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# Phase I DASSHH NI Belfast Lough

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**Further Information**

Agri-Food and Biosciences Institute (AFBI)

Fisheries & Aquatic Ecosystems Branch

Coastal Zone Science Programme

Newforge Lane

Belfast

BT9 5PX

Tel: 028-90255489

# Contents

# Section 1 Phase I – DASSHH, NI – Case study Belfast Lough

## 1.1 Introduction

Belfast Lough is a shallow semi-enclosed marine bay situated at the mouth of the River Lagan, on the east coast of Northern Ireland, with the city of Belfast and the port at its head. Belfast Harbour is Northern Ireland's main port. Belfast Lough is approximately 130 $km^2$ in size and has a catchment of approximately 900$km^2$ of which approximately 60% forms the drainage area of the River Lagan, the Lough's main freshwater source (AFBI 2008, AFBI 2014). The river is some 70 km in length and drains some of the most productive agricultural land in Northern Ireland. The remainder of the catchment is drained by a number of comparatively small rivers and streams. In terms of land use, the Belfast catchment comprises 415 farms covering dairy, sheep, pig and arable farming (1993 Census data, AFBI 2008). There is a general predominance for pasture to the north of the Lough with more mixed agricultural land with the higher urban density to the south. Most of the immediate fringing areas are classified urban (AFBI 2008). Belfast Lough is divided into Inner and Outer Belfast Lough for purposes of the Urban Waste Water Treatment Directive (UWWTD) (NIEA, 2011). The Lough lies between two counties: County Antrim and County Down, the population is centered on Belfast. There is considerable pressure on the existing drainage and wastewater collection and treatment systems that discharge into, or in the immediate vicinity of, Inner Belfast Lough. There are 5 wastewater treatment facilities discharging biologically treated effluent direct to Inner Belfast Lough on a continuous basis (Figure 1). Carrickfergus WwTW discharges to Outer Belfast Lough, but has the potential to impact on the Inner Lough due to the complex hydrodynamics within the Lough. The main anti-clockwise circulation within the lough has potential to ensure that discharges from the North Down WwTW will not generally impact the Inner Lough however this will be explored further in Phase II and III.

There are a further 29 identified wastewater treatment facilities discharging treated effluent to the River Lagan and its tributaries on a continuous basis, for eventual onward discharge to Belfast Lough (Figure 1). Patterns of land use in the Belfast catchment are illustrated in Figure 2, data from the CORINE 1990 database.

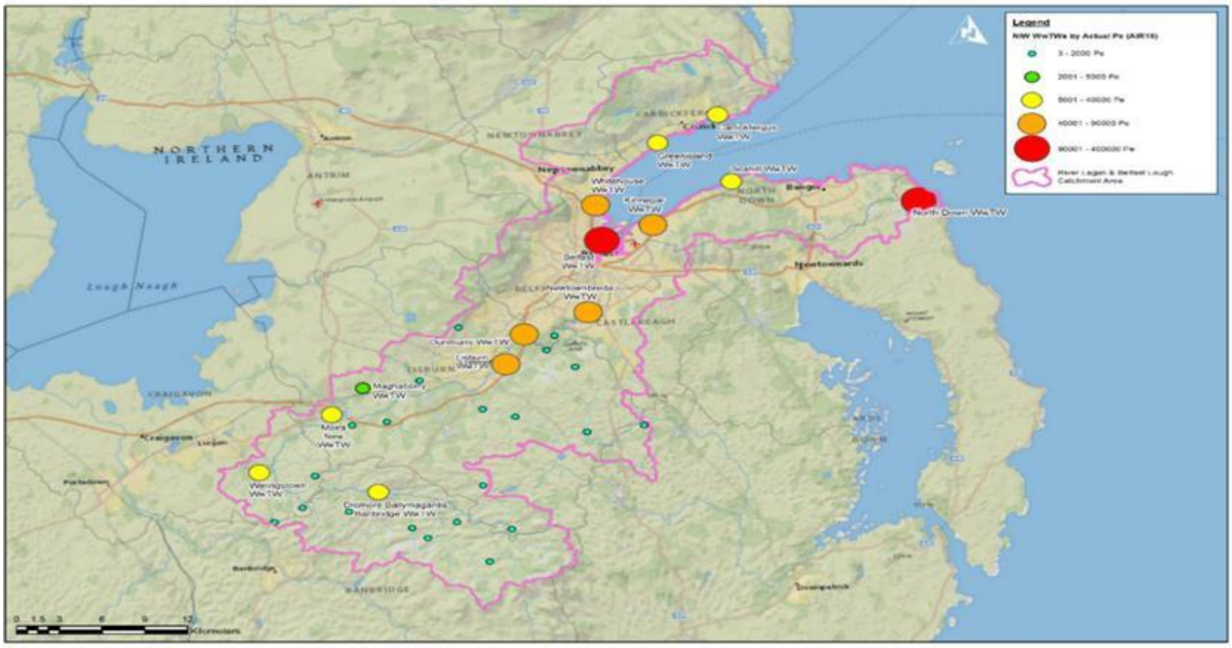


**Figure 1: Location of Belfast Lough catchment WwTWs**

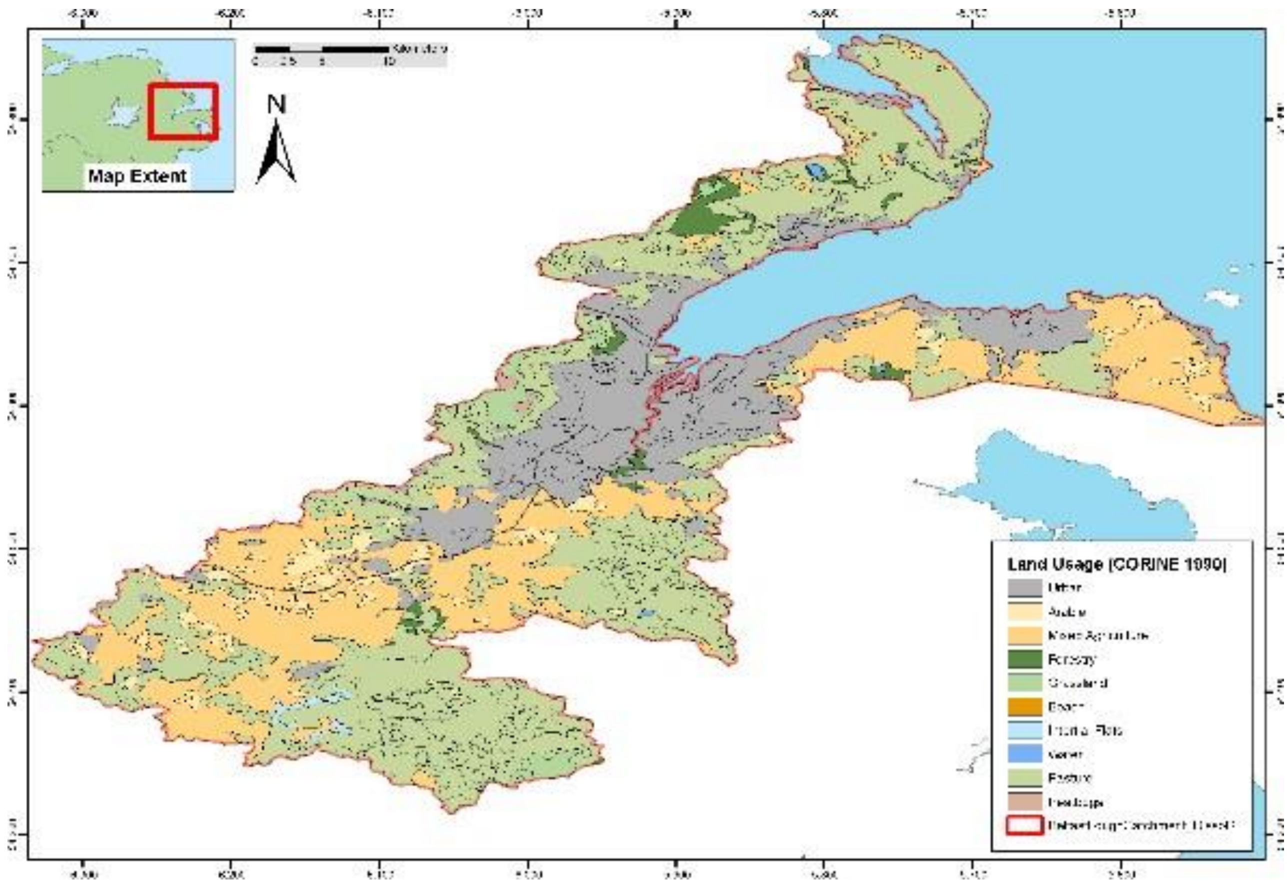


**Figure 2: Land Use classifications of the Belfast Lough Catchment**

Wildlife and non-farm animals are also recognised as a possible source of contamination. The Food Standards Agency Northern Ireland (FSANI) is responsible for classifying shellfish production areas and carry out statutory shellfish sampling in such areas as part of official control monitoring programmes. The microbiological monitoring programme is carried out to determine shellfish classifications that will ensure public health (www.food.gov.uk). Classification of harvesting areas is based on an analysis of *Escherichia coli* (*E. coli*) counts from official control samples, recorded as most probable number (MPN) of *E. coli* per 100g shellfish flesh (Table 1) which determines the level of postharvest treatment required before the product can be placed on the market for human consumption.

**Table 1: EU Food Hygiene legislative criteria for Shellfish water classification based on Most Probable Number (MPN) of *E. coli* analysed in 100g of mussel flesh (FSANI pers.comm.).**

| |
|---|
| ☐ Class A **– 80% of sample results ≤230 *E.coli*/100g, no results exceeding 700 *E.coli*/100g – molluscs can be harvested for direct human consumption.** |
| ☐ Class B **- 90% of sample results must be less than or equal to 4600 *E. Coli*/100g with none exceeding 46000 E. Coli/100g - molluscs can go for human consumption after purification in an approved establishment or after relaying in a classified relaying area or after an EC approved heat treatment process.** |
| ☐ Class C **- ≤46000 *E. Coli*/100g - molluscs can go for human consumption only after either:**<br>• relaying for at least two months in a classified Class B relaying area followed by purification in an approved establishment, or after an EC approved heat treatment process, or<br>• relaying for at least two months in a classified Class A relaying area, or<br>• an EC approved heat treatment process |
| ☐ Prohibited areas[1] (>46000 E. Coli/100g) **- molluscs must not be subject to production or be harvested.** |

Shellfish are commonly cultivated in sheltered waters which are vulnerable to microbial contamination from both point source pollution, e.g. sewage outflow, Combined Sewer Overflow (CSO) and diffuse pollution, e.g. agricultural runoff (Clements *et al.* 2015). Previous research has shown that environmental factors such as seasonality, tidal state and rainfall events may alter the concentrations of *E. coli* detected within shellfish flesh and hence affect the classification assigned to the harvesting area (Stapleton *et al*. 2008, Kay *et al*. 2008). There are currently twenty-one active aquaculture sites in Belfast Lough that have been licensed by the Department of Agriculture, Environment and Rural Affairs (DAERA) for the production of bottom cultivated mussels (Figure 3). Fifteen of these are currently classified by FSANI (FSANI pers.comm.). In recent years, a problem with poor water quality has been highlighted, with an increase in the number of Category C shellfish sample results reported. This has had substantial socio-economic implications for shellfish farmers.

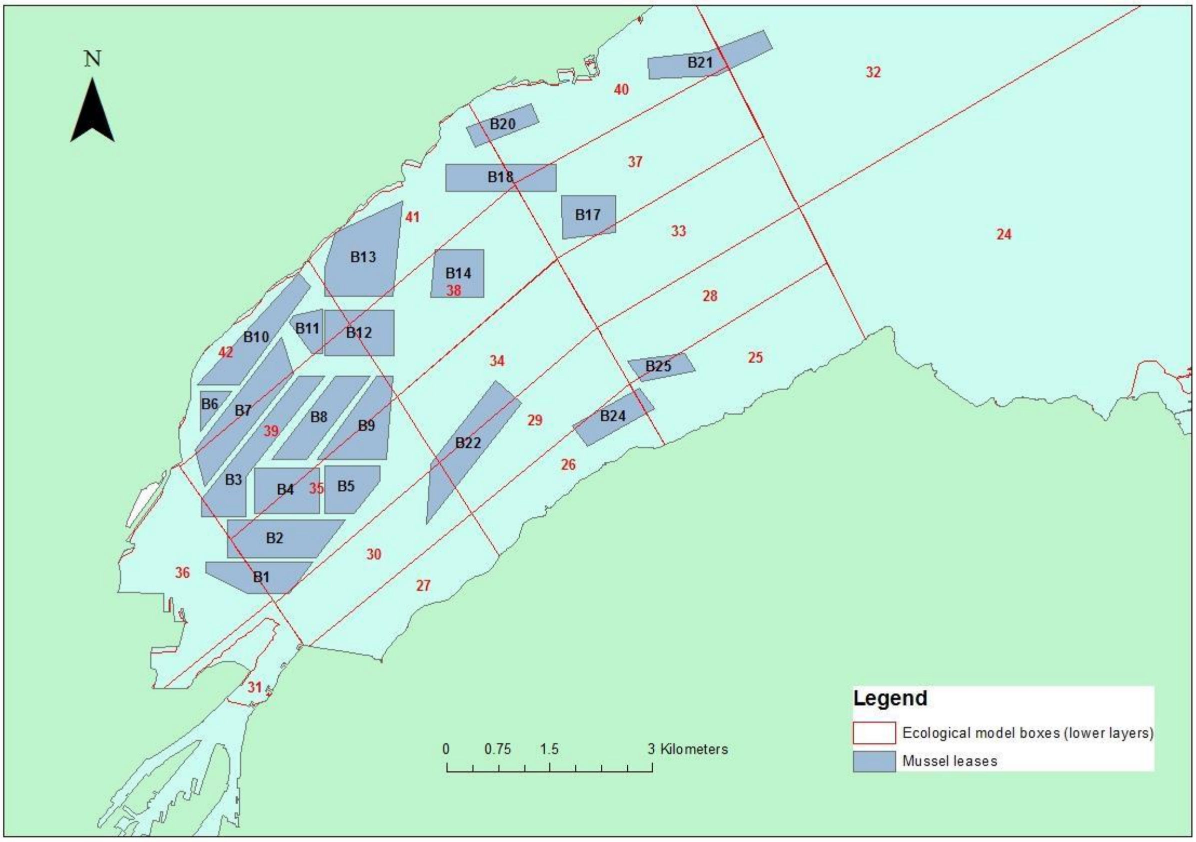


**Figure 3: Map showing the shellfish aquaculture sites in Belfast Lough.**

## 1.2. Updated results from the investigation of factors affecting *E. coli* numbers in Belfast lough mussels (March 2016 to March 2019)

AFBI was initially requested to investigate the issue of high *E. coli* numbers recorded in mussel (*Mytilus edulis*) flesh from both official control and the Food Business Operator’s (FBO) own samples collected from a number of sites in Belfast Lough. Specifically in relation to the FBO cultivating mussels on aquaculture site B4 (Figure 3) who has conducted his own sampling from March 2016 until March 2019. A sanitary survey carried out in 2008 for the FSANI (AFBI 2008) recommended that microbiological sampling of shellfish flesh could be rationalised to five representative monitoring points (RMPs) within the Lough and that samples must be collected within a radius of 50 m from the RMP (Figure 4). RMP 6 at Holywood South was added shortly after the 2008 report (FSANI pers. comm.). A subsequent review (CEFAS 2014) recommended some changes to FSA’s official control microbiological monitoring programme. This resulted in one aquaculture site B4 being re-associated from RMP3 to RMP1 (Figure 4). Concerns were raised by the FBO on B4 as the classification at RMP1 was frequently lower than that at RMP3. In 2014, the nomenclature of RMP 2 and 3 were changed (see Table 2).

**Table 2: RMPs with the 2008 and 2014 naming conventions and locations in Belfast Lough (extracted from CEFAS 2014).**

| RMP Name | 2008 RMP No. | 2014 RMP No. | Latitude (degrees) | Longitude (degrees) | Irish Grid Reference |
|---|---|---|---|---|---|
| Middlebank | RMP 1 | RMP1 | 54.6446 | -5.8809 | J 36782 79453 |
| Ross's Rock | RMP 3 | RMP 2 | 54.6669 | -5.8934 | J 35901 81911 |
| Dougold | RMP 2 | RMP 3 | 54.6625 | -5.8819 | J 36658 81443 |
| Urey | RMP 4 | RMP 4 | 54.6765 | -5.8593 | J 38068 83045 |
| Dougold Carrick | RMP 5 | RMP 5 | 54.7038 | -5.8274 | J 40031 86147 |
| Holywood South | - | RMP 6 | 54.6658 | -5.8007 | J 41884 81972 |

-Not applicable (area classified since 2008)

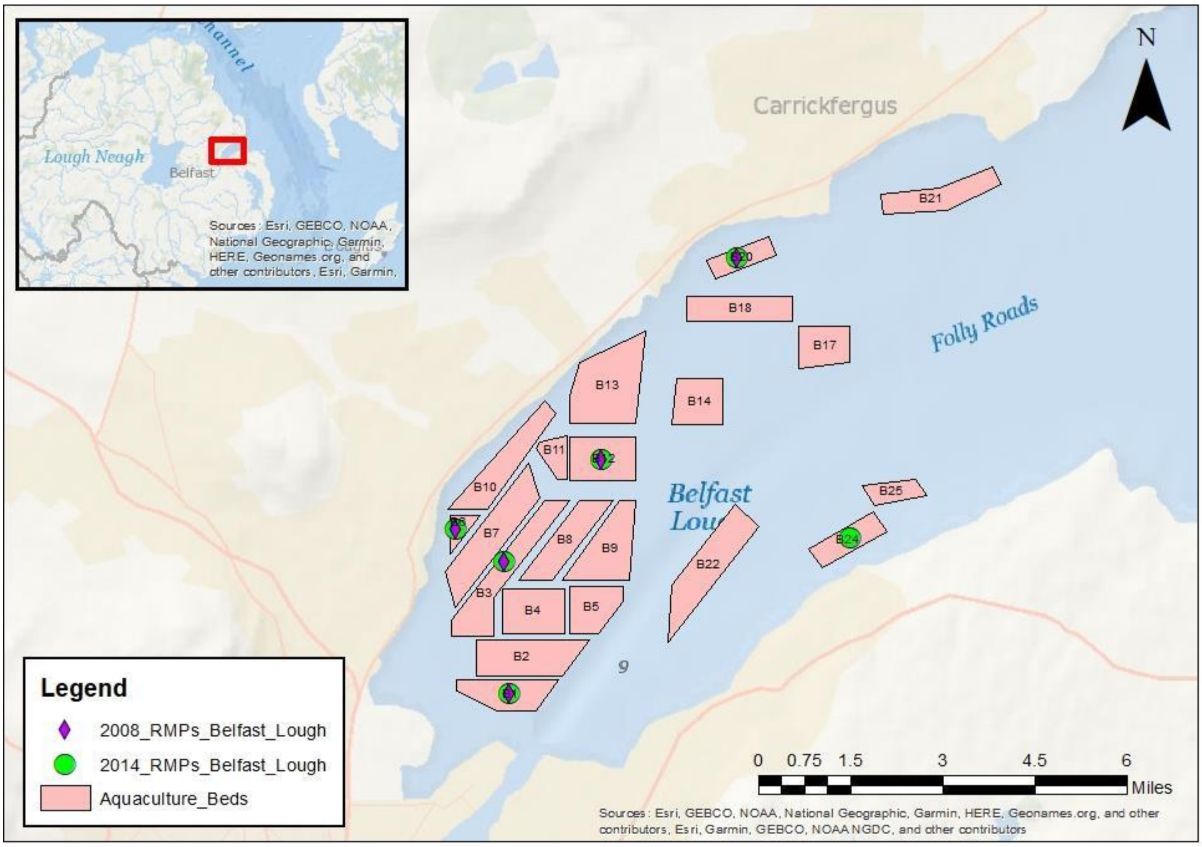


**Figure 4: Shellfish beds in Belfast Lough and locations of co-ordinates for RMPs as shown in 2008 and 2014 Sanitary Surveys.**

## 1.3 Materials and Methods

The data utilised within this study were not collected specifically for the purpose of this study and therefore do not cover all variables required for a full investigation of factors affecting *E. coli* contamination. The present dataset was derived from monitoring undertaken routinely for shellfish classifications on behalf of the Food Standards Agency, NI. Although this dataset was not collected specifically for the purpose of this study, it was the best available data. In March 2016, the FBO of aquaculture site B4 initiated his own sampling and *E. coli* analysis programme, using the same contracted sample collector and analysis laboratory as FSA, hence providing a set of comparable data to that collected at the FSA RMP locations. Further, in August 2016, the FBO of aquaculture site B4 started to sample from two locations within the boundary of the B4 site.

The data has been collated and additional data appended for aquaculture site B4, additional data included surface water temperature during sample collection (extracted from Public Health Laboratory (PHL) reports), state of the tide (Spring, Neap, Flood and Ebb, Admiralty Total Tide software) and rainfall (Digital rainfall Gauge, AFBI Newforge). Analysis of the data included, creating time series and statistical analysis looking at possible correlations between these datasets and the *E. coli* results.

## 1.4 Results

### 1.4.1 Tidal State

To investigate if tidal state at the time of collection influences the FBO's measured *E. coli* MPN numbers and consequent shellfish classification, additional state of the tide data was required. The date and time of mussel sample collection was used to conduct a retrospective search using the ADP - Admiralty Total tide software to find the predicted state of the tide on each mussel sampling occasion. The FBO's own B4 data is presented in Figure 5 and Table 3. The sampling programme, determined by the FBO, relies on the FBO's contracted sample collector completing the sample run and delivering the samples to the Belfast laboratories within 4 hours of collection, this has an effect on mussel sample collection, whereby the mussel collections frequently occur mid-morning and often on the same state of the tide, although there are exceptions.

As shown in the pie-charts (Figure 5) and Table 3, the greatest number of samples have been collected on Spring Flood tides (n = 89) and Neap Ebb tides (n =61). Higher numbers of mussel samples analysed with a category C classification were collected under Spring Flood conditions, values shown on pie chart are percentage.

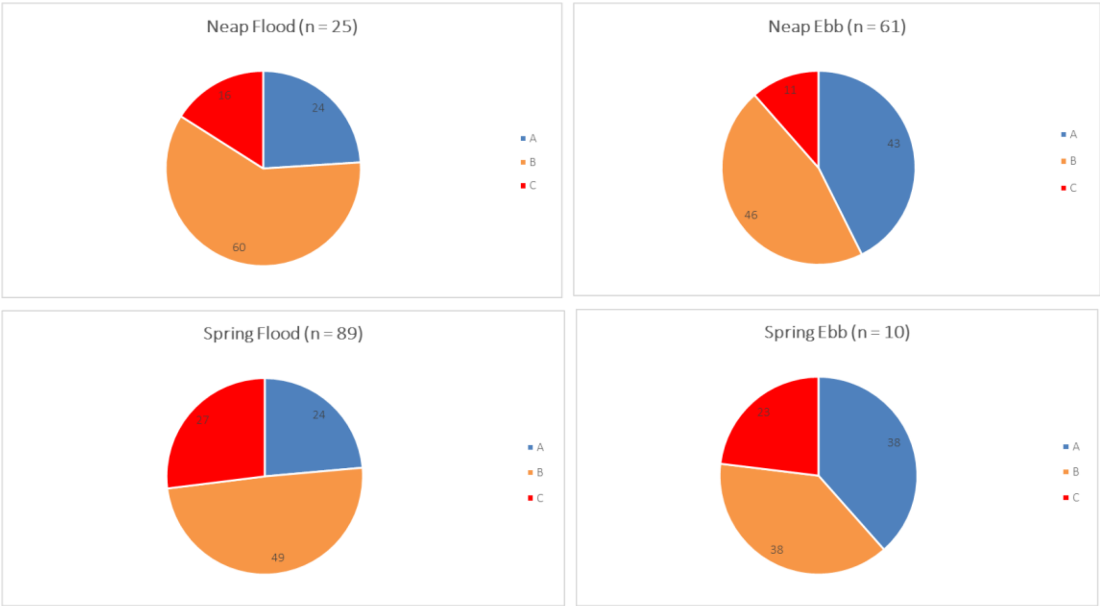


**Figure 5: Pie charts showing the % of category A, B and C classification results of mussel flesh sampled on different states of the tide for B4 mussel samples (FBO's own samples).**

**Table 3: Number of weekly mussel samples falling into category A, B and C based on the EU legislative criteria for the classification of harvesting areas (Table 1) and the state of the tide from March 2016 to March 2019 (FBO B4).**

| Category | Neap Flood | Neap Flood (%) | Neap Ebb | Neap Ebb (%) | Spring Flood | Spring Flood (%) | Spring Ebb | Spring Ebb (%) | |
|---|---|---|---|---|---|---|---|---|---|
| A | 6 | 24 | 26 | 43 | 21 | 24 | 5 | 38 | |
| B | 15 | 60 | 28 | 46 | 44 | 49 | 5 | 38 | |
| C | 4 | 16 | 7 | 11 | 24 | 27 | 3 | 23 | |
| Total | 25 | | 61 | | 89 | | 13 | | 188 |

A Spearman rank correlation coefficient was derived between log10-transformed *E. coli* data (recorded at the B4 sample sites) and the state of the tide.

To quantify the "state of the tide", the % of Spring tides was extracted for each mussel sampling date from the ADP - Admiralty Total tide software and used for statistical analysis. A positive correlation was observed between log10-transformed *E. coli* and % of Spring tides recorded on the day of mussel sampling ($r_s$=0.17, n=188 and P=0.01) (Table 4, Figure 6). This result implies that potentially Spring tides are a contributing factor although the mechanism is as yet unclear.

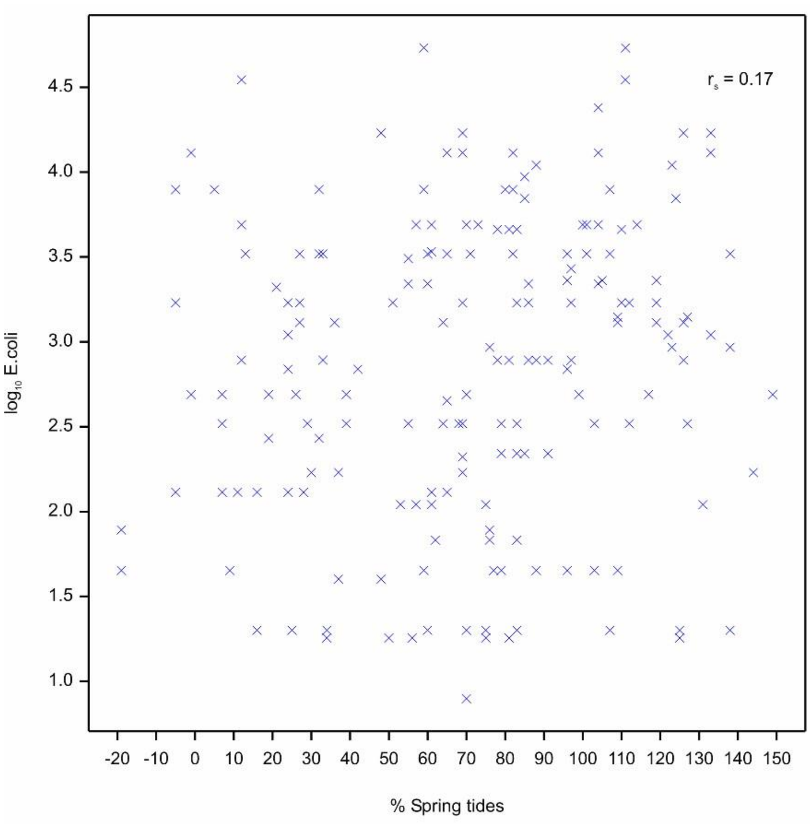


**Figure 6: Relationship between levels of *E. coli* (log10-transformed MPN *E. coli*) in mussels from B4 and % of Spring tides predicted on the date of mussel sampling.**

### 1.4.2 Rainfall

Rainfall data recorded at a digital gauge at Newforge Lane was collated and correlated with the log10-transformed *E. coli* data. The Newforge Lane rainfall data was the best available data and was considered representative of rainfall within the Belfast Lough catchment. The rainfall value for each individual day is the recorded. Rainfall data for the sample day and the preceding 7 days was analysed, following the approach outlined by Campos *et al.* 2015.

The Spearman rank correlation coefficients were derived between log10-transformed *E. coli* data (recorded at the B4 sample sites) and rainfall. Significant positive correlation was observed between log10-transformed *E. coli* and rainfall on the day before mussel sampling (Day -1, $r_s$=0.32, n= 187 and P=< 0.001) (Figure 7, Table 4).

**Table 4: Spearman's rank correlation coefficients ($r_s$) between daily rainfall, cumulative rainfall and % spring tides and log10-transformed *E. coli* (n= 188)**

| Variable | | Spearman's Rank Correlation coefficient (rs) | Probability |
|---|---|---|---|
| Daily Rainfall | Day of sampling | 0.20 | 0.006 |
| | -1 days | 0.32 | < 0.001 |
| | -2 days | 0.21 | 0.003 |
| | -3 days | 0.17 | 0.023 |
| | -4 days | 0.08 | 0.257 |
| | -5 days | 0.12 | 0.100 |
| | -6 days | 0.14 | 0.054 |
| | -7 days | 0.03 | 0.701 |
| Cumulative Rainfall | -2 days | 0.35 | < 0.001 |
| | -3 days | 0.36 | < 0.001 |
| | -4 days | 0.32 | < 0.001 |
| | -5 days | 0.29 | < 0.001 |
| | -6 days | 0.29 | < 0.001 |
| | -7 days | 0.25 | < 0.001 |
| | Previous week | 0.20 | 0.006 |
| % Spring Tide | | 0.17 | 0.01 |

The effect of cumulative rainfall was also investigated, Spearman rank correlation coefficients were derived between the cumulative rainfall and log10-transformed levels of *E. coli* in mussels from the FBO's own B4 site. Statistically significant positive correlation was observed between log10 *E. coli* and cumulative rainfall - 2, -3, -4, -5, -6 and -7 days before mussel sampling (Figure 8, Table 4).

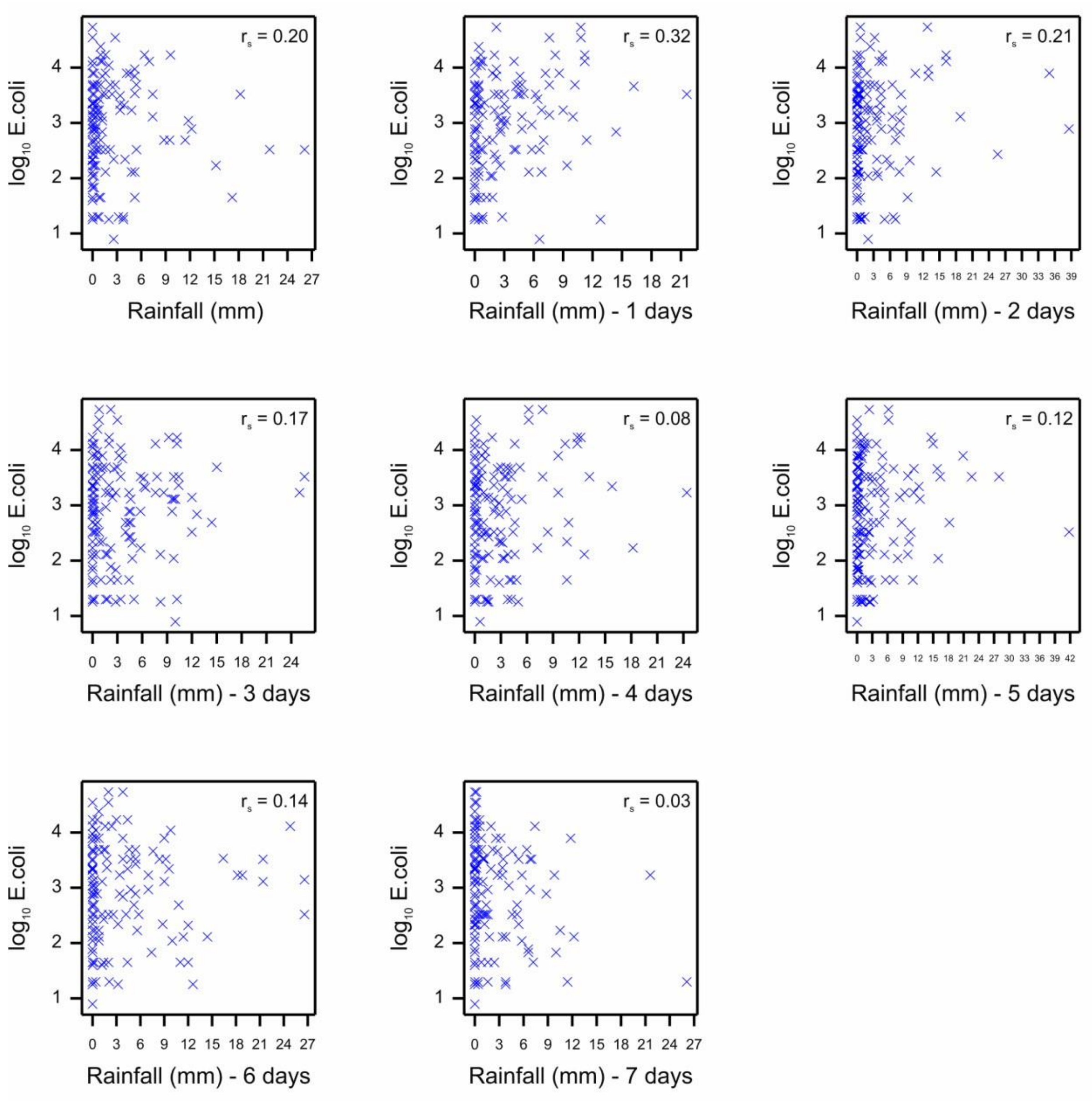


**Figure 7: Relationship between levels of *E. coli* (log10-transformed MPN *E. coli*) in mussels from B4 and daily rainfall recorded on the day of mussel sampling and the preceding seven days with Spearman's rank correlation coefficient ($r_s$) indicated**

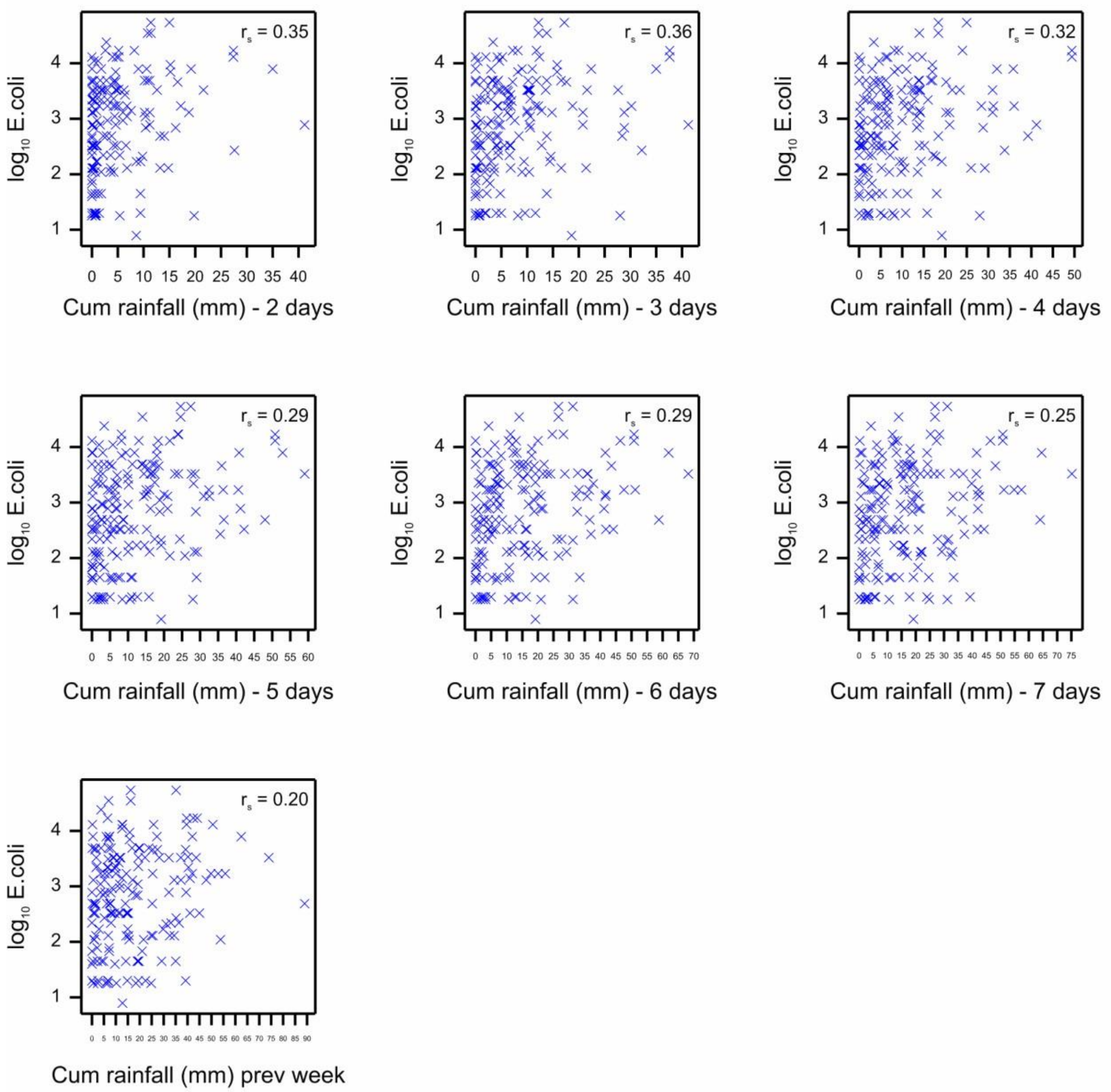


**Figure 8: Relationship between levels of *E. coli* (log10-transformed MPN *E. coli*) in mussels from B4 and cumulative rainfall calculated for a week before mussel sampling and the preceding seven days with Spearman's rank correlation coefficient ($r_s$) indicated.**

### 1.4.3 Log10 *E. coli* Summary statistics

The summary statistics for Log10 *E. coli* results in the mussel flesh sampled from site B4 recorded between March 2016 and the March 2019 are presented in Figure 9, the seasonality showed a high degree of inter-annual variation. This illustrates that seasonality is a factor affecting *E. coli* concentrations in mussel flesh, mussel age / size and health will also be contributing factors.

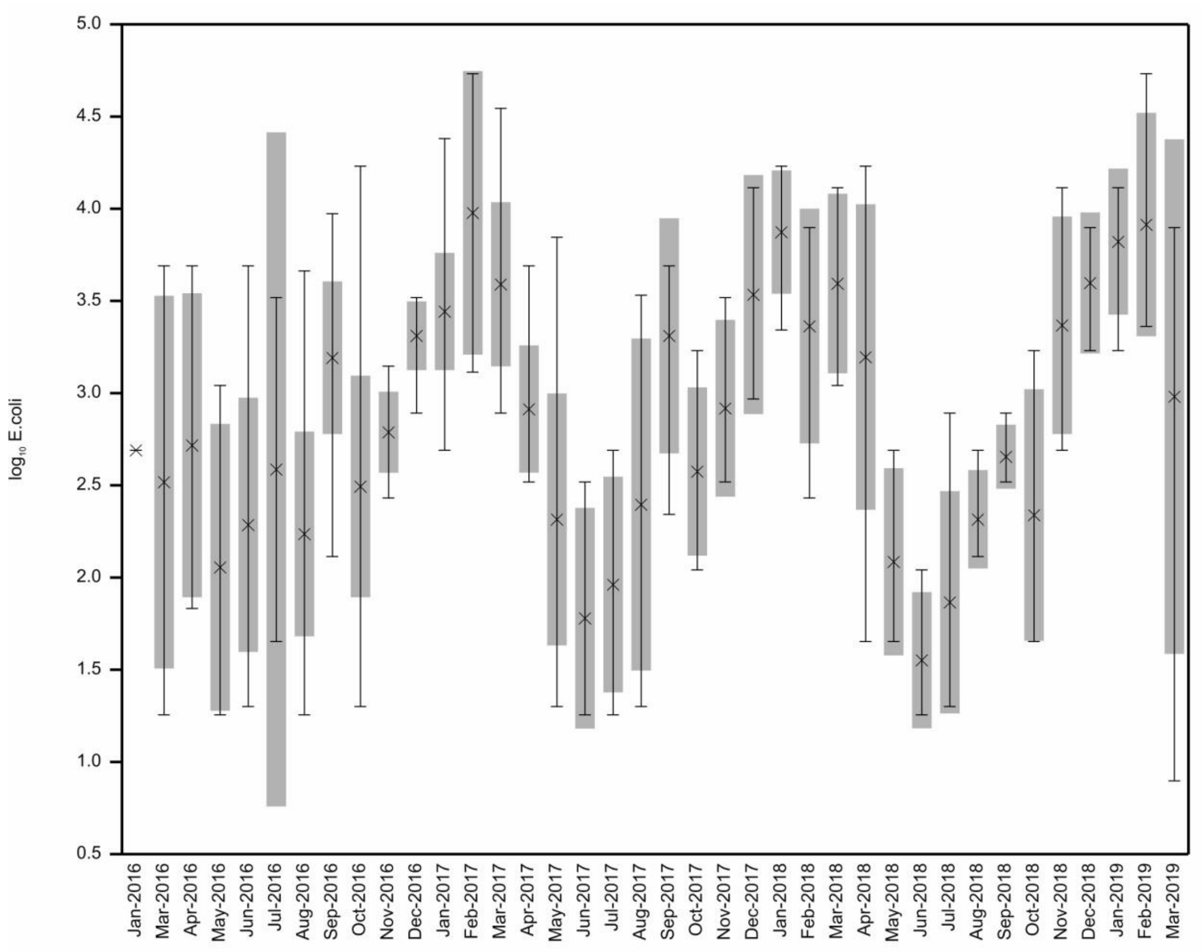


**Figure 9: Summary of Log10 *E. coli* results reported in Mussel flesh from B4, by month from March 2016 to March 2019 showing seasonality (x is the mean and the shaded box is the 95% confidence interval with the tails showing the minimum and maximum values).**

## 1.5 Discussion

Recent studies have examined the spatial and temporal variation of faecal indicator organisms (FIOs) within single intertidal mussel beds, confirming that FIO concentrations across a shellfish bed were heterogeneous over larger spatial and temporal scales (Clements 2015). The accepted FIO at present is *E. coli*. Analysis of the *E. coli* results in this study, show high spatial and temporal heterogeneity within small areas of Belfast Lough, it is therefore only possible to compare results collected during the same sample runs. This has reduced the size of the dataset available to work with and the analyses discussed in this study focus mainly on the B4 dataset.

### 1.5.1 State of the Tide

Overall there is a positive correlation between spring tides and bacterial load (Figure 6, Table 4) of the FBO's own sample results from B4. Practical limitations in the contracted sample collector's programme have resulted in the majority of samples being collected on Spring Flood tides and Ebb Neap tides. The largest number of mussel samples analysed as category C were collected under Spring Flood conditions.

### 1.5.2 Rainfall

Rainfall data recorded at a digital gauge at Newforge Lane was collated and correlated with the log10-transformed *E. coli* data from the B4 site. Significant positive correlation was observed between log10-transformed *E. coli* and rainfall recorded the day before mussel sampling ($p < 0.001$), less significant correlations were observed for rainfall on the day of sample collection and 2 days before sample collection ($p < 0.01$) (Figure 7, Table 4). Therefore, it is not a simple relationship between single rainfall events and more than one rainfall event must be considered when looking at changes in *E. coli* counts. It is important to note that the amounts of rainfall shown to correspond with high *E. coli* counts is low and can depend on the preceding days rainfall. The effect of cumulative rainfall was also investigated. A higher number of positive relationships was found for cumulative rainfall, when mussel sampling was undertaken 2, 3, 4, 5, 6 and 7 days after the rainfall event. This finding suggests the complexity of rainfall events and the knock-on effect within the catchment, hence the requirement for detailed catchment ecosystem /hydrological modelling. This is reflected in current AFBI FAEB studies in Lough Foyle, Carlingford and most developed for the Inner Dundrum bay catchment described in Section 4 for this report.

Kay *et al*. 2008, work on faecal indicator organism (FIO) concentrations and catchment export coefficients in the UK showed significant elevations at high flow compared with base flow, with concentrations increasing by more than an order of magnitude and export coefficients by about two orders. This study also found significantly higher values in summer than in winter under high-flow concentrations and high variability between catchments, which closely reflects land use – with urban areas and improved pastures identified as key FIO sources (Kay *et al*. 2008). This reflects a combination of two factors. First, increased numbers of organisms entering the water courses at high flow, as a result of increased surface runoff, extension of stream networks into contributing areas and entrainment of FIO's from stream bed sources. The second factor is the increased water depth, velocity and turbidity under high flow conditions reduce the chances of FIO die-off and sedimentation along water courses (Kay *et al*. 2008).

### 1.5.3 Summary

Statistical analysis (AFBI Biometrics) resulted in positive correlations between log10-transformed *E. coli* and the % Spring tides on date of collection and with daily / cumulative rainfall. The strongest correlation was with rainfall on the day before mussel sample collection. It is clear from the statistical analysis that rainfall and the state of the tide have a combined effect and that both factors must be considered in any future adaptive management of shellfish beds, should this be adopted.

There are a number of factors not looked at in this study that must be considered in further work including: river flow, diffuse pollution such as those coming from; agriculture, foul sewer misconnections to surface water sewers and watercourses, contamination washed from pavements and beaches, faecal matter from birds, bacteria from waste water treatment work final effluent and storm tank discharges. The latter may lead to the deposition of bacteria contaminated material on the shore line. This contaminated material may be re-suspended on high tides and deposited over the shellfish beds. There is evidence in the literature to support the theory that contaminated material can be re-suspended and deposited on shellfish beds (Clements *et al.* 2015). This research is from intertidal beds but it is possible that this could be a contributing factor within Belfast Lough sub-tidal aquaculture sites. Such an effect may be exacerbated on a Spring flood tide, where high water would reach areas around CSOs and re-suspend material. Correlations do not imply cause and effect but there is sufficient evidence at this stage to suggest that rainfall events compounded by tidal state are the prime drivers in shellfish classification failures for Belfast Lough. River inputs especially in flushes have been recorded to re-suspend contaminated material in river channel beds that could be flushed out over shellfish beds (Wilkinson *et al.* 2006). This could be exacerbated by certain tidal conditions. It is also possible that pulse effects associated with the operation of the Lagan Weir could have a major impact and requires investigation.

## 1.6 Conclusions

Initial conclusions are based on analysis using the best available data, however this data was not collected specifically for the purpose of this study. Data gaps include: lack of *E. coli* profiles during an entire tidal cycle; no analysis of river flow data and updated catchment land use data was not available. These shortfalls will be addressed in Phase I and III in association with the ongoing AFBI work area in the Living with Water Programme (Section 3). The results from Belfast lough to date provide evidence of small scale spatial and temporal variation in *E. coli* results within inner Belfast Lough. Current RMP positions are not adequate to show this fine scale variation; significant relationships between daily / cumulative rainfall and Log10 transformed *E. coli* counts were observed. The variation in lag time is assumed to result from catchment topography and geology determining peak levels of runoff into the Lough, these factors are investigated using an integrated catchment ecosystem modelling approach, currently being developed in AFBI, in collaboration with DAERA. An example of this work is detailed in Section 4 for Dundrum Bay, the underlying principles of this integrated model framework is currently being rolled out for other NI catchments, including Belfast (LWWP, Section 3); the state of the tide at the time of mussel sample collection has been shown to have an effect on the *E. coli* counts recorded in the mussels and whilst additional data and a robust cause and effect study are required to imply causality to the high *E. coli* counts observed in Belfast Lough, there is evidence at this stage that rainfall events compounded by tidal state are prime drivers in shellfish classification failures for Belfast Lough (proposed for DASSHH Phase II and III). A number of these concerns will be addressed in Phase II and III of the DASSHH project in conjunction with the work planned for LWWP, see Section 3.

# Section 2 Preliminary study of the dispersion of coliform bacteria in Belfast Lough

## 2.1 Hydrodynamics

Belfast Lough has a spatially-varying flushing time which can be of the order of days for the outer lough and up to a few weeks for the inner lough. Although tidal action accounts for most of the transport in the lough, the amount of lough water returned over the flood and ebb will depend on the conditions at the shelf. At the inner lough, the modulation of freshwater input with tidal stirring will condition the amount of transient estuarine circulation, thus determining flushing times there. The full representation of these processes requires the use of a 3-dimensional hydrodynamic model that fully describes the salinity and temperature fields, both inside the lough and at the neighbouring shelf, and their interaction with tidal and atmospheric forcing.

## 2.2 Modelling tools

AFBI currently holds a Delft3D-Flow setup for Belfast Lough produced for the SPRES project by IH Cantabria. This model setup was previously used for the simulation of bacteria dispersion in an initial study, and has gone through the calibration and validation stages before production. Hydrodynamic modellers from Longline Environment Ltd (LLE) in agreement with AFBI chose to use this as base for building the *E. coli* dispersion and decay model. This model was used in an exploratory study of the dispersion of coliform bacteria in Belfast lough carried out at the end on 2018, information from this technical report are included here. The models used contain significant simplifications while describing physical and biological processes, forcing the hydrodynamics only with the tide and bundling all of the decay processes into a single time dependent first order decay with a T90 of 2.9 days. Hence, these results should be viewed as a comparative analysis of the spatial distribution of exposure to a set threshold of coliform bacteria and not taken as absolute values. Further work is planned under LWWP to include in the modelling strategy river inputs, density driven flow, atmospheric forcing and coliform decay dependency on temperature, salinity and the light environment.

The hydrodynamic model has a maximum cell size of 2000 m at the outer cells near the ocean boundary and a minimum cell size of 20 m at the inner lough with a total of 222 x 61 cells and 5 vertical, terrain-following sigma layers. It is forced at the ocean boundary by the IBI (Iberian Biscay Irish) model, a MyOcean consortium model run by Puertos del Estado and using the NEMO platform. The Delft3D-WAQ model was used for dispersion and decay of coliform bacteria. The model takes into account a first order decay equation for coliform bacteria as a function of time, temperature, salinity, and ultraviolet light. At the stage of this report AFBI did not possess a validated coliform dispersion model, therefore only the time dependent function was used, bundling all of the other dependencies into this parameter. For the exploratory exercise a conservative decay of rate of 0.8 d-1 was used equivalent to a T90 of 2.9 days.

The products from the exploratory study provided a comparative analysis of the relative distributions in time and space of the several discharge options. Due to the simplifications made in the modelling approach, these results should not be taken as absolute values or be compared against regulatory thresholds.

## 2.3 Scenarios

A number of scenarios were run for the exploratory report the scenario presented here shows the status quo conditions in Belfast lough at present. The scenario assumed constant discharge from well-established point sources. In this case, the model allowed for 1 month adjustment of the *E. coli* concentration inside the lough before the start of the calculation to eliminate transient patterns at the start of operations.

In order to assure numeric stability, the hydrodynamic model was run for 3 months: 1 month for the hydrodynamic spin-up, 1 month for *E. coli* concentration adjustment and 1 month for the calculation of the dispersion patterns. Table 5 lists the loadings and flows associated with each location.

**Table 5 Flows and *E.coli* concentrations for each of the outfalls by scenario number**

| Option | Belfast | | Kinnegar | | Whitehouse | | Greenisland | | Carrickfergus | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Flow (m3.d-1) | *E. coli* conc. (cfu/100mL) | Flow (m3.d-1) | *E. coli* conc. (cfu/100mL) | Flow (m3.d- 1) | *E. coli* conc. (cfu/100mL) | Flow (m3.d-1) | *E. coli* conc. (cfu/100mL) | Flow (m3.d-1) | *E. coli* conc. (cfu/100mL) |
| 1 | 316200 | 12500 | 77000 | 12500 | 68986 | 19500 | 9500 | 14000 | 28250 | 10500 |

## 2.4 Results

Figures 10 and 11 illustrate two discharge scenarios with the distribution of coliform bacteria depending on the emission scenario. The maps depict the spatial distribution of the empirical probability to exceed a set threshold. Usually this threshold can be defined as a fraction of the end-of-pipe *E. coli* concentration or a regulatory compliance. This allowed plotting of exposure risk (frequency) and spatial footprint on a single map. In this particular case, two thresholds were chosen: 230 cfu/mL was chosen as a regulatory limit; and 50 cfu/mL where the differences in the footprint between each options are more clearly seen. The model was run over 2 neap-spring cycles (~1 month) for the adjustment of the lough water to the continuous discharge of wastewater and another 2 neap-spring cycles for the calculation of the empirical probability. Therefore, the results are representative of the range of response to tidal forcing under continuous discharge.

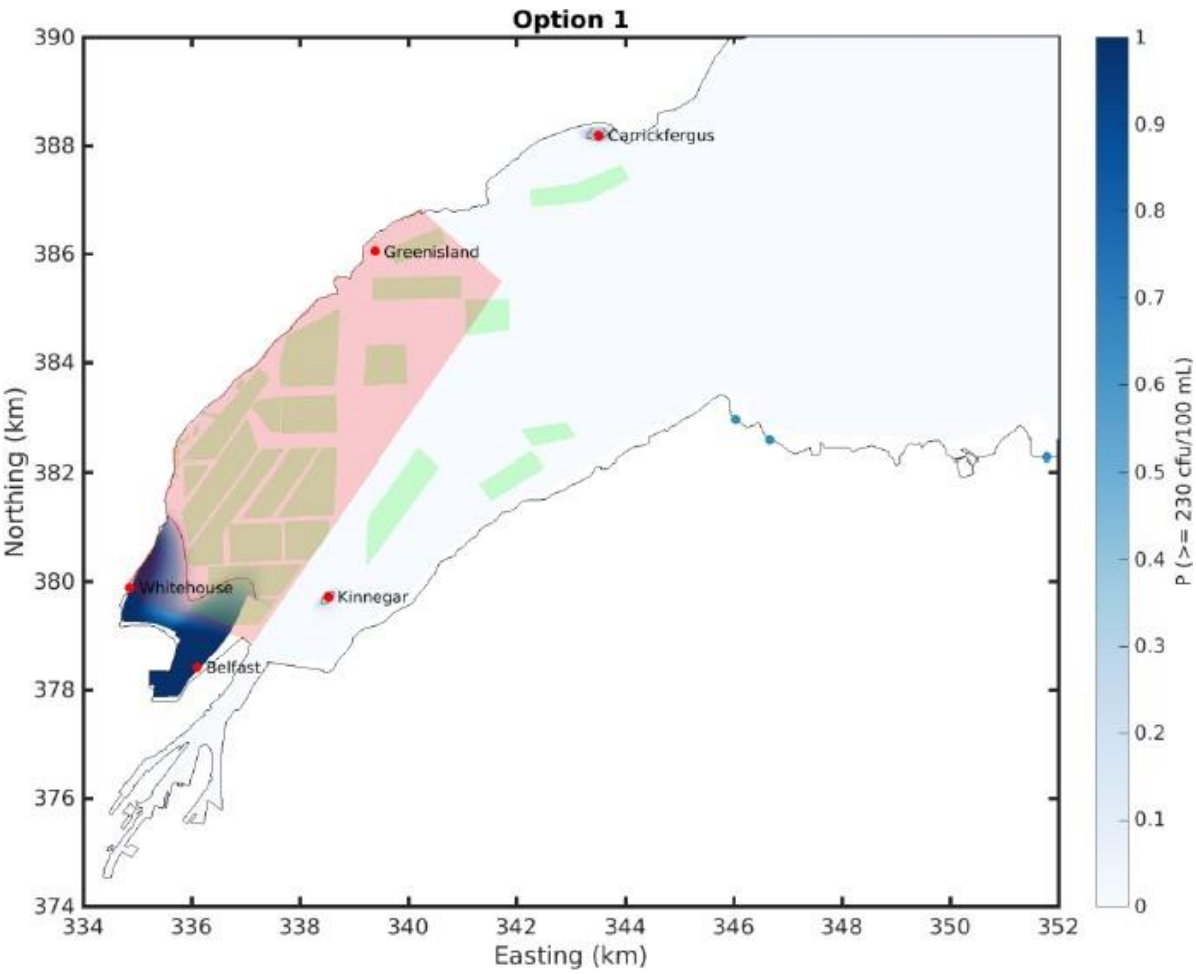


**Figure 10: The probability to exceed 230 CFU/100ml for the base line scenario: 75 % of compliance (red-line), discharge locations (red-dots), aquaculture sites (green areas), shellfish waters (pink area), bathing waters (blue dots).**

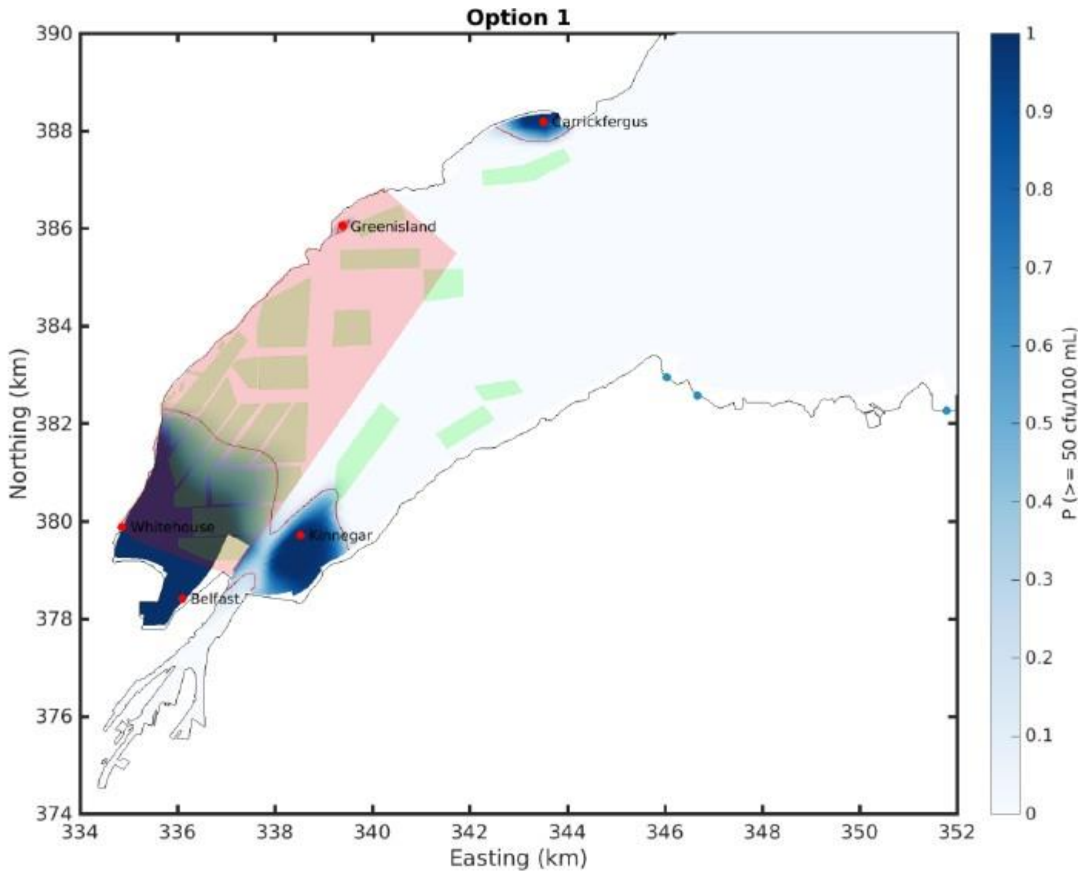


**Figure 11: The probability to exceed 50 cfu/100 mL for the base line scenario: 75 % of compliance (red-line), discharge locations (red-dots), aquaculture sites (green areas), shellfish waters (red area), bathing waters (blue dots).**

## Section 3 Phase II and III monitoring with some preliminary results

### 3.1.1. Routine coliform monitoring of shellfish beds

Data used to progress DASSHH Phase II work utilised samples collected during the Living with Water Programme (LWWP). As part of the LWWP, AFBI are collecting shellfish every two weeks, over a 10 month period, the shellfish flesh is analysed for *E. coli*. Samples will be collected at each of the Representative Monitoring Points (RMPs) (Figure 4), this will enhance the routine FSA monitoring programme. The FSANI is responsible for ongoing monitoring of Shellfish Hygiene throughout the province and some long-term data is available.

### 3.1.2. River Flow Measurements

Flow data at a 15 minute time step from existing gauges deployed throughout the catchment (Figure 12) operated by the Department of Infrastructure (DfI) have been obtained for the Belfast Lough catchment. To increase spatial coverage LWWP will deploy an additional 12 hydrometric gauges throughout the catchment as shown Figure 13.

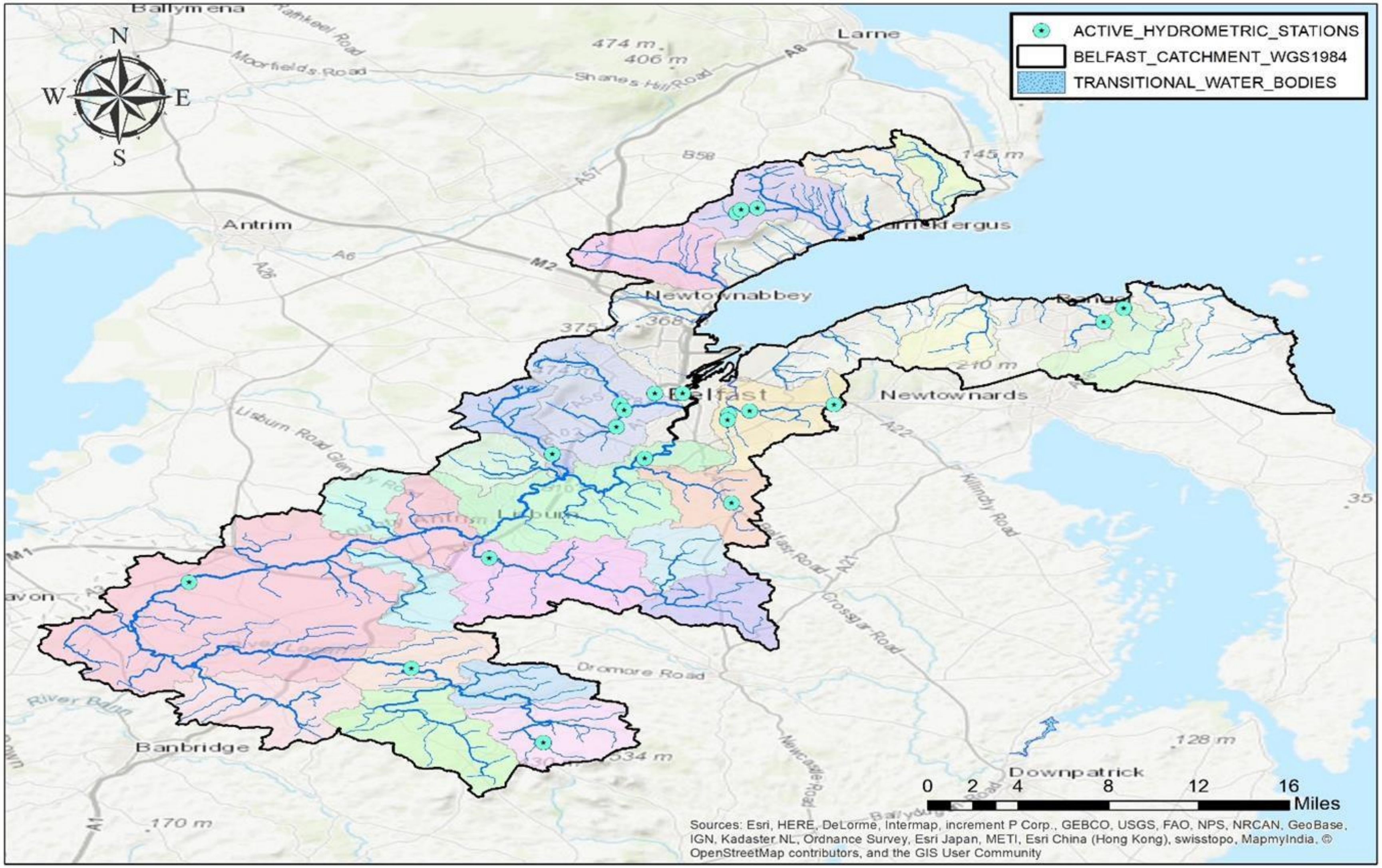


**Figure 12: Active hydrometric stations within the Belfast Lough catchment operated by Department of Infrastructure (DfI)**

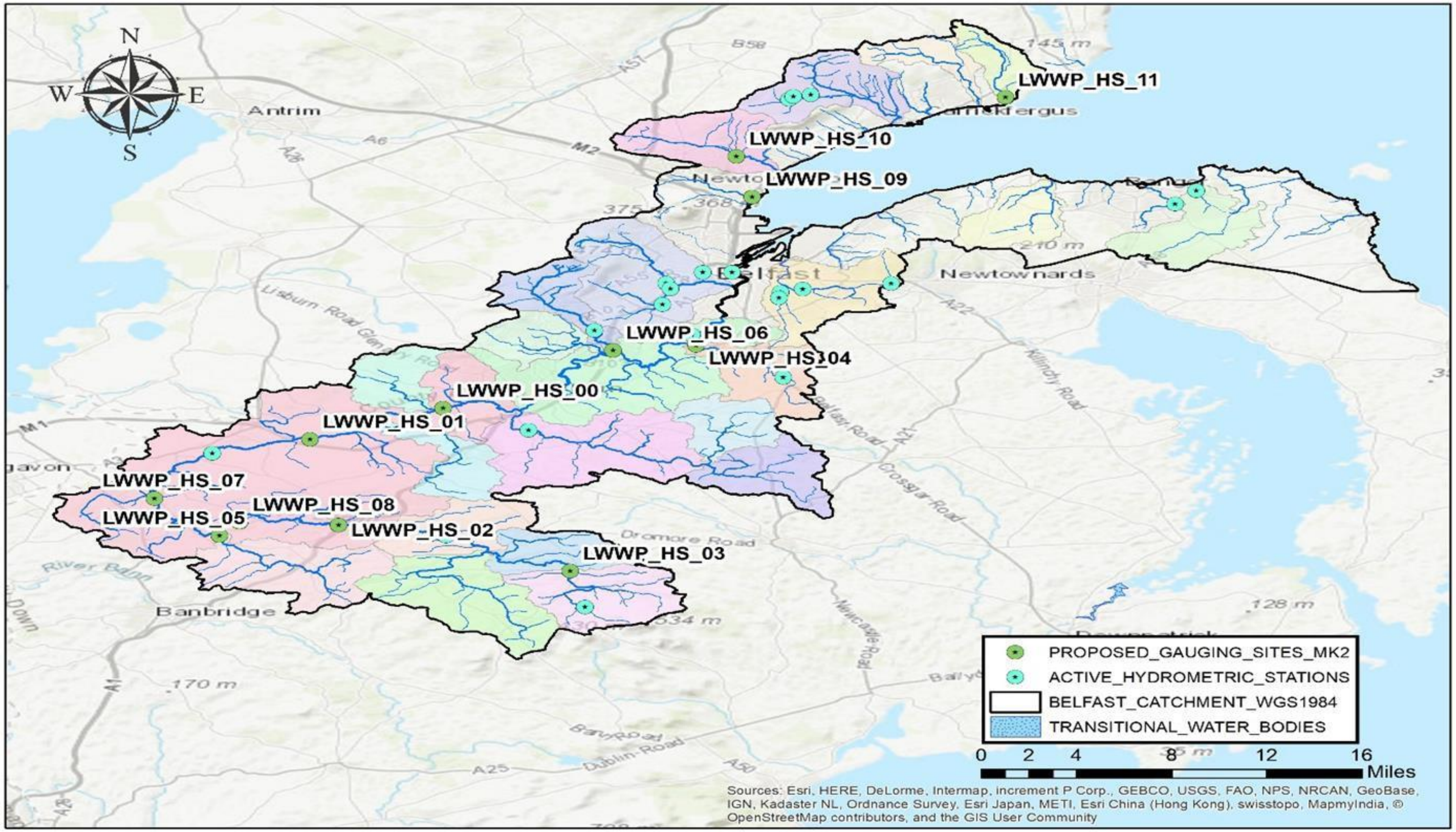


**Figure 13: Hydrometric stations to be deployed as part of LWWP along with existing hydrometric stations**

"Flashiness" of catchments is recognised as another parameter impacting contributing sources of contamination, investigations have started to collate rainfall and river flow data to explore this impact. Figure 14 compares rainfall data collected at AFBI Newforge Lane to flow from four hydrometric stations throughout the River Lagan. Dromara is at the top of the catchment, Feney mid catchment and Newforge is at the lower end of the catchment above Stranmillis Weir and Cutters Wharf is in the impounded Lagan between Stranmillis and Lagan Weirs.

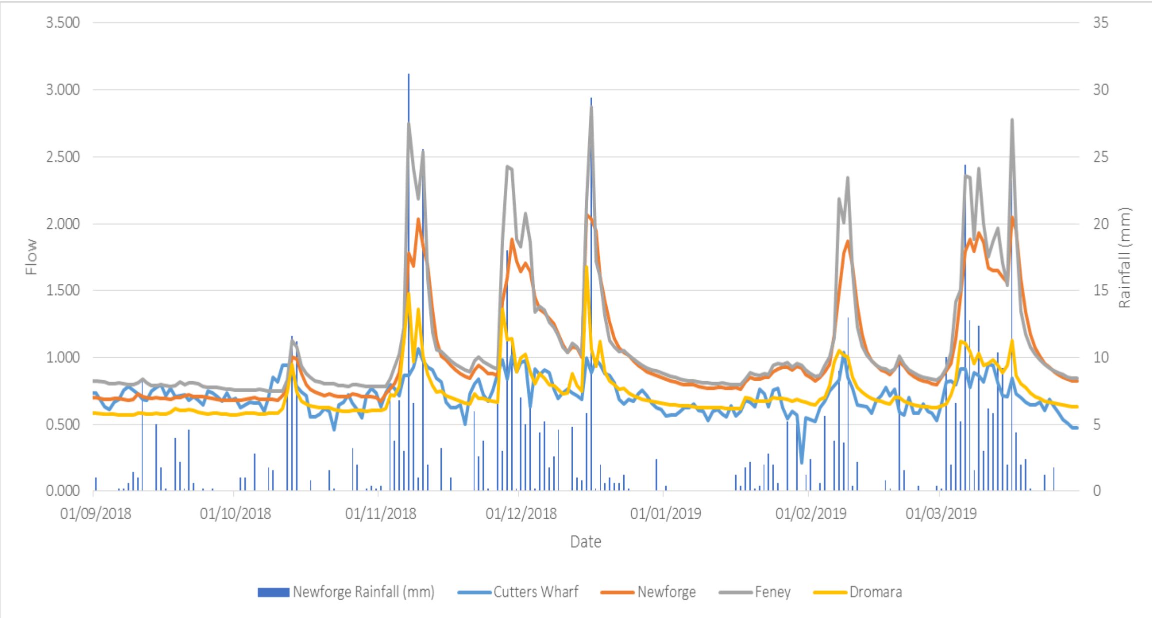


**Figure 14: Graph showing rainfall compared to flow at four locations throughout the catchment**

### 3.1.3. Monthly water quality data

Since October 2018 LWWP has collected samples 1 m below the surface and 1 m above the seabed every two weeks across 22 sites in Belfast Lough (Figure 15). During April and May samples are collected on a weekly basis. Samples are analysed for nutrients (Ammonia, Nitrite, Inorganic Nitrogen, Silica and Phosphate), Chl a, Suspended solids (SPM) and C:N. CTD profiles are collected at each site. At 16 of the sites (excluding sites in outer Lough) top and bottom samples are collected for *E. coli* and Intestinal Enterococcus analysis.

Three sites are sampled in a section of the River Lagan which is impounded between the Lagan and Stranmillis Weirs (Figure 16). Stratification is significant in the section of the river with monitoring equipment showing the river bed to be anoxic. Samples are collected on the same schedule as the marine monitoring from the surface and the riverbed. Samples are analysed for nutrients and bacteria.

AFBI holds historical water chemistry data and CTD casts for Belfast Lough from 1985. Moored instruments in Belfast Lough and the impounded Lagan have provided AFBI with data on temperature, conductivity, dissolved oxygen, fluorescence and turbidity from 1995.

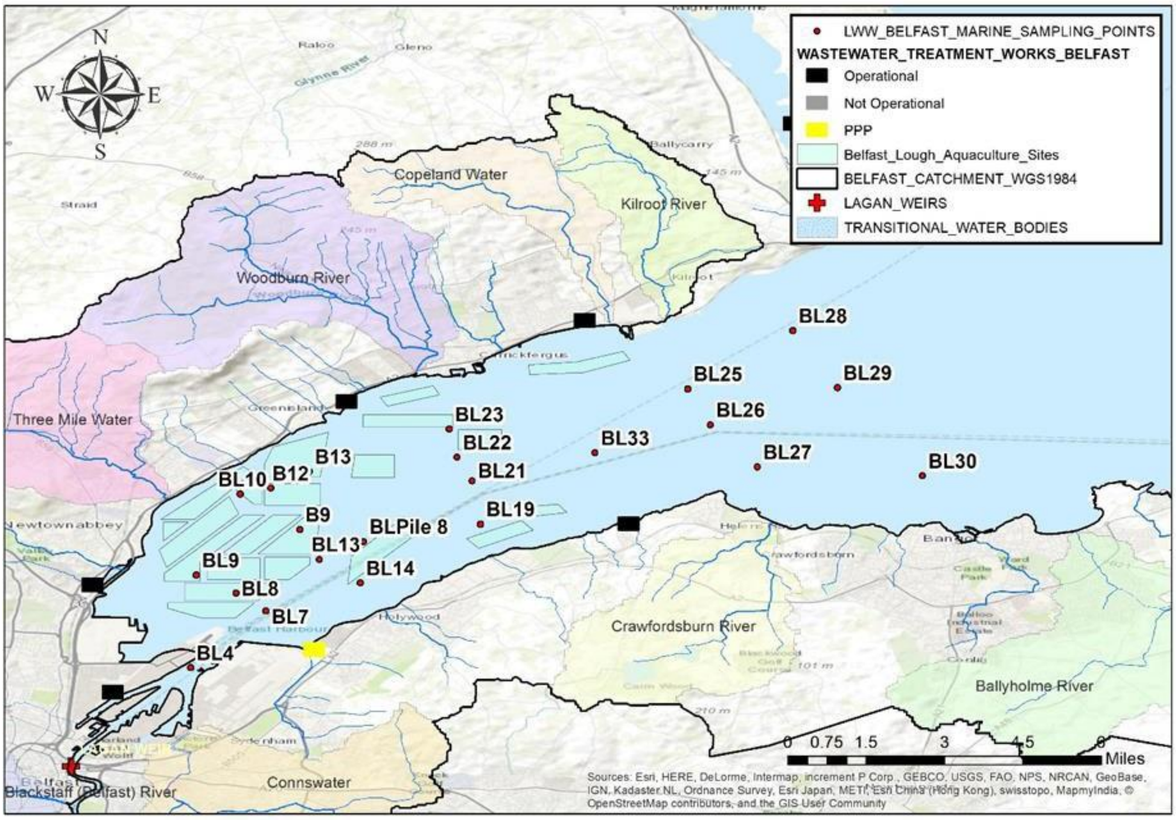


**Figure 15: Sampling sites in Belfast Lough along with designated aquaculture sites. Samples collected BL25 to BL30 are excluded from microbial analysis.**

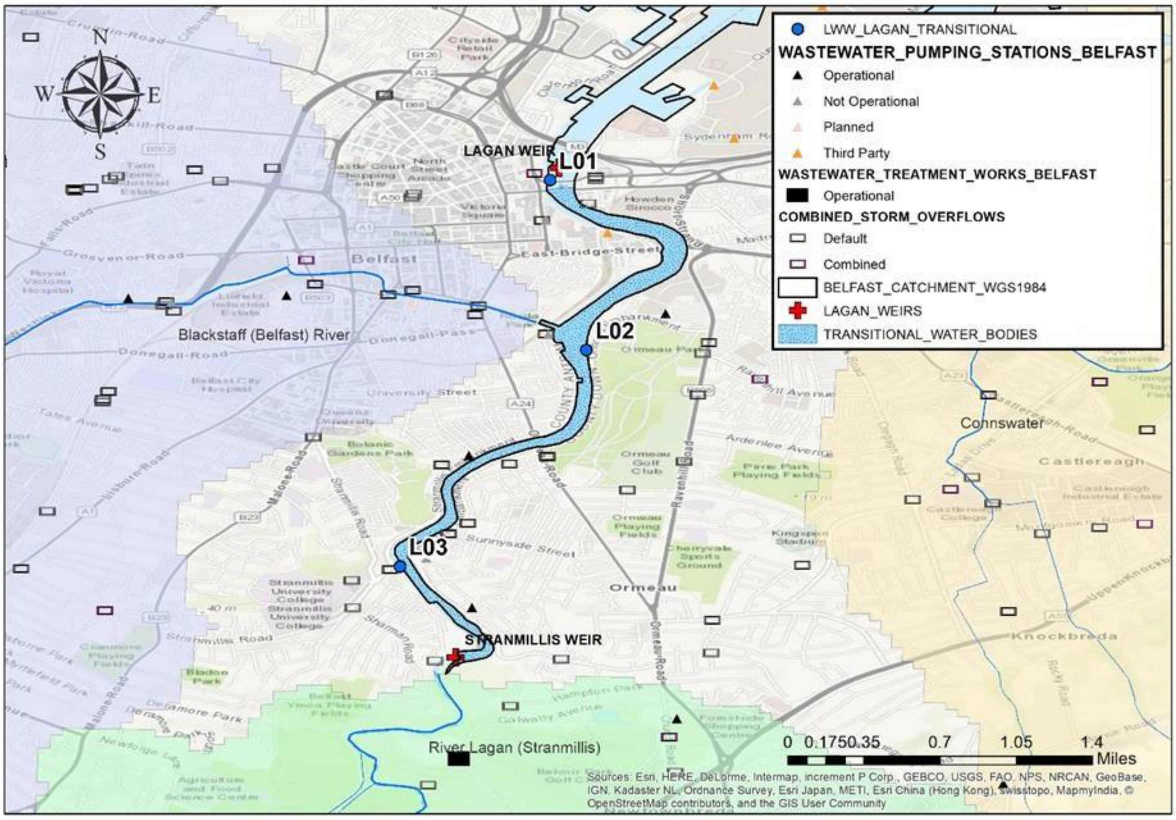


**Figure 16: Sampling sites in the impounded Lagan between Lagan and Stranmillis Weirs.**

### 3.1.4. Water quality monitoring in the catchment

Sampling across 56 river sites was initiated in February 2019 (Figure 17) and is divided into three groups consisting of the River Lagan catchment, Belfast Lough streams and Belfast urban streams. Samples are collected every two weeks and analysed for nutrients and bacteria.

A number of Wastewater Treatment Works (WWTWs) have been selected for routine sampling (Figure 18) with collection due to begin in June 2019. Samples will be collected from the final effluent outflow.

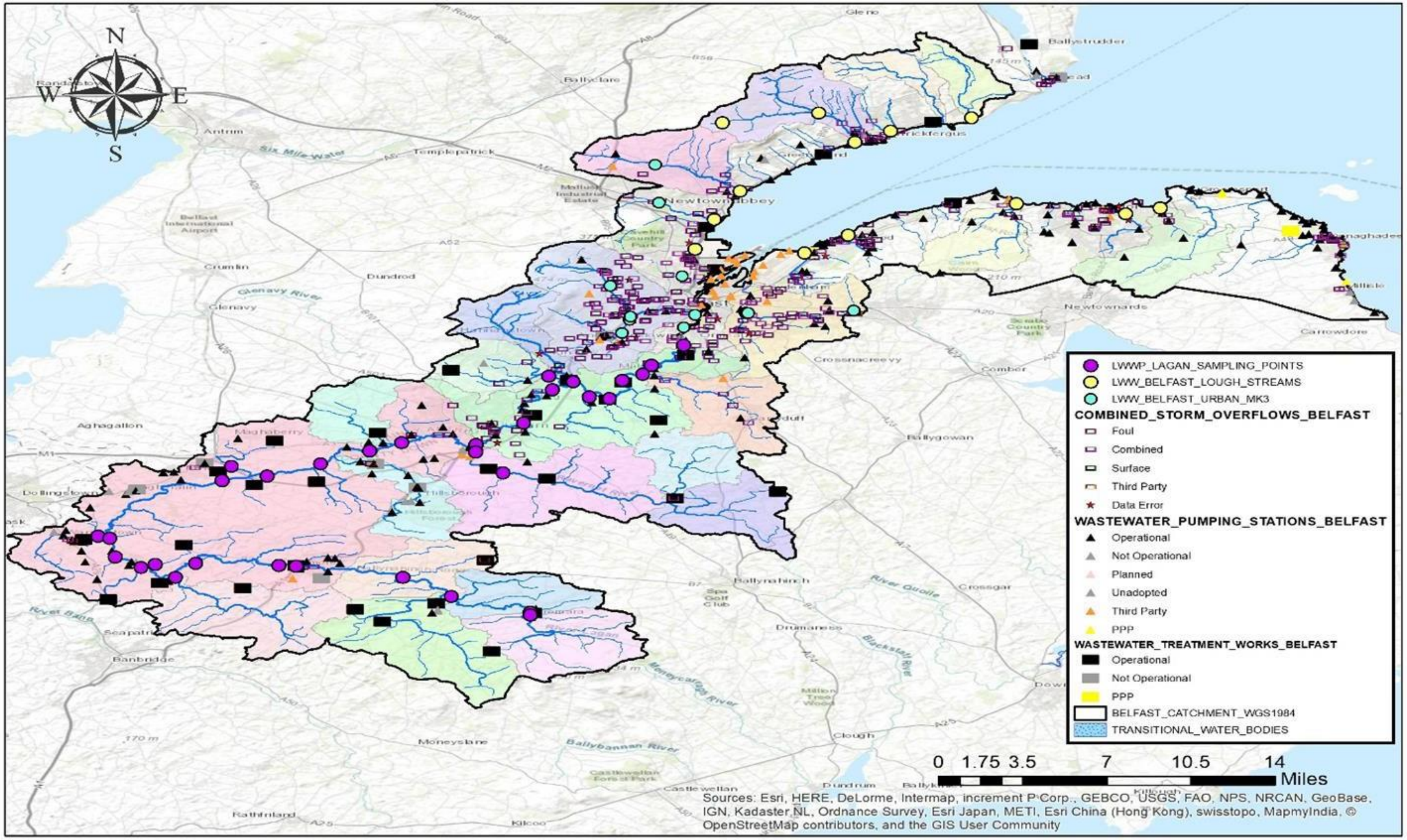


**Figure 17: Freshwater sampling sites as part of routine monitoring for LWWP**

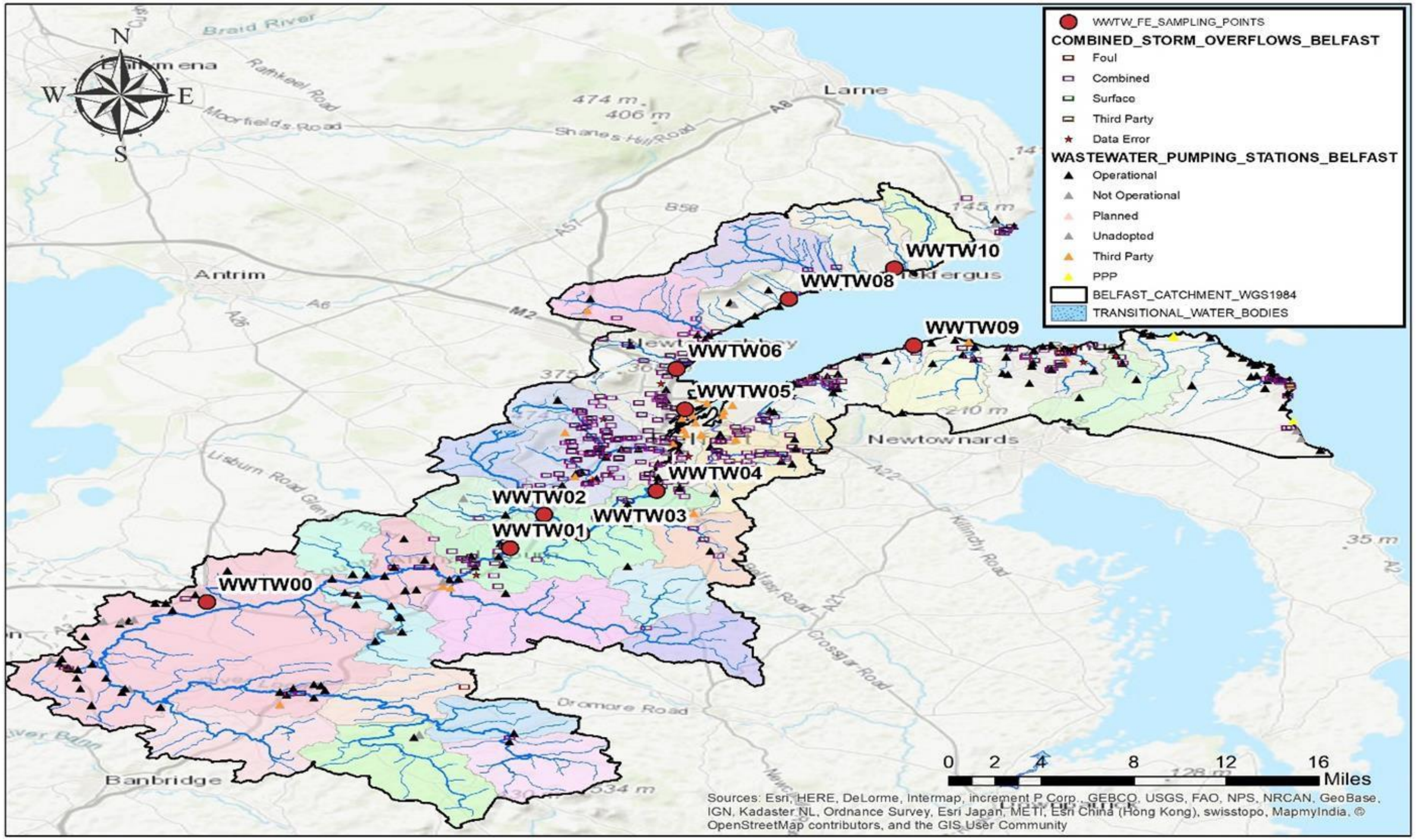


**Figure 18: WWTWs sampling locations along with CSOs and pumping stations in the Belfast Lough catchment**

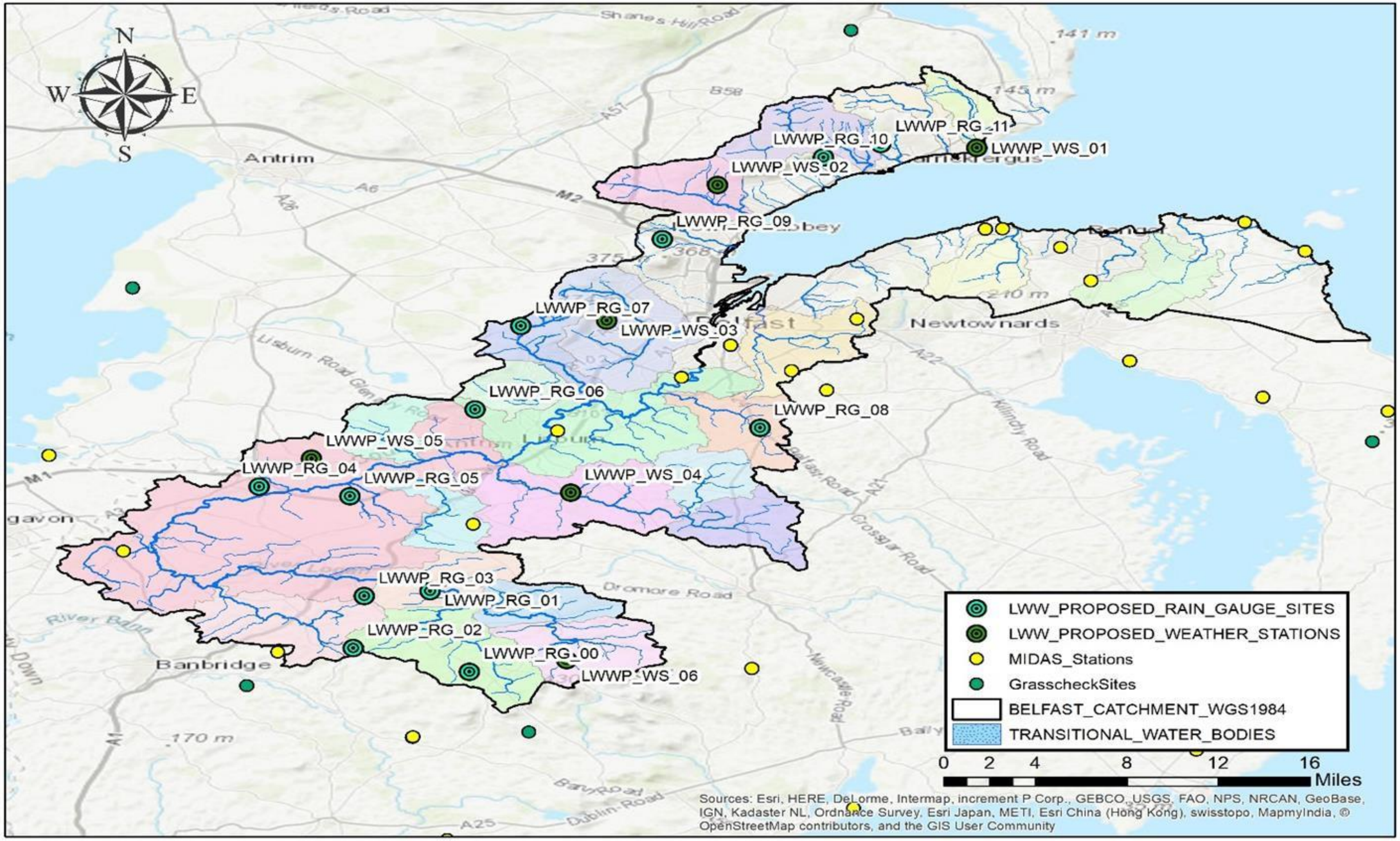


**Figure 19: Locations of meteorological stations and rain gauges**

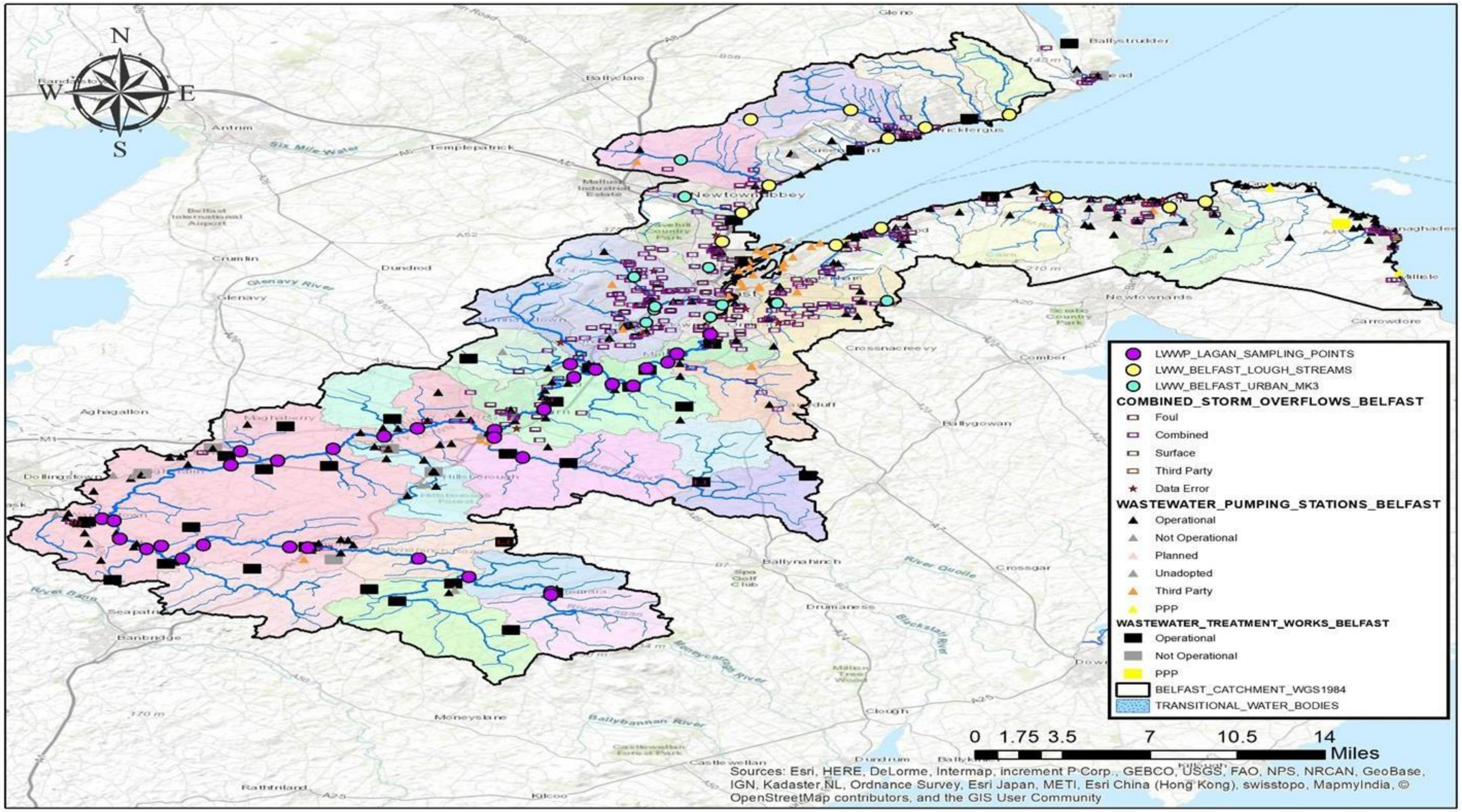


**Figure 20: Locations of WWTWs, CSOs and pumping stations throughout the Belfast Lough catchment**

### 3.1.5. Meteorological Data

In addition to accessing data from an instrument deployed on BL Pile 8 in Belfast Lough and data from CEH, LWWP will deploy six Davis Vantage Pro Meteorological stations and 12 tipping bucket rain gauges throughout the catchment (Figure 19). All of these instruments have telemetry to provide updated data. Rain gauges are also held at Newforge Land and Sydenham which will provide additional data. AFBI holds a 10-year data set of rainfall radar data, whilst Northern Ireland Water (NIW) have access to live rainfall radar which will be utilised.

### 3.1.6. Locations of WWTWs and CSOs in the catchment

Figure 20 shows the locations of WWTWs, CSOs and pumping stations throughout the Belfast Lough catchment and proximity to freshwater sampling locations. Information on the level of treatment, and population equivalent for WWTWs has been provided by NIW (Table 6). Locations of WWTW outlets are shown in Figure 10. Primary treatment removes material the will either float or readily settle out by gravity and uses physical processes such as screening, comminution, grit removal and sedimentation. Secondary treatment is a treatment process to achieve a certain degree of effluent quality by using sewage treatment plants with a physical phase to remove solids and a biological phase to remove dissolved and suspended organic compounds. The works listed in Table 6 use aeration lanes which is an activated sludge process based on pumping air into a tank, promoting microbial growth in the wastewater. Microbes then feed on organic matter and form flocks which easily settle out.

**Table 6: Levels of treatment work at WWTWs throughout the Belfast Lough catchment**

| Works | PE | Treatment level |
|---|---|---|
| Seahill | | Primary and Secondary |
| Kinnegar | 126,655 | Primary and Secondary |
| Belfast | 315,930 | Primary and Secondary |
| Newtownbreda | 31,512 | Primary and Secondary |
| Dunmurry | 429,922 | Primary and Secondary |
| Lisburn | 61,032 | Primary and Secondary |
| Drumbeg | | Primary and Secondary |
| Carrickfergus | 32,070 | Primary and Secondary |
| Greenisland | 10,425 | Secondary |
| Whitehouse | 80,922 | Primary and Secondary |
| Moira | 5,707 | Primary, Secondary and Tertiary |

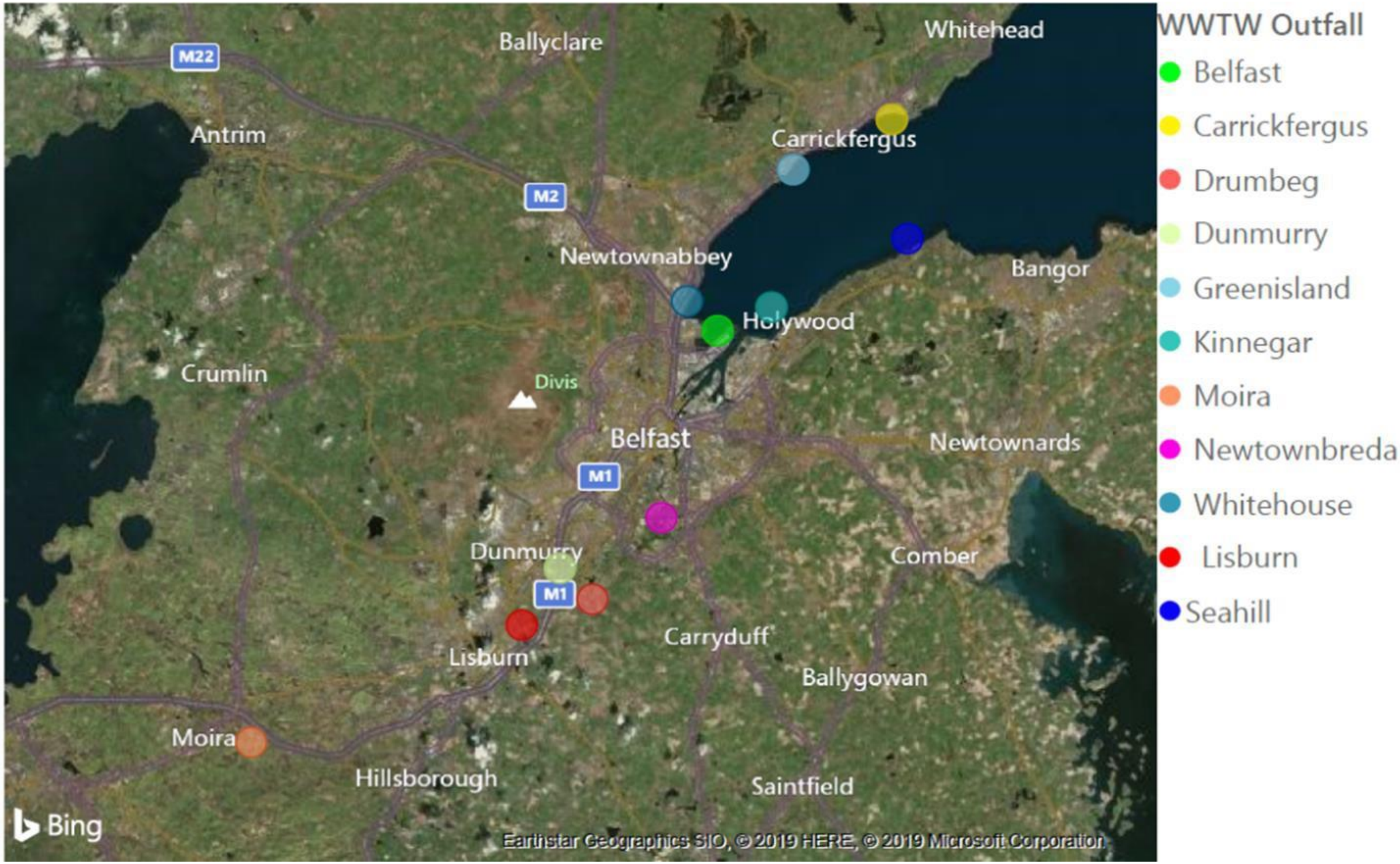


**Figure 21: Locations of WWTW outfalls in the Belfast Lough catchment**

### 3.1.8. Marine monitoring and Tidal Lagan buoy

BL Pile 8 is an instrumented mooring operated by AFBI since 1995. The mooring monitors a number of parameters including; conductivity, temperature, dissolved oxygen, fluorescence and turbidity. This multi parameter monitoring device runs 24\7 with power coming from both internal batteries and solar panels. Real time readings can be accessed and interpreted remotely as it has built in telemetry. This data will be used in conjunction with the tide data AFBI also maintain a Tidal Lagan Buoy, which has been in operation for over 10 years, it measures typically CTD, fluorescence and dissolved oxygen. This is solely an AFBI asset that has been deployed in this area to understand the how fresh water and salt water interact with each other and the affect it has on water quality. It has a built in power source with solar panels to compliment this, the device offers real time telemetry allowing trends to be analysed remotely.

### 3.1.9. Bathymetry data

Most recent bathymetry used in updated SMILE model for Belfast Lough, this was updated during the SPRES project to add a finer grid structure in the Inner Belfast Lough area. Additional satellite derived bathymetry is scheduled for shallow areas of Belfast Lough as part of LWWP.

### 3.1.10. Land cover map for the catchment

Soils – NI 1:50 k soil map and CORINE Landuse (2012 available, seeking access to 2018) will be used in the SWAT model, please see Section 4 for more detail from the Dundrum ecosystem example.

## 3.2 Preliminary findings in Belfast Lough

Figure 22 shows the inversely proportional relationship between Dissolved Inorganic Nitrogen (DIN) and Chlorophyll a at four sites across Belfast Lough. Levels of Chlorophyll a are relatively low over the winter months. A peak in chlorophyll is evident in early April as temperatures increase with a secondary peak following in early May as DIN is utilised in the Lough. Figure 23 is a map which proportionally represents *E. coli* concentrations in the impounded River Lagan and across Belfast Lough following one sampling event. The impounded Lagan is showing high concentrations of *E. coli* which is consistent across all samples collected during the survey period. There are a number of urban rivers which drain into this impounded section of river which could be contributing to the elevated concentrations in this area. These high concentrations are not reflected in the samples collected in Belfast

Lough which are all relatively low. One site which has elevated *E. coli* concentrations is BL14 which is believed to be as a result of hydrodynamics within the lough which circulates in that area, close to a number of WWTW outfalls.

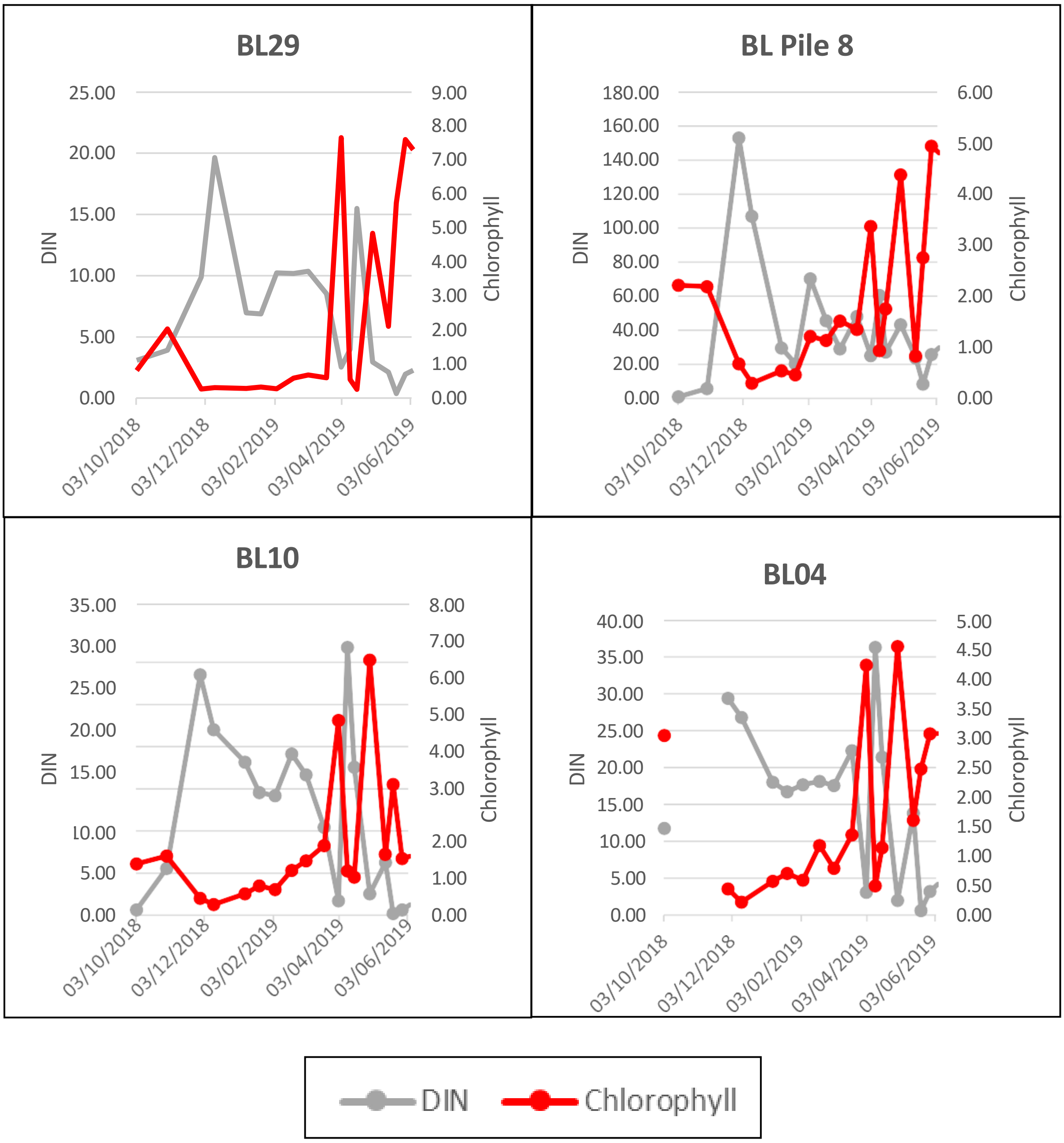


**Figure 22: DIN versus chlorophyll at four locations across Belfast Lough between October 2018 and June 2019. BL29 – outer Lough, BL Pile 8 – mid Lough, BL10 – aquaculture beds, BL04 – harbour inner Lough.**

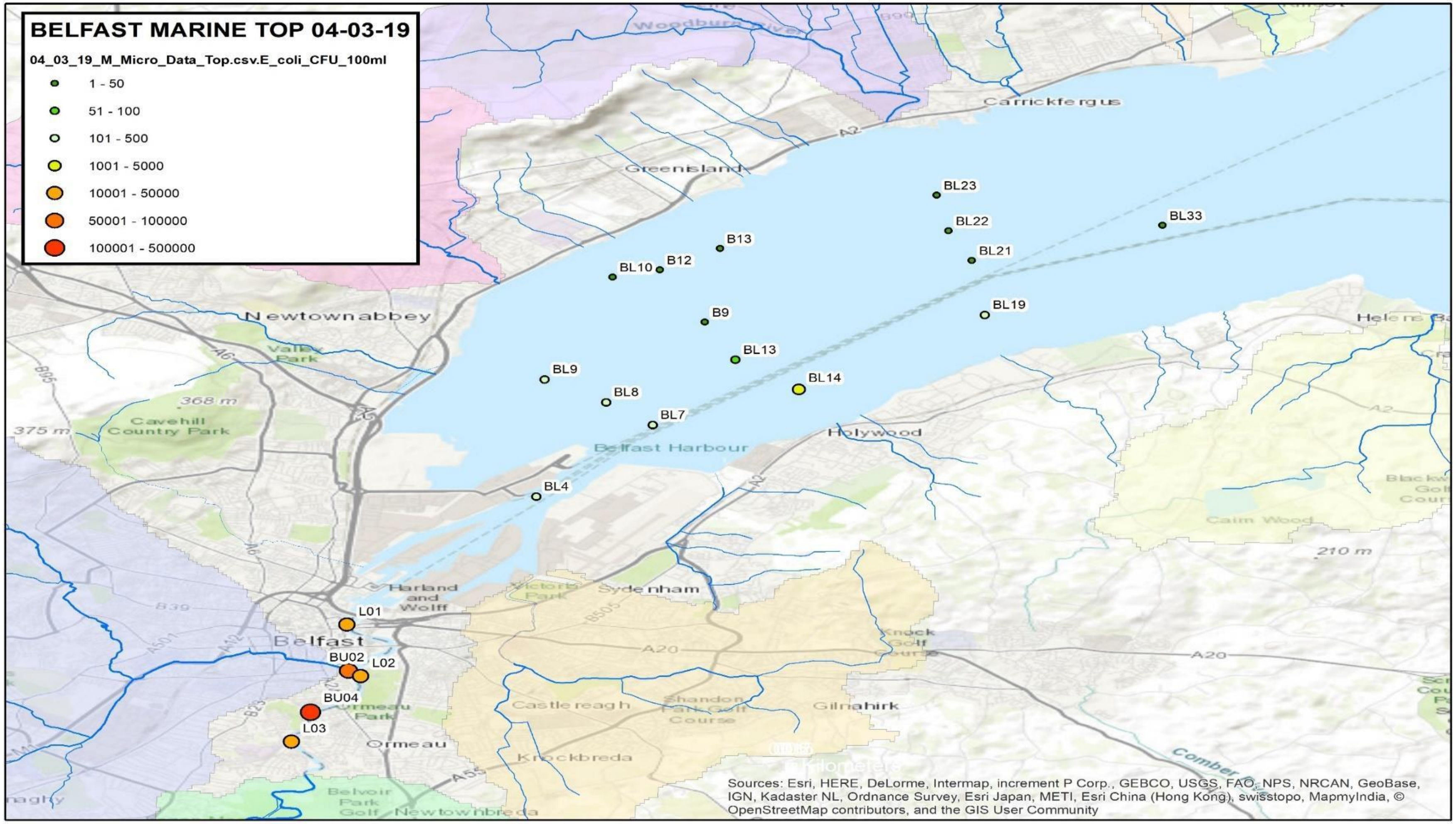


**Figure 23:** ***E. coli*** **concentrations in Belfast Lough and the impounded Lagan during a single sampling period in early March.**

## 3.3 Discussion of preliminary findings in the Belfast Lough Catchment

The preliminary data discussed in this section refers to samples collected between December 2018 and March 2019. Figures 24 and 25 allow a comparison of *E. coli* concentrations in the catchment following a high and low flow event. Following the high rainfall event (Figure 24) a significant number of urban rivers have *E. coli* concentrations ranging from 10,000 to 500,000 cfu/100ml. These rivers have been identified as potential problem areas within the catchment.
*E. coli* concentrations are also elevated in the upper reaches of the catchment which is most likely as a result of rainfall leaching agricultural contaminants into the system. Sampling following a low flow event appears to present a different image (Figure 25) as the “problem” urban sites identified in Figure 24 have much lower *E. coli* levels detected which suggests high rainfall events play an important role in *E. coli* entering the system from the urban environment. Compared to the high flow sampling, higher peaks are evident at L23 at the top of the catchment (as a result of a reported pollution event) and at BLS05. BLS05 is a small stream which discharges directly into Belfast Lough.
Figure 26 represents data collected over an 8 week period (4 sampling events), results from this short time period do not exhibit strong evidence of trends between *E. coli* concentrations and rainfall, however as this data set increases a better idea of any trends will become apparent. There is a peak evident at L37 during the mid-February sampling event which is not reflected at the other sampling locations (>9000 cfu/100ml), it is possible this is evidence of a pollution event. Further analysis of this sample will help to identify the source of the *E. coli* to determine if this is an agricultural pollution event or as a result of a malfunctioning septic tank. The very high peak at the end of March at L23 during low flow is a pollution event which was reported. Although a source was not identified at the time of reporting, further analysis as part of LWWP could help identify potential sources. This peak is not evident at sites downstream suggesting it dispersed quickly.
Figure 27 shows in more detail *E. coli* concentration and daily rainfall of urban rivers and rivers discharging directly into Belfast Lough. These sites have all been identified as potential problem areas. Throughout the sampling period, elevated *E. coli* concentrations are evident, although due to the short sampling period it is not possible to determine if this is directly linked to rainfall. All of these sites require further analysis and Microbial Source Tracking (MST) is scheduled to identify the source.

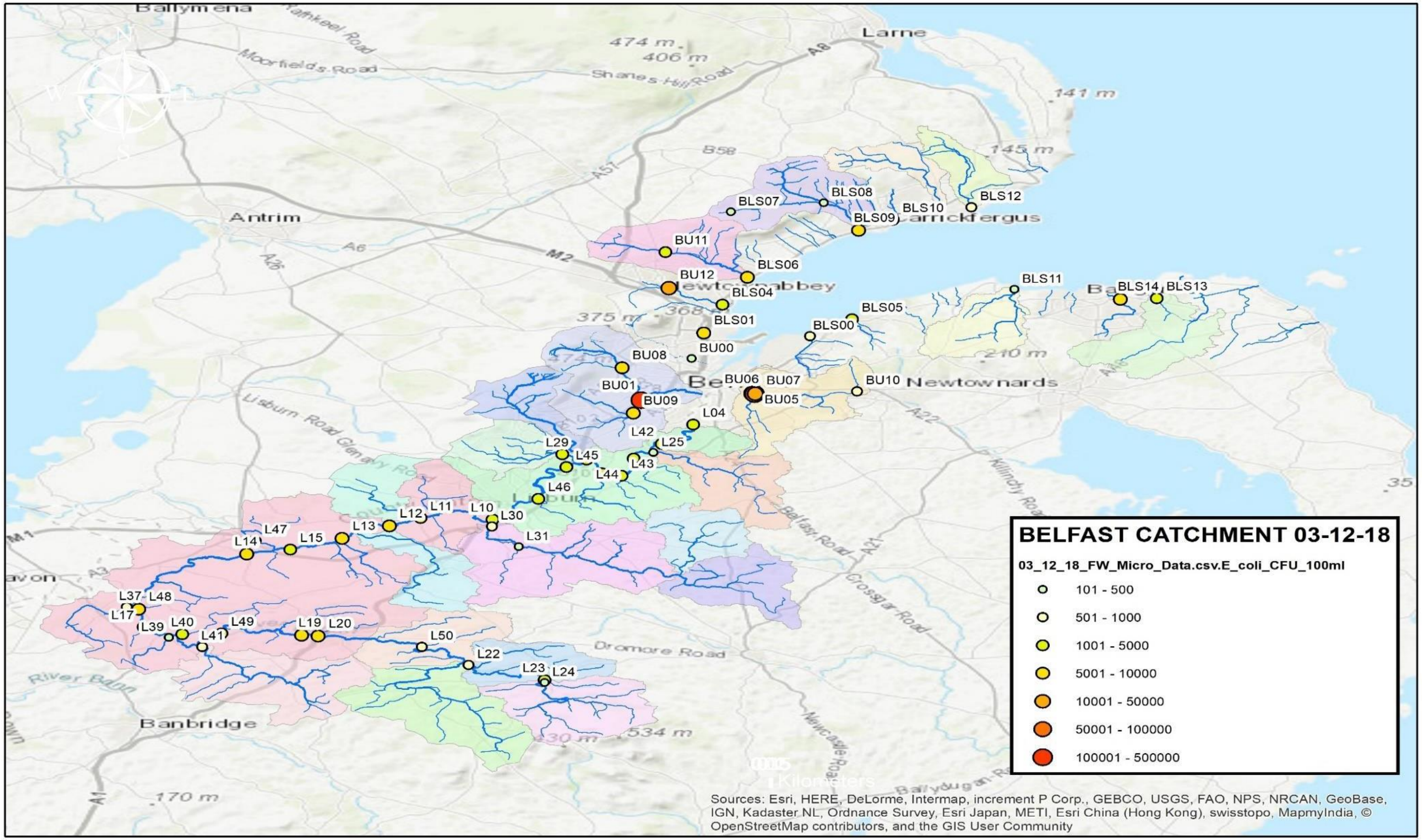


**Figure 24: *E. coli* concentrations across the Belfast Lough catchment following a high flow event in early December 2018.**

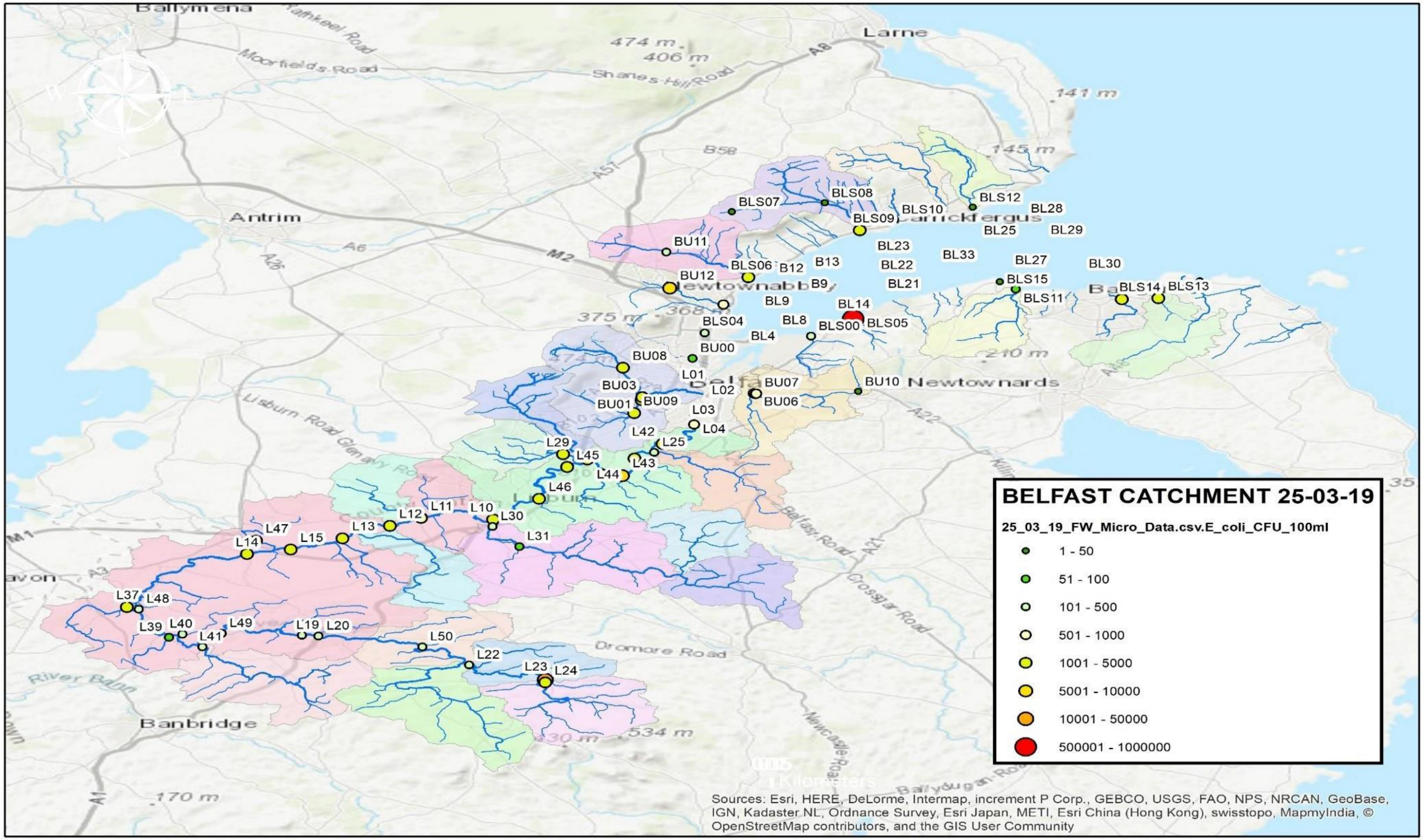


**Figure 25:** ***E. coli*** **concentrations across the Belfast Lough catchment following a low flow event in late March 2019.**

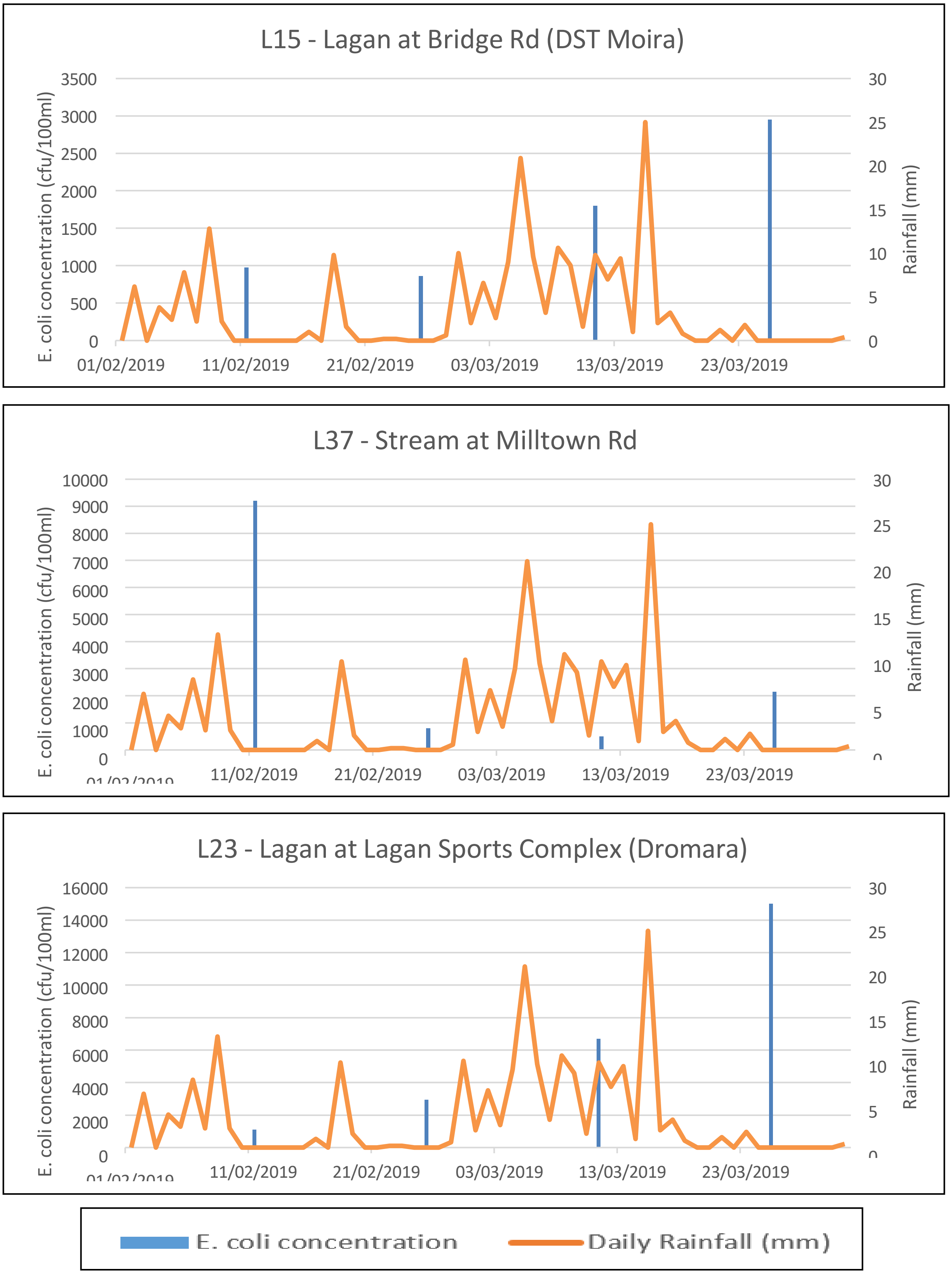


**Figure 26: *E. coli* concentration versus daily rainfall during February and March 2019 at three locations in the River Lagan Catchment. L15 – mid catchment, L37 – mid/ high catchment, L23 – top of catchment.**

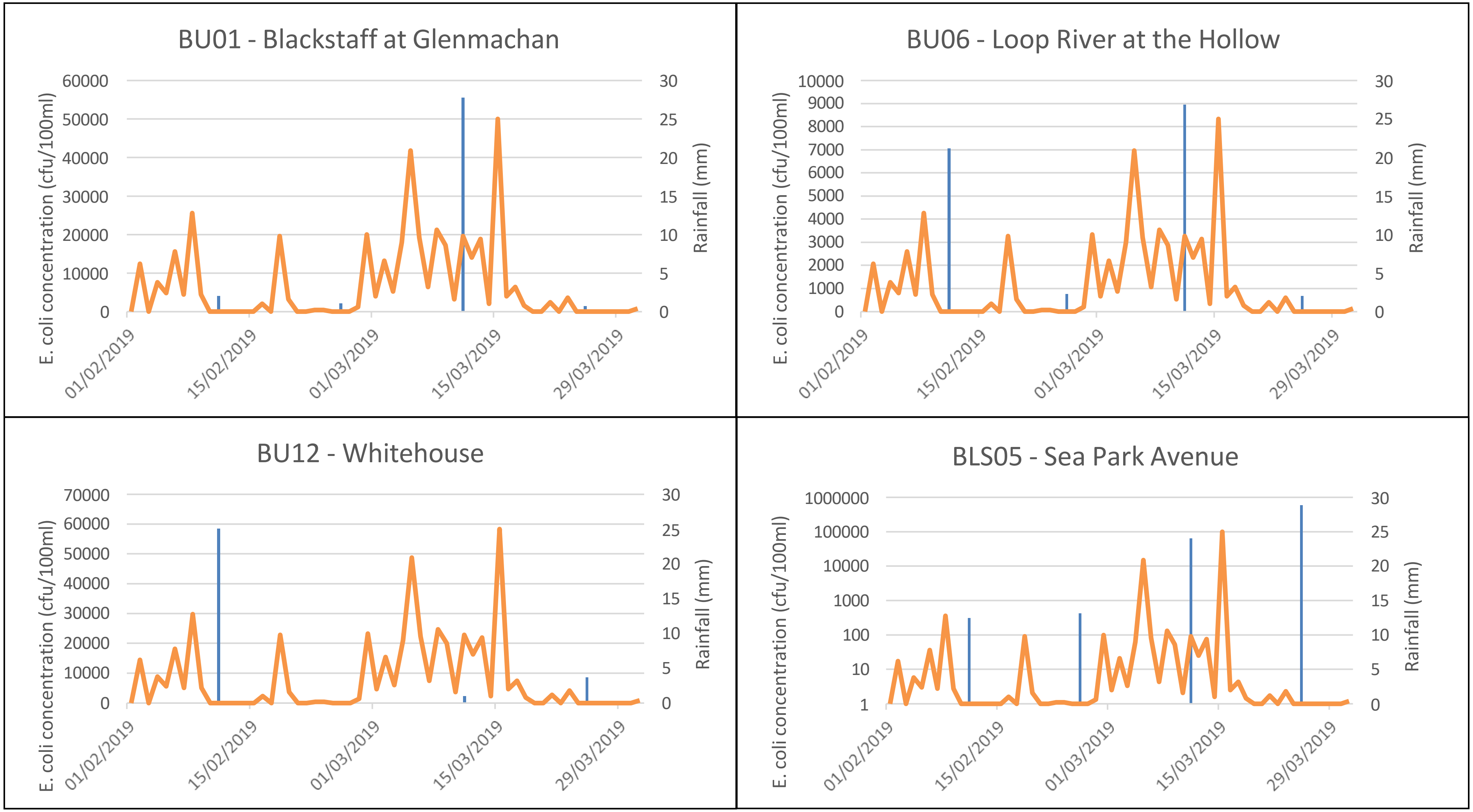


**Figure 27: *E. coli* concentration versus daily rainfall during February and March 2019. BU01, BU06 and BU12 are urban rivers within Belfast. BLS05 is a small stream which discharges directly into Belfast Lough.**

# Section 4 Dundrum Catchment modelling project

## 4.1 Introduction

The Dundrum ecosystem catchment modelling project is nearing completion and illustrates the underlying principles to the AFBI Integrated catchment ecosystem modelling approach, this will be applied to the Belfast catchment. The models to be coupled include: the Dundrum Soil Water Assessment tool (SWAT) catchment model; coupled with Drainage Area models (DAPs) allowing the SWAT to route both diffuse and point sources contaminants and nutrients through the stream and river system to the coastal zone (Figure 28). The Delft3D coastal model will interface both with EcoWin (EWN) and SWAT. Delft3D-Flow hydrodynamic and transport model will provide circulation between the EWN boxes and receive water quantity from the catchment produced by SWAT. The Delft-WAQ model will provide high resolution dispersion and decay of coliform bacteria in the coastal environment.

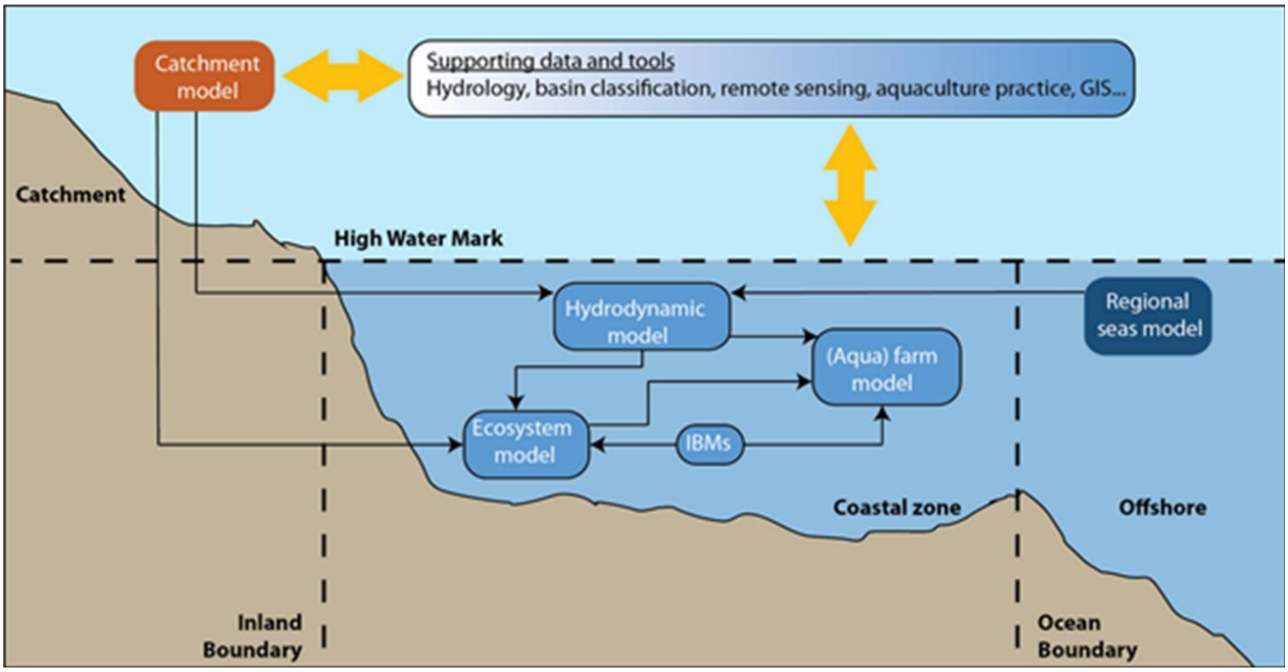


**Figure 28: The general framework for ecosystem modelling used for the Dundrum ecosystem catchment modelling project – The SUCCESS framework (System for Understanding Carrying Capacity, Ecological and Social Sustainability). IBMs are the Individual Biological models representing shellfish and wild species.**

## 4.2 Dundrum catchment SWAT Model

### 4.2.1 Catchment delineation

The delineation of the catchment is the first step in the setup of the SWAT model. The objective is to divide the whole simulated area in several spatial units called subbasins, where water and contaminants simulated at the field scale will be routed through the river network. It is important to select an appropriate number of subbasins to best describe the spatial organization of the simulated area. Too many subbasins may unnecessarily slow down the model computation by introducing a high complexity in the spatial discretization of the catchment, while too few subbasins may not allow the model to correctly consider the spatial variability of the whole area. There are a number of steps involved in catchment delineation and this is an important step in the SWAT model setup. To perform catchment delineation, the model requires a digital elevation model (DEM) and the river network map. In addition, information such as Water Framework Directive freshwater bodies (WFD FBs), drainage areas and gauging stations locations can help with the delineation. The data used for the catchment delineation of Dundrum watershed are listed in Table 7.

**Table 7: List of the data used for the catchment delineation in Dundrum watershed**

| Data | Source |
|---|---|
| Digital elevation model | EU-DEM |
| River network | na |
| Drainage areas | na |
| WFD FBs | EA/EPA |
| Gauging stations: Dundrum | Installed by AFBI/McAdam |

The Dundrum catchment has an area of 142 km$^2$. The outlets have been placed according to the location of the gauging stations installed by AFBI and McAdam Design and to the location of WFD FBs. The delineation has been made to match with the WFD FBs delineation and each FB is represented by at least one subbasin. The catchment delineation results in the creation of 11 subbasins with an average area of 12.9 km$^2$. There are 4 main outlets, corresponding to the four main rivers, discharging into the bay that will be input into the coastal model. Main characteristics of the catchment delineation are shown in Table 8 and the delineation in Figure 29.

**Table 8: Features of the catchment delineation for Dundrum watershed.**

| | Dundrum |
|---|---|
| Simulated area | 142 $km^2$ |
| Number of subbasins | 11 |
| Number of WFD FBs | 6 |
| Threshold for drainage | 3 $km^2$ |
| Average area of subbasins | 12.9 $km^2$ |
| Minimum area of subbasins | 4.4 $km^2$ |
| Maximum area of subbasins | 30.3 $km^2$ |
| Contact points with the coastal model | 4 |

A major objective of the Dundrum catchment ecosystem project was to consider the impact of wastewater on the streams water quality through the integration of the drainage area plans (DAPs) in the modelling framework. DAPs are usually associated with a network model and the ones that do not have models are not expected to be significant contributors. As the SWAT model allows a single input of wastewater per subbasin, the catchment delineation has been constructed to assure having no more than one significant DAP (associated to a network model) per subbasin, in order to evaluate the contribution of each DAP to the river network. In Dundrum watershed, 2 terrestrial drainage area plants (DAPs) will be linked to the catchment model (Annsborough in subbasin 6 and Murlough in subbasin 11) and one coastal DAP will be directly linked to the coastal model (Dundrum). Additional smaller drainage areas and septic tank discharges will also be added to the model. Microbial Source Tracking (MST) is underway to identify the main source of *E. coli* in the rivers sampled throughout this year long survey.

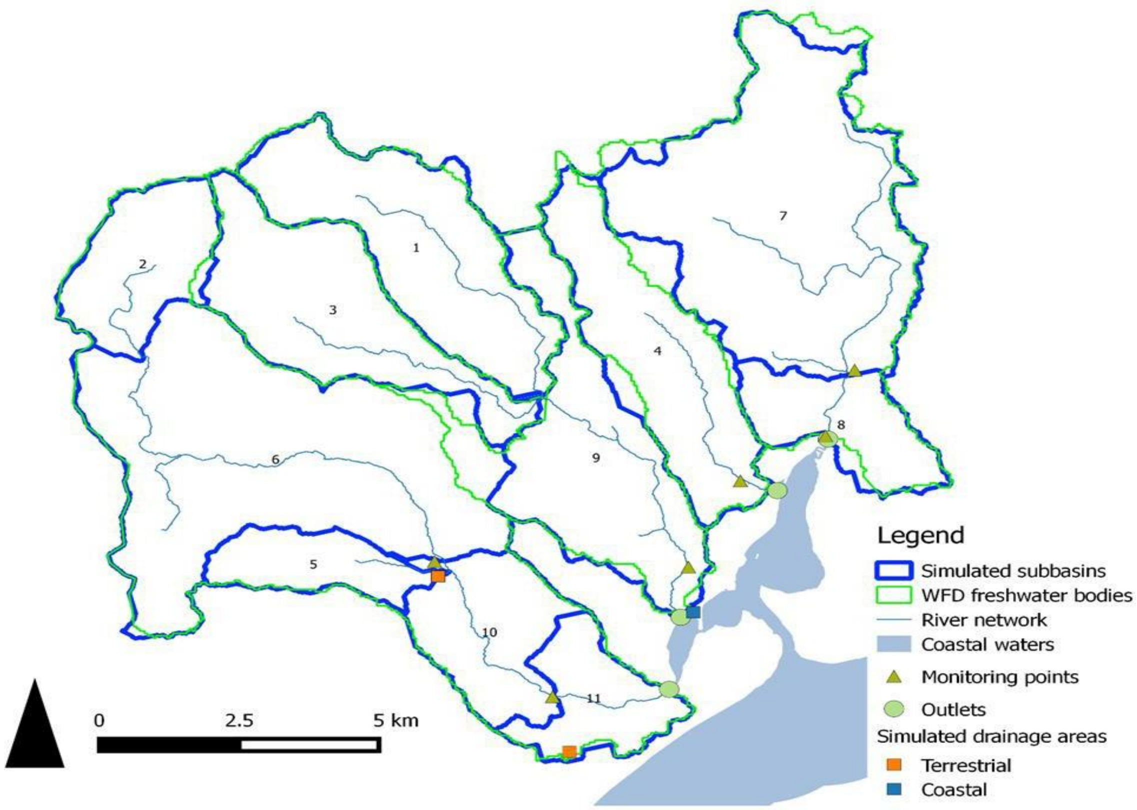


**Figure 29: Catchment delineation of Dundrum watershed**

### 4.2.2 Hydrological response units (HRUs) creation

HRUs are a unique combination of land use, soil and slope classes. HRUs are a subdivision of a subbasin for which field scale processes will be simulated (e.g. water balance, plant growth, nutrients cycling) before being aggregated at the subbasin level where they will be routed through the river network. HRUs are not a spatialized unit but represent a percentage of a subbasin area with homogeneous properties. To calculate HRUs statistics, the model requires information on land use, soil type and slope (Table 9). In this setup, land use was provided by Corine Landcover 2012 (CLC 2012), soil type by the European soil database (ESDB) and slope was calculated from the DEM used in the subbasin creation (EU-DEM).

**Table 9: List of data used for hydrological response units creation**

| Data | Source | Provided by |
|---|---|---|
| Land use | CORINE Land Cover (CLC 2012) | AFBI |
| Soil map | European Soil database (ESDB v2.0) | LLE |
| Digital elevation model | Digital Elevation Model over Europe (EU-DEM) | AFBI |

Land-use, soil and slope classes were reclassified prior to HRUs creation. For land-use, eight classes have been kept based on dominant land uses and previous application of the SWAT model in Ireland (Figure 30). Two classes have been created to represent Irish land cover specificities: Range-Grasses (RLEI) corresponding to natural grasslands and Range-Brush (RBLI) corresponding to shrub lands and other un-forested natural areas (Table 10). Pastures dominate, covering 71% of the Dundrum catchment, followed by natural grasslands (11%), agricultural lands (10%) and forests (5%).

**Table 10: Land-uses of the Dundrum watershed according to CLC12 classifications and correspondences with SWAT classes**

| CLC12 code | Description (CLC12) | SWAT class | Description (SWAT) | % simulated area |
|---|---|---|---|---|
| 112 | Discontinuous urban fabric | URMD | Urban medium density | 0.7% |
| 142 | Sport and leisure facilities | URMD | Urban medium density | 0.2% |
| 211 | Non-irrigated arable land | AGRL | Agricultural Land-Generic | 10.4% |
| 231 | Pastures | PAST | Pasture | 71.2% |
| 243 | Land principally occupied by agriculture | PAST | Pasture | 0.1% |
| 311 | Broad-leaved forest | FRST | Forest-Mixed | 0.8% |
| 312 | Coniferous forest | FRST | Forest-Mixed | 1.2% |
| 313 | Mixed forest | FRST | Forest-Mixed | 2.8% |
| 321 | Natural grasslands | RLEI | Range-Grass | 10.7% |
| 322 | Moors and heathland | RBLI | Range-Brush | 0.3% |
| 324 | Transitional woodland-shrub | RBLI | Range-Brush | 0.4% |
| 331 | Beaches | RBLI | Range-Brush | 0.3% |
| 423 | Intertidal flats | WATR | Water | 0.0% |
| 512 | Water bodies | WATR | Water | 0.7% |

The soils were classified according to the world reference base class of the dominant soil typological unit (WRBFU) indicated in the ESDB. Three classes were found in the Dundrum watershed (Figure 31). Dystric Cambisol (CMdy) cover 75% of the whole area, dystric Gleysol (GLdy) 19% and placic Podzol (PZpi) 6%. Finally, the slopes were divided in 2 classes (inferior and superior to 10%) according to the previous application of the model in Ireland.

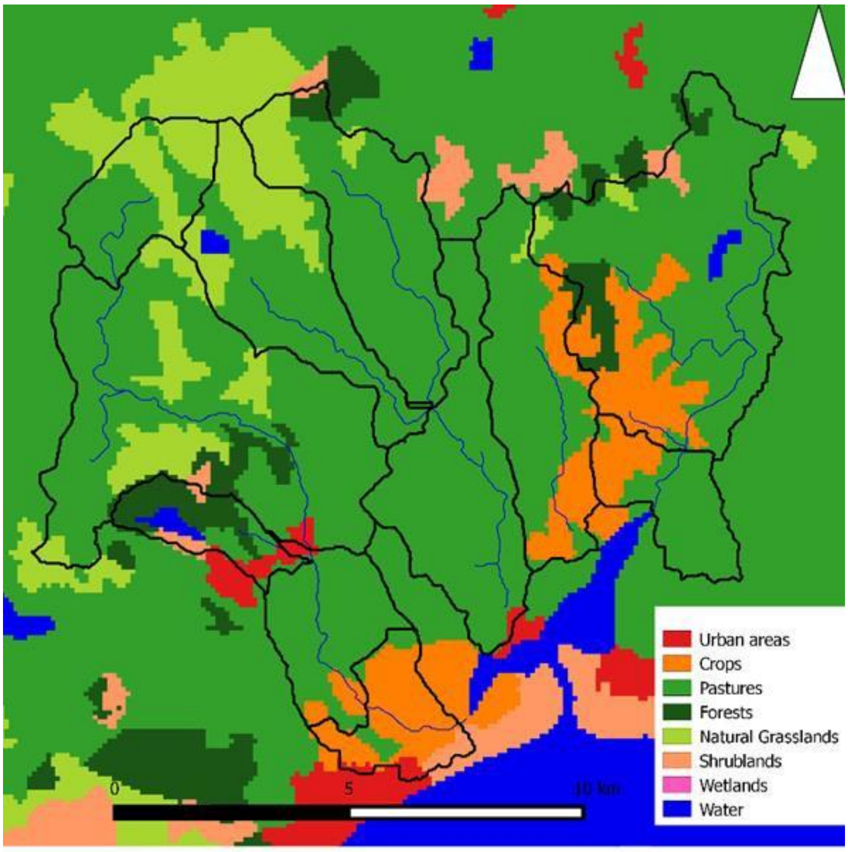


**Figure 30: Land-use map used for hydrologic response units creation in Dundrum watershed, based on CLC12.**

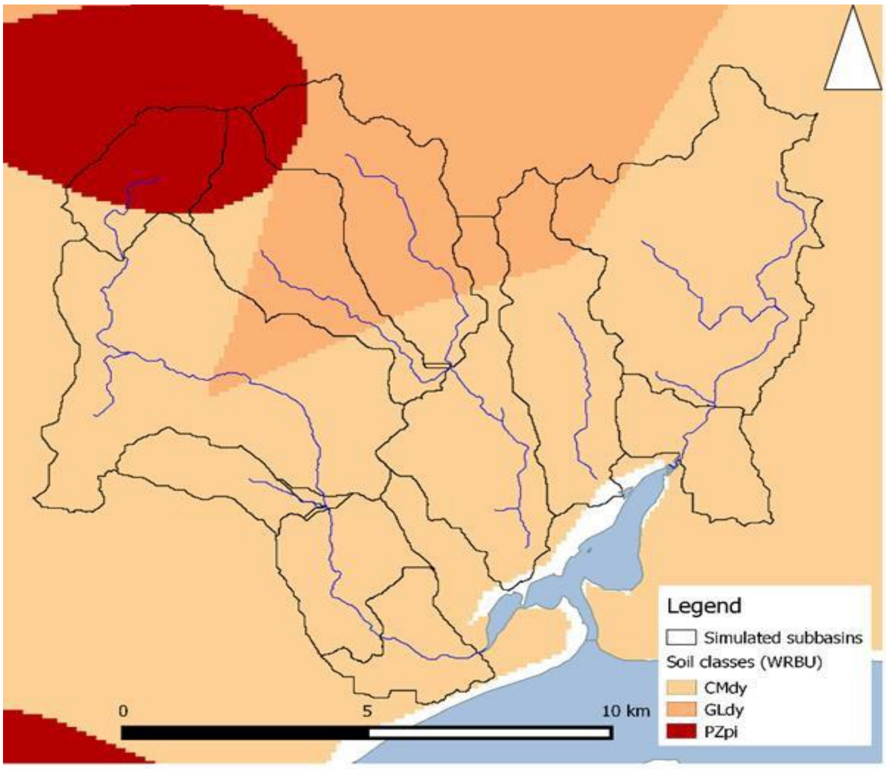


**Figure 31: Soil map used for hydrological response units (HRUs) creation in Dundrum watershed, based on the European soil database**

To avoid having too many HRUs that would slow down the computation of the model, only the most significant HRUs were kept. They were selected by defining a percentage threshold for minimum land uses, soil and slope class's area for each subbasin. The selected thresholds were 5%, 10% and 10% for land-use, soil and slope classes, respectively. This results in a total of 66 HRUs for the 11 subbasins. The final composition of the simulated watershed in terms of land-use, soils and slope is indicated in Table 11.

**Table 11: Percentage of Land-use, soil and slope classes in Dundrum watershed after hydrological response unit creation**

| | | |
|---|---|---|
| Delineation | Number of Subbasins<br>Number of HRUs | 11<br>66 |
| Land use classes (%) | URMD | 0.24 |
| | AGRL | 10.71 |
| | PAST | 73.72 |
| | FRST | 4.54 |
| | RLEI | 10.49 |
| | RLBI | 0.30 |
| Soil classes (%) | Cambisols dys. | 79.66 |
| | Gleysols dys. | 15.88 |
| | Podzol pla. | 4.45 |
| Slope classes (%) | 0-10% | 71.29 |
| | >10% | 28.71 |

### 4.2.3 Climate input data

In order to run the model at an hourly time step, hourly rainfall input is needed. Rain radar data were used to provide a good representation of the spatio-temporal variability in rainfall over the simulated area. Twenty-two rainfall time series were extracted from the Met Office radar data grid (Figure 32). Hourly rainfall values were then combined into one representative rainfall time series for each subbasin using a spatially weighted average.

In addition to hourly rainfall, the SWAT model also required daily climate parameters to compute potential evapotranspiration (max/min temperature, humidity, wind speed and solar radiation). These parameters are available at AFBI's field stations installed within the catchment (Figure 32). Additional data gaps have been filled using correlation with the other meteorological stations located in Northern Ireland.

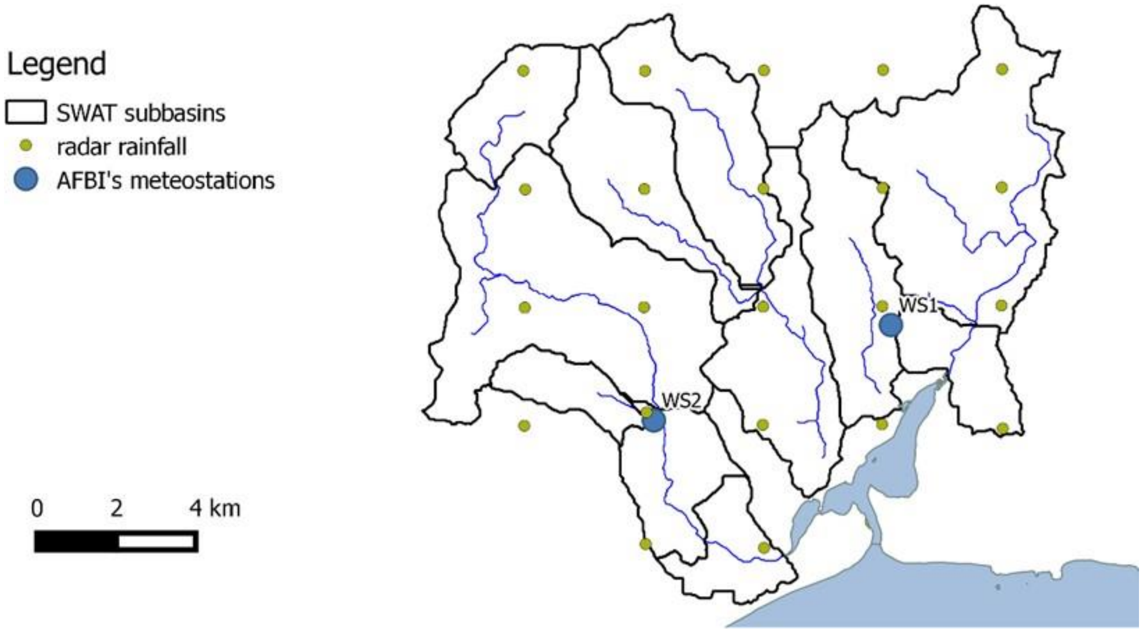


**Figure 32: Location of meteorological station for the Dundrum watershed**

### 4.2.4 Model calibration and validation

The Dundrum catchment SWAT model has been calibrated and validated and at present we await the DAP outputs to couple to the final model. Preliminary coupling is being tested with default drainage area estimates from Northern Ireland Water (NIW). A separate report is available to outline this process.

## 4.3 Dundrum Coastal model

### 4.3.1 Computational grids and bathymetry

Inner Dundrum Bay is a very shallow tidal embayment with a good connection to the adjacent shelf. The residence time of discharges into the bay will depend on the reincorporation of water flushed in previous ebbing phases of the tidal cycle. To quantify this, there was a need to model the shelf circulation. Here the main drivers are not the tide alone but also the wind and the general inner-shelf and mesoscale circulation resulting from the wider pressure field. To represent this, the model consists of two separate domains, one for inner Dundrum Bay and the adjacent shelf (the Inner Domain) and one for the larger region spanning from south of Carlingford Lough to north of Larne (the Outer Domain).

The computational grid for Inner Dundrum Bay that was set up for the simulations has 350x167 cells in the horizontal and is designed so that the grid sizes are refined to a size of ~13 m along sections of the main channels in the bay, ~20 m along the entrance channel and ~250 m at the adjacent shelf. The computational grid for the inner bay and adjacent shelf is shown in

Figure 33 with a detailed view of the grid in the entrance channel and the inner bay presented in Figure 34. The model is set up in cylindrical coordinates (Latitudes and Longitudes), but the grids in Figures 33 and 34 are presented in linear coordinates (UTM) for display purposes.

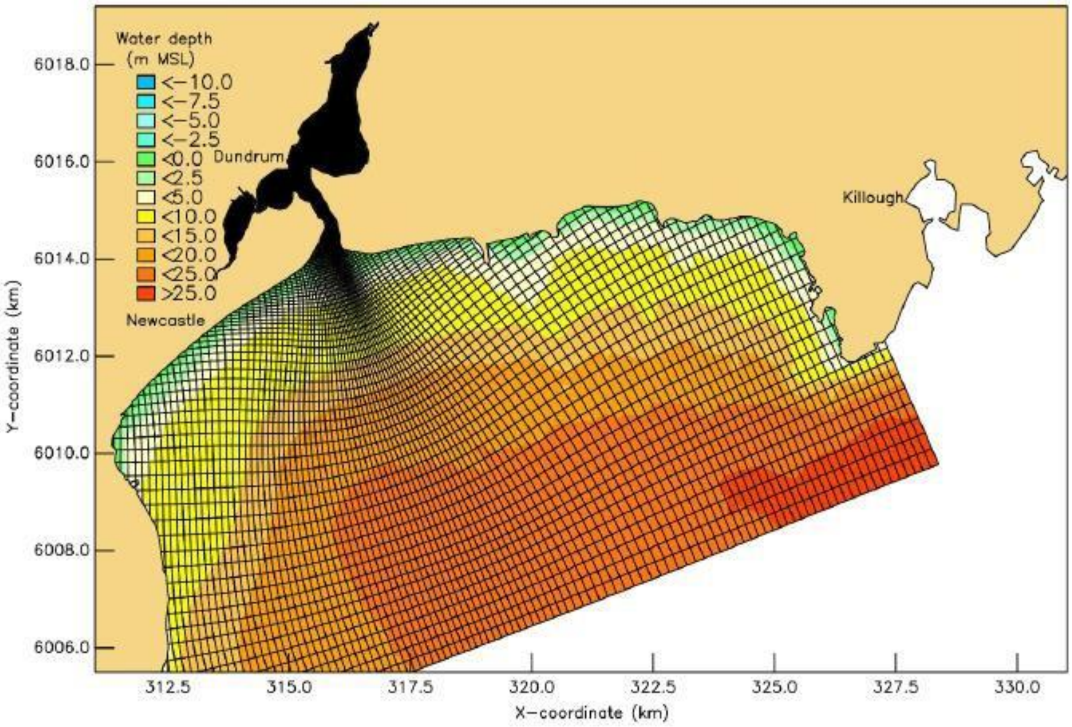


**Figure 33: A view of the grid for inner Dundrum Bay and the adjacent shelf.**

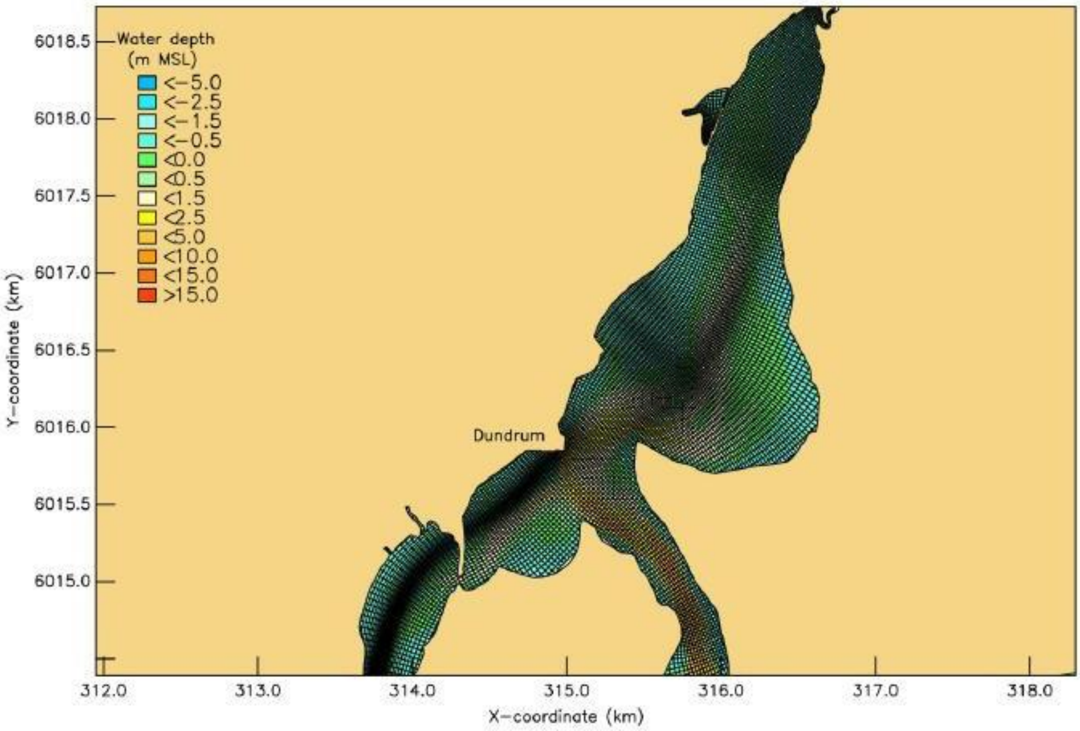


**Figure 34: A view of the grid for inner Dundrum Bay**

The bathymetry was constructed from measurements from a number of sources; the inner bay bathymetry was constructed from a recent LIDAR drone survey; the entrance channel was surveyed by boat (using an M9) and the bathymetry for the outer bay and adjacent shelf was obtained from the UKHO. To fill in the data gap in the shallow near shore area, the 0m, 2m and 5m contours along the coast were digitized from the map Ireland – East Coast. The reference level for the bathymetry in the model is Mean Sea Level and the coordinate system is cylindrical (Latitude and Longitude). The bathymetry is also shown in Figures 35 and 36 using UTM coordinates for display purposes.

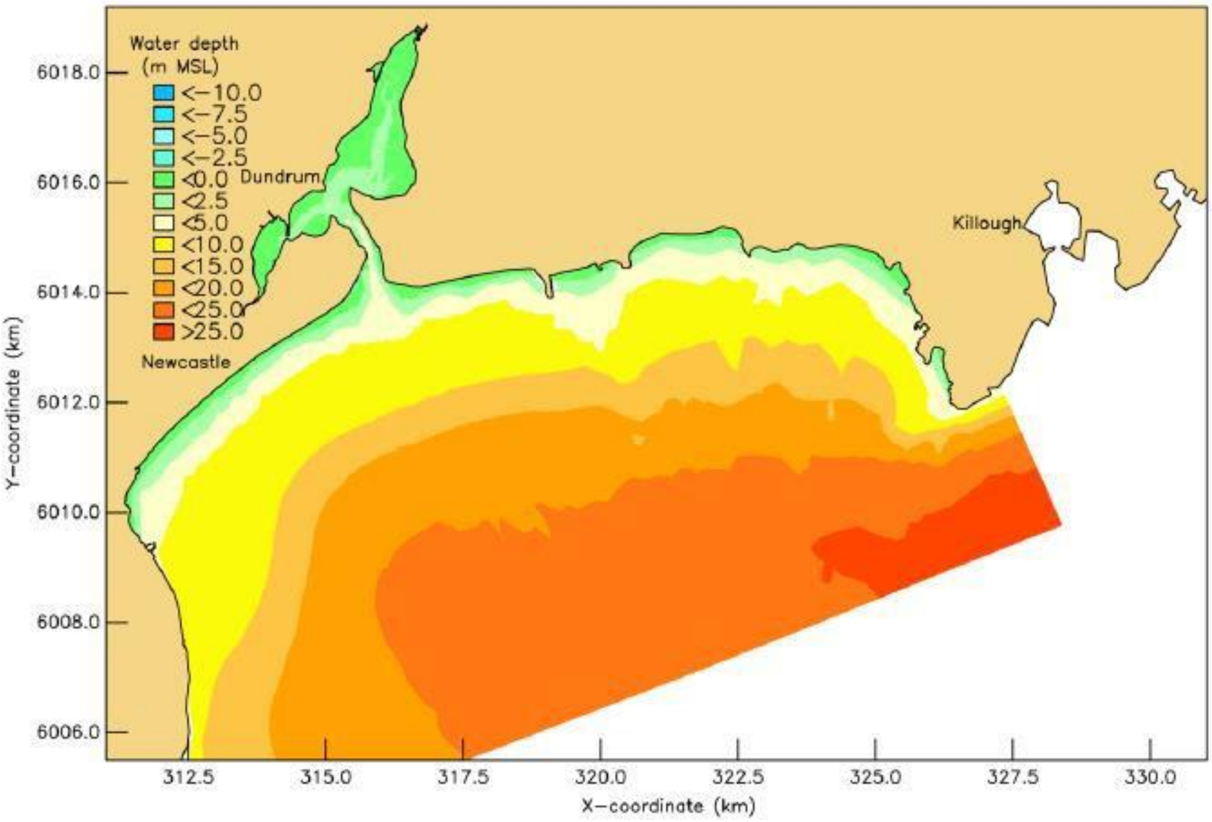


**Figure 35: The bathymetry of inner Dundrum Bay and the adjacent shelf**

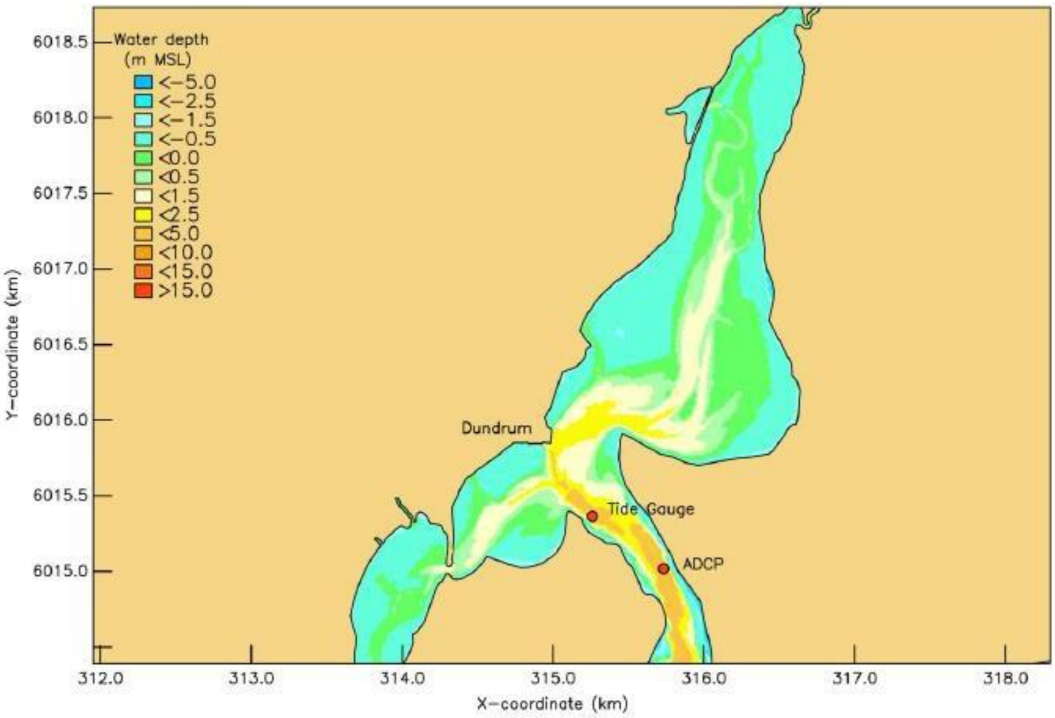


**Figure 36: The bathymetry of inner Dundrum Bay. Also shown are the locations of the ADCP and Tide Gauge.**

### 4.3.2 Parameterization

Tidal forcing is applied to the offshore open boundary while a zero water level gradient is applied to the only lateral open boundary. The tidal constituents were obtained from the FES2014b tidal atlas (Carrere *et al.* 2016; Lyard *et al.* 2016).

Bottom friction is modelled with a Chézy coefficient obtained from the White-Colebrook formulation defined by the Nikuradse roughness length which is set to ks = 0.11 m. The friction in constrained tidal basins are usually higher than along open coasts and the selected value leads to a Chézy-value of approximately 50 m1/2s-1 in the inlet similar to Van Ledden et al. (2004). An advantage of the White-Colebrook formulation is that the friction increases with decreasing depth. Some of the modelling parameters are provided in Table 12.

**Table 12: Hydrodynamic model parameters**

| Parameter | Value/Setting |
|---|---|
| Horizontal eddy viscosity | 1 m2s-1 |
| Bottom roughness formulation | White-Colebrook |
| Roughness length | 0.11 m |
| Threshold depth | 0.1 m |
| Time step | 1 minute |

## 4.4 EcoWin - Ecological model

The ecosystem modelling component of the project aims to build upon the SUCCESS (System for Understanding Carrying Capacity, Ecological and Social Sustainability) modelling framework which was used in both the SMILE and EASE projects. The Dundrum ecosystem catchment model used a combination of different models to simulate hydrological processes in the Dundrum bay catchment (Figure 37).

EcoWin is a system-scale ecological model, typically operated in a three-dimensional formulation. It is applied to simulate extended periods of time, ranging from one year to decadal scales. A ten-year period is frequently used, during which multiple overlapping shellfish cultivation cycles can be simulated.

The main objectives of the EcoWin model, as applied within the SUCCESS framework, are:

1. To provide a tool to simulate the biogeochemical cycles within a coastal system, fully integrating the relevant water column and diagenetic processes, and explicitly accounting for changes in nutrient loading, both land-derived and at the ocean end-member(s);

2. To simulate primary production (both pelagic and benthic, as required), taking into account both bottom-up and top-down control;

3. To explicitly simulate human interaction including the effect on aquaculture yields of

(i) changes to land-based nutrient loading—a model chain derived from SWAT and drainage area modelling can be used to examine the consequential changes to primary production and non-phytoplankton organics and bivalve harvest;

(ii) changes to lease areas, stocking densities, and culture practice, occurrence of invasive species such as *Alcyonidium sp.* or *Crepidula fornicata*, etc.

A range of calibration and validation methods will be employed for the EcoWin model. A number of calibration steps will be employed including literature or experimental data on nutrient biogeochemistry and pelagic primary production and examining size fractioning, simulation flocculation and re-suspension of SPM. The model will be validated using a number of approaches including scale comparison, comparison with measured data, shellfish growth within EcoWin being compared with results obtained from WinShell work bench.

EcoWin typically considers two or three vertical layers to account for processes at the benthic boundary layer - practically all bivalve shellfish culture in Northern Ireland (all in Belfast) is deployed on the seabed. Horizontal and vertical fluxes across boxes and at domain boundaries are provided by fine-grid hydrodynamic models such as Delft3D, POM, and ROMS.

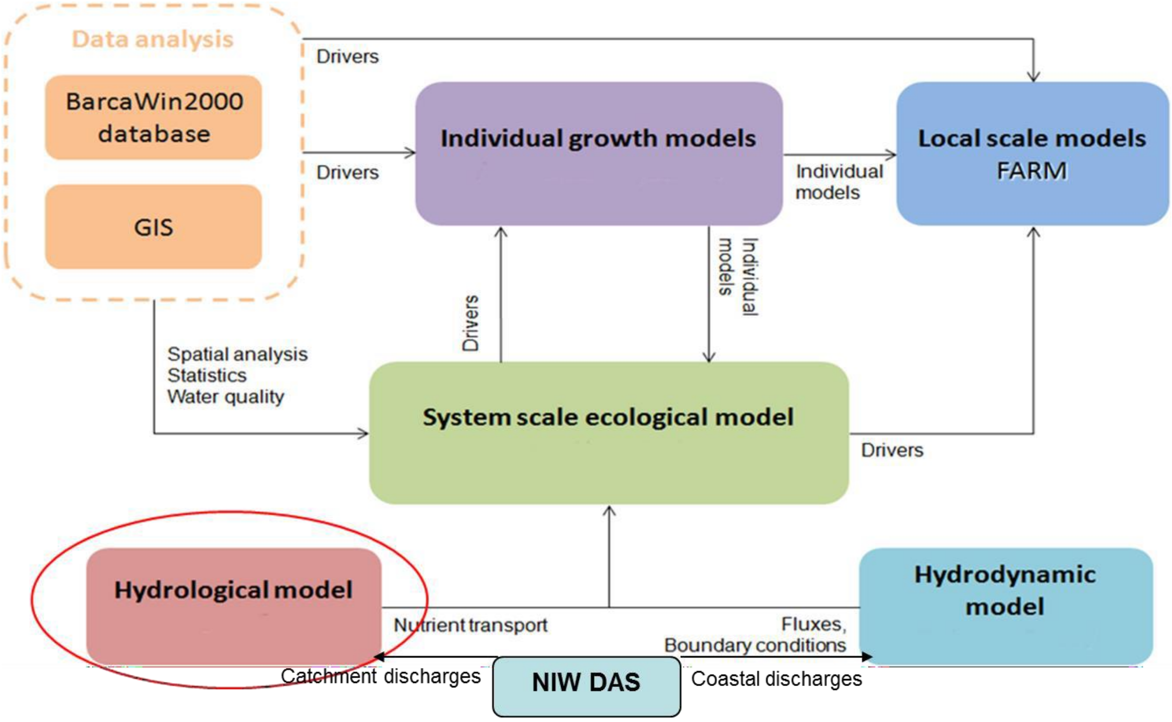


**Figure 37: The SUCCESS (System for Understanding Carrying Capacity, Ecological, and Social Sustainability) modelling framework**

Nutrient loading at the land boundary contact points is provided as daily concentration values by SWAT and combined with the freshwater flows provided by Delft3D. Direct effluent discharge (point-sources) is also included.

A fully-loaded EcoWin model, such as that developed for EASE (Lough Foyle), typically contains 150-200 state variables, 15-25 forcing functions, and simulates a decadal period in under one hour on a fast computer.

## 4.5 Summary

In SMILE, there was no explicit development of a catchment model, which meant that nutrient loads originating from land were simulated on the basis of measured concentration and flow data. Secondly, a decade ago there was a lower availability of ocean models required for simulating boundary conditions in the Irish Sea. The modelling work developed in EASE for Lough Foyle illustrated how much can now be achieved by applying state-of-the-art ocean models. Finally, ecological modelling has also evolved significantly in the last decade, and this can be translated into higher resolution, greater accuracy, and integration of aspects that are key to sustainable development of shellfish aquaculture, such as the incorporation of naturally occurring benthic filter feeders.

The main areas for development are related to the implementation or enhancement of specific models, and to the coupling of these models within the framework. Out of the set of models represented in Figure 37, only three will be developed fully as new tools:

(i) the Soil and Water Assessment Tool (SWAT), which simulates the processes within the catchment, and allows managers to examine the consequences of changes to land management and urban discharge

(ii) the wider ocean boundary component of the hydrodynamic model that simulates water circulation and distribution of key variables in Belfast Lough and the adjacent offshore area;

(iii) the local-scale aquaculture biosecurity and carrying capacity (ABC) model.

The models that form part of the SUCCESS framework address different scales in time and space (Figure 37), and the entire modelling domain of Belfast Lough will differ significantly from the SMILE framework, both in spatial and temporal resolution.

The ecological modelling component includes work to be executed on individual modelling of bivalve physiology, including uptake of enteric bacteria, biogeochemical modelling at the system scale, and modelling of shellfish production and environmental effects, both at the system scale and using local-scale models.

The Phase I DASSHH NI project has drawn on a number of ongoing work streams within AFBI and collated relevant data, whilst developing new work programmes to provide additional data required for DASSHH Phase II and III work. The gap analysis carried out from the current study highlighted areas requiring additional funding going forward.

## Bibliography

**AFBI** (2008) SANITARY SURVEY REPORT Belfast Lough 2008. AFBI Report to FSANI

**AFBI** (2014) Cumulative Impact Assessment: Aquaculture activities within Belfast Lough. Report to the Department of Agriculture and Rural Development.

**Campos C J A, Kershaw S, Lee, R L, Morgan O C and Hargin K** (2011) Rainfall and river flows are predictors for B-glucuronidase positive *Escherichia coli* accumulation in mussel and Pacific oysters from the Dart Estuary (England). J Water and Health 9.2

**Carrere L., F. Lyard, M. Cancet, A. Guillot, N. Picot: FES 2014** (2016) A new tidal model - Validation results and perspectives for improvements, presentation to ESA Living Planet Conference, Prague 2016.

**CEFAS** (2014) Belfast Lough Sanitary Survey Review.

**Clements K, Quilliam R S, Jones DE L, Wilson J and Malham S K** (2015). Spatial and temporal heterogeneity of bacteria across an intertidal shellfish bed: Implications for regulatory monitoring of faecal indicator organisms, Science of the Total Environment 506-507 pp1-9.

**Kay D,J. Crowther, C.M. Stapleton, M.D. Wyer, L. Fewtrel, S. Anthony, M. Bradford, A. Edwards, C.A. Francis, M. Hopkins, C. Kay, A.T. McDonald, J. Watkins, J. Wilkinson** (2008) Faecal indicator organism concentrations and catchment export coefficients in the UK. Water Research 42 (2008) 2649 – 2661

**Lyard F., L. Carrere, M. Cancet, A. Guillot, N. Picot: FES2014** (2016) A new finite elements tidal model for global ocean, in preparation, to be submitted to Ocean Dynamics in 2016.

**NIEA** (2011) Review of Sensitive Areas in Northern Ireland under the Urban Waste Water Treatment Directive 2006-2009. Belfast: Northern Ireland Environment Agency.

**Stapleton, C.M., Wyer, M.D., Crowther, J., McDonald, A.T., Kay, D., Greaves, J., Wither, A., Watkins, J., Francis, C., Humphrey, N., Bradford, M.,** (2008) Quantitative catchment profiling to apportion faecal indicator organism budgets for the Ribble system, the UK's sentinel drainage basin for Water Framework Directive research. J. Environ. Management.

**Wilkinson, J., Kay, D., Wyer, M., Jenkins, A.,** (2006) Processes driving the episodic flux of faecal indicator organisms in streams impacting on recreational and shellfish harvesting waters. Water research. 40, 153-161.