RAY
SILT SOURCES

CLOUGHANEELY ANGLING ASSOCIATION

Local Authority Waters Programme

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CAA, November 2021

Ray River Silt Sources – A Catchment Investgation into Sediment Export

Acknowledgements
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Background

This project has been funded by LAWPRO and MOWI. It was carried out by Cloughaneely Angling Association in a subcatchment of the Ray River. It is intended to provide further characterisation of the catchment to inform an integrated catchment management strategy as enounced in CAA's Catchment Management Plan. The project took place between March and September 2021.

Cloughaneely Angling Association (CAA) has a formal agreement in place with Inland Fisheries Ireland (IF) to manage the catchments of two rivers i.e. the Tullaghobegley and the Ray Rivers. As part of this management role CAA has produced a *Strategic Management Plan* and a *Catchment Management Plan*. In line with aims and objectives set out in these plans CAA has undertaken a number of projects aimed at protecting and improving the river environment in these cathcments. This is necessary because, like most rivers in Ireland, the pressures on our rivers have increased in recent years, and environmental quality has suffered.

Previous CAA projects (Upland Lakes, October 2019; Upland Lakes Survey 2, 2020) have identified that silt eroded from the catchment and settling on river beds is a significant issue impacting river condition at some locations, particularly in the Ray catchment. The silt flushing into streams damages fish spawning grounds, and has a harmful affect on the benthic communities of the river bed that are the basis of food chains for many other animals (including fish, birds, otters, bats). One of the major sources of silt is the loss of peat particles from the extensive areas of cut-over bog that are widespread in the upper part of the Ray catchment. Bare, exposed peat banks that remain after turf has been harvested provide a ready source of fine silt material that is easily transported to rivers through the many drainage ditches cut in the bogs.

Turf cutting for fuel has been ongoing in Ireland for many centuries and continues to be an important part of many rural economies. The long history of turf harvesting means that there are few remaining areas of untouched bog, and many turbary plots are now exhausted. These exhausted plots have little peat remaining, and often have areas of exposed soils. They are of no value for turf, and in their degraded condition provide little environmental or agricultural benefits. They are a significant source of fine silt that ends up in river channels. This project is one step in a plan to address the issue of silt damage in the Ray catchment.

Silt causes turbidity in streams. The level of turbidity and its fluctuations over time are readily measured and such measurements may be used as a proxy for the levels of suspended sediment in stream water. By identifying streams carrying greater amounts of sediment (i.e. with more turbid water), we hope to identify areas that are critical sources of silt and prioritize such areas for future remedial interventions.

Methods to reduce the problem of silt loss will depend on local, site-specific conditions. Some of the methods to be considered include established best practice for drainage ditch management; re-vegetation of bare and denuded soils; native woodland establishment; establishing riparian buffer zones. Of course the consent, and agreement of land owners and users will be critical to the implementation and success of any mitigation actions carried out. Partnering with other groups and agencies in an ethos of integrated catchment management will be essential.

Apart from improved river quality, there will of course be other environmental, social and economic benefits from restoring degraded areas, and exhausted turbary plots. Restored sites will support greater biodiversity i.e. a greater variety of plant and animal species. This in turn will enhance the the 'green' credentials of the area, important for branding image of local produce and an improtant criterion for attracting visitors. In time, expansion of restored plots could return bigger areas to some degree of productivity for extensive mountain grazing. A variety of funding streams and collaborations are being explored for potential support in implementing the restoration works being considered.

Catchment Characteristics

A detailed characterisation of the Cloughaneely Angling Association's catchment areas is provided in the *Tullaghobegly and Ray River Catchments Management Plan 2018 – 2021* (2018). A brief summary is provided here for context.

The Ray catchment is 53km^2 in area (Table 1). The headwaters of the river rise in the Derryveagh range on the northern slopes of Muckish (666m), Crocknalaragagh (603m) and Aghla Beg (564m) and flow some 15km northwards, debouching to the open Atlantic at Dromnatinny beach just east of Ballyness Bay. From source to sea the main channel of the Ray falls some 300m in elevation. The Ray is characterised as a 'flashy' river based on flow duration curves presented in the *Catchment Management Plan 2018-2021* (CAA, 2018), and flows respond rapidly to rainfall events.

Table 1 Catchment descriptors for the Ray Catchment overall and for the study subcatchment

	Ray Overall	Ray Study Subcatchment
Area (km^2)	53	15.8
Rainfall (mm)	1675	1833
Q5 (m^3/s)	8.00	3.23
Q95 (m^3/s)	0.22	0.084
FARL	0.96	0.93
Area Peat (%)	62.7	67.2
Area Poorly Drained (%)	30.0	31.4

The peaks bounding the catchment are quartzite and much of the upland geology is overlain by dolomitic marble and schist. The lowland catchment is mostly pelitic schists. Large areas of outcropping rock occur in the upper catchment and soils are poorly drained acidic till (32% by area) and blanket bog (58%).

Mountain slopes support some natural acid grassland, and areas of heather and moor. Blanket bog is the dominant vegetation feature with extensive peat harvesting and associated drainage.

Agriculture is predominantly rough grazing and largely confined to the lower catchment. Some areas of conifer plantations occur, but remnants of ancient woodland with sessile oak, holly and honeysuckle remain in some steep, inacessible river valley sections.

Sources of Silt

The extensive area of blanket bog and peat soils in the Ray catchment (~32Km^2) has been impacted through long-term peat harvesting and grazing pressures, and some small areas of forestry on peat are also present. Pressure from upland sheep grazing has reduced in recent years and there are some areas of good blanket bog vegetation in remote upland areas. However, some of the areas most intensively harvested for peat show evidence of significant erosion. Previous work by CAA showed Impact on local streams, evidenced by peat silt deposition and depauperate benthic invertebrate communities.

About 32 km^2 (roughly 60%) of the Ray catchment is blanket bog (EPA Hydrotool), almost all of which is under active peat harvesting or has been harvested in the past (Figure 1). Given the large absolute and proportional areas of cutover peatland in the Ray catchment, the potential pressures due to peat silt export to surface waters are significant.

Recently (2021) illegal quarrying has commenced in the upper Ray catchment (Figure 1) and this has become a significant point source of sediment pollution of the main channel of the Ray. The present project has undertaken some assessment of the extent of this pollution and Donegal County Council are pursuing a legal resolution to this serious ongoing issue.

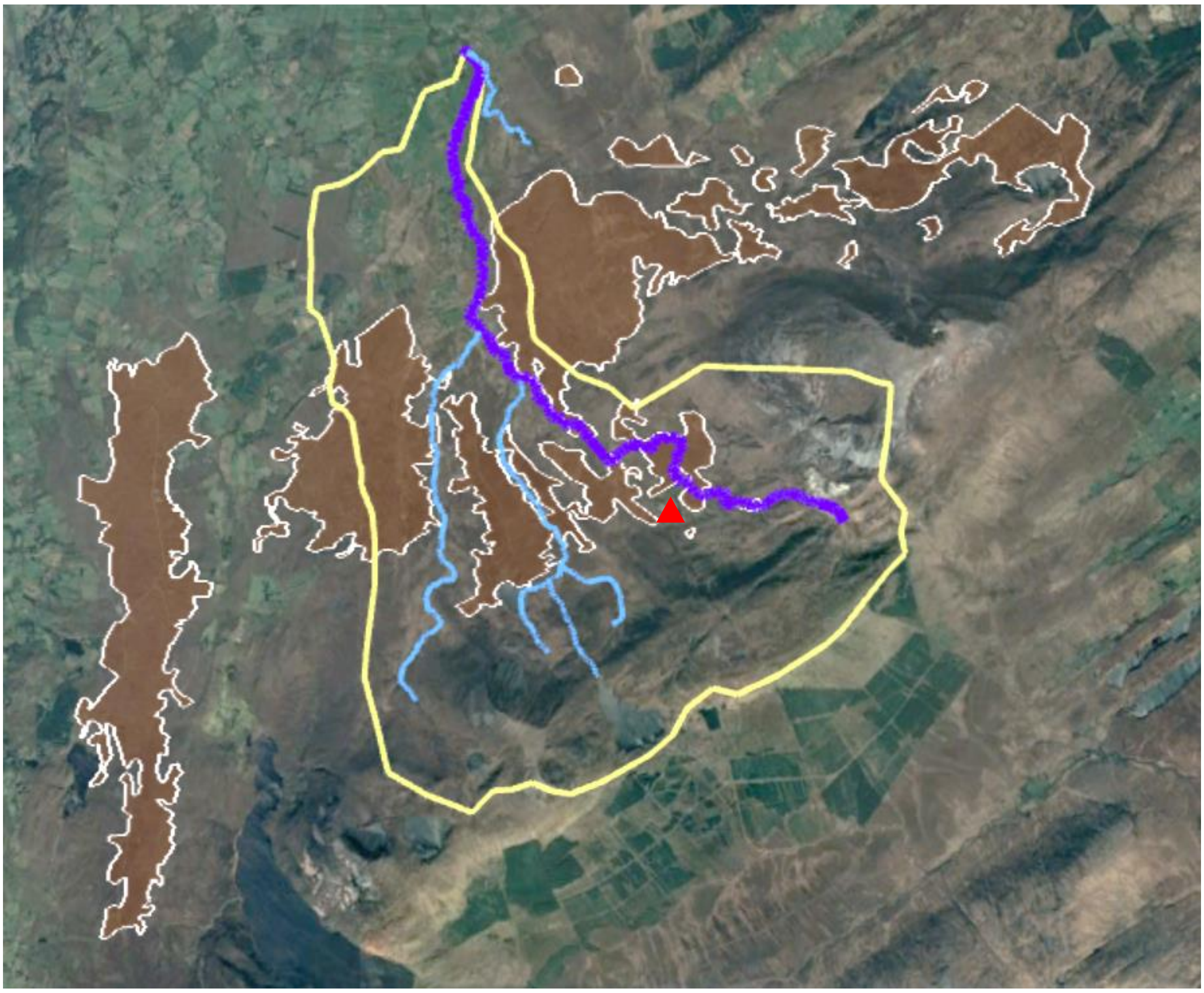

Figure 1 Cutover peat areas are indicated by the dark brown polygons. The study subcatchment is outlined in yellow. Main drainage features are shown in blue. The illegal quarry site is indicated by the red triangle.

Lakes may exert a mitigating effect on their downstream catchcment areas through allowing sediment settlement in their basins and reducing impacts downstream. There are 9 lakes in the Ray catchment (Table 2). While lakes are of critical importance in catchment hydrology, and may play a significant role in sediment trapping, most of the Ray catchment lakes are small, and may have relatively short retention periods. Most are in the upper catchment area (approximately 200m OD or above).

An index of the extent of lakes and their influence in a contributing catchment is available. The FARL index (Flow Attenuation from Rivers and Lakes) is primarily an index that reflects the influence of lakes on flood response, lake area being weighted by the catchment area that feeds it. Values close to unity indicate the absence of attenuation due to lakes, whereas index values below 0.8 indicate a substantial influence of lakes on flood response. This index can also be presumed to reflect the influence of lakes on suspended solids attenuation within the catchment.

Table 2 Lakes in the Ray Catchment

Lakes in the Ray Catchments		
Lake	**Area(ha)**	**Elevation (m)**
Lough Dog	0.7	440
Lough Keel	1.0	440
Lough Nadreega	0.7	405
Nabrackbaddy Lough	3.3	405
Lough Aluirg	21.0	285
Lough Moilt	5.8	197
Lough Agher	17.1	140
Derryreel Lake	7.9	102
Drumlish Lake	4.1	63
Total Area	**61.7**	

For the Ray catchment overall the FARL index is 0.96 (Table 1), whereas for comparison in the adjacent Tullaghobegley catchment it is 0.81. Therefore the potential for attenuation of eroded and transported sediments in lake systems is significantly greater in the Tullaghobegley than in the Ray catchment. Such a difference in lake influence is further circumstantial evidence of the posited greater impact of peat silts in the Ray catchment cf. the still extant population of pearl mussels, and the greater salmon recruitment in the Tullaghobegley River compared to the less well buffered Ray system.

Study Subcatchment

This study focussed on the upper main channel of the Ray River (Figure 1). It comprises the Ray subcatchment upstream of the confluence with the Lough Agher River, and includes the catchments of the Owenbeg, and Owenaltderry tributaries which drain the portion of the catchment west of the main channel.

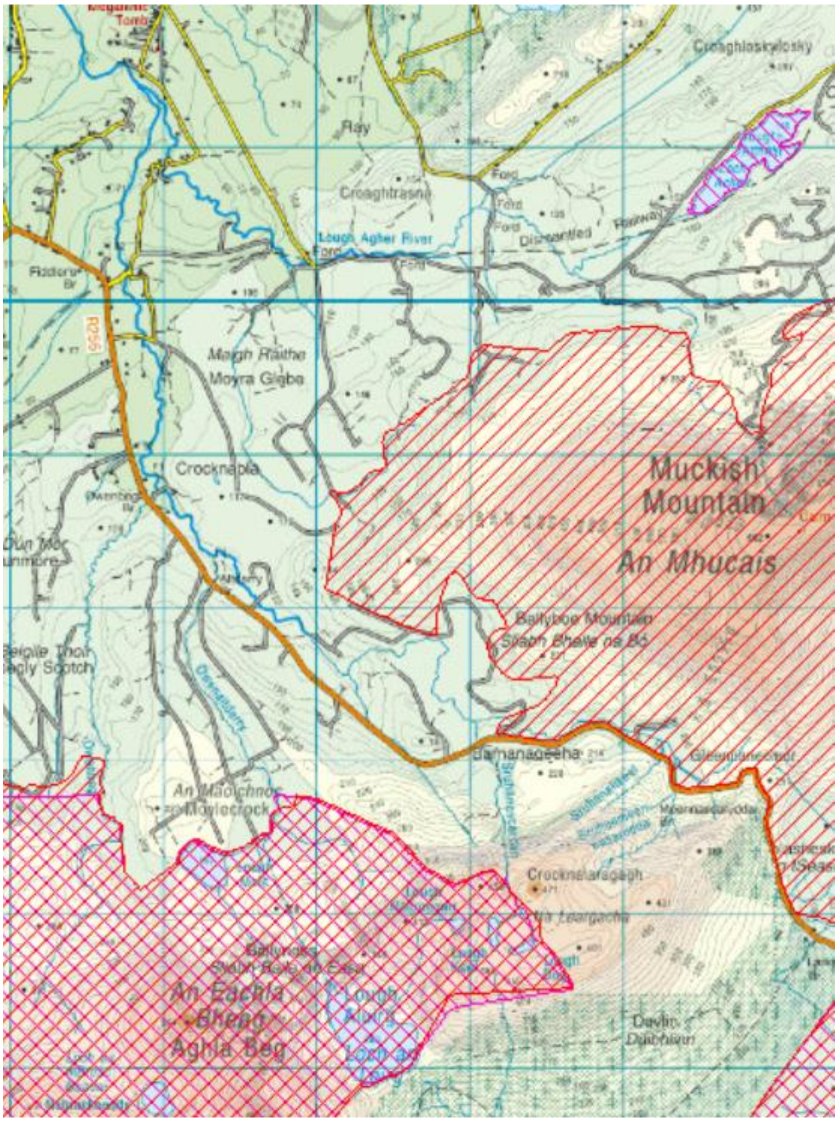

Figure 2 Cloghernagore Bog and Glenveagh National Park SAC / Muckish Mountain SAC / Derryveagh and Glendowan Mountains SPA in the study subcatchment

The area of the study subcatchment is about 16km^2 (about 30% of the entire Ray catchment), of which 67% is peat and 31% is poorly drained. Of the 9 lakes in the entire Ray catchment, 6 of them (highlighted in Table 2) lie in the study subcatchment, reflected by a reduced FARL index of 0.93. Only Lough Moilt in the Owenaltderry subcatchment, the lake at lowest elevation, is downstream of active peat harvesting areas, and there are no lakes downstream of the illegal quarry mentioned above.

Low flows in the study catchment are estimated at 0.084 m^3/s (Q95 i.e. the flow which is exceeded 95% of the time and typical of dry summer flow). High flows are estimated at 3.23 m^3/s (Q5 i.e. the flow which is exceeded 5% of the time and equivalent to full spate conditions).

The upper Ray study subcatchment area is included in a number of sites of European importance (Figure 2) designated as part of the Natura 2000 network. These include Cloghernagore Bog and Glenveagh National Park, and Muckish Mountain Speical Areas of Conservation. The catchment also overlaps part of the Derryveagh and Glendowan Mountains Special Protection Area.

Methods

Measuring suspended sediment in the water column requires laboratory analysis. However, stream turbidity may be measured as a proxy for suspended solids transport. Water turbidity is proportional to suspended solids although the precise nature of the relationship is site specific and varies with sediment type. Nonetheless turbidity is a robust estimate of sediments in suspension. Turbidity can be measured rapidly in situ, allowing for high frequency monitoring of water with respect to its suspended solids status.

Turbidity measurements, and a number of other water quality parameters, were measured electrometrically at critical nodes in the study subcatchment, and are used to examine source areas of peat and sediment erosion. This is seen as a preliminary essential phase to allow selection of suitable areas in which to subsequently undertake mitigation actions. In addition to sporadic measurements at key points, a base station measuring water quality parameters at high frequency was also established at the bottom of the study subcatchment.

Water quality measurments made with the multiparamter meter were augmented by laboratory analyis of occasional water samples taken at the same sites.

Sites Sampled

Seven sites were sampled regularly on ‘river runs’ and these are shown in Figure 5. The coordinates for the individual sites are also listed inTable 3. Sampling was organized by the CAA project committee using voluntary samplers, and appropriate training was provided to all samplers (Figure 3 and Figure 4).

Figure 3 CAA training in use of multiparameter meter

The Base Station was 100m below the confluence of the Ray and Lough Agher Rivers. The Lough Agher River 600m above the confluence was sampled regularly to provide an indication of the turbidity contribution and water quality from its catchment, but no points further upstream were included in the surveys.

6

Figure 4 Project Team measuring water quality parameters on river runs

Sites on the Owenbeg and Owenaltderry allow water quality at the bottom of these catchments, before joining the Ray River, to be resolved. Both these rivers drain intensively harvested bogland areas. However intensively worked peatland areas at Moylecrock drain to Lough Moilt in the Owenaltderry catchment, and this offers some opportunity for peat silt settlement. Evidence of peat silt deposits at drain inflows to the lake was presented in the previous CAA study, Upland Lakes, October 2019. The Upper Ray and Droichead na nDeor sites are above turf cutting areas, but may be affected by erosion of peat on upper catchment areas which was also documented in the earlier study.

A number of points on the Ray River in the vicinity of the illegal quarrying activity (circled in Figure 5), and impacted drainage channels were sampled on an ad hoc basis in response to flood events and release of sediments.

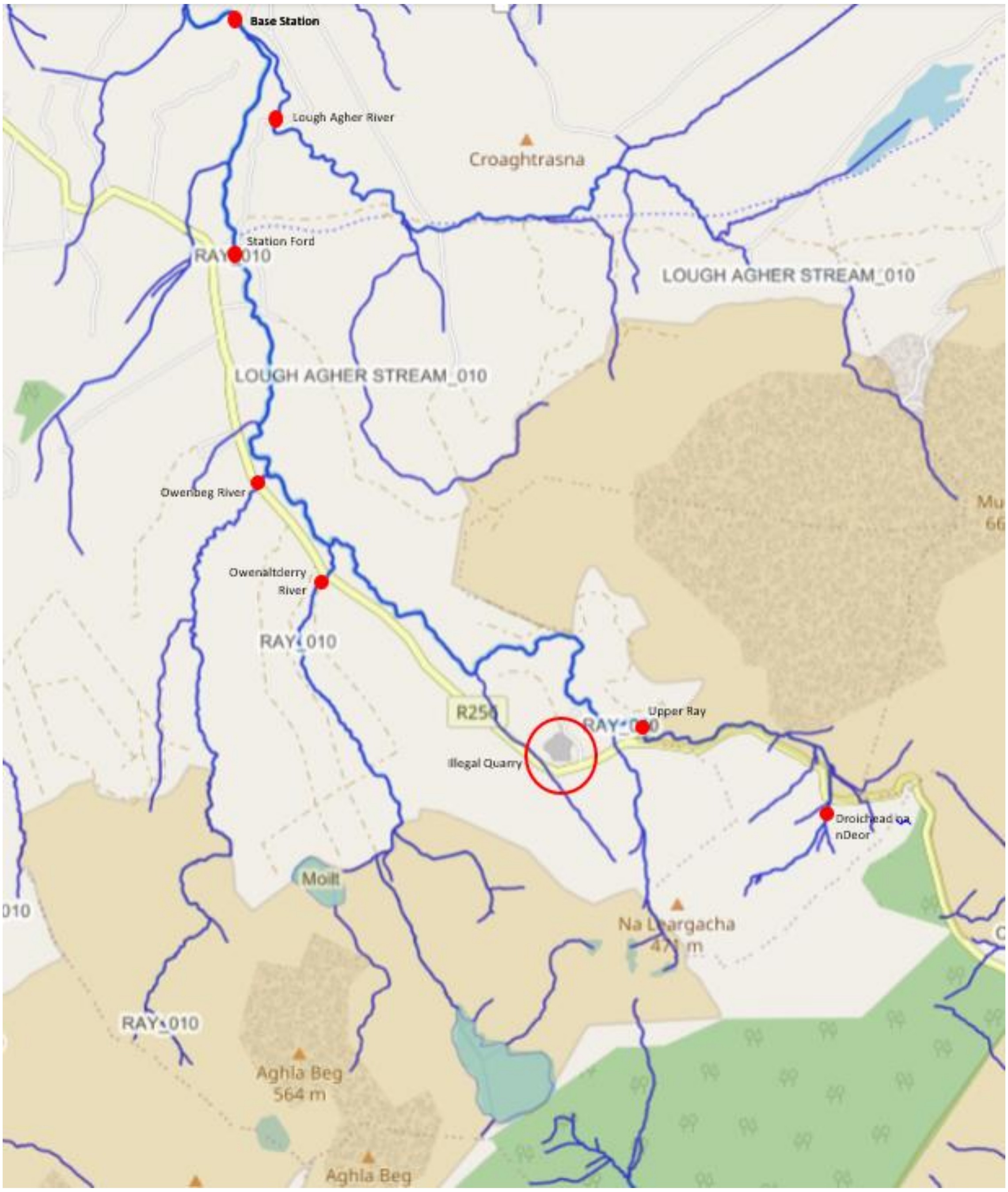

Figure 5 Sampling points in the study subcatchment and the illegal quarrying location circled in red

Table 3 Coordinates of regular sampling locations in the Ray study subcatchment

Description	Grid Reference	X	Y	Latitude	Longitude
Base Station	B 95811 31415	195811	431415	55.13014	-8.06644
Lough Agher R.	B 96024 30893	196024	430893	55.12546	-8.06309
Station Ford	B 95747 30124	195747	430124	55.11855	-8.06743
Owenbeg	B 95908 28682	195908	428682	55.1056	-8.06488
Owenaltderry	B 96314 28128	196314	428128	55.10062	-8.05852
Upper Ray	B 98256 27206	198256	427206	55.09235	-8.02809
Droichead na nDeor	B 99343 26788	199343	426788	55.08859	-8.01106

Parameters Measured

Electrometric data were collected using a Hanna 9829 multiparameter meter and sonde equipped with pH, turbidity, conductivity, and temperature sensors. Sensors were calibrated at regular intervals and before sampling runs. Conductivity is correscted to a standardised temperature of 25°C and reported as specific electrical conductance (SEC).

A base station was established at the bottom of the study subcatchment. At this site a self-powered sonde was deployed for recording parameters at 15 minute intervals. A number of deployments over three to four day intervals were made in March and April 2021. Thereafter, from the 12th May until the 30th September 2021 the sonde was deployed continuously. Data downloads and calibrations occurred at intervals over this period.

The base station sonde was deployed over rocky substrate and in a location with continuous flows across the sensors. Figure 6 shows the location and the upstream view in differing flow conditions.

River runs were carried out on ten occasions, during which a second sonde and meter was used to conduct the upstream catchment surveys, measuring the same suite of parameters as at the base station.

On three occasions, water samples were taken at river survey sites. These samples were submitted for laboratory analysis for the following parameters (abbreviations used subsequently in parentheses):
Alkalinity (Alk), Ammonia (Amm), Biological Oxygen Demand (BOD), Colour (Col), Specific Electrical Conductance (SEC), Nitrate (NO3-N), pH, Phosphate (PO4-P), Total Suspended Solids (TSS), Turbidity (Turb).

It is important to note that turbidity measured with the Hanna multiparameter meter is reported as Formazin Nepholometric Units (FNU). Turbidity reported in the laboraotry-analysed samples is as Nephelometric Turbidity Units (NTU). While results are broadly similar, differences can occur depending on sediment type giving rise to the turbidity. However, comparisons of results for turbidity in meter readings and simultaneous water samples taken during this project shows good agreement and units are taken to be equivalent for practical purposes.

Conductivty measured with the Hanna meter is reported as SEC compensated to a standard temperature of 25°C. In laboratory analysed samples the conductivity was corrected to a standard temperature of 20°C. Therefore meter read SEC is approximately 1% higher than the equivalent laboratory SEC value. This is not considered significant for the purposes of this project.

Figure 6 Base Station showing the deployed water quality sonde (arrowed), and a view upstream in low water levels (above) and during higher flows (below)

Results

Base Station

High frequency measurements of water quality parameters were recorded at 15 minute intervals between March and September 2021. Initially measurements were made over 3 to 4 day intervals, but from 12th May to the 30th September measurement was continuous. The dataset is comprised of more then 14,000 observations for each parameter measured. A number of descriptive statistics are provided to summarise the data in Table 4.

Table 4 Descriptive statistics for Ray Base Station data collected from March to September 2021

Ray Base Station	Temp.[°C]	pH	Cond[µS/cm]	Turb.NTU
n	14043	14043	14038	14043
mean	13.5	7.2	91.6	9.3
median	13.6	7.3	96.0	3.2
mode	13.6	7.4	123.0	1.8
max	23.0	7.9	156.0	330.0
min	3.5	5.8	21.0	0.0
5%ile	8.9	6.4	39.0	1.4
50%ile	13.6	7.3	96.0	3.2
95%ile	17.8	7.7	131.0	45.1

The frequency distributions for each parameter are plotted in Figure 7. While temperature and pH show distributions close to normal, SEC is strongly negatively skewed, and turbidity very strongly positively skewed. This is reflected in the measures of central tendency (mean, median, and mode) for these data (Table 4).

The Base Station data are also plotted against date/time in Figure 8. The plot gives a succinct visual impression of the characteristics of the data. Some features of the data are noteworthy. While pH remained very stable throughout the period of monitoring, a maximum summer water temperature of 23°C was recorded in July. SEC ranged from 21 to 156 µS/cm. Distinctive recurring cycles of progressively increasing SEC followed by abrupt falls are evident. Generally, these abrupt falls in SEC coincide with rainfall events and with turbidity peaks. Turbidity is generally very low, half of all values being less than 3.2 NTU, but peaks above 45 NTU comprise about 5% of the records.

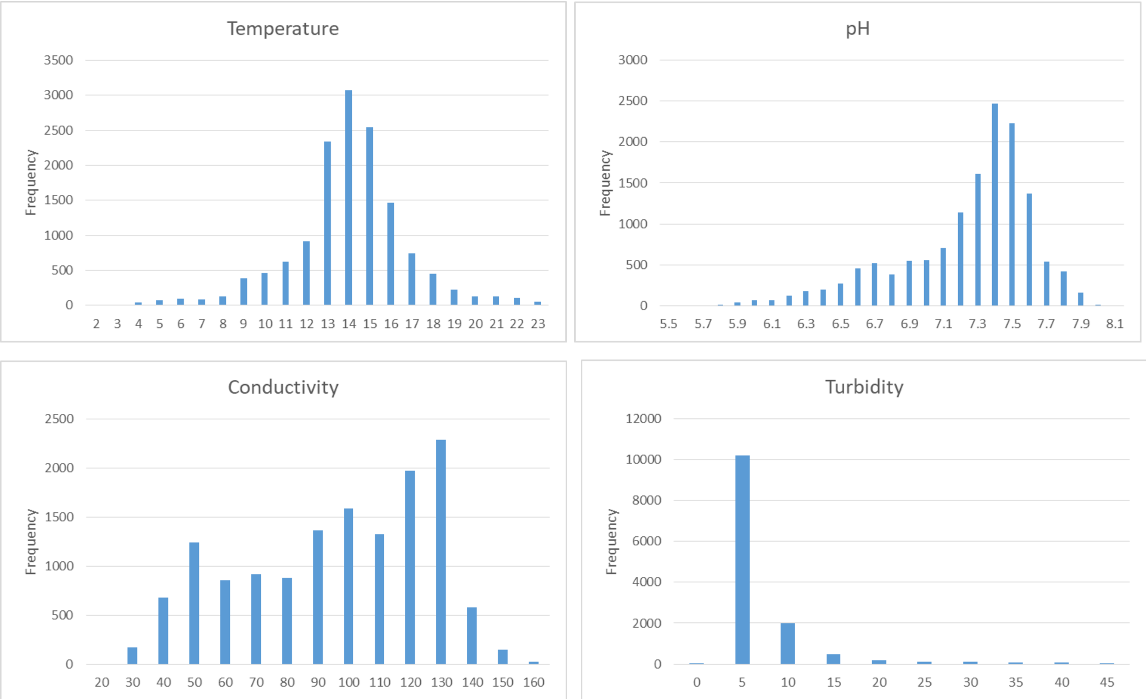

Figure 7 Frequency distributions of Base Station data

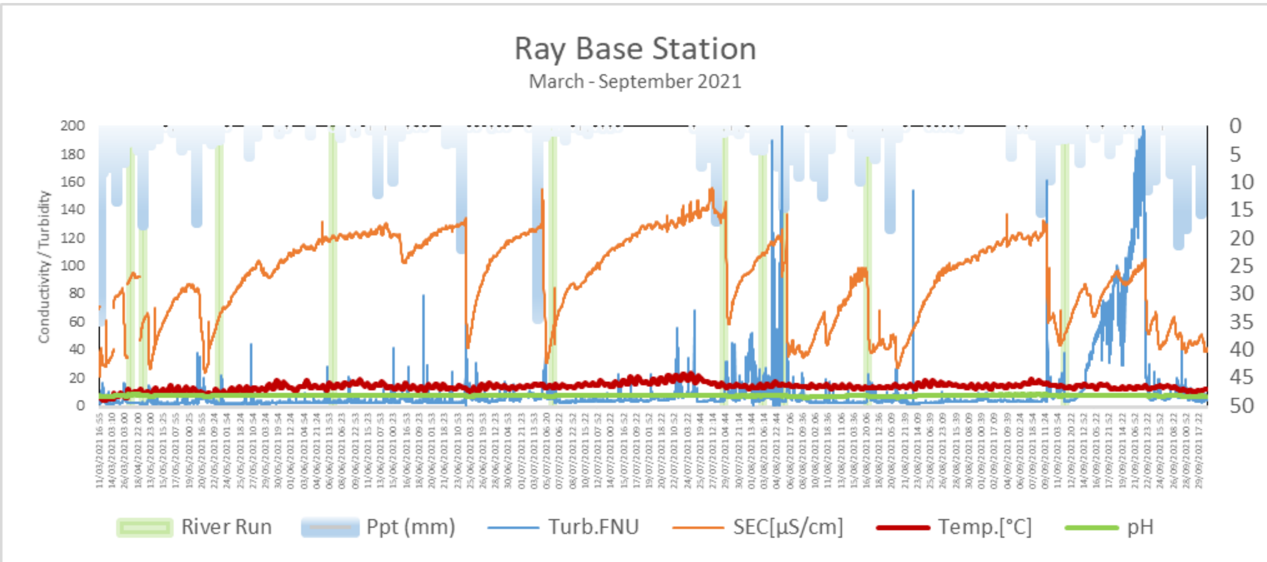

Figure 8 Plots of Temperature, pH, Conductivity (SEC), and Turbidity at Ray Base Station from March to September 2021. Daily rainfall measured at Lough Altan is shown at the top on an inverse scale.

Events over short time periods within these data sets are discussed in greater deteail below.

River Runs

Dates on which river runs were completed and the sites sampled are listed in Table 5. Locations of sites sampled regularly have been shown in Figure 5. However, some sites were sampled ad hoc and infrequently. The locations of these sites are shown in Figure 9 and naming is as in Table 5. The Lough Agher U/S confluence site is not shown but is located 5m above the conflunece with the Ray.

Table 5 Sampling dates and sites sampled. Occasions when meter measurements were made on-site are Indicated by '+', and samples for laboratory analysis are indicated by 'C'.

Date	Ray Droichead na nDeor	Upper Ray	Ray U/S SW3	SW3 Outfall to Ray	Ray D/S SW3	Ray U/S Cascade	Ray D/S Cascade	Drain B Outfall to Ray	Ray U/S Owenaltderry	Owenalderry Ford D/S Moilt	Owenaltderry	Ray U/S Owenbeg	Owenbeg	Ray Station Ford	Ray Base Station	Lough Agher River	Lough Agher U/S Confluence
18/04/2021		+									+		+	+	+	+	
03/05/2021		+									+		+	+	+	+	
23/05/2021		+	+	+	+				+		+		+	+	+	+	
07/06/2021	+	+								+	+		+	+	+	+	
06/07/2021	+C	+C					+C	+C			+C		+C	+C	+C	+	C
29/07/2021	+	+									+		+	+	+	+	
03/08/2021	+	+									+		+	+	+	+	
06/08/2021	+	+				+	+				+		+	+	+	+	
08/08/2021	C	C						C	C		C	C	C	C	C		
17/08/2021	+C	+C							+C		+C	+C	C+	C+	C+	C+	C+
12/09/2021	+	+									+		+	+	+	+	

In total, 10 river runs were completed in the study period using the Hanna Multiparameter meter to record water temperature, pH, SEC and turbidity. The number of stations sampled on each run varied from 6 to 10. Some stations were only sampled on a single occasion. Seven stations (highlighted in Table 5) were sampled on most occasions and the results for these stations are summarised below.

Figure 10 show the results for each parameter on a given date plotted by sampling stations along the catchment. In general, turbidity was relatively low (<10 FNU). However, turbidity above 30 FNU was a feature of all sites on 3 May, and it increased in the lower catchment. The plots of the 23 May clearly show the elevated turbidity associated with the outfall from the illegal quarry at the SW3 site.

Figure 9 Locations of sites sampled on an ad hoc basis

Turbidity is also elevated in plots of the 29 July. Only the Upper Ray and Owenbeg sites recorded turbidity of less than 10 FNU on this occasion. On 6 August turbidity was again elevated, the Upper Ray and Droichead na nDeor sites being lowest, and with sustained increases in all lower sites.

Figure 11 summarises the mean values for parameters ordered from top to bottom of the catchment. On average pH tends to decrease from upper to lower catchment. The influence of the Owenbeg and Lough Agher Rivers on pH is evident. By contrast, SEC tends to increase in the lower catchment sites. Temperature trends are of little significance and masked by seasonal fluctuations. The plot of mean temperature shows an average water temperature of 12°C over the period of the study. Turbidity, although low on average, tends to increase at lower catchment sites.

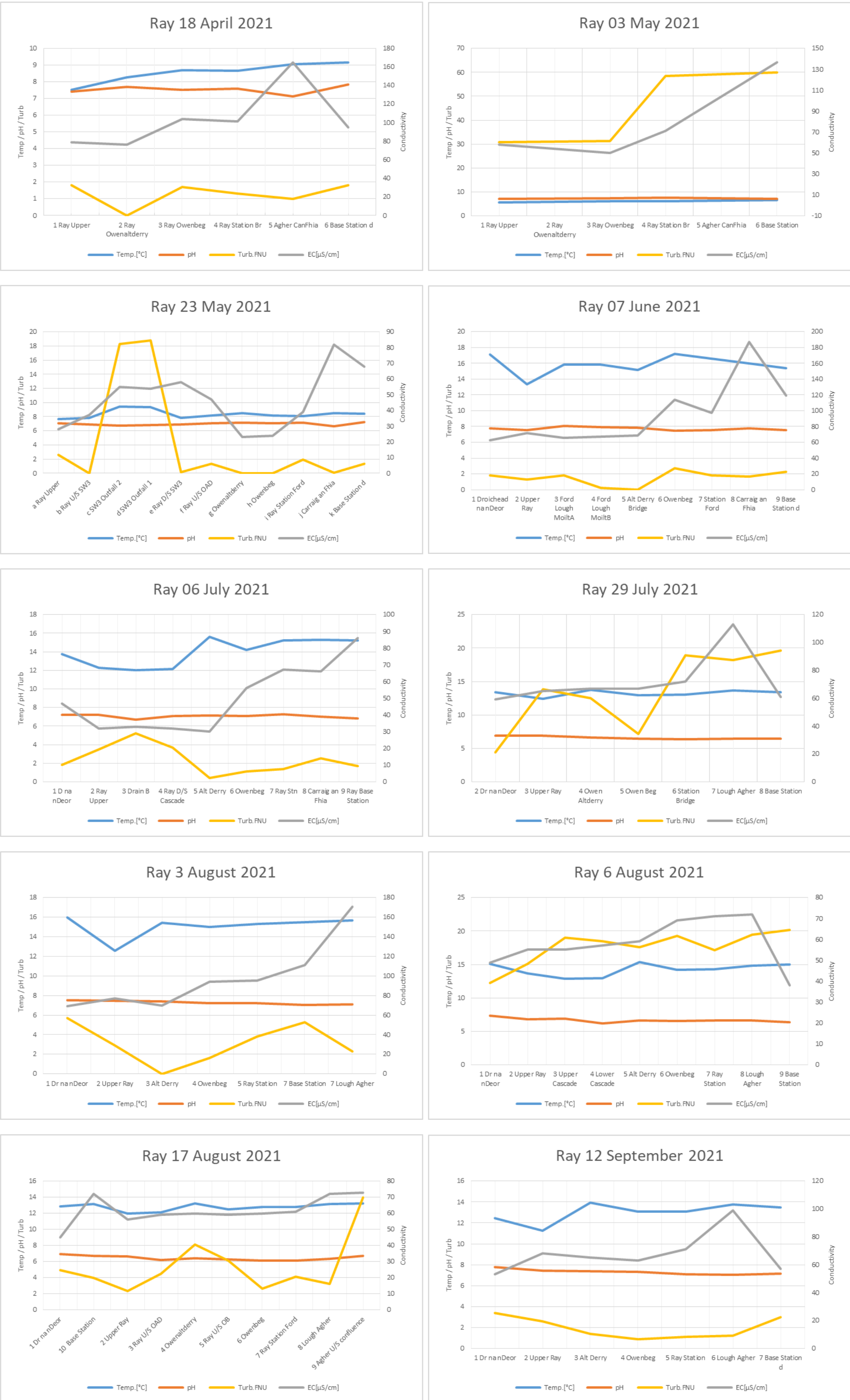

Figure 10 Data for temperature, pH, turbidity and conductivity (SEC) measured at sites in the Ray study subcatchment on ten occasions in 2021

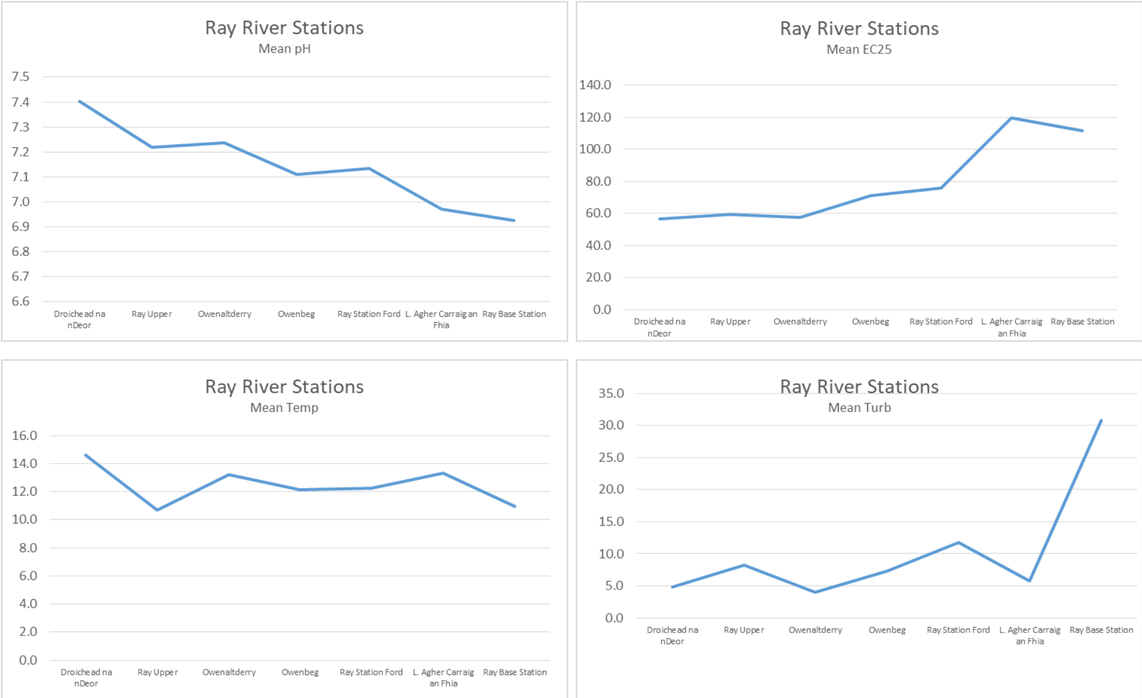

Figure 11 Average values of pH, conductivity (SEC), temperature and turbidity at the seven sites regularly sampled to show spatial trends

Laboratory Analysis

Samples for chemical analysis were taken on three days during the project: 6th July; 8th August; 17th August. Samples were submitted to an accredited laboratory for analysis. Methods applied to analysis of all parameters reported, except Total Suspended Solids, are UKAS accredited.

Summary results for each parameter based on all sampling dates are presented in Table 6. Where reported values were less than the limit of detection (LOD), the LOD/2 was used in the calculation of descriptive statistics below.

Table 6 Descriptive statistics for parameters determined in analysis of water samples.

	Alk mg/l CaCO3	**Amm** mg/l as NH3	**BOD** mg/l	**Col** PtCo Units	**Cond** us/cm @ 20C	**NO3-N** mg/l as N	**pH**	**PO4-P** mg/l as P	**TSS** mg/l	**Turb** NTU
Mean	12.8	0.025	1.1	186	62.5	0.33	6.6	0.009	4	6.7
Max	30	0.09	3	630	101.8	1.62	7.6	0.030	69	128.5
Min	1	0.01	1	59	44.3	0.26	5.6	0.005	1	0.2
95%ile	27.6	0.08	1	257.6	98.8	0.71	7.4	0.016	6	6.1

Some parameters are at very low concentrations and many results for them are close to, or less than the LOD. This is particularly the case for Amm, BOD, nutrients (NO3-N, PO4-P) and TSS.

Results for the remaining parameters are illustrated in Figure 12 in spatial sequence from bottom to top of the Ray study subcatchment.

Water pH remains relatively stable between 5.6 and 7.6, with no consistent pattern evident. Colour tends to increase towards the lower end of the study reach, probably reflecting increasing concentration of humic materials in solution from peats. Drain B gave exceptionally high colour, and turbidity, on the 8th August 2021. Alkalinity is low but with slight increases in the lower catchment. Conductivity (SEC) also displays an increase of 20 to 50 µs/cm on a given sampling run from upper to lower catchment.

With the exception of one high turbidity (128.9 FNU) at Drain B on the 8th August, all remaining turbidity results from the water samples taken were less than 7 FNU.

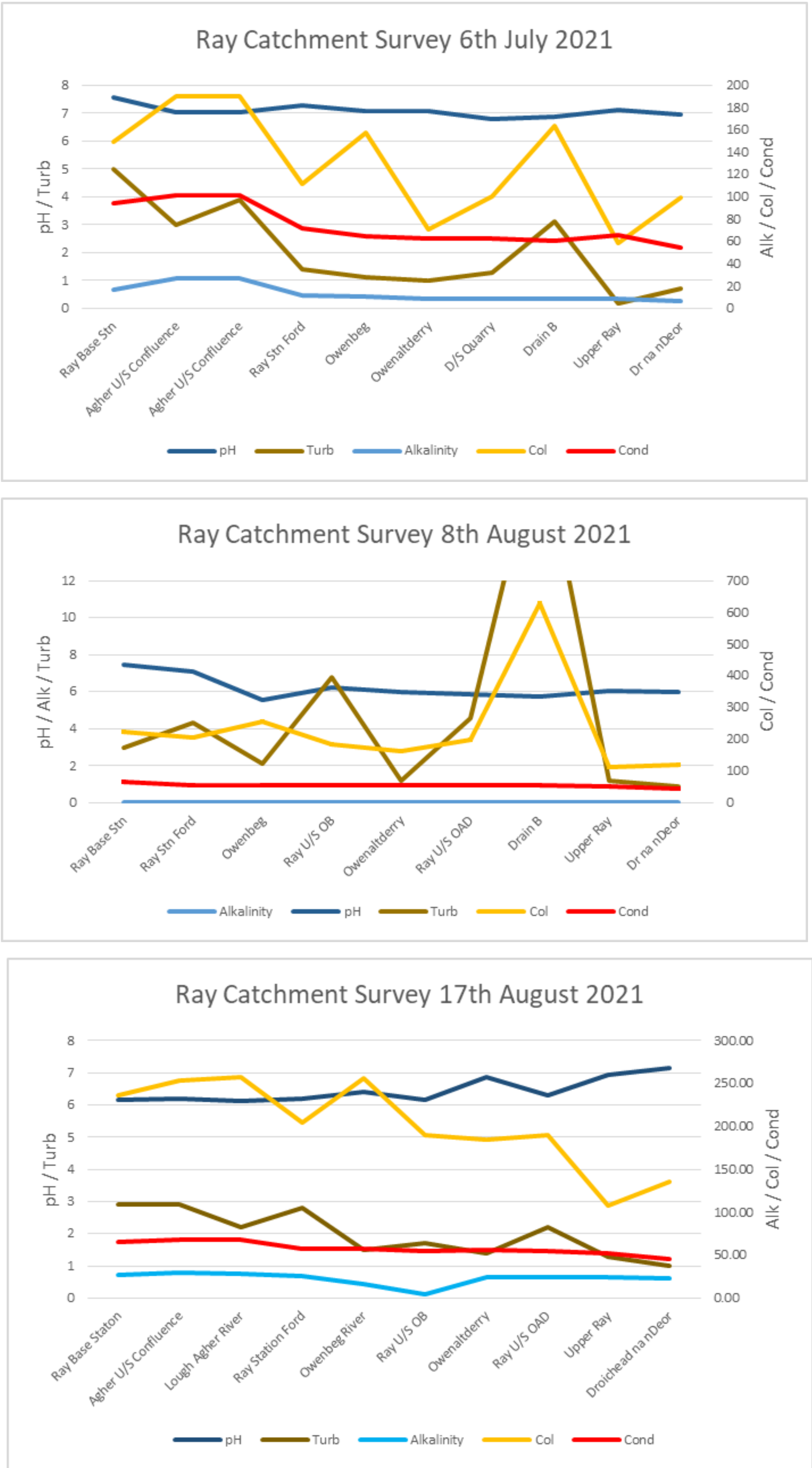

Figure 12 Water quality parameters measured at stations from upper to lower catchment of the Ray River on three dates. Off-scale turbidity on 8th August is 128.9 NTU.

Turbidity and Suspended Solids

Laboratory analysed samples that yielded valid TSS and Turb results (9 samples in total) are used below to derive a tentative relationship predicting TSS based on Turb (Figure 13). Samples where TSS were reported as less than the LOD were not included. The relationship is limited by the fact that most values were at the low end of the relationship. It provides an approximate prediction of TSS only and this is specific to the Ray samples on which it is based. The relationship derived suggests that TSS is almost twice (1.87 times) the Turb measured in NTU.

Addition of samples at higher Turb and TSS could produce a more robust relationship. However, the positive skewness of the turbidity distribution means that frequent small values may be expected during random sampling events, and only a few large values. The implications of random turbidity sampling at various frequencies or intervals, and the likelihood of detecting peaks is discussed further below.

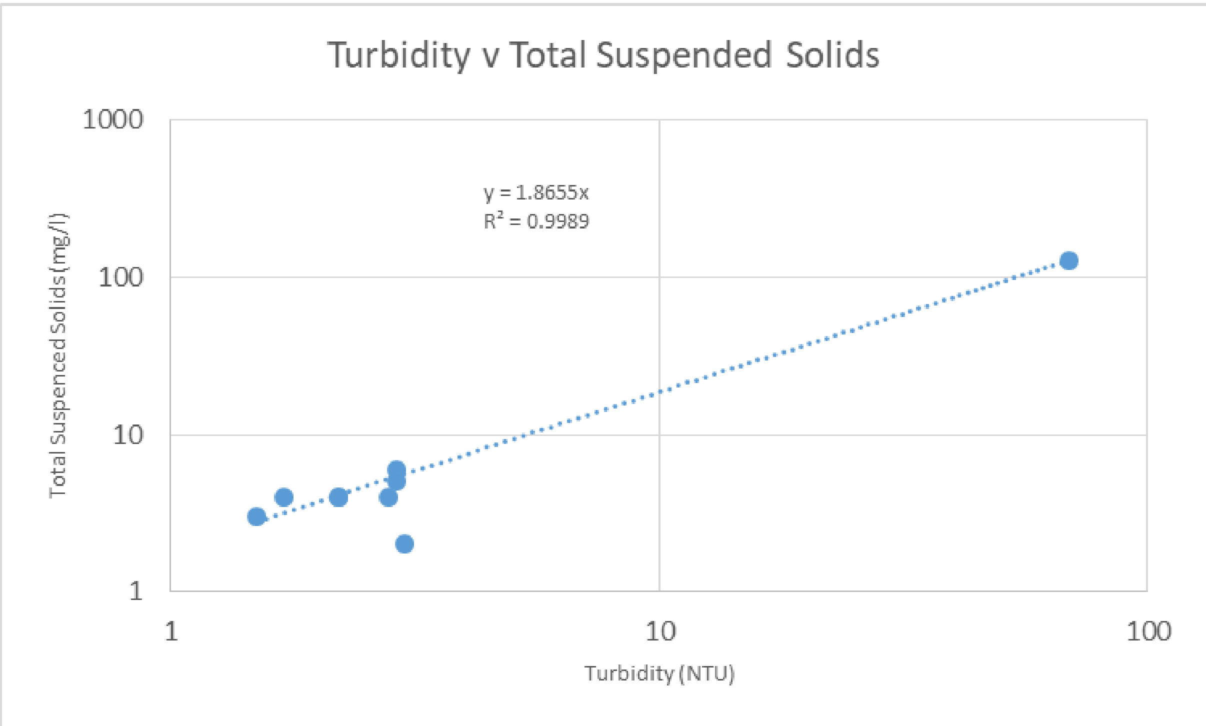

Figure 13 Turbidity v Total Suspended Solids. The linear equation and correlation coefficient squared (r^2) value are indicated on the plot. Note scales on axes are logarithmic.

Specific Electrical Conductance and River Flows

In Figure 14, SEC and turbidity (based on the 15 minute recordings at Ray Base Station) over short periods of time are illustrated. Daily rainfall recorded at nearby Lough Altan (7km distant) is also indicated by the blue bars at the top of the graphs on an inverted scale.

Flows have not been measured in the present project. Plans for installation of a staff gauge at the base station were hampered by Covid restrictions and access at low flows. The SEC curves are used primarily as an index of river flow and response to rainfall in Figure 14. SEC is generally low in the Ray catchment due to the the insoluble nature of the bedrock and subsoils, and the dominance of blanket peats. However, during dry intervals, particularly in this catchment with relatively short retention times, SEC is seen to increase as the proportional contribution of more mineralised groundwater and water inflowing through subsoils increases. Under unperturbed catchment conditions, with the advent of significant rainfall, conductivity falls dramatically due to dilution with waters draining across and through shallow peat soils of low ionic status. These flow pathways are illustrated in Figure 15 copied from Flynn et al (2021). The change in proportional contributions from these various pathways in blanket peat catchments results in a strong inverse relationship between stream flow rates and SEC (Figure 16). Therefore, in such catchments and where point sources of pollution of high ionic strength are not significant causes of distortion, time series of SEC may be a useful marker of flow conditions in streams.

Eight rainfall dilution events, indicating floods, are illustrated. Altogether about 10 such events of significance are obvious in the complete data series (Figure 8). However a number of smaller events are also obvious.

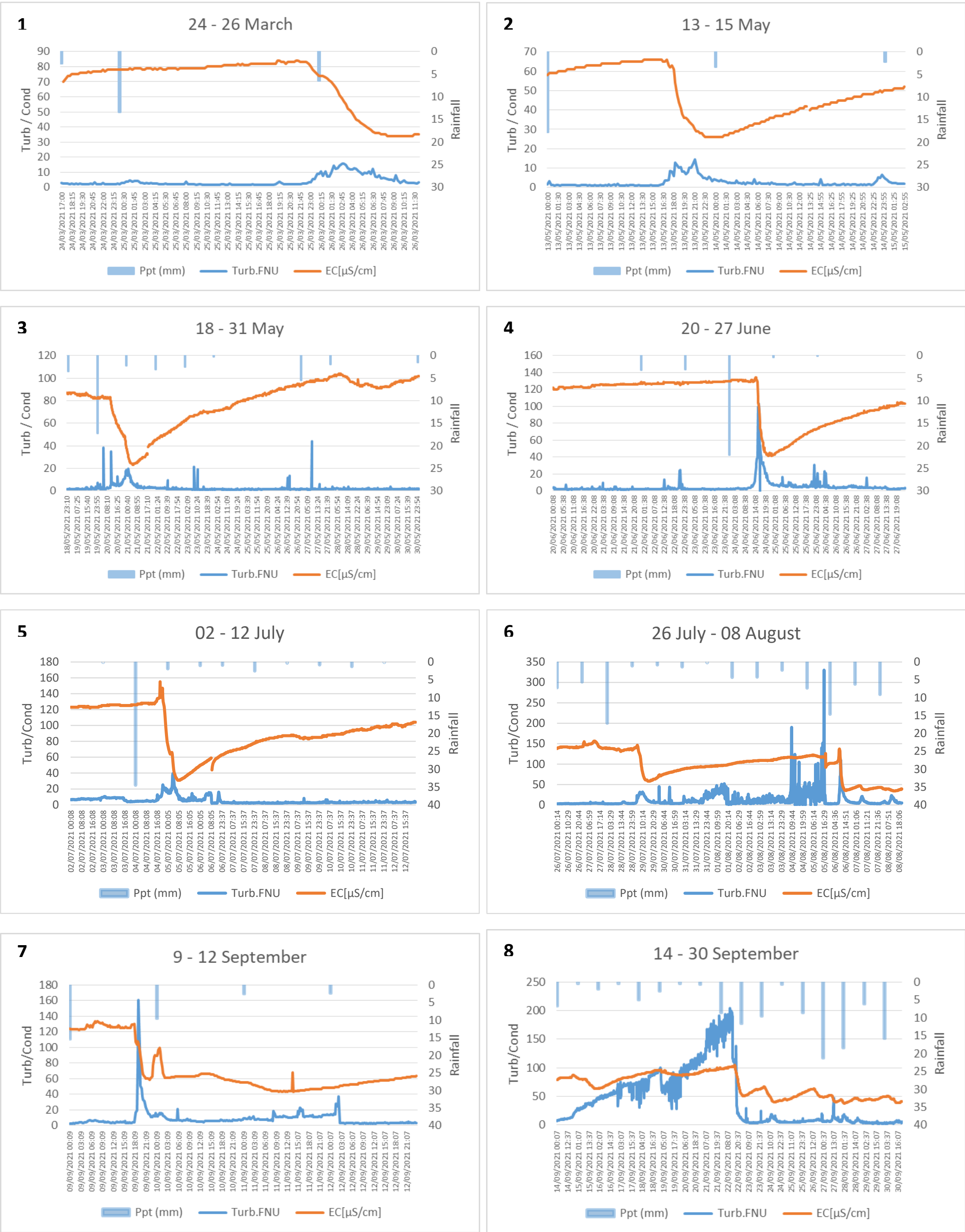

Figure 14 Turbidity and SEC over short events in the period of record. Daily rainfall is shown at the top of panels (inverse scale). Note the daily rainfall value is arbitrarily entered at the first 15-minute interval for the calendar date (usually 00h) so rainfall may graphically appear some time before the SEC fall on a given day.

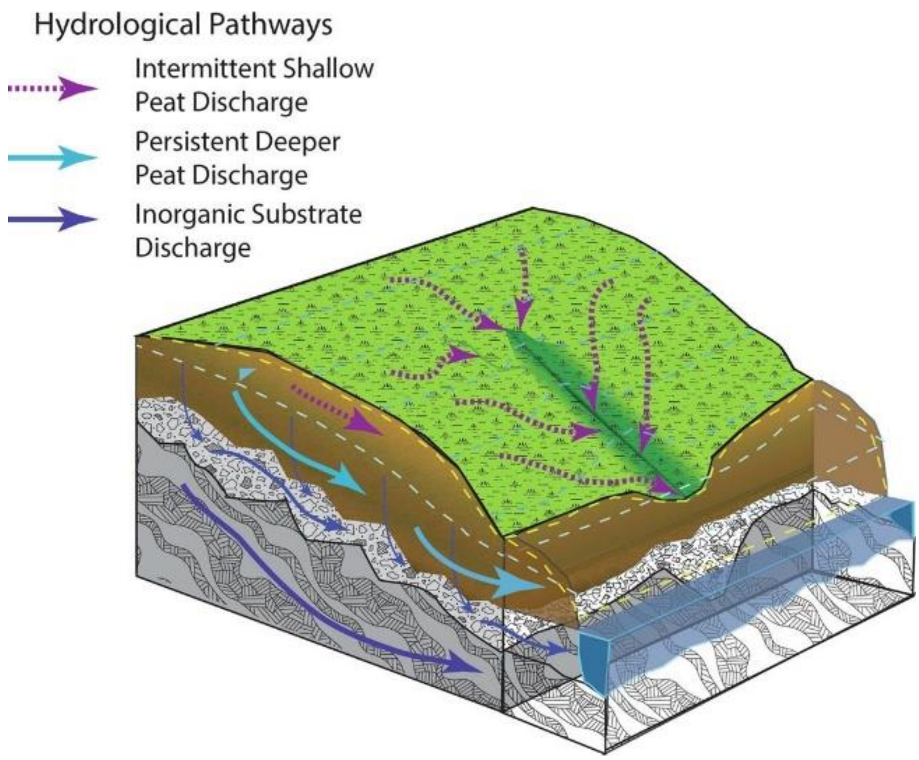

Figure 15 Hydrological pathways in blanket bog areas (copied from Flynn et al, 2021)

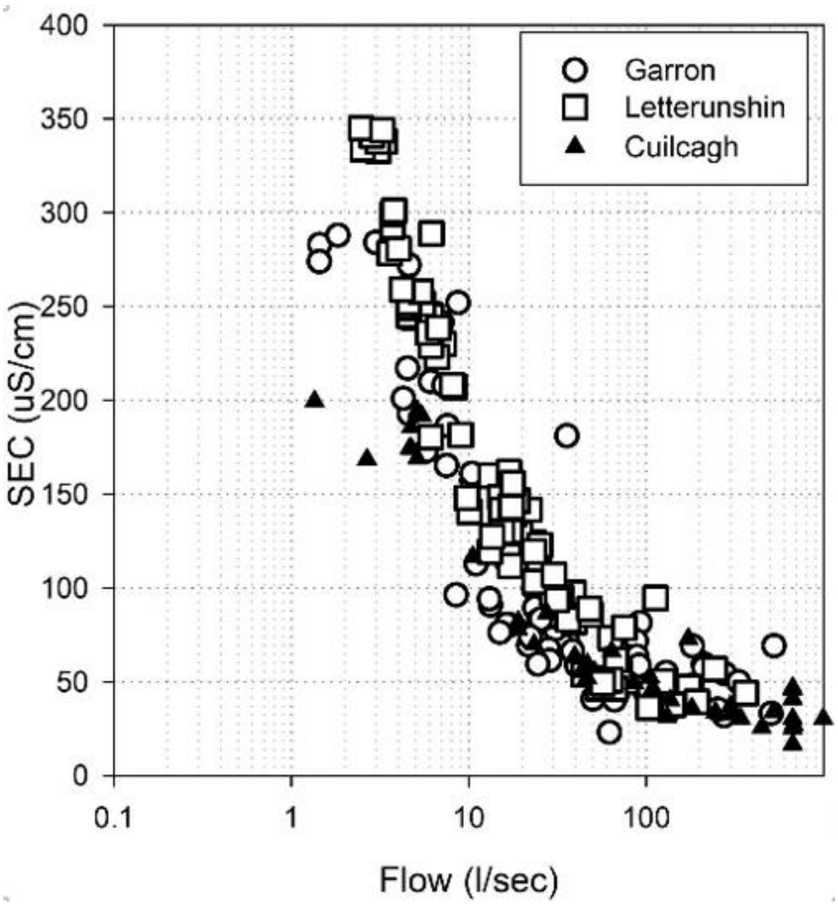

Figure 16 Inverse relationship between Flow and SEC in balnket peat covered catchments (from Flynn et al, 2021)

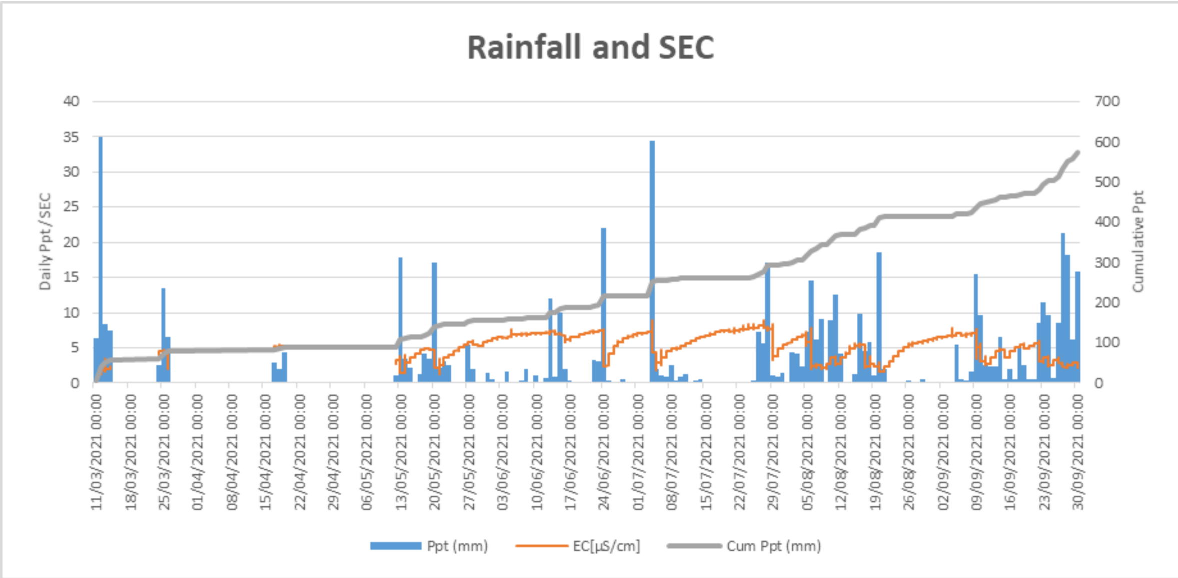

Figure 17 Daily rainfall and cumulative rainfall measured at Lough Altn over the duration of this project. Conductivity (SEC) response measured at Ray base station is also shown.

Turbidity Events

Over the 152 days of record in this project, there were 94 days with rainfall of 0.5mm or more (Figure 17). Daily rainfall of about 10mm or more typically elicit an SEC response involving a sudden drop in conductivity within hours.

Panels 1 to 5 in Figure 14 show an expected typical flood-turbidity response curve. SEC increases in dry periods between significant rain events. The duration of the dry period determines the maximum SEC value achieved, but this is unlikely to greatly exceed 160 µS/cm in this catchment. Baseline turbidity is generally less than 10 FNU outside flood events. An increase in turbidity is generally obvious shortly after the SEC decrease begins. The peaks in turbidity in these events are between 15 and 100 FNU. Using the relationship above between turbidity and suspended solids (Figure 13), this equates to a peak in TSS of approximately 30 mg/l to 190mg/l.

Panels 6 to 8 in Figure 14, covering the period through August and September, indicate a different relationship between turbidity and SEC/rainfall. They illustrate events where turbidity has increased while SEC was also increasing or stable i.e in the absence of flood indications.

In panel 6, rain at the end of July produced the expected fall in SEC followed immediately by a peak in turbidity of about 30 FNU. However, in the ensuing days (1st to 5th August) there are numerous peaks in turbidity. Turbidity ranges from 20 to 50 FNU on 1 August, returning to lower levels, albeit with peaks up to 20 FNU, from the evening of 1 August until the morning of 4 August. Throughout the 4th and 5th August, 8 turbidity peaks of 100 FNU or more were recorded, inlcuding the absolute maximum value recorded during the project of 330 FNU. Throughout this interval (1 – 5 August) SEC increases slowly and shows no indication of flood events until after the rain on the 5th August (7.3mm) and particularly on the 6th August (14.6mm).

Panel 7 shows a fall in SEC from about 130 µS/cm to 60 µS/cm associated with rainfall of 15.4 mm on 9 September. Unusually, this is followed by a substantial rise in SEC to 90-100 µS/cm shortly afterwards. This increase lasts a period of 3 hours and is associated with a slight increase in turbidity. The latter continues to increase, peaking around 40 FNU, while SEC is stable or increasing.

Finally, panel 8 shows a very substantial and protracted period of high turbidity from about the 14th to the 23rd of September. SEC increased gradually over this period and does not indicate flood conditions. Rainfall increased from 23 September and the last week of the month was very wet. During this last week turbidity peaks were mostly minor, a number of them around 20 FNU and a peak of 48 FNU on 27 September when 21.3 mm of rain was recorded.

Silt Sources

River runs were an attempt to identify higher trubidity source waters i.e. sources of higher silt loads. The sampling regime was somewhat distorted by the need for ad hoc responses to illegal quarrying and obvious pollution of the Ray channel. The number of sampling runs was also curtailed due to Covid restrictions.

A core suite of five stations were sampled along the main channel of the Ray and two additional stations on the Owenaltderry and Owenbeg tributaries just above their confluence with the Ray. Differing flow conditions and fluctuating turbidity levels over time make it difficult to directly compare individual stations over the period of the project. Therefore, to allow comparison, the turbidty readings at each site have been indexed to the base station i.e. each record is expressed in proportion to the base station reading on the same day. The base station is index 1 and sites with higher or lower turbidity will have an index of greater than or less than one respectively. Essentially this ranks sites along a scale of low to high turbidity and allows an average ranking to be derived.

The mean index for each site based on 10 river runs is shown in Figure 18. The actual ranking may differ on any particular sampling occasion and will be affected by local activities. However, on average, Owenalderry has yielded lowest turbidity, followed by Owenbeg. The lower ranking of

Owenaltderry may reflect the buffering effect of Lough Moilt in this area of the catchment. Sampling programmes need to consider such mitigating factors, particularly when significant silt sources lie upstream of lakes. It is somewhat unexpected that the Upper Ray and Droichead na nDeor sites, at the upper limit of the catchment, score higher in terms of turbidity. Legacy quarrying issues on the talus slopes of Muckish Mountain and erosion of upland peats may be more signicant than anticipated.

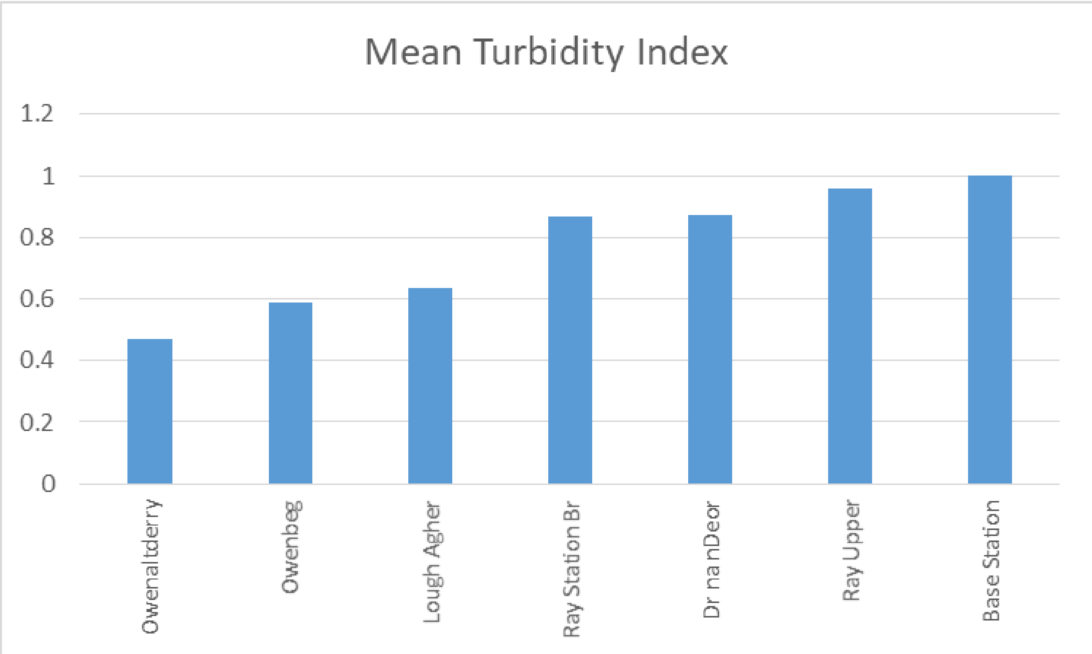

Figure 18 Mean index scores for core river run stations based on 10 sample runs. Stations are ordered low to high index along the bottom axis.

It is unlikely that low frequency sampling such as was carried out in river runs will quickly detect sources of sediment loading. High frequency time series have yielded valuable information allowing characterisation of flow responses in the study subcatchment.

Illegal Quarry

The operation of an illegal quarry at Muckish first came to CAA's attention on 1st March 2021 through reports from its membership. Subsequently CAA became aware that Donegal County Council had been dealing with the matter for some time in advance of this date. The operation and expansion of illegal quarrying activity in the upper Ray catchment over the course of this project became an increasingly urgent focus of attention. Quarrying at this site entails excavation and crushing of rock and transport off site by lorry. Substantial amounts of water are ponded in operational areas and are discharging through piped and excavated drains to the Ray River (Figure 19). The extensive stripping of surface vegetation and soils along with excavations, including construction of lagoons, has resulted in mass mobilisation of sediments and ongoing pollution of the river through discharge of heavily silt laden waters. Such operations account for the high turbidity events described above and illustrated in Figure 14, particularly during August and September when major works were occurring at the illegal quarry.

The principal issues of concern have been notified to the regulator and are listed below.

- The quarrying operation has no planning permission, and no application for planning permission has been submitted to date
- Excavations associated with the quarry are taking place at the boundary of an engineered municipal dump site with a high risk of disruption of hydrology and groundwater flows, and possible damage to containment structures
- There has been no Environmental Impact Assessment, and no Habitats Directive Assessment
- In the absence of planning consents, there is no environmental plan to mitigate quarrying impacts or consideration of noise, vibration, dust, effects on the amount and quality of water, lowering of the water table, effects on the natural heritage, the cultural heritage, landscape, traffic and waste materials
- No monitoring regime and compliance conditions are in place
- There is no operational landscaping scheme, no after-life site restoration scheme, and no lodgement of bond or financial contribution by the operators to ensure satisfactory reinstatement of the site
- Wide heavy vehicles are operating on narrow and winding mountain roads, especially dangerous in the absence of a lead warning vehicle, with risk of damage to, or catastrophic failure of stone bridges of heritage value, used as roosting sites by bats and nesting sites by dippers due to road transport of excessive loads of quarried material
- Soiling of local roads is occurring in the absence of wheelwash facilities, and sediment contamination of local road drainage which discharges to a salmonid river
- Un-vetted and unreviewed plans for settlement lagoons developed unilaterally by the operator have been allowed with potential for exacerbation of environmental damage

Orderly development in compliance with statutory instruments requires a systematic prior assessment of proposals. There is a lack of knowledge of the spatial extent (present and future) and duration of the ongoing illegal quarrying works. Since such assessments have not taken place and no consultation with regulatory authorities, the local community and stakeholders has occurred, the illegal operation is without environmental mitigation, and no environmental management system is in place.

Figure 19 Illegeal quarrying in upper Ray catchment and discharges of polluting material to the Ray River

The impacts of the sediment release from the quarry are obvious downstream to the bottom of the subcatchment study area. Figure 20 illustrates the impact of mobilised sediment in the Ray channel just above the base station on 3 May 2021, and in similar flow conditions when silt release was not occurring. Turbidity on the 3rd May was measured at almost 60 FNU at this location and nearby upstream at the Station Bridge. By comparison turbidity in the Upper Ray and Owenbeg tributaries, which are unaffected by quarry discharges, was half this value on the same day.

Figure 20 The left panel shows sediment pollution in the Ray River at the bottom of the study subcatchment 100m above the base station on 3 May 2021. The right panel shows the same site in similar flow conditions in the absence of silt pollution

While legal resolution of the qarrying issue is being pursued largely through planning regulation instruments, the regulatory authorities are unable or unwilling to address the acute issue of ongoing serious pollution and bring about an immediate cessattion of illegal polluting discharges. The inadequacy of legislative provisions, or lack of effective timely implementation in relation to numerous illegal quarrying operations nationally has been exposed repeatedly in recent years.

Monitoring Frequencies

The frequency of sampling of trade effluent discharges stipulated in licenses is often at intervals of weeks or months. Such frequencies are considered here in relation to turbidity, and the validity of results obtained in terms of actual environmental conditions and potential impacts.

The high frequency (15 minute intervals) turbidity data set acquired at Ray base station during this project is subsampled at increasing intervals of days, weeks and months (Figure 21) and analysed below. The starting point in this process is arbitrary, and the actual results will differ in any particular repeat subsample of data. However, the general trends and findings remain true for all iterations.

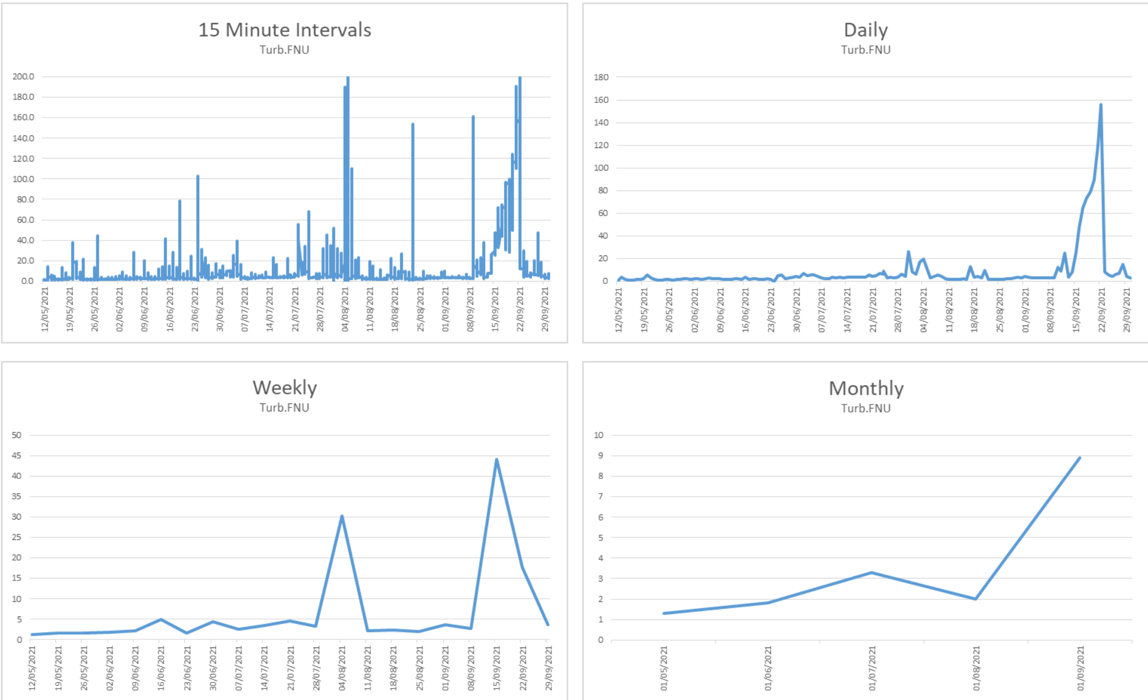

Figure 21 Plots of original turbidity data at 15 minute intervals, and sets subsampled at daily, weekly and monthly intervals

It is apparent in Figure 21 that variance of the data reduces dramatically as sampling interval increases. Note also that the absolute scale and range of turbidity records reduces from greater than 300 FNU at highest frequency, to less than 10 FNU at weekly and monthly sampling intervals. Summary statistics in Table 7 illustrate the consequences of reducing sampling frequency.

Table 7 Summary statistics for turbidity sampled at decreasing frequency intervals

	15min	Daily	Weekly	Monthly
Mean	9.5	8.6	6.8	3.5
Median	3.2	3.2	2.8	2.0
Mode	1.8	1.8	1.7	#N/A
max	330.0	156	44.1	8.9
Min	0.0	0	1.2	1.3
Std Dev	22.5	20.6	10.9	3.1
n	13516	141	21	5

The trends of reducing means, and in particular reducing maxima, with increasing sampling intervals is a consequence of the skewed positive distribution of turbidity records. It has implications for compliance monitoring in relation to emission limit thresholds.

It is apparent that the likelihood of detecting siltation events based low frequency sampling is small. Damaging releases of sediment at irregular intervals are likely to remain undetected. A realistic approach requires high frequency monitoring using turbidity as a proxy for detecting suspended solids emissions from facilities. Use of in-situ high frequency monitors should be a standard requirement where there is a risk of discharge of silts to receiving waters from licensed facilities. There are two licensed facilities in the CAA catchment area.

Conclusions

Time series of turbidity and SEC show typical response curves during flood events. Sediments are mobilised during floods through erosion from the terrestrial catchment, or re-mobilisation of bed load.

Analsyis of turbidity measured during low frequency sampling has given some insights into diffuse silt sources in the catchment, and will inform future investigative approaches for mitigation implementation. Legacy issues and upland peat erosion may be of greater significance than expected.

Evidence is presented of non-flood related turbidity events. The worst of these coincided with major works at an illegal quarry site when lagoons were excavated in September. Mass mobilisation of sediments at the quarry site is a significant impact on the Ray and an immediate threat to its salmonid status.

The inability of regulators to deal with largescale illegal quarrying operations in a timely and effective manner is a cause for great concern and despondency in communities that are striving to protect and improve their local environment.

An examination of turbidity data shows it is strongly positively skewed. This has implications for sampling programmes and detection of sediment source areas. Implications for turbidity/suspended solids monitoring in receiving waters is discussed. Threshold limits and monitoring requirements currently set out in discharge consents will not allow detection of pollution events or provide protection for receiving waters. The use of high frequency turbidity monitoring is recommended.