Science of the Total Environment 468–469 (2014) 345–357

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessing suspended sediment dynamics in relation to ecological thresholds and sampling strategies in two Irish headwater catchments

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HIGHLIGHTS

- We assessed the dynamics of fine sediment concentrations in two headwater catchments.
- Exceedances of FFD guidelines were found be 8.3% and 17.8% of the monitoring period.
- Exceedances were short in duration, in contrast to receptor response experiments.
- The 7 h sampling method was found to predict exceedance most accurately.

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form 22 August 2013
Accepted 23 August 2013
Available online 14 September 2013

Editor: Eddy Y. Zeng

Keywords:
High resolution monitoring
Suspended sediment
Turbidity
Sampling frequency
Load estimation
Exceedance frequency

ABSTRACT

Prediction of the impact of suspended sediment on aquatic ecosystems requires adequate knowledge of sediment dynamics in surface waters. Often, studies reporting the response of aquatic biota to suspended sediment are concerned with concentrations, while catchment erosion studies often report sediment delivery as annual loads and yields, making the comparison to documented ecological impacts difficult. Similarly, the European Union Freshwater Fish Directive (FFD) (78/659/EC) stipulates a guideline value of 25 mg l^{-1} which should not be exceeded, with the exception of floods and droughts. In this respect, the significance of suspended sediment in two Irish rivers was assessed using turbidity sensors calibrated for suspended sediment. Sediment yields of 0.07 tonnes (t) ha^{-1} $year^{-1}$ and 0.44 t ha^{-1} $year^{-1}$ and annual FFD exceedance frequency of 8.3% and 17.8% were estimated for the two catchments. Contrasts in the frequency of exceedance events between both catchments was observed, yet duration was typically short (<5 h). Additionally, this study evaluated different sampling resolutions to assess the impact on estimated loads and exceedance frequency. Increasing resolution improved accuracy and reduced uncertainty, with the 24–7 'Plynlimon' sampling method (sampling every 7 h) providing the best solution to estimating both loads and exceedance. This study documents some of the first data on sediment dynamics in Ireland and indicates that periods of elevated suspended sediment concentration in the two study catchments may be significant.

1. Introduction

Rivers and streams carry sediment comprised of both organic and inorganic material suspended in the water column (Droppo, 2001). The quantity of suspended sediment fluctuates with discharge in response to processes occurring along the transfer continuum linking sources, mobilisation, delivery, and impact (Haygarth et al., 2005). In addition, the magnitude of sediment loss from the landscape can be enhanced to varying degrees by agricultural activity (Collins et al., 2012; Silgram et al., 2010; Withers and Haygarth, 2007; Withers et al., 2006) and industrial effluents (Collins et al., 2010). Sediment loss is not only a concern from a soil erosion perspective (on-site problems), but also its impact on aquatic ecosystems (off-site problems) (Bilotta et al., 2012b).

Off-site problems are extensive, and high suspended sediment concentrations (SSC) within streams can lead to mortality of riverine fish during the embryonic life-stage (Greig et al., 2005; Heywood and Walling, 2007), alteration of local species composition by invertebrates drifting with sediment (Quinn et al., 1992), restriction of periphyton growth (Yamada and Nakamura, 2002) and the reduction of light penetration within the water column thereby limiting primary productivity (Cloern, 1987). Furthermore, suspended sediment can enhance the delivery of phosphorus (P) (Ballantine et al., 2009; Quinton et al., 2001). This directly increases the abundance of rooted macrophytes (Rattray et al., 1991) leading to increased sedimentation, particularly in lowland catchments (Heppell et al., 2009).

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http://dx.doi.org/10.1016/j.scitotenv.2013.08.069

To address these issues, the European Union (EU) Water Framework Directive (WFD) (2000/60/EC) has been instrumental in adopting a cohesive approach to achieving good ecological status of all water bodies by 2015. The WFD recognises the importance of pollutant loadings on chemical water quality, but also places particular emphasis on its impact on biological communities and on ecosystems. Transposition of the WFD into national legislation has led to the management of freshwaters at the scale of river basin districts; with detailed programmes of measures (POMs) to be implemented from 2012 (Doody et al., 2012a).

Existing EU legislation regarding SSC within freshwaters is minimal. However, the EU Freshwater Fish Directive (78/659/EC) contains a guideline value of 25 mg l^{-1} for streams suitable for salmonid and cyprinid fish, which should not be exceeded except during storms or droughts. The FFD will be repealed from 2013 with designated FFD habitats falling under the protection of the WFD. Limitations of the FFD 25 mg l^{-1} guideline value have been repeatedly highlighted within the literature (Bilotta and Brazier, 2008; Kemp et al., 2011), with criticism pointing to evidence of variable species preference (Bilotta et al., 2012a) and response of aquatic biota to SSC (Collins et al., 2011). Many of the laboratory experiments that form the evidence base for this threshold, vary in dosage, duration, and the geochemical composition of the particulate material the organisms are exposed to, making comparison difficult (Bilotta and Brazier, 2008) and presents a challenge for setting SSC targets and predicting ecosystem improvement and degradation trajectories (Bilotta et al., 2012a; Sarr, 2002).

Studies of sediment loss are traditionally concerned with loads in order to characterise on-site problems (erosion), yet the vast majority of receptor-response literature related to sediment is primarily concerned with concentration and duration (Collins et al., 2011). The applicability of dosage values reported in laboratory experiments to natural conditions observed in UK and Irish catchments is questionable. For example, a study by Bilotta et al. (2010) reported SSC to reach 1140 mg l^{-1} in a headwater stream, yet occurrences of SSC in excess of 100 mg l^{-1} were restricted to <10% of the 6 month study period. Reviews of receptor response for macro-invertebrates and riverine fish by J.I. Jones et al. (2012) and Collins et al. (2011) detail ranges of dosage from well in excess of these values up to 207 000 mg l^{-1}, and duration of exposure up to 1152 h, with the majority of studies reviewed detailing dosage values >500 mg l^{-1}. Nevertheless, characterisation of dosage or exceedance frequency dynamics within UK and Irish catchments is urgently required to inform receptor-response experiments. Modelling using approaches such as Collins and Anthony (2008) provide regional assessments of average SSC. Although these may present good indications of water quality, estimations using annual sediment and runoff yields remain problematic. For example, the poor relationship between SSC and flow, and high levels of uncertainty associated with sediment rating curves is well documented (Rustomji and Wilkinson, 2008). Accordingly, using sediment and runoff yields to derive mean annual SSC may fail to predict high SSC during periods of low flow, and also fail to capture the characteristics of each exceedance event in terms of its duration and frequency. Furthermore, the assessment of exceedance frequency dynamics may require high resolution data capture, yet water quality monitoring by public bodies is typically spatially extensive but temporally coarse (Foy et al., 2003).

In light of these issues, this study utilised near-continuous turbidity data as a surrogate for SSC in two catchments to (1) assess whether SSC dynamics are significant in relation to EU ecological thresholds by examining the extent to which they exceed FFD guideline values, and (2) to assess the appropriate sampling regimes to characterise SSC in Irish headwater streams to inform regulatory bodies tasked with monitoring regional water quality.

1.1. Study sites

Study sites were located in Co. Down, Northern Ireland and Co. Louth, Republic of Ireland (Fig. 1) and are referred to herein as the Down Catchment (+54° 32′ N,−5° 35′ E) and Louth Catchment (+53° 45′ N, −6° 27′ E), respectively.

The Down Catchment drains a 752 ha area, with elevations between 0 m and 60 m Ordnance Datum (OD), while the Louth Catchment drains 2096 ha, with elevations between 80 m and 220 m OD.

Land use classifications into arable, improved grassland and broad-leaved woodland were 16.7%, 65.2%, and 12.1% for the Down Catchment, and 14.6%, 77.8% and 2.4% for the Louth Catchment. Although land use classifications between the two catchments were comparable as both catchments were dominated by improved grassland, the Down Catchment has a greater percentage of broad-leaved woodland. As noted in Thompson et al. (2013), sediment inputs to surface water receptors from these sediment source classifications were predicted to fall between 6–10%, 84-87%, 4%, and 2–3% within the Down Catchment and 79–85%, 10–17%, 2–3% and 2–3%, within the Louth Catchment for sediment contributions from arable, channel bank, grassland, and woodland sources, respectively. Further information regarding the uncertainties of these predictions is reported in Thompson et al. (2013).

Soils within the Down catchment were comprised of gleys (42.5%), rankers (41.5%), alluvium and organic alluvium (14.8%), peat (0.6%) and brown earth (0.6%). The Louth catchments were also dominated by gleys (72.3%), with the remainder comprising of lithosol and regosol (13.6%), brown earths (8.9%), alluvium (4.4%), artificial material (0.7%) and podsol (0.1%).

Both sites are underlain by low permeability bedrock units, part of the Southern Uplands-Longford-Down terrane, with sandstone and shale greywackes with some Tertiary dykes in the Down Catchment and faulted series of greywacke and tuffs in the Louth Catchment. Bedrock at both sites are overlain by glacial tills in the form of drumlins in the Down Catchment and by a more complex combination of often thick glacial and fluvioglacial sediments in the Louth Catchment.

In the Down Catchment, 32% of the catchment area had slope gradients >5%, whereas in the Louth Catchment this figure was 41%, indicating a greater proportion of high slope values, associated with greater susceptibility to erosion.

2. Methods

2.1. Sampling and laboratory analysis

Campbell Scientific OBS 3+ sensors and data loggers (CR200X Series) were installed at the outlet of each catchment to record turbidity at 15 min time steps, corresponding to discharge measurements. Probes were positioned within the thalweg, or a well mixed section of the stream channel, at each monitoring station to ensure representative measurements. Probes were manufacturer calibrated with an accuracy of 0.5 NTU and minimal annual drift of <2%.

Equipment was installed at the catchment outlet to monitor the hydrological response of both the Louth and Down Catchments over the 2011–12 hydrological season. Discharge was measured at 15 min intervals, using a rated weir in combination with an OTT Orpheus Mini pressure transducer positioned in a stilling-well located >1 m up-stream of the weir. Flow calming sections upstream of the measuring point for both field sites had a length in excess of 3 m. Catchment rainfall was measured at 15 min intervals using a tipping bucket rain gauge.

One complete year was used in this analysis, spanning the period 29th September 2011–29th September 2012 for the Down Catchment and 16th November 2011–16th November 2012 for the Louth Catchment.

Turbidity values were related to stream SSC by sampling stream water during storm events, complemented by sampling of non-flood periods on a monthly to bi-weekly basis during 2011 and 2012. Stream water sampling was conducted using an ISCO 6712 automatic sampler with a 24 x 1 l sampling capacity. Automatic sampling frequency during storm events was set to hourly intervals and triggered manually, prior to incoming weather fronts. Cross-contamination of samples was minimised by setting 3 × 30 s rinse and purge cycles before each 1