Review of Environmental monitoring during KerryLIFE with respect to requirements of the freshwater mussel (*Margaritifera margaritifera*) and the impact of project actions on ecosystem functions

KerryLIFE Project

Sustainable land use management for the conservation of the freshwater pearl mussel
LIFE13 NAT/IE/000144

The KerryLIFE project 'Sustainable land use management for the conservation of freshwater pearl mussels' worked with farmers and forest-owners in two river catchments to develop and demonstrate sustainable land use practices to conserve the freshwater pearl mussel and to benefit the unique natural environment of the Iveragh Peninsula. It operated from 2014–2020 and was funded through the EU LIFE Nature Fund (50% LIFE funding; 50% Irish project partners funding). The project demonstrated measures to address sources of excess silt and nutrients and hydro-morphological changes associated with the farming and forestry sectors contributing to the deterioration of the freshwater pearl mussel's habitat. The project coupled local farming knowledge and experience with the scientific expertise of project partners to improve the conservation status of the Natura sites.

LIFE+ Nature and Biodiversity
LIFE+ Nature and Biodiversity is one of the main strands of the European Union's funding programme for the environment. It supports projects that contribute to the implementation of the EU Birds and Habitats Directives, the NATURA 2000 network and that contribute to the EU's goal of halting the loss of biodiversity.

Prepared by members of the KerryLIFE project team and contractors

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Executive Summary

KerryLIFE (LIFE13 NAT/IE/000144) was an EU LIFE project that aimed to demonstrate sustainable land use management to conserve the freshwater pearl mussel (*Margaritifera margaritifera*) in the Caragh and Kerry Blackwater rivers in South Kerry, Ireland. The freshwater pearl mussel is a large filter-feeding freshwater bivalve that is generally found in cool, oligotrophic, acid to neutral watercourses over granite or sandstone bedrock. The species has declined dramatically in the last century, is of unfavourable conservation status in Ireland and is critically endangered worldwide. The *Margaritifera* populations of both the Caragh and the Kerry Blackwater catchments are two of the largest, densest and most important mussel populations in the world; however, they are also the two populations in most serious and rapid decline. They are both populations considered to be in the "Top 8" mussel rivers in Ireland. These populations hold 80% of the Irish resource and the results of the KerryLIFE project should inform conservation efforts in these most important catchments.

This report cross analyses the results of various monitoring actions associated with the KerryLIFE project and relates them to the condition of *Margaritifera* in the rivers of both catchments, and the ecosystem services provided by the mussels and their habitats, both in their current condition and where there is potential for improvement.

Monitoring of the mussels and their habitat and water quality in the context of activities being undertaken upstream of this monitoring demonstrates key differences between water quality derived from agricultural activities and those derived from forestry activities.

Nitrogen levels were much higher in agricultural streams compared with forestry streams. Damaging levels of Phosphorus arose from both agriculture and forestry sites. Dissolved organic carbon and colour was much higher in streams derived from forestry compared with agriculture.

The project found that turbidity and suspended solids are derived from all land use, but differed in fine sediment type, with heavier mineral losses coming from agriculture and erosion and lighter peat sediment coming from afforested sites.

It is concluded that the agricultural measures undertaken by KerryLIFE to lower nutrient loss and to increase the wetness of peatlands through implementation of farm plans, which considered the conservation requirements of the mussel, and through active measures such as fencing, alternative watering sources and drain blocking were very successful.

It is concluded that the forestry techniques that focused on the restructuring of existing conifer forests to long-term native woodland and mitigation measures trialled may play a role in management of immediate risk posed by forests; however, they were less successful in demonstrating benefits to freshwater pearl mussels as the measures did not eliminate all sediment/nutrient losses and the phased restructuring may only temporary improvements.

From recent research, is concluded that drainage of peat and the consequent lowering of water tables is of prime importance in the decline of the KerryLIFE rivers, and the restoration of undrained conditions with high water tables is the most important future task in the rehabilitation of sustainable condition of these populations.

Contents

1 Background and Introduction

1.1 Introduction

KerryLIFE (LIFE13 NAT/IE/000144) is an EU LIFE+ project that aims to demonstrate sustainable land use to conserve the freshwater pearl mussel (*Margaritifera margaritifera*) in the Caragh and Kerry Blackwater rivers in South Kerry, Ireland. The freshwater pearl mussel is a large filter-feeding freshwater bivalve that is generally found in cool, oligotrophic, acid to neutral watercourses over granite or sandstone bedrock. The species has declined dramatically in the last century, is of unfavourable conservation status in Ireland and is critically endangered worldwide.

The Caragh and Kerry Blackwater have two of the largest remaining populations of freshwater pearl mussel (FPM) in Ireland with approximately 2.8 million adults in each catchment at the commencement of the project. However, these populations and their habitat were not meeting target conservation conditions and are therefore likely to decline if current conditions persist. Three main pressures have been identified as negatively impacting these freshwater pearl mussel catchments: (i) excessive fine sediment losses to water, (ii) excessive nutrient losses to water causing filamentous algal and macrophyte growth and (iii) negatively impacted hydrology (e.g. from land drainage).

This report focuses on the range of environmental monitoring that was undertaken as part of the KerryLIFE project in order to determine which pressures are most impacting the mussel and whether the measures trialled during KerryLIFE reduced these pressures and whether they have the long term potential to reduce them s. This is expressed with regard to the value of ecosystem services achieved through catchment level restoration.

Since the project commenced in 2014, research on *Margaritifera* has continued. This has provided further information that the greatest pressure in the largest mussel populations in western peat-dominated catchments in Ireland is flow pressure, mainly due to lowered peatland water tables and particularly during low flow and drought conditions (National Standards Authority of Ireland (NSAI), 2017; Moorkens & Killeen, 2014; Killeen & Moorkens, 2020; Kuemmerlan et al., 2021). Therefore measures that include the restoration of higher water table conditions in conjunction with those that encourage a low loss of carbon, nutrient and sediment from the catchment to the aquatic zone are considered to be of primary importance and essential to restoring a sustainable *Margaritifera* population into the future.

Monitoring reports from tasks within the KerryLIFE project have been reviewed in conjunction with project actions. The monitoring reports are listed in Table 1.1. Learnings from the project actions have been written up as information notes for practitioners (Table 1.2).

Table 1.1 Monitoring reports produced during the KerryLIFE project.

Annex	Title
D01-01	*Margaritifera* Monitoring 2014 Report
D01-02	*Margaritifera* Monitoring 2016 2017 Report
D01-03	*Margaritifera* Monitoring 2019 Report
D02-01	Margaritifera Habitat 2015 Report
D02-02	Macroinvertebrates and Macrophyte Report 2016
D02-03	*Margaritifera* Habitat 2016 Report
D02-04	Macroinvertebrates and Macrophyte Report 2017
D02-05	*Margaritifera* Habitat 2017 Report
D02-06	Macroinvertebrates and Macrophyte Report 2018
D02-07	*Margaritifera* Habitat 2018 Report
D02-08	Macroinvertebrates and Macrophyte Report 2019
D02-09	*Margaritifera* Habitat 2019 Report
D03-01	Redox Report 2015
D03-02	Redox Report 2016
D03-03	Redox Report 2017
D03-04	Redox Report 2018
D03-05	Redox Report 2019
D03-06	Turbidity Report 2015
D03-07	Turbidity Report 2016
D03-08	Turbidity Report 2017
D03-10	MPhil Thesis - Sustainable Land-Use Management for the Conservation of the Freshwater Pearl mussel: Sediment Flux and provenance
D04-01	Water Chemistry Report 2015
D04-02	Water Chemistry Report 2016
D04-03	Water Chemistry Report 2017
D04-04	Water Chemistry Report 2018
D04-05	Water Chemistry Report 2019

Table 1.2 Information notes arising from KerryLIFE project.

Annex	Title
E08-05	Drain management
E08-06	Firebreaks
E08-07	Forest Restructuring
E08-08	Livestock and Grazing Management
E08-09	Silt fencing
E08-10	Log dams
E08-11	Halo-thinning
E08-12	Grass re-seeding
E08-14	Cattle drinking troughs
E08-15	Riparian fencing
E08-16	Nutrient management planning
E08-17	Crossing points for livestock
E08-18	Freshwater pearl mussel wall poster
E08-19	Book chapter – Farming for Nature

1.2 The “Top 8” populations

The process of producing 27 draft sub-basin plans for *Margaritifera* SAC populations in Ireland (2008 – 2010) investigated the status, distribution and habitats of all 27 mussel populations along with the pressures present in each catchment and how they related to the condition of each protected population. Based on the population conditions and the catchment pressures a ranking system was produced (Moorkens, 2010). This resulted in the prioritization of eight populations, which remarkably supported 80% of all *Margaritifera* individuals in the Republic of Ireland.

The most important aspect of these populations was the habitat of the mussels. Unlike the smaller populations these mussels were spread across wide areas of river bed habitat, sometimes in every quadrat across each river width, and in very dense numbers, up to 550 mussels per metre square in places. In contrast, smaller populations have very restricted areas of occupancy and are in much lower densities per metre square. This is a result of flow patterns in poorer populations preventing mussels from occupying sections of river bed where flows become too severe in high flows, or too sluggish in low flows. This has become the “normal” situation in mussel populations across Europe and has made the vast majority of protected populations’ conservation dependent, requiring ongoing captive breeding to repopulate river beds in order to continue future generations to live in the wild from sub-adult onwards.

The “Top 8” populations are currently in decline due to landuse intensification within these catchments, which results in hydrological changes that restrict the potential of mussel populations to successfully recruit young mussels for the next generation as sections of river bed become unsuitable. Drained catchments result in more aggressive flows during high rainfall periods as the retention time of water in catchment habitats reduce, and water quickly reaches the river through the drain network. During drought conditions, there is less catchment storage of water to move to the river and water levels and velocities drop to unsustainable levels. Low flows exacerbate nutrient and sediment concentrations and intensification leads to further increases in nutrient levels and sediment transport. Climate change has exacerbated the irregularity of water movement into the catchment with more periods of extreme rainfall and drought.

The “Top 8” populations are all in catchments whose recent (last 100 years) state was mostly blanket bog and related peat habitats. The land use intensification of these peat habitats for agriculture and forestry is impacting the ability of the catchment for water storage and safe delivery to the open water courses due to the lowering of the water tables during drainage and the growth of vegetation with higher interception, evaporation and transpiration levels than natural peat vegetation. Catchments dominated by drier habitats, such as those of naturally occurring oak woodland as in Killarney National Park do not support a wide distribution or high density of pearl mussels in spite of their natural condition. Natural forest catchments are important for reasons other than pearl mussels but due to their high use of water mussel population sizes are relatively low. The best population associated with Killarney National Park was estimated at 100,000 maximum in 2010, only 3% of that of each of the Caragh and Kerry Blackwater population estimates in the same year.

1.3 Environmental requirements of *Margaritifera margaritifera*

A number of reports and peer reviewed papers have published environmental requirements for the freshwater pearl mussel (Bauer, 1988; Skinner et al., 2003; Moorkens, 2006 ; NSAI, 2017), with the CEN standard (NSAI, 2017) providing a comprehensive review of requirements and how they differ within the Holarctic range of the species. Older studies erred on the side of considering freshwater pearl mussels to be less sensitive than they are. This was due to central European studies dealing with poor, non-recruiting freshwater pearl mussel populations. Due to the decline of mussels over the last 50 years, finding environmental conditions that are appropriate for mussels is very challenging.

The greatest difficulty for mussels in the best catchments is in the impact of very short periods of low flows, perhaps only a few days a year, perhaps not even every year. A few days of poor conditions can result in the loss of five years of juvenile recruitment. This can result in a declining population whose habitat displays excellent mean or median water chemistry, macrophyte, algal, redox and even water velocity conditions, while missing the short periods that result in the loss of juvenile mussels. For this reason mean or median values are not recommended for use by the CEN standard (NSAI, 2017), or in the 2009 *Margaritifera* regulations.

Evidence for the source of decline in mussel populations needs to be accumulated through cross referencing water chemistry, algal and redox conditions with flow velocity and temperature status in order to determine sources of pressures, and actions of multiple stressors.

Recent advances in remote sensing have provided a means of looking back on a number of years data to identify key times of unsustainable pressure on the populations, and attributes that can be measured continuously such as turbidity, water depth, discharge and temperature provide much better information than snapshot sampling. Water chemistry sampling is recommended for investigative monitoring rather than general monitoring for status in the CEN standard (NSAI, 2017).

Flow impairment can lead to mussel death even when water chemistry conditions are within appropriate parameters, as low flows concentrate natural levels of sediment and nutrient to unnatural concentrations. However, impaired water quality can work alone to damage mussel populations, as well as in combination with low flow problems. The CEN standard underlines that high water quality is vitally important in maintaining sustainable *Margaritifera* populations. Together with direct damage, flow changes and sedimentation, a decline in water quality is often responsible for the loss of *Margaritifera* recruitment and ultimately for the extinction of populations.

The CEN standard describes the ecological requirements of *Margaritifera* in three separate sections: fish hosts, water quality, and hydromorphology (including flow and habitat structure). However, the most important message is that all of these factors must be in good condition. They do not act in isolation from each other and their combined effects need to be taken into account when determining the requirements of any specific pearl mussel population.

The vast majority of extant *Margaritifera* populations throughout their range are depleted and lacking in natural juvenile recruitment, which over the long lifetime of the species leads to small populations of elderly individuals and then extinction. The conservation response to saving these populations from reaching extinction has been captive breeding. Over the last two decades the greatest conservation efforts for the species have been in efforts to maintain population genetics through the laboratory rearing of young and their maintenance until they reach a level of robustness that survive translocation to the wild. A much greater challenge is to find the best catchment management approaches for small populations where individuals are now restricted to pockets of preferential flows. These habitat pockets are likely to represent the locations of the last successful survival of juvenile mussels, which may have been 50 years ago, and are now not demonstrating any juvenile survival at all. The biggest conservation research question for these rivers is whether catchment actions could improve conditions to the extent that natural juvenile recruitment could recommence within the residual habitat suitability available in a changed i.e. intensified catchment. The answers to this key conservation question is far from resolved, the most recent trials are focussed on the survival of translocated captive bred individuals such as in projects in the Ballinderry River (Kyle et al., 2017) and the Irt River[1].

The only *Margaritifera* population to date that has successfully been restored is the Lutter River population, where catchment purchase and de-intensification succeeded in restoring natural habitat conditions and juvenile recruitment (Altmueller & Dettmer, 2006).

The differences in approach and indeed potential objectives for the 27 Irish *Margaritifera* SAC populations need to be based on what research demonstrates is the ultimate potential for each population. This is discussed later when considering the value of different catchment actions. The restoration of full catchment function for the Irish “Top 8” – the largest and most dense mussel populations in Europe - is challenging but ultimately achievable. As the most important populations of the most endangered animal on the EU Habitat’s Directive this is of both national and international importance and urgency. Of the “Top 8”, the Caragh and Kerry Blackwater populations have the highest numbers of mussels in the country, and so were ideal to act as the target for this LIFE project.

1.4 Methodologies

A very wide range of methodologies were used throughout the varied monitoring programmes. The individual methodologies followed can be found in the individual reports referenced.

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[1] https://www.fba.org.uk/FBA/Public/Discover-and-Learn/Projects/Freshwater_Mussel_Reintroductions_Project.aspx

2 Ecosystem Services provided by mussels and their wider catchment habitats

2.1 Ecosystem services provided by freshwater mussels

Freshwater pearl mussels perform many important functions in aquatic ecosystems, which can be described as the ecosystem services that they contribute to or provide. These include:

Regulating services such as water purification (biofiltration), estimated at an average of 50l of water per day per mussel (Ziuganov and Nezlin, 1988). A large population of mussels can filter the entire water supply in the river at low flow, cleaning the water and providing better visibility for fish to find their prey. Their nutrient recycling and storage services assist the natural balance of their oligotrophic habitat. Freshwater pearl mussel faeces feed the smaller invertebrates to provide a larger supply of food for salmon and trout. Food is typically the limiting factor for fish size and density in oligotrophic waters. DuBose et al. (2019) conclude that the presence of adult freshwater mussels and the resources that increase in their presence potentially mitigate stress to fish in "ecological crunch times", and that by conserving mussels, fish populations might withstand droughts more easily.

Structural services as habitat modifiers. Freshwater pearl mussels become an intrinsic part of the river bed substrate with their cobble-sized shells sheltering gravels and sands beneath them, providing a much wider range of microhabitat conditions than a river without them (Atkinson et al., 2020; Nickerson et al., 2021). This biogenic habitat functions in the same way as an oyster reef in supporting a much wider food web, and on death the mussel shells decay into smaller fragments providing more habitat and eventually recycling Calcium within the river bed substrate where it can be concentrated into other invertebrate shell and exoskeleton (Gutierrez et al., 2003; Vaughn, 2018).

Food and other use services cannot be ignored, although *Margaritifera* is not a human food, dead and decaying mussels are eaten by scavengers. Until it was prohibited, mussel pearls were harvested for jewellery and shells were used as spoons in prehistoric times, and as fertilizer during more recent times (Lucey, 2005). Removal of shells from the river bed provides the fertilizer service but this takes away from the service, as a natural source of calcium in the river itself.

Environmental monitoring services are some of the most important ecosystem services that freshwater pearl mussels provide. They are sentinels or biomonitors of environmental change, providing a record of past conditions and monitoring future change. Mussel stress levels can be used to identify periods of inappropriate conditions in advance of a survey (Moorkens & Killeen, 2018b). Because they are sessile filter feeders they bioaccumulate particles, allowing measurement of stressor levels in their soft tissues (Fritts et al., 2015). They are long lived, and so repeated sampling can provide evidence over a much wider period of time than most animals. Geochemistry of mussel shells can reveal past physical and chemical conditions, growth rates and stress periods and retain patterns of the chemical and physical environment long after the animal's death, and thus can act as historical archives to reveal long-term environmental change, with up to 1,000 years of data available from old shell middens (Dunca et al., 2005, 2011; Geist et al., 2005; Fritts et al., 2017). Monitoring mussels provides an important means of following the progress towards the rehabilitation of wider catchment conservation measures, as has been done in the KerryLIFE project, as well as in many projects across the distribution of Unionid mussels (Haag & Williams, 2014; Donohue et al., 2006; Moorkens, 2010; DuBose et al., 2019;).

Economic services arise from the financial benefits from cleaner water for human and animal consumption as well as the tourism value of clean water for walking, swimming and particularly for game fishing. The financial benefits from agri-environmental schemes to support lower intensity habitats as part of conservation and climate efforts is increasingly important. The integration of economic and biophysical models to evaluate the effects that agri-environmental policies have on the value of freshwater ecosystem services is an emerging and important area of research (Lupi et al., 2020). The conservation value and ecosystems benefit of restored habitats needs to feature in the whole catchment approach to economics such as the SEEA-EA geospatial approach whereby existing data on ecosystem stocks and flows, at a range of scales, are collated. (United Nations et al., 2014).

Cultural and spiritual services value goes beyond the use of pearls for jewellery in the past. Where mussels were historically very abundant, they invoked as ‘‘sense of place’’ that was translated into names associated with their dark colour such as “Bundorragha” (dark bottom) and “Blackstones Bridge” on the Caragh, the “Perlenback” stream in Germany, and the many name associations with American Unionid mussels, such as the city of Mussel Shoals in California and Muscle Shoals in Alabama (Haag, 2012; Vaughn, 2018). The memory of finding freshwater pearl mussels as a child is a regular source of anecdotal stories for mussel surveyors, and it displays the spiritual value of nature and the importance of conserving it for mental health and wellbeing into the future.

Ecosystem services provided by freshwater mussels in different quality condition

The ecosystem services of all Irish *Margaritifera* populations are lower than they could be if they were restored to more natural function. The populations that are considered capable of rehabilitation to fully functioning *Margaritifera* populations are in the peat catchments of the “Top 8” catchment populations. At present, these populations are deteriorating rapidly and losing the ability to provide the ecosystem services that they are capable of. Due to their remaining distributions and densities, they provide a greater ecosystem service value than poorer populations, and will eventually reduce to the lower contribution that is associated with the poorer depleted *Margaritifera* populations. The small remnant populations do not have the distribution or density to filter much of the water travelling through the system, nor do they have the biomass to produce as much available food from their faeces, or physical river bed structure to support a wider biodiversity. The reduction in mussel numbers is then reflected in lower invertebrate biodiversity and a less balanced fish community. However, any *Margaritifera* population is better than none, and the mussels in remnant populations still perform limited structural, food and economic services, and their environmental monitoring and cultural service value remains very high.

The most ideal ecosystem services can be provided by a fully functioning *Margaritifera* population in a restored peat environment within the “Top 8” catchments. With favourable flows, water quality and fish populations these can also be identified as ecosystem services relating to functional peat habitats as shown below.

2.2 Ecosystem services from restored peatland

The main ecosystem services provided by intact and restored peat are shown below. The services from intact undisturbed peat will be at the highest end of these services, but the services from restored, formerly drained peat where the water table has been raised to within 20cm of the surface can in the worst case scenario reduce the loss of carbon and hydrological damage from prior intensification and in the best case scenario return the peat habitats to a net carbon sink rather than source.

Climate services from peatlands are of high importance to government, statutory agencies, NGOs, business, farmers and other landowners, as well as researchers from the natural and social sciences. This interest is due to the increasing awareness of the roles which peat ecosystems might or actually play in the delivery of ecosystem services (Maltby, 2010). The role of peat in absorbing water means that functional open peatlands can regulate water delivery to a more continuous basis than in drained, artificially planted soils and can therefore mitigate against irregular rain delivery that is already a response to climate change. The climate benefits from peat restoration can be used as part of government policy mitigation actions, and can potentially be paid for in schemes where businesses need to offset their carbon footprint. This can be done where enough effort is put into understanding the carbon balance and flux of greenhouse gases. Where peatlands have had prior damage through drainage and water table lowering, they are likely to be net carbon sources. The reduction of carbon loss, even where it may take a long time to reverse, is a net environmental benefit from early drain blocking actions.

Flood regulating services follow on from above. Where functional peat can regulate water through absorption into a high water table, it follows that this higher capacity for water absorption means more water in the wetland habitats and less flooding into agricultural fields, roads and property. The more regulated movement of water also has benefits as

Erosion Risk services, as landowners will lose less land to the erosive power of very high flows.

Water quality services from restored peat habitats are of great benefit to both the river ecosystem as well as to cost reductions from drinking water treatment, especially from the reduction in dissolved organic carbon, release of iron and fine solids and trihalomethanes (THMs) that are expensive to remove. Further climate change, leading to an increase in mean summer temperatures will likely increase conditionally carcinogenic trihalomethane formation, with a 1.8°C temperature increase and 39% THMs increase by 2050 representing a midrange scenario (Valdivia-Garcia et al., 2019).

Ecological services of natural peat habitats include supporting a wide range of native flora and fauna, for example, birds of prey that manage agricultural pests such as excessive crow numbers. A wide variety of native plants that flower at different parts of the growing season, supporting pollinators over a longer time period, which will be available to pollinate agricultural crops during their shorter flowering season.

As with freshwater pearl mussels, peat habitats provide **cultural services** that provide areas of open wilderness that are of high value for local and international tourism. There are widespread Neolithic and less ancient monuments of interest to add value to the tourist visitor.

3 Seasonal and weather patterns during the KerryLIFE project

Monitoring results need to be considered within the natural climate of the area and interpreted, in particular, with the variations in rainfall during the monitoring periods of the project.

All weather data was provided by Met Eireann (www meteireann.ie). Rainfall data for annual weather conditions are averaged from four Met Eireann rain gauges stationed in the project area at Cloon, Glencar, Glenvickee and Ballaghbeama. Cloon, Glencar and Glenvickee are located within the Caragh catchment whereas Ballaghbeama is located in the Kerry Blackwater catchment. Soil and air temperature was recorded at the nearest weather station (Valentia Island) which is ~25km from the project area. Comparisons are made with the 30-year period from 1981 to 2010 as recommended by Met Eireann (https://www.met.ie/climate-ireland/30year-averages.asp). More detailed information is provided in Phelan et al. (2017, c, 2018 h,i,j, 2019c).

The timescale of the project provided a good range of weather patterns. The rainfall in the Caragh and Kerry Blackwater catchments are some of the highest in Ireland. However, rainfall levels varied considerably by month compared with their monthly averages, as shown in Figure 3.1. The monthly variation through the life time of the project varied from a low of 41% (June 2018) to a high of 179% (August 2016) of average monthly rainfall. In spite of this range, all 4 years had above average rainfall levels. Annual averages were 139% for 2016, 103% for 2017, 111% for 2018, and 108% for 2019.

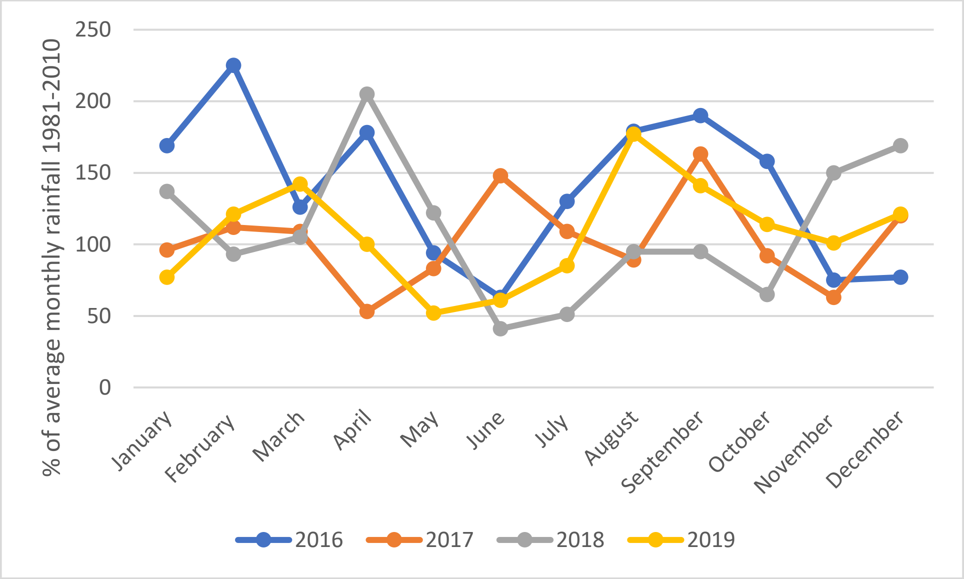


Figure 3.1. Rainfall by month as a percentage of average monthly rainfall for the nearest available rainfall gauge (data from Met Eireann).

Seasonal variation is therefore important, and results are divided into 4 seasons, shown as 1 (January to March), 2 (April to June), 3 (July to September) and 4 (October to December). This seasonal variation is shown in Figure 3.2. While overall rainfall follows the 30-year average, the pattern of rainfall is showing evidence of changing to more periods of drought and other periods of higher rainfall. This fits in with Met Éireann Senior Climatologist Keith Lambkin statement:

"As the WMO publishes its 'Provisional Statement of the State of the Global Climate 2020', it's an opportunity to reflect on how 2020 compares to Ireland's normal climate. Extreme weather experienced in Ireland in 2020 is likely to become more common into the future. Our analysis shows a

wetter Winter and drier Spring than we have been used to. This pattern is in line with predicted climate change-related trends for Ireland. We saw the impact of such weather on our daily lives this year with the high level of flooding in February, particularly in the Shannon catchment. At the other end of the spectrum, a national hosepipe ban was introduced after parts of the East had its driest Spring on record This pattern is in line with predicted climate change-related trends for Ireland. We saw the impact of such weather on our daily lives this year with the high level of flooding in February, particularly in the Shannon catchment. At the other end of the spectrum, a national hosepipe ban was introduced after parts of the East had its driest Spring on record. A number of significant storms during 2020, including Brendan and Ellen, caused the loss of electricity, affecting people and businesses throughout the country.” (Department of Housing, Local Government and Heritage, 2020).

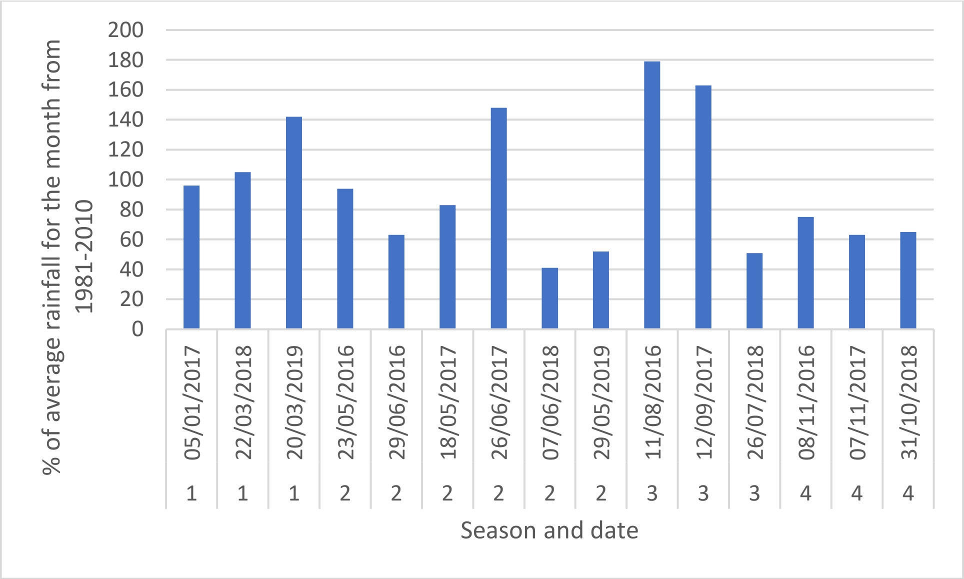


Figure 3.2. Seasonal comparison of rainfall by month as a percentage of average monthly rainfall for the nearest available rainfall gauge (data from Met Eireann).

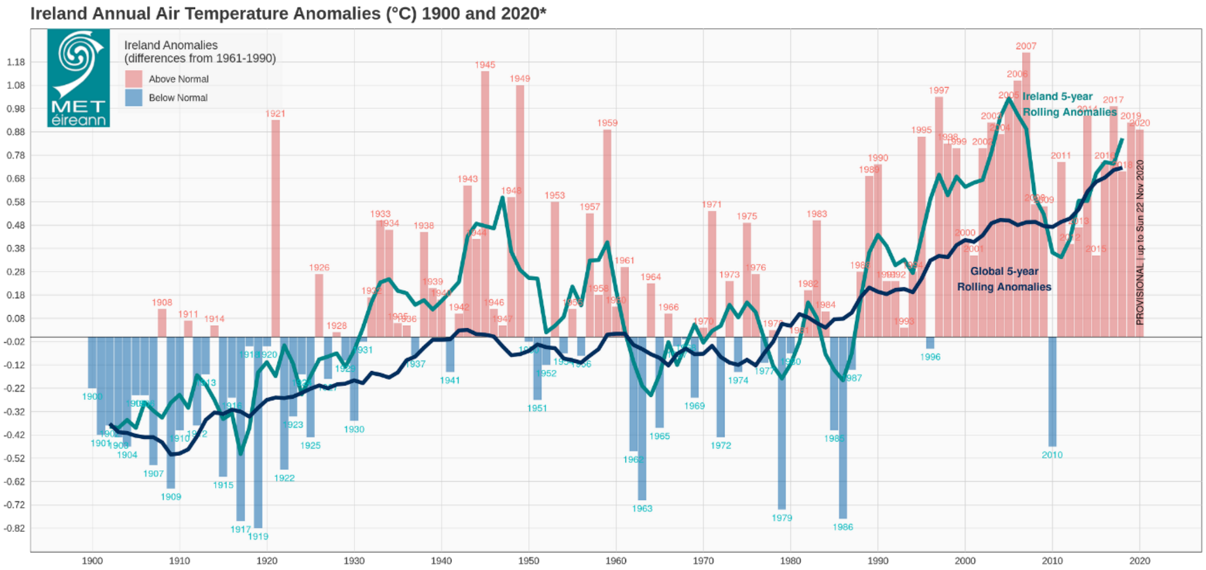


Figure 3.3. Air Temperature anomalies in Ireland since 1900 (figure from Met Eireann website).

Temperature patterns (Figure 3.3) as well as rainfall pattern changes are also important for choosing which *Margaritifera* populations to place the most effort. The high rainfall patterns associated with the "Top 8" populations is on reason to place the highest effort into their rehabilitation to sustainability.

The rainfall and temperature patterns in the KerryLIFE catchments are shown in Figures 3.4 to 3.8. The 30-year average rainfall in the project area is 2,725 mm (range: 1,885 to 3,497 mm). Comparing this with the project period, there were 3,036 mm of rain in 2015, 2,549 mm in 2016, 2,364 mm in 2017, 2,473 mm in 2018 and 2,499 mm in 2019.

Rainfall was frequent in these catchments with 252 wet days (days with > 1mm of rain) in 2015, 229 in 2016, 255 in 2017, 225 in 2018 and 247 in 2019.

There was prolonged heavy rainfall in January and February 2016 and there were pronounced dry periods in the following March, April, May, October and November. On the 3rd of October 2016 there was an extreme rainfall event with 149 mm of rain. This was the third largest daily rainfall amount recorded for the area (from records dating back to 1949: 176 mm on the 05/08/1986 and 165 mm on the 18/09/1993). In 2017 April was by far the driest month (69 mm rainfall and September was the wettest (300 mm rainfall). In 2018 the driest months were June and July when heat wave and drought conditions were reported across Ireland. In the KerryLIFE project area, combined rainfall for June and July was the lowest on record (since 1950) and was only 38 % of the 30-year average for these two months (116 mm compared to 302 mm). In contrast January and November of 2018 were the wettest months with 403 and 429 mm each month, respectively. Mean soil temperatures during the time of the project showed a pattern of increased averages compared to the 30-year average.

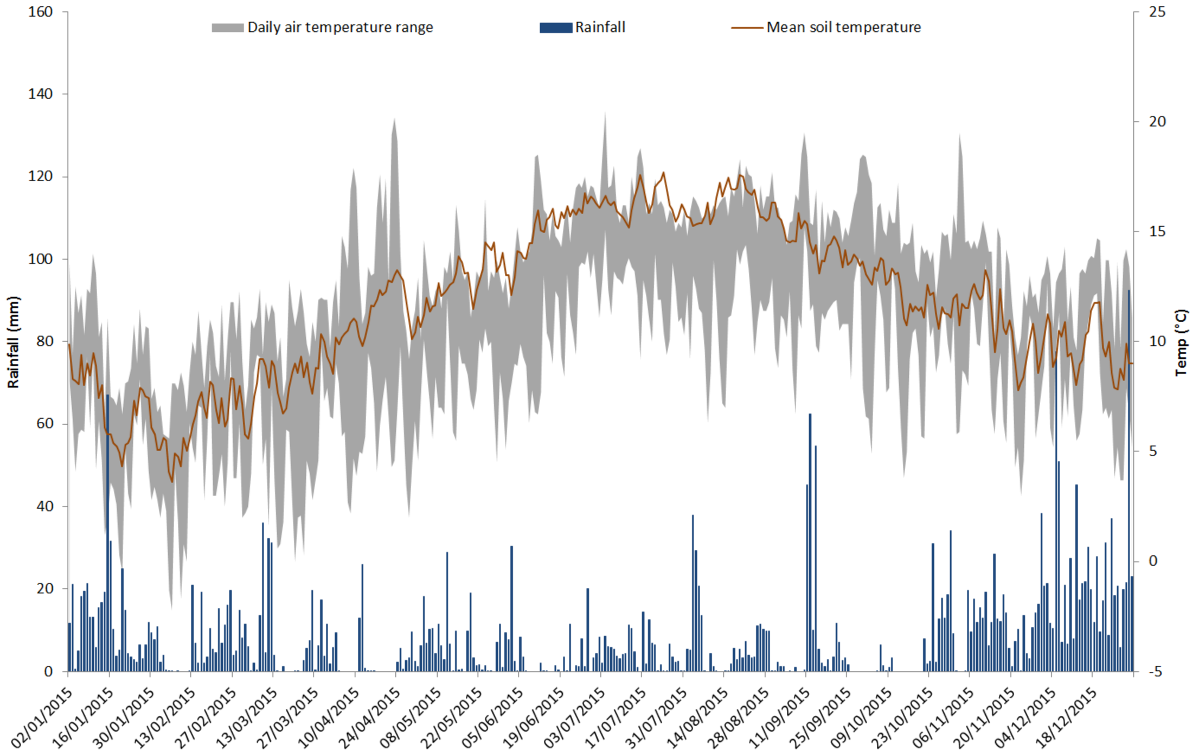


Figure 3.4. 2015 air and soil temperature and daily rainfall in the project area (Met Eireann data)

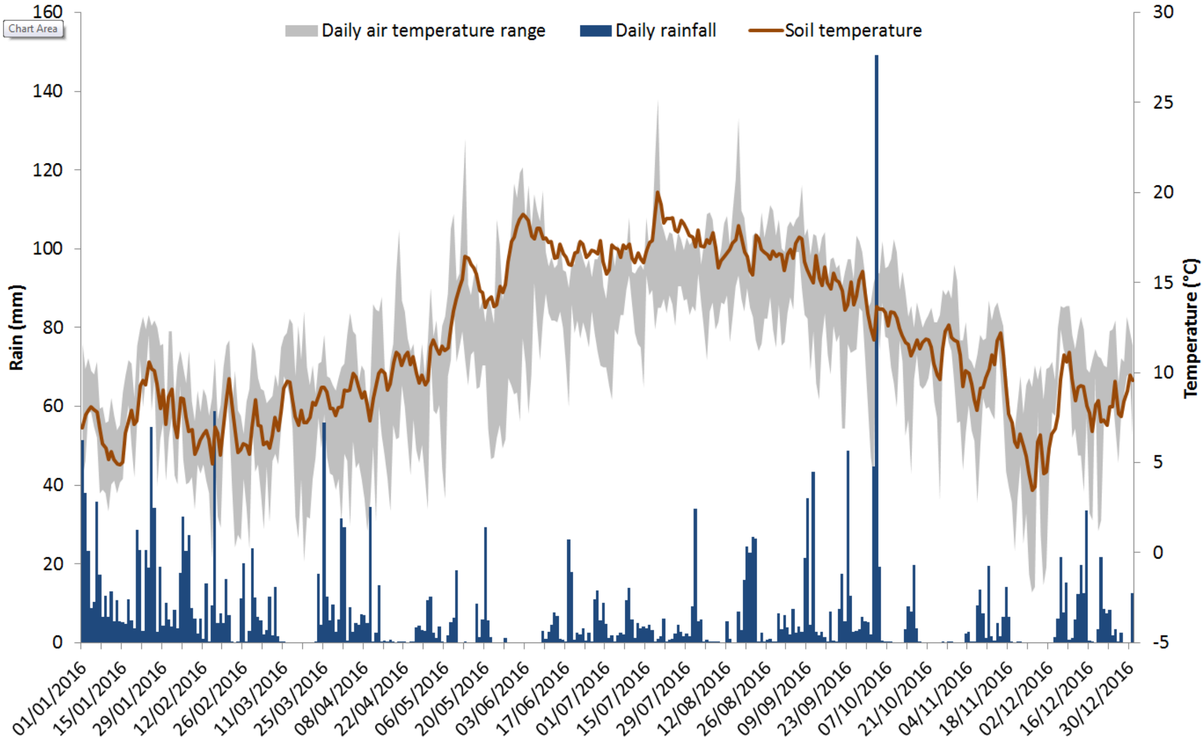


Figure 3.5. 2016 air and soil temperature and daily rainfall in the project area (Met Eireann data)

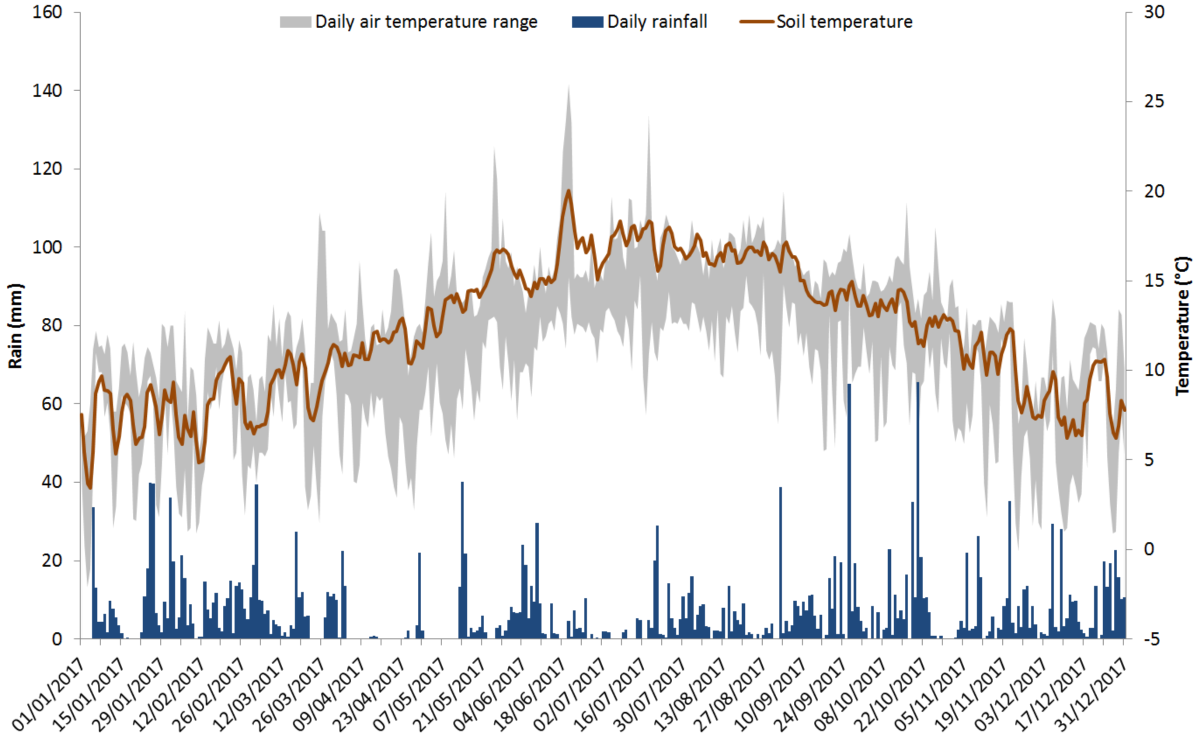


Figure 3.6. 2017 air and soil temperature and daily rainfall in the project area (Met Eireann data)

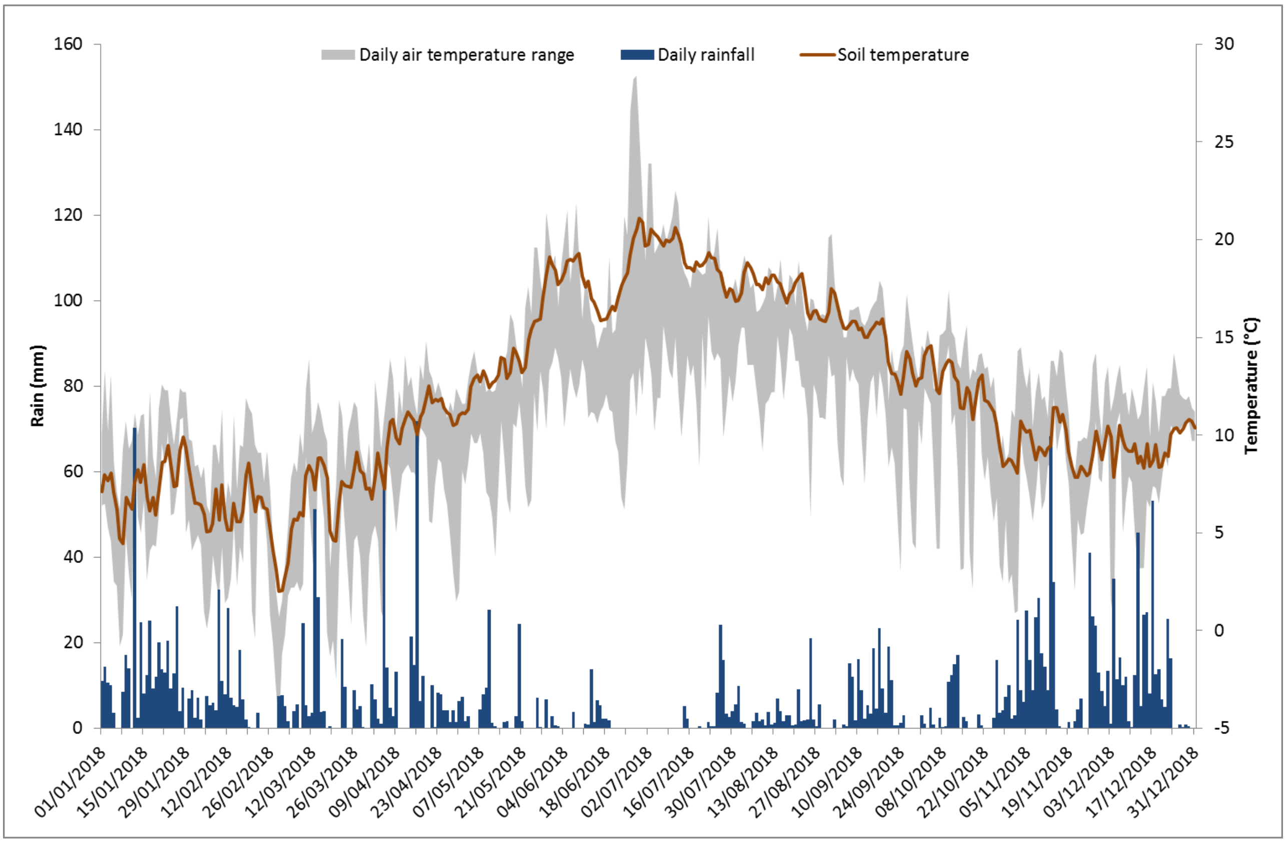


Figure 3.7. 2018 air and soil temperature and daily rainfall in the project area (Met Eireann data)

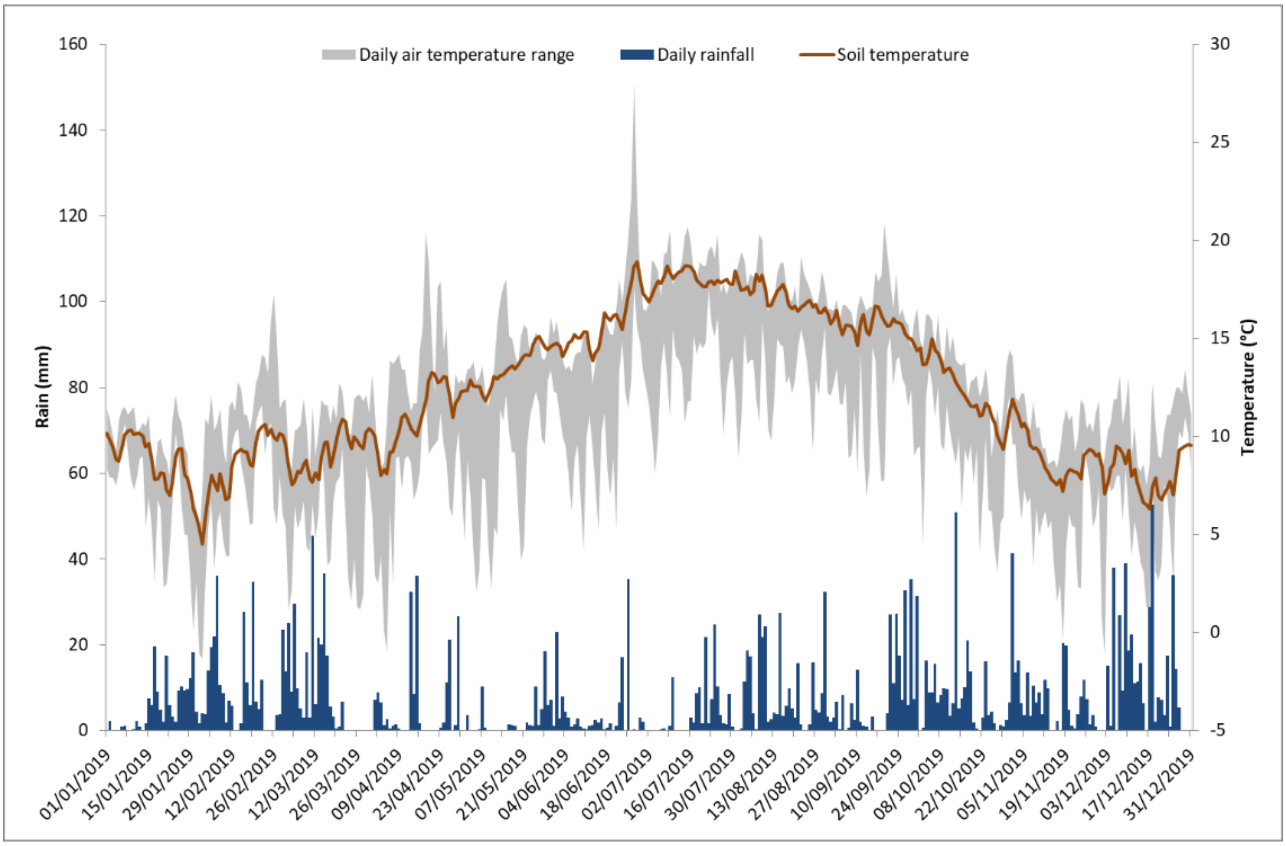


Figure 3.8. 2019 air and soil temperature and daily rainfall in the project area (Met Eireann data)

4 Water Chemistry

Water chemistry was monitored during the KerryLIFE project through the use of a series of quarterly repeated samples that represented the main channels of the catchments; the streams associated with agricultural participants in the project; and forestry streams associated with actions in the project. The sites are listed Table 4.1 with full details being available in Phelan et al. (2017c,d, 2018j,k, 2020), these being reports for 2015, 2016, 2017, 2019 and 2019 respectively. N.B. Only one forestry stream was analysed in the Caragh Catchment, whereas 14 were monitored in the Kerry Blackwater Catchment, so comparisons should not be over interpreted.

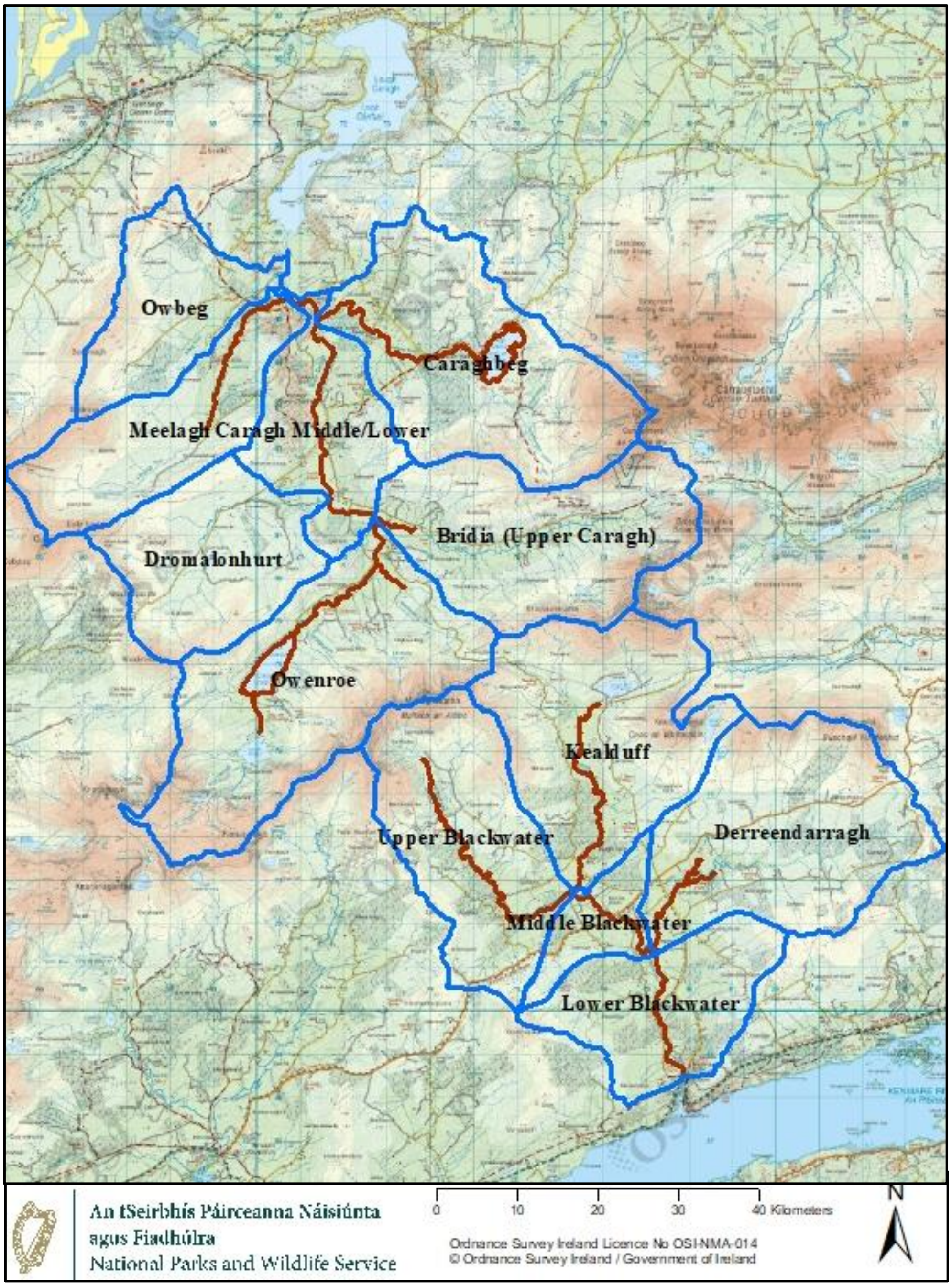


Figure 4.1 Map of KerryLIFE project area and principal sub-catchments.

Table 4.1. Sites used to interpret repeated water chemistry sample results.

Caragh main channel sites (in downstream order)	Caraghbeg main channel sites (in downstream order)	Owenroe main channel sites (in downstream order)	Caragh agricultural streams		Caragh forestry stream
Caragh (CA007)1	Caraghbeg (CA016)	Owenroe (CA013)	Agri (CA004)	Agri (CA011)	For (CA008)
Caragh (CA005)	Caraghbeg (CA003)	Owenroe (CA018)	Agri (CA006)	Agri (CA012)	
Caragh (CA002)		Owenroe (CA009)	Agri(CA010)	Agri (CA014)	

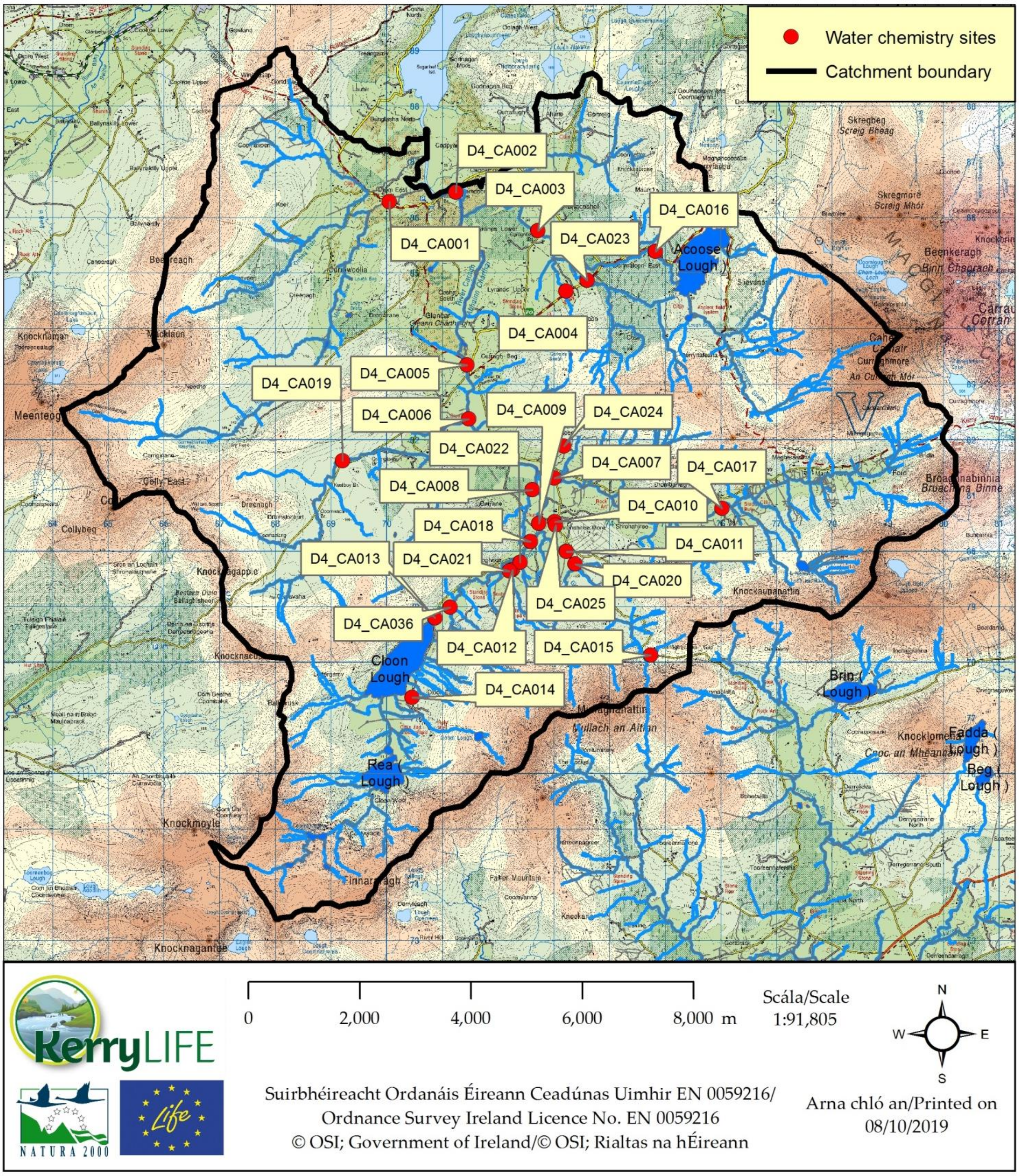


Figure 4.2 Map of Caragh catchment showing location of all water chemistry monitoring stations.

Table 4.2. List of Kerry Blackwater sites used to interpret repeated water chemistry sample results.

Kerry Blackwater main channel sites (in downstream order	Kealduff main channel sites (in downstream order)	Kerry Blackwater agricultural streams	Kerry Blackwater forestry streams	
Blackwater (BL012)	Kealduff (BL001)	Agri (BL002)	For (BL004)	For (BL014)
Blackwater (BL027)	Kealduff (BL030)	Agri (BL003	For (BL005)	For (BL016)
Blackwater (BL037)	Kealduff (BL009)	Agri (BL011)	For (BL006)	For (BL017)
Blackwater (BL020)		Agri (BL015)	For (BL007)	For (BL023)
Blackwater (BL022)		Agri (BL018)	For (BL008)	For (BL024)
		Agri (BL019)	For (BL010)	For (BL025)
		Agri (BL029)	For (BL013)	For (BL026)

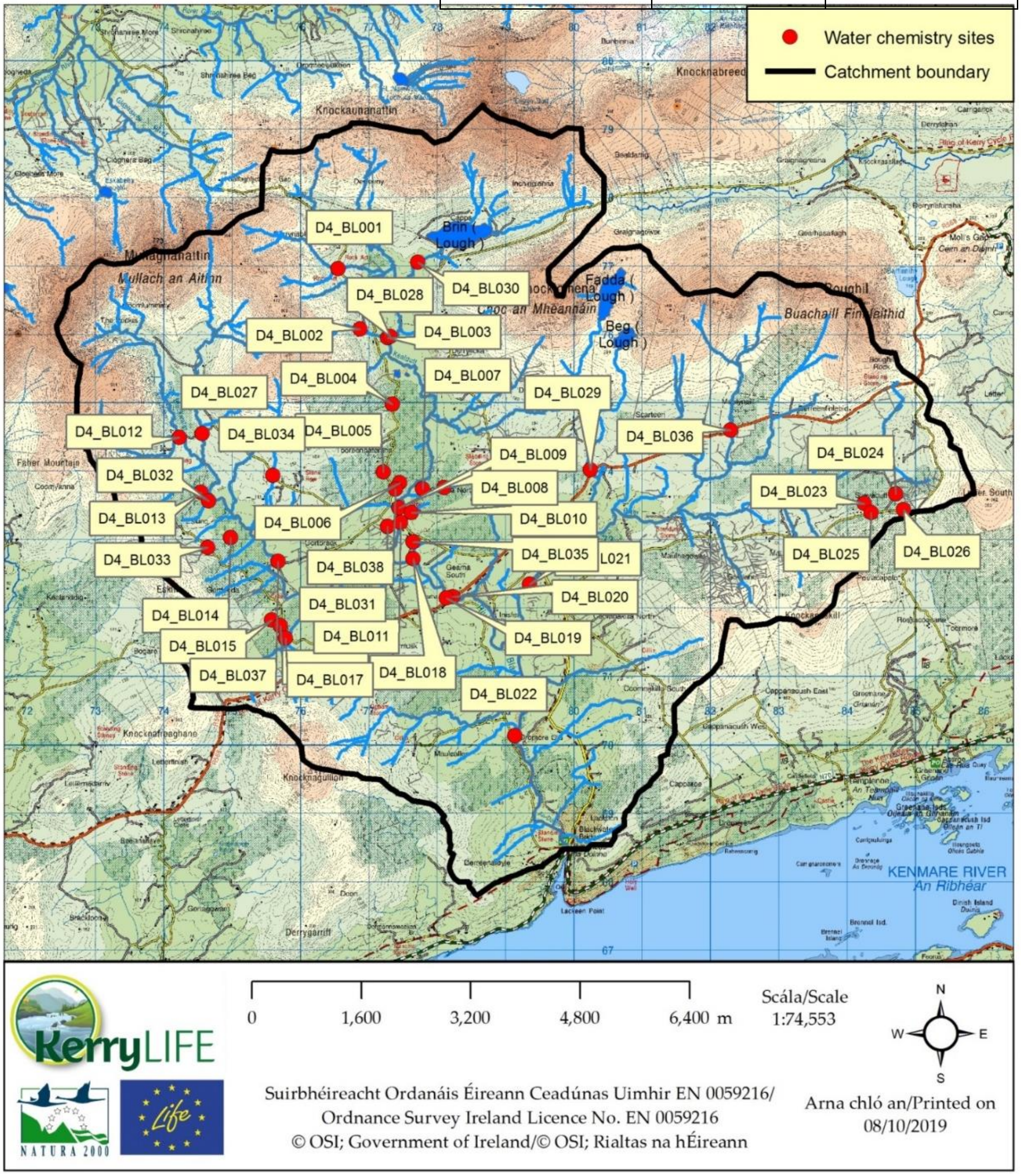


Figure 4.3 Map of Kerry Blackwater showing location of all water chemistry monitoring sites

4.1 Phosphorus and Nitrogen

Phosphorus and Nitrogen, along with temperature and light, are the essential ingredients of algal production in rivers, and excess quantities result in eutrophication. In particular, phosphorus plays a key role as the limiting factor in causing nutrient pollution in systems that should be naturally oligotrophic.

Setting targets for phosphorus, particularly molybdate reactive phosphorus (MRP) that represent an acceptable status for *Margaritifera* is fraught with difficulty, and concentration level targets have been avoided in both the 2009 *Margaritifera* regulations, and in the recent CEN standard for protecting freshwater pearl mussel populations (NSAI, 2017).

The main reason for avoiding targets is that undetectable levels of MRP are not necessarily a guarantee of good health; if all the available phosphorus is being transferred into filamentous algae then it will not be detectable as MRP in open water. While a summation of phosphorus levels over time has been trialled in freshwater pearl mussel rivers using phosphorus-sensitive gels, it is subject to maximum absorbance levels (Mohr et al., 2015), and even regular water sampling only provide snapshot levels. Taking a series of water samples using automatically timed samplers on a rising flood can provide good evidence of source and pathway, but there is no reliable way of establishing exact levels and timing of phosphorus pollution, so some combination of these methods must be chosen for investigative monitoring, and phosphorus release to water can be regularly underestimated (Ulén et al., 2012; Valkama & Ruth, 2017). A combination of very low MRP with the absence of filamentous algae is considered to indicate nutrient levels conducive to *Margaritifera* populations in favourable condition. Equally, the damage that can be caused by short pollution events during warm conditions - i.e. at times when juvenile mussels are most vulnerable to death - mean that the typical approach to nutrient monitoring based on mean or median values is not useful in assessing risk to freshwater mussels. Thus low P values during the colder months of the year cannot mitigate in any way the damage that can be done by the single incident in summer. For these reasons, the CEN standard target for phosphorus is a time series with consistently very low MRP and total P in conjunction with no evidence of eutrophication (e.g. algal growth). Low levels of MRP in the *Margaritifera* context are around the level of determination, with no more than 0.005 mg l^{-1} in summer conditions, and no more than 0.008 mg l^{-1} equivalent if total P is measured.

Total P and MRP were measured in approximately quarterly surveys from winter 2015 to summer 2019. The target values for freshwater pearl mussel of consistently very low MRP and total P in the context of 0.005 mg l^{-1} MRP and 0.008 mg l^{-1} TP were exceeded every year, most extremely in 2018.

This report follows the most indicative sampling sites with the most samples. However, serious elevations of phosphorus and other pollutants were also found at BL021 in the Derreendarragh and BL020 on the main Kerry Blackwater. Of the main channel sites sampled in 2017, four out of 11 sites on the Caragh and five out of 10 sites on the Kerry Blackwater exceeded 0.008 mg l^{-1} TP with their annual mean total phosphorus levels, with damaging incident levels being much higher.

High phosphorus concentrations downstream of forestry were found downstream of a two year-old clearfell at Gearha North and may have been due to continued release of nutrients from brash (branches and needles) residues left after harvesting Phelan et al.(2018j). High phosphorus concentrations are associated with tree felling (Cummins & Farrell, 2003; Piirainen et al., 2004, 2007).

The highest total phosphorus values in the Caragh were recorded in farm drains flowing into the Glashawee river (CA010) and Cloon lake (CA014) and in a drain flowing from in mature, unfelled forestry at Garrane (CA008). In the main channels of the Caragh, the highest levels of total phosphorus were recorded in the Caraghbeg downstream of Lough Acoose (CA016) and further down the Caraghbeg at CA003).

In the Kerry Blackwater, the highest total phosphorus values were recorded as part of investigative sampling upstream and downstream of a silt fence in a roadside drain (BL039 and BL040) at Slievaduff forest. High values were also recorded at BL024 downstream of a combination of land reclamation/improvement, roadworks and forest clearfelling (also downstream of the aforementioned investigative sampling). High total P values were also recorded downstream of farms at BL011 and BL018.

The distribution of MRP values was similar to the distribution of total P values in that the highest MRP values in the Caragh were recorded in a drain flowing from mature, unfelled forestry at Garrane (CA008) and farm drains at CA010 and CA014.

In the Kerry Blackwater, the highest MRP values were recorded as part of investigative sampling upstream and downstream of a silt fence in a roadside drain (BL039 and BL040) at Slievaduff forest. High values were also recorded at BL024 downstream of land reclamation/improvement, roadworks and forest clearfelling (also downstream of the aforementioned investigative sampling). High total P values were also recorded downstream of farms at BL011 and BL018.

MRP concentrations in the main channels of the Caragh and Kerry Blackwater Rivers were <0.005 mg P l^{-1} at all sites on both sampling rounds. The majority of agricultural and forestry sites achieved this or were close to achieving this lower target. As with TP, sites CA010 and BL019 had elevated concentrations of MRP, especially with the May sample (0.072 and 0.195 mg P l^{-1}). Episodic inputs of nutrients from sources such as agriculture and forestry coinciding with the beginning of the growing season are concerning. The MRP levels observed are also likely to not be a true reflection of the level of nutrient inputs as MRP is readily taken up by plants (macroalgae and macrophytes) in oligotrophic rivers.

Figures 4.4 – 4.6 show molybdate reactive phosphorus (MRP) measurements for the KerryLIFE period, to relevant scales in Figures 4.4-4.5 but shown together to the same scale in Figure 4.6 to demonstrate that firstly the MRP levels are excessive in all stream types in both catchments, and that the nutrient status in the Kerry Blackwater catchment is worse than in the Caragh catchment.

― =Appropriate level for freshwater pearl mussel

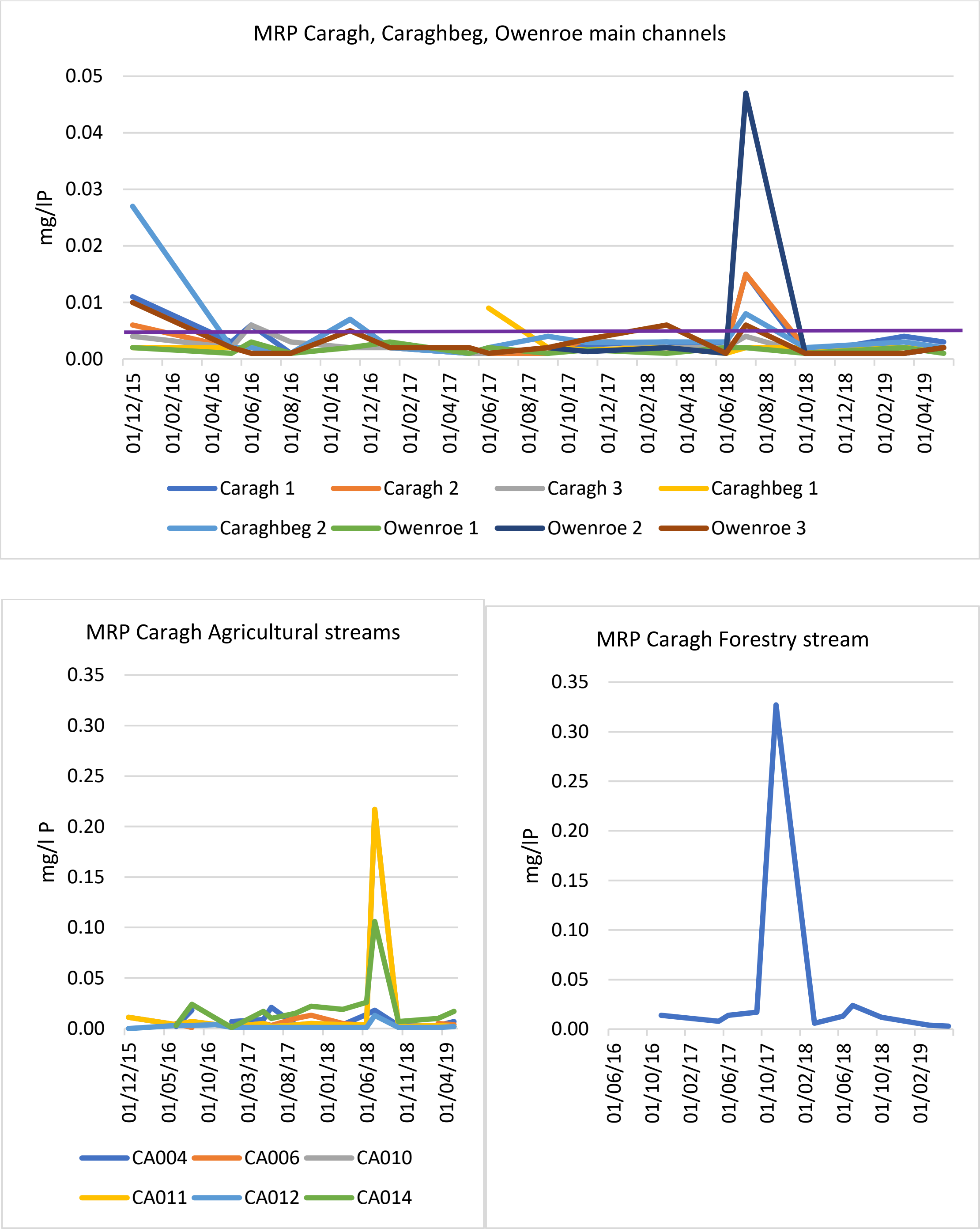


Figure 4.4 Molybdate reactive phosphorus levels in the Caragh Catchment.

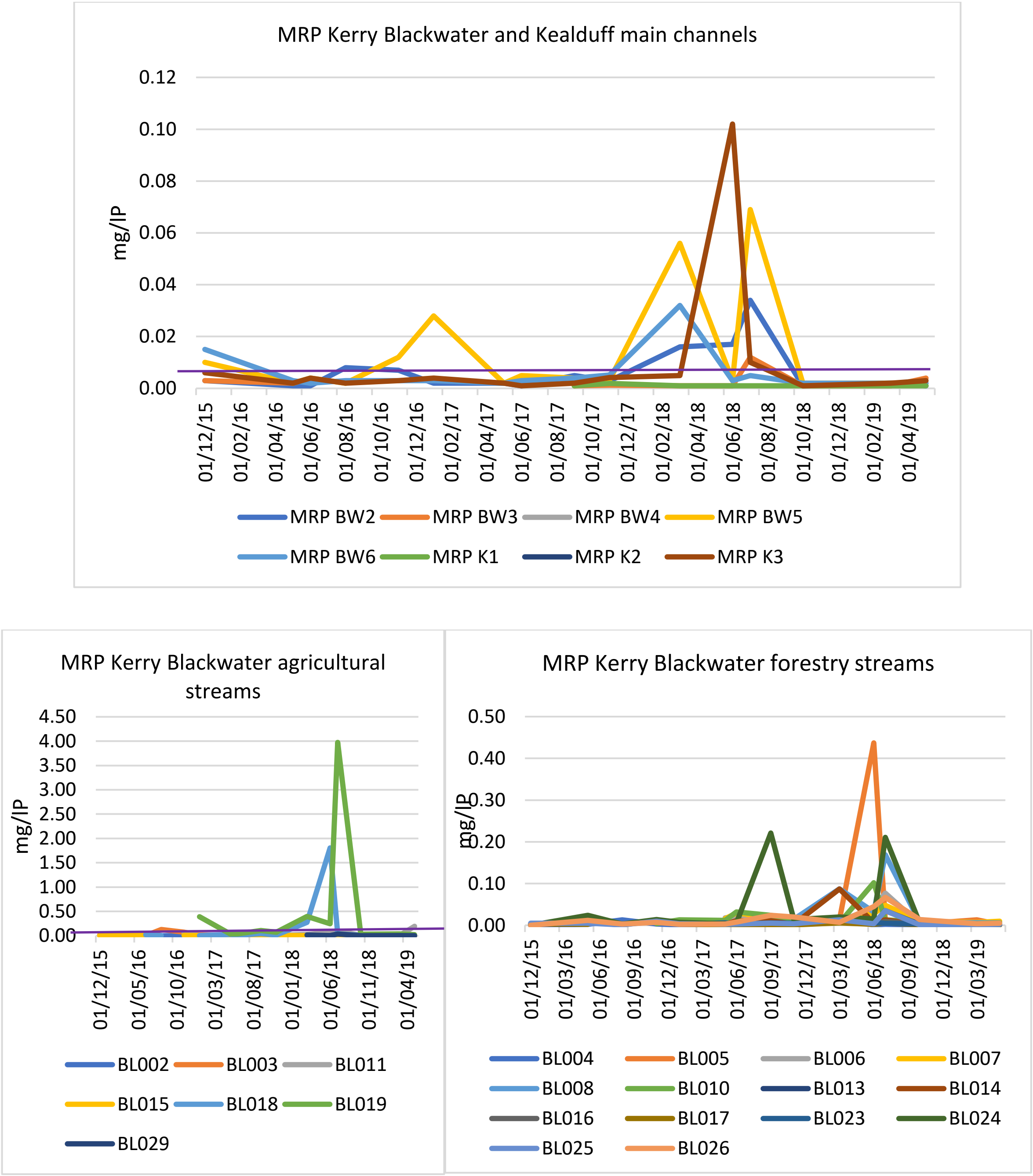


Figure 4.5 Molybdate reactive phosphorus levels in the Kerry Blackwater Catchment.

——— =Appropriate level for freshwater pearl mussels

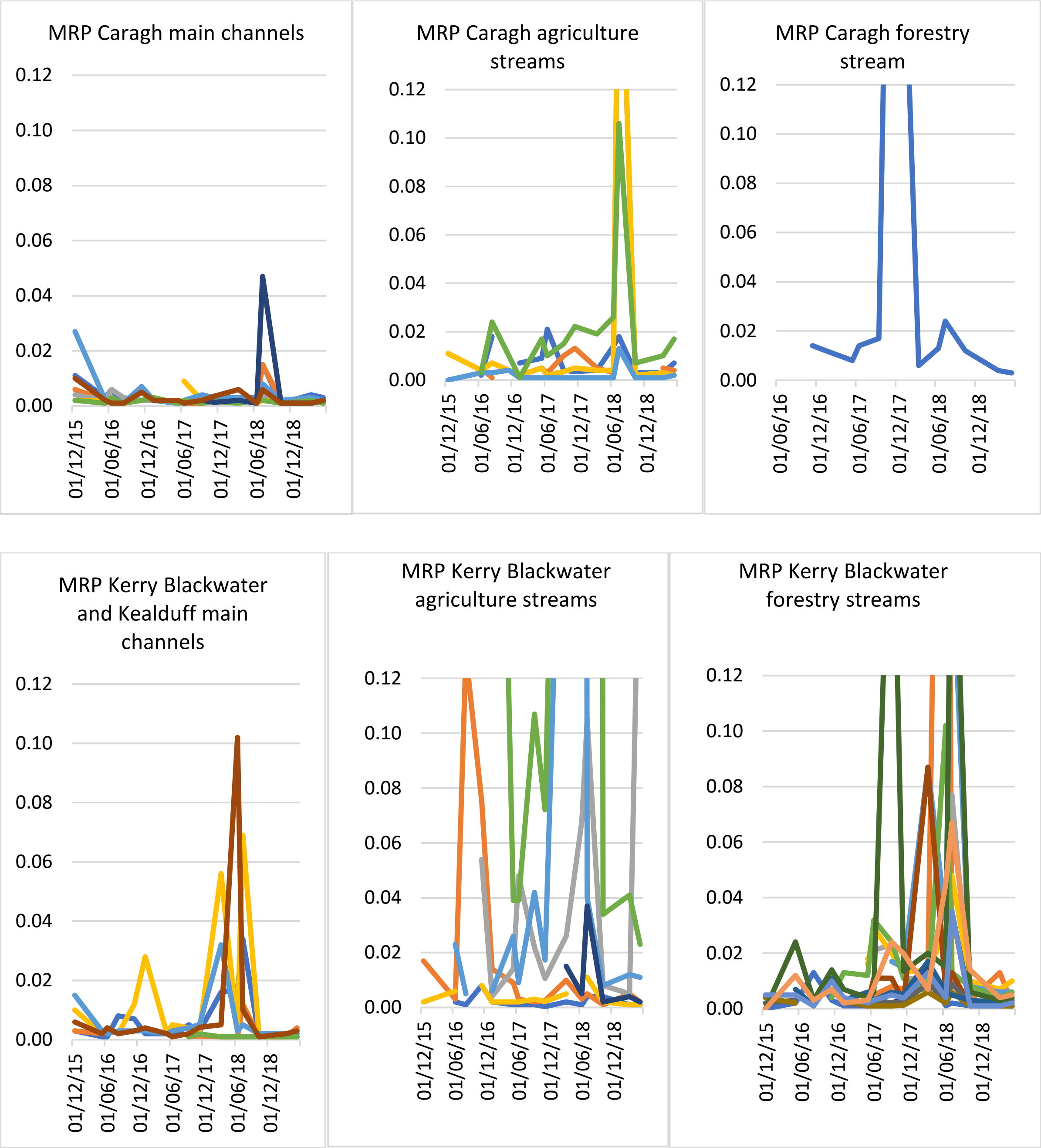


Figure 4.6. MRP levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams shown at the same scale, with MRP on the vertical axis shown as mgl^{-1} P.

In all, none of the streams surveyed were of *Margaritifera* quality throughout the study. The agricultural streams had as much as 43 times the safe *Margaritifera* level of 0.005 mg.l^{-1} in the Caragh, and by 795 times in the Kerry Blackwater. The forestry stream exceeded safe MRP by as much as 65 times the safe *Margaritifera* level in the Caragh, and by 87 times in the Kerry Blackwater (Tables 4.3 to 4.5).

Table 4.3 Caragh agricultural streams MRP measurements and Caragh forest stream (CA008) MRP measurements. Red cells show where safe *Margaritifera* levels have been exceeded.

MRP	CA004	CA006	CA010	CA011	CA012	CA014	CA008 Forestry stream
	Agricultural streams						
03/12/15			0.0110	0.0110			
29/06/16	0.0020	0.0050	0.0040	0.0040	0.0030	0.0030	0.0100
11/08/16	0.0180	0.0010	0.0070	0.0070	0.0030	0.0240	
08/11/16			0.0040	0.0040	0.0040	0.0100	0.0140
05/01/17	0.0070	0.0020	0.0020	0.0020	0.0010	0.0010	0.0120
18/05/17	0.0090	0.0050	0.0050	0.0050	0.0010	0.0170	0.0080
26/06/17	0.0210	0.0030	0.0020	0.0020	0.0010	0.0100	0.0140
12/09/17	0.0040	0.0100	0.0035	0.0035	0.0010	0.0150	0.0170
07/11/17	0.0035	0.0131	0.005	0.005	0.0010	0.0221	0.3270
22/03/18	0.004	0.005	0.004	0.004	0.001	0.019	0.006
07/06/18	0.014	0.003	0.004	0.004	0.001	0.026	0.013
26/07/18	0.018		0.217	0.217	0.013	0.106	0.024
31/10/18	0.0030		0.0020	0.0020	0.0010	0.0070	0.0120
20/03/19	0.0030	0.0050	0.0030	0.0030	0.0010	0.0100	0.0040
29/05/19	0.0070	0.0040	0.0020	0.0020	0.0020	0.0170	0.0030

Table 4.4 Kerry Blackwater Agricultural streams MRP measurements. Red cells show where safe *Margaritifera* levels have been exceeded.

MRP	BL002	BL003	BL011	BL015	BL018	BL019	BL029
03/12/15		0.0170		0.0020			
29/06/16	0.0020	0.0030	0.0090	0.0060	0.0230		
11/08/16	0.0010	0.1290			0.0050	0.0810	0.0030
08/11/16	0.0080	0.0750	0.0540	0.0080			
05/01/17	0.0020	0.0140	0.0040	0.0020	0.0060	0.3930	
18/05/17	0.0010	0.0090	0.0140	0.0020	0.0260	0.0390	
26/06/17	0.0010	0.0030	0.0480	0.0020	0.0090	0.0390	
12/09/17	0.0010	0.0020	0.0220	0.0030	0.0420	0.1070	
07/11/17	0.0003	0.0026	0.0106	0.0022	0.0173	0.0721	
22/03/18	0.002	0.010	0.026	0.005	0.274	0.400	0.015
07/06/18	0.001	0.003	0.068		1.806	0.246	0.005
26/07/18	0.004	0.005	0.105	0.011	0.040	3.974	0.037
31/10/18	0.0040	0.0010	0.0080	0.0020	0.0080	0.0340	0.0020
20/03/19	0.0010	0.0050	0.0050	0.0010	0.0120	0.0410	0.0040

Table 4.5 Kerry Blackwater forestry streams MRP measurements. Red cells show where safe Margaritifera levels have been exceeded.

a)

MRP	BL004	BL005	BL006	BL007	BL008	BL010	BL013	BL014
03/12/15								
23/05/16	0.0020	0.0110	0.0140	0.0420	0.0560	0.0170	0.0040	0.0040
11/08/16	0.0130							
08/11/16	0.0030	0.0090	0.0090	0.0300	0.0380	0.0040	0.0040	0.0050
05/01/17	0.0010					0.0130		
18/05/17	0.0010	0.0030	0.0180	0.0160	0.0130	0.0120	0.0010	0.0020
26/06/17	0.0010	0.0050	0.0210	0.0290		0.0320	0.0030	0.0110
12/09/17	0.0020	0.0080	0.0230	0.0200	0.0170	0.0240	0.0020	0.0110
07/11/17	0.0019	0.0071	0.0112	0.0131	0.0147	0.0109	0.0035	0.0026
22/03/18	0.013	0.013	0.010	0.014	0.087	0.006	0.016	0.087
07/06/18	0.001	0.437	0.042	0.028	0.032	0.102	0.004	0.006
26/07/18	0.002	0.011	0.077	0.048	0.169	0.013	0.035	0.013
31/10/18	0.0010	0.0030	0.0030	0.0100	0.0080	0.0080	0.0020	0.0010
20/03/19	0.0010	0.0130	0.0030	0.0070	0.0060	0.0040	0.0010	0.0010

b)

MRP	BL016	BL017	BL023	BL024	BL025	BL026
03/12/15	0.0020	0.0040			0.0050	
23/05/16	0.0030	0.0020	0.0070	0.0240	0.0050	0.0120
11/08/16			0.0010	0.0030	0.0010	0.0030
08/11/16	0.0110	0.0110	0.0110	0.0140	0.0100	0.0070
05/01/17	0.0020	0.0030	0.0030	0.0070	0.0040	0.0020
18/05/17	0.0010	0.0010	0.0060	0.0040	0.0020	0.0030
26/06/17	0.0030	0.0010	0.0030	0.0060	0.0030	0.0080
12/09/17	0.0020	0.0010	0.0060	0.2210	0.0050	0.0240
07/11/17	0.0026	0.0013	0.0051	0.0135	0.0038	0.0199
22/03/18	0.009	0.006	0.017	0.020	0.013	0.007
07/06/18	0.003	0.002	0.006	0.015	0.004	0.045
26/07/18	0.009	0.006	0.005	0.211	0.035	0.067
31/10/18	0.0020	0.0010	0.0030	0.0060	0.0010	0.0140
20/03/19	0.0010	0.0010	0.0020	0.0030	0.0010	0.0040

Figures 4.7 – 4.8 show Total phosphorus (TP) measurements for the KerryLIFE period, to relevant scales in Figures 4.7-4.8 but shown together to the same scale in Figure 4.9 to demonstrate that firstly the TP levels are also excessive in all stream types in both catchments, and that the nutrient status in the Kerry Blackwater catchment is worse than in the Caragh catchment, and that agriculture is a greater source of phosphorus compared with forestry during that period. This did not include clear felling episodes, which are known to have the potential to elevate P measurements to damaging levels (Cummings & Farrell, 2003).

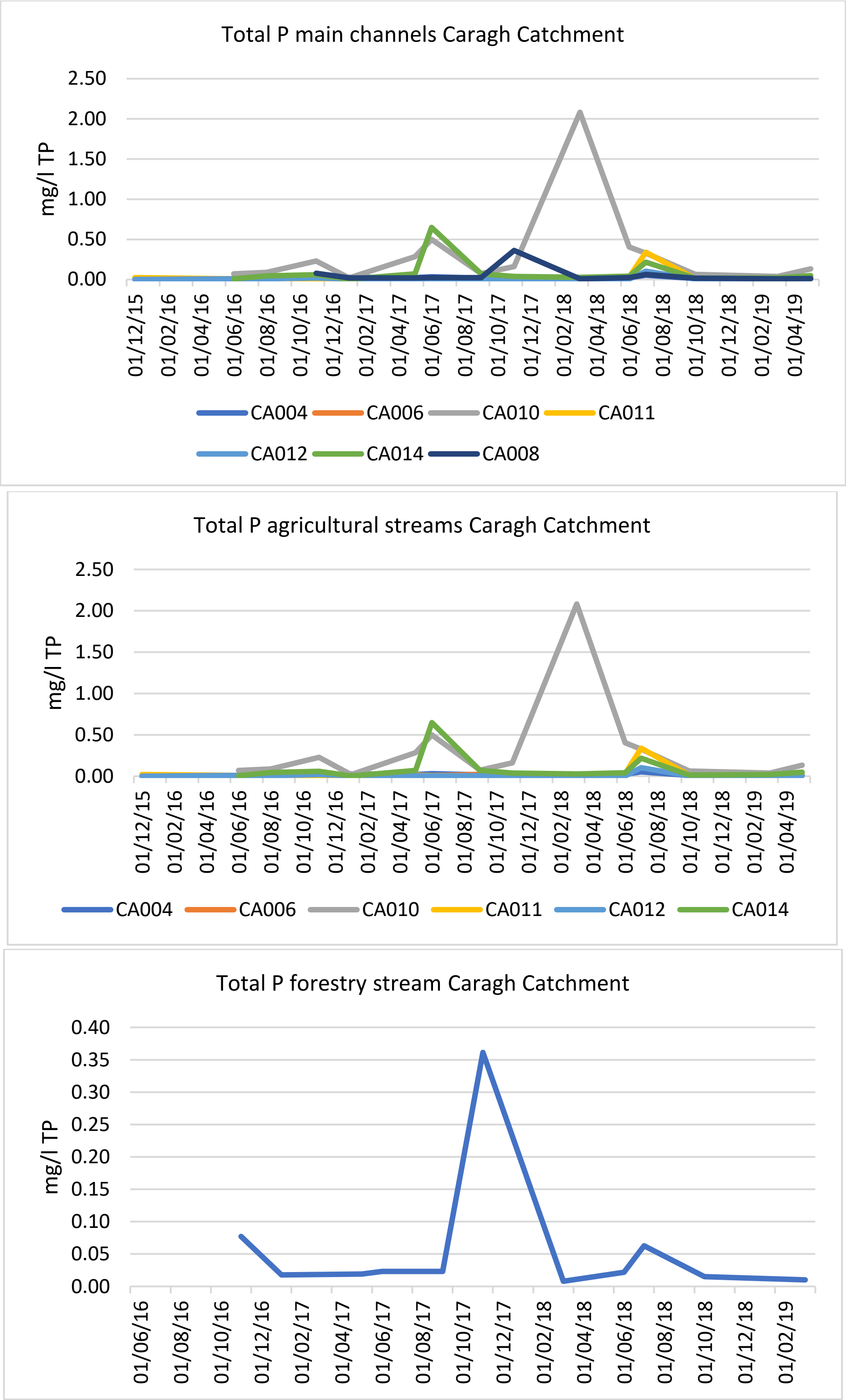


Figure 4.7 Total reactive phosphorus levels in the Caragh Catchment.

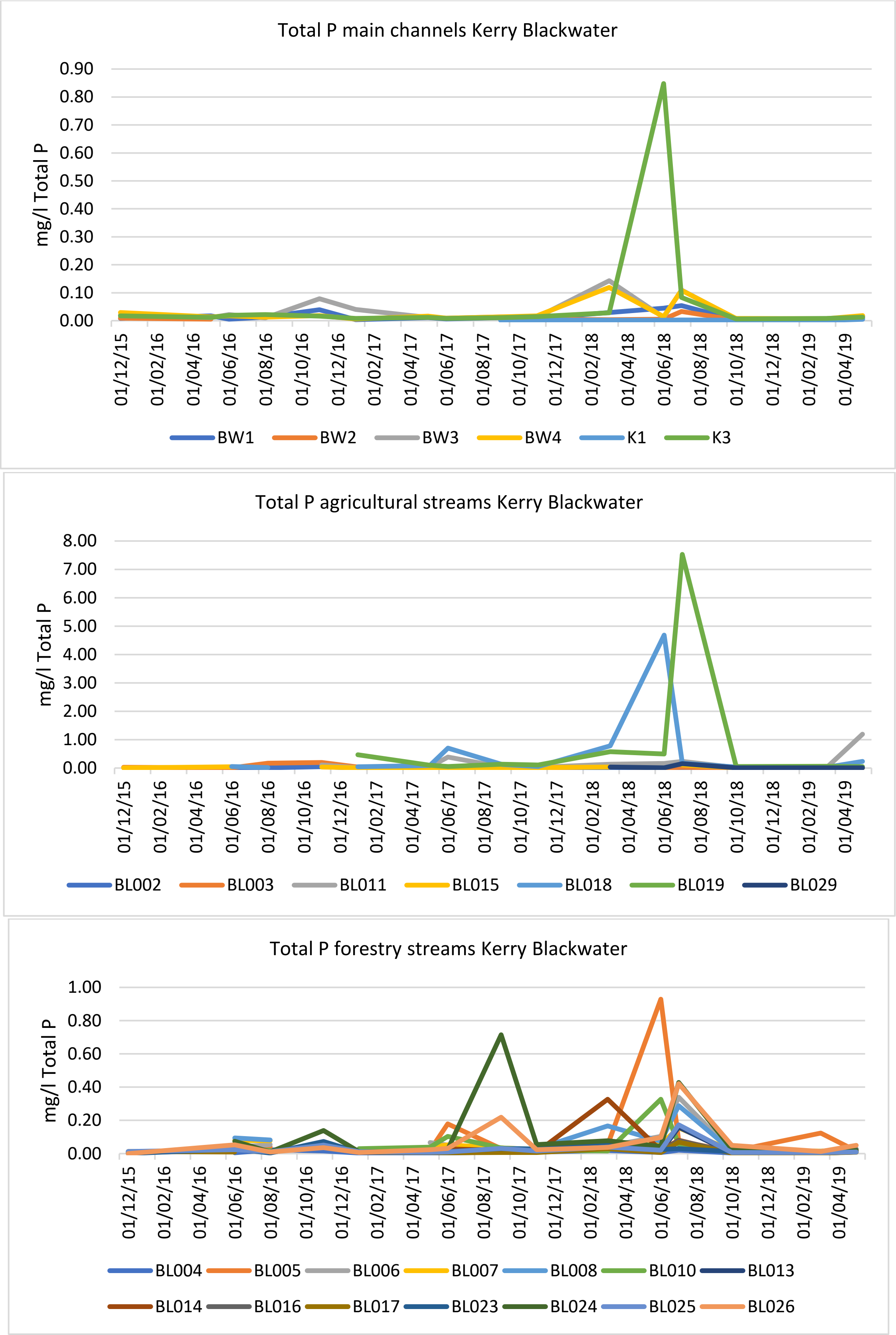


Figure 4.8. Total P levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams of the Kerry Blackwater catchment (appropriate level under 0.008 mg l^{-1})

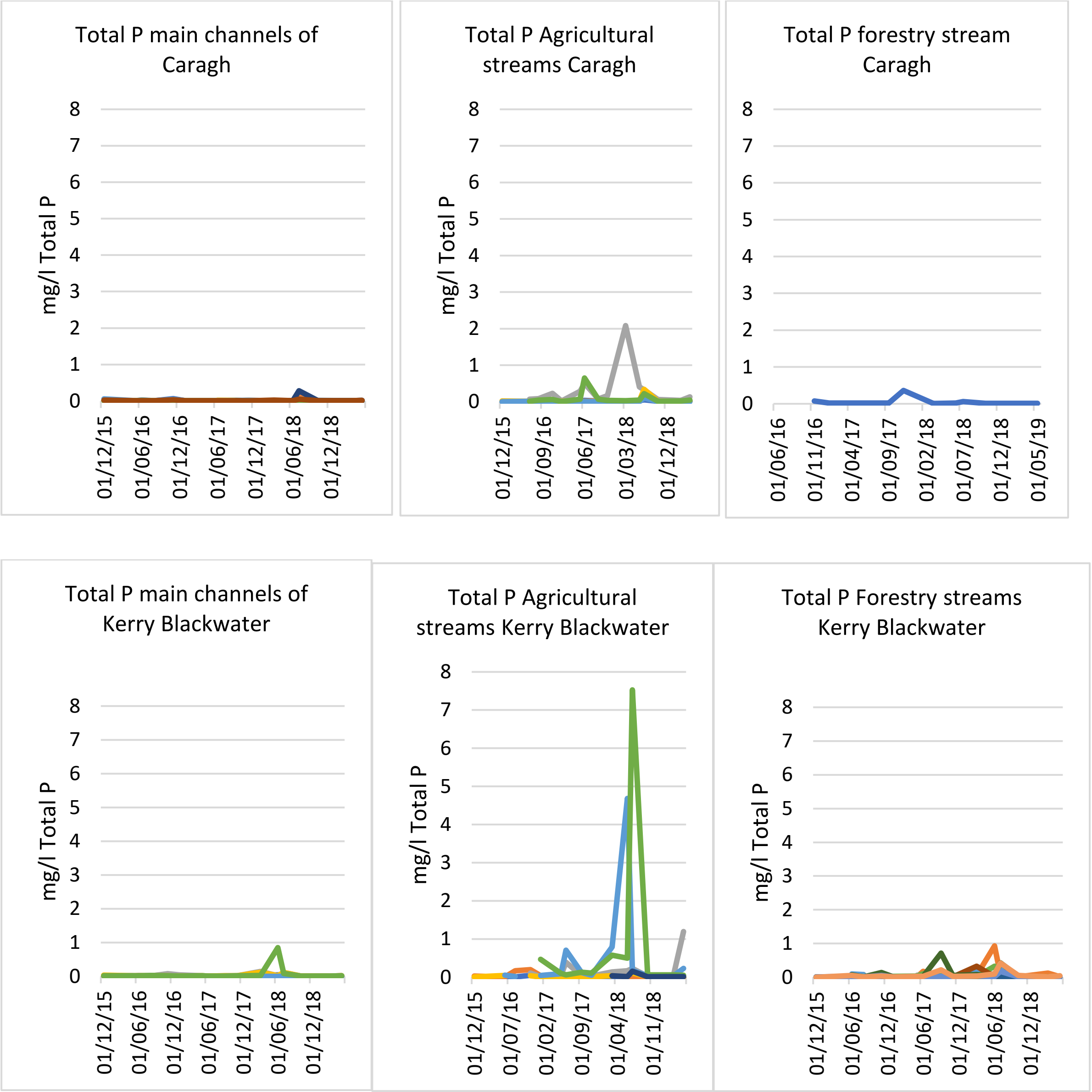


Figure 4.9. Total P levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams of the Caragh and Kerry Blackwater catchments shown at the same scale (appropriate level under 0.008 mg l^{-1})

The main pressure from Nitrogen compounds is the role in eutrophication of Total Oxidised Nitrogen (TON), although this is not normally the limiting factor in algal growth, which is generally Phosphorus, and from Ammoniacal Nitrogen (NH4-N), which is very toxic to freshwater pearl mussels. Toxicity of ammonia (as total ammonia) increases as temperature increases (U.S. EPA https://www.epa.gov/caddis-vol2/ammonia). Ammonia concentration and toxicity increases as pH increases, however less ammonia is required to produce toxic effects at lower pH (Kleinhenz et al., 2019). Ammonia is highly toxic to freshwater mussels (Wang et al., 2007).

Figures 4.10 – 4.12 show Total Oxidised Nitrogen measurements for the KerryLIFE period, to relevant scales in Figures 4.10-4.11 but shown together to the same scale in Figure 4.12 to demonstrate that firstly the TON levels are also excessive in all stream types in both catchments, and that the nutrient status in the Kerry Blackwater catchment is worse than in the Caragh catchment, and that agriculture is a greater source of phosphorus compared with forestry during that period.

Figures 4.13 – 4.15 show Ammonia results for the KerryLIFE period in the same manner as before. This demonstrates that excessive Ammonia (>0.01mg l^{-1}) is regularly reaching the main channel areas from both agricultural and forestry stream sources.

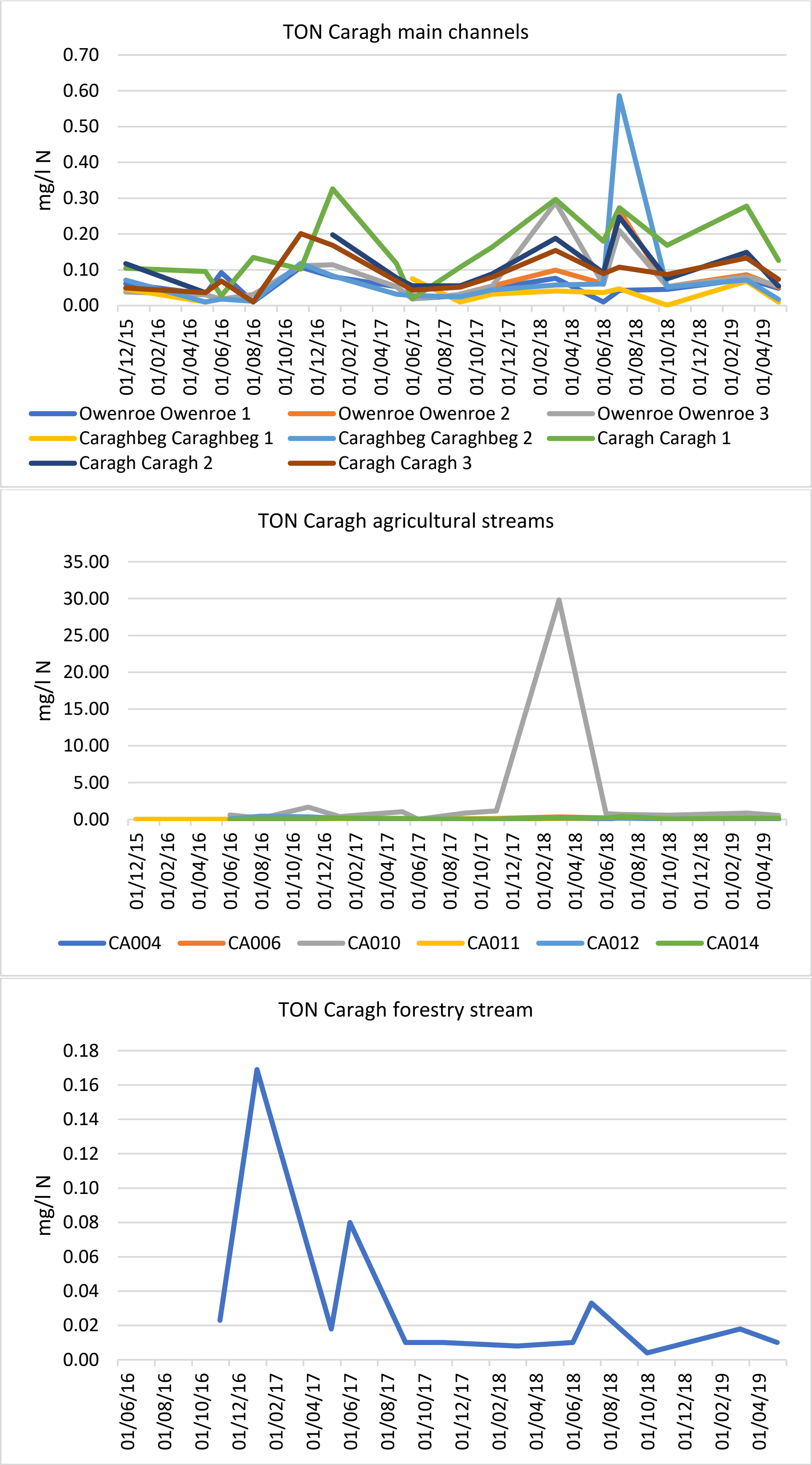


Figure 4.10 Total Oxidised Nitrogen levels measured in the Caragh Catchment.

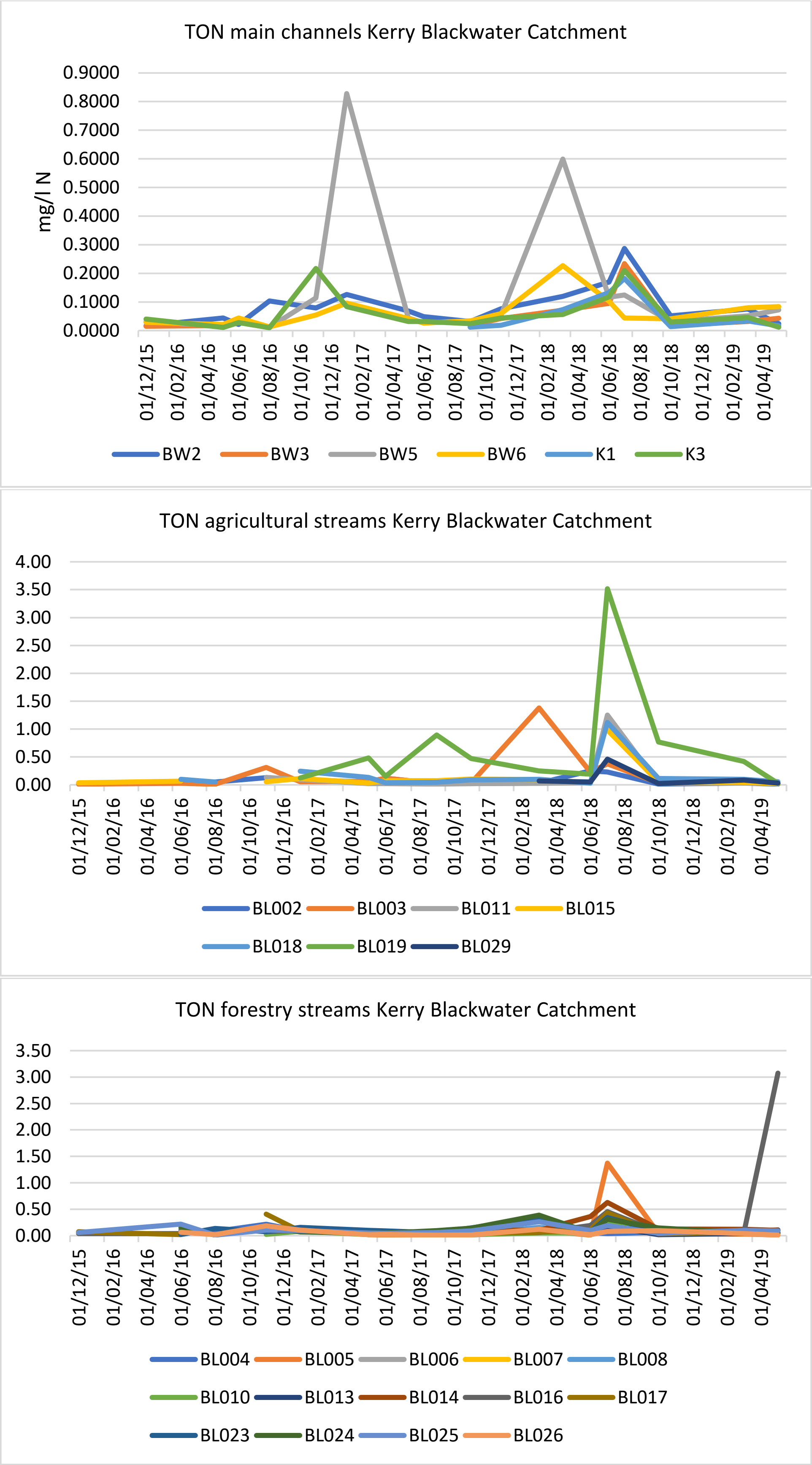


Figure 4.11 Total Oxidised Nitrogen levels measured in the Kerry Blackwater Catchment.

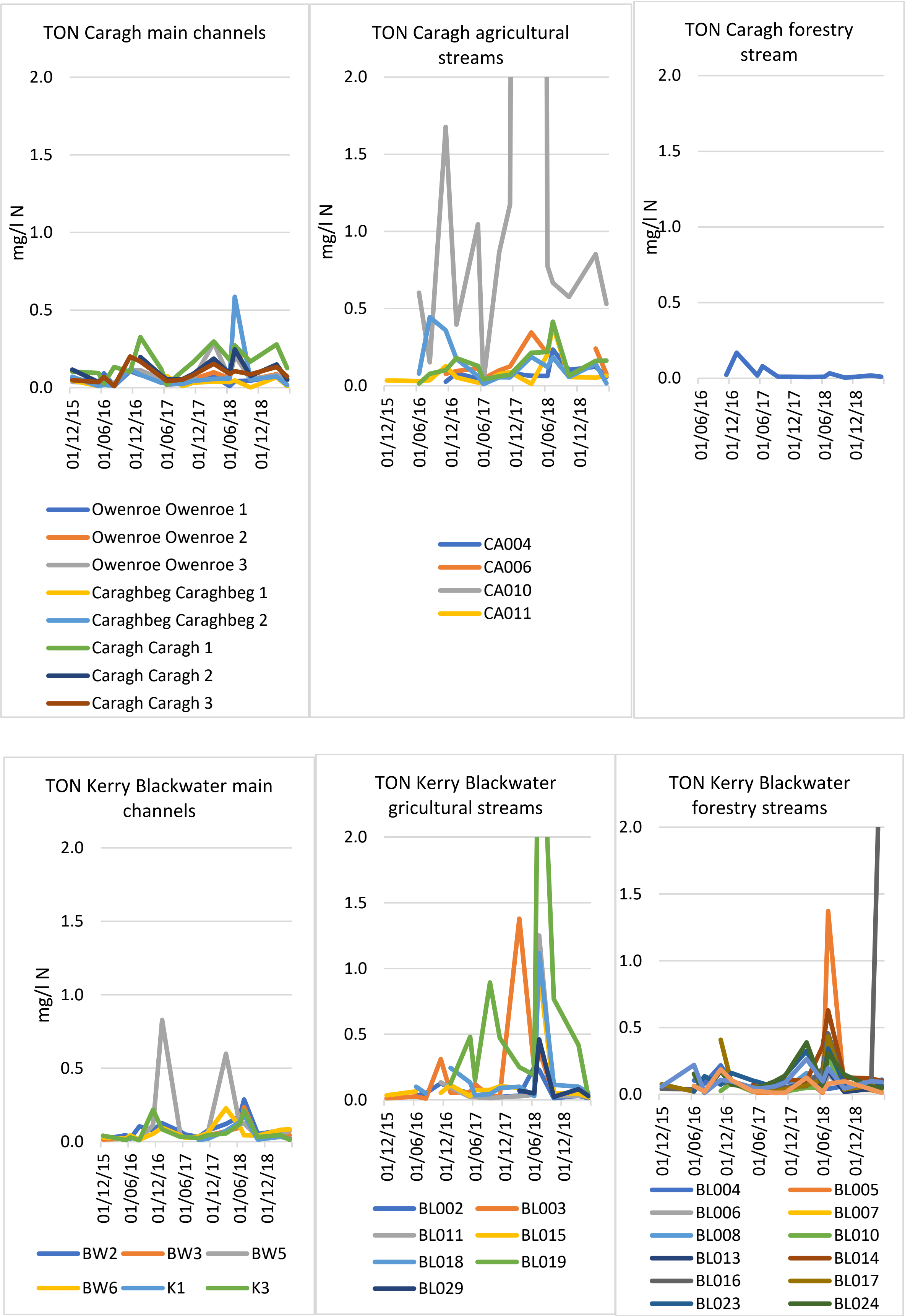


Figure 4.12 Total Oxidised Nitrogen levels measured in the Caragh and Kerry Blackwater Catchment shown to the same scale.

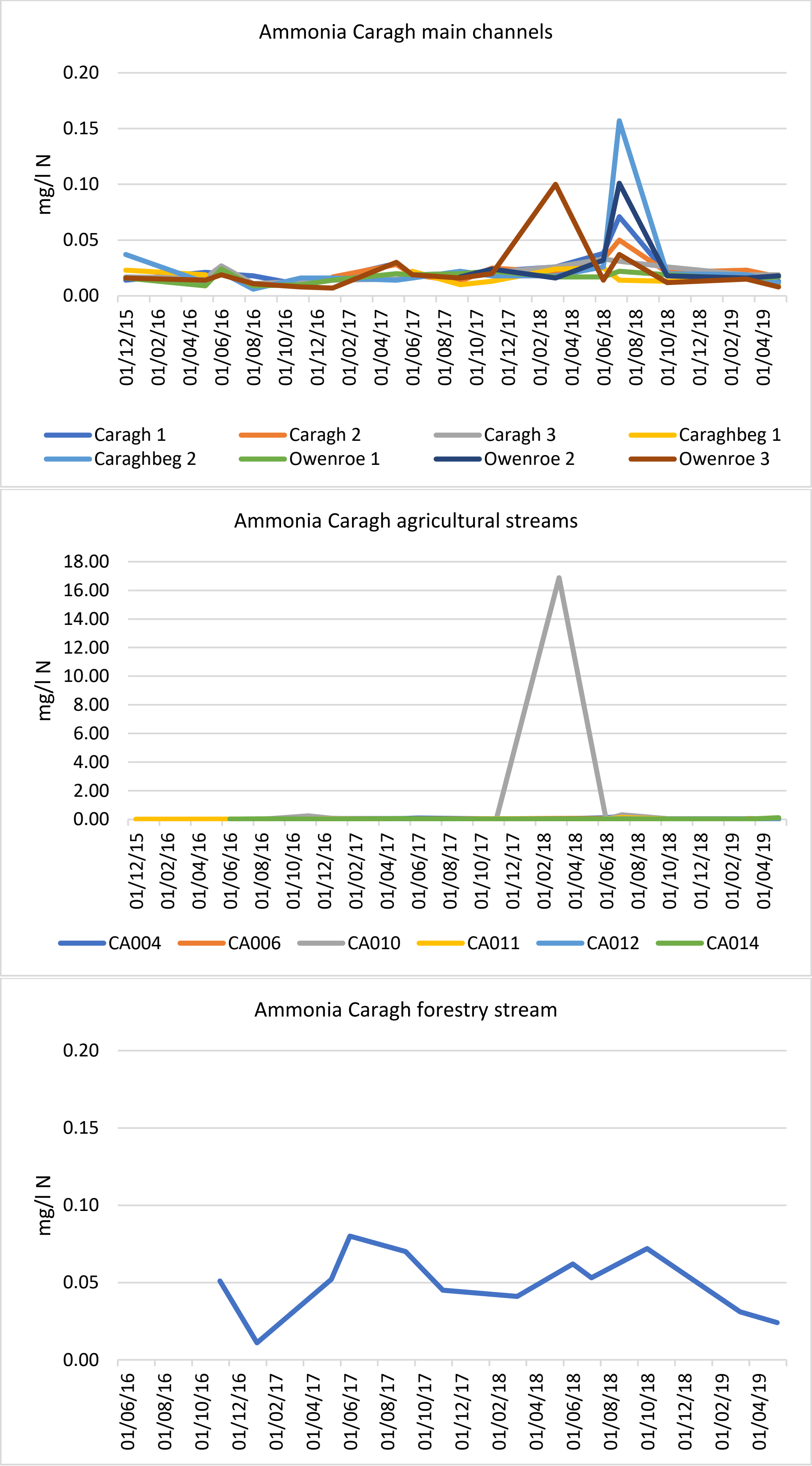
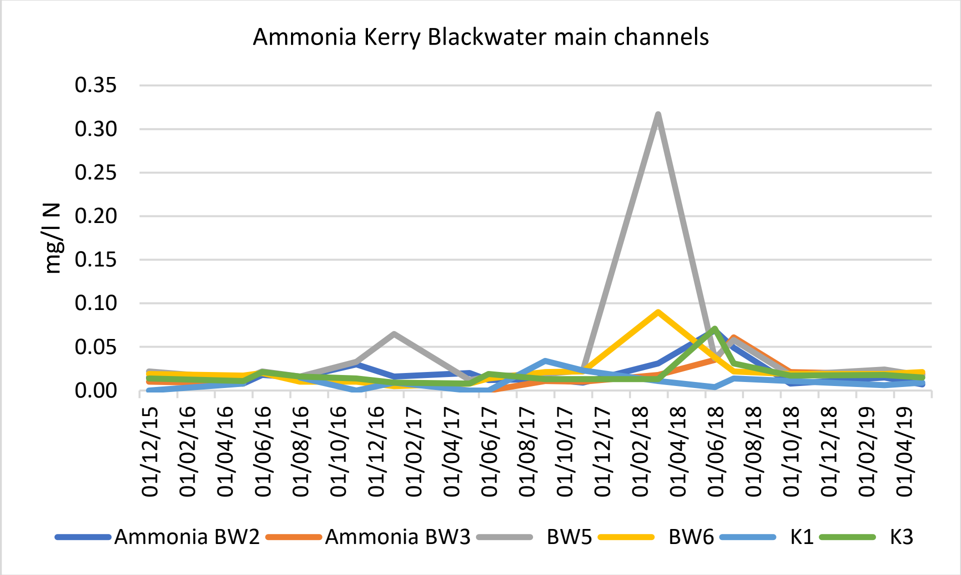
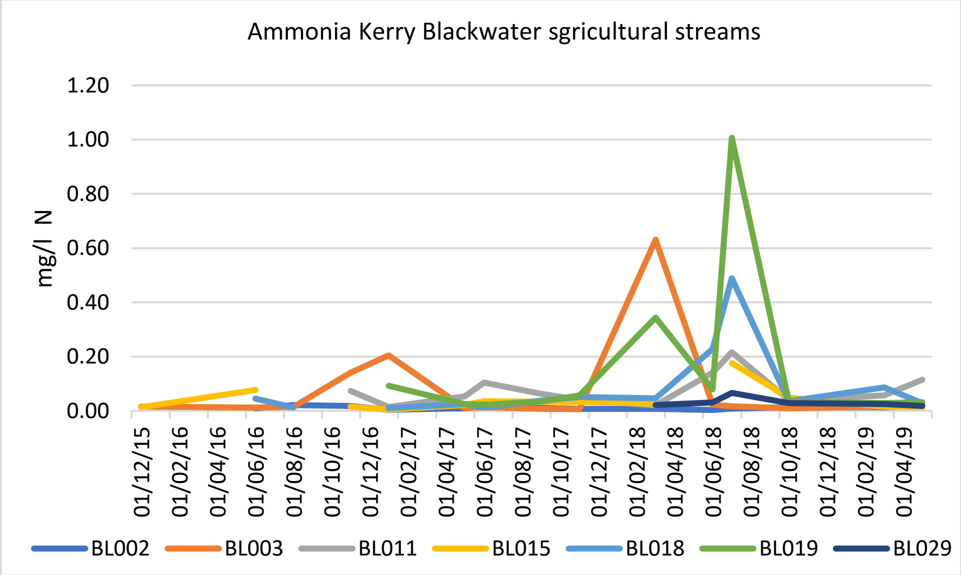


Figure 4.13 Ammoniacal Nitrogen levels measured in the Caragh Catchment.


Ammonia Kerry Blackwater main channels


Ammonia Kerry Blackwater sgricultural streams

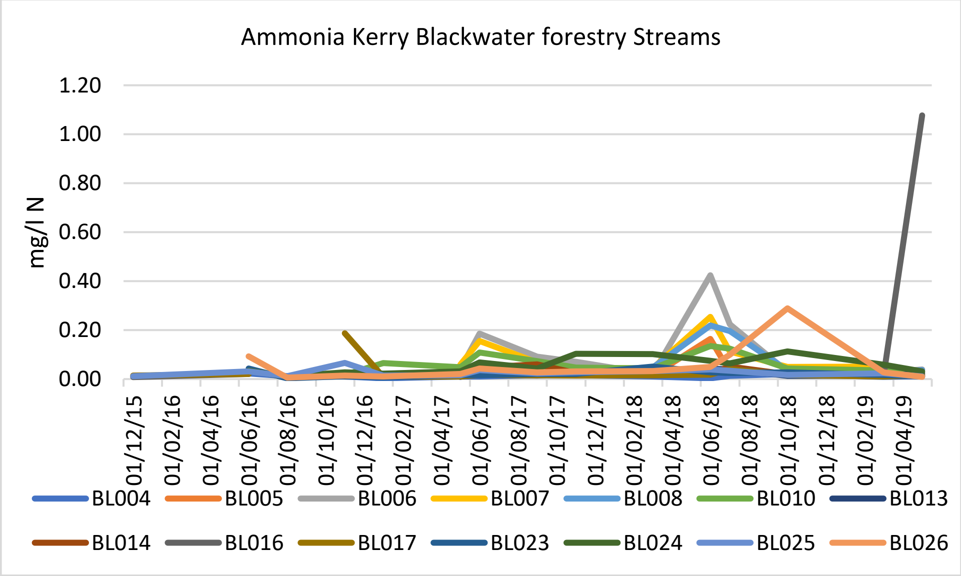

Ammonia Kerry Blackwater forestry Streams

Figure 4.14 Ammonia levels measured in the Kerry Blackwater Catchment.

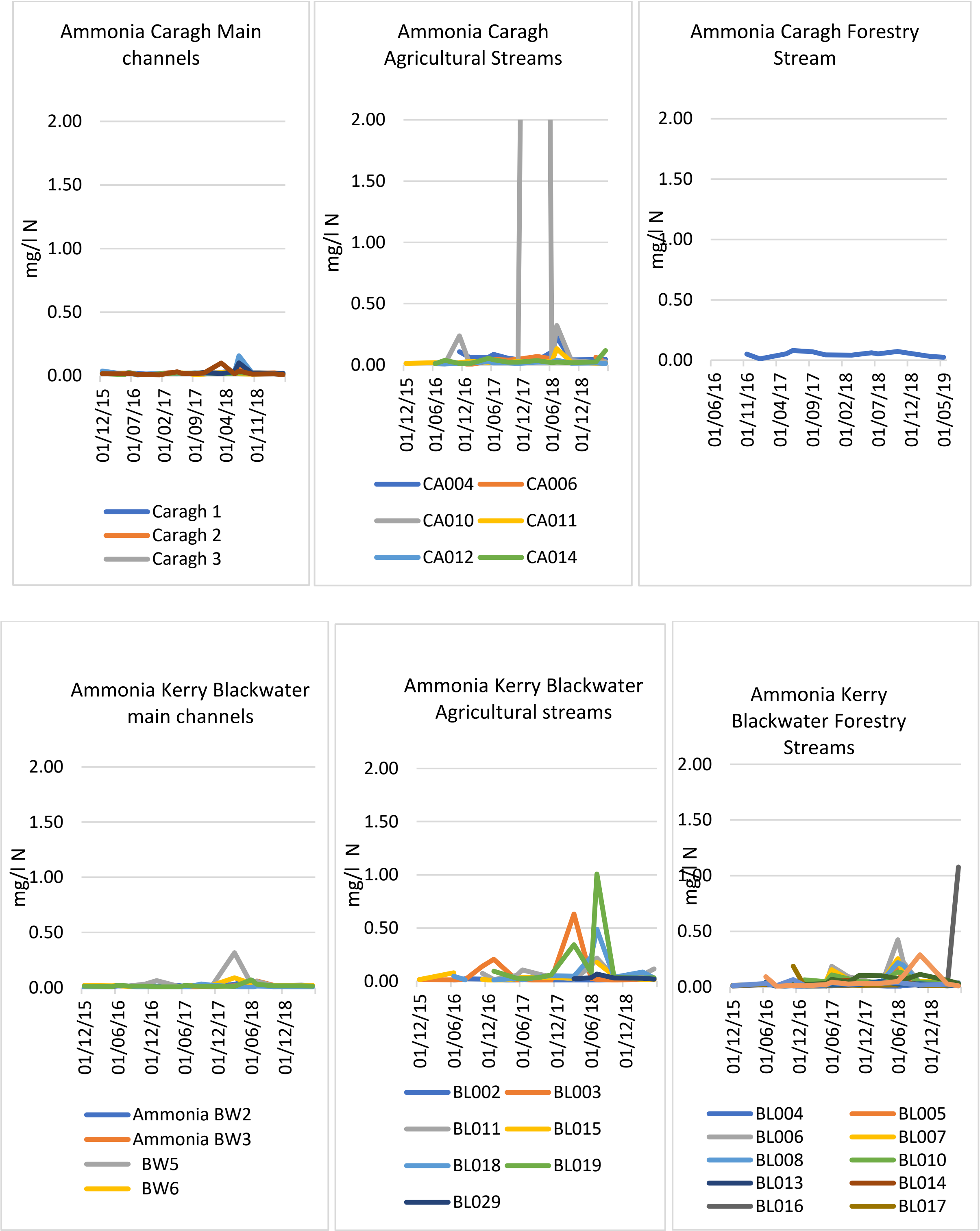


Figure 4.15. Ammonia levels measured in both catchments shown to the same scale.

4.2 Turbidity and Suspended Solids

Turbidity is a very useful measurement in *Margaritifera* rivers and feeder streams as it provides for continuous monitoring through very frequent readings. All turbidity meters vary, and each requires calibration against suspended solid weights in order to establish comparable data. Figures 4.15 – 4.17 show the turbidity results of the quarterly water chemistry sampling by KerryLIFE, and suspended solids results are shown in Figures 4.18 to 4.20. Turbidity in good freshwater pearl mussels rivers is very low (<1 NTU Nephelometric Turbidity unit) with small peaks following rainfall of <10 NTU. However, both catchments had very high turbidity peaks, with the Kerry Blackwater having high peaks in the main channels, agricultural and forestry streams. The suspended solid quantities were particularly high in the Kerry Blackwater catchment and were present in levels that cause stress and death to freshwater pearl mussels, based on monitored stress and kill events in the River Ehen in Cumbria (United Utilities unpublished reports for English Environment Agency).

Also of importance is the type of solids that are suspended. Lighter peat solids are much more harmful than heavier mineral soil particles to adult and young mussels at the surface filtering open water, as these fine particles negatively affect both food and oxygen supply, and their lighter nature keeps them in suspension longer and farther down the river. Both mineral and peat fine sediment negatively impact juvenile mussels buried in the substrate when the particles eventually fall out of suspension and smother the river bed gravels, preventing oxygen and food supply (Tuttle-Raycraft et al., 2017).

A regression equation of suspended solids v turbidity can highlight areas of peat sedimentation as the regression equation is lower than that of a regression with heavier mineral soil.

Division into small streams shows a significant difference between agricultural and forestry streams in the Kerry Blackwater catchment. The ratio of suspended solids to turbidity in the forestry streams is much lower than the agricultural streams, demonstrating that the high turbidity levels are caused by loss of lighter peat solids rather than heavier mineral solids. The higher values in the lower Caragh channel, and main Kerry Blackwater and Kealduff channels are likely to be through a mix of mineral and peat erosion, including bank erosion. The highly forested Caraghbeg regression equations are also low, representing a high proportion of lighter peat sediment, compared to the Owenroe and Caragh main channel.

The results of Karen O'Neill's studies, with much higher numbers of data points, show the Upper Caragh (Bridia) channel with a higher regression value than the Owenroe or Kealduff, suggesting more mineral soil erosion influencing the equation (O'Neill, 2019). Importantly, O'Neill also studied sediment storage levels and sediment sources (through fingerprinting trapped sediment).

O'Neill's results from the June 2017 (summer) period, estimated that total sediment storage was 8.43 tonnes (t) (0.22 – 2.26 per 500 m reach), 8.49 t (0.11 – 2.07) and 4.67 t (0.08 – 2.34) for the Owenroe, Bridia and Kealduff channels respectively. Her repeat measurements of sediment storage in January 2018 (winter) found lower load estimates of 1.34 t (0.03 – 0.43), 1.64 t (0.1 – 0.28) and 2.93 t (0.03 – 1.68) for these catchments.

Sediment fingerprinting was used by O'Neill to identify non-point sources of sediment using trace and heavy metals and organic content. Source samples were taken across a wide area of different potential sources and river sediment was collected in time-integrated sediment samplers (TISS).

Her results found forestry to be the dominant source of sediment in the Kealduff catchment, with contributions ranging from 28 to 53%. However, improved grassland contributed 17% of sediment in the Kealduff catchment even though it covers less than 5% of the catchment. This may account for the heavier regression ratio in the Kealduff compared with the forestry small streams, whose lower ratio demonstrates a high peat content. In contrast, O'Neill found extensively farmed areas and bank erosion contributed the highest sediment loads in the Bridia sub-catchment, and concluded that in spite of the low intensity of grazing there is extensive drainage and erosion. Destabilization of this area may partly be due to overgrazing. Where present, forestry contributed to the Owenroe sediment downstream of forestry drains (14-43%). Downstream dominant sources were improved grassland (average 26%) and road verges (27%). Tables 4.2 and 4.3 show the regression equations of both the KerryLIFE water chemistry sampling and the work of O'Neill in the Bridia, Owenroe and Kealduff Rivers.

Table 4.4. Regression equations for KerryLIFE water chemistry sampling of suspended solids and turbidity. Note the very light (peat erosion) suspended solids of the Caraghbeg and Kerry Blackwater forestry streams

River Type	Data Points	Max measured T (NTU)	Regression Equation SSC – Suspended Solid Concentration	R^2
Caragh main channel	21	33.2	SSC = 1.0702(NTU) - 0.0154	0.996
Caraghbeg main channel	12	7.93	SSC = 0.6302(NTU) + 0.4928	0.8229
Owenroe main channel	18	130.8	SSC = 1.0972(NTU) + 0.0373	0.9996
Caragh agricultural streams	36	39.3	SSC = 1.5255(NTU) - 1.813	0.8837
Caragh forestry stream	6	2.23	SSC = 5.1578(NTU) - 3.2104	0.8583
Kerry Blackwater Main Channel	27	39.4	SSC = 1.3442(NTU) - 0.7304	0.9692
Kealduff Main Channel	13	199.2	SSC = 1.7402(NTU) - 1.5629	0.9992
Kerry Blackwater agricultural streams	43	797.5	SSC = 1.331(NTU) + 2.1591	0.9957
Kerry Blackwater forestry streams	87	1677	SSC = 0.71(NTU) + 9.8681	0.9457

Table 4.5. Regression equations for suspended solids and turbidity from O'Neill (2019).

Sub-catchment	Data Points	Max measured T (NTU)	Regression Equation	R^2
Owenroe	264	24.7	SSC = 1.52(NTU) + 0.25	0.84
Kealduff	182	12.3	SSC = 1.55(NTU) + 0.30	0.84
Bridia	192	140.7	SSC = 1.94(NTU) + 0.84	0.94

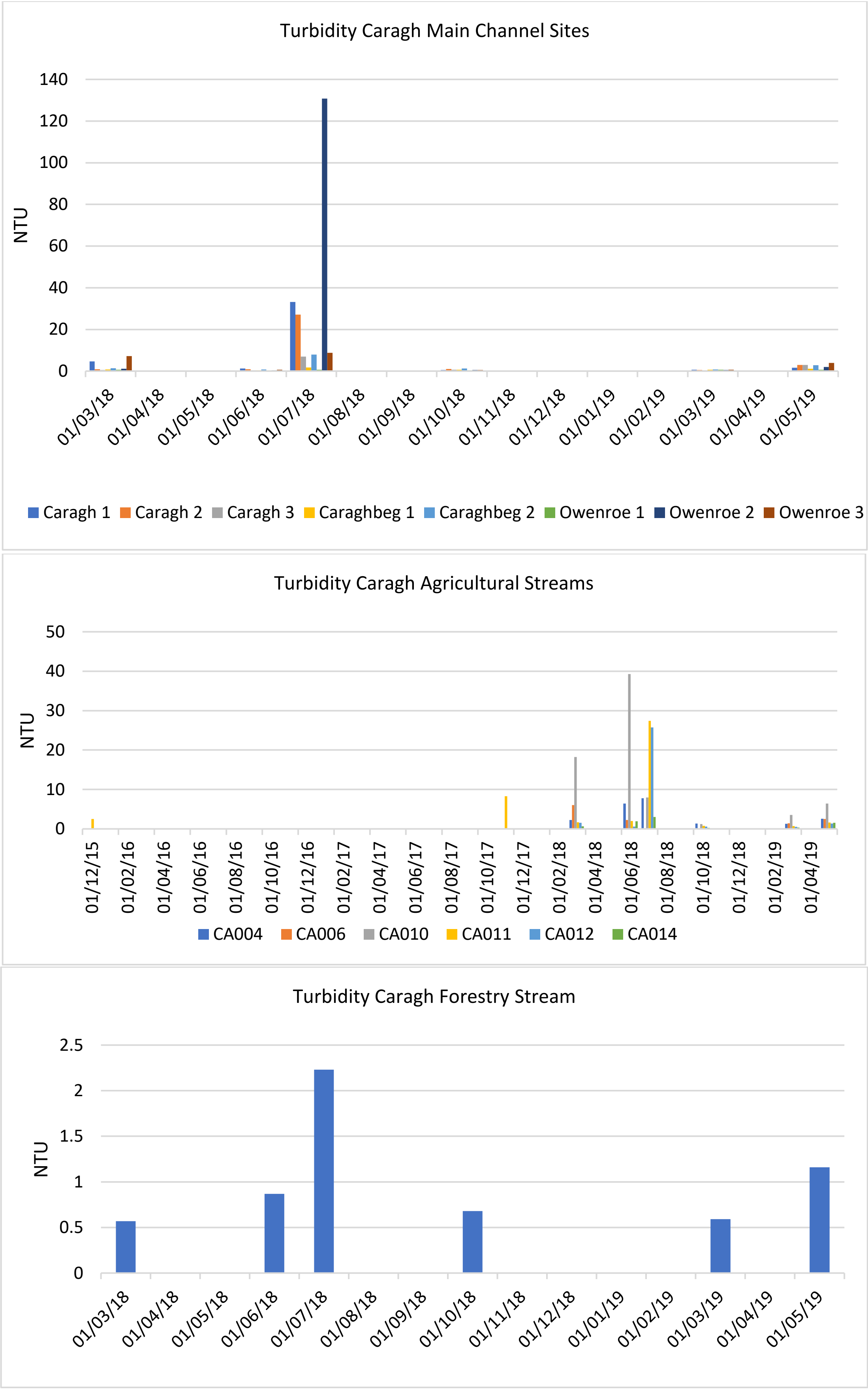
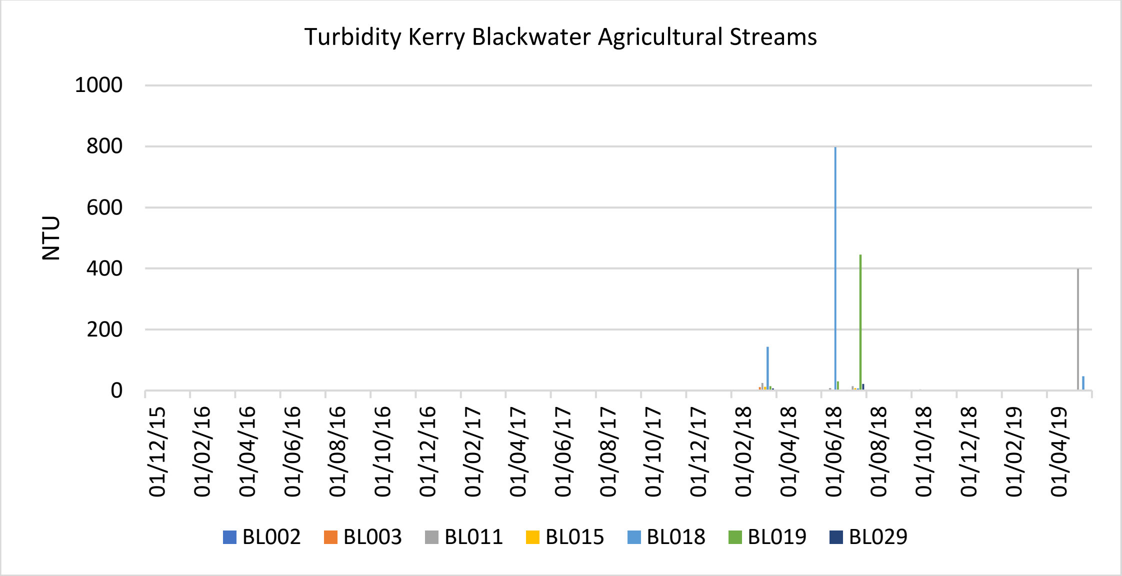


Figure 4.16. Turbidity levels measured in the Caragh Catchment.



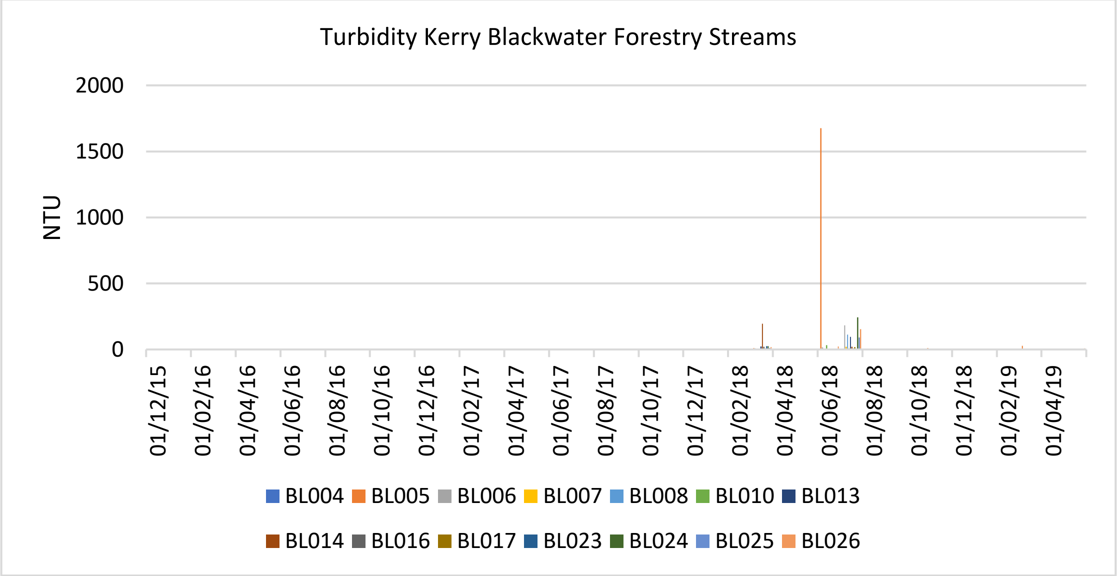


Figure 4.17 Turbidity levels measured in the Kerry Blackwater Catchment.

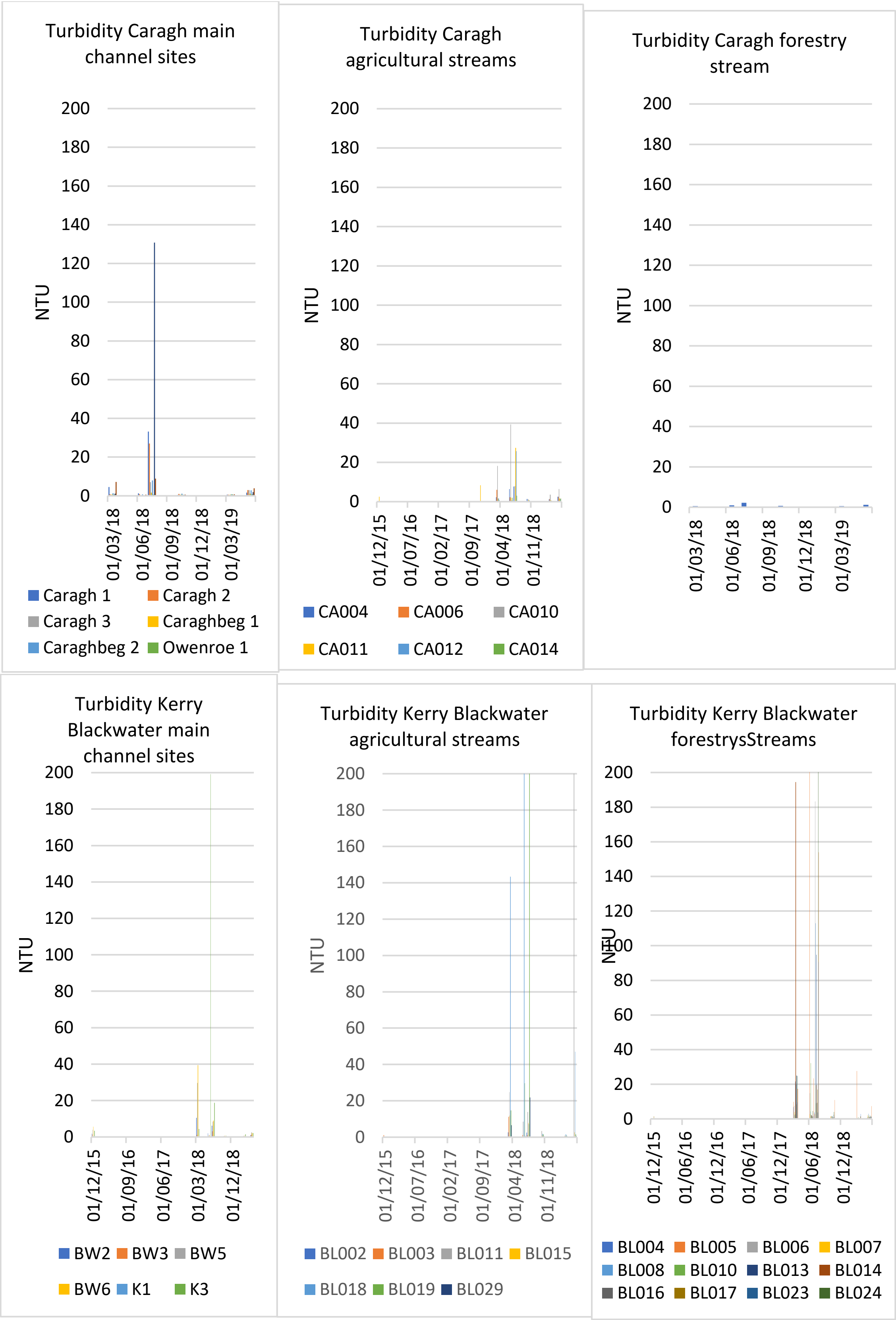
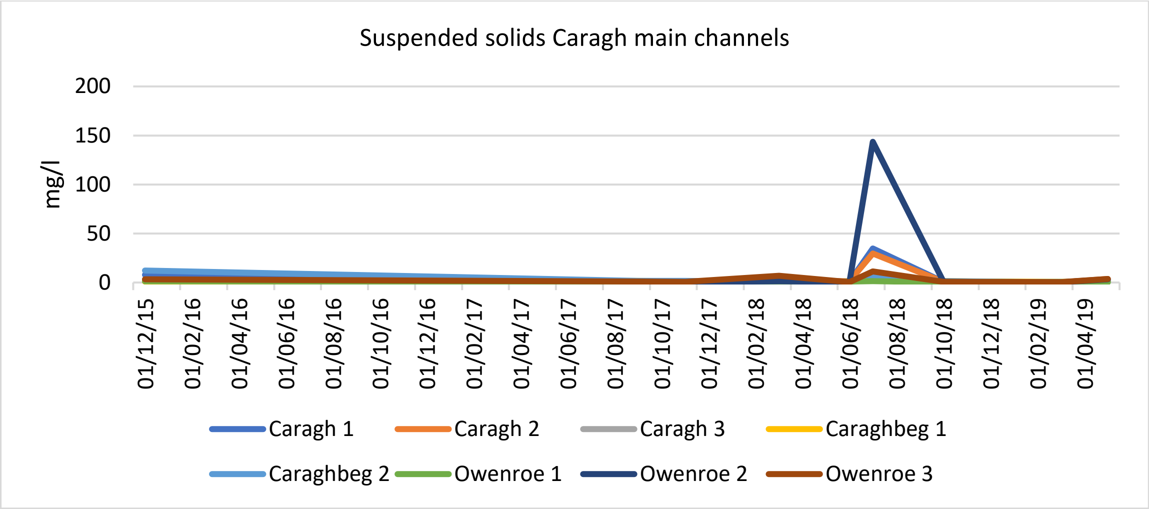
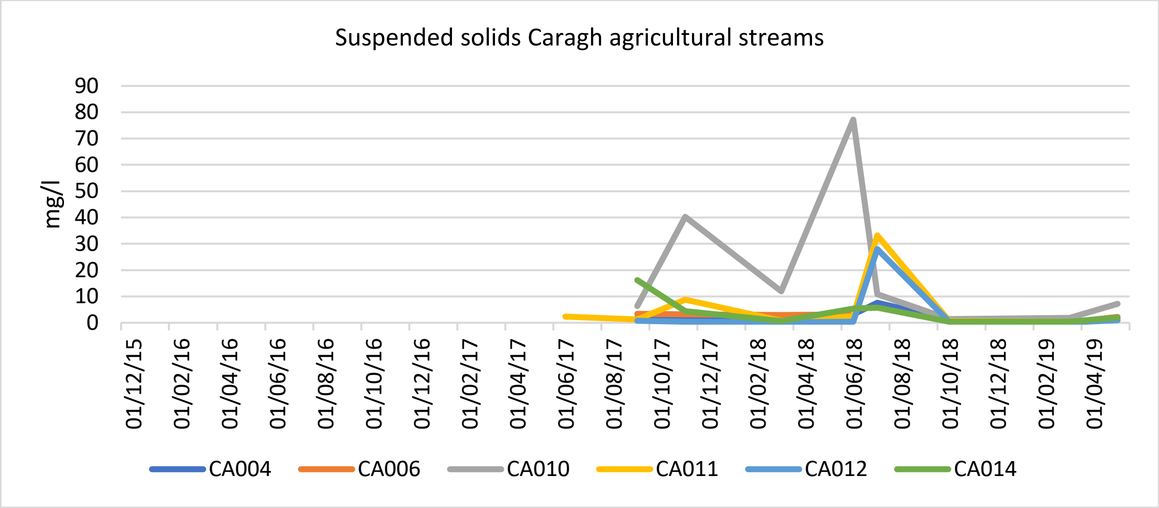


Figure 4.18. Turbidity levels measured in the both Catchments at the same scale.





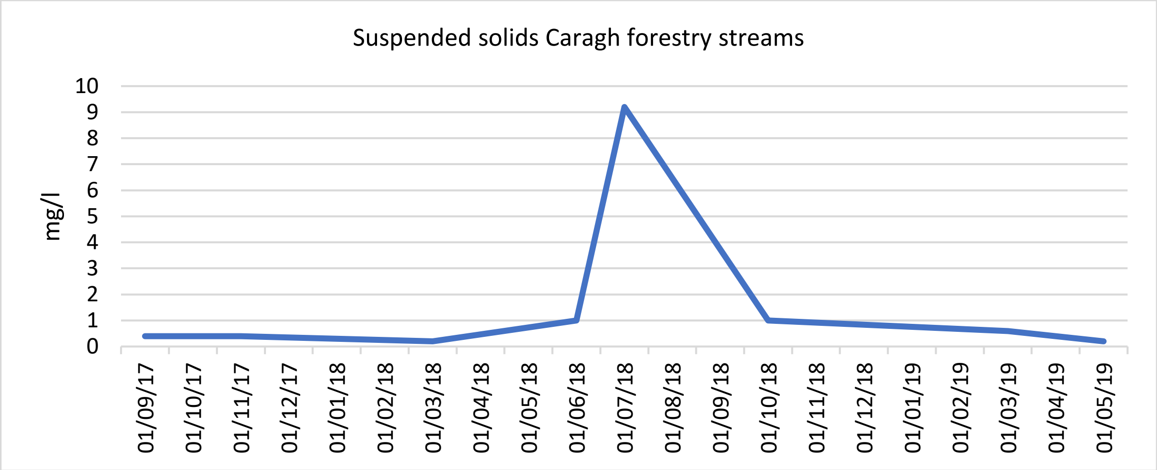
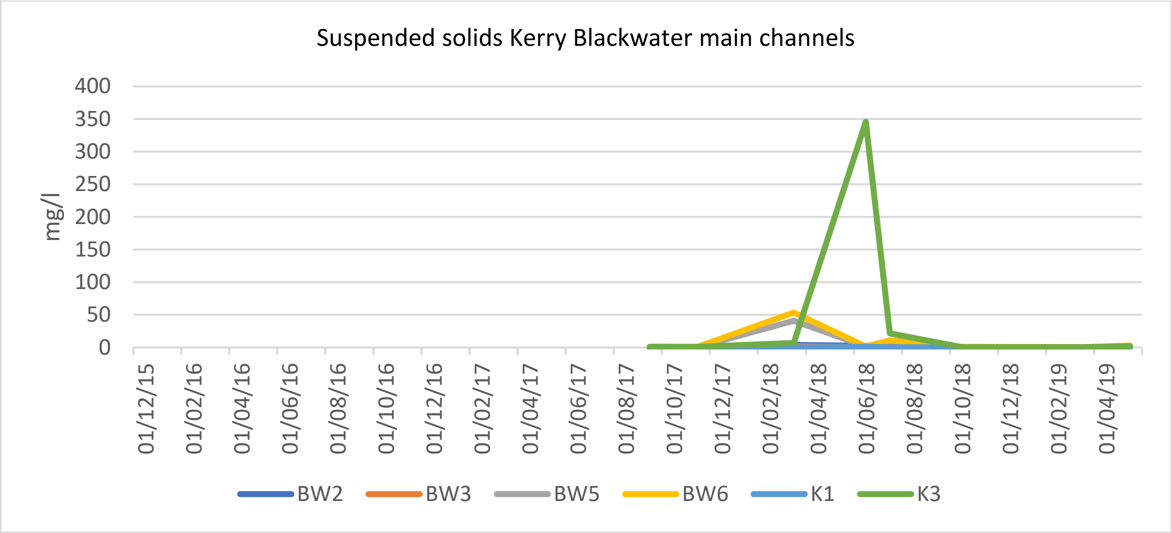
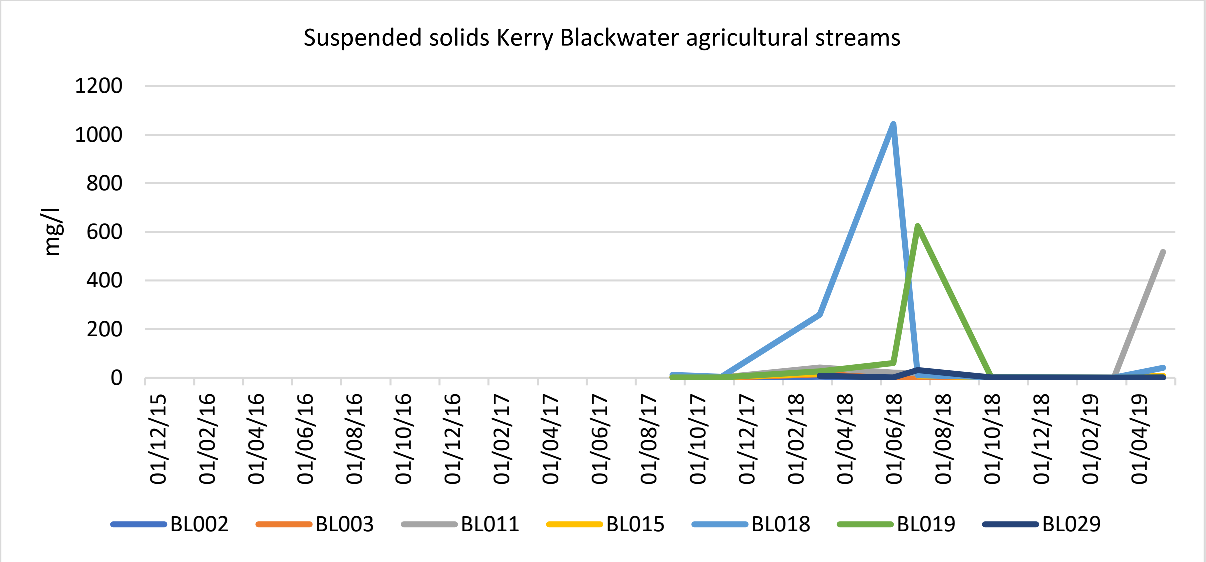


Figure 4.19 Suspended solids in the Caragh Catchment, measured by filtering a well-mixed sample through a 0.45 µm weighed glass fibre filter. The residue retained on the filter was dried to a constant weight at 103-105 °C.





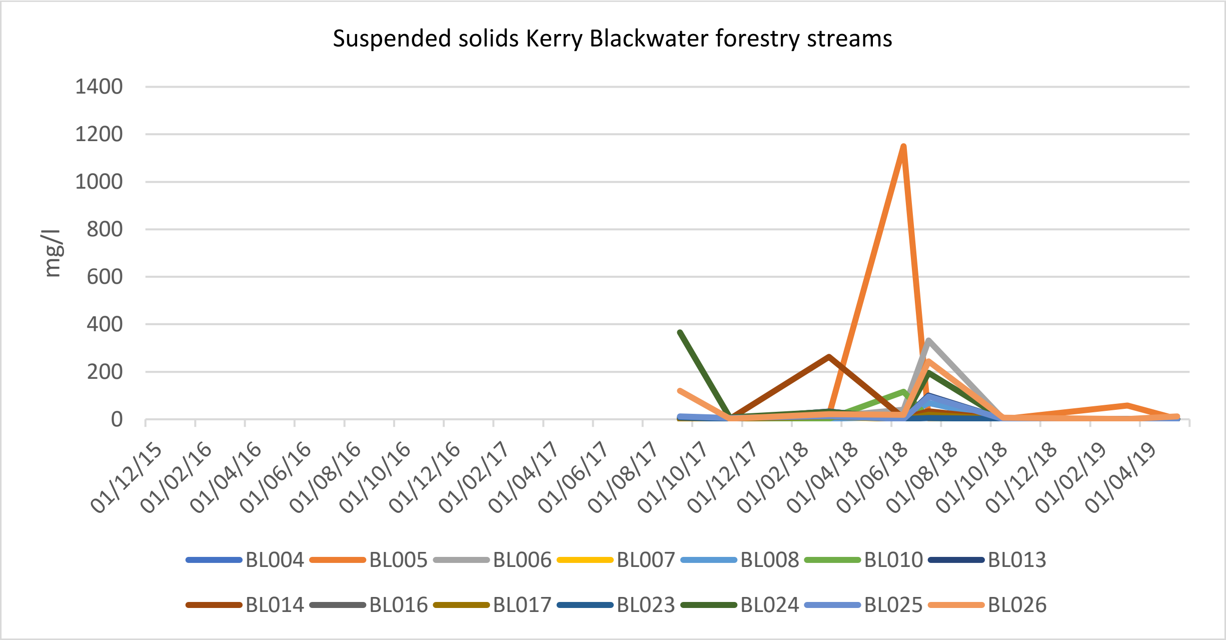


Figure 4.20. Suspended solids in the Kerry Blackwater Catchment, measured by filtering a well-mixed sample through a 0.45 µm weighed glass fibre filter. The residue retained on the filter was dried to a constant weight at 103-105 °C.

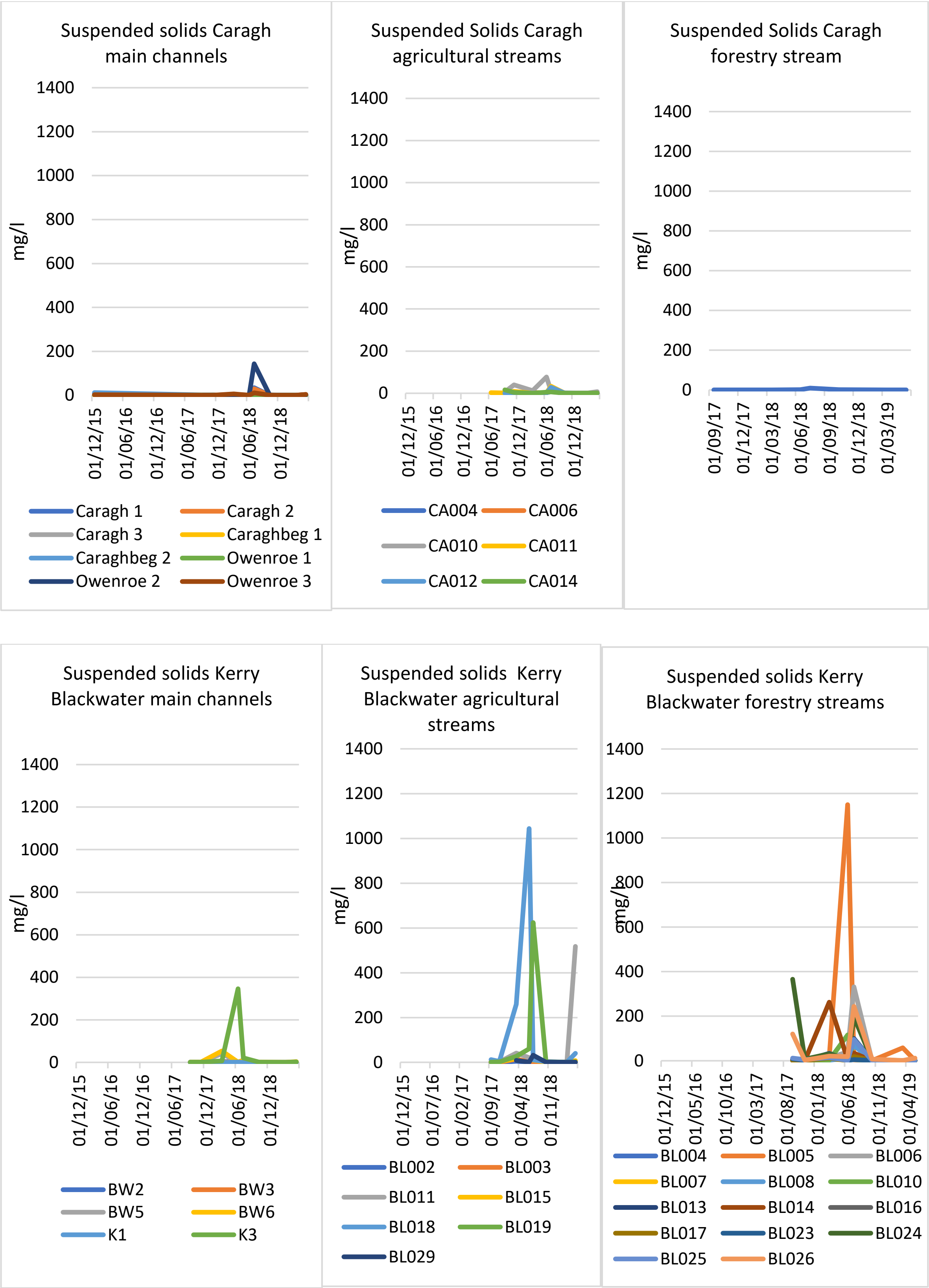


Figure 4.21. Suspended solids in both catchments shown at same scale

4.3 Dissolved organic carbon and colour

The results from suspended solids and turbidity monitoring in the section above provide an alert regarding the likely level of peat that is being lost from catchments, particularly forestry sites.

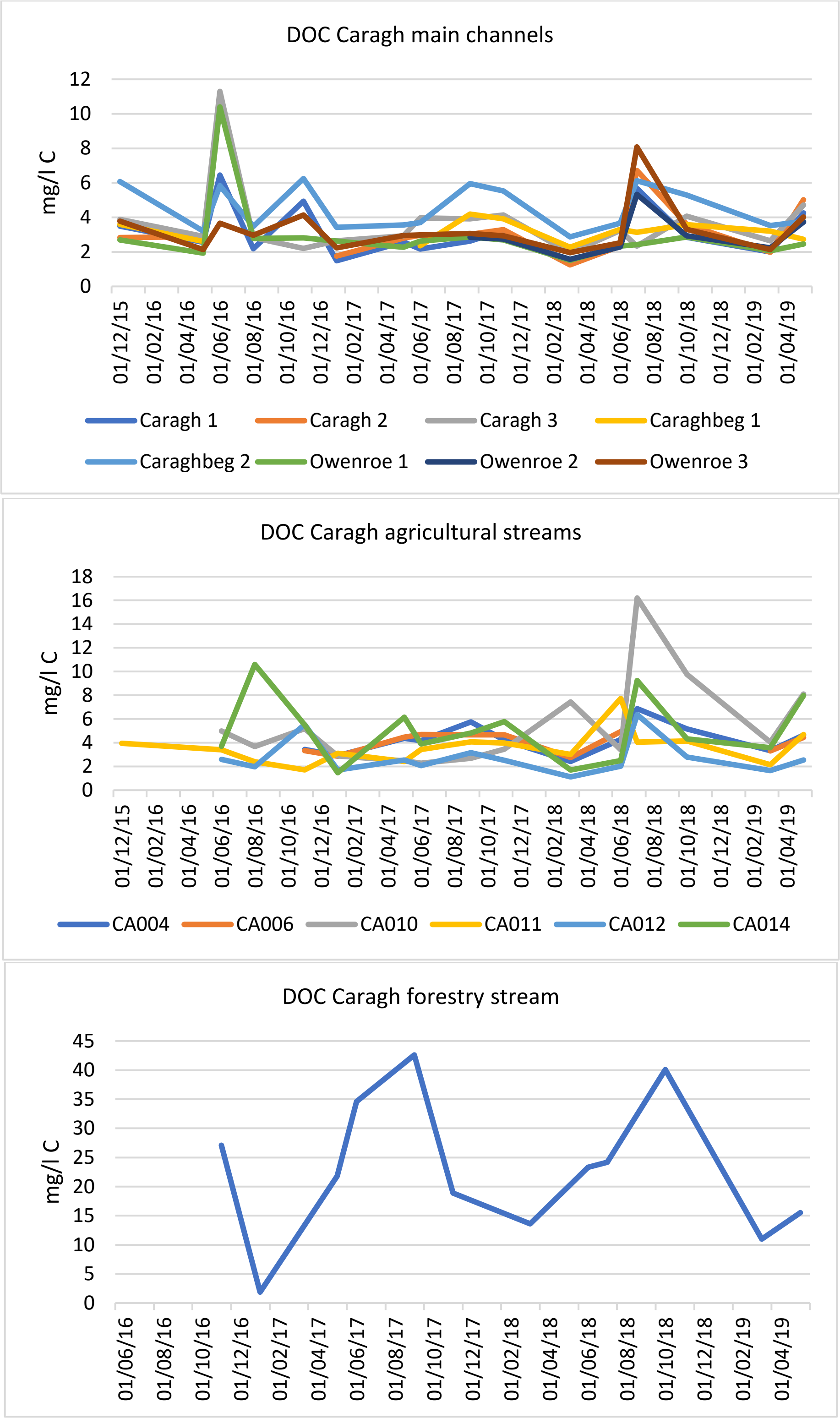
Drainage of peat leads to drying and erosion of peat particles resulting in the release of particulate and molecular carbon to water courses downstream. Dissolved organic carbon (DOC) in fluvial systems can be mineralized to CO2, thereby contributing to atmospheric CO2 concentrations (Winterdahl et al., 2016). Additionally, DOC can affect ecosystem function through a reduction in light penetration, through binding with trace metals (Rothwell et al., 2007), leading to toxic conditions for mussels (Young, 2005). The colour change resulting from DOC is expensive to remove and creates a high cost for the management of a potable water supply (Flynn et al., 2021), including the prevention of trihalomethanes in drinking water following chlorination (Werner et al., 2016).

Dissolved organic carbon levels, along with colour, are the most important measurement to be considered in considering the conservation remedial actions needed for KerryLIFE rivers. High levels represent the condition of maximum damage to freshwater pearl mussel populations of lower water tables and chemical and sediment pollution in association with ongoing damaging net carbon losses from catchments that should be highly protective of mussels, as well as being acting as net carbon sinks (Holden et al., 2007, 2011). The lowered groundwater table results in inappropriate hydrological conditions, with low flow stress impacting oxygen exchange in the river bed substrate, thus exacerbating the pollution impact (Moorkens & Killeen, 2014). Where drainage and carbon loss is due to tree plantations, further stress on the water table is caused by the interception, evaporation and transpiration of high tree densities (Kuemmerlan et al., submitted).

The rewetting of drained peatlands is considered to be an important step in climate and catchment function recovery (Evans et al., 2016; Wilson et al., 2016), and it is considered essential to reduce the loss of carbon and to reverse the decline of the most important large mussel populations through water table recovery (Wilson et al.2011; Kuemmerlan et al., 2021). Even in damaged peat where it is unlikely to be restored to a net carbon sink, the reduction in carbon loss can be a positive climate action and restore target conditions for hydrology and water chemistry for *Margaritifera*.

Colour closely matches DOC patterns and is another way of measuring carbon lost from peatland to the aquatic zone through erosion of degraded peat (Jones et al., 2016). Samples were analysed using the colorimetric method against a Pt-Co colour standard and a measuring wavelength of 455nm, given in Hazen Units (minimum detection level 1 Hazen).

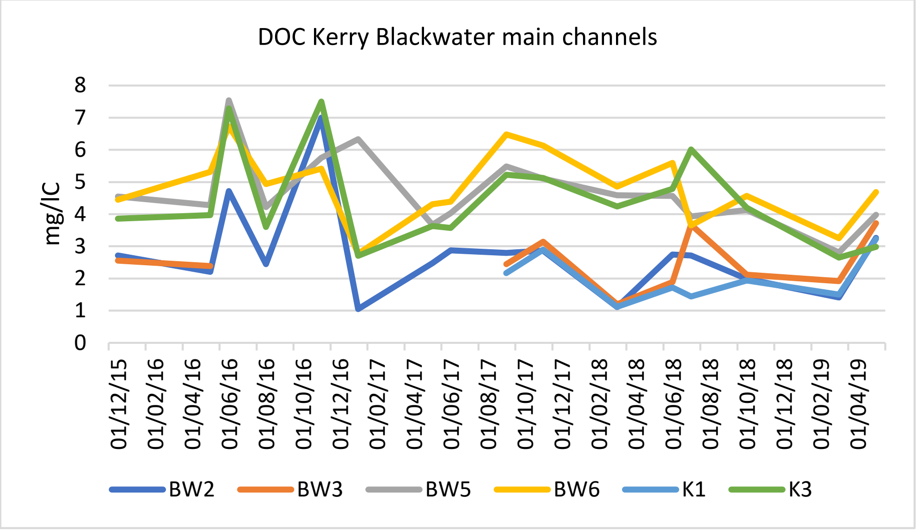
DOC results are shown in Figures 4.22 to 4.23, and colour in Figures 4.24 to 4.27.

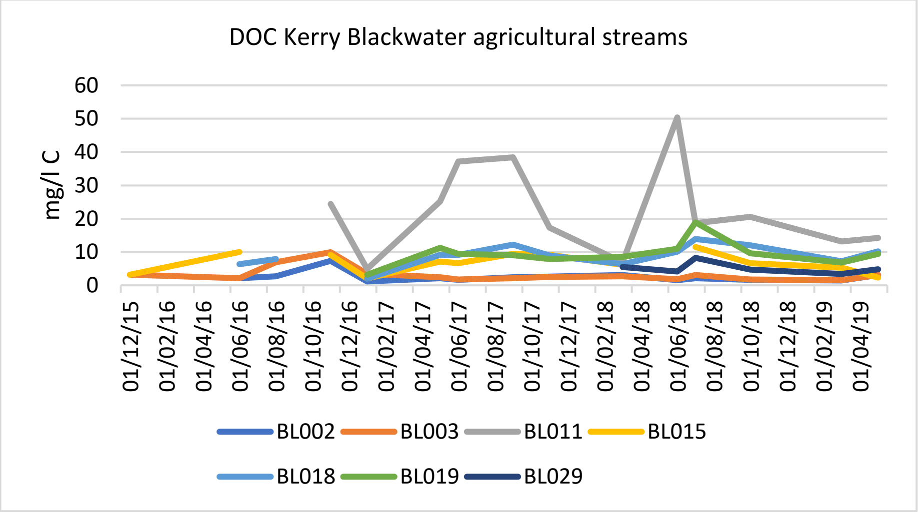

DOC Caragh main channels

DOC Caragh agricultural streams

DOC Caragh forestry stream

Figure 4.22. Dissolved Organic Carbon levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams of the Caragh catchment





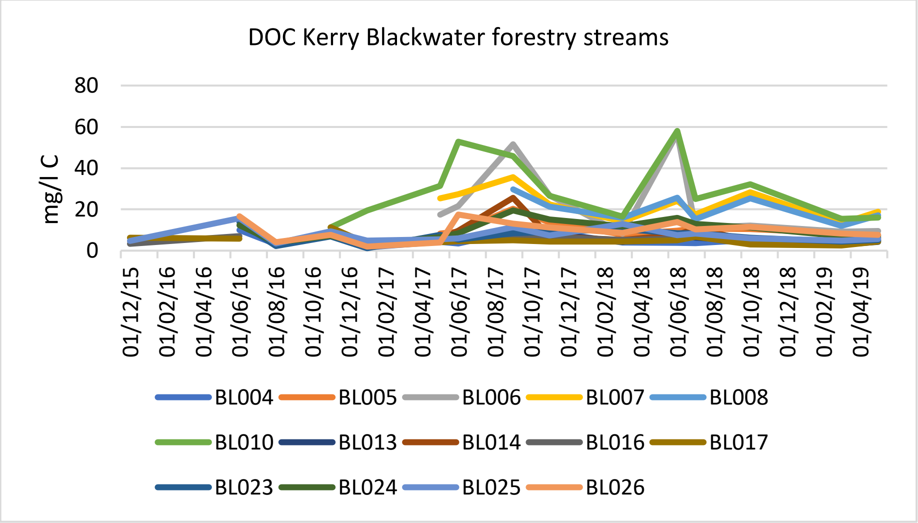


Figure 4.23. Dissolved Organic Carbon levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams of the Kerry Blackwater catchment

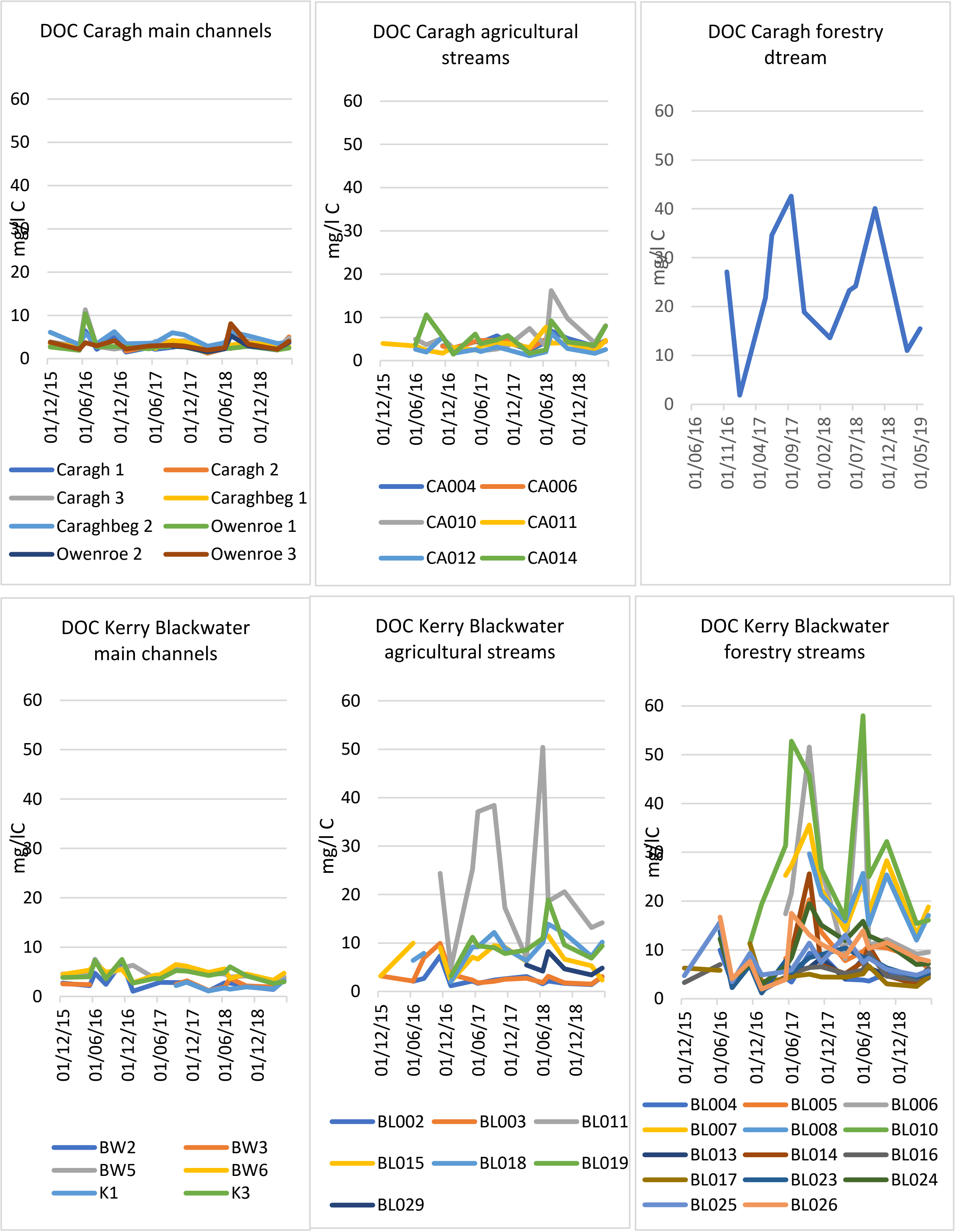
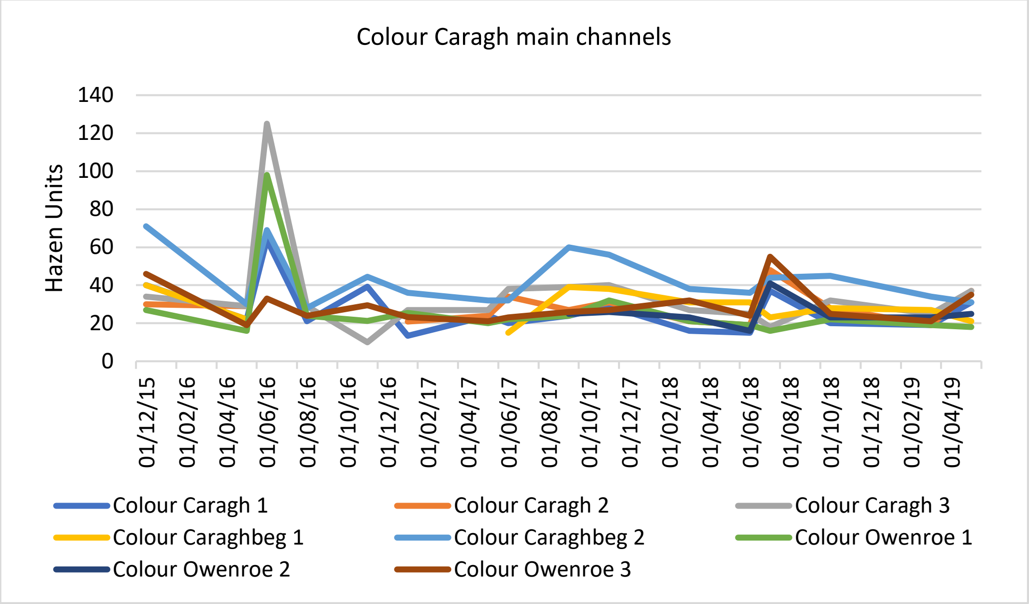
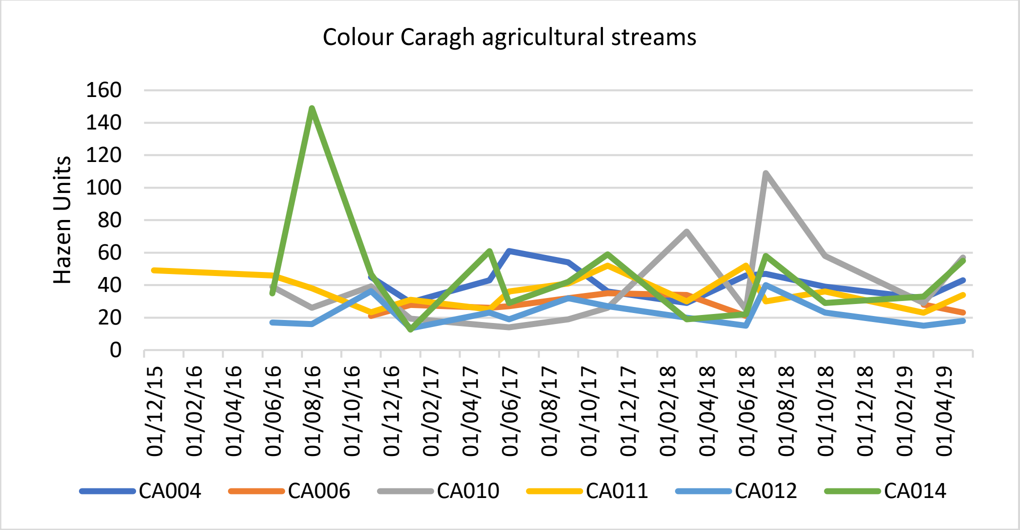


Figure 4.24. Dissolved Organic Carbon levels measured by the KerryLIFE team shown on same scale for both catchments.





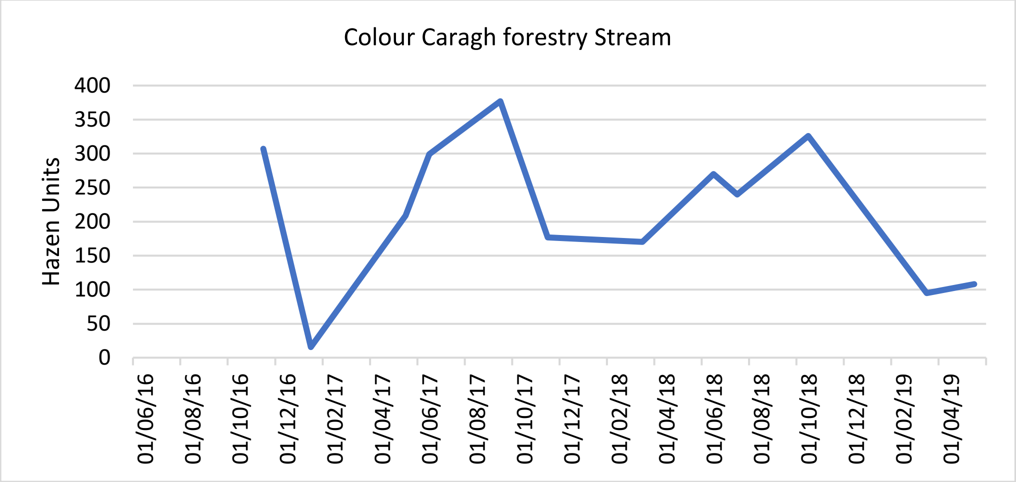


Figure 4.25. Colour levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams of the Caragh catchment

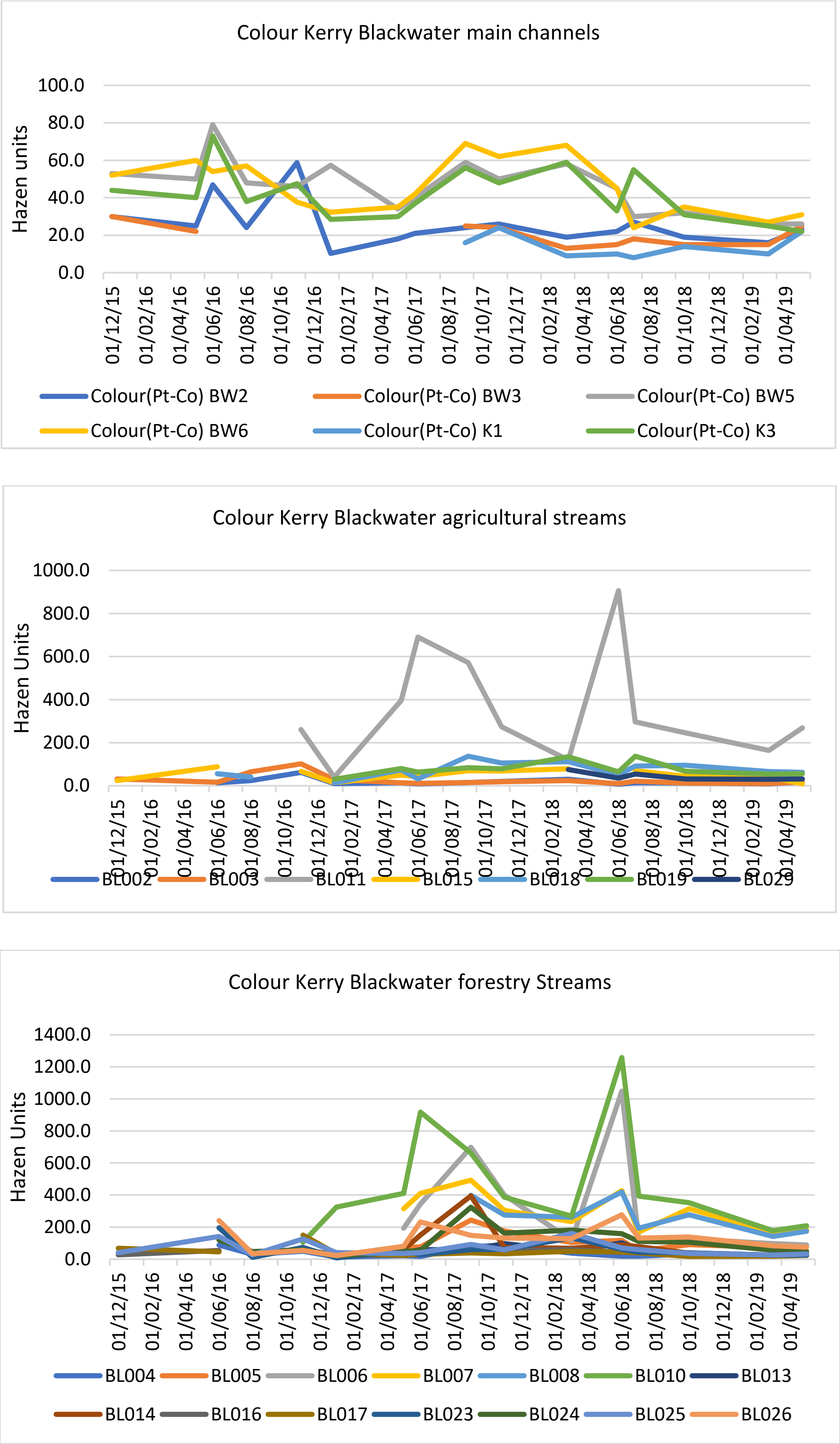


Figure 4.26. Colour levels measured by the KerryLIFE team in the main channels and agriculture and forestry streams of the Kerry Blackwater catchment

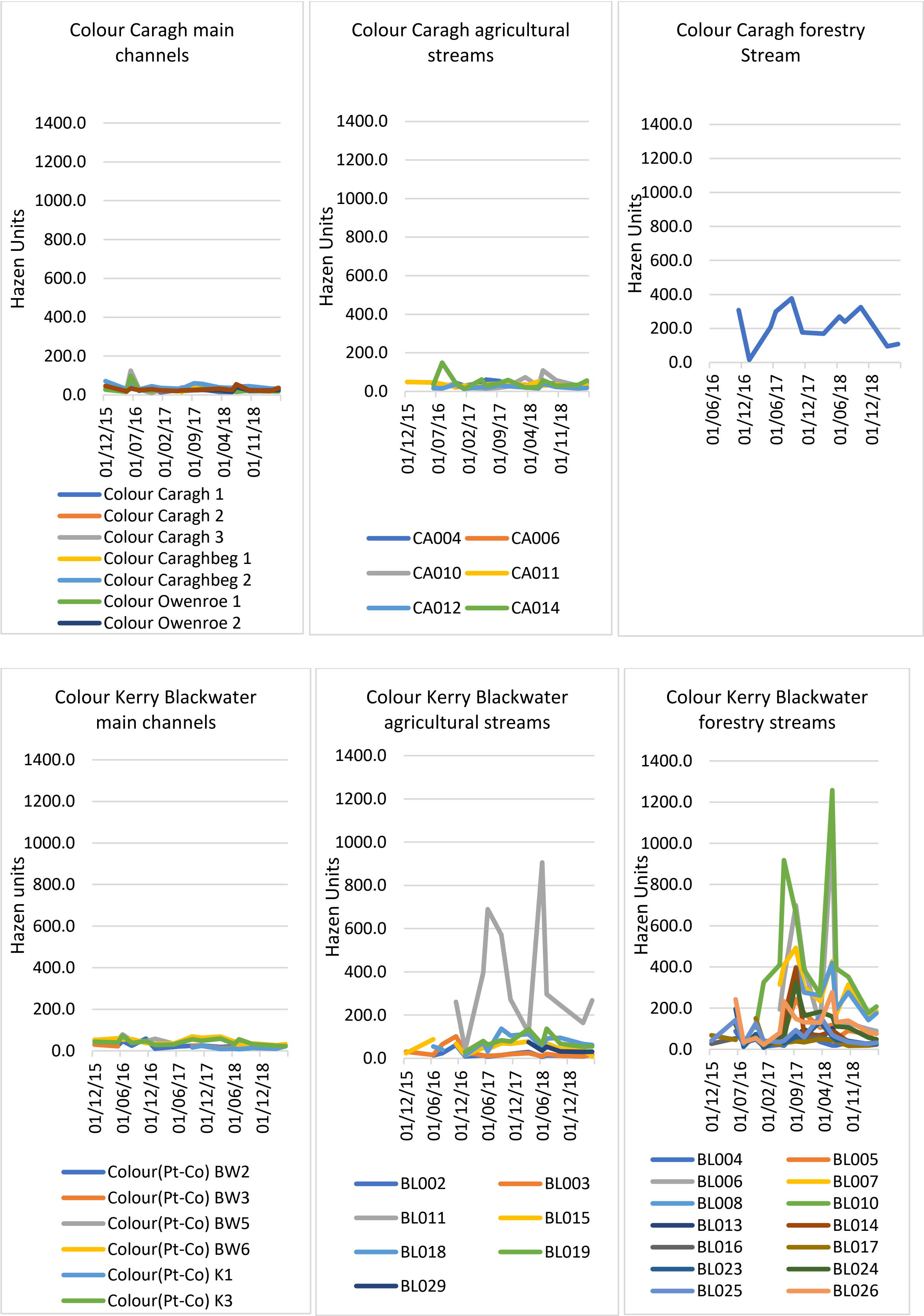


Figure 4.27. Colour levels measured by the KerryLIFE team shown on same scale for both catchments.

5 Habitat monitoring

Habitat or biological monitoring was undertaken by the KerryLIFE team each year to assess levels of filamentous algal, macrophye and bryophyte growth and levels of fine sediment at mussel habitat (Phelan et al. 2017a, 2018a,b,c, O'Callaghan, et al. 2020). Habitat monitoring was also undertaken by Moorkens (2014, 2017, 2019). Details can be found in the reports listed in Table 1.1.

5.1 Frequent habitat monitoring

Frequently-monitored river stretches/sections (15 m) were visually assessed without entering the water. This was generally done on a weekly basis between April and September when low flow conditions with good visibility made it possible. Infrequent sites were monitored less often. Results taken from the main river channels between July and September, for which there were results both before and after implementation of measures were used. Results for each site from both 2015 and 2016 ("before") were compared to results from both 2018 and 2019 (after). Locations of sites are shown in Figures 5.1 and 5.2, from the KerryLIFE reports.

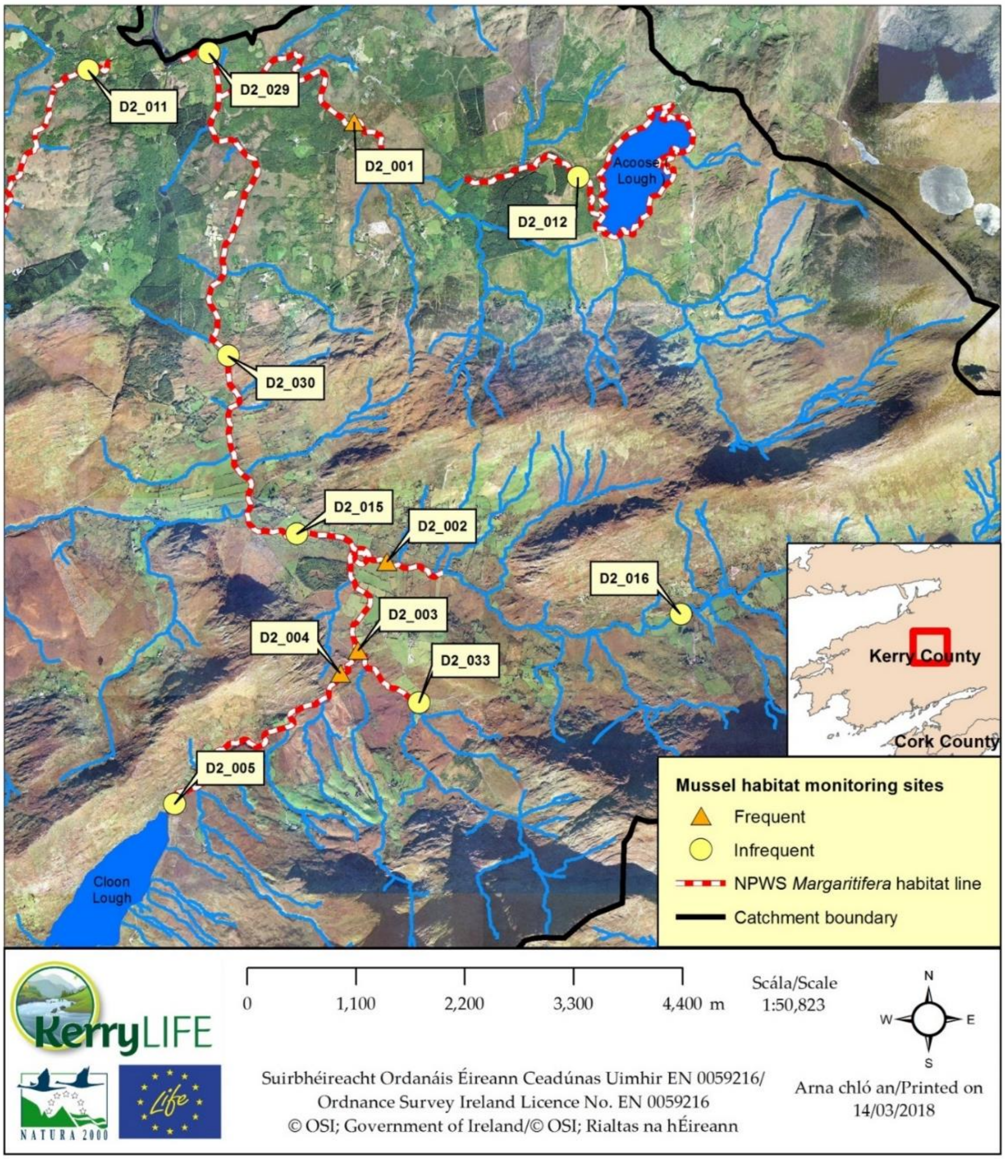


Figure 5.1. KerryLIFE *Margaritifera* habitat monitoring reaches in the Caragh.

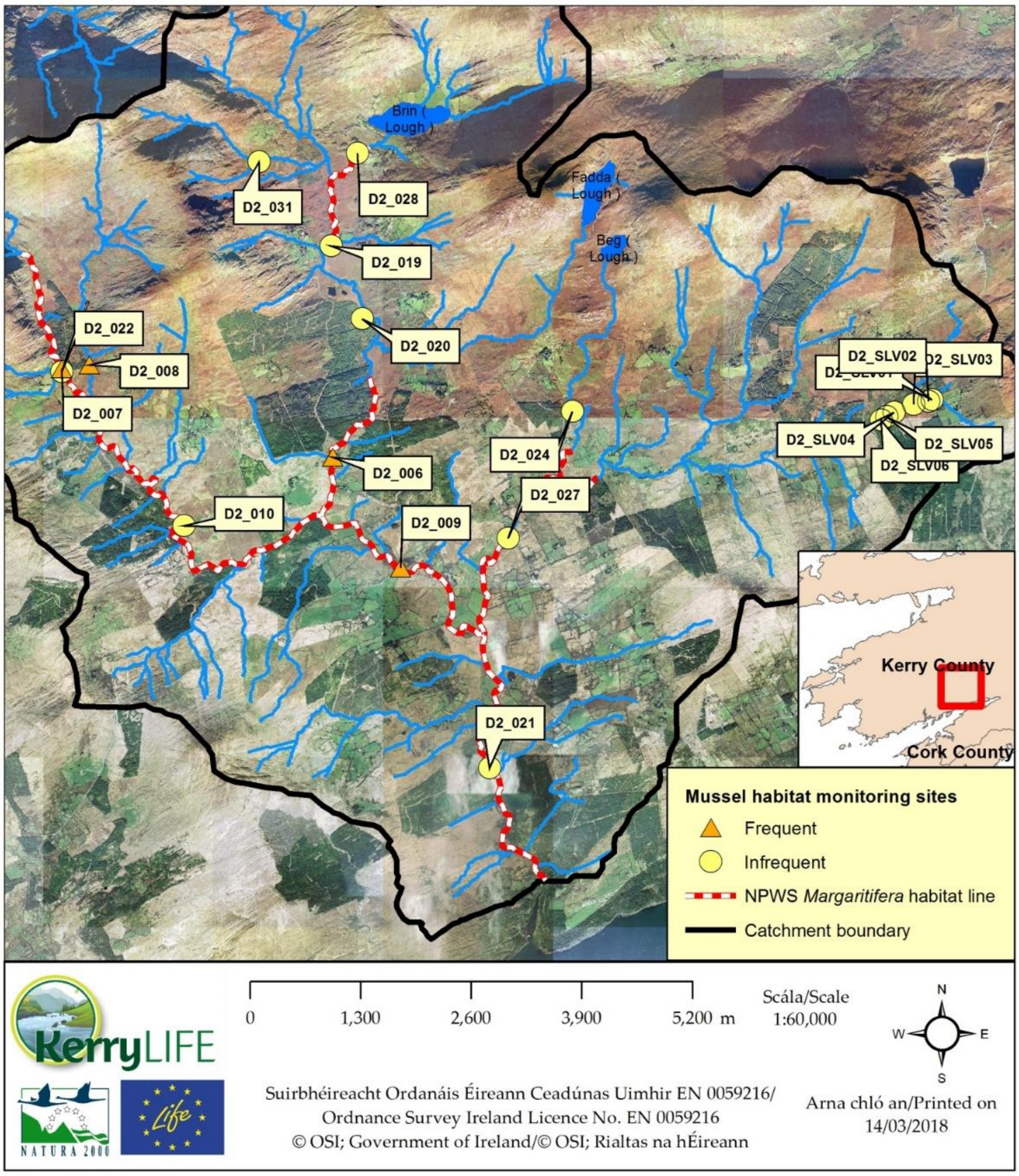


Figure 5.2. KerryLIFE *Margaritifera* habitat monitoring reaches in the Kerry Blackwater.

The results of the frequent and infrequent habitat monitoring by the KerryLIFE team (Phelan et al. 2017a, 2018a,b,c, O'Callaghan, at al 2020) is well summarised in the 2019 report (O'Callaghan, et al. 2020). The results are summarised as:

1. Mean silt plume severity declined by 21% between the 2015-2016 (before KerryLIFE measures) and 2018-2019 (after KerryLIFE measures) sampling periods ($P < 0.001$).
2. Mean filamentous algal severity declined by 54% between '2015-2016' and '2018-2019' sampling periods ($P < 0.001$).
3. Mean silt plume severity appeared to remain the same (3.0), but algae severity appeared to decline by approximately 30% (1.0 to.0.7) between the 2015-2016 and 2018-2019 sampling periods at a control site with no KerryLIFE measures upstream (D2_011 on the Meelagh).
4. In quadrats that contained visible freshwater pearl mussels, there was decline in the mean count of freshwater pearl mussels (from 13.6 to 12.8) which approached significance (P = 0.066).

Frequently-monitored river stretches/sections (15 m) were visually assessed without entering the water. This was generally done on a weekly basis between April and September when low flow conditions with good visibility made it possible. The main results from this frequent-monitoring were:

1. In general, algal severity at the frequently-monitored sites tended to peak in May/June and then declined before peaking again in August/September. However, there was a large amount of variation between years and sites
2. There was no significant change in algal severity at the frequently-monitored sites before and after implementation of KerryLIFE measures, and there was an amount of variation in the dataset.

Nonetheless, as shown in Table 5.1, an improvement was found in the Owenroe but not the Caraghbeg, and in the Caragh Catchment rather than the Kerry Blackwater catchment. In the Kerry Blackwater catchment conditions deteriorated in the main channel site and remained particularly bad in the Kealduff. In 2016, a mussel kill was observed in the Kealduff with trailing clumps of green algae filling the channel, accompanied by large amounts of dead mussel shells (approximately 500) of varying ages. There were numerous mussels in low flow areas close to the water surface and covered in algae (Phelan et al., 2018b). However, it should be noted again that the mean values do not necessarily capture the damage done by short-term instances of poor conditions, such as during the mussel kill in 2016.

Table 5.1 Mean annual algal cover severity (0-3) at frequently-monitored river stretches.

	2015	2016	2017	2018	2019
Caragh					
Bridia lower (Keeas) (D2_002)	1.5	1.0	0.7	1.2	1.6
Caraghbeg middle (D2_001)	1.3	1.4	1.2	1.1	1.3
Owenroe lower (Shronaree) (D2_003)	1.1	1.3	0.6	0.6	0.6
Owenroe middle (Cloghera) (D2_004)	1.9	1.8	1.5	1.2	1.4
Kerry Blackwater					
Blackwater u/s Boston bridge (D2_009)	0.5	0.3	0.9	1.1	0.8
Kealduff lower bridge (D2_006)	2.1	2.7	2.1	2.5	2.4
Mean	**1.43**	**1.41**	**1.16**	**1.29**	**1.33**

When results from the 2015/2016 period were compared to the 2018/2019 period, there was a reduction over time in mean silt plume severity by 21 % (2.59 vs 1.91: 2-tailed paired-t, *P* < 0.001, t-Stat = 3.71, 47 df.; (Figure 5.3).

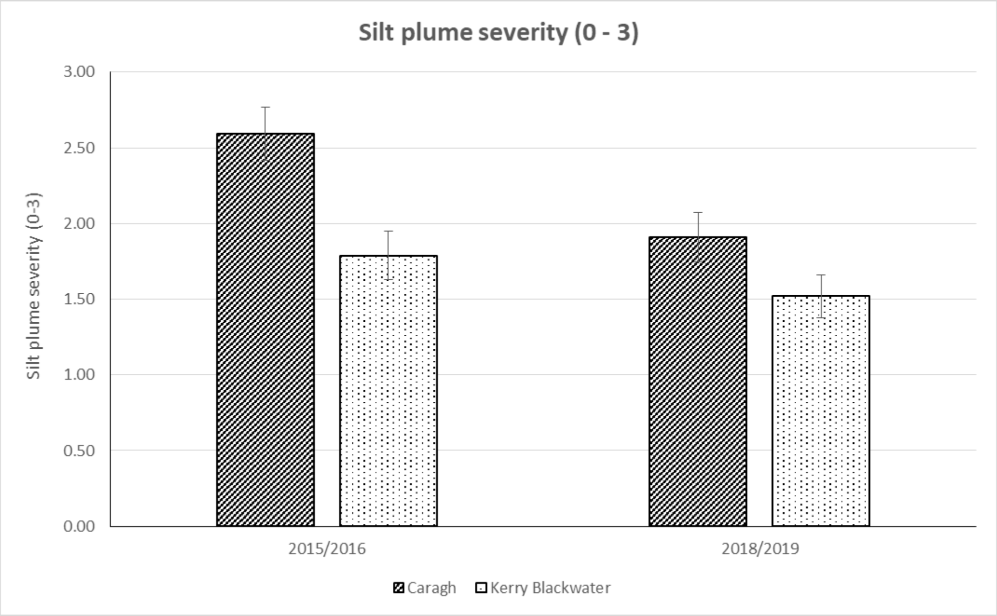


Figure 5.3 Mean changes in silt plume severity between 2015/2016 and 2018/2019 in quadrats in freshwater pearl mussel habitat in the Caragh and Kerry Blackwater (error bars show mean standard error of the mean).

Individual results of the redox monitoring and the time integrated sampling of O'Neill (2019) need to be interpreted alongside silt plume monitoring. In particular, this work showed that the very fine silt produced by peat particles does not settle as quickly or as much as the larger mineral soil particles.

5.2 Macroinvertebrate Sampling

Macroinvertebrate sampling was undertaken by Twomey & Quirke (2017a & b, 2018, 2019) on behalf of KerryLIFE at a range of sites in streams and main channels upstream of *Margaritifera* locations, with an assessment of macrophyte and siltation levels also included in this work package. Full details are in these reports.

The results of the annual biological assessments indicate that only 1 site of the 20 sites assessed in each of 2016 and 2018 meets all of the requirements of the 2009 *Margaritifera* regulations. The macroinvertebrate requirement was met at 20% of sites in 2016 and 41% of sites in 2019, the silt requirement was met at 3 or 4 of the sites across the sampling period, the filamentous algae requirement was met at 60-75% of the sites each year, and the macrophyte requirement was met at 91-95% of the sites. The results also indicated possible toxic impacts on the macroinvertebrates at some locations, possibly as a result of high iron concentrations, which may be due to drainage of peatlands and other acidic soils.

5.3 Redox monitoring

Redox potential monitoring was undertaken as part of *Margaritifera* monitoring (Moorkens 2015, 2017, 2019), and by the KerryLIFE team as part of the habitat monitoring programme(Phelan et al. 2017a, 2018a,b,c, O'Callaghan, et al 2020).

In the Caragh catchment, redox potential results in the Owenroe River were spatially mixed, with mean loss of redox varying between 9.72% in Transect 1 to 23.6% in transect 2 in the 2014 study. Mean loss should be no less than 20%. As a range of redox measurements are taken in the vicinity of mussels living in the habitat mean values are useful, as they express the general condition of a very precise area of mussel habitat at one point in time. The percentage of readings that fall into the sustainable range of less than 20% loss is also a useful parameter to analyse. However, redox measurements across a range of sites or a range of times should not be averaged, as the clean conditions at certain periods cannot mitigate against a period of poor redox conditions, when juvenile mussels are at risk of death.

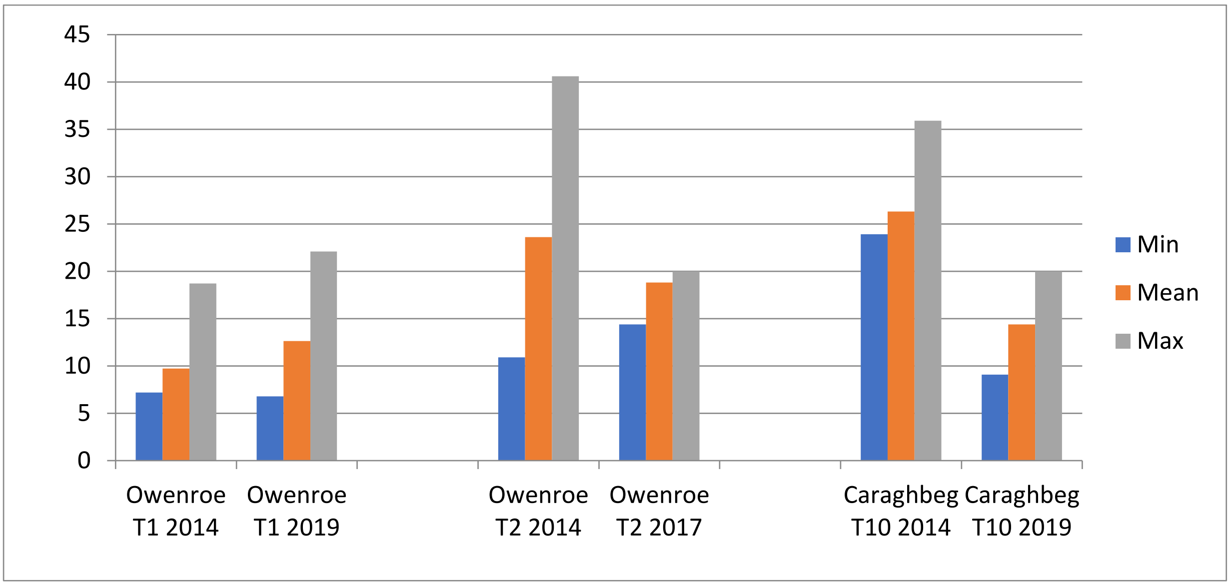


Figure 5.4 Mean, max and min loss of redox potential at 5cm depth (Moorkens, 2019). Codes refer to river/tributary , transect number (T) and year. Further details available in Moorkens (2019)

Figure 5.4 shows the Moorkens and Killeen data in the Owenroe and Caraghbeg rivers. Redox potential results in the Owenroe River marginally deteriorated over 5 years in T1, but not by any significant amount, and they improved to sustainable levels in the 5 years in the T2 location. The results from KerryLIFE measurements suggest poorer conditions compared with those measured by Moorkens and Killeen. However, their measurements were taken across a wider range of algal conditions. Macrophyte levels were severe at times in mussel habitat in the Caraghbeg River, suggesting longer term catchment dysfunction with regard to flow and movement of fine sediment into the river bed. This could account for poor redox results before high flows as fine sediment moves through the river.

The algal conditions suggest that the Owenroe River has had excessive nutrient problems in the past, and these may be resolving thanks to the KerryLIFE agricultural measures.

The Caraghbeg conditions are not unlike the Owenroe, with reasonable redox and algal conditions. However, juvenile loss is much higher, suggesting that incidences of low flow is a bigger problem on the Caraghbeg compared with the Owenroe.

In the Kerry Blackwater Catchment both the Moorkens & Killeen data and the KerryLIFE data show that redox measurements vary widely with location and particularly with time of survey. Conditions differ across different parts of the transect and the changes over short periods of time underline the vulnerability that the habitat has to deterioration and juvenile loss through multiple repeated negative pressures.

The differences between the maximum, mean and minimum redox levels measures are shown in both the Kealduff and the Kerry Blackwater (Figures 5.5 and 5.6). The results correlate with periods of intermittent algal growth and decay, which may account for the wide variation in redox scores.

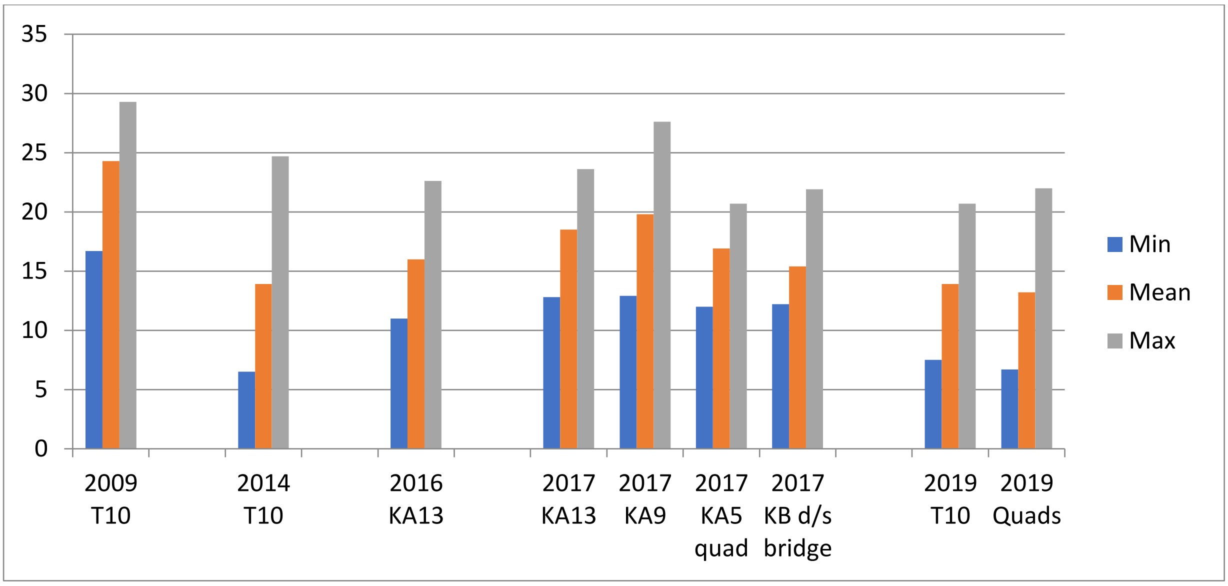


Figure 5.5: Comparison of redox potential loss at all sites in the Kealduff 2009-2019. Codes refer to river/tributary (KA= Kerry Blackwater, KB=Kealduff); transect number (T/KA/KB); quadrats (Q); and year. Further details available in Moorkens (2015,2017 and 2019)

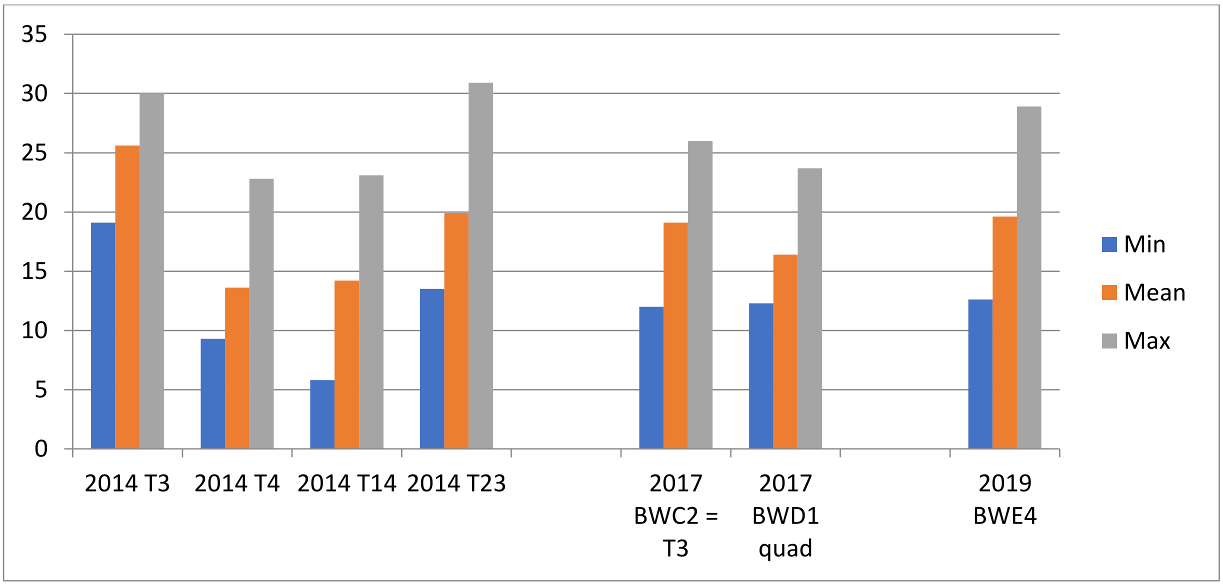


Figure 5.6: Comparison of redox potential loss at all sites in the Kerry Blackwater main channel 2014-2019. Codes refer to transect number (T); Habitat mapping sections (BWC= Kerry Blackwater d/s of Kealduff confluence, BWD=Kerry Blackwater, Gearha Bridge; BWE = Kerry Blackwater); quadrats (Q); and year. Further details available in Moorkens (2015,2017 and 2019)

6 *Margaritifera* monitoring

Monitoring of the freshwater pear mussel was undertaken in 2014, 2016, 2017 and 2019 (Moorkens, 2015, 2017, 2019).

6.1 Caragh Catchment distribution and density studies

The results of the permanent transect counts show a general decline over time, but it is likely to be masked by the movement of mussels both in and out of transects. Changes can demonstrate an instability in the mussel locations. However, this is quite typical in large populations with extensive habitat in good condition throughout the rivers, as the large population of mussels results in high levels of glochidiosus in fish hosts, and therefore a higher chance of juvenile mussels dropping off in a wider range of river bed conditions. The mussels that settle in less stable sub-optimal habitat are more likely to be moved during high flows. However, the variation in transect counts need to be considered along with the results of demographic and redox potential studies, as poor recruitment and redox condition may mean that mussels are being moved due to stressed conditions, and this is a much more serious situation. Interpretation of all survey results must be taken together, in particular with habitat mapping results, to provide a more accurate assessment of the condition of the population.

To assess whether a river is declining or recovering, juvenile habitat mapping (Killeen & Moorkens, 2020) can be used to assess the distribution and density of mussels in a number of ways by looking at their proportionality relative to:

a) The distribution of the quality of the habitat
b) The distribution of depth of the habitat
c) The distribution of flow in the stretch

A good population that has retained excellent condition should map mussels in densities related to the quality of the juvenile habitat, with little movement of mussels over time from where they were born. Mussels should also relate to moderate depths and flows, demonstrating no excessive nutrient pressures that could stress mussels and wash them into deeper pools, or altered hydrology, which could pull mussels into pools during excessively high flows, or kill or make them move out of good habitat into deeper water during excessively low flows.

The mapped condition of the habitat and the presence of excessive macrophytes or filamentous algae, or poor redox condition implies current negative pressures, which can be caused either by excessive nutrients, or inadequate hydrology, or both. Comparing this data with recruitment patterns demonstrates whether a population is declining due to these pressures, or improving due to more recent protective measures.

There is a marked difference between the Caragh main channel and the two tributaries with respect to the distribution of mussels. All three sub-catchments have an average of approximately 6 mussels per m^2, but the Caragh main channel had less than 5 mussels per m^2 in good juvenile habitat, suggesting a destabilization of the habitat resulting in the removal of mussels from the best habitat into poorer areas unlikely to support juvenile mussels. In contrast the two tributaries have higher densities of mussels in suitable juvenile habitat, particularly in the Owenroe (Figures 6.1 and 6.2).

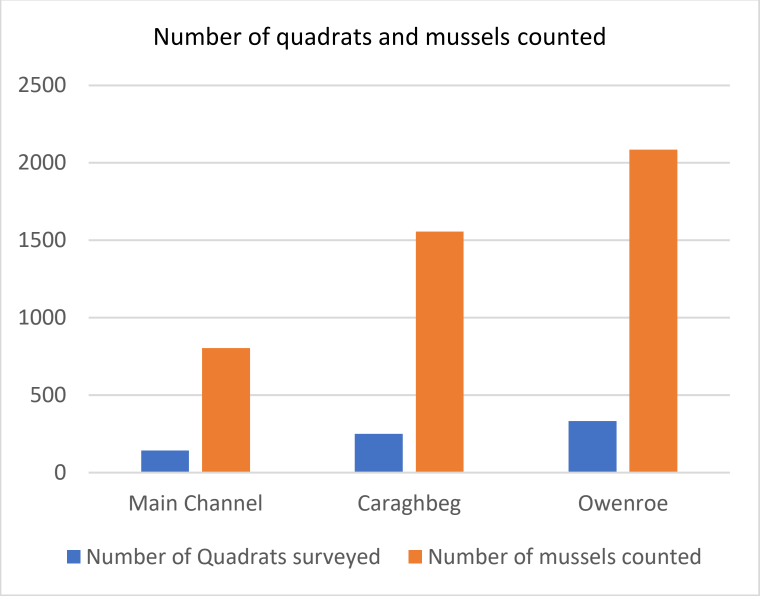


Figure 6.1. Numbers of quadrats and mussels counted

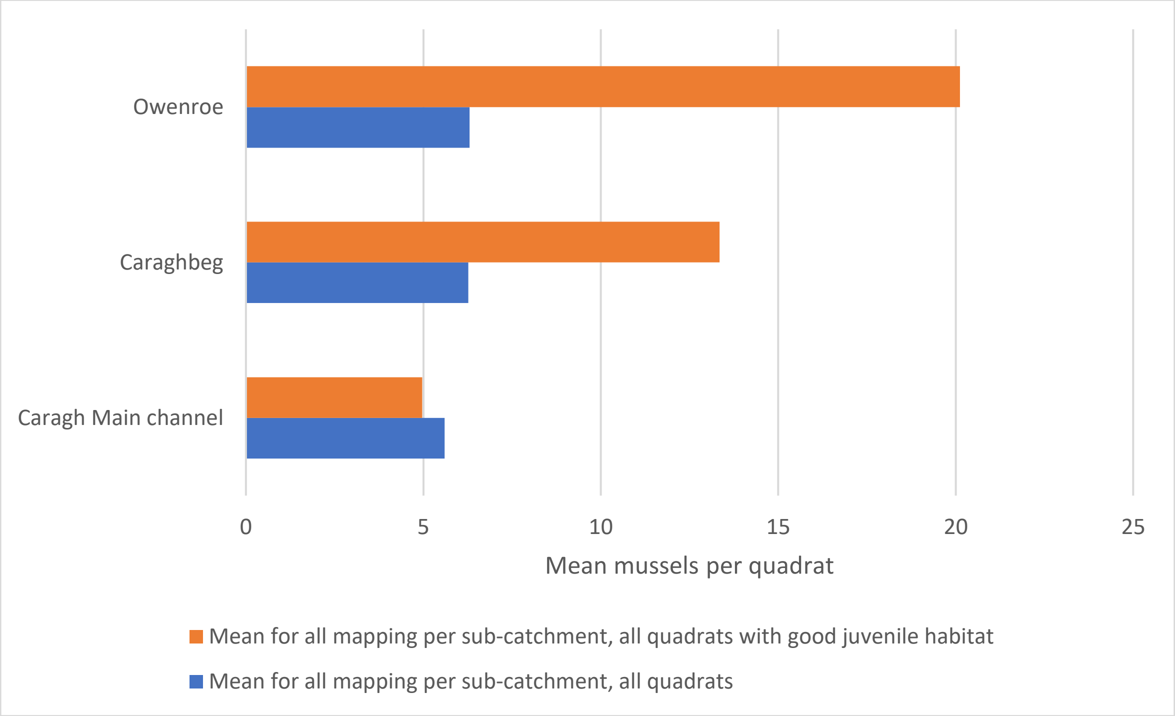


Figure 6.2. Mean mussels per quadrat in Habitat Mapping Sections

The flow patterns can be seen for all quadrats in Figure 6.3, and for quadrats with mussels >5 in Figure 6.4. Note that relatively lower flows were found in the Caraghbeg and main channel compared with the Owenroe, in spite of conditions being the same at all surveys (i.e. Q < 85%). Although the Owenroe River had elevated nutrient conditions, the flow conditions appear to be much more positive, following the pattern of mussel densities by near bed velocity as demonstrated by Moorkens & Killeen (2014). In large populations with appropriate hydrology, mussels should be present across all flows, but concentrated in moderate flow areas, which in turn should be dominant. Mussels in slow or standing water are indicative of situations where aggressive flows have washed them in, and mussels in the fastest flow are usually adults that have deliberately moved into better flow during drought periods, and these areas can become aggressively scouring in high flows, which initiates another episode of mussels being pulled out of the river bed and washing in to slow or standing water areas. The Caraghbeg had a relatively high percentage of mussels in standing water, which is a negative indicator of population condition, demonstrating a deterioration of good mussel habitat and catchment flow.

The mean number of mussels per quadrat is mapped against flow category for all quadrats (Figure 6.5), and for quadrats with >5 mussels (Figure 6.6). The higher number of mussels in faster flow is evident in the Owenroe, and the higher number of mussels in slow and standing water can be seen in the Caraghbeg.

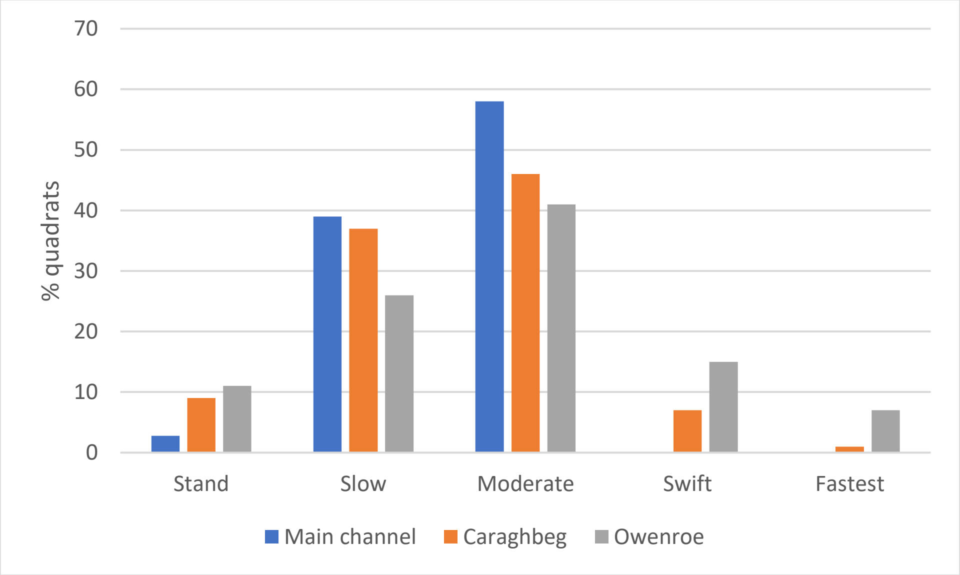


Figure 6.3. Percentage of quadrats by flow category – all quadrats (N=697)

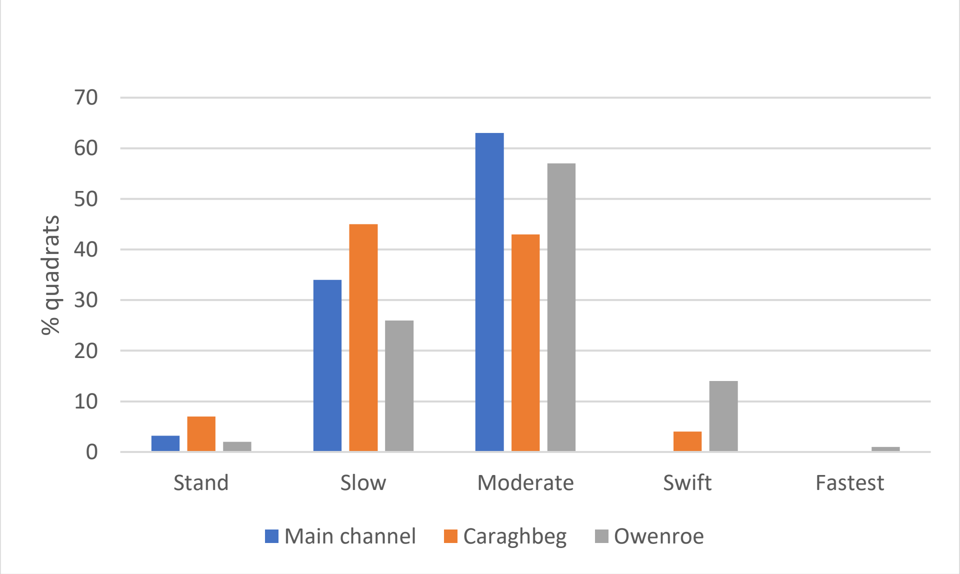


Figure 6.4. Percentage of quadrats by flow category – quadrats with >5 mussels (N quadrats = 223)

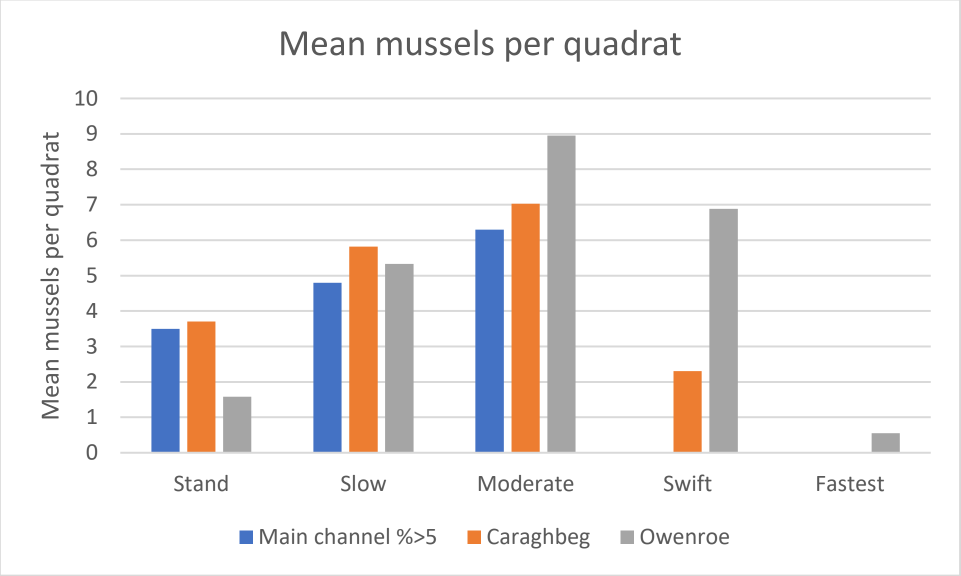


Figure 6.5. Percentage of mussels by flow category – all quadrats (N quadrats = 697)

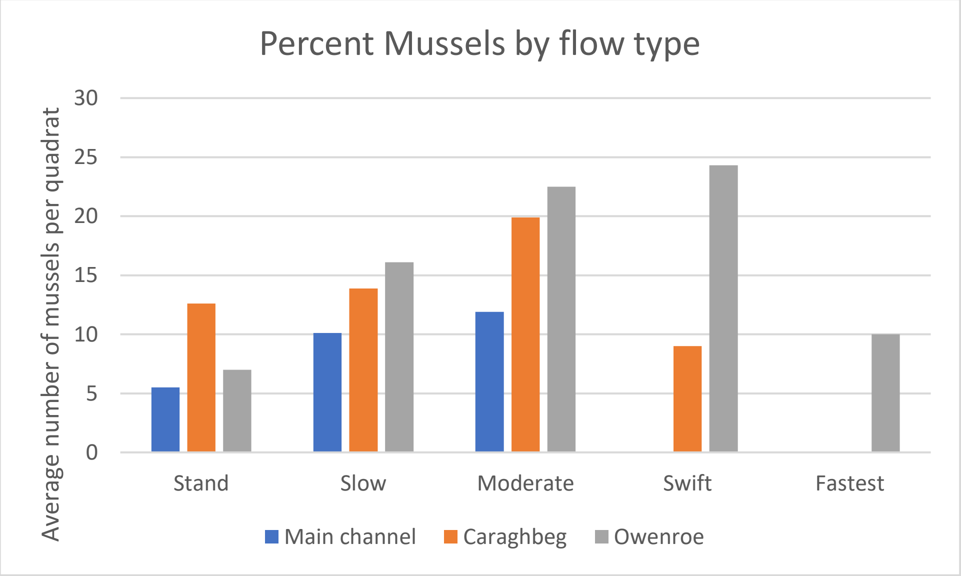


Figure 6.6. Percentage of mussels by flow category –quadrats with >5 mussels (N quadrats = 223)

6.2 Kerry Blackwater distribution and density studies

There is a marked difference between the Kerry Blackwater main channel and the Kealduff River with respect to the distribution of mussels. The Kealduff has over three times the average number of mussels per quadrat across all habitat types, and twice the average in good juvenile habitat (Figures 6.7 and 6.8).

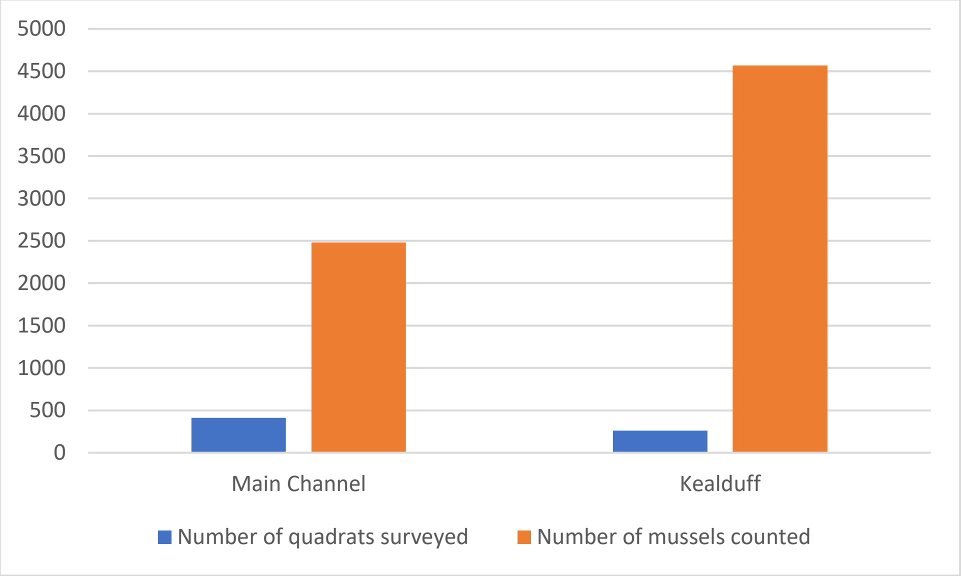


Figure 6.7. Numbers of quadrats and mussels counted

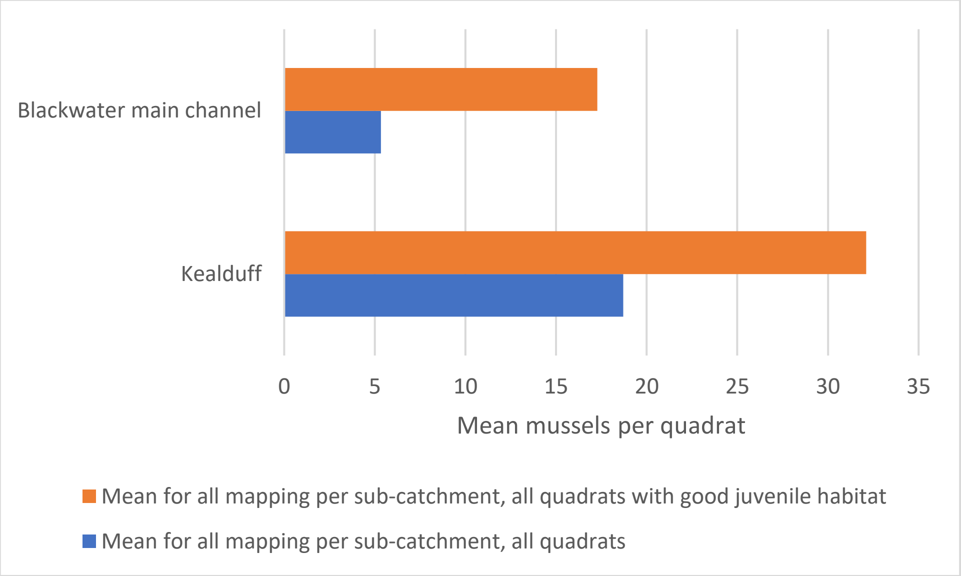


Figure 6.8. Mean mussels per quadrat in Habitat Mapping Sections

The flow patterns can be seen for all quadrats in Figure 6.9, and for the percentage of mussels counted in each sub catchment in Figure 6.10. The flow pattern in the quadrats followed the expected pattern at low flows, with the highest percentage flow type being moderate flow, which is the modal category for mussel habitats.

The mussel percentages should rise from a small number in slow areas to the majority in moderate flow, and some in swifter flowing water. This pattern is seen in the main channel, but with an excess of mussels in slow flow, indicating that poor conditions have moved mussels into slower habitat. The majority remain in moderate flow.

In the Kealduff River, in spite of the normal range of flows, mussels are inappropriately distributed with the majority in slower water, and some excess in swift flow.

In general, movement into slower flows indicates stress, with mussels pulled out of their habitat and then getting trapped in slower areas. Movement into swifter areas indicates mussel voluntary movement out of conditions that are difficult for them, such as excessively low flows or high levels of algae affecting siphon action in open water. The two conditions are likely to be related, where mussels move in poor flows to faster areas, and may be weakened by the stress event that precipitated it. They are vulnerable to being washed into slower flow areas during the next high flow event.

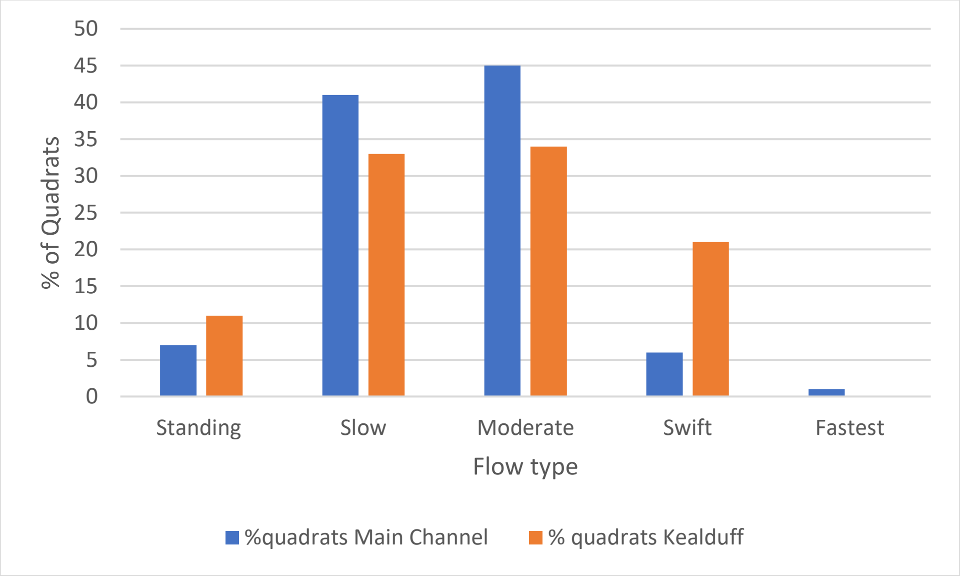


Figure 6.9. Percentage of quadrats in each flow type category

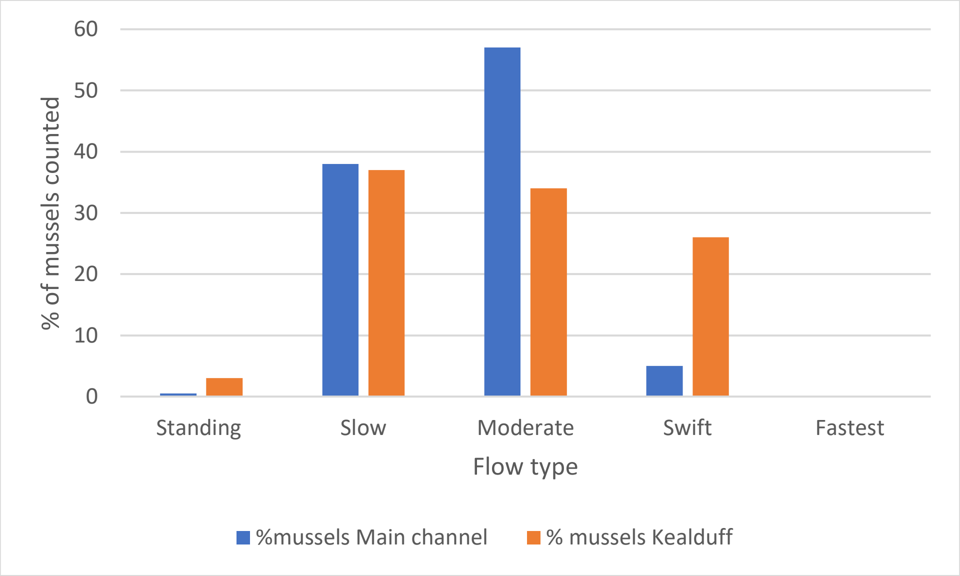


Figure 6.10. Percentage of mussels in each flow type category

In both sub-catchments mussels have been pulled into slow flow. In the Kealduff, conditions are also drawing mussels from the best habitat into sub-optimally faster areas through velocity and nutrient stresses.

The pull of mussels into slow flow is generally into pools of deeper water, and this can be seen in the two scatterplots of mussel distribution related to depth in Figures 6.11 and 6.12 (note different scales), and the concentration of mussels towards deeper water which is incompatible with juvenile survival.

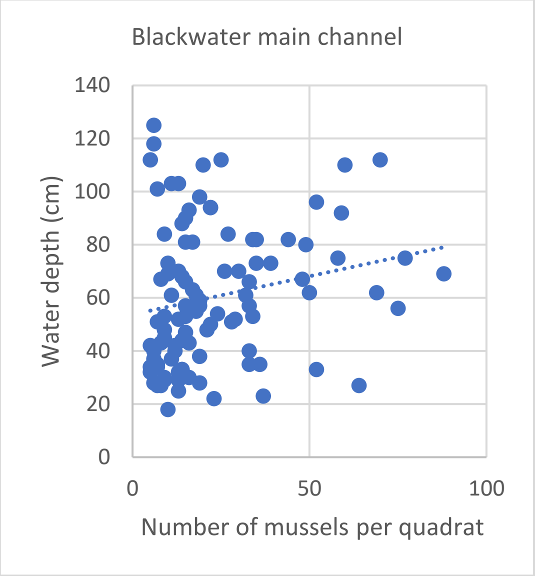


Figure 6.11. Mussel distribution by depth in the main channel Kerry Blackwater

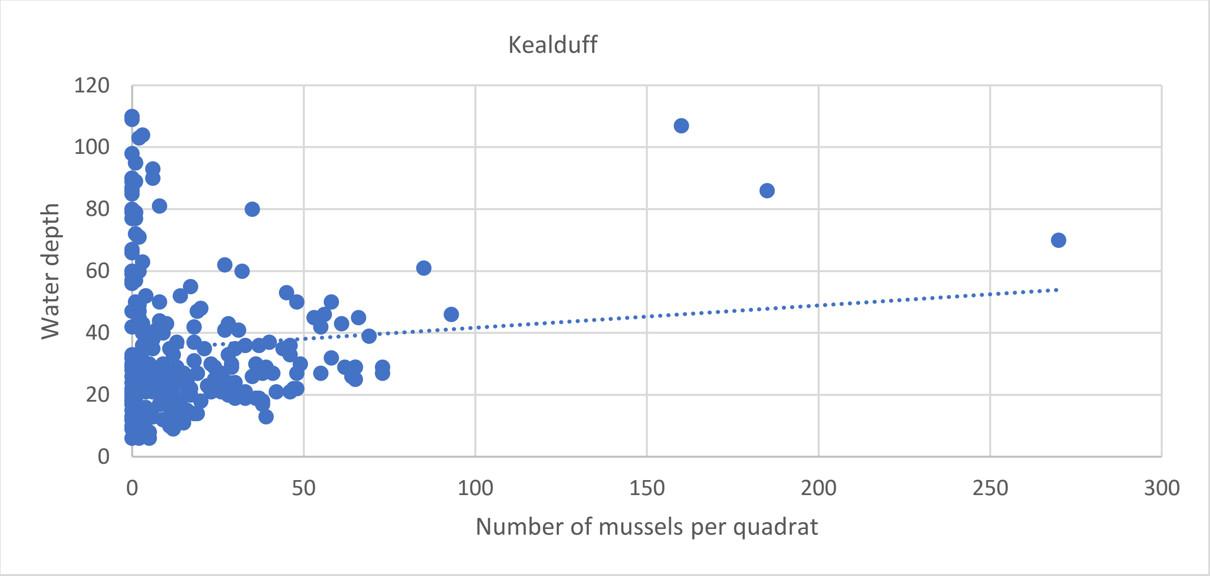


Figure 6.12. Mussel distribution by depth in the Kealduff River

At low flow, most mussels should be in less than 60cm depth in moderate flow. The majority of the mussels in the areas surveyed are now in deeper water and concentrated in small areas of deeper pools within a wider area of shallow habitat. This demonstrates a serious decline, linked to flow stresses, potentially in combination with nutrient stress.

6.3 Demographic Studies

Demographic studies in the field represent longer term conditions, as it is difficult to find juveniles under 1.5mm, and individuals found in the smallest size categories may not survive to reach the sub-adult stage of 30mm or larger. Consequently, the results of improvements due to KerryLIFE, most of the actions being undertaken in 2017, may not be evident until 2027.

In the Caragh Catchment, the Caraghbeg and Owenroe river sub-catchment studies indicate declines as the trend before KerryLIFE actions. In the Caragh main channel considerable differences were found between sites, even when relatively close together. Summarized results are in Figure 6.13.

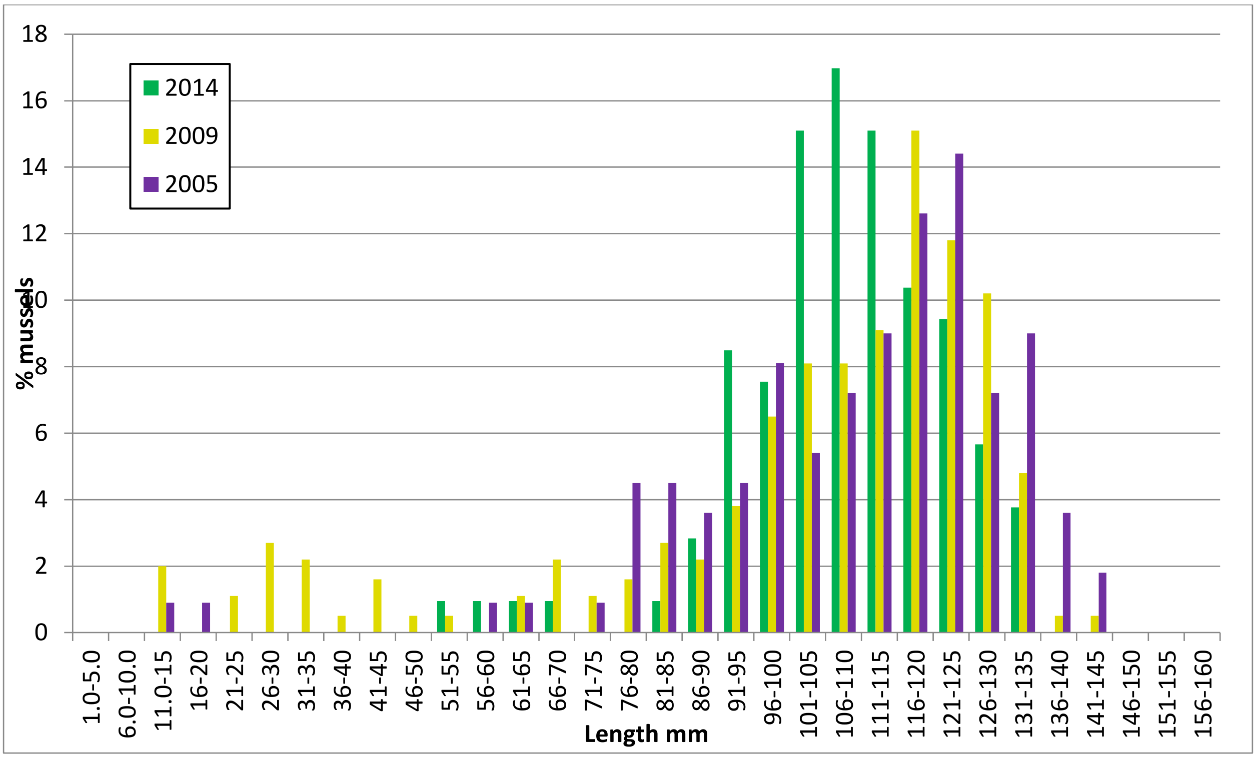


Figure 6.13: Caragh main channel demography 2005 to 2014

In the Caraghbeg River, one site was directly comparable between 1999 and 2005, the location being 300m upstream of confluence with Caragh, Grid Ref V 71712 86200. Juveniles had reduced from 0.55% to none and young mussels <65mm had reduced from 16.6% to 12.2% in the 6 years (Figure 6.14). Demographies across the age range show a sharp trend towards older mussels in the Caraghbeg (Figure 6.15). There is no excessive level of macrophyte or filamentous algae, but the habitat mapping showed that flow velocities are lower in the Caraghbeg compared with the Owenroe. Figure 6.16 shows that there was little change in demography in the Owenroe between 1999 and 2005. Similarly Figure 6.17 shows a better recruitment pattern throughout 2005 to 2019. The 2019 results followed 5 years of agricultural measures undertaken through the KerryLIFE project, and while not yet at sustainable levels, they show improvement towards sustainability if the smallest of the juveniles survive. The cohort of 1.5mm juveniles found in 2019 is of particular interest in this respect.

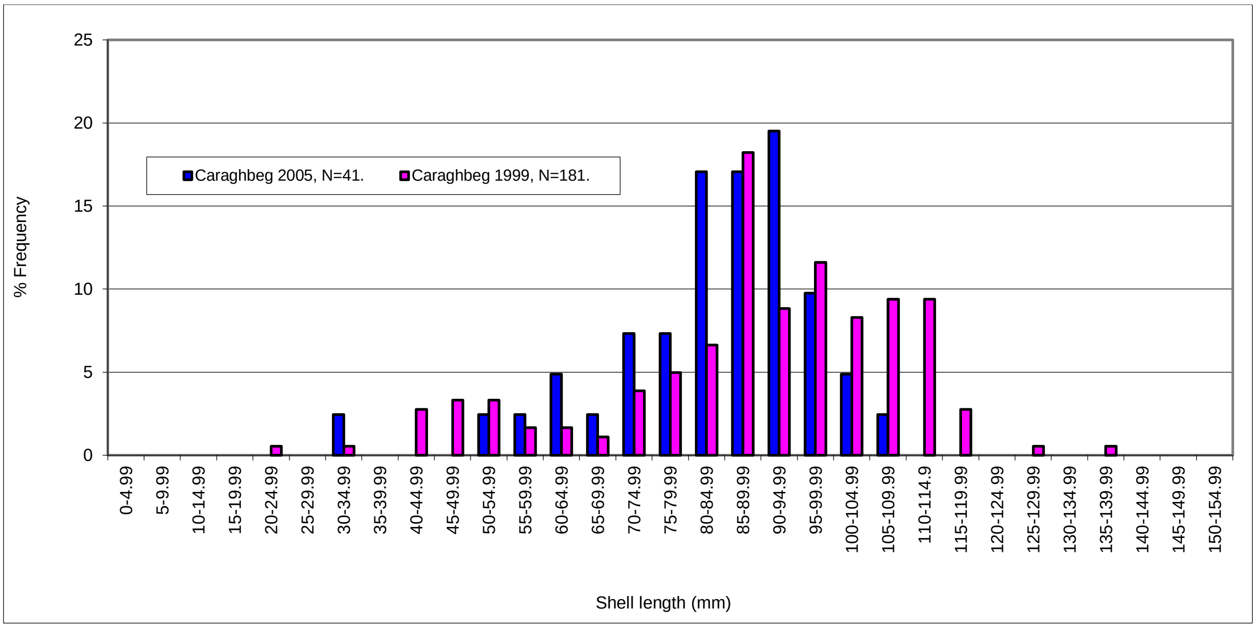


Figure 6.14: Caraghbeg comparison at site upstream of the Caragh confluence 1999 and 2005

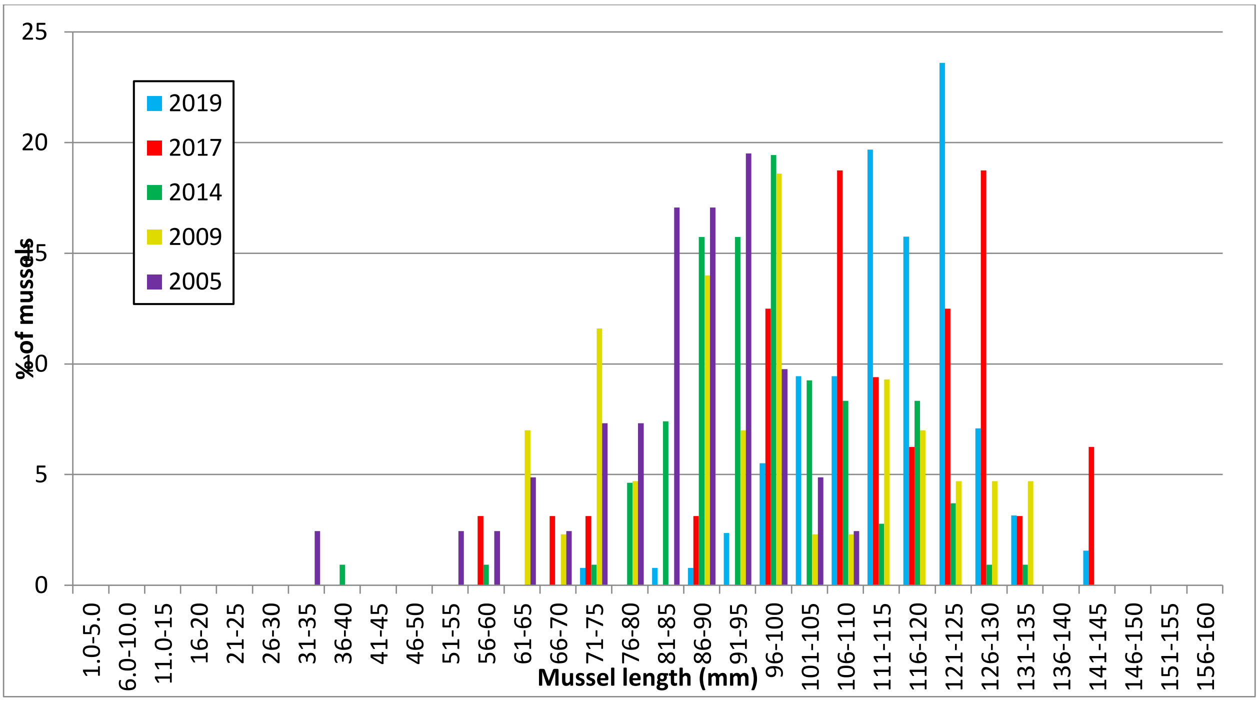


Figure 6.15: Caraghbeg demography pattern 2005 to 2019

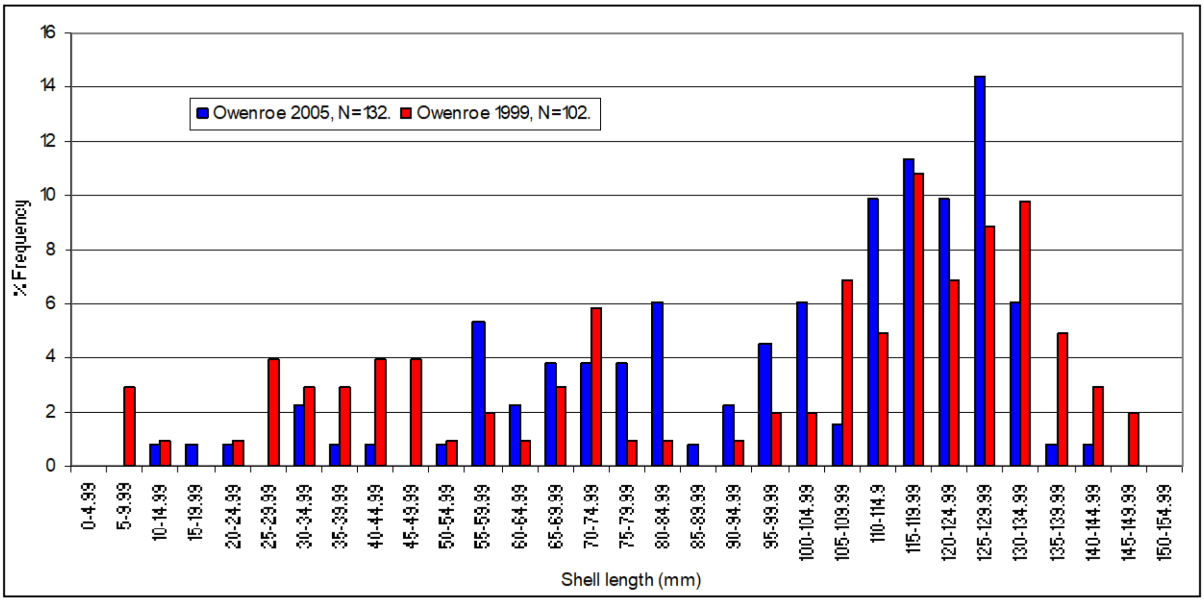


Figure 6.16: Owenroe 1999 and 2005

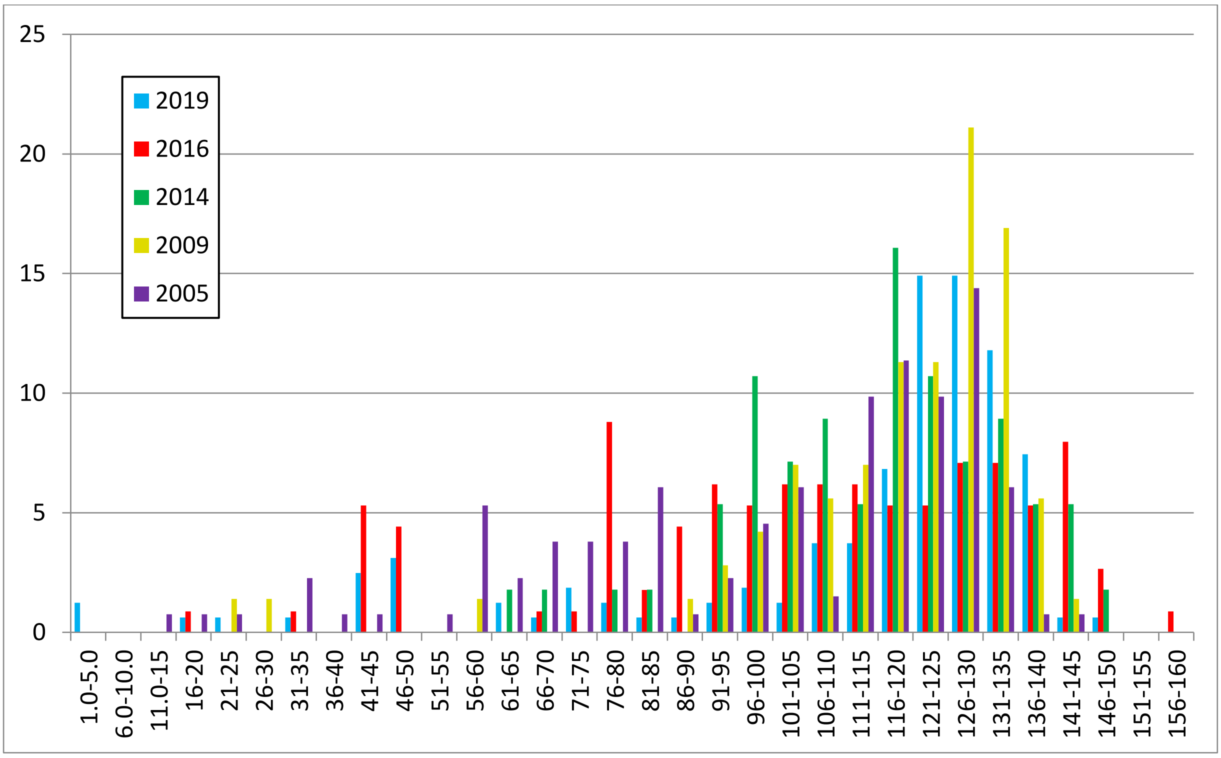


Figure 6.17: Owenroe demography pattern from 2005 to 2019

The results of demographic studies show very poor juvenile recruitment in all three sections of the main Kerry Blackwater channel (Figures 6.18, 6.19 and 6.20), and intermittent loss and recovery in the Kealduff River population (Figure 6.21).

The situation in the Kealduff River is skewed by the amount of effort put into the 200m upstream of Kealduff Bridge, as it is the most important stretch for mussels in the Kerry Blackwater catchment.

The functional seepage providing juvenile food in the field on the right bank of the river upstream of the bridge plays an important role in the ongoing production of juveniles. They are produced in great numbers here, but as the Figure 6.21 demonstrates, they are lost on intermittent occasions of stress. Due to excessive macrophytes or filamentous algae, poor oxygen conditions as shown from redox condition, in combination with inadequate hydrology.

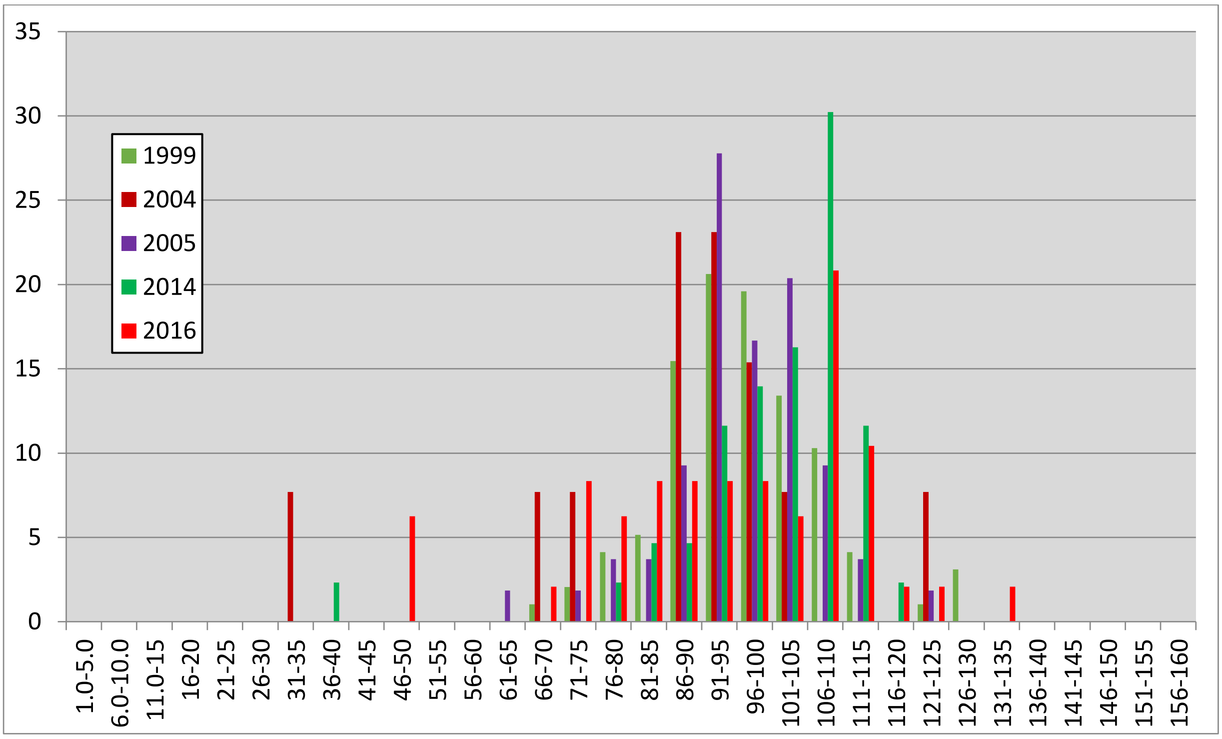


Figure 6.18: Upper Kerry Blackwater, Transect 3 area from 1999 to 2016

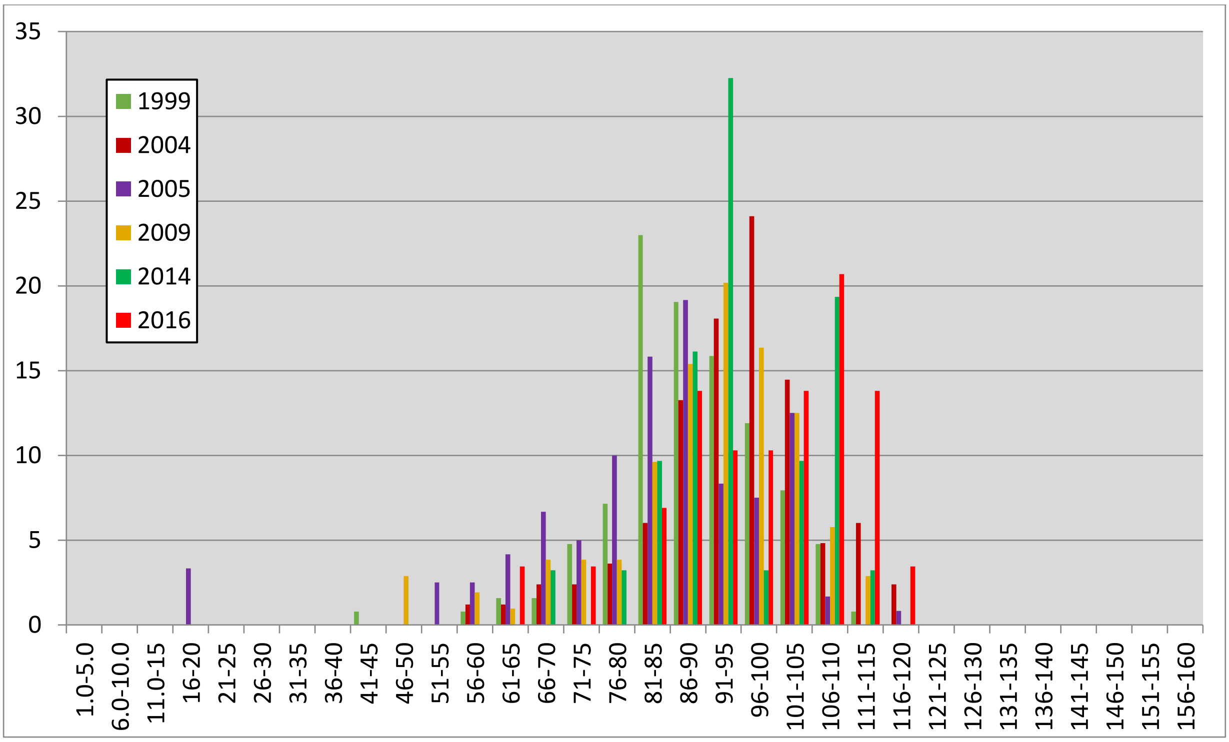


Figure 6.19: Middle Kerry Blackwater, Transect 13-16 area from 1999 to 2016

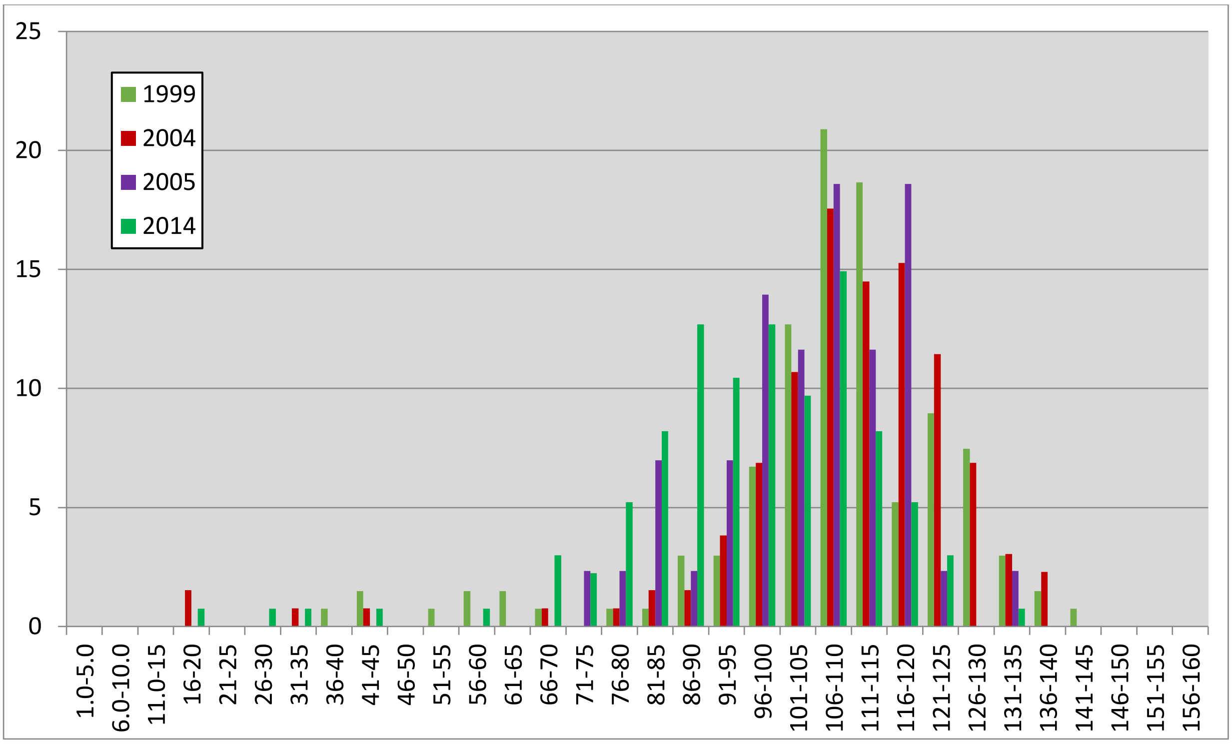


Figure 6.20: Lower Kerry Blackwater, Transect 23 and 24 area (d/s Derrenderragh) from 1999 to 2014

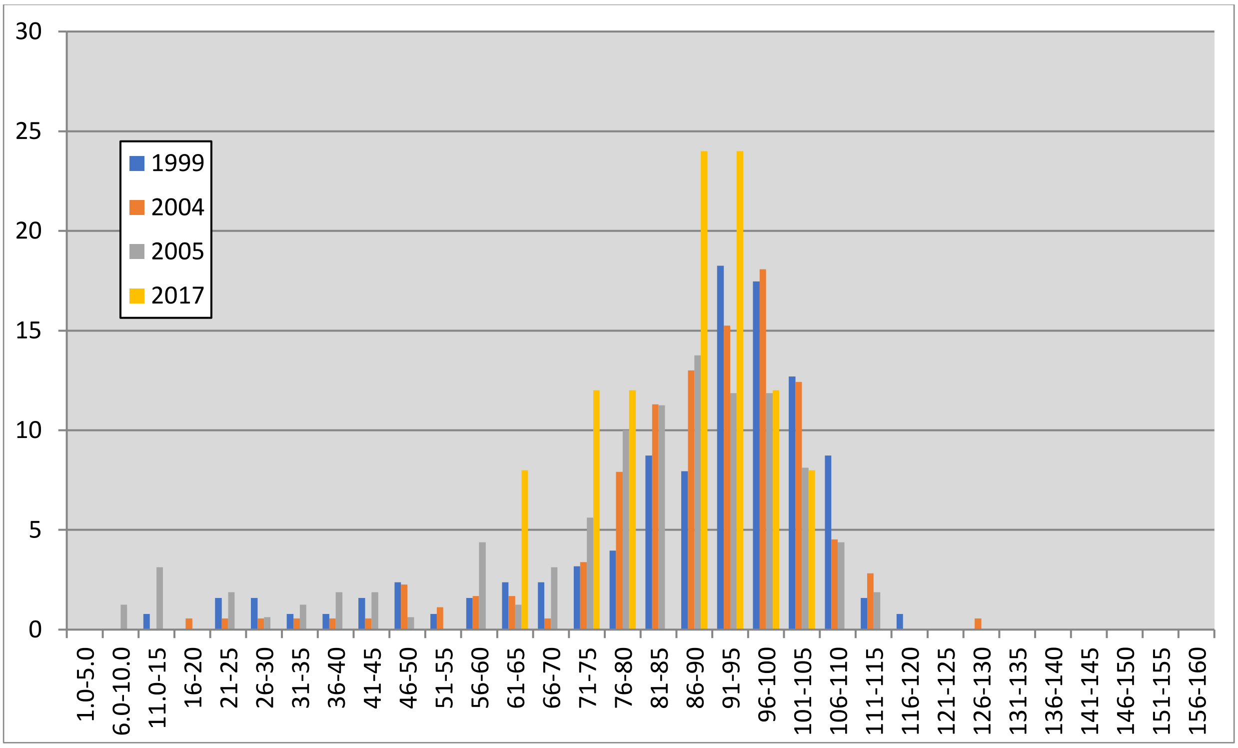


Figure 6.21: Kealduff d/s Kealduff Bridge, Transect 11 area from 1999 to 2017

6.4 Velocity studies in relation to mussels

Velocity measurements were taken in 2014 and 2019 at low flow conditions (Q<85%) across a range of transects in both catchments.

In the Caragh Catchment, the Owenroe River near bed velocity follows the pattern as described by Moorkens & Killeen (2014) in having low mussel numbers at low velocity, with increased numbers at higher velocities and reduced numbers again at the highest velocities (Figure 6.22). The situation is not as obvious in the Caraghbeg River, as this is a poorer river for mussels the results are skewed by the quadrats that have no mussels living in them, and by pools with mussels washed into them. This can be seen by the comparison of the graph containing all data with the graph showing only quadrats with more than 10 mussels (Figures 6.23 and 6.24). This velocity study demonstrates how much better the Owenroe River habitat is for *Margaritifera*.

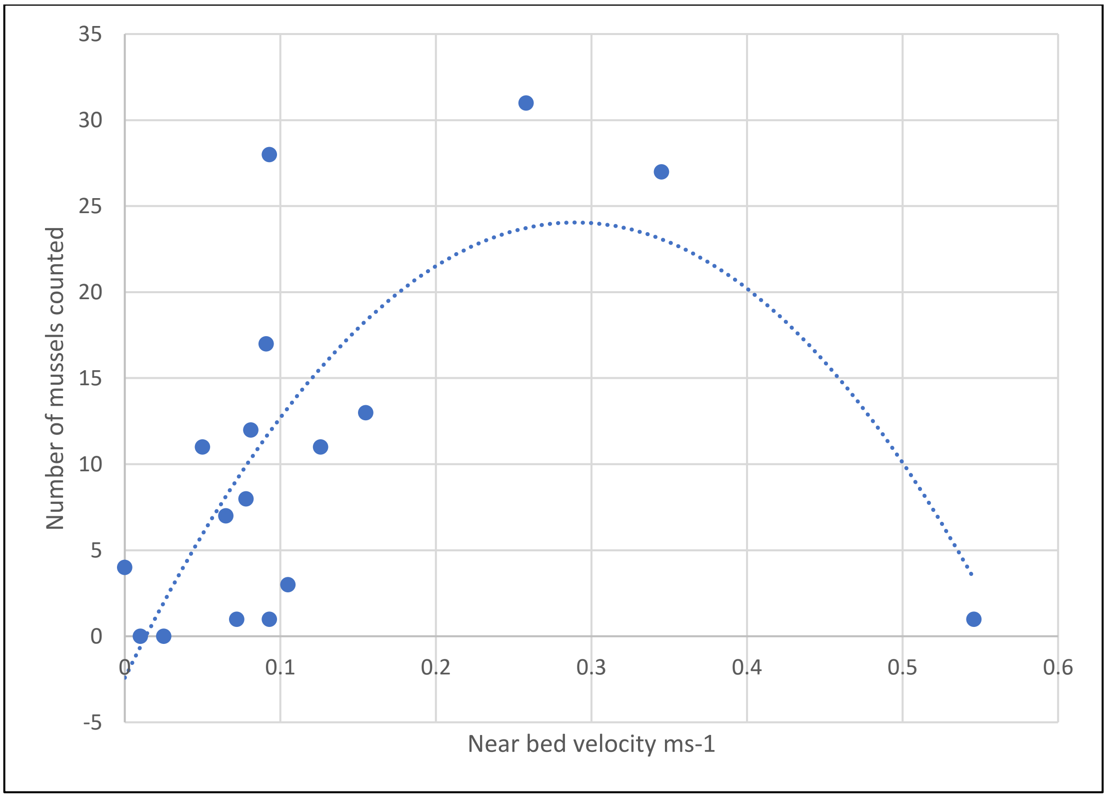


Figure 6.22 Near bed velocity versus number of mussels per quadrat in the Owenroe River study 2019

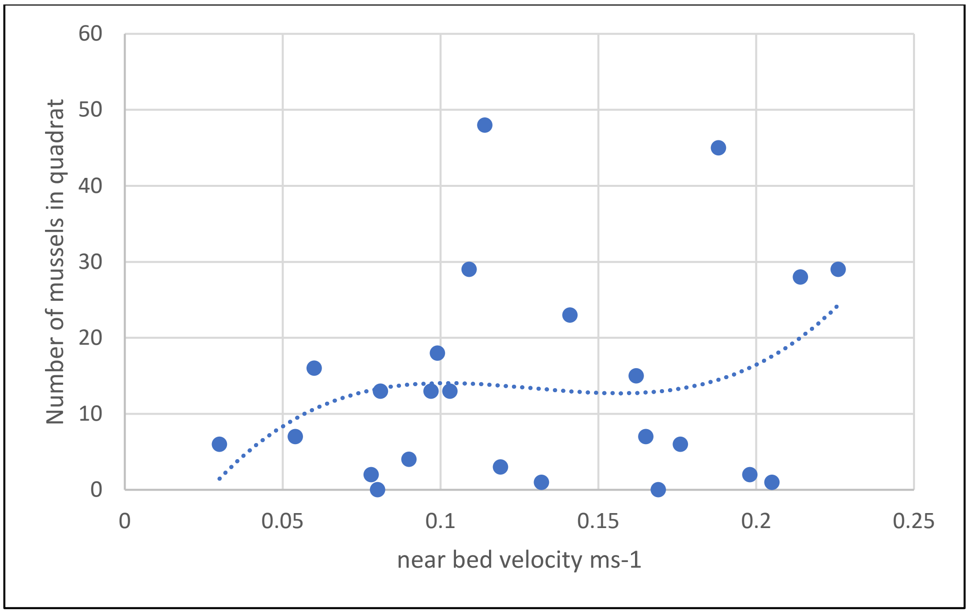


Figure 6.23 Near bed velocity versus number of mussels per quadrat in the Caraghbeg River study 2019 (all quadrats)

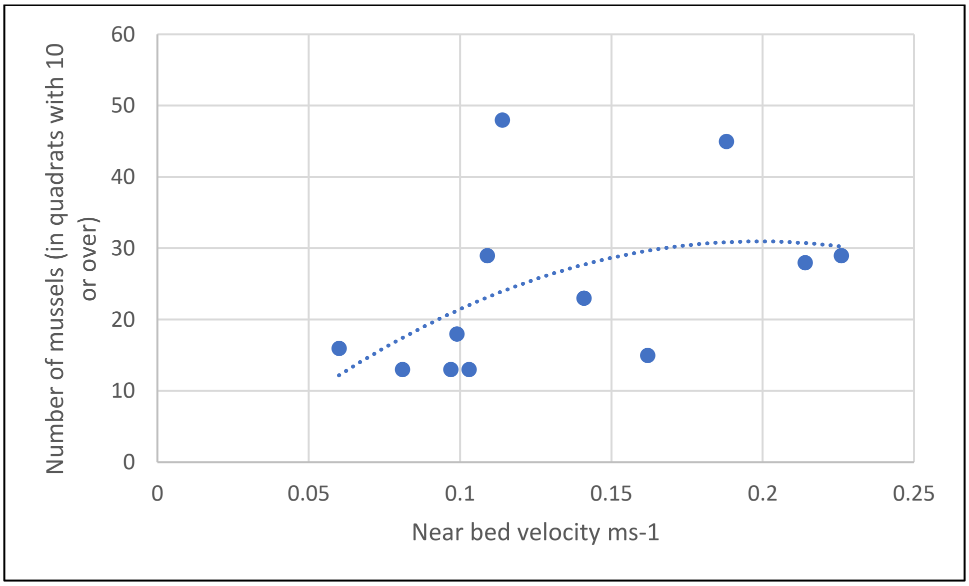


Figure 6.24 Near bed velocity versus number of mussels per quadrat in the Caraghbeg River study 2019 (quadrats with 10 or more mussels)

The velocity results of both rivers can be compared by the 9 combinations of habitat and condition from the habitat mapping survey (Figure 6.25). Quadrats are categorized by juvenile habitat mapping category combinations (of habitat, condition pairings) with the Good (G), potential (P) and No (N) habitat categories and the Good (G), Moderate (M) and Poor (P) condition category combinations. The Owenroe shows a better variation in velocity in the open habitat, while the Caraghbeg more even velocity shows lower variation, probably because of the steeper tree-lined banks leading to restriction of water to a more channelled pattern of deeper water. In the velocity transects the average water depth in the Owenroe River was 19cm +/- 10cm, and the Caraghbeg River average water depth was 31cm +/- 9cm. This again shows a relatively good level of catchment protection in the Owenroe River compared with the Caraghbeg.

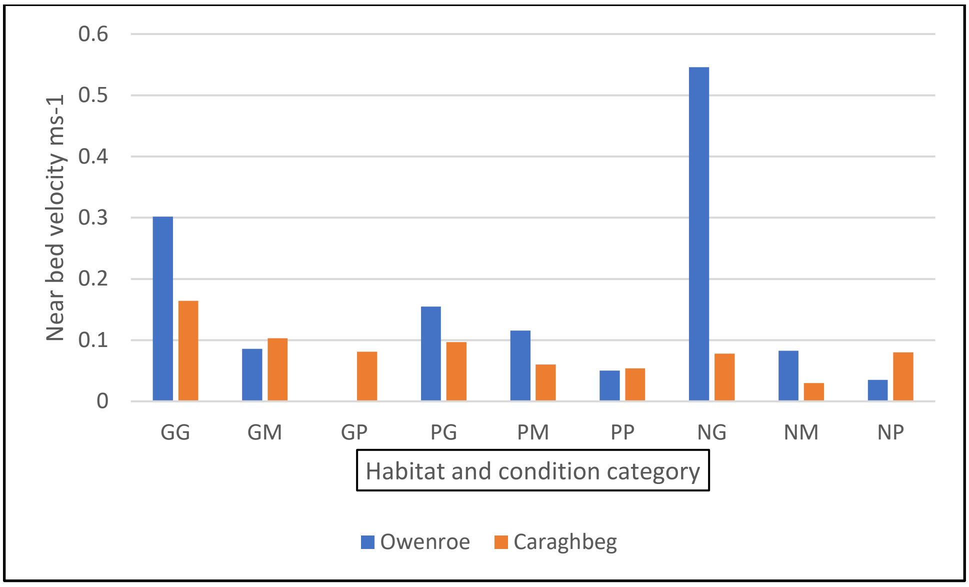


Figure 6.25 Near bed velocity versus habitat and condition category per quadrat in the Owenroe and Caraghbeg River study 2019

The velocity studies in the Kerry Blackwater catchment showed that in both sub-catchments mussels have been pulled into slow flow. In the Kealduff, conditions are also drawing mussels from the best habitat into sub-optimally faster areas close to shallow parts of the river that suffer most frequently from low velocities and filamentous algal cover. The near bed velocities relationship with habitat and condition, as measured in the quadrats described by juvenile habitat mapping category combinations (of habitat, condition pairings) with the Good (G), potential (P) and No (N) habitat categories and the Good (G), Moderate (M) and Poor (P) condition category combinations (Figure 6.26). This demonstrates the situation in the Kealduff, where the correct velocities for juvenile survival are in habitat surveyed as “good”, whether the condition is good or moderate. However, mussels are being drawn to higher velocities, and these are associated with “no juvenile habitat” in “good” condition.

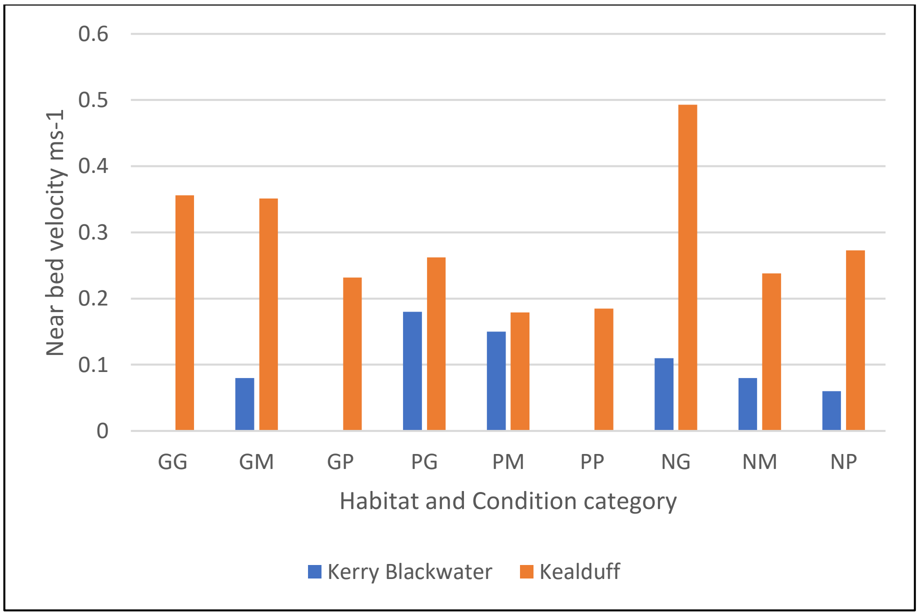


Figure 6.26: Near bed velocity versus habitat and condition category per quadrat in the Kealduff and Kerry Blackwater River study 2019

Moorkens (2018a) compared the Kerry Blackwater catchment flows with a range of population velocities in Ireland (Figure 6.27). The report concluded:

"The impairment of flow velocity was found to be a major pressure in some of the most important populations in Ireland. The inadequate velocities measured in the Caragh, Kerry Blackwater and Dawros Rivers, if allowed to continue, are likely to result in continuing sharp declines in adult numbers and a continuation of inadequate recruitment."

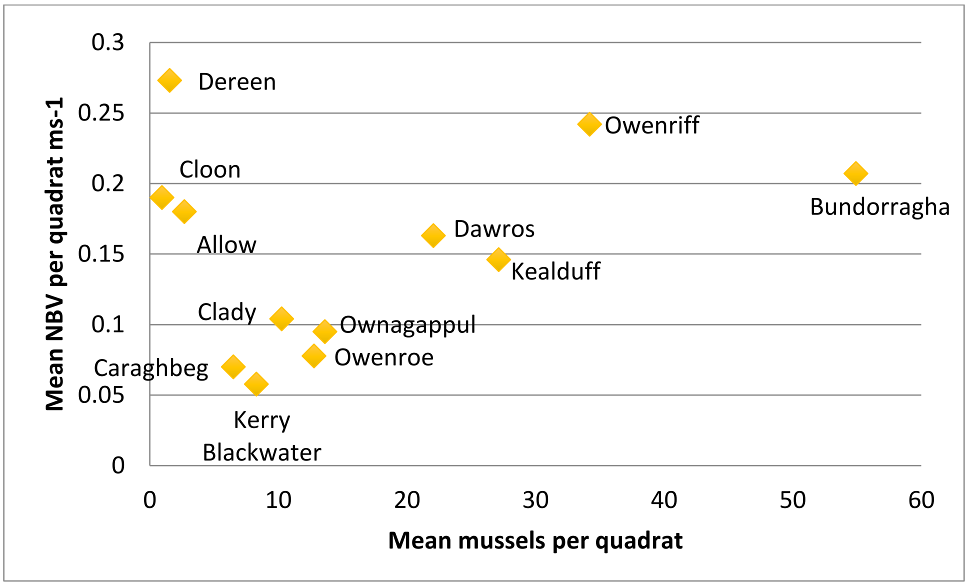


Figure 6.27: Mean mussels per quadrat versus mean near bed velocity in a range of Irish Rivers (from Moorkens, 2018a)

Since then, the Kealduff River mussels have been shown to be moving towards faster flow that is not juvenile habitat, or slower flow pools that are likely to be the result of washing in. The situation in this critically important population is of rapid deterioration.

6.5 Fish Host studies

The presence of adequate numbers of fish hosts are considered to be an essential aspect of sustainable mussel populations (NSAI, 2017). Fish host investigations were undertaken in 2009. Three sites in the Caragh catchment were surveyed on 14th and 15th May 2009 (Johnston, 2009 a&b). In the first site on the Owenroe River, 1 trout and 34 salmon were caught, and 4 salmon and no trout were found to be encysted with glochidia. At the second site (on the Caragh main channel), 8 trout and 13 salmon were caught, and 1 salmon was found to be encysted with glochidia, and no trout. At the third site (on the Caraghbeg), 11 trout and 8 salmon were caught, and no salmon and no trout was found to be encysted with glochidia Thus salmon rather than trout are acting as hosts to the Caragh mussel population, with the average level of encystment of salmon at 11.8% in the Owenroe, 7.7% in the Caragh, and 0% in the Caraghbeg. The macrophyte levels of 95% in the Caraghbeg River are so severe that they are covering the adult mussels, and this may be preventing encystment through physically preventing glochidia reaching their hosts as well as any juveniles reaching or surviving within the sediment.

One site on each of the Kerry Blackwater, Kealduff and Derreendarragh Rivers were investigated on 14th May 2009 (Paul Johnston Associates, in DEHLG, 2010b). A total of 1 trout and 37 salmon were caught in the Kerry Blackwater main channel, and no trout and 4 salmon were found to be encysted with glochidia. A total of 1 trout and 34 salmon were caught in the Kealduff River, and no trout and 4 salmon were found to be encysted with glochidia. A total of 2 trout and 30 salmon were caught in the Derreendarragh River, and no trout and 3 salmon were found to be encysted with glochidia. Thus, as well as effective glochhidial production, salmon are hosting the larval stage across the catchment, again supporting the conclusion that loss of sustainable numbers of juvenile mussels is one of survival, fitting in with the intermittent flow velocity and algal pressures in the river.

6.6 Genetic studies

A 2016 study of the genetic component of 12 populations of *M. margaritifera* in Ireland were undertaken with the Technical University of Munich (Feind et al., 2016; Geist et al., 2018). Samples collected by the KerryLIFE project from the Caragh and Kerry Blackwater populations both emerged as highly diverse populations, and contributed greatly to the Irish population exceeding all results from other countries for the genetic parameters of allelic richness and heterozygosity, indicating a diversity hotspot of the freshwater pearl mussel in Europe. The substantial high genetic diversity in the Irish pearl mussel populations are concentrated in the multi-million populations such as the Caragh and Kerry Blackwater.

7 Contribution of KerryLIFE conservation actions to *Margaritifera* recovery

7.1 The KerryLIFE project objectives

The objectives of the KerryLIFE project were as follows:

- To demonstrate effective conservation measures that will restore the freshwater pearl mussel to favourable conservation condition in the Caragh and Kerry Blackwater catchments.
- To enhance awareness and understanding of the freshwater pearl mussel amongst local stakeholders.
- To demonstrate sustainable management techniques for farming and forestry in freshwater pearl mussel catchments.
- To provide guidance for farming and forestry practices that support the conservation of freshwater pearl mussels.

The key deliverables and outputs for the freshwater pearl mussel were to achieve:

- An improvement in the condition of the habitat of the freshwater pearl mussel through a reduction in siltation and nutrient enrichment
- Increased recruitment of juvenile mussels to the population which will support achievement of favourable conservation condition

7.2 Contribution of KerryLIFE actions to freshwater pearl mussel conservation

The project actions were designed to achieve the above objectives, specifically, the concrete conservation actions which included drainage management, livestock and grazing management measures to reduce sediment and nutrient loads, planting of hedgerows, provision of alternative drinking water facilities and the restructuring commercial conifer plantations to long-term retention woodland using sensitive techniques. Table 7.1 evaluates some of the key tasks of KerryLIFE in the Caragh and Kerry Blackwater catchments based on the monitoring results undertaken in the project. This does not include the many tasks that supported the work and are essential to a successful project, but aims to evaluate the type of practical measures undertaken in the project that could be repeated in other mussel catchments. Overall, the key to achieving the projects objectives was the strong engagement with the farming and forest communities. The project worked closely with farmers and forest-owners within these two SACs. The original target area was 2,500 ha of farmland and 515 ha of forestry (in both public and private ownership) was exceeded with 5,038 ha of farmland and 542 ha of forest involved.

Table 7.1 Evaluation of key actions in the KerryLIFE project

Action	Foreseen in the Grant Agreement	Achieved	Evaluation
A.2	Production of 25 farm management plans covering 2,500 ha	40 farm management plans produced covering 5,038 ha of farmland. Drain audit of watercourses Habitat mapping Condition scores of Critical Source Areas	The increase in farms expanded the reach of the project within the project area. Greater participation in key sub-catchments such as Owenroe and the Kealduff sub-catchments were also achieved. The results of the drain audit improved information on pathways and resulted in a repeatable methodology.

Action	Foreseen in the Grant Agreement	Achieved	Evaluation
A.3	Production of 8 forest management plans covering 485 ha and 2 private forest properties covering 30 ha.	8 plans for public forests covering 495 ha and 9 plans for private land covering 47.56 ha were produced. Source and pathway mapping methodology Integrated risk assessment method.	The forest management plans collated important information on sources of sediment and nutrient. Hydrological studies assessed the pathways between forests and pearl mussel habitat, demonstrated the serious hydrological impacts at each site (e.g. Mackin 2016). This information was integrated in a novel risk assessment to inform the selection of trials implemented under Actions C.7-C.9. The plans contributed to a reduction of nutrient and sediment during operations by disrupting pathways between source areas to the river, but did not achieve sufficient hydrological improvement.
C.1	Management of drains at 1,500 locations on project farms and forests.	Hydrological studies were conducted on all participating farm and forests covering 5,532.9 ha. Conservation measures were implemented at 2,829 locations on project farms/ forests.	The measures implemented were demonstrated as being effective at breaking the pathway between sources of sediment and/or nutrients and the pearl mussel's habitat (the receptor).Where raising the water table has been achieved it has been considered to be favourable for mussels in the context of managing or restoring open habitats. Drain blocking was the most effective method to reduce losses of sediment and nutrients and to restore hydrological function. Riparian buffers together with alternative drinking water facilities for livestock in Action C.6 were effective at eliminating cattle access from pearl mussel habitat. This task is considered to be positive and repeatable in other catchments.
C.2	Establishment of 40 ha of native woodland to stabilise riparian sediments	4 woodland establishment sites covering 27.17 ha (two of which expanded existing native woodland stands) 4 woodland conservation sites 14.91 ha 1 conversion site 5.5 ha.	Strategic tree planting at vulnerable locations was proposed to reduce sediment and nutrient run-off and the undercutting and slumping of river banks was not achievable under Native Woodland Scheme as envisaged. Potential sites did not meet the schemes specifications due to their small size, linear shape and high cost per unit area (fencing/ management). Experience of measures developed by the project could be considered for future adaptations of the NWS
C.3	600 m of new hedgerow, 600 m of re-laying hedgerow and 1,500 m of in-field buffers. Total length = 2,700 m	3,211 m of new hedgerow and 382 m of in-field buffers have been achieved. Total length = 3,593 m	The condition of existing hedgerows on farms was better than expected and therefore no hedges were re-laid. These sub-targets were replaced with the planting of additional hedgerows. This measure was effective at reinstating field boundaries and has aided management of livestock on farms.

Action	Foreseen in the Grant Agreement	Achieved	Evaluation
C.4	Reduce vegetation damage and soil erosion across 375 ha of critical source and transport areas. Establish 100 alternative feeding stations Erect 5,000 m of fencing	Measures have been recommended across 437 ha of critical sources and transport areas on project farms. 100 alternative feed stations established Erected 42.6km of fencing; 20 gateways; 10 footbridges	This measure has led to improvements in the condition of the critical source and transport areas, with improvements observed in all categories. Fencing has eliminated cattle access to pearl mussel habitat and improved grazing management This task is considered to be positive and repeatable in other catchments.
C.5	Reduce nutrient inputs across 375 ha of farmland.	A bespoke nutrient management planning system was developed to meet the requirements of freshwater pearl mussels. 530 ha of 'green' farmland was soil sampled. 76 cattle and 20 ewes have been destocked from project farms	This measure is considered to be positive and repeatable in other catchments. Nutrient levels must be in line with the achievement of conservation objectives and monitored through regular water sampling.
C.6	Establishment of 20 alternative drinking water facilities	262 alternative drinking water facilities installed.	The need for water-facilities was much greater than envisaged in the grant agreement. This measure has been invaluable in reducing / eliminating cattle access to pearl mussel habitat and reducing river bank erosion. This measure is considered to be positive and repeatable in other catchments.
C.7	Restructure 175 ha of conifer forest to long-term protective woodland	178 ha of commercial conifer plantation have been restructured to long-term retention woodland. A feasibility study into the use of heli-logging.	The project successfully trialled a wide range of techniques to permanently restructure conifer forests into long-term retention woodland. Methods of restructuring that minimised sediment and/or nutrient losses were partially effective at reducing sediment and nutrients during operations. The approaches used as trials need to be considered with regard to the projects remit.
C.8	Trial continuous cover forestry	A 2.8 ha continuous cover forest trial was implemented.	There were limited sites identified in the project area suitable for the continuous cover forestry due to soil type, wind exposure, stand age and environmental sensitivities. This approach is considered more suited to non-peat soils or to catchments where water table restoration is not an objective.
C.9	3,000 m of firebreak trials	3 types of firebreak demonstrated - Prescribed burning; grazed firebreaks; and willow planting across 2,918 m	Unsuitable weather and ground conditions impacted prescribed burning trials. Grazed firebreaks were considered the most effective once established

The farm measures were very successful, and have been continued in the European Innovation Partnership Project, the Pearl Mussel Project (PMP) that has followed the KerryLIFE project in the

Caragh and Kerry Blackwater and has also expanded to the six other priority freshwater pearl mussel populations that host 80% of Ireland's freshwater pearl mussels. The PMP took the advice of the KerryLIFE experience to concentrate on the restoration of hydrological function in the open peaty catchments of the "Top 8" populations. The landowners participating in the scheme agree to have their land parcels scored every year for quality (wetness and appropriate floral scores), and payments under the scheme are made relative to the value of the scores for the freshwater pearl mussel.

The forestry trials were less successful in demonstrating benefits to freshwater pearl mussels. The trials implemented by KerryLIFE focused on the sensitive restructuring of commercial conifer plantation to long-term retention woodland and have been described in the project information notes. The use of an extensive suite of mitigation measures deployed with the restructuring trials were effective at reducing the risk of sediment and nutrient loss and the measures contributed to the partial re-wetting of project areas, especially in areas left unplanted. The phased restructuring of current forests into long-term native woodland may result in some temporary improvements during the time between the removal of mature trees and the growth of the newly planted trees to maturity but may not adequately restore the hydrological function long-term. The techniques and mitigation measures trialled may play a role in management of immediate risk posed by high risk forests, however, in practice the mitigation measures did not eliminate all sediment/nutrient losses and therefore residual risks posed from forest operations remained.

The enhancement of awareness through all generations has been evident as so many landowners signed up for the follow on EIP Pearl Mussel Project scheme. The eagerness and knowledge with which landowners have contributed to the locally led approach to improving wetness and lowering nutrients moving from their land has been very positive.

The cumulative impact of the projects actions on the site specific conservation objectives for freshwater pearl mussels in the Caragh and Kerry Blackwater catchments (NPWS 2017, 2019) were examined by combining the monitoring data. For each SAC, the site-specific conservation objectives aims to define favourable conservation condition for the habitats and species listed as a qualifying interests of the site. For freshwater pearl mussel the conservation objectives are made up of 12 attributes for the species itself and its habitat (listed in Table 7.2).

Table 7.2: Site Specific Conservation Objectives for freshwater pearl mussel in the Caragh and Kerry Blackwater Catchments (NPWS 2017, 2019)

Attribute	**Measure**	**Conservation objective target**	
		Caragh	**Kerry Blackwater**
Distribution	Kilometres	Maintain Caragh distribution at 35.06km	Maintain Kerry Blackwater at 18.95km
Population size	Number of adult mussels	Restore populations to at least: 2.8 million adult mussels in the Caragh	Restore populations to at least: 2.7 million adults in the Kerry Blackwater
Population structure: recruitment	Percentage per size class	Restore to at least 20% of each population no more than 65mm in length; and at least 5% of each population no more than 30mm in length	

Attribute	**Measure**	**Conservation objective target**	
		Caragh	**Kerry Blackwater**
Population structure: adult mortality	Percentage	No more than 5% decline from previous number of live adults counted; dead shells less than 1% of the adult population and scattered in distribution	
Suitable habitat: extent	Kilometres	Restore suitable habitat in more than 33.06 km in the Caragh and any additional stretches necessary for salmonid spawning	Restore suitable habitat in more than 18.26 km in the Kerry Blackwater and any additional stretches necessary for salmonid spawning
Water quality: macroinvertebrates and phytobenthos (diatoms)	Ecological quality ratio (EQR)	Restore water quality - macroinvertebrates: EQR greater than 0.90 (Q4-5 or Q5); phytobenthos: EQR greater than 0.93	
Substratum quality: filamentous algae (macroalgae); macrophytes (rooted higher plants)	Percentage	Restore substratum quality - filamentous algae: absent or trace (less than 5%); macrophytes: absent or trace (less than 5%)	
Substratum quality: sediment	Occurrence	Restore substratum quality - stable cobble and gravel substrate with very little fine material; no artificially elevated levels of fine sediment	
Substratum quality: oxygen availability	Redox potential	Restore to no more than 20% decline from water column to 5cm depth in substrate	
Hydrological regime: flow variability	Metres per second	Restore appropriate hydrological regime	
Host fish	Number	Maintain sufficient juvenile salmonids to host glochidial larvae	
Fringing habitat	Hectares	Maintain the area and condition of fringing habitats necessary to support the population	

The distribution of mussels within the two river networks and the extent of suitable habitat were not expected to have changed during the lifetime of the project compared to the conservation objectives targets. Population structure (recruitment and adult mortality) was found to be inadequate or insufficient, with higher than expected losses in the main channels of both rivers and in some tributaries. The number of adult mussels has declined in the life time of the project, though it is important to recognise that this trend predates the project (NPWS 2008, 2013) and the 2019 assessment reported an acceleration in the rate (NPWS 2019). This decline sets an important context in evaluating the impact of the actions implemented by the project, as their full effect is likely not to be reflected in the 2019 assessment due to the lag time between the putting the measures in place and seeing the response in population, which may take up to 10 years. The scale of the project, covering 20% of the catchment area meaning measure the measures that are causing the decline have not been addressed. Nevertheless, where measures were concentrated by the project and with high levels of landowner participation in a sub-catchment such as the Owenroe (Caragh), with significant mussel population, recruitment was found to have stabilised though still at inadequate levels is of mussels.

The impact of the project actions are expected to be seen first in the habitat condition and the results of habitat (biological and physical) monitoring showed some improvements or the halting of the decline in some environmental measures. For, example, the ecological quality ratio (EQR) for macroinvertebrates was met in 41% of sites in 2019 compared to 20% in 2016; filamentous algae was met at 71% of sites in 2019, up from 60% in 2016; and macrophytes EQR was met at 91-95% of sites in all years. Nevertheless, other measures of habitat condition, in particular, siltation or silt plumes (infiltrated sediment in the river bed) did not met the criteria at the majority of sites and remained unchanged. Redox potential losses were found to be appropriate, however intermittent problems were detected and these episodic events can negatively affect juvenile survival in the gravels. In the Kerry Blackwater, water quality started at a lower level than in the Caragh, and agricultural improvements may be masked by the higher level of forestry in all areas of the Kerry Blackwater catchment. It may take a lot longer to see the effects of gradual improvements. The level of water samples where water quality did not meet conditions required for *Margaritifera* was high, particularly for phosphate, ammonia, suspended solids and DOC and associated colour. This is contributing to ongoing declines in the freshwater pearl mussel populations, particularly when concentrated at low flows in an environment of reduced water table conditions.

The overall outcome of the project was that the actions undertaken were generally successful and the combination of all the monitoring above can conclude that the project has gone a long way to improving the general condition of the mussel habitat through a reduction in siltation and nutrient enrichment. However, it was not possible to document improvements of recruitment of juvenile freshwater pearl mussels in the project area during the project period, principally because it is very difficult to detect these small mussels. Nevertheless, streams within the project area are part of an ongoing monitoring programme, which will proved evidence of the success of the project actions over the longer term. The achievements of the project can only succeed longer-term insofar as the cooperative effort of all the catchment users to support the restoration of much higher water table levels to ensure sufficient increase in water table levels are achieved so that sustainable near bed velocities can support juvenile survival to a level that will reverse the recent declines.

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