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Sediment Flux - Measurement, Impacts, Mitigation and Implications for River Management in Ireland

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Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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Sediment Flux – Measurement, Impacts, Mitigation and Implications for River Management in Ireland

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by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Contents

List of Figures

List of Tables

Executive Summary

The SILTFLUX project addressed three major objectives related to sediment pollution in rivers:

1. to increase knowledge and understanding of suspended sediment flux and dynamics in Irish rivers to help set standards for suspended solids for the protection of sensitive catchments;
2. to assess the benefits of sediment reduction that mitigation measures can achieve, differentiating between the effects of fine and coarse sediment;
3. to understand the relationship between suspended silt concentration/ flux, deposited silt and ecological impacts in different river typologies and under variable land use.

Monitoring stations with automatic water samplers and continuously recording turbidity instruments were installed at sites on the Rivers Slaney, Glyde, Clodiagh, Camlin and Urrin, selected on the basis of their land use and geology. These were connected via a live internet link to a data management system, facilitating data collection in real time for both high and low flows. Water samples were also collected at critical times by a separate automatic sampler, triggered by SMS text messages or when water levels reached pre-defined thresholds. In each river, upstream (minimally impacted conditions) and downstream (affected by land use) monitoring sites were established. Additional data from the River Clare were provided by the Office of Public Works. All data collected by the project were quality controlled and analysed to establish a methodology for generating numerical models of suspended sediment yield from ungauged catchments to contribute to knowledge about the total export of sediment from Irish rivers.

The ecological studies in SILTFLUX focused largely on sediment deposited on river beds, as there it has the highest potential for impact on aquatic biota. Five investigations relating to the biological impacts of elevated sediment levels were undertaken, starting with an evaluation of methods for measuring deposited sediment. Potential sediment impact on macroinvertebrate communities was considered at two scales, local and catchment-wide. The local sources investigated were cattle access points on streams for drinking, a widespread and potentially significant contributor to pressures on water quality in agricultural catchments in Ireland. The data from these field observations were combined with data derived from mesocosm studies to test the relationship between various macroinvertebrate metrics and sediment metrics. The catchment scale investigations examined macroinvertebrate communities with respect to the influence of two land uses (tillage and pasture), and associated levels of deposited and suspended sediment. Finally, the responses of a number of selected macroinvertebrate taxa to burial by sediment were investigated in an attempt to explain some of the responses in the aforementioned investigations.

Conclusions

Monitoring and measuring

There are large differences in turbidity measurements [measured in nephelometric turbidity units (NTU)] from different makes of instruments. Care must therefore be taken when comparing turbidity values obtained from different makes or models of instruments, and turbidity alone should certainly not be the basis for setting national standards.

Nevertheless, good, but instrument and site-specific, calibration equations can be established between turbidity and suspended sediment concentrations (SSCs), and, despite instrument differences in measured turbidity, the individual calibration equations developed for each instrument can produce reasonably consistent estimates of SSC. Thus turbidity can be used as a proxy for SSC, and hence for estimating sediment loads, as long as site-specific and instrument-specific calibrations are used.

Continuous real-time, remote monitoring of SSC using turbidity as a surrogate requires resilient infrastructure and reliable instrumentation, together with regular maintenance, facilitated by real-time telemetry, to ensure the integrity of the data stream.

SILTFLUX constructed a database of annual values of suspended sediment yield (SSY) from extant studies of Irish catchments. These data indicate levels of (area-specific) SSY ranging from as low as 2.11 to a maximum of 48.39 $t\,km^{-2}\,y^{-1}$. These values are comparable to the lower SSY values reported for catchments of central, western and northern Europe.

SILTFLUX data exhibited inter-annual variations in estimated sediment loads. Short-term suspended sediment monitoring is, therefore, unlikely to provide an accurate estimate of the range of suspended sediment flux/yields possible from a given catchment because of the inherent variability of weather, flows and sediment supply. Longer term monitoring is needed to ascertain the degree of variability between seasons, years and over longer decadal timescales in Irish rivers.

SILTFLUX has demonstrated a methodology for developing regression equations that can be used to estimate annual sediment yields from ungauged catchments. Strong associations were found between sediment yields and catchment variables related to its soil (particularly poorly drained soils and peat soils), topography (*S*1085 slope), hydrology (runoff, annual mean flows and *Q*5 – the flow exceeded 5% on the time on average) and climate (seasonal rainfall for winter and spring). These regression models offer a framework for the creation of a national inventory or map of sediment yields in Ireland, but they require further testing and validation using longer time series and across a wider range of land use types. They could potentially represent a cost-effective method for estimating reference conditions to support, together with other factors, the setting of sediment-related environmental quality standards in Irish catchments.

Freshwater biology

The durations of exceedance of specific sediment thresholds are particularly relevant for assessments of potential biological impacts, and site-specific sediment exceedance–duration relationships are required for determining these impacts. SILTFLUX established the importance of deposited sediment in causing biological impacts on macroinvertebrates and there is a strong argument that ecological quality standards should focus on deposited sediment in addition to SSCs and flux. Percentage sediment surface cover and EPT[1] abundance may be useful metrics for assessing the negative effect of excessive sediment on macroinvertebrates. However, since EPT metrics are also used to indicate eutrophication and general degradation of water quality, there is a need for further research to refine sediment-specific metrics. The experimental testing indicated biological impacts at > 30% bed sediment cover, although further research is needed to investigate key sediment cover thresholds for a range of organisms.

Species-specific responses to burial in sediment varied with the depth and nature of the sediment accumulated, as well as the source of the taxa. Such variation and the paucity of mechanistic investigations challenge efforts to produce global metrics to detect sediment effects.

There was a strong relationship between visual estimates of percentage surface cover and sediment amounts. This suggests a simple method of quantifying deposited sediment amounts. However, if this is adopted nationally, training protocols should be undertaken to improve inter-observer consistency and increase the precision and accuracy of visual estimates.

Generally, macroinvertebrates in mid-channel habitats, rather than at the channel margins, were most sensitive to the added pressure of cattle access points. Although there were some seasonal differences and site-specific impacts, it remains difficult to disentangle the effects of sediment from those of excessive nutrients.

Implications for Management of Suspended Sediment in Rivers

SSCs and loads in Irish rivers are generally low in comparison with rivers in the UK and Europe. Because they include land use factors that can be adjusted to reflect more or less intense land use, the equations developed in SILTFLUX provide a basis for a methodology that can be used to estimate reference conditions, but longer term data covering a wider range of catchments are needed to establish both annual variability and dependence on a larger range of physical and land use characteristics.

1 EPT refers to Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies).

In addition, for small catchments, the sediment flux equations provide a "first pass" at estimating long-term average conditions by using long-term mean annual flows, runoff or *Q*5 values, determined from hydrometric records where available or estimated from ungauged catchment equations. These equations can help to estimate the likely mean annual sediment yield (SY) or SSY value for a given ungauged catchment.

There are specific locations within some Irish rivers that are inhabited by protected and sediment-sensitive species. Special consideration should be given to protecting these areas and SILTFLUX has developed a series of management steps, relating to sediment, for sensitive habitats. While these provide a framework for informing potentially suitable mitigation measures, the degree of impact and the characteristics of specific sites will also require consideration in deciding which measure, or combination of measures, is most appropriate. In addition, the risks arising from the inter-annual variability of weather and thus SY and SSY (not taken into account in the above), should be studied and eventually incorporated into this framework.

Further Challenges in Quantifying Sediment Loads

(i) Investigate the sediment yields from rivers under different land uses

As SILTFLUX focused on tillage and pasture land uses, the equations developed here should be tested for catchments dominated by other land uses (e.g. forestry), topography and geology (e.g. karst), surface cover and soil type to gauge their utility and suitability. Furthermore, separate studies could be undertaken to develop equations specific to these land uses, slopes, soils or settings. Thus, this project was not able to establish any different behaviour patterns for other settings and this is an area for future research.

(ii) Investigate the sediment yields from rivers subjected to arterial drainage

The SILTFLUX project included only one catchment that had been subject to extensive arterial drainage. The sediment yields from this catchment were relatively low given its high proportion of tillage. Further investigation is needed to quantify the potential effects of arterial drainage on sediment loads.

(iii) Investigate sediment yields and dynamics in lake areas

Only one of the SILTFLUX sub-catchments included lakes that may trap sediment. Given the high number of natural lakes in Ireland, particularly in the midlands and in some upland regions of the country, this is also an area for future research.

(iv) Investigate how to extend this study to larger catchments

A project steering committee member made a very useful suggestion of applying models that include upscaling for separate sediment production and transport models for larger catchments.

(v) National suspended sediment yield map

This study provides the first steps towards producing a national map estimating the amount of sediment transported and exported by Irish rivers using the regression equations developed here. These estimates can be used to support reporting under the OSPAR Convention. The SILTFLUX equations are suitable for inclusion in a geographic information system-based erosion risk tool for use on a sub-catchment basis, analogous to the critical source areas tool for nutrients (nitrogen and phosphorus) already used by the EPA.

(vi) Suspended and deposited fine sediment relationships

The potential links between fine sediment flux at a reach scale and deposited fine sediment should be studied, together with the associated river morphology and hydraulic regime.

(vii) Visual estimates of fine sediment cover should be made routinely

Visual estimates of fine sediment cover under experimental conditions reflected the amount of sediment added and correlated well with EPT metrics. There is growing evidence that it has the potential to be applied in water quality monitoring to gauge potential ecological impact, as percentage surface sediment cover is now routinely recorded by the EPA during Water Framework Directive bioassessment, but standardised protocols and observer training are required.

(viii) Thresholds for impacts from deposited sediment should be investigated

Noticeable responses in aquatic invertebrate communities have been detected for between 10% and 10-fold increases in deposited sediment. Salmonid habitat is reported to be impacted at less than 10% cover and mortality is associated with 20% cover. Further investigation is required to refine thresholds for impact.

(ix) New sediment-specific biological metrics are needed (disentanglement)

EPT metrics respond to the amounts of deposited sediment. However, EPT metrics are known to also respond to organic pollution and eutrophication and are therefore general indicators of ecological degradation in agricultural catchments. Further studies are required to develop sediment-specific biological metrics.

(x) Interim suggestion

In the interim, field sampling for *Q*-value estimates should record the overall representation of EPT fauna in terms of richness and abundance. These data should be extractable from the EPA *Q*-value metrics database.

(xi) Outdoor overwintering of cattle

Outdoor overwintering of cattle on steep slopes in the vicinity of watercourses during periods of high soil moisture content is not recommended practice in terms of water quality protection.

1 Introduction

1.1 Objectives

The SILTFLUX project addressed three major objectives:

1. to increase knowledge and understanding of silt flux in Irish rivers to help set standards for suspended solids for the protection of sensitive catchments;
2. to assess the benefits of silt reduction that mitigation measures can achieve, differentiating between the effects of fine and coarse sediments;
3. to understand the relationship between suspended silt concentration/flux, deposited silt and ecological impacts in different river typologies and under variable land use.

1.2 Methodology

The project started with a review of knowledge of sediment flux, its measurement and, later, of measures for reducing or mitigating its impact. In parallel, the project selected study catchments in which sediment flux data and biological information would be collected. The data provided information on the factors influencing sediment flux in Irish rivers under a range of conditions and on its biological impact. The catchment studies were augmented by laboratory investigations of specific topics relating to both turbidity measurement and biological impact. The datasets collected by the project, together with other published data, provided a basis for establishing a methodology for generating predictive equations relating annual sediment yield (SY) to catchment and climate characteristics. All of the information and results generated by the project support a wide range of recommendations, both for how this information can inform river management policy and also what further research is required.

1.3 Staffing the Project

SILTFLUX involved two main partner institutions, University College Dublin and the University of Birmingham. However, many other Institutions contributed during the course of the project, including the Cork Institute of Technology and the Marine Institute. Dr Martin O'Grady was an advisor to the project, particularly in its initial phases. The main researchers involved are listed in Table 1.1.

The project made occasional use of research assistants to accompany and assist the project researchers in the field. Mr John Wallace of IDS Monitoring liaised with the project team in relation to the installation and maintenance of the equipment and the posting of live data on the project website (cwrr.ucd.ie/projects/current-projects).

Table 1.1. Main reasearchers and their roles

Name	Institution	Role
Michael Bruen	UCD	PI, Project Co-ordinator
Mary Kelly-Quinn	UCD	PI
John O'Sullivan	UCD	PI
Jonathan Turner	UCD	PI
Damian Lawler	UB (subsequently, CU)	PI
Joe Harrington	CIT	Collaborator
Elvira de Eyto	MI	Collaborator
Elizabeth Conroy	UCD	PhD researcher
Anna Rymszewicz	UCD	PhD researcher
Ahilan Sangarilingam	UCD	Postdoctoral researcher (GIS)

CIT, Cork Institute of Technology; CU, Coventry University; GIS, geographic information systems; MI, Marine Institute; PI, principal investigator; UB, University of Birmingham; UCD, University College Dublin.

1.4 Workshops

The project organised and managed three workshops, each with specially invited expert speakers, to generate and communicate ideas related to SILTFLUX objectives. Relevant stakeholder groups were invited to each workshop. The topics of each workshop are listed below.

1.4.1 Workshop 1: Sediment flux in Irish rivers

The workshop was intended both (1) as an information gathering activity, to allow the project team to make contact with people who may have information, data or practical experience to contribute to the project and (2) as an opportunity to make all relevant people and organisations with an interest in sediment and its effects aware of the purpose and scope of the SILTFLUX project. Participation included representatives from the Environmental Protection Agency (EPA), the Office of Public Works (OPW), government departments with an environmental remit [including the National Parks and Wildlife Service (NPWS)], local authorities, Teagasc, Inland Fisheries Ireland, the Marine Institute, the Geological Survey of Ireland and other research organisations, particularly universities and other third-level institutions.

1.4.2 Workshop 2: Effects of specific pressures on sediment flux

This workshop focused on the impact of specific pressures on sediment flux. It described the experience and interim results of the project in relation to (1) the role of land use in sediment flux; (2) the role of weather (rainfall and flows) in mobilising and transporting sediment; and (3) the impact of cattle access points.

1.4.3 Workshop 3: Policy, targets and the reduction of sediment in Irish rivers

This workshop focused on the performance of sediment mitigation approaches, including land use management and agricultural practices and in-stream river measures. The project team described its literature review/desk study on the performance of measures, and preliminary work on the development of a management strategy. Participation was extended to stakeholder groups, such as SWAN (Sustainable Water Network) Ireland.

1.5 Organisation of Reporting

1.5.1 Project documents and datasets

- Literature review of sediment-related research, including measurement methods, ecological impacts and reduction measures, which is available electronically through the EPA website (http://erc.epa.ie/safer/reports).
- Main technical report, which is a full description of the project and its outcomes. It is intended that this document will be made available electronically through the EPA website.
- Synthesis report (this report), which is a short description of the project methodology and its results. This is intended for publication by the EPA as a printed report and will also be made available through the EPA website.
- A short non-technical summary of project outcomes and policy implications.
- Database of sediment data and associated metadata for suspended sediment research and monitoring undertaken for Ireland to date.
- Repository of project data, which has been uploaded to the EPA SAFER data repository.

2 Site Selection, Instrumentation and Operational Methods

2.1 Catchment and Site Selection Criteria

Site selection for field data collection was carried out using national datasets, field site visits and consultation with stakeholders and landowners. The criteria used in the initial screening were as follows:

- river typology;
- presence of a dominant land use in catchment;
- absence of active quarries in catchment;
- absence of water treatment works discharges in catchment;
- absence of significant water abstractions in catchment;
- presence of active OPW or EPA flow gauging stations;
- EPA *Q*-values to identify reference and impacted water bodies.

Figure 2.1 shows the original experimental design, typically incorporating upstream and downstream monitoring locations, corresponding to high or high–medium status (control) sites and impacted sites, respectively. This experimental design was adopted for the first phase of catchment monitoring. In some cases, the upstream monitoring site was not always included in the project second phase, although upstream conditions were still chosen on the basis of high or high–medium water quality status.

2.1.1 Chosen SILTFLUX monitoring catchments

The river catchments chosen for instrumentation were the upper Slaney (Counties Wicklow/Carlow), the Glyde (Counties Louth/Monaghan/Cavan/Meath), the Clodiagh (Counties Laois/Offaly) the Camlin (County Longford) and the Urrin (County Wexford) (Figure 2.2 and Table 2.1). Nine monitoring sites within these catchments were fitted with *in situ* turbidity instruments and water samplers for suspended sediment flux estimation. Additional data collection for the ecology studies took place at these locations and at other “intermediate” upstream or downstream locations. Subsequently, co-operation between the SILTFLUX team and the OPW allowed for the addition of two further sites where turbidity measurements were being collected by the OPW for the monitoring of maintenance works (Table 2.2).

2.2 Selecting Field Sites for Instrumentation

The optimal location for generating suspended sediment flux estimates was near existing hydrometric stations. However, where these were unavailable or deemed unreliable, a site upstream or downstream of a bridge structure was considered the best alternative. All sites were checked for the presence of potential

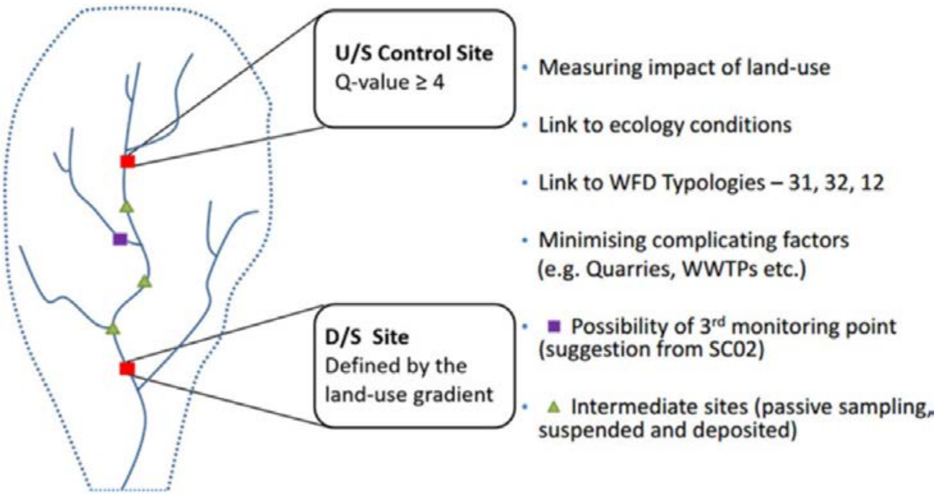

Figure 2.1. The experimental design used for locating monitoring sites. D/S, downstream; U/S, upstream; WFD, Water Framework Directive; WWTPs, waste water treatment plants.

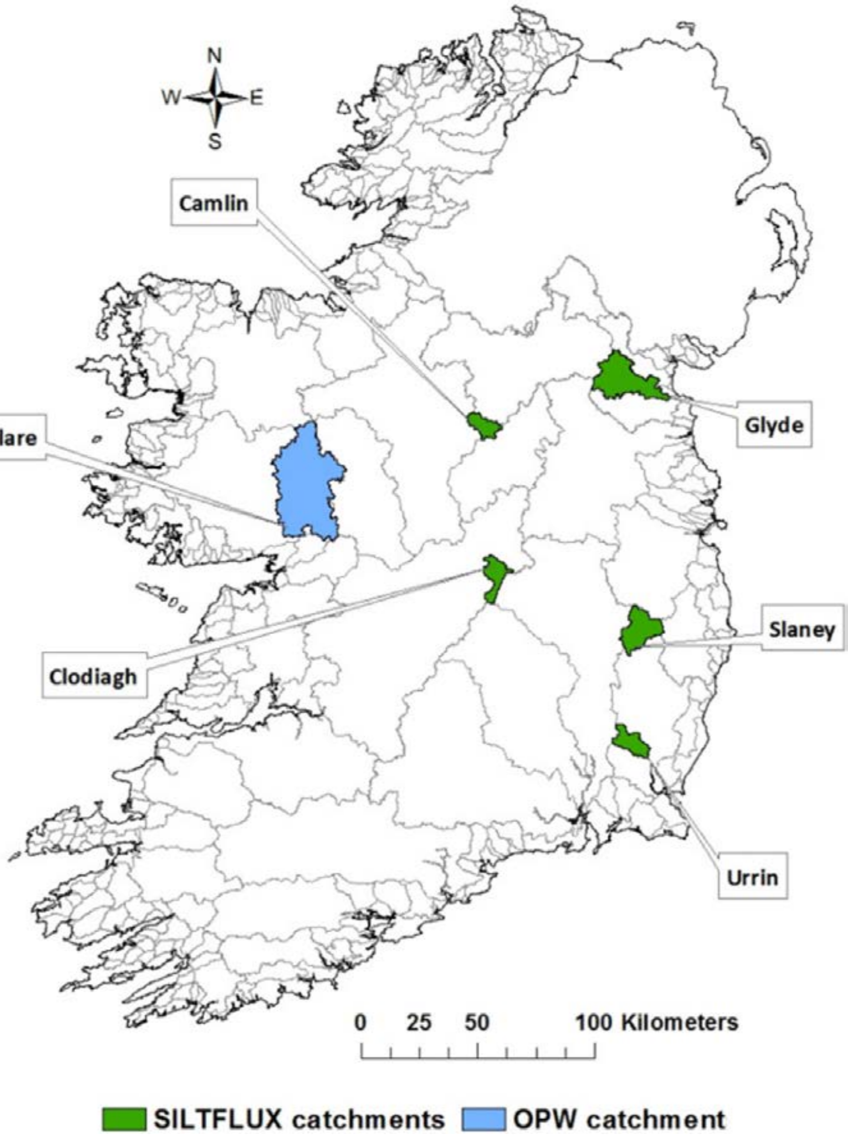

Figure 2.2. Location of SILTFLUX project and OPW catchments.

point sediment sources that were not included in the catchment screening. These included cattle access points, drainage works and other human activities that disturb the riverbed and the banks periodically. Checks were also made for evidence of active natural bank erosion associated with channel instability and migration. Actual instrument setups were determined by site conditions and local flood risk factors.

2.3 Description of Chosen Instrumental Approach and Operational Methods

2.3.1 Background

Accurate quantification of sediment flux requires high resolution discharge and corresponding suspended sediment concentration (SSC) data that can account for the temporal variability of transported sediment (see Figure 2.3). SILTFLUX SSC data were derived using the well-established turbidity surrogate method (Lawler, 2016).

2.3.2 Measuring turbidity and SSC

Turbidity measurements were obtained through high-frequency (10-minute intervals) measurements. These were field calibrated to SSC via sampling campaigns using automatic ISCO water samplers (model 6712) to capture SSCs across a range of flows, focusing on storm events and high sediment transport/flux episodes. Sensor-specific mechanical wipers were installed to limit the degree of sensor fouling.

Table 2.1. SILTFLUX monitoring sites

No	Catchment	Site name and location	WFD type	Sediment monitoring		Ecology sampling	OPW/EPA gauge	Grid reference	GIS EU_CD coding name[a]
				SSC	Turbidity				
1	Slaney	Gibstown Br.	12	✓	✓	✓	N/A	52°59′14.26″N, 6°36′20.29″W	IE_SE_12S020400
2		George's Br.	12			✓	N/A	52°59′6.65″N, 6°39′1.01″W	IE_SE_12S020400
3		Tuckmill Br.	12	✓		✓	N/A	52°58′0.17″N, 6°41′49.24″W	IE_SE_12S020600
4		Aldborough Br.	12			✓	N/A	52°54′51.81″N, 6°40′45.96″W	IE_SE_12S020800
5		Rathvilly	11	✓	✓	✓	EPA Rathvilly St. No. 12013	52°53′7.53″N, 6°41′33.90″W	IE_SE_12S021010
6		U/S of Tullow Br.	11	✓			OPW Tullow Br. U/S St. No. 12005	52°48′40.82″N, 6°45′0.92″W	IE_SE_12S021400
7	Glyde	Lagan Br.	31		✓	✓	OPW Aclint St. No. 06026	53°54′36.26″N, 6°40′13.70″W	IE_NB_06G020400
8		Killaney Br.	31		✓	✓	N/A	53°57′3.50″N, 6°38′21″W	IE_NB_06P010600
9		Tallanstown Br.	31	✓		✓	OPW Tallanstown St. No. 6014	53°55′12.46″N, 6°32′50.35″W	IE_NB_06G020700
10		Mansfieldstown Br.	31	✓	✓	✓	OPW Mansfieldtown St. No. 06021	53°53′33″N, 6°27′8″W	IE_NB_06G021230
11	Clodiagh	Bracknagh Br.	31	✓	✓	✓	OPW Bracknagh St. No. 25301	53°10′49.16″N, 7°30′18.43″W	IE_SH_25C060300
12		Clonad Br.	31			✓	N/A	53°13′27.15″N, 7°31′57.06″W	IE_SH_25C060340
13		Unnamed bridge north of Clonagh Br.	31			✓	N/A	53°14′18.79″N, 7°32′18.12″W	IE_SH_25C060340
14		Annamoe Br.	31			✓	N/A	53°16′9.14″N 7°33′57.2943W	IE_SH_25C060500
15		Kilgortin Br.	31	✓	✓	✓	EPA Kilgortin St. No. 25039 (inactive)	53°16′25.55″N, 7°34′21.18″W	IE_SH_25C060500
16	Camlin	Kilnacarrow Br.	31	✓	✓	✓	EPA Kilnacarrow St. No. 26331	53°46′14.94″N, 7°40′37.57″W	IE_SH_26C010600
17	Urrin	Ballycrystal Br.	12			✓	N/A	52°34′55.55″N, 6°43′34.098″W	IE_SE_12U010050
18		D/S of EPA Mangan Station	12	✓			EPA Mangan St. No. 12036	52°32′13.47″N, 6°41′19.14″W	IE_SE_12U010300
19		U/S of St John's Br.	12	✓	✓	✓	OPW St John's Br. St. No. 12007 (WL only)	52°29′36.13″N, 6°34′36.22″W	IE_SE_12U010500

[a]Note that the sampling site is located within GIS sub-basin polygon but not necessarily at the exact sub-basin outlet location.

D/S, downstream; GIS, geographic information system; N/A, not available; U/S, upstream; WFD, Water Framework Directive; WL, water level.

Table 2.2. Sites for *in situ* turbidity sensors (OPW and SILTFLUX)

Catchment	Site name and location	WFD type	Equivalent OPW/EPA hydrometric station	Grid reference	GIS EU_CD coding name[a]
Clare	Ballygaddy	31	OPW Ballygaddy St. No. 30007	53°31′50.98″N 8°52′28.73″W	IE_WE 30C010500
	Cregmore U/S of EPA Claregalway St	31	EPA Claregalway St. No. 30012	53°20′37.95″N 8°53′9.07″W	IE_WE 30C011100

[a]Note that the sampling site is located within GIS sub-basin polygon but not necessarily at the exact sub-basin outlet location.
GIS, geographic information system; U/S, upstream; WFD, Water Framework Directive.

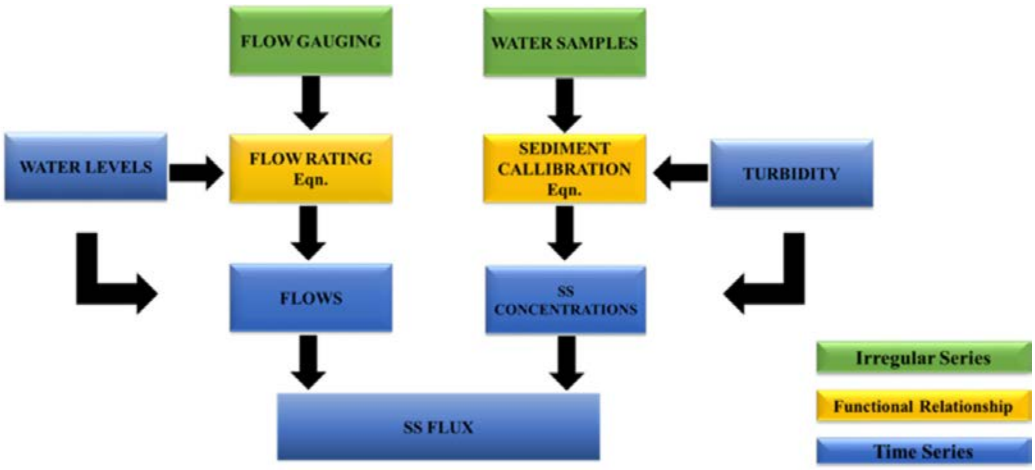

Figure 2.3. Methodology for estimating sediment flux. SS, suspended sediment.

Data collection was carried out using the IDS DataPOD real-time data acquisition system (IDS Monitoring), which allows a multiple sensor connection (analogue and digital) and real-time data transmission via integrated Global System for Mobile Communications (GSM)/General Packet Radio Service (GPRS) telemetry. The measured data were transmitted live to the project website, which allowed live data screening during storm events, early problem detection, data download and monitoring of power supply levels. The DataPOD system was also integrated with the ISCO automatic water sampler. The firing of the autosampler was controlled via SMS text commands sent to the datalogger.

Initially, ISCO water samples were analysed in house to determine total suspended solids (TSS) (APHA Standard Method 2540D, using standard glass microfibre filters with particle retention of 1.2 μm), but water samples were also processed later by the IAS Laboratories using the same TSS method. A few selected samples were analysed for volatile suspended solids (i.e. organic matter) by a loss-on-ignition (LOI) method (Heiri *et al*., 2001).

2.3.3 Estimating suspended sediment flux

Estimating suspended sediment flux requires corresponding high-resolution flow data (see Figure 2.3). For SILTFLUX, where possible, these data were obtained from the OPW/EPA hydrometric station located at the site. When such flow data were unavailable, flows were estimated from water level data obtained from either a nearby hydrometric station or a water level recorder installed at the site. This latter scenario required flow gauging measurements (obtained from either EPA/OPW hydrometric datasets or field measurements obtained by the SILTFLUX team) and the establishment of a flow rating curve for the site. When high flow measurements were unavailable, the upper part of the flow rating curve was estimated from channel geometry using the HEC-RAS model from the US Army Corps of Engineers, which required a survey of channel and bridge geometries at the site.

3 Instrument Evaluation – Laboratory and Field Tests

3.1 Introduction

Changing hydrological conditions can introduce significant variability into the source and characteristics of suspended sediments being transported in freshwater systems. The potential impact of such variability on the response of commercially available turbidity sensors was systematically explored under both laboratory and field conditions.

3.2 Laboratory Testing

Using a purpose-built experimental rig, tests were done on a total of 12 instruments simultaneously, using 240-litre test solutions with fixed sediment concentrations ranging from 20 mg L^{-1} to 6 g L^{-1}. Two mechanical agitators ensured that the sediment remained suspended and well mixed throughout the tests. Particle flocculation was minimised by soaking

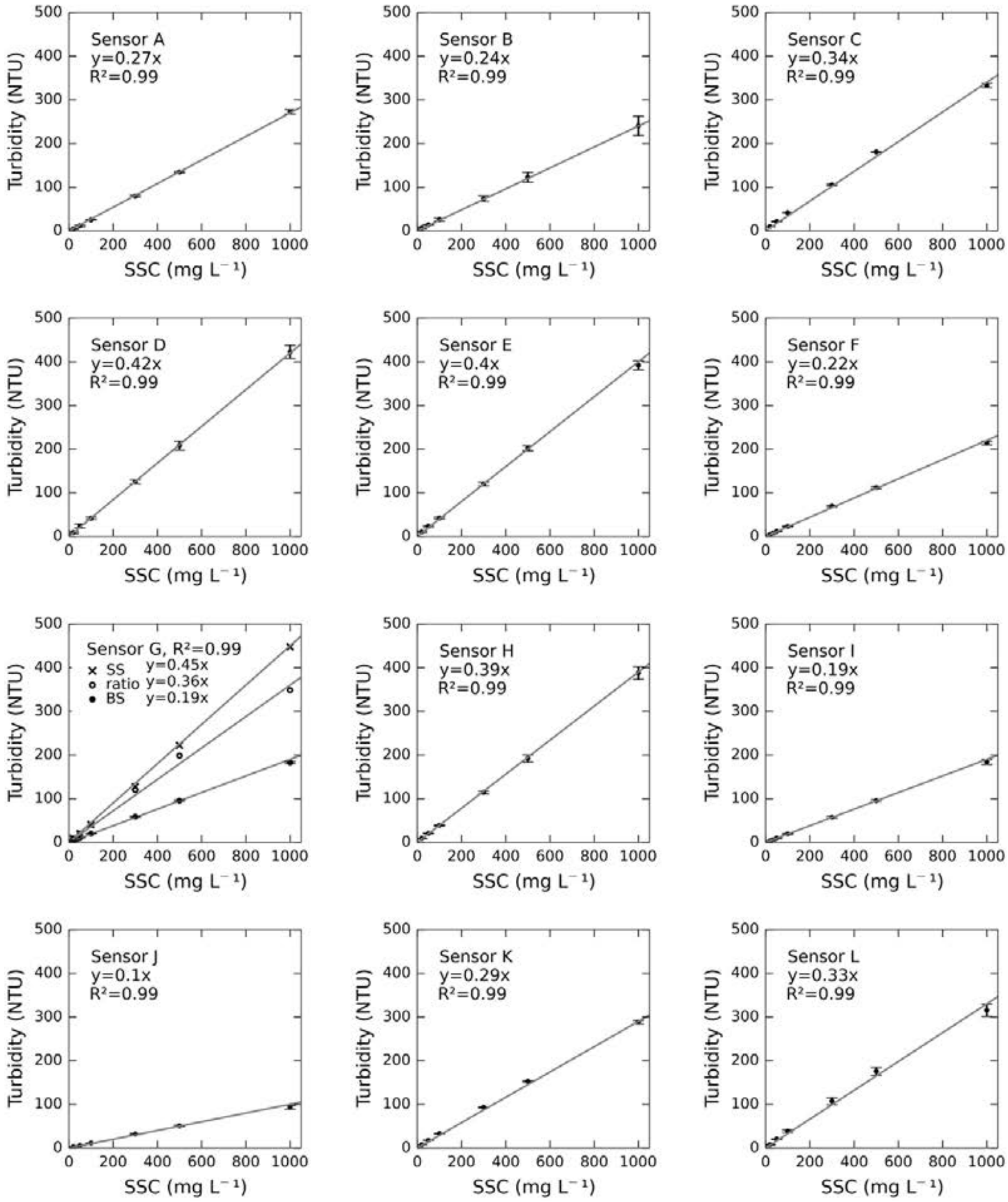

Figure 3.1. Turbidity–suspended sediment concentration relationships for the 12 tested instruments.

sediments in a 5% sodium hexametaphosphate solution for a period of 24 hours prior to testing. The resulting turbidity–suspended sediment concentrtion (T–SSC) relationships are shown in Figure 3.1. The turbidity values from all instruments were shown to correlate well with SSC. Linear relationships fitted to the data were typically characterised by r^2 coefficients ≥0.99. However, despite prior calibration of all instruments to the same Formazin standards, the T–SSC relationships showed up to a five-fold difference in turbidity responses between instruments for a given test solution. The results, shown in Figure 3.1, are associated with the same, closely graded, sediments of a given colour and low organic matter content. The observed differences in the relationships shown are therefore associated with sensor differences (Rymszewicz *et al*., 2017).

3.3 Field Testing

Four sensors were compared in the field for a measured storm event from 16 to 20 December 2014 on the River Slaney. The results are shown in Figure 3.2, together with calculated sediment loads using estimated river flows from an EPA rating (Hydrometric Station No. 12013) at the site. Increased flexibility to account for the more heterogeneous characteristics of the mobilised sediments encountered in natural systems, particularly at the high end of the flow range, was provided by using non-linear T–SSC relationships that gave high correlations, with r^2 coefficients between 0.92 and 0.98.

Figure 3.2 indicates that a strong, but complex, relationship exists between turbidity and flow. A slight hysteresis effect is observed in all the data, although the range of observed turbidity across the four instruments is markedly different. The level of cross-sensor variation is again substantial. The maximum recorded turbidity values were 140, 110, 63 and 22 NTU (nephelometric turbidity units) for Sensors D, H, F and J, respectively. Regardless of the differences in the instrument-specific T–SSC relationships, the final calculated sediment loads for the event were similar. This is reflected in sediment loads of 66, 66, 65 and 71 tonnes, calculated using data from Sensors D, H, F and J, respectively (Figure 3.2).

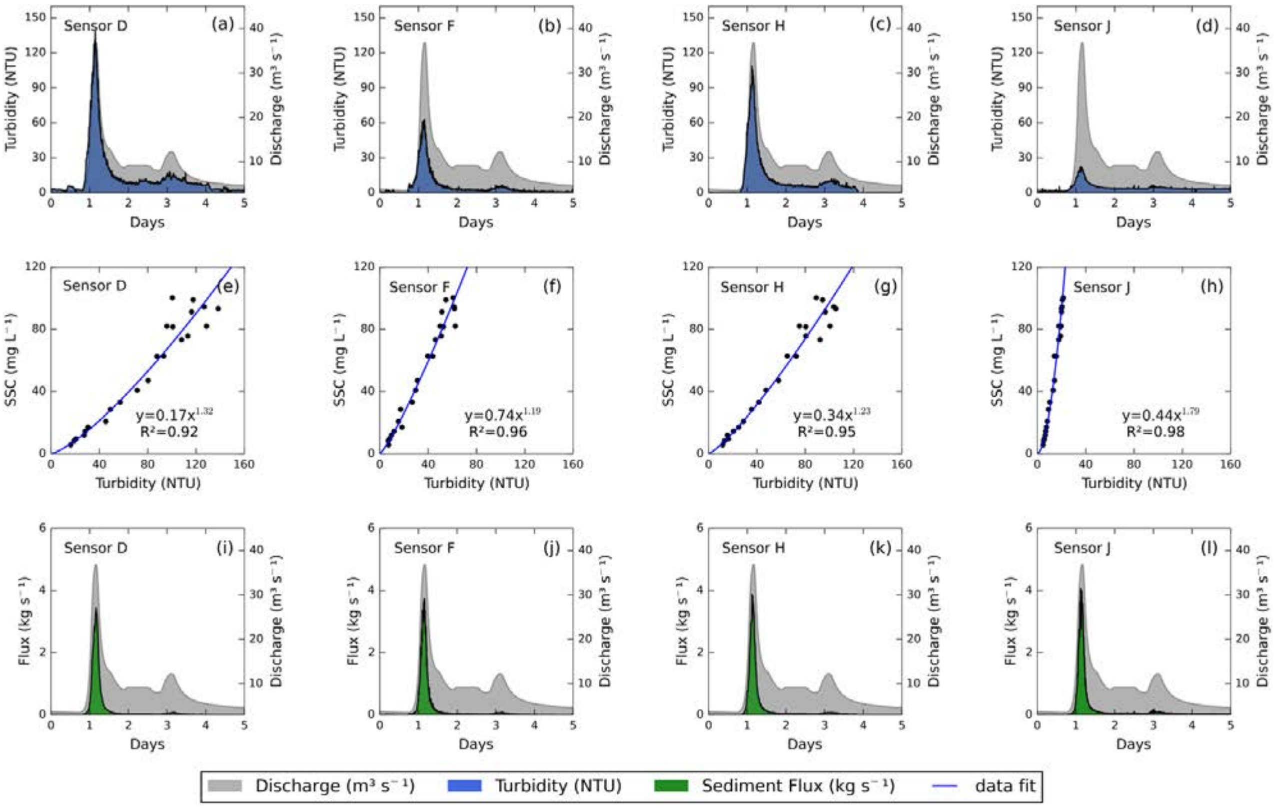

Figure 3.2. Comparison of field-tested turbidity sensors for the River Slaney at Rathvilly monitoring station for the storm of 16–20 December 2014; (a) to (d): turbidity readings and corresponding discharge data; (e) to (h): T–SSC rating relationships for tested instruments; and (i) to (l): estimated sediment flux with corresponding discharge.

3.4 Discussion

Laboratory testing of 12 commercially available optical turbidity probes indicated that turbidity measurements can vary by a factor of five, with differences increasing as the sediment concentrations of the tested solutions increased.

Notwithstanding the instrument-dependent differences, the turbidity measurements did give good quality, but instrument-specific, T–SSC rating relationships. Despite differences in these relationships, the four field-tested instruments produced reasonably similar estimates of SSCs and sediment loads, over the range of 65 to 71 tonnes for the storm event considered. Therefore, the use of turbidity as a proxy for SSC, and hence sediment load estimates, can be reliable, as long as site-specific and instrument-specific calibrations are determined and used.

While the reported cross-sensor variability is potentially problematic when turbidity is the property of interest, differences are masked when turbidity is used as a proxy or surrogate for determining sediment flux from established T–SSC relationships. This is because the unique T–SSC relationship calibrated for each instrument takes account of the differences in instrument turbidity measurements.

4 Field Data: Processing, Presentation, Analyses and Quality Control

4.1 Introduction

The determination of sediment flux and loads requires time series of SSCs and these were established for each project site using individual sensor-specific T–SSC relationships. A summary of these data is given in Table 4.1. This chapter presents these data and explains how they were utilised to meet the project aim of sediment load and flux estimation at the candidate sites.

Table 4.1. Summary of data collected at monitoring sites during the SILTFLUX project

Station	Turbidity record[a]	Turbidity instrument	No. of SSC (mg L^{-1}) samples[b]	Water level recorded at the station	Discharge estimate method
Slaney U/S (Gibstown Br.)	25/01/2014 – 23/01/2016	Ponsel[c]	135	✓	M3
Slaney D/S (Rathvilly)	24/09/2012 – 03/05/2013	Seapoint	89	✓[d]	M2
	15/05/2013 – 23/02/2016	Ponsel	263		
Glyde D/S	14/09/2014 – 30/09/2016	Ponsel	77		M1
Clodiagh U/S (Bracknagh Br.)	03/10/2014 – 22/07/2016	OBS 300+ (Sensor 1)	151		M2
	25/02/2015 – 11/06/2015	OBS 300+ (Sensor 2)	65		
Clodiagh D/S (Kilgortin Br.)	05/08/2015 – 27/06/2016	OBS 300+	136	✓	M3
	16/07/2015 – 30/09/2016	Pentair TS 1000	137		
Urrin	23/09/2014 – 03/12/2015	Ponsel	139	✓[d]	M2
	16/07/2015 – 29/07/2016	Turner Design CYCLOPS 7	56		
Camlin	16/10/2014 –04/06/2016	Ponsel	263		M1
Clare U/S	23/09/2011 – 09/05/2016	Multi-parameter sonde TROLL 9500	82		M1
Clare D/S	22/09/2014 – 25/05/2016	Multi-parameter sonde TROLL 9500	70		M1

SILTFLUX data were collected at 10-minute intervals; OPW data (Clare U/S and D/S) were collected at 15-minute intervals.

M1, Method 1: discharge data obtained from OPW/EPA hydrometric station; M2, Method 2: discharge data obtained with derived rating curve based on OPW/EPA measurements; M3, Method 3: discharge data derived with HEC-RAS model.

[a]Data record may contain gaps.

[b]Number of samples refer to SSC (mg L^{-1}) used for T–SSC relationship (at some sites there were more samples collected).

[c]Slaney U/S station was fitted with another Ponsel sensor between 07/09/2013 and 15/06/2014; however, the data record is poor quality owing to sensor malfunction.

[d]Although water level was recorded at the station, the water level record was obtained from nearby OPW/EPA hydrometric station.

D/S, downstream; U/S, upstream.

4.2 Time Series of Water Turbidity

At all study sites, measurements were undertaken using single or multiple turbidity sensors in combination with either a telemetrically controlled or water-level-activated ISCO automatic water sampler. Water samples were subsequently analysed to determine SSCs (see Chapter 2). The data obtained are illustrated for the River Slaney in Figure 4.1. Similar data were obtained for all the study sites. Statistically robust T–SSC relationships were established for all sites (illustrated here for the River Slaney in Figure 4.2), which were ultimately used to transform the time series of water turbidity at project sites to a corresponding SSC time series.

Site- and instrument-specific T–SSC calibration relationships were constructed using the paired *in situ* turbidity measurements and corresponding SSC values. The relationships, together with their descriptive statistics, are summarised in Table 4.2.

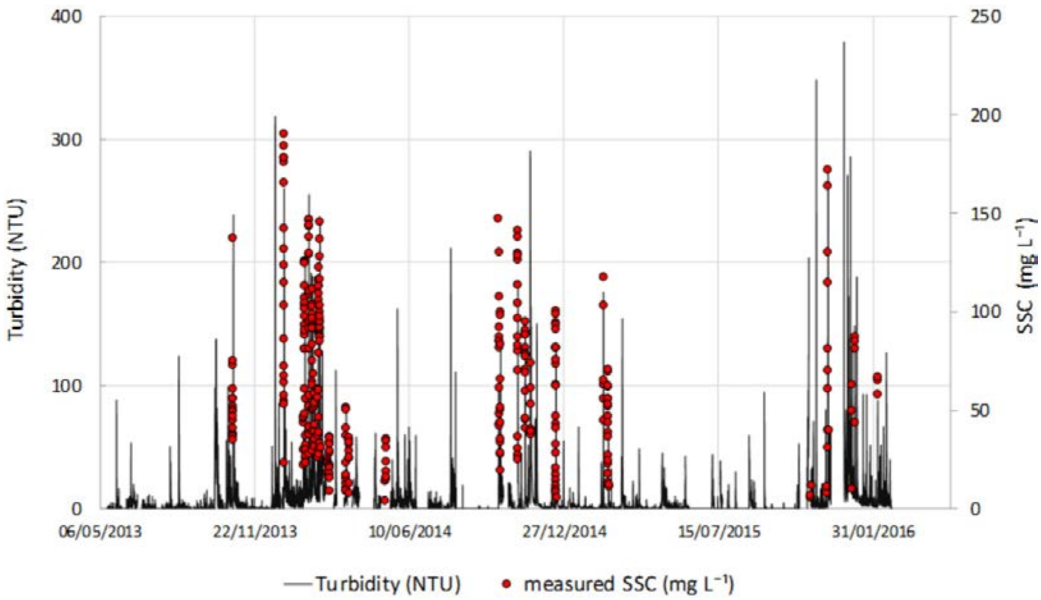

Figure 4.1. River Slaney downstream: turbidity (NTU) record (Ponsel sensor) and corresponding suspended sediment concentrations (mg L^{-1}) from water samples.

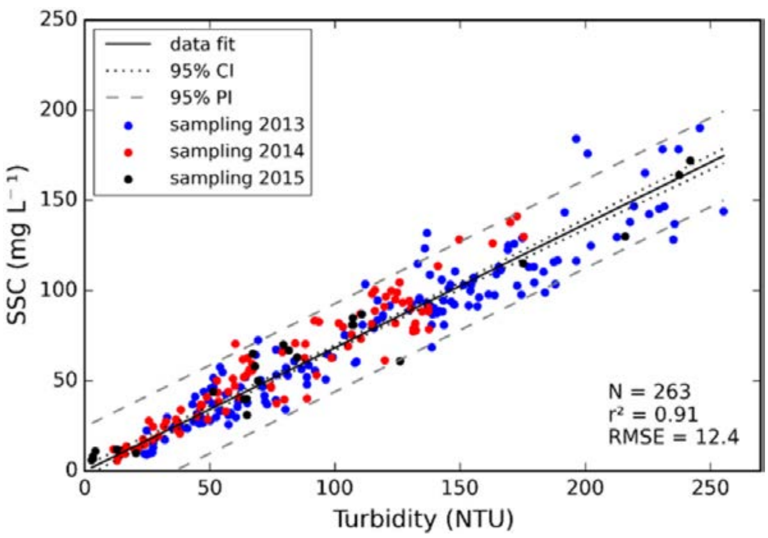

Figure 4.2. River Slaney downstream turbidity–suspended sediment concentration relationship. CI, confidence interval; PI, prediction interval.

Table 4.2. Turbidity–suspended sediment concentration equations

Site	Calibration period[a]	Sensor	Operation range	T–SSC equation	*n*	r^2	RMSE
Slaney U/S	2013 2014	Ponsel	0–1000	SSC = 0.6544 × T	135	0.89	9.3
Slaney D/S	2012	Seapoint	0–125[b]	SSC = 4.2461 × T – 5.1996	89	0.92	7.6
Slaney D/S	2013 2014 2015	Ponsel	0–1000	SSC = 0.6847 × T	263	0.91	12.4
Glyde D/S	2014 2015	Ponsel	0–1000	SSC = 1.2855 × T	77	0.59	7.2
Camlin	2014 2015	Ponsel	0–1000	SSC = 0.8366 × T – 0.7763	263	0.92	27.9
Clodiagh U/S	2014 2015	OBS 300+ (sensor 1)	0–2000	$SSC = 0.0075 \times T^2 + 1.7869 \times T$	151	0.94	23.7
Clodiagh U/S	2014	OBS 300+ (sensor 2)	0–2000	$SSC = 0.0111 \times T^2 + 1.2138 \times T$	65	0.94	9.2
Clodiagh D/S	2015	OBS 300+	0–2000	SSC = 2.0265 × T	136	0.91	20.3
Clodiagh D/S	2015	Pentair TS 1000	0–400	SSC = 0.968 × T	137	0.91	20.3
Urrin	2014 2015	Ponsel	0–1000	SSC = 0.7284 × T	139	0.87	18.8
Urrin	2015	Turner Design CYCLOPS 7	0–300 0–3000[c]	SSC = 1.5978 × T	56	0.98	19
Clare U/S	2015[d]	Troll 9500 sonde	0–2000	$SSC = 0.0208 \times T^2 + 0.5602 \times T$	82	0.66	14.7
Clare D/S	2015[d]	Troll 9500 sonde	0–2000	$SSC = 0.067 \times T^2 + 0.5688 \times T$	70	0.82	14.4

[a]Calibration period refers to the hydrological year (October to September of the following year).
[b]Possible incorrect sensor settings suggesting the use of the 0–25 NTU range – this does not affect the final SSC estimate.
[c]Two range settings were used throughout the study.
[d]Period refers to SILTFLUX SSC measurements. SSC measured by the OPW is included in the T–SSC relationship.
D/S, downstream; RMSE, root-mean-square error; U/S, upstream.

4.3 Discharge Data

Flow data at the SILTFLUX sites were obtained from high temporal resolution flow records provided by the OPW/EPA (Method 1), the use of OPW/EPA rating relationships to determine flows for water level data collected as part of the project (Method 2) or through hydraulic modelling of non-standard controls (Method 3). The specific method employed at each site is shown in Table 4.1.

4.4 Issues Encountered in Collecting Field Data

A range of problems were encountered (and overcome) during the SILTFLUX project. These included (1) fouling of the instruments as a result of wiper failure; (2) biofouling related to invertebrate infestations, particularly black fly larvae; and (3) fouling of the instruments by vegetation and debris build up. It is for these reasons that some instruments (e.g. multi-parameter sondes) are supplied complete with protective systems for sensor heads. Additional protection can be provided by taking measurements from within perforated steel or plastic pipes anchored to the channel bed and banks, but regular maintenance is essential. Purpose-built debris deflectors were designed by the SILTFLUX team and added to the site infrastructures to minimise the impact of floating debris.

4.5 Data Quality Assurance and Control

Specific data quality issues addressed included:

- averaging algorithm of turbidity instrument;
- data spikes and outliers;
- tidal influences on water level record;
- excessive "noise" in turbidity signals;
- data gaps in annual suspended sediment yield estimates.

4.6 Time Series of Suspended Sediment Concentrations

SSC time series, established using the T–SSC ratings in combination with the turbidity time series, are shown for the Slaney in Figure 4.3. SSCs derived from collected water samples over the monitoring period are also shown.

SSCs recorded during storm events typically ranged between 100 and 200 mg L^{-1} for both downstream sites in the Rivers Slaney and Clodiagh. A wider range of *c*. 100–300 mg L^{-1} was observed at the upstream Clodiagh and River Urrin stations, and values in the Camlin broadly varied between 200 and 250 mg L^{-1}. Considerably lower values of *c*. 50 mg L^{-1} were observed in the Glyde. Given that the primary land use in this catchment is tillage, these lower values were unexpected. While values reported here were typically observed during storm events, occasionally higher SCC values were recorded for all project sites with the highest SCC of 1218 mg L^{-1} observed for River Clodiagh (upstream station) (Table 4.3).

Differences in SSC between events result from sediment supply effects (e.g. sediment exhaustion) that depend on sediment availability and the proximity of mobile sediment to the stream network. Flow and rainfall regimes in the catchment, together with antecedent conditions, are also influencing factors. At some sites, for example, high SSC events occurred after prolonged and reasonably dry periods (e.g. SCCs of up to 800 mg L^{-1} were recorded for the storm events in November 2014 and August 2015 in the River Camlin) and may be attributed to the presence of readily erodible material that accumulated over these drier periods. Subsequent sediment exhaustion within the catchment may thereafter contribute to the lower SSCs observed for successive events. However, high SSC events can also succeed events of lower SSC, emphasising the complexity of the sediment delivery process. The surprisingly low SSCs in the River Glyde (typically < 50 mg L^{-1}) were observed over a 2-year monitoring period, but, following an extended wet period in the catchment, an event on 27 January 2016 produced an estimated SSC of 221 mg L^{-1}. This event was also characterised by high rainfall intensities and followed tillage operations (observed by the project team in site visits on 25 November and 17 December 2015) that had exposed areas of bare soil and increased vulnerability to erosion. Given that low SSCs

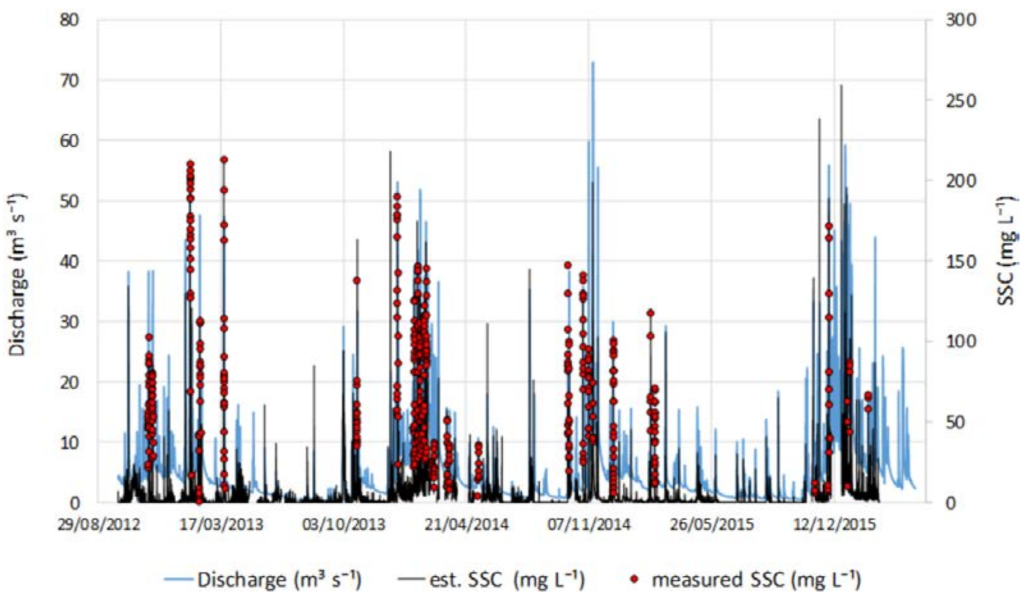

Figure 4.3. River Slaney downstream: suspended sediment concentration with corresponding discharge, showing measured suspended sediment concentrations from water samples.

were recorded during rainfall events in November and December 2015, when bare soils were exposed, the saturation of soils and the increased connectivity of overland pathways may be more dominant influences.

The data in the majority of floods across most sites appear to exhibit typical positive hysteresis, with maximum SSCs occurring in advance of peak discharge. These "sediment exhaustion" effects are commonly observed with supply-limited fine sediment transport in open channels. Evidence of lagged sediment supply, which has been reported in low-gradient systems with high sediment loads (Turner *et al.*, 2008) and urban catchments (Lawler *et al.*, 2006), has been shown to be less common during the summer months for SILTFLUX project sites.

4.7 Sediment Flux Data

A key goal of the SILTFLUX project was to estimate sediment flux ($kg\,s^{-1}$), yields ($t\,y^{-1}$) and specific yields ($t\,km^{-2}\,y^{-1}$) and the data collection and monitoring programmes at the study sites underpinned this objective. Using the time series of SSC, corresponding sediment flux time series were developed. An example of these is shown in Figure 4.4 for the River Slaney.

Estimates of SY (in units of $t\,y^{-1}$) and specific sediment yield (SSY) (in units of $t\,km^{-2}\,y^{-1}$) at the project sites are summarised in Table 4.3. Total rainfall recorded for the corresponding periods, together with mean river flows, are also included.

Estimated area-specific annual suspended sediment yields varied between 3.89 (River Glyde) and 38.23 $t\,km^{-2}\,y^{-1}$ (downstream River Clodiagh). The high SSY in the River Clodiagh is consistent with sediment patterns for steep catchments, with significant areas of both poorly drained and peaty soils. Although a higher SSY was estimated in the River Clodiagh, where the dominant land use is pasture, compared with the River Urrin, which is characterised by significant arable areas, the reported values in Table 4.3 were obtained for different monitoring periods and are therefore not directly comparable.

The occurrence of high SSCs in all studied catchments was infrequent (Figure 4.5). The European Freshwater Fish Directive (FFD) (2006/44/EC) (now repealed) threshold of 25 $mg\,L^{-1}$ was exceeded for between 1% and 9% of the year, depending on catchment.

Figure 4.5 shows concentration duration curves (CDCs) indicating the percentage of time, on average, a particular concentration was exceeded for the study sites. Figure 4.6 shows the event-based concentration duration frequency curves for events that exceeded SSC cut-offs of 25, 50 and 150 $mg\,L^{-1}$ in the selected years of observation for some SILTFLUX rivers. These show a typical progression in which the frequency and duration decreases with increasing SSC threshold. The lowest number of observed events was in the River Glyde (15 events exceeding 25 $mg\,L^{-1}$), while the highest number was observed in the downstream

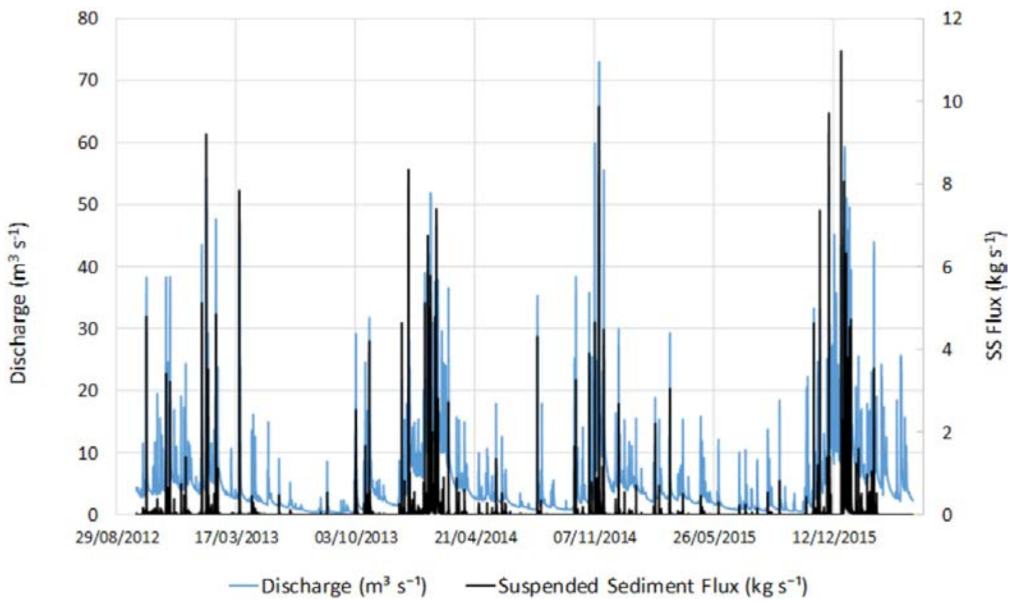

Figure 4.4. River Slaney downstream: suspended sediment flux and discharge.

Table 4.3. Summary of annual rainfall, discharge, suspended sediment concentration and sediment yield data

Station	Observation period	Rainfall (mm)	Mean annual discharge ($m^{-3}s^{-1}$)	Max SSC ($mg\,L^{-1}$) (all observation periods)	Max SSC ($mg\,L^{-1}$) (turbidity derived)	SY ($t\,y^{-1}$)	SSY ($t\,km^{-2}\,y^{-1}$)
Clodiagh U/S	1 Oct 2014 – 30 Sept 2015	1142.6	0.88	524	545	599.56	22.33
	1 June 2015 – 31 May 2016	1110.2	1.04		1219[b]	833.35	31.03
Camlin	16 Oct 2014 – 30 Sept 2015	1230.3	2.00	814.5	899	766.47	8.32
	1 June 2015 – 31 May 2016	1334.4	2.14		1035	760.71	8.26
Urrin	Oct 2014 – Sept 2015	1337.2	2.68	282 (430)[a]	612 (979)[a]	1543.3	13.4
Clodiagh D/S	1 Oct 2015 – 30 Sept 2016	1199.5	4.54	292	386	4455.02	38.23
Slaney D/S	1 Oct 2012 – 30 Sept 2013	1093.2	3.82	213	213	1706.78	8.21
	1 Oct 2013 – 30 Sept 2014	1497.5	5.18		217	2790.18	13.42
	1 Oct 2014 – 30 Sept 2015	1238.9	3.89		199 (259)[a]	1571.58	7.56
Glyde D/S	1 Oct 2014 – 30 Sept 2015	1001.8	7.06	58	70	1344.10	3.89
	1 Oct 2015 – 30 Sept 2016	863	8.67		221	2891.21	8.37
Clare U/S	1 Oct 2011 – 30 Sept 2012	1172.92	12.39			3455.8	7.35
	1 Oct 2012 – 30 Sept 2013	1011.5	10.32			2632.9	5.6
	1 Oct 2013 – 30 Sept 2014	1160.2	12.27			1947.7	4.15
	1 Oct 2014 – 30 Sept 2015	1275.9	12.29			3067.7	6.53
Clare D/S	1 Oct 2014 – 30 Sept 2015	1271.9	20.77	121	148 (195)[a]	6118.1	6.16

Sources for rainfall data: Slaney: Met Éireann St. 2415, 2115, 5414 and 3823; Glyde (2014): Met Éireann St. 3638, 2038, 3038, 2638 and 1838; Glyde (2015): SILTFLUX rainfall data (please note that records exist to August 2016 pending a further data download); Camlin: Met Éireann St. 7229; Clodiagh U/S (2014): Met Éireann St. 3222; Clodiagh U/S (2015): SILTFLUX rainfall data; Clodiagh D/S: SILTFLUX rainfall data; Urrin: Met Éireann St. 4115 and 4014.

[a]Values in brackets relate to the monitoring period October 2015 – September 2016

[b]Typical high SSC events reach approximately 500 $mg\,L^{-1}$ and only five values between 734 $mg\,L^{-1}$ and 1219 $mg\,L^{-1}$ were recorded during the 29 December storm.

D/S, downstream; U/S, upstream.

station of the River Clodiagh (117 events exceeding 25 $mg\,L^{-1}$). The longest continuous period during which sediment concentrations remained above 25 $mg\,L^{-1}$ was 79.6 hours (or 3.3 days) in the River Clodiagh. Events that exceeded 50 $mg\,L^{-1}$ lasted for about 24 hours in the Camlin, the Clodiagh downstream, the Urrin and the Slaney, and lasted for about 12 hours in the Glyde and upstream Clodiagh stations. Events exceeding 150 $mg\,L^{-1}$ were typically short, and the longest exceedance duration of this concentration was *c.* 7 hours in the River Urrin.

There are seasonal patterns in sediment transport with significant loads occurring in the wettest (usually the winter) months of the year (Figure 4.7). This is also shown to vary between years. For example, the highest sediment loads for the River Slaney were observed in January, February and November in three different years of observation (Figure 4.7f).

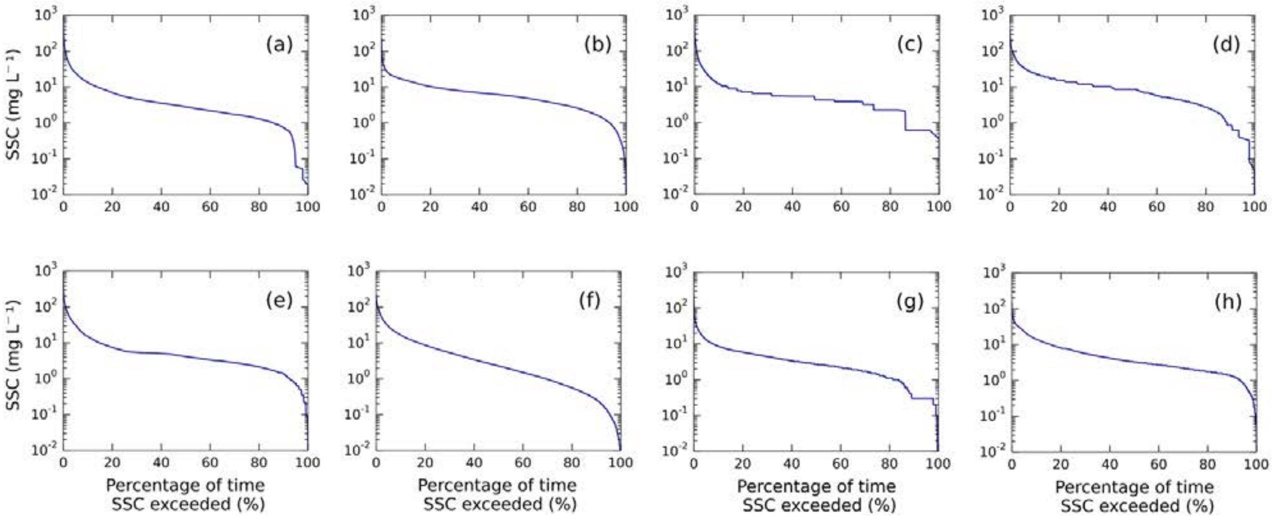

Figure 4.5. Concentration duration curves of suspended sediment concentration exceedance with time for the study sites. (a) Camlin (2014), (b) Glyde (2014–2015), (c) Clodiagh upstream (2014), (d) Clodiagh downstream (2015), (e) Urrin (2014), (f) Slaney downstream (2012–2014) and (g) Clare upstream (2011–2014), (h) Clare downstream (2014).

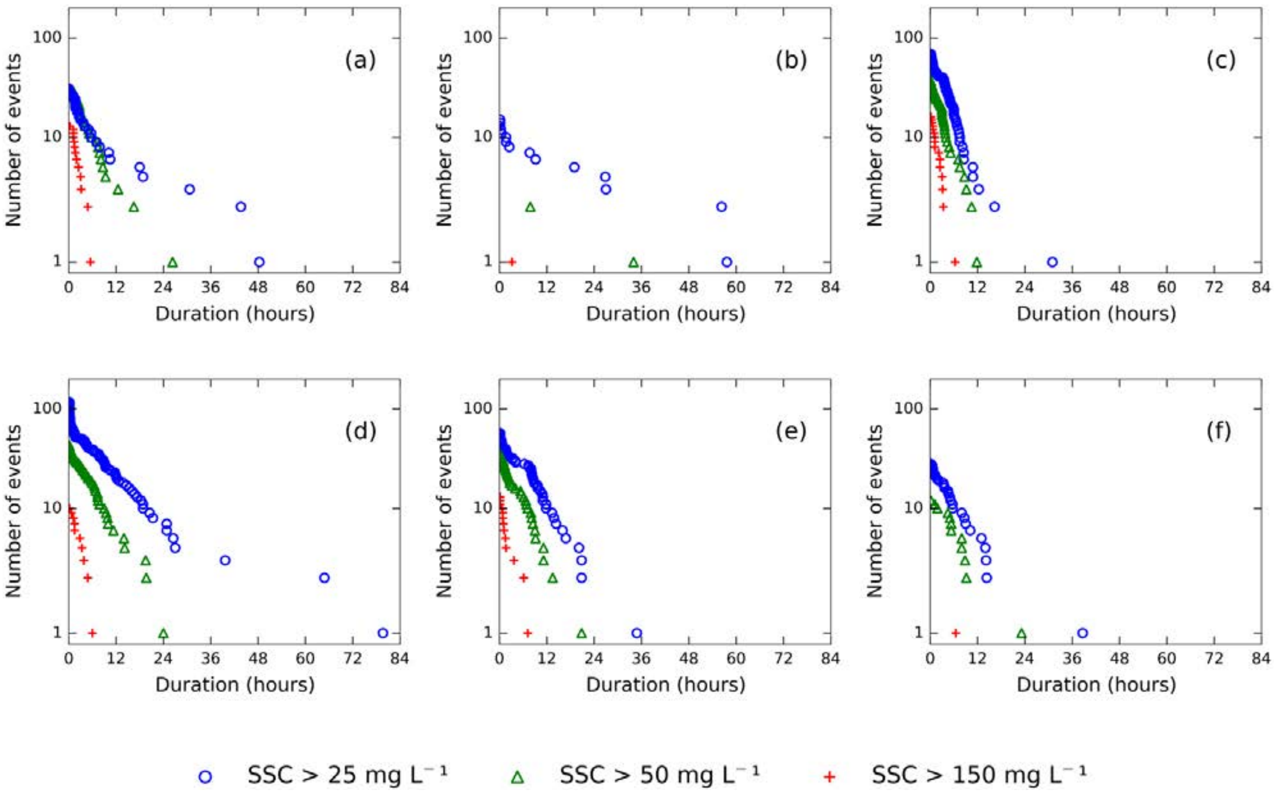

Figure 4.6. Concentration duration frequency curves for the study sites for the events that exceeded 25 mg L^{-1}, 50 mg L^{-1} and 150 mg L^{-1}. (a) Camlin (2014), (b) Glyde (2015), (c) Clodiagh upstream (2014), (d) Clodiagh downstream (2015), (e) Urrin (2014) and (f) Slaney downstream (2014).

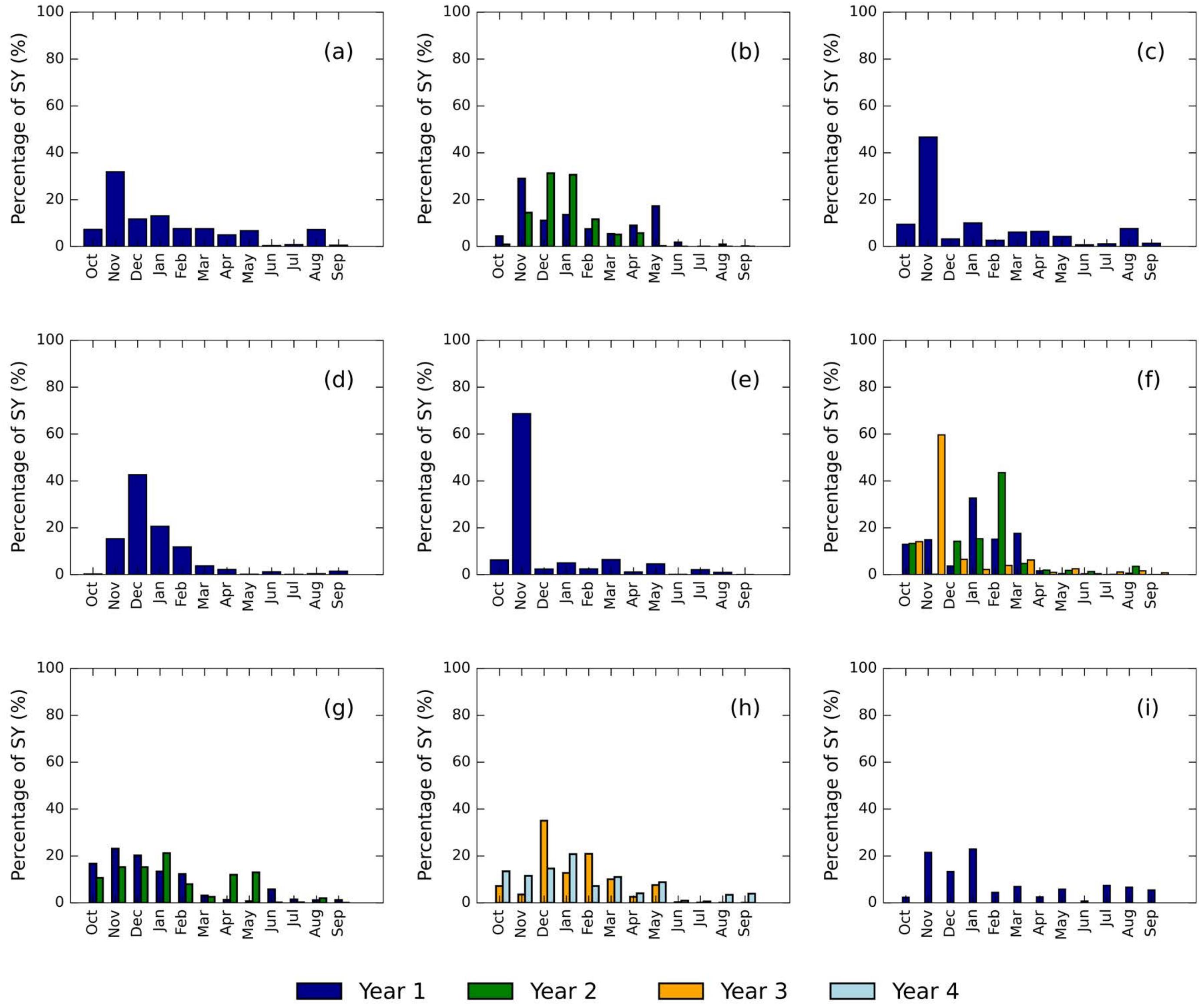

Figure 4.7. Percentage distribution of sediment load for each month of the year for the study sites. (a) Camlin, (b) Glyde, (c) Clodiagh upstream, (d) Clodiagh downstream, (e) Urrin, (f) Slaney downstream, (g) Clare upstream (2011–2012), (h) Clare upstream (2013–2014) and (i) Clare downstream.

5 Modelling Annual Suspended Sediment Yields

5.1 Introduction

Annual catchment sediment yields, expressed as total (SY in $t\,y^{-1}$) or area-specific (SSY in $t\,km^{-2}\,y^{-1}$) values are functions of erosion and sediment transport mechanisms and assist in the reporting of sediment export and in the development of sediment targets. Comprehensive assessment of sediment export from all catchments requires estimates of sediment loads at a national scale, and basing these on direct measurements is challenging and limiting because of the substantial human and financial resources required. In practice, sediment monitoring programmes are mainly limited to a small number of catchments and therefore require support tools such as sediment yield models, which can extend the scope of sediment level estimates to unmonitored catchments. Regression equations derived from catchment characteristics and weather conditions can be used for the prediction of sediment yield. The main advantage of this type of approach over spatially distributed process-based soil erosion models is a smaller data requirement and easier application. In addition, the regression analysis used in developing such models can provide some understanding of the factors influencing sediment production in the study region.

5.2 Purpose of Analysis

Typically, regression-based sediment yield models are based on average SY. Such models require long-term measurements to account for inter-annual variations between observed SSYs (Vanmaercke *et al.*, 2012). However, this does not account for important inter-annual temporal variability in sediment yields. Moreover, lack of sufficiently long records to adequately represent average SSY introduces considerable uncertainty into such models, whereas the use of averaged climatic explanatory variables (that often may not be derived for the same observation period as SSY) may mask the importance of climatic factors in predicting SSY. In this study, we explored whether or not regression models can explain both the spatial and temporal variations in contemporary suspended sediment yields in Irish catchments, based on derived catchment characteristics, and the observation-specific climatic and hydrological variables. The principal aims were:

- to compile and review all available sediment yield data for Irish catchments;
- to explore a wide range of factors potentially controlling sediment levels specific to the Irish environment;
- to develop regression model(s) that can be used to predict contemporary suspended sediment yields in ungauged Irish catchments.

5.3 Annual Load Data, Catchments and Sources

Annual suspended sediment yield data were compiled for 21 catchments covering 51 catchment-years of SY values. The locations of these catchments, classified according to the project or agency responsible for the measurements, are shown in Figure 5.1. The catchments range in size from 3.3 km^2 to 992.7 km^2 and their locations are well distributed throughout Ireland, covering different land uses, soil types, catchment gradients and rainfall regimes.

Both SSY and SY were investigated in this analysis and the SSY data are presented in Table 5.1. Each sediment yield value covers a 12-month period. However, the start date of the monitoring record differs between some of the studies reported in the literature.

5.4 Potential Predictor Variables with National Availability

Twenty-one predictor variables, currently available with national coverage, were derived for each catchment outlet from the available geographic information system (GIS) datasets. These describe different catchment characteristics potentially influencing sediment yield amounts and include factors such as catchment area, land cover, lithology, topography and hydrological descriptors (Table 5.2). To account for year-to-year variability in sediment yields, weather-related factors were included in the analysis in the form of meteorological or hydrological descriptors specific to the study period. Those predictor variables

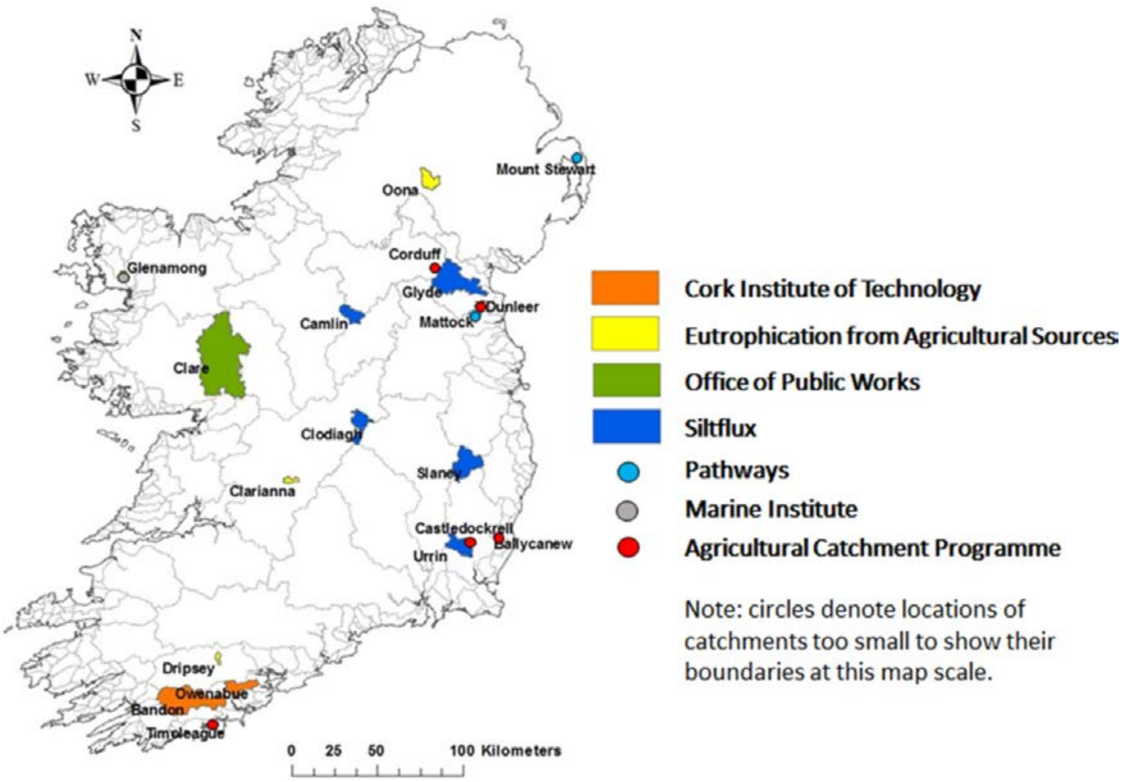

Figure 5.1. Locations of study catchments and sources of data.

Table 5.1. SSY data for Irish catchments, catchment size, study period and data source

ID	Catchment (published name/gauging station)	Area (km^2)	Study period	SSY ($t\,km^{-2}\,y^{-1}$)	Reference
1a	Corduff (Grassland C)	3.3	Oct 2010 – Sept 2011	6.07	Sherriff *et al.* (2015)
1b			Oct 2011 – Sept 2012	22.28	
1c			Oct 2012 – Sept 2013	6.52	
2	Mount Stewart (Down/Glen Burn)	7.52	Sept 2011 – Sept 2012	6.70	Thompson *et al.* (2014)
3a	Timoleague (Grassland A)	7.9	Oct 2010 – Sept 2011	3.95	Sherriff *et al.* (2015)
3b			Oct 2011 – Sept 2012	6.61	
3c			Oct 2012 – Sept 2013	14.92	
4a	Dunleer (Arable B)	9.5	Oct 2009 – Sept 2010	15.59	Sherriff *et al.* (2015)
4b			Oct 2010 – Sept 2011	15.97	
4c			Oct 2011 – Sept 2012	24.20	
4d			Oct 2012 – Sept 2013	41.81	
5a	Ballycanew (Grassland B)	11	Oct 2009 – Sept 2010	48.39	Sherriff *et al.* (2015)
5b			Oct 2010 – Sept 2011	6.65	
5c			Oct 2011 – Sept 2012	13.46	
5d			Oct 2012 – Sept 2013	30.08	
6a	Castledockrell (Arable A)	11.2	Oct 2009 – Sept 2010	17.44	Sherriff *et al.* (2015)
6b			Oct 2010 – Sept 2011	2.11	
6c			Oct 2011 – Sept 2012	5.22	
6d			Oct 2012 – Sept 2013	23.10	
7a	Dripsey	15.24	Jan 2002 – Dec 2002	16.10	Kiely *et al.* (2007)
7b			Jan 2003 – Dec 2003	9.80	

Table 5.1. Continued

ID	Catchment (published name/gauging station)	Area (km^2)	Study period	SSY ($t\,km^{-2}\,y^{-1}$)	Reference
8a	Glenamong	18.21	Jan 2001 – Dec 2001	16.00	May *et al.* (2005); Ryder *et al.* (2014) (Marine Institute raw data[a])
8b			Oct 2010 – Sept 2011	17.42	
9	Mattock (Louth)	20.96	Nov 2011 – Nov 2012	44.00	Thompson *et al.* (2014)
10	Clarianna	29.80	Jan 2002 – Dec 2002	8.50	Kiely *et al.* (2007)
11a	Clodiagh U/S (Bracknagh Br.)	26.85	Oct 2014 – Sept 2015	22.33	SILTFLUX
11b			June 2015 – May 2016	31.03	
12a	The Oona	84.5	Oct 2001 – Sept 2002	29.00	Kiely *et al.* (2007)
12b			Jan 2002 – Dec 2002	41.00	
13a	Camlin (EPA Kilnacarrow St)	92.1	Oct 2014 – Sept 2015	8.32	SILTFLUX
13b			June 2015 – May 2016	8.26	
14a	Owenabue (OPW Ballea St)	103.28	Sept 2009 – Sept 2010	25.52	Harrington and Harrington (2013)
14b			Oct 2010 – Sept 2011	14.10	Harrington (2016)
14c			Oct 2011 – Sept 2012	20.14	Robertson (2015)
14d			Oct 2012 – Sept 2013	16.76	Robertson (2015)
14e			Oct 2013 – Sept 2014	30.92	Robertson (2015)
14f			Oct 2014 – Sept 2015	24.33	Robertson (2015)
15	Urrin (U/S of OPW St John's Br.)	115.15	Oct 2014 – Sept 2015	13.4	SILTFLUX
16	Clodiagh D/S (EPA Kilgortin Br.)	116.52	Oct 2015 – Sept 2016	38.23	SILTFLUX
17a	Slaney D/S (Rathvilly WTW)	207.84	Oct 2012 – Sept 2013	8.21	SILTFLUX
17b			Oct 2013 – Sept 2014	13.42	
17c			Oct 2014 – Sept 2015	7.56	
18a	Glyde (U/S of OPW Mansfieldstown Br.)	345.28	Oct 2014 – Sept 2015	3.89	SILTFLUX
18b			Oct 2015 – Sept 2016	8.37	
19a	Bandon (OPW Curranure St)	423.74	Mar 2010 – Feb 2011	10.21	Harrington (2016)
19b			Mar 2011 – Feb 2012	9.22	
20a	Clare (OPW Ballygaddy St)	469.9	Oct 2011 – Sept 2012	7.35	OPW/SILTFLUX
20b			Oct 2012 – Sept 2013	5.6	
20c			Oct 2013 – Sept 2014	4.15	
20d			Oct 2014 – Sept 2015	6.53	
21	Clare (Cregmore)	992.71	Oct 2014 – Sept 2015	6.16	OPW/SILTFLUX

[a]The 2014 value is based on Marine Institute data following additional quality control checks that involved the comparison of nephelometer data with flow hydrograph data and the removal of spurious spikes.

U/S, upstream; WTW, water treatment works.

were calculated based on rainfall and flow conditions. Their descriptions and data sources are shown in Table 5.3.

5.4.1 *Area-specific suspended sediment yield multiple regression model*

A suite of regression models with the highest explanatory value for SSY were developed based on six, five, four and three predictor variables and are shown below (Equation 5.1, Equation 5.2, Equation 5.3 and Equation 5.4, respectively). The model details for the six-variable equation, with associated significance levels of each parameter and model fit measures, are provided in Table 5.4. Scatter plots showing the fit of all these models to the data are shown in Figure 5.2.

- Best six-variable SSY model:
  $$SSY = 0.000026 \times Runoff^{1.16} \times PD^{0.47} \times (Peat\_S + 0.1)^{-0.14} \times (Pasture + 0.1)^{0.22} \times S1.085^{0.36} \times P_{spring}^{0.5} \quad \text{(Equation 5.1)}$$

Table 5.2. Catchment characteristics obtained for each study catchment

Variable	Factor	Description	Derived from	Units
A	Scale	Originally reported catchment area size	Original source	km^2
Arable	Land cover	Percentage of the catchment that is covered by arable land	Corine 2012 GIS dataset (codes: 211, 242)	%
Pasture	Land cover	Percentage of the catchment that is covered by pasture	Corine 2012 GIS dataset (codes: 231, 243)	%
Conifer	Land cover	Percentage of the catchment that is covered by coniferous forests	Corine 2012 GIS dataset (code: 312)	%
Natural	Land cover	Percentage of the catchment that is covered by forests (mixed and broadleaf) and semi-natural areas	Corine 2012 GIS dataset (codes: 311, 313, 321, 322, 324, 333)	%
Peat_LC	Land cover	Percentage of the catchment that is covered by peatlands	Corine 2012 GIS dataset, (code: 412s)	%
WD	Soil properties	Percentage of well-drained soils within the catchment	EPA wet/dry soil GIS dataset	%
PD	Soil properties	Percentage of poorly drained soils within the catchment	EPA wet/dry soil GIS dataset	%
Alluv	Soil properties	Percentage of mineral alluvium soils in the catchment	EPA wet/dry soil GIS dataset	%
Peat_S	Soil properties	Percentage of peaty soils within the catchment	EPA wet/dry soil GIS dataset	%
S1085	Topography	Mainstream slope determined between 10 and 85 percentiles of the mainstream length	OPW FSU catchment descriptors	$m\,km^{-1}$
ALTBAR	Topography	Catchment mean altitude	OPW FSU catchment descriptors	m
TAYSLO	Topography	Taylor Schwarz mainstream slope determined by weighting 500 m channel segments by the square root of their slope	OPW FSU catchment descriptors	$m\,km^{-1}$
MSL	Drainage network	Mainstream length based on longest path distance to source	OPW FSU catchment descriptors	km
DRAIND	Drainage network	Drainage density, index relating the length of the upstream network (km) to the catchment area (km^2)	OPW FSU catchment descriptors	km^{-1}
NETLEN	Drainage network	Length of upstream hydrological network	OPW FSU catchment descriptors	km
STMFRQ	Drainage network	Stream frequency recording the number of discrete channel segments above the gauge	OPW FSU catchment descriptors	Dimensionless
BFISOIL	Drainage	Baseflow index derived from soils	OPW FSU catchment descriptors	Dimensionless
FLATWET	Climate/ lithology	Index of wetness indicating the proportion of the time for which soils can be expected to be typically wet (estimated from Met Éireann estimates of soil moisture deficit)	OPW FSU catchment descriptors	Dimensionless
SAAPE	Climate	Standard average annual potential evapotranspiration based on Met Éireann data	OPW FSU catchment descriptors	$mm\,y^{-1}$
SAAR	Climate	Standard period average annual rainfall based on Met Éireann data	OPW FSU catchment descriptors	$mm\,y^{-1}$

FSU, Flood Studies Update.

- Best five-variable SSY model:
  $SSY = 0.000122 \times Runoff^{1.36} \times PD^{0.42} \times (Peat\_S + 0.1)^{-0.13} \times (Pasture + 0.1)^{0.22} \times S1.085^{0.37}$ (Equation 5.2)
- Best four-variable SSY model:
  $SSY = 0.00036 \times Runoff^{0.88} \times PD^{0.46} \times (Peat\_S + 0.1)^{-0.21} \times P_{winter}^{0.59}$ (Equation 5.3)
- Best three-variable SSY model:
  $SSY = 0.0025 \times Runoff^{1.13} \times PD^{0.4} \times (Peat\_S + 0.1)^{-0.19}$ (Equation 5.4)

where SSY is modelled area-specific suspended sediment yield ($t\,km^{-2}\,y^{-1}$), Runoff (mm) is calculated based on observation-specific annual mean flow (Q, $m^{-3}\,s^{-1}$) and catchment area (A, km^{-2}) according to the formula:

$$Runoff = \frac{Q}{1000} \times \frac{(365 \times 24 \times 60 \times 60)\,sec}{A}$$

(Equation 5.5)

Pasture represents percentage pasture area in the catchments based on Corine 2012 GIS dataset (Corine codes: 231, 243); PD is the percentage of poorly drained soils in the catchment-derived EPA GIS dataset (WET/DRY soils); Peat_S is the percentage of peat soils found in the catchment derived from the same dataset as PD; S1085 is the mainstream slope determined between 10 and 85 percentiles of the

Table 5.3. Catchment hydrological descriptors specific for the study period derived for each catchment

Variable	Factor	Description	Derived from	Units
P	Climate	Total rainfall for the study period	Original source or Met Éireann	mm
P_{spring} P_{summer} P_{autumn} P_{winter}	Climate	Total rainfall during spring (March – May), summer (June – August), autumn (September – November) and winter (December – February)	Original source or Met Éireann	mm
R	Climate	Total rainfall erosivity factor for the study period, calculated using the Rainfall Intensity Summarisation Tool (RIST) (US Department of Agriculture) utilising Brown and Foster (1987) energy equation and Renard *et al.* (1997) rainfall erosivity conditions	Original source or Met Éireann (available rainfall data resolution varied between catchments and the calculations were based on 1-minute, 15-minute and in some cases hourly data)	$MJ\,mm\,ha^{-1}\,h^{-1}\,y^{-1}$
Q	Climate	Annual mean flow	Original data/OPW or EPA/NI Rivers Agency hydrometric data	$m^{-3}\,s^{-1}$
Runoff	Climate	Annual runoff depth based on observed annual mean discharge and catchment area	Original data/OPW or EPA hydrometric data	mm

Table 5.4. Six-variable SSY model summary (with significance levels of each parameter and model fit to log transformed data)

Coefficients	Estimate	Standard error	*t*-value	Pr(>|*t*|)
(Intercept)	–10.55454	1.77376	–5.950	3.99×10^{-7}***
Runoff	1.16328	0.23279	4.997	9.73×10^{-6}***
PD	0.46615	0.07154	6.516	5.88×10^{-8}***
Peat_S_01	–0.13889	0.03746	–3.708	0.000582***
P_{spring}	0.49644	0.23139	2.145	0.037474*
Pasture_01	0.21998	0.06543	3.362	0.001611**
*S*1085	0.35734	0.10082	3.544	0.000947***

Significance levels: * ≤0.001; ** ≤0.01; * ≤0.05.**

Residual standard error 0.4563 on 44 degrees of freedom; multiple R^2 0.6603; adjusted R^2 0.6139; *F*-statistic 14.25 on 6 and 44 degrees of freedom, *p*-value 6.094×10^{-9}.

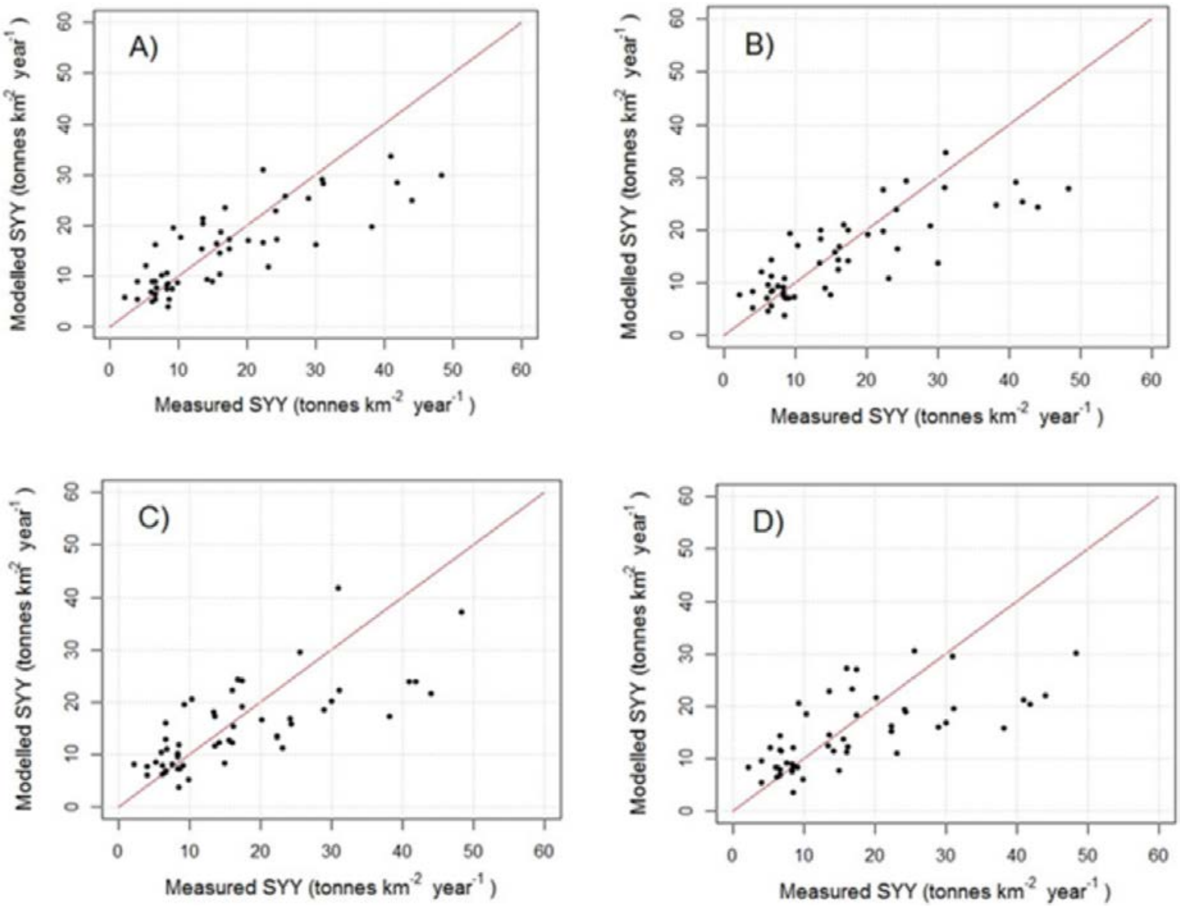

Figure 5.2. SSY model fit showing scatter plots of measured and modelled SSY. (a) Shows the six-variable model (Equation 5.1); (b) shows the five-variable model (Equation 5.2); (c) shows the four-variable model (Equation 5.3); and (d) shows the three-variable model (Equation 5.5).

mainstream length (m km^{-1}) available through Flood Studies Update point catchment descriptors, and P_{spring} is observation-specific total rainfall (mm) during the spring season (March to May).

5.4.2 *Absolute suspended sediment yield multiple regression model*

Building analogous models (Equations 5.6 to 5.9) for absolute sediment yield involved a similar approach as for SSY. The fit of the best six-variable model is shown in Table 5.5 and scatter plots show the fit of all the SY models (Figure 5.3).

- Best six-variable SY model:
  $$SY = 1.72 \times Q \times PD^{0.47} \times (Peat\_S + 0.1)^{-0.13} \times (Pasture + 0.1)^{0.21} \times S1085^{0.38} \times P_{spring}^{0.55} \quad \text{(Equation 5.6)}$$
- Best five-variable SY model:
  $$SY = 38.25 \times Q^{1.07} \times PD^{0.41} \times (Peat\_S + 0.1)^{-0.12} \times (Pasture + 0.1)^{0.2} \times S1085^{0.44} \quad \text{(Equation 5.7)}$$
- Best four-variable SY model:
  $$SY = 4.41 \times Q^{0.94} \times PD^{0.45} \times (Peat\_S + 0.1)^{-0.19} \times P_{winter}^{0.62} \quad \text{(Equation 5.8)}$$
- Best three-variable SY model:
  $$SY = 187.83 \times Q^{0.97} \times PD^{0.38} \times (Peat\_S + 0.1)^{-0.16} \quad \text{(Equation 5.9)}$$

In these equations, SY is the modelled suspended sediment yield (t y^{-1}), Q is the observation-specific annual mean flow (m^3 s^{-1}), Pasture is the percentage area of the catchment under pasture based on the Corine 2012 GIS dataset (Corine codes: 231, 243), PD is the percentage area of poorly drained soils in the catchment derived from an EPA GIS dataset

Table 5.5. Six-variable sediment yield model output (with significance levels of each parameter and model fit to log transformed data)

Coefficients	Estimate	Standard error	*t*-value	Pr(>|*t*|)
(Intercept)	0.54120	1.32847	0.407	0.685700
Q	1.01865	0.05682	17.929	$<2\times10^{-16}$***
PD	0.46926	0.06946	6.756	2.61×10^{-6}***
Peat_S_01	–0.12936	0.03652	–3.542	0.000952***
Pasture_01	0.21061	0.06014	3.502	0.001073**
*S*1085	0.37803	0.12233	3.090	0.003462**
P_{spring}	0.55188	0.22199	2.486	0.016786*

Significance levels: * ≤0.001; ** ≤0.01; * ≤0.05.**

Residual standard error: 0.4448 on 44 degrees of freedom; multiple R^2 0.9361; adjusted R^2 0.9273; *F*-statistic 107.3 on 6 and 44 degrees of freedom; *p*-value < 2.2e–16.

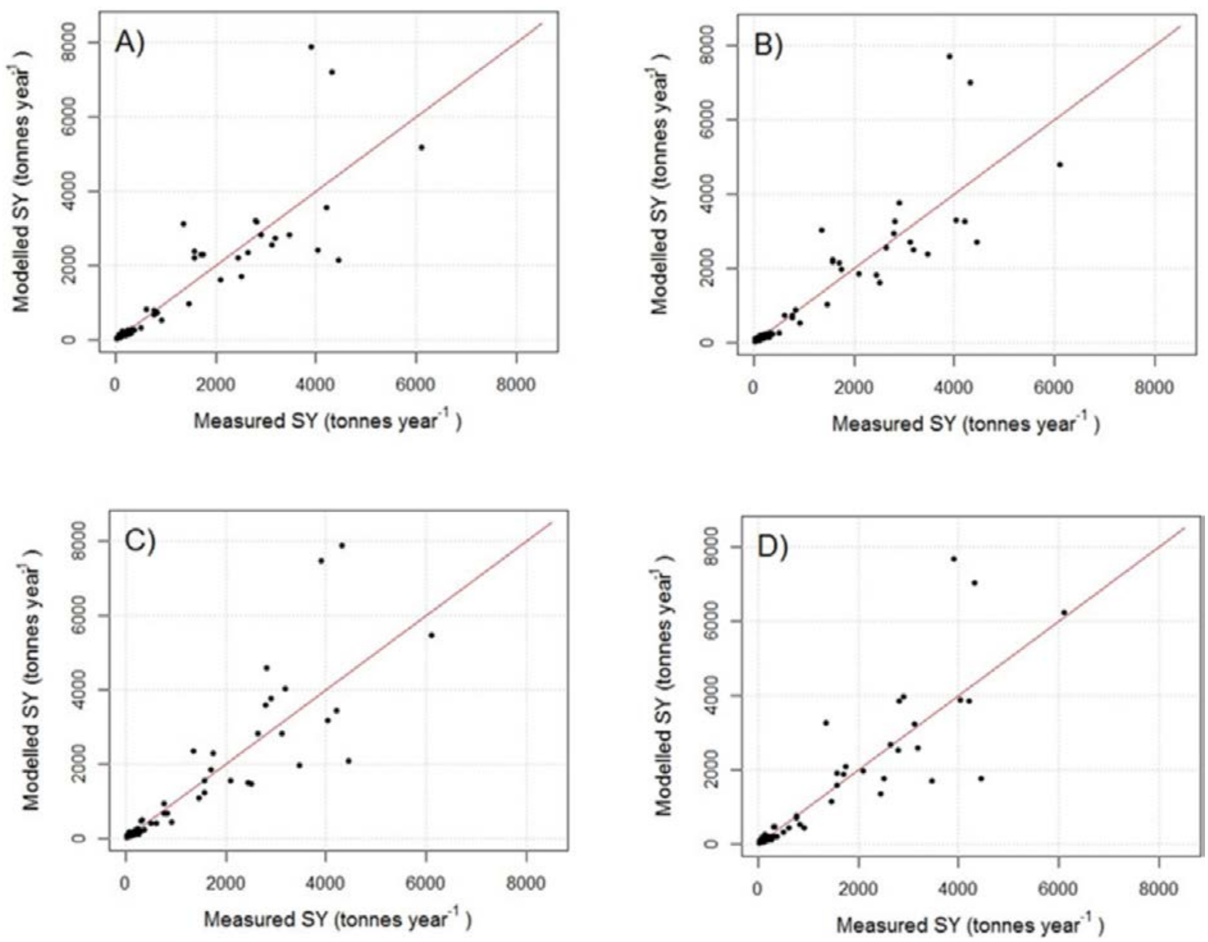

Figure 5.3. Sediment yield model fit: scatter plots of measured and modelled sediment yield. (a) The six-variable model (Equation 5.6); (b) the five-variable model (Equation 5.7); (c) the four-variable model (Equation 5.8) and (d) the three-variable model (Equation 5.9).

(wet/dry soils), Peat_S is the percentage area of peat soils found in the catchment derived from the same dataset as PD, *S*1085 is the mainstream slope determined between the 10th and 85th percentile points of the mainstream channel length (m km^{-1}) available as FSU point catchment descriptors, P_{winter} is observation-specific total rainfall (mm) during the winter season (December to February) and P_{spring}

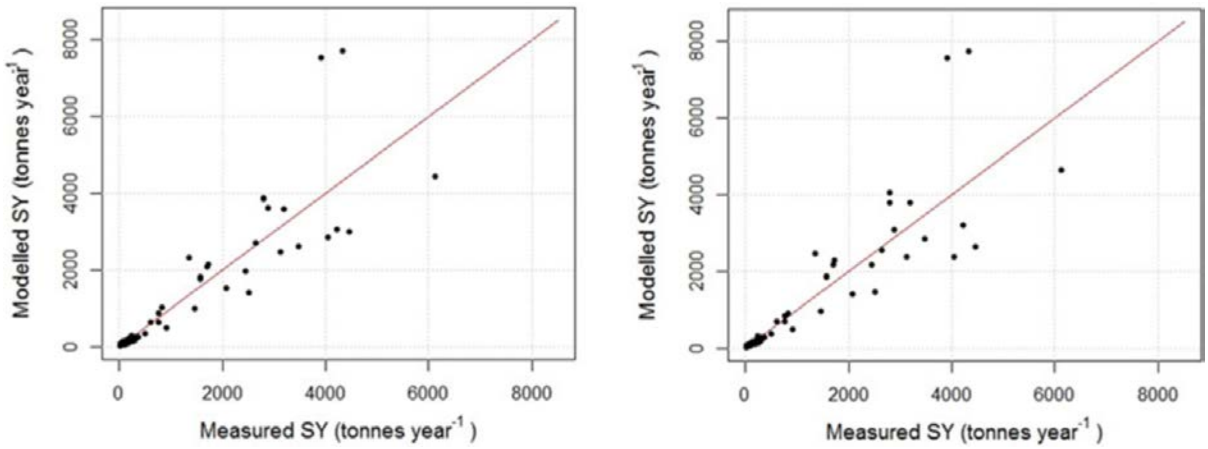

Figure 5.4. Six-variable model fit: scatter plots between measured and modelled sediment yield. Left: model with P_{winter} variable; right: model with the combination of P_{winter} and P_{spring} ($P_{winter}+P_{spring}$) variables.

is observation-specific total rainfall (mm) during the spring season (March to May).

The best fit six-variable model for SY is based on the variables *Q*, PD, Peat_S, Pasture, *S*1085 and P_{spring}. The adjusted R^2 of the log transformed data for this model is 0.927. A similar good fit (adjusted R^2 of 0.926) was also obtained when P_{winter} was substituted for P_{spring}. Variations of the model were tested, e.g. by using the sum of the above variables ($P_{winter}+P_{spring}$), which marginally improved the model, giving an adjusted R^2 of 0.9311 (based on the log transformed data). Scatter plots of the additional six-variable models (based on P_{winter} or the sum of P_{winter} and P_{spring}) are shown in Figure 5.4.

Unexpectedly, the best regression equations for SY prediction do not include catchment area (*A*), which would be expected to be an important scaling factor in the prediction of sediment yield. In the model building process, however, catchment area was eliminated in the stepwise regression; this was preferred instead of the variable *Q*, which is strongly correlated (0.98) with area. Forcing these models to retain area as a predictor also gave good model fits but with slightly lower adjusted R^2 values between 0.84 and 0.89 (based on log transformed data). Therefore, using annual mean flows instead of area (as an indicator of scale) improves model fit for all established SY models. Very importantly, having *Q* in the equations instead of area allows additional predictive strength in predicting annual loads for specific years, as *Q* will vary from year to year in the same catchment, responding to weather and land use, while area (if included) would remain constant. Therefore, accounting for inter-annual variations in the catchment gives a better model fit.

5.4.3 Validation of the sediment yield model

Independent model validation was undertaken for all models and is illustrated here for the three-variable SY model. The full dataset (51 SY data values) was split into two datasets, A ($n=26$) and B ($n=25$), based on the odd and even ranks assigned when sorted according to increasing catchment size and latest observation year. Coefficients fitted to the three-variable SY model (Equation 5.9), i.e. using variables *Q*, PD and Peat_S, were first fitted to the data in subset A (calibration) resulting in a new model. This model was then used to estimate SY for the data in subset B (validation). Measured versus modelled SY values were plotted for both calibration dataset A and validation dataset B (Figure 5.5).

This procedure was repeated by swapping the two datasets. This time calibration was done with the data in subset B and the resulting model was used to estimate SY for the data in subset A, with similar results (Figure 5.6).

Both validation tests show good agreement between calibration and validation datasets as indicated by calculated measures of fit (Table 5.6). Both R^2 and adjusted R^2 values are not significantly different between calibration and validation. Mean bias and mean absolute error decreases or increases depending on the dataset used. This indicates that the established model is relatively stable.

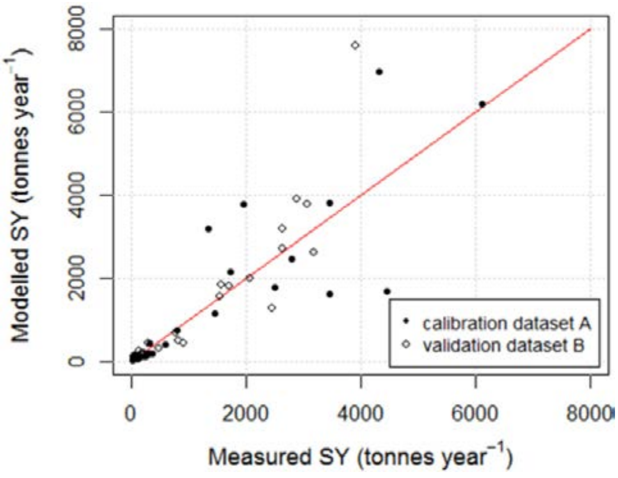

Figure 5.5. Calibration and validation scatter plots for sediment yield.

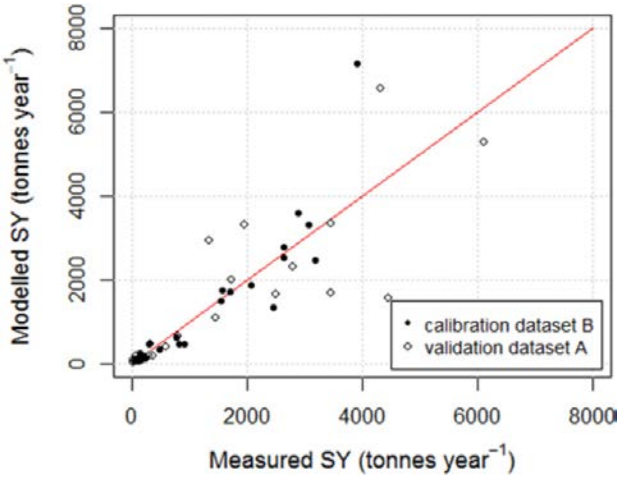

Figure 5.6. Calibration and validation of the sediment yield model with datasets swapped.

Table 5.6. Measure of model fit between calibration and validation datasets

Variable	Calibration: dataset A	Validation: dataset B	Calibration: dataset B	Validation: dataset A
n	26	25	25	26
R^2	0.65	0.51	0.63	0.69
adjusted R^2	0.60	0.44	0.58	0.65
Mean bias	28.43	157.44	61.24	–92.82
Mean absolute error	551.86	397.92	337.77	541.17

5.5 Extension of Models with Additional Predictors

The previous section described an approach to developing predictive equations to estimate annual sediment loads using predictors that were readily available at a national scale. The approach was illustrated with the datasets available to the project. As more data become available, particularly for catchments representing a wider range of land use categories, the resulting equations are likely to change somewhat, both in terms of the numerical value of their coefficients and even in the choice of predictor variables. To illustrate this, we have fitted a model with a predictor variable not used in the original analysis because it is not currently available with national coverage. This is commonly known as the "Q5" value, i.e. the discharge that is exceeded 5% of the time on average in a given period. This quantity is not mapped on a national basis (so was not used in the original analysis) but was subsequently calculated from discharge data (or estimated from the EPA's HydroTool program) for each catchment year of data. Adding "Q5" to the list of potential predictors gives a different six-variable equation (Equation 5.10).

$$SY = 20.7 \times PD^{0.59} \times Q5^{1.08} \times (Peat\_S + 0.1)^{-0.24} \times (Arable + 0.1)^{0.13} \times S1085^{0.31} \times DRAIND^{-1.5} \quad \text{(Equation 5.10)}$$

Its fitting statistics are shown in Table 5.7. Note that, while its adjusted R^2 value (0.8774) for the log transformed data is not quite as good as that for Equation 5.6 (0.927) given above, it provides a better fit for the larger catchments, with higher annual sediment loads values (Figure 5.7). This is confirmed by its substantially better adjusted R^2 value of 0.89 for the untransformed data, compared with 0.62 for the original six-variable Equation 5.6. Note the data for the Corduff catchment are not used in fitting this equation. Corduff is the smallest of all the catchments considered (3.3 km^2) and its river network was too short to derive *Q*5 values from HydroTool.

Applying the split-sample validation technique to this equation gives adjusted R^2 values of 0.93 for calibration with dataset A and 0.81 for validation with dataset B (Table 5.8 and Figure 5.8). When dataset B is used for calibration and dataset A for validation, the corresponding values are 0.83 and 0.89, respectively (Table 5.8 and Figure 5.9), which are again

Table 5.7. Alternative six-variable sediment yield model output with associated significance levels of each parameter and model fit to log transformed data

Coefficients	Estimate	Standard error	*t*-value	Pr(>|*t*|)
(Intercept)	3.03	0.49	6.2	2.31×10^{-7}***
PD	0.59	0.11	5.5	2.02×10^{-6}***
Peat_S_01	–0.24	0.06	–4.1	0.000207***
*S*1085	0.31	0.14	2.1	0.039028*
*Q*5	1.08	0.09	12.6	9.94×10^{-16}***
DRAIND	–1.51	0.55	–2.7	0.009689**
Arable_01	–0.130	0.05	–2.4	0.021943*

Significance levels: * ≤0.001; ** ≤0.01; * ≤0.05.**

Residual standard error: 0.5395 on 41 degrees of freedom; multiple R^2 0.8931; adjusted R^2 0.8774; *F*-statistic 57.08 on 6 and 41 degrees of freedom; *p*-value $< 2.2 \times 10^{-16}$.

Table 5.8. Measures of alternative sediment yield model fit between calibration and validation datasets

Variable	Calibration: dataset A	Validation: dataset B	Calibration: dataset B	Validation: dataset A
n	24	24	24	24
R^2	0.95	0.86	0.87	0.92
adjusted R^2	0.93	0.81	0.83	0.89
Mean bias (ty^{-1})	–14.68	71.60	–56.82	–47.47
Mean absolute error (ty^{-1})	218.88	458.83	391.04	252.46

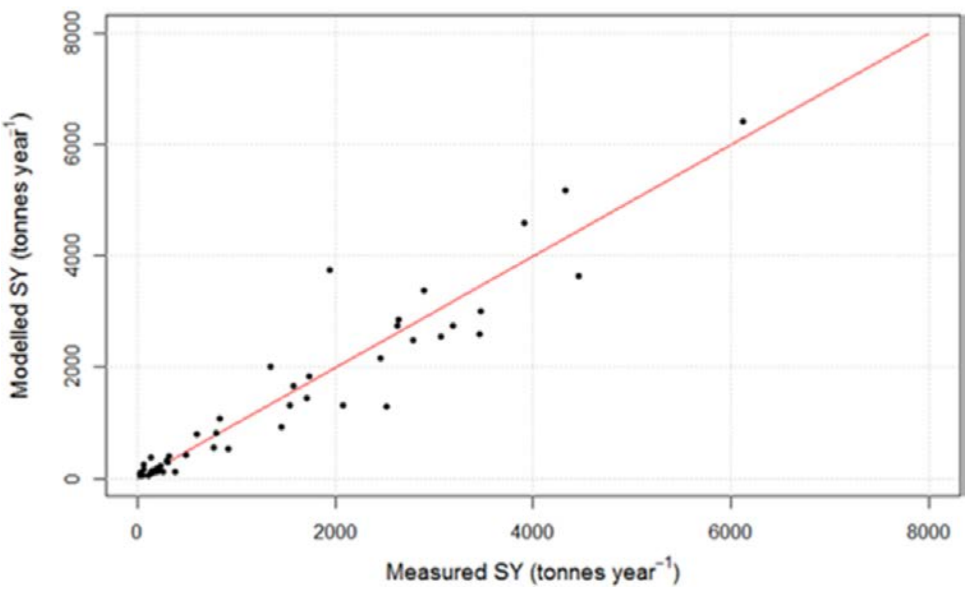

Figure 5.7. Fitting of alternative six-variable equation with *Q*5 as a predictor.

substantially better than the corresponding values for Equation 5.9 shown in Table 5.6.

5.6 Discussion

A database of annual values of suspended sediment yield was constructed for Irish catchments showing low levels of SSY (between 2.11 and 48.39 t km^{-2} y^{-1}), which is comparable to the lower range of SSY values found in central, western and northern Europe. Soil properties strongly influence sediment yields. Other strongly influential factors include slope and amount of pasture. Sediment yield can be related to total annual rainfall but seasonal rainfall totals for winter and spring are more powerful predictors of suspended sediment loads. Other controlling variables include mean annual flow and runoff calculated for the specific year of observation.

An interesting, non-linear relation between catchment size and SSY was found (Figure 5.10). SSY initially increases with increase in catchment size, possibly due to increased contributions from different erosional processes, until the catchment area reaches a threshold of approximately 80–100 km^2, above which SSY decreases due to increased storage opportunities on the lower catchment slopes of the larger catchments. Smaller catchments are also more sensitive to climatic variations as indicated by higher inter-annual variations in SSY.

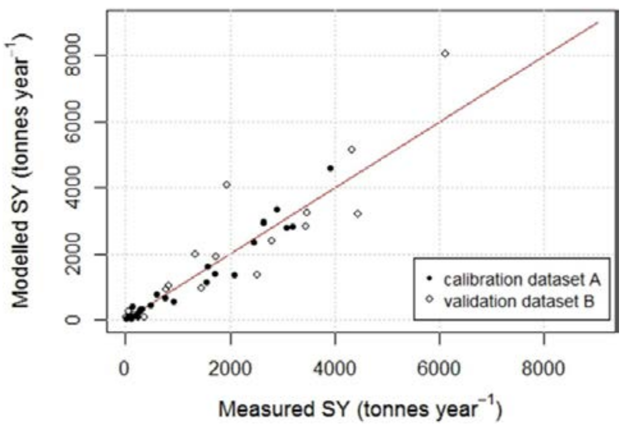

Figure 5.8. Scatter plots for alternative sediment yield model for both calibration (dataset A) and validation (dataset B) data.

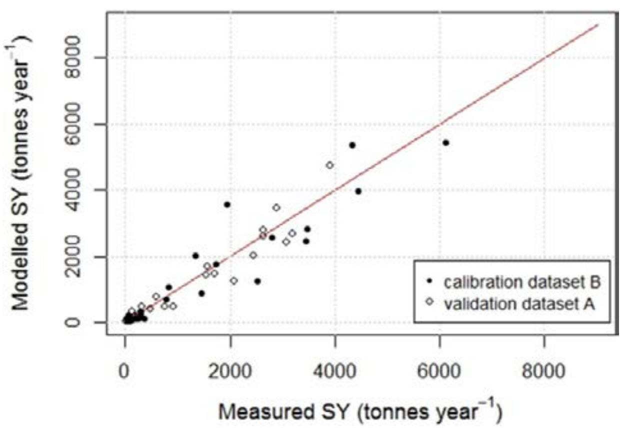

Figure 5.9. Calibration (dataset B) and validation (dataset A) of alternative sediment yield model with datasets reversed.

Regression models for area-specific sediment yield (SSY) and absolute sediment yield (SY) fit better for SY than for SSY. Non-linearity of the relationship between SSY and catchment area (*A*) may be the reason for unsuccessful SSY model development.

The model for SY is based on a combination of observation-specific annual mean flow (*Q*), percentage poorly drained soils (PD), percentage peat soils (Peat_S), percentage pasture land use (Pasture), *S*1085 slope and total rainfall during either the spring or the winter season (P_{winter}, P_{spring}). Split-sample tests indicate that the model is robust.

Use of appropriate additional predictor variables, which are not necessarily available with national coverage, can improve the fit of the estimated equations even further.

Observation-specific climatic and hydrological variables can be successfully incorporated into regression-based models to predict inter-annual variation of contemporary absolute suspended sediment yields and can improve prediction performance. However, a limitation is that the equation assumes that the effect of spatial and of temporal variation of the variables on sediment yield can be combined in the same equation. Although this is suggested by the empirical analysis, the physical basis of this assumption requires testing. In addition, the database used here to derive the equations has many more catchments than it has years for the same catchment. A longer-term study would provide the additional data needed to address this imbalance.

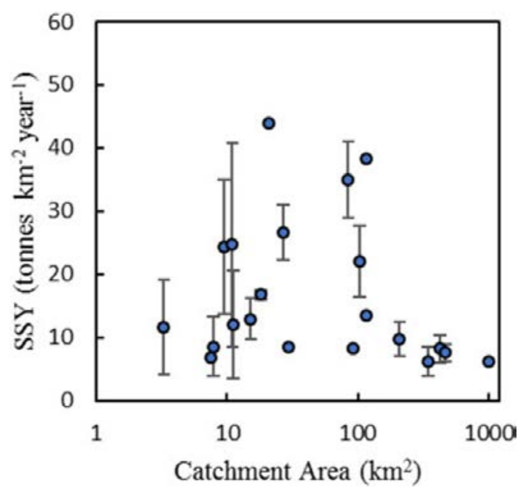

Figure 5.10. Relationship between catchment area and annual specific sediment yield.

6 Biological Investigations

Five investigations relating to the biological impacts of elevated sediment were undertaken. The focus was largely on deposited sediment, as it is considered to have the highest potential for impact on aquatic biota, and the first task was to evaluate the various methods of measuring deposited sediment. Next, sediment impacts on macroinvertebrate communities were considered at both localised and catchment scales. The localised sources were points of cattle access to streams for drinking water, which is a widespread and potentially significant contributor to pressures on water quality in agricultural catchments in Ireland. These data and additional information from mesocosm studies were used to test the relationships between various macroinvertebrate metrics and sediment metrics. The catchment-scale investigations examined the effects of two land uses (tillage and pasture) and associated levels of deposited and suspended sediment on macroinvertebrate communities. Finally, the responses of a number of selected macroinvertebrate taxa to burial by sediment were investigated in an attempt to explain some of the responses in the abovementioned investigations.

6.1 Evaluation of Methods to Estimate Levels of Deposited Sediment

Known amounts of sediment were added to mesocosms containing substrates representing streambed conditions to achieve sediment covers of between 0 and 50%. Three categories of deposited sediment were used: silty-sand (< 150 µm), top soil from a stream bank (< 63 µm) and peat (< 300 µm). The four evaluation methods tested were re-suspended sediment turbidity; re-suspended sediment concentration; Turner–Hillis deposited sediment sampler (DSS); and visual cover estimation.

The Turner–Hillis DSS method produced the weakest relationships and was unable to resolve differences between any of the levels of sediment added. Measurements of turbidity and the re-suspendable sediment method showed a statistically strong relationship with the levels of sediment added. However, both methods had difficulty resolving small differences in amounts of sediment and their performance differed with sediment type. Site-specific factors may influence turbidity readings and thus make inter-site comparisons more challenging. There was a strong relationship between visual estimates of percentage surface cover and added sediment levels, and this method distinguished between all levels of sediment, with the exception of 50 g and 100 g (Conroy *et al.*, 2016b).

6.2 Impact of a Localised Sources (Cattle Access Points) of Sediment on Ecological Water Quality in Streams

Four rivers (Barrow, Clodiagh, Douglas and Glenlahan) classified as having "high/good" water quality status (Q4–5, Q4) and four rivers (Boycetown, D'arcy, Dee and Erkina) at "moderate" water quality status (Q3–4, Q3) were selected (Figure 6.1) and comparable study sites upstream and downstream of cattle access points were chosen in each.

Macroinvertebrate samples were collected upstream and downstream of each cattle access point in spring and autumn 2013 using a Surber sampler at each of six mid-channel locations and six margin sampling points. An additional upstream site (U/S+) was chosen on the Clodiagh, Erkina and Glenlahan Rivers, and at the D'arcy crossroad stream in autumn (September/October) 2013 to account for any natural variability between sampling locations. Visual estimates of percentage area covered by deposited fine sediment (< 2 mm) (regardless of depth of sediment) were made within the Surber sampler frame and turbidity and concentrations of re-suspendable sediment from the stream bed were measured. Benthic sediment samples were taken in low-flow conditions upstream and downstream of each cattle access point at all sites and analysed for total Kjeldahl nitrogen, total phosphorus (TP) and organic matter (%).

For the most part, macroinvertebrates in mid-channel habitats were more sensitive than those at the margins to the added pressure of cattle access points (Conroy *et al.*, 2016c). There were some seasonal differences

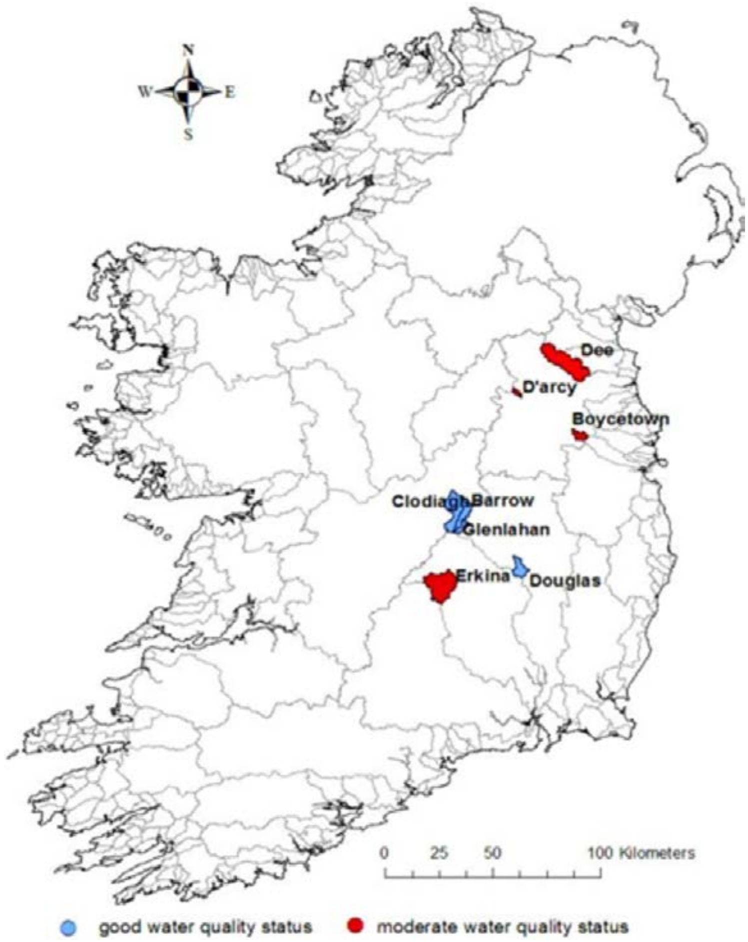

Figure 6.1. Location of the eight study rivers catchments, colour coded for water quality upstream of the cattle access points.

and site-specific impacts across both high/good and moderate status rivers. Overall, downstream changes in macroinvertebrates in rivers of high/good water quality status (Barrow, Clodiagh, Douglas and Glenlahan) were observed more frequently in autumn than in spring. Significant changes in at least two metrics (total richness and EPT[2] richness together with taxon, E, or Ephemeroptera, and EPT abundance) were observed in both seasons for all four high/good status rivers.

There was some support for the hypothesis that moderate status rivers would be less susceptible to impacts from cattle access points compared with high/good status rivers, with significant downstream impacts detected in only two of the four moderate status rivers, the Boycetown and Dee. The other two rivers showed either no response (D'arcy) or a change in one metric at most (Erkina). In spring, there were downstream increases in oligochaete, a burrowing taxon, and the collector/gatherer, detritus-feeding *Elmis aenea,* while in the autumn there was a downstream increases in *E. aenea* and the shredder *Gammarus duebeni* (+13%), indicating that detritus and burrowing taxa were favoured over other taxa at this site. The overwintering of cattle on a steeply sloping, heavily poached field bordering the Boycetown river may be the reason for the observed downstream increases in *G. duebeni* (+18.6%) and oligochaetes (+14.8%).

In rivers that already have moderate water status at the upstream sampling location, due in part to the presence of excessive nutrient levels, it may be more challenging to detect any further changes in community structure and composition due to cattle access or to disentangle cattle access effects from upstream stressors. The presence of these two

2 EPT refers to Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies).

stressors may be a contributing factor in this study and may explain the variation in the seasonal and site-specific responses found.

6.3 Relationship Between Biotic and Sediment Metrics

The biotic response to deposited sediment was investigated using a combination of mesocosm laboratory channels and a field study (Conroy *et al.*, 2016a). The mesocosms demonstrated responses to sediment addition through analysis of macroinvertebrate drift and of the taxa remaining in the channels at the end of the experiment.

In the mesocosm channels, a predetermined weight of fine sediment (< 1 mm) was evenly spread over parts of the gravel substrate to achieve areas of sediment surface covers of 100%, 90%, 70%, 50%, 30%, 10% and 5% of the total area. A control mesocosm did not receive any sediment. Macroinvertebrates were exposed to one of these treatments in a randomised block design, with four replicates per treatment. Drifting macroinvertebrates were collected at midnight and 6 a.m. and combined to give daily drift on each of 6 consecutive days. Macroinvertebrates remaining in the channels on day 7 were retrieved. In the laboratory, they were identified to the lowest practicable taxonomic level (species, where possible).

The analysis suggests that percentage sediment surface cover and EPT abundance metrics may be useful for assessing the negative effect of sediment on macroinvertebrates. There was a 30 to 40% increase in drift rates in channels with higher sediment amounts (50 to 100% sediment surface cover) compared with the control. The numbers of drifting Heptageniidae were generally higher in channels with higher sediment cover (> 30% coverage) (Figure 6.2).

The strongest correlations with sediment cover in the mesocosm study were with metrics derived from the abundance of sensitive taxa. For instance, percentage EPT abundance, percentage Ephemeroptera abundance and, to a lesser degree, Ephemeroptera abundance decreased with increasing sediment cover.

Since many EPT metrics are also used to indicate eutrophication and general degradation of water quality, there is a need for further research to refine sediment-specific metrics. Further research is also needed to investigate the possibility of a sediment cover threshold.

6.4 Land Use Effects on Benthic Macroinvertebrate Communities

It was hypothesised that downstream increases in percentage pasture and percentage tillage land cover would result in changes in abundance and richness metrics, and changes in community structure, with losses of sensitive taxa and increases in pollution-tolerant taxa mainly influenced by increased sediment and nutrient inputs. This was investigated in detail in four of the SILTFLUX catchments situated in the north-east, the midlands and south-east of Ireland. These catchments represent the two dominant land uses, pasture (Slaney and Clodiagh Rivers) and arable/tillage (Glyde and Urrin Rivers). Five sites were included in the Slaney and Clodiagh Rivers catchments, representing a gradient of pasture land use from 22% to 57%. Two upstream and two downstream sites were chosen in the Glyde catchment. Two sites were located on the River Urrin. The catchment of the downstream Urrin site had a relatively high percentage of arable/tillage interspersed with some pasture.

Macroinvertebrates were collected at both patch scale (in autumn) and reach scale. Patch-scale visual estimates of substrate composition and percentage cover of deposited fine sediment (< 2 mm) were made within a Surber sampler frame. Reach-scale sampling was undertaken in both spring (May) and autumn (September/October). This comprised three replicate, 1-minute multi-habitat kick samples collected using a standard 0.9 mm mesh Freshwater Biological Association (FBA) pond net.

A standardised taxon list was prepared following taxonomic adjustment and a range of univariate metrics were estimated. Differences in total taxon richness and abundance were tested using two-factor analysis of variance/permutational multivariate analysis of variance (ANOVA/PERMANOVA) where river was a random factor and land use was fixed, with two levels (low/high). A two-factor design was also applied to test for differences in community structure. Similarity percentage (SIMPER) analysis was used to investigate which taxa were responsible for any detected differences in community structure between

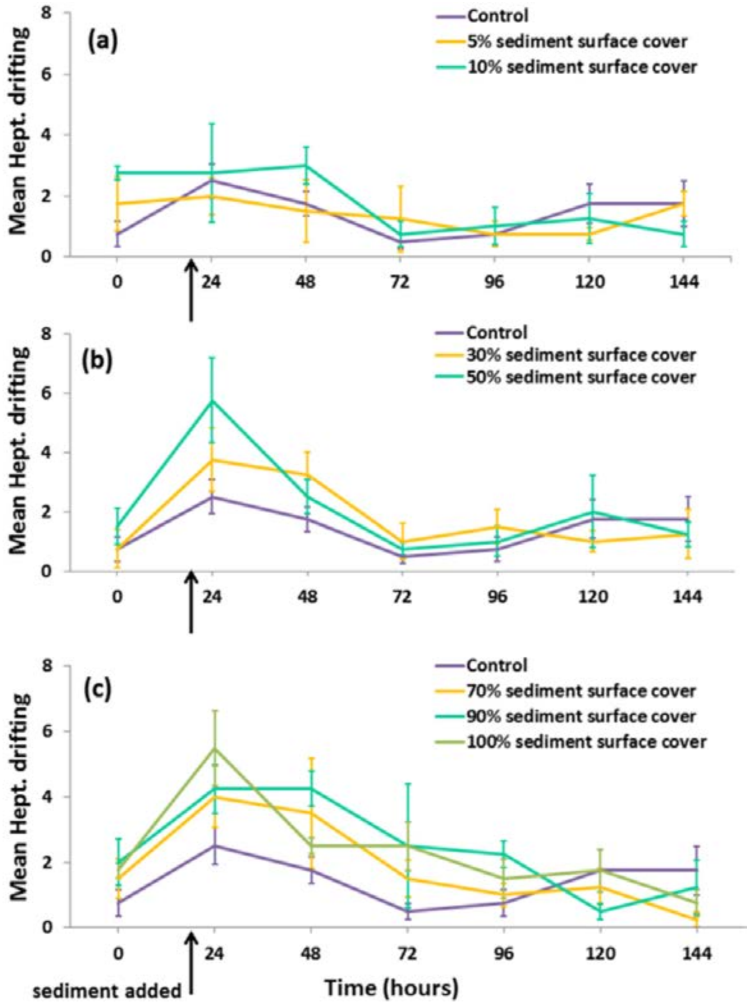

Figure 6.2. Mean (± standard error) abundance of Heptageniidae (Hept.) drifting. (a) Control, 5% and 10% sediment surface cover; (b) control, 30% and 50% sediment surface cover; and (c) control, 70%, 90% and 100% sediment surface cover in mesocosm study.

sampling locations as returned by PERMANOVA (Clarke, 1993).

Draftsman's (correlation) plots were examined to identify pairs of environmental variables that were strongly correlated (i.e. $r > 0.8$ and $r > –0.8$) and one of each was eliminated. The remaining variables were normalised and a resemblance matrix was calculated on the basis of Euclidian distance. BIOENV (BEST) analysis, which links environmental variables to community structure, was then used to identify the best sets of environmental variables (i.e. percentage run, riffle, pool, glide, sand/silt cover, riparian shading, mean wetted width, depth, velocity, conductivity, pH, temperature and dissolved oxygen) that were most strongly correlated with the biological data. Non-parametric multifactor multiple regression was used to describe the patterns in community structure using the environmental variables identified in the BEST procedure. A forward step-wise selection procedure, which was used to sequentially build a model using an Akaike information criterion (AIC), identified the set of environmental variables most responsible for variation in community structure.

At patch scale there was a significant interaction between river and land use intensity levels for total taxon richness and EPT richness based on the data that were available only for autumn. The observed significant differences in EPT richness in the Slaney were due to the lower richness values in high pasture sites. No other significant differences were identified. Community structure varied significantly between the low and high pasture sites in autumn due to downstream increases in Chironomidae, which made the largest contribution (29.8%) to the dissimilarities between low and high pasture sites. Decreases in abundance of *Limnius volckmari* at high pasture sites contributed a further 21.0% to the dissimilarity. Increases in abundances of Chironomidae at the high pasture sites also made a substantial contribution (33.7%) to the dissimilarity between pasture levels in the Clodaigh, together with large increases in *G. duebeni* (contribution: 19.1%) (Table 6.1).

There were no significant differences in most of the metrics between the various sites at reach scale in both spring and autumn. However, there was a significant interaction between river and land use intensity level (low/high) affecting community structure. SIMPER analysis for the River Slaney (reach scale) revealed that downstream increases in Chironomidae made the single largest contribution (33.6%), being four times as abundant in the high pasture sites, followed by *L. volckmari* (17.1%), which was more abundant in low pasture sites. Similarly, in the River Clodiagh, downstream increases in Chironomidae contributed 31.5% to the dissimilarity between the sites, while downstream increases in *L. volckmari* contributed a further 20.7% to site differences.

At patch scale in autumn, each of the environmental variables, with the exception of percentage fine gravel (i.e. percentage of loose material), had a significant

Table 6.1. SIMPER analysis identifying the main taxa that made the largest contributions to community structure in autumn

River/season/scale	Taxa	Average abundance low pasture sites	Average abundance high pasture sites	% contribution
Slaney	Chironomidae	1.5	23	29.8
Autumn	*Limnius volckmari*	20.3	4.3	21.0
(patch scale)	*Elmis aenea*	9.8	3.5	9.2
	Oligochaeta	0.5	5.8	6.8
	Esolus parralellepipedus	5.3	1.5	5.0
	Oulimnius tuberculatus	4.8	1.8	4.3
	Silo pallipes	3	0	4.1
	Dicranota sp.	1.3	3	3.5
Clodiagh	Chironomidae	0	11.5	33.7
Autumn	*Gammarus duebeni*	0	6.3	19.1
(patch scale)	*Limnius volckmari*	5.5	5.8	11.8
	Elmis aenea	2.5	5.8	10.7
	Leuctra sp.	0	2.3	5.1
	Dicranota sp.	0	1.5	4.7
	Oligochaeta	0	2.3	4.6
	Baetis sp.	1	0	2.9
Slaney	Chironomidae	32.3	126.0	33.6
Autumn	*Limnius volckmari*	74.0	15.7	17.1
(reach scale)	*Esolus parrallelepipedus*	43.3	26.3	9.6
	Elmis aenea	39.3	17.3	8.7
	Baetis sp.	2.3	11.0	5.0
	Lymnaeidae sp.	0.0	14.7	4.9
	Hydropsyche sp.	6.7	7.3	3.8
Clodiagh	Chironomidae	5.3	60.0	31.5
Autumn	*Limnius volckmari*	31.3	47.0	20.7
(reach scale)	*Elmis aenea*	14.0	18.7	10.9
	Gammarus duebeni	0.3	12.3	9.8
	Leuctra sp.	0.0	6.7	6.7
	Baetis sp.	4.3	0.3	4.9
	Esolus parrallelepipedus	5.0	2.3	4.2

relationship with community structure (Table 6.2). Land use, suspended solids, re-suspendable sediment, percentage fine gravel (i.e. percentage of loose material), and percentage surface cover of fine sediment accounted for just 22.5% of the variance in community structure. At reach scale in autumn, depth, percentage shading, percentage sand/silt, and dissolved oxygen had significant relationships with community structure and explained 62.4% of the total variance in community structure, with changes in depth alone explaining 29.4% of the observed variance in Table 6.2

The results for tillage were less consistent than for pasture. At patch scale, only community structure varied significantly between the tillage intensity levels, except for the River Urrin. SIMPER analysis identified increases in a range of taxa including *Glossosoma* sp., Oligochaeta, Chironomidae, *Esolus parrallelepipedus* and *G. duebeni* at the high tillage sites, contributing a total of 51.9% to the dissimilarities between sites. Although no significant differences were found in community structure in the River Glyde, there was a four-fold decrease in *Agapetus* sp., together with a substantial increase in *E. aenea* in high tillage sites, compared with low tillage sites (Table 6.3).

Analysis of spring reach-scale samples gave mixed results. Of note were significantly lower abundances at high tillage sites in the River Glyde. Differences in EPT and percentage EPT abundances in the Urrin were due to somewhat unexpected increases in EPT abundances at high tillage sites. However, this increase was partially due to higher abundances of *Seretalla ignita*, which is considered to be a sediment-tolerant taxon. Community structure varied significantly between the low and high tillage sites in spring and there were significant differences in community structure in the tillage catchments of the River Urrin and the River Glyde. In the River Glyde there were downstream increases in *G. duebeni* and decreases in *S. ignita* contributing 35.86% to the dissimilarities between tillage sites. In the River Urrin, a four-fold decrease in Chironomidae, coupled with substantial increases in *Rhithrogena semicolorata*, *S. ignita,* and *Agapetus* sp., differentiated high and low tillage sites (Table 6.3).

Similarly to the autumn patch-scale samples, there were only differences in community structure between high and low tillage sites in the Urrin. Here, downstream increases in Oligochaeta, *Baetis* sp., and *E. parrallelepipedus,* as well as decreases in *Protonemura meyeri,* contributed a total of 53.1% to the dissimilarities between tillage sites.

The limited differences between sites in the Glyde may be related to hydromorphological conditions, as it has been subjected to channelisation, a process in which the natural riffle/pool/glide sequence of rivers

Table 6.2. Results of non-parametric multiple regression of pasture community structure

Variable	% Variance	Pseudo-*F*-value	*p*-value	Cum. (%)[a]
Autumn patch scale				
Fitted variables				
Land use	8.9	3.2	0.01	8.9
Suspended solids	5.7	2.6	0.01	14.6
RSS	4.1	3.1	0	18.7
% Fine gravel	2.6	1.8	0.06	21.3
% Surface cover	1.2	1.9	0.05	22.5
Autumn reach scale				
Fitted variables				
Depth	29.4	1.8	0.07	29.4
% Shading	17.5	1.5	0.15	46.9
% Sand/silt	9.8	2.1	0.05	56.6
Dissolved oxygen	5.8	1.1	0.39	62.4

Autumn patch scale and autumn reach scale on environmental variables.

[a]Cum. (%) refers to the cumulative percentage of the variance.

RSS, re-suspended solids.

Table 6.3. SIMPER analysis identifying the main taxa that made the largest contributions in community structure for patch- and reach-scale tillage sites

River/season/ scale	Taxa	Average abundance low tillage sites	Average abundance high tillage sites	% contribution
Glyde	*Agapetus* sp.	107.5	32.3	29.8
Autumn	*Elmis aenea*	16	54.5	17.5
(patch scale)	*Simulium* sp.	31.8	4	11.0
	Hydropsyche sp.	11.3	33.8	9.4
	Gammarus duebeni	30.3	25.3	7.9
Urrin	*Glossosoma* sp.	0	8.3	15.6
Autumn	Oligochaeta	0.8	8.5	13.6
(patch scale)	Chironomidae	0	4.8	8.2
	Esolus parrallelepipedus	3.3	6	7.3
	Gammarus duebeni	0	3.8	7.2
	Baetis sp.	7	4.8	6.7
Glyde	*Gammarus duebeni*	21	78.7	18.5
spring	*Serratella ignita*	50.7	1.3	17.3
(reach scale)	*Limnius volckmari*	70.7	31	11.7
	Oligochaeta	40.7	6	11.0
Urrin	Chironomidae	140	37	21.6
spring	*Rhithrogena semicolorata*	5	68.3	15.2
(reach scale)	*Serratella ignita*	35	89	13.1
	Agapetus sp.	0	45	10.6
	Esolus parrallelepipedus	1.3	23.3	5.2
	Elmis aenea	37.3	14.7	4.9
	Limnius volckmari	0.3	18	4.2
Glyde	*Elmis aenea*	31.3	225	19.8
autumn	*Agapetus* sp.	234.3	86	17.7
(reach scale)	Chironomidae	53	213.3	17.5
	Hydropsyche sp.	23.3	151	13.3
	Simulium sp.	36.3	110	10.4
	Gammarus duebeni	59.7	106.3	6.1
Urrin	Oligochaeta	1	50.3	16.3
autumn	*Protonemura meyeri*	43.3	0	13.4
(reach scale)	*Baetis* sp.	27	69	13.3
	Esolus parrallelepipedus	4.7	34.3	10.1
	Chironomidae	38.3	45	6.9
	Limnius volckmari	5.3	25.7	6.7

is disturbed and this, coupled with the low gradient, may have resulted in a “homogenisation” of the river, potentially diminishing or masking any land use effects.

Regression parameters explaining the variation in community structure in the tillage sites are given in Table 6.4. Land use features only in the autumn patch-scale analysis.

6.5 Responses of Selected Macroinvertebrate Taxa to Burial by Sediment

This investigation tested the response of three Ephemeroptera, *Baetis rhodani* (Baetidae), *Ecdyonurus insignis* (Heptageniidae) and *Rhithrogena semicolorata* (Heptageniidae), two Trichoptera, *Hydropsyche siltalai* (Hydropsychidae)

Table 6.4. Results of non-parametric multiple regression of tillage community structure

Variable	% Variance	Pseudo-*F*-value	*p*-value	Cum. (%)[a]
(a) Autumn patch scale				
Fitted variables				
Land use	13.2	2.4	0.04	13.2
Turbidity	9.8	2.4	0.03	23
% Coarse gravel	2	3.2	0.01	25
(b) Spring reach scale				
Fitted variables				
% Riffle	52.5	3.6	0.03	52.5
% Pool	17.8	1.5	0.22	70.3
% Sand/silt	13.5	1.3	0.29	83.8
Conductivity	3.8	4.5	0.01	87.6
(c) Autumn reach scale				
Fitted variables				
pH	52.9	4.4	0	52.9
Temperature	18.5	4.3	0.01	71.4
Conductivity	4.8	4.2	0.01	76.2

[a]Cum (%) refers to cumulative percentage of the variance.

and *Rhyacophila dorsalis* (Rhyacophilidae), and the amphipod *G. duebeni* (Gammaridae) to burial by four sediment size classes (1 = 125–249 μm, 2 = 250–499 μm, 3 = 500–999 μm and 4 = 1–2 mm). An additional test, using sediment sourced from a lowland field adjacent to the River Urrin (County Carlow) investigated if sediment from a typical agricultural catchment influenced larval responses to burial.

Two response times were recorded: the length of time for the individual to become visible above the sediment surface (head emergence) and the length of time taken for the individual to completely excavate itself from the sediment and to swim or walk on the sediment surface (body emergence). A time limit of 900 seconds (15 minutes) was set for each experiment, as described by Wood *et al.* (2001, 2005).

Nymphs of two species were separated into two size categories based on body length (excluding the caudal cerci): *B. rhodani* nymphs (large > 0.7 mm and small < 0.6 mm) and *R. semicolorata* nymphs (large > 0.6 mm and small < 0.5 mm). As there was limited variation in body sizes in the other four taxa (*E. insignis, H. siltalai*, *R. dorsalis* and *G. duebeni*), they were not split into groups based on size. Five replicates of each taxon were exposed to each burial depth using the four sediment classes, using taxa from both upland and lowland rivers. In the case of *B. rhodani* and *R. semicolorata*, the operation was carried out on the two abovementioned size classes. In addition, five replicates of four lowland taxa (two body sizes for *B. rhodani* and *R. semicolorata;* one body size for *E. insignis* and *H. siltalai*) were also buried with the sediment (< 4.25 mm) from the lowland field, which may replicate the heterogeneous nature of particles naturally depositing in rivers. Only lowland taxa were exposed to this sediment fraction, as upland taxa would not be exposed to sediment from a lowland source under field conditions.

Nymphs of three ephemeropteran taxa (*B. rhodani*, *R. semicolorata* and *E. insignis*) and *G. duebeni* generally emerged from the sediment in one quick movement and the time difference between the emergence of the head and the body was typically 1 to 2 seconds (Conroy *et al*., 2017). The two trichopteran taxa (*H. siltalai and R. dorsalis*) exhibited a longer lag time between the emergence of the head and the body. The shrimp *G. duebeni* was the only taxon that could escape from all sediment classes at both burial depths, indicating that it is relatively tolerant or adapted to conditions of sedimentation. Burial depth had variable effects across species, with nymphs of most taxa able to excavate themselves from the 5-mm burial depth. Increased burial depth (10 mm) resulted in either greatly extended emergence times (*G. duebeni*, *H. siltalai*, *R. dorsalis* and *B. rhodani*) or nymphs became trapped (*R. semicolorata* and *E. insignis*). This indicates that the amount/depth of sediment is an important factor contributing to species-specific responses.

The response to the higher burial depth varied among the Ephemeroptera. Few *B. rhodani* were trapped by the higher burial depth compared with the Heptageniidae. Generally, slower escape times were observed from the finer sediment classes, while body size had no effect on escape ability. Taxa source also impacted responses, with some upland taxa taking longer or failing to emerge from burial. Such variation and the paucity of mechanistic investigations challenge efforts to produce global metrics to detect sediment effects.

7 Measures for Reducing Suspended Sediment Impacts

7.1 Introduction

Measures can be classified under a number of headings, relating to their purpose and location. The main group of measures address the reduction of sediment inputs to rivers and these can be sub-grouped into (1) field-based and (2) riparian measures. Other measures relate (1) to modifying the transport of sediment in water courses and (2) to modifying the impact the suspended sediment has on the natural biota in the river. There is a large body of literature addressing the performance of such measures and many collections of such information, either as literature reviews or as databases of performance coefficients for use in modelling systems. This review will not duplicate these existing works, but summarises briefly the main measures relevant to Irish conditions, together with performance information, where available, and citations of the original source publications or reports.

There seems to be a strong consensus (e.g. Hershey, 1999) that sediment reduction at a catchment scale should start with on-farm methods to reduce erosion losses, together with measures to limit animal access to stream banks or the channel itself (Table 7.1). Measures associated with or in the channel itself are listed in Table 7.2.

7.1.1 Riparian and in-stream options

The tables show that a large variety of options is available for reducing sediment loads and their impacts in rivers and streams. A number of sources have reported on the effectiveness of these measures and some of these have informed software packages and other tools used to simulate these measures. The overall impression is that there are large variations in the performances of different measures and in performance across the same measure, and these depend on site-specific characteristics. There seems to be a strong consensus that sediment reduction at a catchment scale should start with on-farm methods to reduce erosion losses together with measures to limit animal access to stream banks or to the channel itself. For specifically sensitive species, in-stream measures, especially those designed to reduce deposited sediment (which are not practical for entire river reaches) can be targeted at specific, important locations.

Implementing the types of measures outlined in Tables 7.1 and 7.2 clearly requires the co-operation of riparian landowners. Understanding the perception and attitudes of farmers remains central to the ongoing challenge of obtaining their support and buy-in that is necessary for adopting such measures in the integrated management approaches that are essential for regulation and policy compliance. Quinlan *et al*. (2015a) consider that “a sound understanding of farmers’ motivations and risk attitudes is required in a regional, industry and environmental context — to tailor public investments aimed at providing relevant improvements in the environmental performance of agriculture”. This is necessary for informing effective policy (Allen and Vaughn, 2010) and the “human development” paradigm is considered to be a more effective approach to influencing farmer behaviour than a formal knowledge transfer (advisory) relationship (Hardison and Layzer, 2001).

Table 7.1. On-farm options for reducing sediment export

Method	Citation	Performance
Tramline management	Dermisis *et al*. (2010)	Field tracks can contribute significantly to sediment loads in rivers, from small proportions to over 50%, depending on circumstances
Tramline management	Alexakis *et al*. (2013)	Tramline management measures can reduce sediment contributions by between 72% and 99% (UK)
Tramline management	Evrard *et al*. (2008); Fiener and Auerswald (2003)	Up to 46% more runoff was reported from ploughed fields where tramlines ran up and down the slope than for cross-slope tramlines. However, the former contributed up to five times more sediment loss. Where reduced cultivation practices were adopted, there was very little sediment loss via tramlines due to better cover and firmer ground for tractor wheels
Field drains	Willobee and Kabbes (2007)	Field drains transport more sediment than surface runoff in lowland agricultural catchments in the UK and should be the primary focus for mitigation in such catchments
Crop residues (on sand)	Willobee and Kabbes (2007)	9–200 $kg\,ha^{-1}$ reduction in overwinter losses (40–43% reduction)
Contour cultivation	Willobee and Kabbes (2007)	90–1223 $kg\,ha^{-1}$ reduction in overwinter losses on clay (44–79% reduction)
Contour cultivation	Morales *et al*. (2006)	“Significant effects” without quantification
Minimum tillage	Willobee and Kabbes (2007)	54–1133 $kg\,ha^{-1}$ reduction in overwinter losses (37–98% reduction)
Tillage practices	Michel *et al*. (2013)	Report a 50% reduction in sediment export for no-till (532 $kg\,ha^{-1}\,y^{-1}$) versus disk tillage (1152 $kg\,ha^{-1}\,y^{-1}$) in Ohio, USA
Minimum tillage	Morales *et al*. (2006)	Very little effect in areas of wheat and oats
Reduced tillage	Somma (2013)	EU-JRC-RBN 30% to 60% reductions on clay soils, up to 90% on loamy-sand (UK DEFRA project MOPS1)
Beetle bank (on clay)	Willobee and Kabbes (2007)	41–228 $kg\,ha^{-1}$ reduction in overwinter losses (16–94% reduction)
Beetle bank	Morales *et al*. (2006)	Marginal additional suspended sediment benefit when added to contour cultivation, but additional biodiversity benefits
Tramline modifications	Willobee and Kabbes (2007)	49–4890 $kg\,ha^{-1}$ reduction in overwinter losses (75–99% reduction)
Cover crops	Somma (2013)	EU-JRC-RBN effectiveness from 10% to 15%
Conservation tillage	Owens *et al*. (2002)	Annual sediment losses of 532, 828 and 1152 $kg\,ha^{-1}$ for no-till, chisel plough and disk cultivation, respectively, in Ohio (over 2 years)
Tramline management	Deasy *et al*. (2010)	Tramline management was found to be the most consistently effective way of reducing sediment losses
Contour cultivation	Deasy *et al*. (2009)	Contour cultivation resulted in sediment reductions of 40–43% and minimum tillage of 45–79%
Farm tracks	Turley *et al*. (2015)	Contribution of farm tracks to overall sediment load from agriculture very variable from very little to up to 20% in one case
Field wetlands	Allen and Vaughn (2010); Gangloff and Feminella (2007)	Effective at trapping sediment with rates dependent on soil type, but up to 6 $t\,ha^{-1}\,y^{-1}$ in sandy UK soils; need dredging, but relatively low cost
Land use change	Lundekvam and Skoien (1998)	Plot study in Norway found that spring tillage reduces the annual soil loss by 90% compared with autumn ploughing
Spring cropping and maintaining winter cover	Bechmann and Stålnacke (2005)	From early 1990s, between 25 and 36% of the arable area was not cultivated in autumn (through agricultural subsidies for high soil erosion risk areas); produced significant reductions in stream suspended sediment and total phosphorus
Reduced stocking density	Evans (2005)	Long-term studies in the Peak District indicated reduction in livestock densities caused a rapid reduction in erosion rates
Reduced stocking density	McHugh *et al*. (2002)	Reduced sheep stocking density in upland England and Wales likely to result in revegetation and reduced erosion
Contour cultivation	Deasy *et al*. (2009)	Contour cultivation resulted in sediment reductions of 40–43% and minimum tillage of 45–79%
Blocking tile drains	Clarke *et al*. (2012)	In reviewing soil erosion data for Norway, soil losses of from 2000 to 6000 $kg\,ha^{-1}\,y^{-1}$ from ploughed fields and tile drains contributed significantly to the transport of sediment from silty-clay fields. However, this was not apparent in very old drains (over 40 years old)

EU-JRC-RBN, European Union Joint Research Centre’s River Basin Network platform.

Table 7.2. Stream bank/riparian methods for sediment reduction

Method	Citation	Performance
Fencing on stream banks	Engle and Jarrett (1995)	Single strand fencing at least 2 m from river banks was effective at eliminating poaching and increasing the diversity of the riparian vegetation
Fencing on stream banks	Pulley *et al.* (2017)	More information needed to determine effect on stream banks as sediment sources
Fencing on stream banks	Quinlan *et al.* (2015b)	Reported 10-fold reduction in bank-side sediment input and channel erosion following fencing and management in Australia
Fencing on stream banks	Bieroza and Heathwaite (2015)	Fingerprinting estimated that a high proportion of sediment from channel banks appear in salmon spawning beds, indicating importance of protecting banks from erosion
Fencing on stream banks	Collins *et al.* (2010)	Revisiting sites 10 years post fencing suggested the contribution of bank (sub-surface sources) to gravel siltation was dramatically reduced relative to surface sources in several catchments
Fencing on stream banks	Owens *et al.* (1996)	Average annual sediment concentrations were reduced by over 50% and annual soil losses by 40% in small Ohio catchment
Animals crossing streams	Ivanovich and Hamid (2014)	A special study of the effects of sheep herds crossing streams in Australia found elevated SSCs, but that these were short-lived and localised and by 500 m downstream sediment concentrations had returned to background amounts
Animals crossing streams	Cocchiglia *et al.* (2012)	Reported the effect of stream bank fencing on sediment losses from a field used for grazing cattle (before fencing the cattle had access to the stream); fencing reduced in-stream sediment concentrations by 50% and soil loss by 40%
Riparian buffer	Willobee and Kabbes (2007)	Design principles
Riparian buffer	Duhallow LIFE project (2016)	Retention strongly related to input sediment load
Riparian buffer	Hendry *et al.* (2003)	Reluctance of Irish farmers to provide buffers significantly larger than minimum set-aside owing to loss of production
Riparian buffer	Clary and Leisenring (2015)	Preferences for (woody) vegetated buffer strips and meandering stream morphology in the USA
Buffer strips	Somma (2013)	EU-JRC-RBN: particulates reduction 55% to 97%; narrow buffer strips (< 1 m) not effective, wide (> 6 m) very effective
Buffer strips	Liu *et al.* (2008)	A review of over 80 studies suggested that sediment removal efficiency varies from 45% to 100%, with increasing removal up to 10-m width; concentrated flows significantly compromise the effectiveness of riparian buffer strips because much of their sediment is not effectively filtered
Buffer strips	Yuan *et al.* (2009)	This study found that buffer strips of 3-m width are efficient at low slope angles, but are less effective where the slope exceeds five degrees. They concluded that studies suggest buffer strips of 5-m width remove 80% of sediment. A 6-m buffer strip was found sufficient, regardless of slope or buffer vegetation type
Buffer strips	Gharabaghi *et al.* (2006)	First 5 m of filter strip trapped more than 95% of the aggregates larger than 40 μm in diameter
Vegetated filter strip	McHugh *et al.* (2002)	Effectiveness depends on the width of the strip. In Canada, effectiveness increased from 50% to 98% as the width increased from 2.5 m to 20 m. However, the first 5 m of the strip captured most of the sediment – in the Canadian case, over 95% of the sediment particles greater than 40 μm.
Vegetated filter strip	Warburton *et al.* (2003)	Confirmed effect of width of buffer; performance increasing dramatically with widths up to about 6 m, and reports that the US Natural Resources Conservation Services recommend widths of 8 to 10 m
Vegetated filter strip	Owens *et al.* (1996)	After a review of over 80 studies, suggested a strip width of 10 m and allowed for slopes of up to 9%
Vegetated filter strip	Owens *et al.* (2002)	However, in an important comment on the above paper by (Owens *et al.*, 1996, 2002) argued for the inclusion of a hydrological variable based on runoff reduction/infiltration, in a set of equations for performance efficiency
Sedimentation basins	Fox and Sabbagh (2009)	Report that sediment loads can be estimated from amounts dredged from sedimentation basins and report values from 0.2 to 6 $m^{-3} ha^{-1} y^{-1}$ from loess soil catchments in Belgium

Table 7.2. Continued

Method	Citation	Performance
Sedimentation basins	Evrard *et al*. (2008)	Measured the effect of control dams in a 300 ha catchment in loess belt of Belgium and estimated a 93% reduction in SSCs at the outlet compared with upstream of the three dams; however, costs of construction and maintenance of such structures are high
Retention basins	Golman *et al*. (1986)	Efficiencies of retention basins tabulated
Small weirs	Kay *et al*. (2009)	Reported very low SSCs downstream of small weir in upland stream; studied effect on freshwater pearl mussels
Channel rehabilitation	Collins *et al*. (2010); Layzer and Madison (1995)	Reported costs of stream restoration methods
Grass waterways (or “swales”)	Liu *et al*. (2008)	A grassed waterway in Belgium (together with earthen check dams) reduced runoff by 69% and sediment discharge by 93% in a “muddy flood” catchment dominated by loess soils. Part of the mechanism at least was the prevention of the formation of erosion gullies (i.e. probably a backwater effect)
Gravel additions, raking stream bed	Wilkinson *et al*. (2014)	Introduction of gravel and substratum raking improved macroinvertebrate and macrophyte communities. Boulder placement had little effect. However, habitat conditions for trout were not improved sustainably
Grassed waterways	Lundekvam and Skoien (1998)	Report two grassed waterways as reducing runoff by 90% and 10%, the big difference being due to different layouts, but both reduced sediment loads by 97% and 77%, respectively
Grassed waterways	Dermisis *et al*. (2010)	Average runoff was reduced by approximately 20% and sediment by 60% in a small Iowa catchment
Grassed waterways	Fiener and Auerswald (2003); Fiener and Auerswald (2006)	A 7-year study in Germany found that sediment delivery reductions of 97% and 77% for catchments with grassed waterways compared with paired catchments, respectively. However there were seasonal variations in effectiveness

EU-JRC-RBN, European Union Joint Research Centre’s River Basin Network platform.

8 What Has Been Learned About Sediment Flux in Irish Rivers and What are the Implications for Policy Formulation?

8.1 Monitoring and Measuring

8.1.1 Instrument differences

There are large differences, up to a factor of five, in turbidity measurements (NTU) from different makes of instruments. These differences occurred even between makes of instrument using the same optical operating principle. Thus, turbidity values should not be compared between different makes or models of instruments and certainly should not be the basis for setting standards.

8.1.2 Instrument noise

"Noise" in the turbidity signal generally increases with increasing sediment concentration and can introduce uncertainty into estimated SSCs, particularly in the higher concentration range. This should be recognised by users for specific applications.

8.1.3 Sediment particle size influences turbidity measurements

An understanding of particle size effects at a given site is critical for building accurate rating relationships between SSCs and turbidity, which may change between floods, but are probably not as significant for estimates of medium- to long-term sediment flux.

8.1.4 Good T–SSC relationships can be established

Despite the abovementioned observations, it was possible to establish good, but instrument-specific, linear and polynomial relationships between turbidity (as measured by that particular instrument) and SSCs.

8.1.5 Calibrated estimates of SSC can be used to estimate suspended sediment flux and loads

Despite instrument differences in measured turbidity, the calibration equations developed for each instrument will produce reasonably similar estimates of SSC. Turbidity can be used as a proxy for SSC, and hence sediment load, estimates as long as site-specific and instrument-specific calibrations are used.

8.1.6 Turbidity should not be used as a water quality metric in a regulatory framework

The scale of variation between turbidity estimates from different instrument types has the potential to produce datasets that may be difficult to compare. This is important when interpreting water quality metrics based on turbidity. The transferability and comparability of such datasets across different monitoring technologies and systems must therefore be treated with caution in a scientific and regulatory context.

8.1.7 Need for instrument metadata

Reported turbidity records would benefit from the inclusion of metadata that define the make and model of the measuring sensor used, as well as the sediment and flow conditions associated with turbidity sampling or monitoring. Such data would, in many instances, facilitate a more meaningful and consistent comparison and interpretation of turbidity data across different water quality monitoring programmes.

8.1.8 Maintenance and resilience

Continuous real-time, remote monitoring of SSC using turbidity as a surrogate requires resilient infrastructure and reliable instrumentation, together with regular (fortnightly to monthly) maintenance to ensure the integrity of the data stream. This approach could potentially be integrated into EPA water quality monitoring programmes or into work being carried out at hydrometric stations (EPA and OPW), albeit at a capital cost (based upon the SILTFLUX project, this would be in the order of €10,000 per site).

8.2 Data Quality

8.2.1 Turbidity data may contain spurious trends and data peaks

Continuous and high-resolution records of turbidity are rarely free from data spikes or other defects and therefore an actual turbidity record often requires quality checking and "cleansing", ideally based on knowledge of the catchment and site setting.

8.2.2 Real-time data collection systems can assist in the timely response to data collection problems

Linking sensors to a real-time data collection system will greatly expedite the response by technical staff to instrument problems and therefore contribute to the acquisition of more complete turbidity records.

8.2.3 Secondary datasets can be used to assist in data quality assessment

The use of concurrent datasets captured at the same location (e.g. water level or *Q*), may assist in the identification and rectification of data anomalies.

8.3 Flux and Yield Estimates

8.3.1 Database

A database of annual values of suspended sediment yield was constructed from extant studies of Irish catchments. These data indicate levels of (area-specific) SSY ranging from as low as 2.11 to a maximum of 48.39 $t\,km^{-2}\,y^{-1}$. These values are comparable to the lower SSY values found in central, western and northern Europe.

8.3.2 Need for long-term sediment monitoring in catchments

SILTFLUX data exhibited considerable inter-annual variation in estimated sediment loads. Short-term suspended sediment monitoring is, therefore, unlikely to provide an accurate estimate of the range of suspended sediment flux/yields possible from a given catchment because of the inherent variability of weather, flows and sediment supply. Longer term monitoring is needed to ascertain the degree of variability between seasons, years and over longer decadal timescales in Irish rivers.

8.3.3 Estimating sediment yields using regression models

SILTFLUX has demonstrated a methodology for developing regression equations that can be used to estimate SYs and has demonstrated the performance of several of these. Strong associations were found between sediment yields and catchment variables related to its soil (particularly poorly drained soils and peat soils), topography (*S*1085 slope), hydrology (runoff and annual mean flows) and climate (seasonal rainfall for winter and spring).

8.3.4 Towards a national inventory of sediment yields and the setting of environmental quality standards for sediment

The regression models developed in SILTFLUX offer a framework for the creation of a national inventory of sediment yields in Ireland, but they require further testing and validation using longer time series and across a wider range of land use types. This could potentially represent a cost-effective method for estimating reference conditions to support, together with other factors, the setting of sediment-related environmental quality standards (EQS) in Irish catchments.

8.4 Impacts on Freshwater Biology

8.4.1 Concentration–duration–frequency curves for suspended sediment

The durations of exceedance of specific sediment thresholds are particularly relevant for assessments of potential biological impacts, and site-specific sediment exceedance–duration relationships are required for determining these impacts.

8.4.2 Importance of deposited sediment

SILTFLUX established the importance of deposited sediment in causing biological impacts on macroinvertebrates.

8.4.3 Standards for deposited sediment

In line with the biological impact of deposited sediment, there is a strong argument that ecological quality standards should focus on deposited sediment in addition to SSCs/flux.

8.4.4 Burial can be a factor in the impact of deposited sediment

Species-specific responses to burial in sediment varied with the depth and nature of the sediment applied as well as the source of the taxa. Such variation and the paucity of mechanistic investigations challenge efforts to produce global metrics to detect sediment effects.

8.4.5 Metrics should be based on sediment-sensitive taxa

Percentage sediment surface cover and EPT abundance may be useful metrics for assessing the negative effect of excessive sediment on macroinvertebrates.

8.4.6 Thresholds based on sediment cover require more research

Since EPT metrics are also used to indicate eutrophication and general degradation of water quality, there is a need for further research to refine sediment-specific metrics. The experimental testing indicated biological impacts at 30% sediment deposited cover, although further research is needed to investigate sediment cover thresholds.

8.4.7 Deposited sediment amounts can be assessed visually

There was a strong relationship between visual estimates of percentage surface cover and sediment amounts. This suggests a simple method of quantifying deposited sediment amounts. However, if this is adopted, training protocols should be undertaken to improve inter-observer consistency and increase the precision and accuracy of visual estimates.

8.4.8 Mid-channel organisms are most affected at cattle access points

Generally, macroinvertebrates in mid-channel habitats, rather than at the channel margins, were most sensitive to the added pressure of cattle access points. There were some seasonal differences and site-specific impacts.

8.4.9 Cattle access points' impact was greater on higher status rivers

Significant changes in at least two metrics were observed downstream of cattle access points in both seasons for all four high/good status rivers in this study.

8.4.10 Seasonal effects on the impact of cattle access points

Overall, changes in macroinvertebrates downstream of cattle access points in rivers of high/good water quality status were more frequently observed in autumn than in spring. This may be due to river recovery following indoor wintering of cattle, but further research is needed to test this hypothesis.

8.4.11 Outdoor overwintering of cattle

Out-wintering of cattle on steep slopes near watercourses during periods of high soil moisture content is not recommended practice in terms of water quality protection.

8.4.12 Challenge of disentangling sediment effects from those of nutrients and organic matter

In the SILTFLUX study, nutrient levels and organic matter were generally higher downstream of cattle access across all rivers. Thus, it may be more challenging to detect any further changes in community structure and composition due to cattle access or to disentangle cattle access effects from upstream stressors.

8.4.13 Different responses to scales of pressures

The macroinvertebrate community responses detected at the two spatial scales used in this study were somewhat different. The localised disturbances from cattle access generally resulted in increases in tolerant taxa and there was a more variable result for pollution-sensitive taxa. The reach-scale land use study also detected a downstream increase in tolerant taxa (e.g. Chironomidae) but showed little or no effect on pollution-sensitive taxa.

8.4.14 Pasture impacts

Both patch- and reach-scale sampling in the autumn partially supported the hypothesis that downstream increases in percentage pasture would result in losses of sensitive taxa and increases in tolerant taxa.

8.4.15 Tillage impacts less consistent

Results for tillage land use were less consistent than for pasture. Only the River Urrin showed significant changes in macroinvertebrate community metrics at both patch and reach scale in both seasons, while there were minimum effects in the Glyde. However, no SILTFLUX catchment was completely dominated by a tillage land use, so this result requires more investigation.

8.5 Implications for Management of Suspended Sediment in Rivers

8.5.1 Scale of problem

SSCs and loads in Irish rivers are generally low in comparison with rivers in the UK and Europe. Because they include land use factors that can be adjusted to reflect more or less intense land use, the equations that have been developed in SILTFLUX provide a basis for a methodology that can be used to estimate reference conditions, but longer term data covering a wider range of catchments are needed to establish both annual variability and dependence on a larger range of physical and land use characteristics.

In addition, for small catchments, the equations provide a “first pass” at estimating long-term average conditions. By using long-term mean annual flows, runoff or *Q*5 values, depending on the equation used (determined from hydrometric records where available or estimated from ungauged catchment equations), they can be used to estimate the likely mean SY or SSY value for a given catchment. Such estimates can be used in either of two ways:

1. By applying them to individual, ungauged, sub-catchments, the equations can be used, in a screening-type process, to rank these in terms of their likelihood of producing high sediment loads and thus to target investigations (catchment visit) and possibly data collection. This would be done using long-term annual mean flow (*Q*), runoff or *Q*5, as required, in the equation for each sub-catchment.
2. If sediment measurements in a sub-catchment indicate that it is contributing substantially more sediment than predicted by our equations, e.g. in a badly overgrazed catchment, the catchment can be targeted for appropriate measures. Therefore, the equations will provide something that may only approximate a reference condition flux value, which, when compared with measurements, may trigger measures.

However, there are specific locations within some Irish rivers that are inhabited by protected and sediment-sensitive species. Special consideration should be given to protecting these areas. The approach described above should be tailored to these specific locations, but it will generally require the steps described in the following section.

8.5.2 Management steps for sensitive habitats

The following steps are recommended for determining measures to reduce the delivery and impact of sediment in sensitive habitats:

- Identify priority locations of aquatic species of particular concern that have high susceptibility to impact from sediment. Estimate the baseline sediment regime required by that species.
- Divide the full catchments of these locations into their constituent sub-catchments and assess the potential risk of elevated suspended sediment loads in these sub-catchments, based on estimates of their mean annual load from SILTFLUX equations (using the mean annual flows, runoff or *Q*5, as appropriate)
- Identifying the sub-catchments with the highest suspended sediment risk can be facilitated by incorporating the suspended sediment equations developed here into a GIS-based tool such as the EPA’s Catchment Characterisation Tool (CCT).
- Inspect these “hot spots” to confirm their high-risk status, identify the sources of the risk and inform the choice of measures to best reduce suspended

sediment loads in the watercourse or mitigate their effects.

- Prioritise measures to reduce suspended sediment loads from these "hot spots" to below the baseline required by the sensitive species. These will be determined largely by site conditions in consultation with riparian landowners, but should generally be in the following order:
  - measures to reduce sediment mobilisation from the catchment;
  - measures to reduce mobilised sediment from reaching the river channel;
  - measures to prevent sediment settling or sediment scour at the location of the species to be protected.

While these steps provide a framework for informing potentially suitable mitigation measures, the degree of impact and the characteristics of specific sites will also require consideration in deciding which measure(s) is/are most appropriate. In addition, the risks arising from the inter-annual variability of weather and thus SY and SSY (not taken into account in the above), should be studied and eventually incorporated into this framework.

9 Priority Areas for Immediate Action

9.1 Use of Turbidity

Turbidity should not be used as the basis for regulation or policy, but it can be used to estimate SSCs with instrument- and site-specific calibration equations. All regulatory turbidity-based metrics and all reports or papers using turbidity data should explicitly describe the specifications of the instrument employed. All turbidity instruments used in the field should be equipped with a wiper.

9.2 Further Challenges in Quantifying Sediment Loads

9.2.1 Investigate the sediment yields from rivers under different land uses

As SILTFLUX focused on tillage and pasture land uses, the equations developed here should be tested for catchments dominated by other land uses (e.g. forestry) and settings (e.g. karst) and either confirmed as applicable or a separate study could be undertaken to develop a specific equation for that land use or setting. For instance, only one of the SILTFLUX catchments had a substantial karst influence on flood generation and presumably on sediment mobilisation. Thus, this project was not able to establish any different behaviour patterns. However, given the extent of karst in Ireland, it is an area for future research.

9.2.2 Investigate the sediment yields from rivers subjected to arterial drainage

The SILTFLUX project included only one catchment that had been subject to extensive arterial drainage. The sediment yields from this catchment were relatively low given its high proportion of tillage. Further investigation is needed to quantify the potential effects of arterial drainage on sediment loads.

9.2.3 Investigate sediment yields and dynamics in lake areas

Only one of the SILTFLUX sub-catchments included lakes that may trap sediment. Given the high number of natural lakes in Ireland, particularly in the midlands and some uplands, this is an area for future research.

9.2.4 Investigate how to extend this study to larger catchments

A project steering committee member made a very useful suggestion of applying models that include separate sediment production and transport models for larger catchments.

9.2.5 Investigate and model hysteresis in the suspended sediment dynamics in rivers

This project explored the possibility of modelling the hysteretic relationship between SSCs and discharge. However, this was not a simple relationship between only these two variables, which suggests that other factors have to be considered and this is a topic for further research.

9.2.6 National suspended sediment yield map

This study provides the first steps towards producing a national map estimating the amount of sediment exported by Irish rivers using the regression equations developed here and future equations resulting from the studies suggested above. These estimates can be used to support reporting under the OSPAR Convention. The SILTFLUX equations are suitable for inclusion in a GIS-based erosion risk tool for use on a sub-catchment basis, analogous to the critical source areas tool for nutrients (nitrogen and phosphorus) already used by the EPA.

9.2.7 Suspended and deposited fine sediment relationships

The potential links between fine sediment flux at a reach scale and deposited fine sediment should be studied, together with the associated river morphology and hydraulic regime.

9.3 Biology

9.3.1 Scale of future studies

Observations at both catchment and reach scale over multiple sites are needed to have a clear understanding of the impacts of catchment-wide land use effects on biology. Catchment-wide information allows the targeting of mitigation measures to where they are likely to have the most beneficial effects throughout the whole catchment. Patch-scale information will inform and aid the targeting of measures against localised pressures such as cattle access.

9.3.2 Visual estimates of fine sediment cover should be made routinely

Visual estimates of fine sediment cover under experimental conditions reflected the amount of sediment added and correlated well with EPT metrics. There is growing evidence that it has the potential to be applied in water quality monitoring to gauge potential ecological impact, as percentage surface sediment cover is now routinely recorded by the EPA during WFD bioassessment. However, there are scale issues and, if used, standardised protocols and observer training would be needed to improve inter-observer consistency and increase the precision and accuracy of visual estimates.

9.3.3 Thresholds for impacts from deposited sediment should be investigated

Clapcott *et al*. (2011) detected noticeable responses in aquatic invertebrate communities, with between 10% and 10-fold increases in deposited sediment. Salmonid habitat is reported to be impacted at less than 10% cover and mortality is associated with 20% cover. Further investigation is required to refine thresholds for impact.

9.3.4 New sediment-specific biological metrics needed (disentanglement)

EPT metrics respond to the amounts of deposited sediment. However, EPT metrics are known to also respond to organic pollution and eutrophication and are therefore general indicators of ecological degradation in agricultural catchments. Further studies are required to develop sediment-specific biological metrics.

9.3.5 Interim suggestion

In the interim, field sampling for *Q*-value estimates should record the overall representation of EPT fauna in terms of richness and abundance. These data should be extractable from the EPA *Q*-value metrics database.

9.3.6 Long-term datasets needed

There is a paucity of long-term datasets for agricultural catchments in Ireland and even those that are available are confined to a small number of sites. Long-term datasets are well placed to detect the effects of pressures, providing a multitude of insights that may not be obvious from short-term studies.

9.3.7 Outdoor overwintering of cattle

Outdoor overwintering of cattle on steep slopes in the vicinity of watercourses during periods of high soil moisture content is not recommended practice in terms of water quality protection.

9.4 Priority Actions

9.4.1 Initiate long-term monitoring of turbidity and suspended sediment flux

The SILTFLUX project was conducted over 4 years and its data provide baseline information on SSC and sediment flux, and reveal variability associated with storms and antecedent conditions. However, they are too short to fully capture inter-annual variability, including potential threshold behaviour associated with extreme climate events and dynamic trends linked to climate and land use change. Priority should therefore be given to the implementation of a national strategy of long-term, high-resolution monitoring of suspended sediment flux, using turbidity as a surrogate for SSC.

9.4.2 Initiate suspended sediment monitoring across a broader range of land use and catchment conditions

As the first national project on suspended sediment in Irish catchments, SILTFLUX focused on the most common river typologies under the WFD and the dominant land uses of pasture and tillage. The multi-variate, linear regression models that have been developed from these data provide a basis for developing regional sediment flux estimates, but require further refinement and validation across a wider range of catchments types, including systems with karst and lakes. Similarly, other land uses, such as forestry, peatland and urban areas, were not considered. A priority action is therefore to expand on the catchment typologies used in the SILTFLUX project.

9.4.3 Set standards for suspended sediment concentrations in Irish catchments

Priority should be given to the setting of standards for suspended sediment in Irish catchments. The modelling framework developed in the SILTFLUX project can contribute to this process. These standards may consider location-specific habitat requirements and should be subject to rigorous review on a regular basis, as new data from a wider range of catchments and settings become available from the additional monitoring recommended here.

9.4.4 Ensure collaboration of agencies and stakeholders collecting suspended sediment data in Ireland

As part of the new initiatives for expanding the collection of high-quality suspended sediment data, the co-ordination of existing and future activities involved in sediment monitoring is recommended. Consideration should also be given to the potential for taking advantage of existing statutory turbidity monitoring (such as that carried out at water treatment plants) in cases where cost-effective calibration would enable reliable estimation of sediment concentration and flux.

9.4.5 Establish standard operating procedures for the monitoring of suspended sediment in rivers

To promote best practice and allow the seamless integration of outputs from a range of projects and sources, we recommend publication of national guidelines for standardising the collection of suspended sediment data, including mandatory requirements to incorporate metadata, such as instrument specifications, when results are reported.

9.4.6 Establish standard protocols for assessment of deposited sediment in rivers

Standardised protocols should be developed and training undertaken to improve inter-observer consistency and increase the precision and accuracy of visual and other estimates of deposited sediment in rivers. These measurements should be carried out when *Q*-value assessments are being undertaken.

9.4.7 Establish a threshold for deposited sediment in rivers

Estimates of deposited sediment should be established for reference conditions to inform the development a deposited sediment threshold. In the interim, a precautionary deposited sediment cover target not exceeding 20% is recommended for the upper reaches of river networks. However, for areas with sediment-sensitive species, a lower target may be advisable.

References

Alexakis, D.D., Hadjimitsis, D.G. and Agapiou, A., 2013. Integrated use of remote sensing, GIS and precipitation data for the assessment of soil erosion rate in the catchment area of “Yialias” in Cyprus. *Atmospheric Research* 131: 108–124.

Allen, D.C. and Vaughn, C.C., 2010. Complex hydraulic and substrate variables limit freshwater mussel species richness and abundance. *Journal of the North American Benthological Society* 29: 383–394.

Bechmann, M. and Stålnacke, P., 2005. Effect of policy-induced measures on suspended sediments and total phosphorus concentrations from three Norwegian agricultural catchments. *Science of the Total Environment* 344: 129–142.

Bieroza, M.Z. and Heathwaite, A.L., 2015. Seasonal variation in phosphorus concentration–discharge hysteresis inferred from high-frequency *in situ* monitoring. *Journal of Hydrology* 524: 333–347.

Brown, L.C. and Foster, G.R., 1987. Storm erosivity using idealized intensity distributions. *American Society of Agricultural and Biological Engineers* 30: 379–386.

Clapcott, J.E., Young, R.G., Harding, J.S., Matthaei, C.D., Quinn, J.M. and Death, R.G., 2011. *Sediment Assessment Methods: Protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values*. Cawthron Institute, Nelson, New Zealand.

Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. *Austral Ecology* 18: 117–143.

Clarke, P.E., Moffet, C.A., Lewis, G.S., Seyfried, M.S., Hardegree, S.P. and Peierson, F.B., 2012. Water quality effects of herded stream crossings by domestic sheet bands. *Journal of Environmental Quality* 41: 1580–1590.

Clary, J. and Leisenring, M., 2015. Agricultural Best Management Practice Database (AgBMPDB). Available online: http://www.bmpdatabase.org/Docs/AgBMPDB%20V1%20Data%20Summary%20August%202015_wAppendices.pdf (accessed 30 August 2017).

Cocchiglia, L., Purcell, P.J. and Kelly-Quinn, M., 2012. A critical review of the effects of motorway river-crossing construction on the aquatic environment. *Freshwater Reviews* 5: 141–168.

Collins, A.L., Walling, D.E., McMellin, G.K., Zhang, Y., Grey, J., McGonigle, D. and Cherrington, R., 2010. A preliminary investigation of the efficacy of riparian fencing schemes for reducing contributions from eroding channel banks to the siltation of salmonid spawning gravels across the south west UK. *Journal of Environmental Management* 91: 1341–1349.

Conroy, E., Turner, J.N., Rymszewicz, A., Bruen, M., O’Sullivan, J.J., Lawler, D.M., Lally, H. and Kelly-Quinn, M., 2016a. Evaluating the relationship between biotic and sediment metrics using mesocosms and field studies. *Science of the Total Environment* 568: 1092–1101.

Conroy, E., Turner, J.N., Rymszewicz, A., Bruen, M., O’Sullivan, J.J. and Kelly-Quinn, M., 2016b. An evaluation of visual and measurement-based methods for estimating deposited fine sediment. *International Journal of Sediment Research* 31: 368–375.

Conroy, E., Turner, J.N., Rymszewicz, A., O’Sullivan, J.J., Bruen, M., Lawler, D., Lally, H. and Kelly-Quinn, M., 2016c. The impact of cattle access on ecological water quality in streams: examples from agricultural catchments within Ireland. *Science of the Total Environment* 547: 17–29.

Conroy, E., Turner, J.N., Rymszewicz, A., Bruen, M., O’Sullivan, J.J., Lawler, D.M., Stafford, S. and Kelly-Quinn, M., 2017. Further insights into the responses of macroinvertebrate species to burial by sediment. *Hydrobiologia* Available online ahead of print: https://link.springer.com/article/10.1007/s10750-017-3328-7

Deasy, C., Brazier, R.E., Heathwaite, A.L. and Hodgkinson, R., 2009. Pathways of runoff and sediment transfer in small agricultural catchments. *Hydrological Processes* 23: 1349–1358.

Deasy, C., Quinton, J.N., Silgram, M., Bailey, A.P., Jackson, B. and Stevens, C.J., 2010. Contributing understanding of mitigation options for phosphorus and sediment to a review of the efficacy of contemporary agricultural stewardship measures. *Agricultural Systems* 103: 105–109.

Dermisis, D., Abaci, O., Papanicolaou, A.N. and Wilson, C.G., 2010. Evaluating grassed waterway efficiency in southeastern Iowa using WEPP. *Soil Use and Management* 26: 183–192.

Duhallow LIFE project, 2016. Reduction and elimination of trampling and soiling of rivers by cattle by fencing vulnerable river bank sections. Available online: https://www.duhallowlife.com/sites/default/files/C2%20Final%20Technical%20Report%20-%20Fencing%20Report%20-%20Reduction%20and%20elimination%20of%20trampling.pdf (accessed 30 August 2017).

Engle, B.W. and Jarrett, A.R., 1995. Sedimentation retention efficiencies of sedimentation basin filtered outlets. *Transactions of the ASAE* 38: 435–439.

Evans, R., 2005. Monitoring water erosion in lowland England and Wales – a personal view of its history and outcomes. *Catena* 64: 142–161.

Evrard, O., Vandaele, K., van Wesemael, B. and Bielders, C.L., 2008. A grassed waterway and earthen dams to control muddy floods from a cultivated catchment of the Belgian loess belt. *Geomorphology* 100: 419–428.

Fiener, P. and Auerswald, K., 2003. Effectiveness of grassed waterways in reducing runoff and sediment delivery from agricultural watersheds. *Journal of Environmental Quality* 32: 927–936.

Fiener, P. and Auerswald, K., 2006. Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil and Tillage Research* 87: 48–58.

Fox, G.A. and Sabbagh, G.J., 2009. Comment on "Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis". *Journal of Environmental Quality* 38: 1–2.

Gangloff, M.M. and Feminella, J.W., 2007. Stream channel geomorphology influences mussel abundance in southern Appalachian streams, U.S.A. *Freshwater Biology* 52: 64–74.

Gharabaghi, B., Rudra, R.P. and Goel, P.K., 2006. Effectiveness of vegetative filter strips in removal of sediments from overland flow. *Water Quality Research Journal of Canada* 41: 275–282.

Golman, S.J., Jackson, K. and Bursztynsky, T.A., 1986. *Erosion and Sediment Control Handbook.* McGraw Hill, New York, NY.

Hardison, B.S. and Layzer, J.B., 2001. Relations between complex hydraulics and the localized distribution of mussels in three regulated rivers. *Regulated Rivers: Research & Management* 17: 77–84.

Harrington, S., 2016. *Suspended sediment and nutrient concentrations and loads in two Irish rivers.* PhD thesis, Cork Institute of Technology, Cork.

Harrington, S.T. and Harrington, J.R., 2013. An assessment of the suspended sediment rating curve approach for load estimation on the Rivers Bandon and Owenabue, Ireland. *Geomorphology* 185: 27–38.

Heiri, O., Lotter, A.F. and Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25: 101–110.

Hendry, K., Cragg-Hine, D., O'Grady, M., Sambrook, H. and Stephen, A., 2003. Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research* 62: 171–192.

Hershey, R. W. 1999. *Hydrometry: Principles and Practices*. John Wiley & Sons, Chichester, UK.

Ivanovich, E.V. and Hamid, K., 2014. An alternative approach for assessing sediment impact on aquatic ecosystems using single decision tree (SDT). *Journal of Water Sustainability* 4: 181–204.

Kay, P., Edwards, A.C. and Foulger, M., 2009. A review of the efficacy of contemporary agricultural stewardship measures for ameliorating water pollution problems of key concern to the UK water industry. *Agricultural Systems* 99: 67–75.

Kiely, G., Morgan, G., Quishi, X., Moles, R., Byrne, P., O'Regan, B., Jordan, P., Manary, W. and Daly, K., 2007. *Eutrophication from Agricultural Sources (Phosphorus and Nitrogen) – Soil and Phosphorus*. ERTDI Report 75, EPA, Ireland. Available online: http://www.epa.ie/pubs/reports/research/water/ertdireport75.html (accessed 30 August 2017).

Lawler, D.M., 2016. Turbidity, Turbidimetry and Nephelometry. In Reedijk, J. (ed.) *Chemistry, Molecular Sciences and Chemical Engineering.* Elsevier, Waltham, MA.

Lawler, D.M., Petts, G.E., Foster, I.D.L. and Harper, S., 2006. Turbidity dynamics during spring storm events in an urban headwater river system: the Upper Tame, West Midlands, UK. *Science of the Total Environment* 360: 109–126.

Layzer, J.B. and Madison, L.M., 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. *Regulated Rivers: Research & Management* 10: 329–345.

Liu, X., Zhang, X. and Zhang, M., 2008. Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. *Journal of Environmental Quality* 37: 1667–1674.

Lundekvam, H. and Skoien, S., 1998. Soil erosion in Norway. An overview of measurements from soil loss plots. *Soil Use and Management* 14: 84–89.

McHugh, M., Harrod, T. and Morgan, R.P.C., 2002. The extent of soil erosion in upland England and Wales. *Earth Surface Processes and Landforms* 27: 99–107.

May, L., Place, C., O'Hea, B., Lee, M., Dillane, M. and McGinnity, P., 2005. Modelling soil erosion and transport in the Burrishoole catchment, Newport, County Mayo, Ireland. *Freshwater Forum* 23: 139–154.

Michel, C., Schmidt-Posthaus, H. and Burkhardt-Holm, P., 2013. Suspended sediment pulse effects in rainbow trout (*Oncorhynchus mykiss*) — relating apical and systemic responses. *Canadian Journal of Fisheries and Aquatic Sciences* 70: 630–641.

Morales, Y., Weber, L.J., Mynett, A.E. and Newton, T.J., 2006. Effects of substrate and hydrodynamic conditions on the formation of mussel beds in a large river. *Journal of the North American Benthological Society* 25: 664–676.

Owens, L.B., Edwards, W.M. and Van Keuren, R.W., 1996. Sediment losses from a pastured watershed before and after stream fencing. *Journal of Soil and Water Conservation* 51: 90–94.

Owens, L.B., Malone, R.W., Hothem, D.L., Starr, G.C. and Lal, R., 2002. Sediment carbon concentration and transport from small watersheds under various conservation tillage practices. *Soil and Tillage Research* 67: 65–73.

Pulley, S., Foster, I. and Collins, A.L., 2017. The impact of catchment source group classification on the accuracy of sediment fingerprinting outputs. *Journal of Environmental Management* 194: 16–26.

Quinlan, E., Gibbins, C., Malcolm, I., Batalla, R., Vericat, D. and Hastie, L., 2015a. A review of the physical habitat requirements and research priorities needed to underpin conservation of the endangered freshwater pearl mussel *Margaritifera margaritifera*. *Aquatic Conservation: Marine and Freshwater Ecosystems* 25: 107–124.

Quinlan, E., Gibbins, C.N., Batalla, R.J. and Vericat, D., 2015b. Impacts of small scale flow regulation on sediment dynamics in an ecologically important upland river. *Environmental Management* 55: 671–686.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yoder, D., 1997. *Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE)*. Agricultural Handbook, Vol. 703. US Department of Agriculture.

Robertson, M., 2015. A study of sediment transport on the River Owenabue. MEng thesis, Cork Institute of Technology, Cork.

Ryder, E., de Eyto, E., Dillane, M., Poole, R. and Jennings, E., 2014. Identifying the role of environmental drivers in organic carbon export from a forested peat catchment. *Science of the Total Environment* 490: 28–36.

Rymszewicz, A., O'Sullivan, J.J., Bruen, M., Turner, J.N., Lawler, D.M., Conroy, E. and Kelly-Quinn, M., 2017. Measurement differences between turbidity instruments, and their implications for suspended sediment concentration and load calculations: a sensor inter-comparison study. *Journal of Environmental Management* 199: 99–108.

Sherriff, S.C., Rowan, J.S., Melland, A.R., Jordan, P., Fenton, O. and Ó hUallacháin, D., 2015. Investigating suspended sediment dynamics in contrasting agricultural catchments using *ex situ* turbidity-based suspended sediment monitoring. *Hydrology and Earth System Sciences* 19: 3349–3363.

Somma, F., 2013. Practical experiences and knowledge exchange in support of the Water Framework Directive Implementation (2010–2012). River Basin Network on Water Framework Directive and Agriculture. Joint Research Centre of the European Commission, Publications Office of the European Union, Luxembourg.

Thompson, J., Cassidy, R., Doody, D.G. and Flynn, R., 2014. Assessing suspended sediment dynamics in relation to ecological thresholds and sampling strategies in two Irish headwater catchments. *Science of the Total Environment* 468–469: 345–357.

Turley, M.D., Bilotta, G.S., Krueger, T., Brazier, R.E. and Extence, C.A., 2015. Developing an improved biomonitoring tool for fine sediment: combining expert knowledge and empirical data. *Ecological Indicators* 54: 82–86.

Turner, J.N., Brewer, P.A. and Macklin, M.G., 2008. Fluvial-controlled metal and As mobilisation, dispersal and storage in the Rio Guadiamar, SW Spain and its implications for long-term contaminant fluxes to the Donana wetlands. *Science of the Total Environment* 394: 144–161.

Vanmaercke, M., Poesen, J., Radoane, M., Govers, G., Ocakoglu, F. and Arabkhedri, M., 2012. How long should we measure? An exploration of factors controlling the inter-annual variation of catchment sediment yield. *Journal of Soils and Sediments* 12: 603–619.

Warburton, J., Evans, M.G. and Johnson, R.M., 2003. Discussion on "The extent of soil erosion in upland England and Wales". *Earth Surface Processes and Landforms* 28: 219–223.

Wilkinson, S.N., Dougall, C., Kinsey-Henderson, A.E., Searle, R.D., Ellis, R.J. and Bartley, R., 2014. Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. *Science of the Total Environment* 468–469: 1210–1224.

Willobee, M.R. and Kabbes, K.C., 2007. Regulatory issues in soil erosion and sediment control: ASCE EWRI MPCES subcommittee on regulatory tools. Restoring our Natural Habitat. *Proceedings of the 2007 World Environmental and Water Resources Congress*. 15–19 May, Tampa, Florida, USA, American Society of Civil Engineers, pp. 1–10.

Wood, P.J., Toone, J., Greenwood, M.T. and Armitage, P.D., 2005. The response of four lotic marcoinvertebrate taxa to burial by sediments. *Archiv für Hydrobiologie* 163: 145–162.

Wood, P.J., Vann, A.R. and Wanless, P.J., 2001. The response of *Melampophylax mucoreus* (Hagen) (Trichoptera: Limnephilidae) to rapid sedimentation. *Hydrobiologia* 455: 183–188.

Yuan, Y., Binger, R.L. and Locke, M.A., 2009. A review of the effectiveness of vegetated buffers on sediment trapping in agricultural areas. *Ecohydrology* 2: 321–336.

Abbreviations

DDS	Deposited sediment sampler
EPA	Environment Protection Agency
EPT (index)	Ephemoptera, Plecoptera, Tricoptera
GIS	Geographic information system
NTU	Nephelometric turbidity units
OPW	Office of Public Works
PERMANOVA	Permutational multivariate analysis of variance
Q	Discharge
SIMPER	Similarity percentage
SSC	Suspended sediment concentration
SSY	Annual specific sediment yield
SY	Annual sediment yield
T–SSC	Turbidity–suspended sediment concentration
TSS	Total suspended solids
WFD	Water Framework Directive

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 230

Sediment Flux - Measurement, Impacts, Mitigation and Implications for River Management in Ireland

Authors: Michael Bruen, Anna Rymszewicz, John O'Sullivan, Jonathan Turner, Damian Lawler, Elizabeth Conroy and Mary Kelly-Quinn

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Identify Pressures

The SILTFLUX project measured sediment flux at high temporal resolution and studied the biological response in selected river catchments of common typologies found in Ireland (focussing, on siliceous and calcareous geologies in combination with pasture and tillage land-uses). While sediment loads delivered by Irish rivers were low in comparison with many European rivers, deposited sediment was more closely associated with biological impact, although disentangling the impacts of sediment from other influences, such as nutrients, is challenging.

Inform Policy

While further study is required before definitive sediment thresholds for impact can be established, a precautionary deposited sediment cover target not exceeding 20% is recommended for the upper reaches of river networks. However, for areas with sediment-sensitive species, a lower target may be advisable. Coordination of methods between agencies collecting sediment data is recommended to facilitate inter-comparison of datasets. SILTFLUX produced a checklist of measures to reduce and mitigate sediment effects in sensitive habitats.

Develop Solutions

SILTFLUX showed that, with care, turbidity can be used to estimate suspended sediment flux in Irish rivers, but that site and instrument specific calibration equations are required. Long term datasets of these variables are required to establish reliable relationships. The project produced a list of measures for reducing sediment loads and mitigating their effects. The project developed a modelling approach from its own data that could be extended with additional data to estimate sediment flux from ungauged small catchments which can contribute to a national sediment yield map.

The project showed that visual methods for estimating deposited sediment are useful and recommends that the methodology be standardised to enhance the usefulness of such data and in particular their relationship with reference conditions.

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