9	7.91	7.6	438	11.06	94	3.45	3.46	3.55	3.33	123.3	0.5	1300 @ 24.39C

APPENDIX C: CANARY Output Files

Table C1: Details for CANARY Output File

TIME_STEP	IDX	P_Event	Status	Clust_ID-1	Clust_Prob-1	Clust_ID-2	Clust_Prob-2	Clust_D-3	Contrib_{Temp}	Contrib_{Conductance}	Contrib_{Turbidity}	Resid_{Temp}	Resid_{Conductance}	Resid_{Turbidity}
Date & Time	Index position	P_Event is the probability of an event for that algorithm and ranges from 0-1	0 is base behavior, no alarm,	Clustering Algorithm - rarely used and not used in this analysis so 'nan' values in this data set					Contrib_{XX} shows the fact that something is contributing to an alarm			For statuses of -1, 0, or 1, Resid will calculate the residual difference between the predicted behavior and measured value. This is then compared to the “outlier threshold”.		
			, -1 is a reset signal related to the event timeout period						0, does not contribute					
			1 is actively alarming, which means P_event exceeds the						1 or -1 is the direction of contribution associated with			Outlier threshold - this parameter specifies the number of standard deviations of predicted error that must be met or exceeded before an outlier is declared (section 2.4 of user manual)		
			to zero the station is considered offline, the data is Status 3 - when all signals drop to zero the station is considered offline, the data is not analysed and these values are not shown in the plot											

References

Haxton, T. *et al.* (2013) ‘Canary Training Tutorials’. USEPA/NHSRC. Available at: https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=516747. Burkhardt, J. (2024) Email to Lisa Cronin, 6th August.

APPENDIX D: Logic for identifying full match and partial match between manually verified events and events identified by EPA CANARY

D.1: Workflow for Identifying Water Quality Hydrodynamic Events in Time Series Data

D.1.1: Logic for identifying full match and partial match between manually verified events and events identified by EPA CANARY event detection software.

Manually identified events are identified by visual screening of the turbidity data.

Take the following scenario:

- Alarm A: 13:00 – 17:00 ○ Event start timestep – 13:00 ○ Event end timestep – 17:00

- Alarm B: 15:00 – 22:00 ○ Event start timestep – 15:00 ○ Event end timestep – 22:00

Full Match

For a Full Match the timestep when the event starts and the timestep when the event ends must match in both the manually identified file and in the CANARY output file.

Partial Match

For a partial match, there mut be an overlap in either the start time or the end time of an event.

If Alarm B is from a "true" case i.e. is manually verified via visual inspection of the water quality trend, it is deemed a partial match if:

Case 1: A is completely in B
Case 2: B is completely in A
Case 3: start of A is within the start and end time of B
Case 4: end of A is within the start and end time of B

(Burkhardt, 2024)

Burkhardt, J. (2024) 'Event Matching for Near real time event detection for watershed monitoring with CANARY'. Email correspondence between Jonathan Burkhardt and Lisa Cronin.

Example of the Logic applied to dataset (Step 8 of the workflow)

1. Code locates the start and end index at which each verified alarm occurs. In the example shown below, the *start index* is 3 and the *end index* is 9.

TIME_STEP	CANARY_Alarm	Verified_Alarm	Index
26/11/2022 00:00	0	0	1
26/11/2022 00:15	0	0	2
26/11/2022 00:30	1	1	**3**
26/11/2022 00:45	1	1	4
26/11/2022 01:00	1	1	5
26/11/2022 01:15	1	1	6
26/11/2022 01:30	1	1	7
26/11/2022 01:45	1	1	8
26/11/2022 02:00	1	1	**9**
26/11/2022 02:15	0	0	10
26/11/2022 02:30	0	0	11
26/11/2022 02:45	0	0	12
26/11/2022 03:00	0	0	13

2. The length of the Verified_Alarm is calculated as $(end\ index - start\ index) + 1$. In this example Verified_Alarm length is 7.

3. Code then looks at the "CANARY_Alarm for those same indices and creates a "test chunk" between them. The test chunk is shaded in orange in the example below. This test chunk is called "CANARY Chunk 1".

TIME_STEP	CANARY_Alarm	Verified_Alarm	Index
26/11/2022 00:00	0	0	1
26/11/2022 00:15	0	0	2
26/11/2022 00:30	1	1	**3**
26/11/2022 00:45	1	1	4
26/11/2022 01:00	1	1	5
26/11/2022 01:15	1	1	6
26/11/2022 01:30	1	1	7
26/11/2022 01:45	1	1	8
26/11/2022 02:00	1	1	**9**
26/11/2022 02:15	0	0	10
26/11/2022 02:30	0	0	11
26/11/2022 02:45	0	0	12
26/11/2022 03:00	0	0	13

4. The values in the test chunk are all added together.

5. If the test chunk values sum to '0'. This is a MISSED ALARM.

6. If the test chunk values sum to less than 7, this is a PARTIAL MATCH.

7. If the test chunk values sum is the same as Verified_Alarm length, this *may* indicate a FULL MATCH. In this example the values sum to give a value of 7 which is the same as the length of the Verified_Alarm.

8. So, the "test chunk" and Verified_Alarm, *may* be the same length.

9. One other possibility is that the CANARY test chunk is wider than the Verified Alarm. To see if this is the case, a 2nd test chunk is created by extending the original test chunk one step earlier and later. In this example, the 2nd test chunk is shown in blue below.

TIME_STEP	CANARY_Alarm	Verified_Alarm	Index
26/11/2022 00:00	0	0	1
26/11/2022 00:15	0	0	2
26/11/2022 00:30	1	1	**3**
26/11/2022 00:45	1	1	4
26/11/2022 01:00	1	1	5
26/11/2022 01:15	1	1	6
26/11/2022 01:30	1	1	7
26/11/2022 01:45	1	1	8
26/11/2022 02:00	1	1	**9**
26/11/2022 02:15	0	0	10
26/11/2022 02:30	0	0	11
26/11/2022 02:45	0	0	12
26/11/2022 03:00	0	0	13

10. Now the values in "test chunk" 2 are all added together. If the sum doesn't change (still 7 in this example), then the extra time steps which were incorporated both contain "0s". In other words, the CANARY_Alarm and Verified_Alarm are a "FULL MATCH".

11. If the sum in "test chunk 2" does change (to 8 or 9 in this example), that indicates the CANARY_Alarm is wider than the verified alarm. This is a PARTIAL MATCH.

12. The code loops over every Verified alarm in the manner described above.

APPENDIX E: Example of Match logic applied to an event Data File

Table E1: Example of Match logic applied to_Dat_ET0.89063alg_1.pdf.

TIME_STEP	P_Event	Turbidity	Verified_OW_Event_Alarm	Ver_Alarm_Start	Ver_Alarm_End	CANARYTurb_Alarm_Start	CANARYTurb_Alarm_End	FULL_MATCH	PARTIAL_MATCH
0	0	0	0	0	0	0	0	999	999
06/10/2024 13:45	0	3.2	0	0	0	0	0	999	999
06/10/2024 14:00	0	3.2	0	0	0	0	0	999	999
06/10/2024 14:15	0	3.2	0	0	0	0	0	999	999
06/10/2024 14:30	0	3.2	0	0	0	0	0	999	999
06/10/2024 14:45	0	2.8	0	0	0	0	0	999	999
06/10/2024 15:00	0	2.9	0	0	0	0	0	999	999
06/10/2024 15:15	0	3.2	0	0	0	0	0	999	999
06/10/2024 15:30	0	3.3	0	0	0	0	0	999	999

06/10/2024 15:45	0	3.5	0	0	0	0	0	999	999
06/10/2024 16:00	0	3.2	0	0	0	0	0	999	999
06/10/2024 16:15	0	3.2	0	0	0	0	0	999	999
06/10/2024 16:30	0	3.1	0	0	0	0	0	999	999
06/10/2024 16:45	0	3.5	0	0	0	0	0	999	999
06/10/2024 17:00	0	3.4	0	0	0	0	0	999	999
06/10/2024 17:15	0	2.9	0	0	0	0	0	999	999
06/10/2024 17:30	0	3	0	0	0	0	0	999	999
06/10/2024 17:45	0	2.9	0	0	0	0	0	999	999
06/10/2024 18:00	0	3.1	0	0	0	0	0	999	999

06/10/2024 18:15	0	3.1	0	0	0	0	0	999	999
06/10/2024 18:30	0	2.7	0	0	0	0	0	999	999
06/10/2024 18:45	0	3.1	0	0	0	0	0	999	999
06/10/2024 19:00	0	2.8	0	0	0	0	0	999	999
06/10/2024 19:15	0	2.9	0	0	0	0	0	999	999
06/10/2024 19:30	0	2.5	0	0	0	0	0	999	999
06/10/2024 19:45	0.003906	2.8	0	0	0	0	0	999	999
06/10/2024 20:00	0.035156	2.6	0	0	0	0	0	999	999
06/10/2024 20:15	0.144531	2.8	0	0	0	0	0	999	999
06/10/2024 20:30	0.363281	2.8	0	0	0	0	0	999	999

06/10/2024 20:45	0.636719	2.8	0	0	0	0	0	999	999
06/10/2024 21:00	0.855469	2.7	0	0	0	0	0	999	999
06/10/2024 21:15	0.964844	3	0	0	0	0	0	999	999
06/10/2024 21:30	0.996094	2.7	0	0	0	0	0	999	999
06/10/2024 21:45	1	2.7	0	0	0	1	0	999	999
06/10/2024 22:00	1	2.6	0	0	0	0	0	999	999

06/10/2024 22:15	1	2.6	0	0	0	0	0	999	999
06/10/2024 22:30	1	2.6	0	0	0	0	0	999	999
06/10/2024 22:45	1	2.3	0	0	0	0	0	999	999
06/10/2024 23:00	1	2.7	0	0	0	0	0	999	999
06/10/2024 23:15	1	2.7	0	0	0	0	0	999	999
06/10/2024 23:30		2.5	0	0	0	0	0	999	999

06/10/2024 23:45	1	2.6	0	0	0	0	0	999	999
07/10/2024 00:00	1 1	2.5	0	0	0	0	1	999	999
07/10/2024 00:15	0.035156	4.3	0	0	0	0	0	999	999
07/10/2024 00:30	0.035156	2.6	0	0	0	0	0	999	999
07/10/2024 00:45	0.035156	2.6	0	0	0	0	0	999	999
07/10/2024 01:00	0.035156	2.5	0	0	0	0	0	999	999
07/10/2024 01:15	0.035156	2.7	0	0	0	0	0	999	999
07/10/2024 01:30	0.035156	2.6	0	0	0	0	0	999	999
07/10/2024 01:45	0.035156	2.6	0	0	0	0	0	999	999
07/10/2024 02:00	0.035156	2.5	0	0	0	0	0	999	999
07/10/2024 02:15	0.035156	2.6	0	0	0	0	0	999	999
07/10/2024 02:30	0.144531	2.6	0	0	0	0	0	999	999
07/10/2024 02:45	0.363281	2.6	0	0	0	0	0	999	999
07/10/2024 03:00	0.636719	2.7	0	0	0	0	0	999	999
07/10/2024 03:15	0.855469	2.5	0	0	0	0	0	999	999
07/10/2024 03:30	0.964844	2.8	0	0	0	0	0	999	999
07/10/2024 03:45	0.996094	2.6	0	0	0	0	0	999	999
07/10/2024 04:00	1	2.8	0	0	0	1	0	999	999

07/10/2024 04:15	1	2.6	0	0	0	0	0	999	999
07/10/2024 04:30	1	2.6	0	0	0	0	0	999	999
07/10/2024 04:45	1	2.8	0	0	0	0	0	999	999
07/10/2024 05:00	1	2.8	0	0	0	0	0	999	999
07/10/2024 05:15	1	2.7	0	0	0	0	0	999	999
07/10/2024 05:30	1	2.8	0	0	0	0	0	999	999
07/10/2024 05:45	1	2.8	0	0	0	0	0	999	999
07/10/2024 06:00	1	2.8	0	0	0	0	0	999	999
07/10/2024 06:15	1	2.9	0	0	0	0	1	999	999
07/10/2024 06:30	0.035156	3.5	0	0	0	0	0	999	999
07/10/2024 06:45	0.035156	2.9	0	0	0	0	0	999	999
07/10/2024 07:00	0.035156	2.9	0	0	0	0	0	999	999

07/10/2024 07:15	0.035156	2.9	0	0	0	0	0	999	999
07/10/2024 07:30	0.035156	3.1	0	0	0	0	0	999	999
07/10/2024 07:45	0.035156	2.8	0	0	0	0	0	999	999
07/10/2024 08:00	0.035156	3	0	0	0	0	0	999	999
07/10/2024 08:15	0.144531	3.1	0	0	0	0	0	999	999
07/10/2024 08:30	0.035156	2.9	0	0	0	0	0	999	999

07/10/2024 08:45	0.035156	2.9	0	0	0	0	0	999	999
07/10/2024 09:00	0.035156	3	0	0	0	0	0	999	999
07/10/2024 09:15	0.035156	2.9	0	0	0	0	0	999	999
07/10/2024 09:30	0.144531	3.1	0	0	0	0	0	999	999
07/10/2024 09:45	0.363281	3.4	0	0	0	0	0	999	999
07/10/2024 10:00	0.636719	3.1	0	0	0	0	0	999	999
07/10/2024 10:15	0.636719	3	0	0	0	0	0	999	999
07/10/2024 10:30	0.855469	3.1	0	0	0	0	0	999	999
07/10/2024 10:45	0.964844	3.8	0	0	0	0	0	999	999
07/10/2024 11:00	0.996094	3.2	0	0	0	0	0	999	999
07/10/2024 11:15	1	3.1	0	0	0	1	0	999	999
07/10/2024 11:30	1	3.5	0	0	0	0	0	999	999
07/10/2024 11:45	1	3.2	0	0	0	0	0	999	999
07/10/2024 12:00	1	3.1	0	0	0	0	0	999	999
07/10/2024 12:15	1	3.8	0	0	0	0	0	999	999
07/10/2024 12:30	1	3.2	0	0	0	0	0	999	999
07/10/2024 12:45	1	3.2	0	0	0	0	0	999	999
07/10/2024 13:00	1	3.1	0	0	0	0	0	999	999
07/10/2024 13:15		2.9	0	0	0	0	0	999	999

07/10/2024 13:30	1 1	3.1	0	0	0	0	1	999	999
07/10/2024 13:45	0.035156	3.7	0	0	0	0	0	999	999
07/10/2024 14:00	0.144531	3.4	0	0	0	0	0	999	999
07/10/2024 14:15	0.363281	3	0	0	0	0	0	999	999
07/10/2024 14:30	0.636719	3.2	0	0	0	0	0	999	999
07/10/2024 14:45	0.855469	3.6	0	0	0	0	0	999	999
07/10/2024 15:00	0.964844	2.9	0	0	0	0	0	999	999
07/10/2024 15:15	0.996094	3	0	0	0	0	0	999	999
07/10/2024 15:30	1	3	0	0	0	1	0	999	999
07/10/2024 15:45	1	2.9	0	0	0	0	0	999	999
07/10/2024 16:00	1	3	0	0	0	0	0	999	999

07/10/2024 16:15	1	3	0	0	0	0	0	999	999
07/10/2024 16:30	1	2.9	0	0	0	0	0	999	999
07/10/2024 16:45	1	3.1	0	0	0	0	0	999	999
07/10/2024 17:00	1	3	0	0	0	0	0	999	999
07/10/2024 17:15	1	3.1	0	0	0	0	0	999	999
07/10/2024 17:30		3	0	0	0	0	0	999	999

07/10/2024 17:45	1 1	2.8	0	0	0	0	1	999	999
07/10/2024 18:00	0.003906	2.8	0	0	0	0	0	999	999
07/10/2024 18:15	0.003906	2.8	0	0	0	0	0	999	999
07/10/2024 18:30	0.003906	2.8	0	0	0	0	0	999	999
07/10/2024 18:45	0.003906	2.8	0	0	0	0	0	999	999
07/10/2024 19:00	0.003906	2.8	0	0	0	0	0	999	999
07/10/2024 19:15	0.035156	3.3	0	0	0	0	0	999	999
07/10/2024 19:30	0.144531	3.4	0	0	0	0	0	999	999
07/10/2024 19:45	0.363281	3.2	0	0	0	0	0	999	999
07/10/2024 20:00	0.363281	3.1	0	0	0	0	0	999	999
07/10/2024 20:15	0.363281	3.3	0	0	0	0	0	999	999
07/10/2024 20:30	0.363281	2.9	0	0	0	0	0	999	999
07/10/2024 20:45	0.636719	2.8	0	0	0	0	0	999	999
07/10/2024 21:00	0.636719	3.3	0	0	0	0	0	999	999
07/10/2024 21:15	0.363281	2.9	0	0	0	0	0	999	999
07/10/2024 21:30	0.363281	2.7	0	0	0	0	0	999	999
07/10/2024 21:45	0.363281	2.8	0	0	0	0	0	999	999
07/10/2024 22:00	0.636719	2.5	0	0	0	0	0	999	999

07/10/2024 22:15	0.855469	2.8	0	0	0	0	0	999	999
07/10/2024 22:30	0.964844	2.8	0	0	0	0	0	999	999
07/10/2024 22:45	0.964844	2.8	0	0	0	0	0	999	999
07/10/2024 23:00	0.996094	2.7	0	0	0	0	0	999	999
07/10/2024 23:15	1	150.5	1	1	0	1	0	999	999
07/10/2024 23:30	1	8.8	1	0	0	0	0	999	999
07/10/2024 23:45	1	5.2	1	0	0	0	0	999	999
08/10/2024 00:00	1	105.5	1	0	0	0	0	999	999
08/10/2024 00:15	1	89.2	1	0	0	0	0	999	999
08/10/2024 00:30	1	20	1	0	0	0	0	999	999
08/10/2024 00:45	1	11.2	1	0	0	0	0	999	999
08/10/2024 01:00	1	4.9	1	0	0	0	0	999	999

08/10/2024 01:15	1	542.6	1	0	0	0	1	999	999
08/10/2024 01:30	0.003906	6.8	1	0	0	0	0	999	999
08/10/2024 01:45	0.035156	5.6	1 1	0	0	0	0	999	999
08/10/2024 02:00	0.144531	5.4		0	0	0	0	999	999

08/10/2024 02:15	0.363281	79.8	1	0	0	0	0	999	999
08/10/2024 02:30	0.636719	6	1	0	0	0	0	999	999
08/10/2024 02:45	0.855469	110.1	1	0	1	0	0	999	TRUE
08/10/2024 03:00	0.964844	2.8	0	0	0	0	0	999	999
08/10/2024 03:15	0.996094	2.9	0	0	0	0	0	999	999
08/10/2024 03:30	1	2.8	0	0	0	1	0	999	999
08/10/2024 03:45	1	2.9	0	0	0	0	0	999	999
08/10/2024 04:00	1	2.6	0	0	0	0	0	999	999
08/10/2024 04:15	1	2.9	0	0	0	0	0	999	999
08/10/2024 04:30	1	2.8	0	0	0	0	0	999	999
08/10/2024 04:45	1	2.8	0	0	0	0	0	999	999
08/10/2024 05:00	1	2.8	0	0	0	0	0	999	999
08/10/2024 05:15	1	2.8	0	0	0	0	0	999	999
08/10/2024 05:30		2.9	0	0	0	0	0	999	999

08/10/2024 05:45		2.8	0	0	0	0	1	999	999
08/10/2024 06:00	0.035156	2.8	0	0	0	0	0	999	999
08/10/2024 06:15	0.144531	2.9	0	0	0	0	0	999	999
08/10/2024 06:30	0.363281	2.9	0	0	0	0	0	999	999
08/10/2024 06:45	0.636719	2.9	0	0	0	0	0	999	999
08/10/2024 07:00	0.855469	3	0	0	0	0	0	999	999
08/10/2024 07:15	0.964844	2.9	0	0	0	0	0	999	999
08/10/2024 07:30	0.996094	3	0	0	0	0	0	999	999
08/10/2024 07:45	1	3	0	0	0	1	0	999	999
08/10/2024 08:00	1	2.8	0	0	0	0	0	999	999
08/10/2024 08:15	1	3.2	0	0	0	0	0	999	999
08/10/2024 08:30	1	2.9	0	0	0	0	0	999	999
08/10/2024 08:45	1	2.9	0	0	0	0	0	999	999
08/10/2024 09:00	1	3.1	0	0	0	0	0	999	999

08/10/2024 09:15	1	3.4	0	0	0	0	0	999	999
08/10/2024 09:30	1 1	3.4	0	0	0	0	0	999	999
08/10/2024 09:45		3.3	0	0	0	0	0	999	999
08/10/2024 10:00		3.3	0	0	0	0	1	999	999