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Influence of a cattle access point on temporal changes in stream turbidity

M. ONeill[1], C. Briciu-Burghina[1], E. Jennings[2], P. Antunes[2], D. Ó hUallacháin[3], M. Kelly-Quinn[4], M. O'Sullivan[4] and F. Regan[1†]

[1]Water Institute, School of Chemical Sciences, Dublin City University, Glasnevin, Dublin 9, Ireland
[2]Centre for Freshwater and Environmental Studies, Department of Life and Health Sciences, Dundalk Institute of Technology, Dundalk Co. Louth, Ireland
[3]Teagasc, Crops, Environment & Land Use Programme, Johnstown Castle Research Centre, Wexford, Ireland
[4]School of Biology and Environmental Science and UCD Earth Institute, University College Dublin, Belfield, Dublin 4, Ireland

Abstract

Unrestricted cattle access can have negative impacts on aquatic systems, including increases in stream water turbidity and suspended sediment levels. Many agri-environmental policies require the exclusion of livestock from waterbodies; however, data that quantify these impacts are scarce. This study used sensors measuring turbidity, a proxy for suspended sediment, together with motion-detecting cameras, to examine the influence of cattle in-stream activity on water quality in north-east Ireland. Two nephelometers, which automatically measured and logged turbidity, were placed upstream and downstream of a cattle access point in July 2017, while cameras were used to record cattle behaviour. A second deployment was made during February 2018 when cattle were absent. During low flows, frequent short-lived increases in turbidity were recorded at the downstream nephelometer only. These coincided with cattle accessing the water. There was a significant positive relationship between the longitudinal differences (downstream − upstream) in turbidity and the total number of cattle accessing the stream. There was no relationship between turbidity and stream discharge in July (when cattle were present), although that period was dominated by lower flow levels, with only 2 days in which discharge increased above baseflow. In contrast, there were no similar short-lived increases in turbidity in February 2018 when cattle were absent from the field, but there was a strong significant positive relationship between stream discharge and turbidity. These results highlight the consequences of cattle access for water column turbidity levels, particularly during periods of low streamflow, and therefore inform future agri-environmental policy in Ireland.

Keywords

Automatic monitoring • cattle • turbidity • water quality

Introduction

Cattle are attracted to riparian areas as they provide shade, palatable vegetation and drinking water (Haan *et al.*, 2010; Bond *et al.*, 2012). Facilitating animal access to watercourses allows farmers to have an affordable, low-maintenance source of water for their livestock. However, cattle access too can have detrimental effects on water quality, leading to increases in the concentrations of suspended sediment, nutrients and pathogens (O'Callaghan *et al.*, 2019; O'Sullivan *et al.*, 2019a, 2019b; Vidon *et al.*, 2008). It can also lead to erosion of riparian margins and banks at the access point, thus potentially altering the hydrology and the drainage pathways of the site, as well as disturbing the bed sediment. Studies have also shown that cattle preferentially urinate and defecate in watercourses which may elevate organic matter, nutrients and microorganisms (Bond *et al.*, 2012). Bed sediments can be an important reservoir of nutrients and bacteria which may be resuspended into the water by cattle movement (Terry *et al.*, 2014). High levels of resuspended fine sediment can increase water column turbidity, and can therefore limit light penetration and reduce primary productivity (Hickey & Vickers, 1994; Davies-Colley *et al.*, 2008; Izagirre *et al.*, 2009). Elevated sediment levels can also negatively affect aquatic macroinvertebrates (Jones *et al.*, 2012a, 2012b; Conroy *et al.*, 2016). For species of conservation concern, such as the freshwater pearl mussel *Margaritifera margaritifera*, excessive fine sediment can impede shell development, growth, the filter

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[†] Corresponding author: F. Regan
E-mail: fiona.regan@dcu.ie

feeding ability of adults and juvenile survival, and is cited as a primary factor in their decline (Geist & Auerswald, 2007; Hauer, 2015; Leitner *et al.*, 2015).

Exclusion of cattle from watercourses is a widely used mitigation measure to address declines in water quality. Studies by Owens *et al.* (1996) and McKergow *et al.* (2003) have demonstrated that fencing significantly reduced sediment yield in runoff from pastures, while Collins *et al.* (2010) observed a reduction in the contribution of stream bank sediment to the sediment load in salmon spawning gravels in England following implementation of riparian fencing. In the absence of cattle, riparian vegetation also has an opportunity to establish, thus stabilising banks (Scrimgeour & Kendall, 2003). Measures to exclude livestock from streams and rivers have been included in many European agri-environment schemes (AES) (Dworak *et al.*, 2009). In Ireland, past AES included either partial exclusion (e.g. the Rural Environment Protection Scheme [REPS]) or full exclusion (e.g. the Agri-Environment Options Scheme [AOES]) measures to restrict stream access by cattle. The most recent Irish AES, the Green Low-carbon Agri-environment Scheme (GLAS) was part of the Rural Development Programme 2014–2020. This contained similar measures to AEOS aimed at reducing inputs to watercourses, including the establishment of riparian buffers and the prevention of bovine access to waterways. Although such measures are commonly implemented, relatively few studies have quantified the effects of cattle on suspended sediment or turbidity in a European or Irish context (see O'Callaghan *et al*., 2019). A study by O'Sullivan *et al*. (2019a) found higher levels of fine sediment in the bed downstream from cattle access points in five Irish catchments. Those study locations included the site used in the current paper. The higher fine sediment levels observed by O'Sullivan *et al*. (2019b) were spatially confined to, in most cases, the area immediately downstream of the point of cattle access. The study design, however, did not link the changes in fine sediment directly to cattle movement.

Turbidity is a measure of the optical properties of water and is frequently used as an indicator of water column suspended sediment levels (Riley, 1998). Turbidity sensors (nephelometers) can be deployed for long periods and can log real-time data. They are advantageous over discrete grab sampling of the water column, normally used to measure suspended sediment, as they capture changes at high frequency, ensuring that scarcer events are captured (Voigt *et al*., 2007; O'Flynn *et al*., 2010). A previous study by Terry *et al*. (2014) in the UK (that used sensors) found no statistical relationship between high levels of turbidity and cattle numbers, but did find that the majority of occasions when turbidity was high were associated with cattle presence in the stream.

The aims of the current study were to assess whether a relationship between cattle access and turbidity could be found and to quantify this effect. It used a combination of *in situ* nephelometers and motion-activated cameras. Wilson & Everard (2018) demonstrated that cattle trampling has an impact on sediment mobilisation using turbidity data. However, this Irish study represents important evidence of the impact of cattle access, using camera and sensor data, on turbidity and thus water quality. A better understanding of the impact of cattle in-stream activity on water quality parameters will provide important information for policymakers in relation to the Nitrates and Water Framework Directives. It will also help guide agri-environmental policy and facilitate sustainable objectives under the EU Farm to Fork Strategy (EC, 2020).

Materials and methods

Study site and period

The study took place in the north-east region of the Republic of Ireland, in 2017. The study site was located in close proximity (upstream) to the Agricultural Catchments Programme (ACP)-monitoring site in County Louth (53°5005.9"N 6°2453.2"W). The ACP is an intensive, high-resolution, monitoring programme assessing farming impacts on water quality. Precipitation at the site is typical of areas in eastern Ireland, with an annual total precipitation of 756 mm/yr in 2017 and rainfall occurring 244 days. The land in the study field was used as a grazing area for cattle. In 2017, it had approximately between 10 and 25 heifers and 2 and 6 dairy cows present. The field was bordered on its north-eastern side by the Commons River, which is a tributary of the White River, from which cattle could access the stream (Figure 1). The stream width at the access point was between 1 m and 3 m depending on discharge. The access point was only accessible from one side of the river. Electric fencing prohibited cattle from going further upstream or downstream from the access point (Figure 1).

Instrumentation and deployment

Two multi-parameter sondes (Model YSI 6600 EDS V2-2) were deployed: one 3 m upstream and one 1 m downstream from the cattle access point (Figure 1). Each sonde was equipped with a nephelometer (YSI 6136), protected by a mechanical wiper and measuring turbidity in nephelometric turbidity units (NTU). The sondes were deployed between 12 June 2017 and 30 June 2018, with a 15-min sampling frequency. Other parameters available from the sondes, but not discussed here, include temperature, conductivity and pH. Data from 6 to 30 July 2017 when cattle were present in the field were used in this study. In addition, a period from 1 to 28 February 2018 when cattle were absent was used to illustrate an equivalent time period but without cattle accessing the stream.

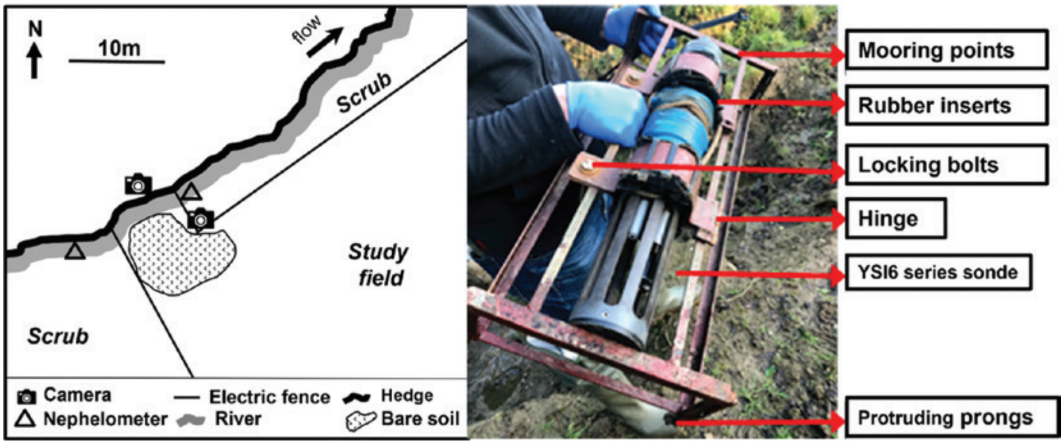

Figure 1. Diagram of the study cattle access point showing the location of the upstream and downstream nephelometers and the cameras (left). Mounting frame used in the stream for horizontal sonde deployment (right).

For sensor deployment, two custom-made steel frames were built *in-house* to allow horizontal deployment and ensure the probes were completely submerged, particularly in dry periods (Figure 1). The sondes were secured with hinged steel covers that were bolted. The steel securing the sonde was also lined with rubber to ensure that the sondes were locked within the cage. Sondes were placed in the middle of the stream, fixed in the streambed via protruding prongs and further secured with rope to a mooring point on the riverbank. Sensor service was carried out every 3 months in the laboratory. Briefly, the sensors were thoroughly cleaned and assessed for water intrusion. If required, batteries, O-rings and wiper assemblies were changed. A two-point calibration was carried out following manufacturer recommendations using the 100-NTU standard (part number 607300) and deionised water. Prior to deployment, the sensors were allowed to run overnight in the same sample to ensure the readings are consistent and there is no significant sensor inter-variability.

Site visits were carried out every 2–4 weeks to ensure sensors were operational. At each site visit, the data were transferred to a laptop and the sonde was removed from its cage, cleaned, inspected for damage and then redeployed. Calibration checks were carried out in the field using a portable turbidity meter Turb® 430 IR (VWR, Dublin, Ireland), calibrated prior to each site visit. A calibration criterion of ±5% of the measured value was used to determine if the sensor required calibration. If the calibration criterion was breached, a drift correction was applied as described by Wagner *et al*. (2006), between two service dates. Sensor drift due to fouling generally begins as soon as the sensor is deployed and was therefore assumed to occur at a constant rate. A zero correction was applied at the start of the interval, while the full correction was applied at the end of a period. Between these dates, the data were linearly interpolated. The following equation (Horsburgh *et al*., 2010) was used:

$$V_c = V + (V_f - V_s)\left(\frac{T_t - T}{T_t}\right)$$

where V_c is the drift-corrected value; V is the original measured value; V_f is the response of the sensor immediately before cleaning and validation at the end of the correction interval; V_s is the response of the sensor after cleaning and calibration; T_t is the total time interval for which the correction is applied and T is the time between the end of deployment and the time when the value is measured.

Motion detection

The study aimed to determine the impact of cattle “events” on stream turbidity. An event was defined as a time with continuous cattle activity in the watercourse. Image data at the cattle access site were captured by two Bushnell Trophy HD motion-activated cameras (Model 119676) located to capture images from two different angles: one situated at the downstream side and one front-facing (Figures 1 and 2). The cameras worked by detecting the motion of cattle entering and leaving the stream. The cameras also included infra-red night vision which captured any events taking place in darkness. Cameras were inspected during site visits for damage and to ensure they were still in the correct line of sight. The images were stored on a memory card and downloaded for further examination.

Data management and statistical analysis

Data for cattle access to the stream were extracted from the camera images, including (1) the time that cattle entered the

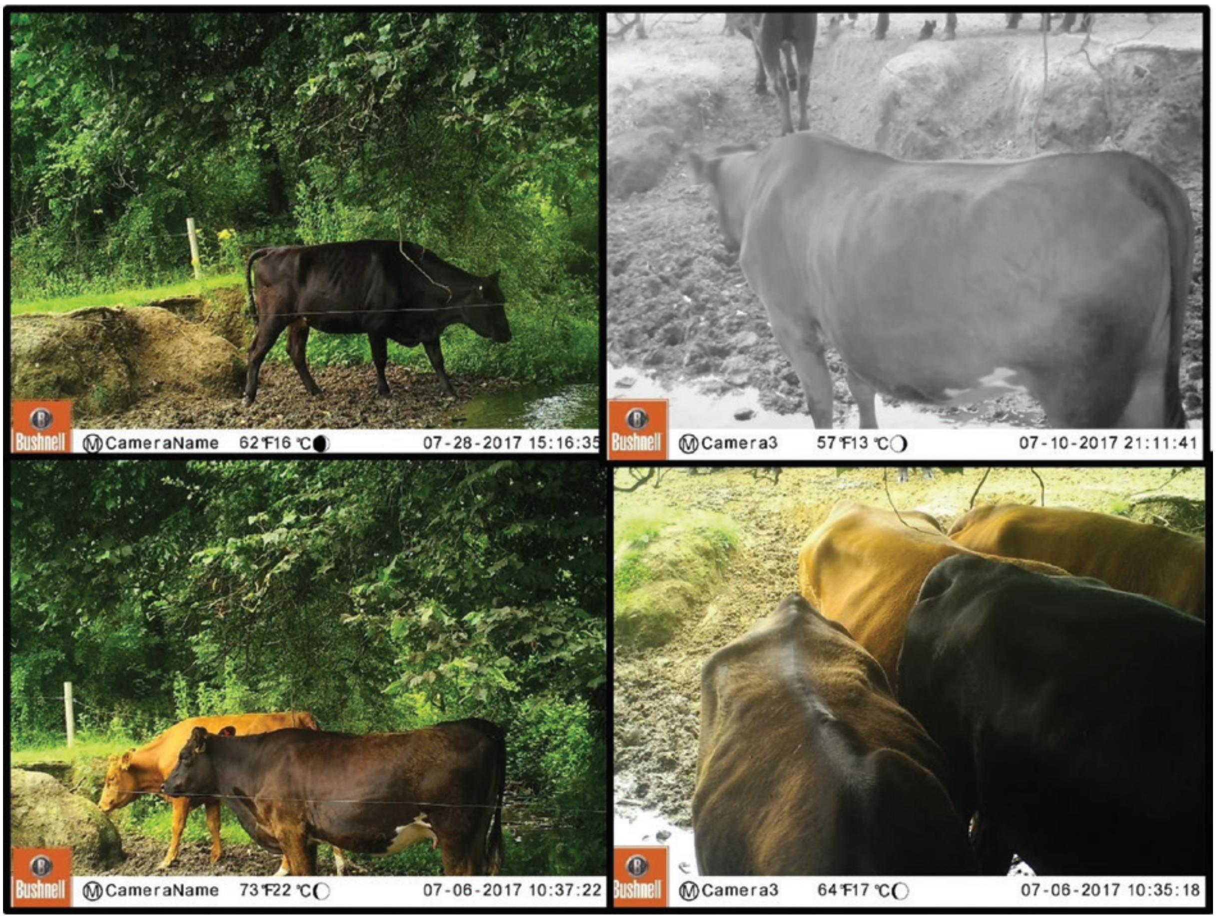

Figure 2. Top and bottom right: images from the side camera including one infra-red image taken at 21.11 in the evening; top and bottom left: images from the front camera.

stream, (2) the number of cattle entering the stream and (3) the time when they exited the stream. A cattle access event was defined as a time with continuous cattle access, with the event start being defined as the time when cattle first entered the stream, and the event end being defined by a period of at least 5 min with no cattle in the stream. Events, where humans and animals other than cattle (dogs, foxes, etc.) entered the water, were noted but not used in statistical analysis as these were able to venture further upstream and downstream than the cattle. When more than 5 min elapsed between cattle exit from the stream and the entry of more cattle, this was counted as the start of a new cattle event. The duration of each event from the first entry to the last exit of the cattle was also recorded. Each movement by cattle triggered an image capture, ensuring that many images were available for each event. As animals were often bunched tightly together (Figure 2), multiple images were used to estimate the total number of cattle entering the stream over any event duration.

The longitudinal differences (downstream − upstream) in turbidity between the upstream and downstream nephelometers were calculated for every 15-min time step. As turbidity was recorded every 15 min, but cattle events lasted up to 34 min, the maximum difference in turbidity during any total event period was used in the statistical analyses. When an event had a duration of less than 15 min and no turbidity data were available during the event, the nephelometer data closest to the end of that event were used.

The relationship between the longitudinal difference in turbidity during the July study period and the total number of cattle entering the stream during an event was assessed using a generalised additive mixed model with a cubic regression smoothing spline using the mgcv package (Wood, 2006) in R (version 4.1.1) (R core team, 2021). The same approach was used to assess the relationships between (1) turbidity at each nephelometer and (2) the longitudinal difference in turbidity and stream discharge. All models were tested for

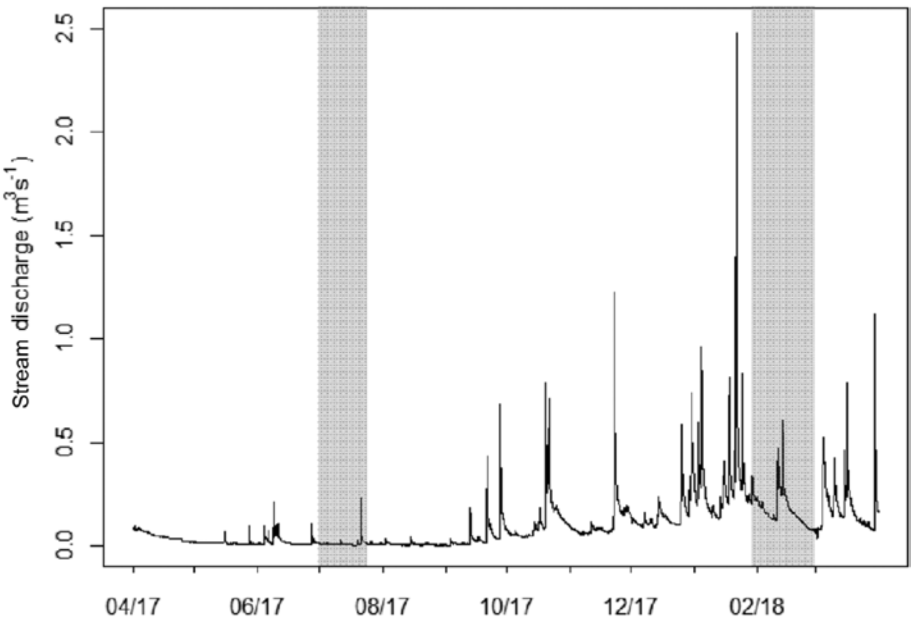

Figure 3. Time series of stream discharge from 1 April 2017 to 30 March 2018. The shaded areas are the study periods of 6–30 July 2017 (1) and 1–28 February 2018 (2).

violations of the assumptions of homogeneity, independence and normality, and correlation or variance structures included as appropriate following Zuur *et al.* (2009).

Stream water level data were collected by an Orpheus Mini OTT HydroMet sensor (OTT HydroMet, Kempten, Germany) adjacent to a Corbett non-standard flat-v weir) located 280 m downstream of the cattle access site at the Teagasc ACP study site. The level data were used to calculate discharge based on a rating curve (using flow meters and the WISKI 10-SKED rating curve editor (Shore *et al.*, 2016)) in cubic meter per second ($m^3\ s^{-1}$). Mean hourly data for the annual cycle for the period 1 April 2017 to 30 March 2018 were used in this study. The 5th percentile and the 95th percentile were extracted from the data for this overall period. Summary data were also extracted for the two study periods of 6–30 July 2017 and 1–28 February 2018.

Results

Changes in stream discharge

Stream discharge had a typical annual cycle and was higher between the months of September 2017 and March 2018, with generally lower rates between April and September 2017 (Figure 3). The overall 5th percentile and 95th percentile of discharge values for the site for the period from 1 April 2017 to 30 March 2018 were 0.004 and 0.315 m^3/s, respectively. A summary of data on stream discharge, maximum number of cattle, duration and longitudinal difference in turbidity is shown in Table 1.

Table 1: Summary data on stream discharge, maximum number of cattle, duration and longitudinal difference in turbidity (NTU difference) for each cattle access event between 6 and 30 July 2017

Variable	Min	Max	Median	Mean	s.d.
Discharge (m^3/s)	0.003	0.226	0.007	0.011	±0.017
Upstream turbidity (NTU)	0.7	211.9	2.3	5.0	±15.2
Downstream turbidity (NTU)	1.0	187.1	3.0	6.1	±14.9
NTU difference: all times	−24.8	159.9	0.6	1.0	±5.9
NTU difference: in events	−8.6	159.9	2.8	16.2	±30.7
No. individual cattle per event	1.0	12.0	4.0	3.9	±2.7
Event duration (min)	<1	34	5	7	±7

NTU = nephelometric turbidity units; s.d. = standard deviation.

Turbidity levels in the two study periods

The turbidity data for the nephelometers deployed upstream and downstream of the cattle access site had similar overall ranges, and summary values in July 2017 are given in Table 1. For both sensors, the maximum values (211.9 NTU, upstream; and 187.1 NTU, downstream) coincided with the high-flow event on 21–22 July (Figure 4C). The longitudinal differences in turbidity for this July study period, however, ranged from −24.8 NTU to +159.9 NTU. Negative values indicated higher turbidity at the upstream sensor, while the most negative value (−24.8 NTU) was during the high-flow event on 22 July. Short-lived positive differences greater than 5 NTU occurred on a total of 68 of 2,400 measurement occasions over the 25 days of the study (2.8%) (Figure 4C). These abrupt increases in turbidity in the downstream data were not apparent during the high-flow event on 21–22 July. There was no similar erratic pattern in turbidity in the February 2018 study period in either the upstream or downstream nephelometer, with both sensors showing strong synchronous increases and decreases (Figure 4D). The maximum turbidity levels recorded both upstream and downstream of the access point during that period were similar at 176 and 170 NTU, respectively, and the two datasets had the highest values coinciding with values of higher stream discharge.

Cattle access during 6–30 July 2017

The minimum number of cattle entering the water (i.e. an event) in July 2017 was 1, while the maximum was 12 (Table 1 and Figure 5), with a median of four cattle per event. Events when seven or more cattle entered the stream were less frequent, only happening six times over the course of the study period. For comparison, events with less than seven cattle entering the stream occurred on 60 occasions. The duration of cattle events varied from less than 1 min to a maximum of 34 min (Table 1). These duration data had a relatively high standard deviation of ±7 min. Cattle spending longer than 13 min in the stream were always in groups of two or more. It was notable that cattle also entered the stream on 21–23 July when there was an increase in streamflow in response to precipitation (Figure 4C). The average event duration for the days when discharge was higher, 21–23 July, was 4 min 27 s (*n* = 11), with an average maximum number of cattle of 4, while that for

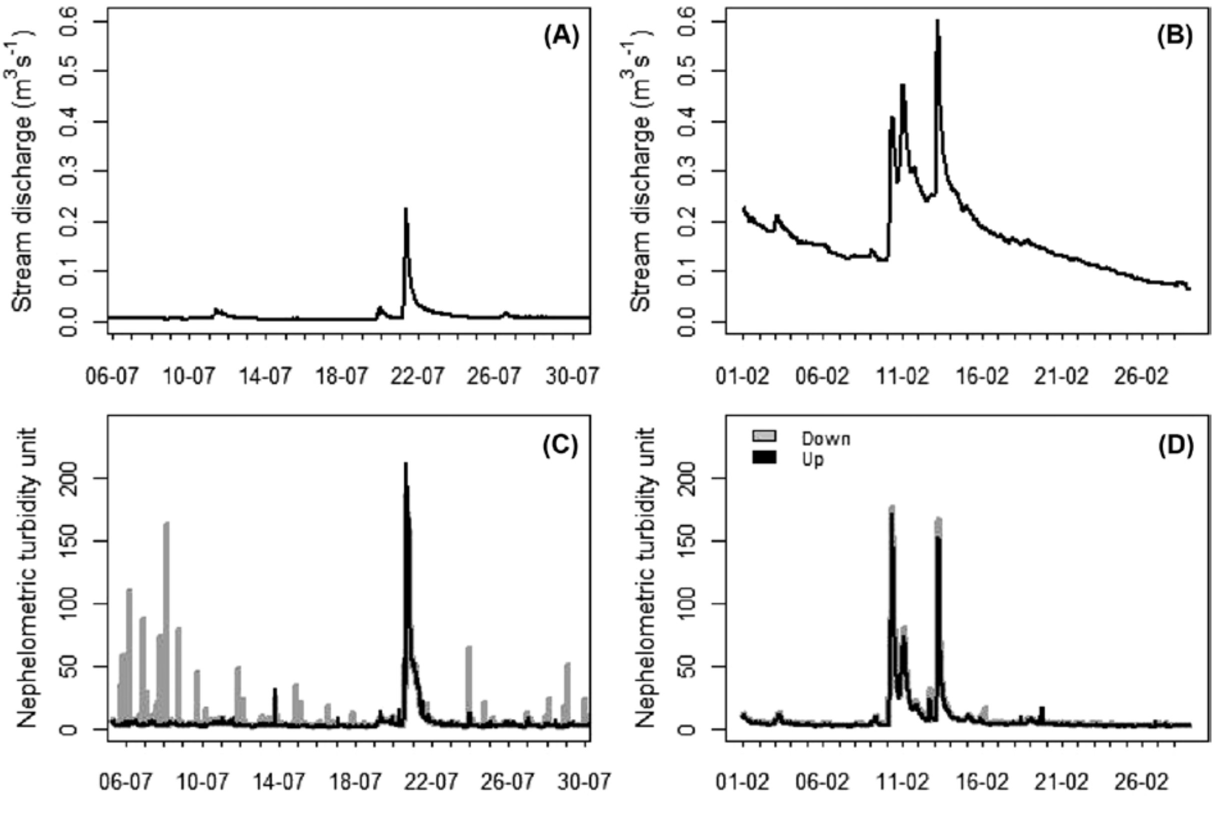

Figure 4. Time series of hourly stream discharge data for a period when cattle were in the field ((A) 6–30 July 2017) and when cattle were not in the field ((B) 1–28 February 2018); time series (every 15 min) of turbidity levels for upstream (black) and downstream (grey) of the cattle access point for 6–30 July 2017 with the maximum number of cattle accessing the stream (C); for 1–28 February 2018 (D).

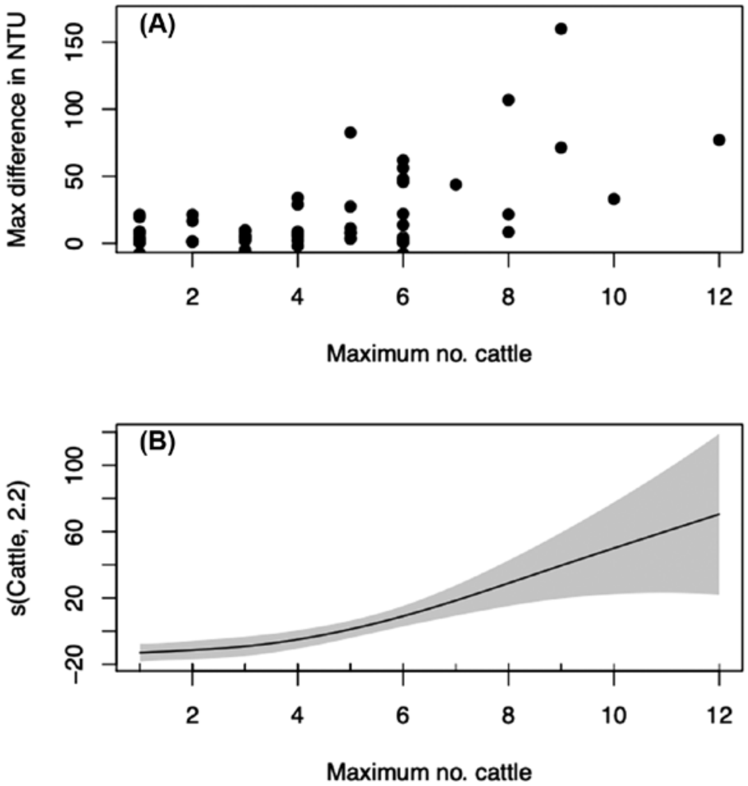

Figure 5. (A) Maximum number of cattle entering the stream versus maximum longitudinal difference in nephelometric turbidity units (NTU); (B) Smoother for the generalised additive models: maximum longitudinal difference in turbidity = response variable, and maximum number of cattle = independent variable. The Y-axis units are the centred linear predictor of the model with the estimated degrees of freedom also given in the Y-axis title.

3 days prior to this period (15–17 July) was 2 min 45 s (*n* = 5) with an average of four cattle. No cattle were recorded on 18 and 19 July and likely were absent from the study field.

Relationship between turbidity levels, cattle access and stream discharge

There was a significant relationship between the number of cattle accessing the stream in an event and the longitudinal difference in turbidity (R^2 adjusted = 0.22, estimated degrees of freedom [edf] = 2.16, $P < 0.0001$) (Figure 5A and B). The relationship was non-linear, as indicated by edf of greater than 1 (Zuur *et al.* 2009), and generally positive with higher values when more than six cattle accessed the stream. There was no significant relationship between stream discharge and the longitudinal difference in turbidity during the period with cattle in July 2017. There was also no significant relationship between stream discharge and the turbidity data from either nephelometer for this study period.

In contrast, there was a significant positive and non-linear relationship for the study period in February when cattle were absent from the field (Figure 6A and B, R^2 adjusted = 0.56, edf = 8.19, $P \leq 0.0001$). It was notable that the plot of turbidity versus stream discharge for February 2018 also indicated two differing relationships for the first and second high-flow events, with higher turbidity being associated with the first of the two events (Figure 6A).

Discussion

Turbidity is a measure of the concentration of suspended sediments. Investigating the transport of suspended solids by water sampling can lead to an underestimation of loads, and an unrealistically high sampling frequency is required to properly characterise temporal trends. An alternative method is to use *in situ* optical turbidimeters to estimate the concentration of suspended solids. Gippel (1995) reported that the relationship between turbidity and concentration of suspended solids is potentially confounded by variations in particle size, particle composition and water colour. The study found that turbidity instruments were most sensitive to dispersions with a median diameter of 1.2–1.4 µm. Some

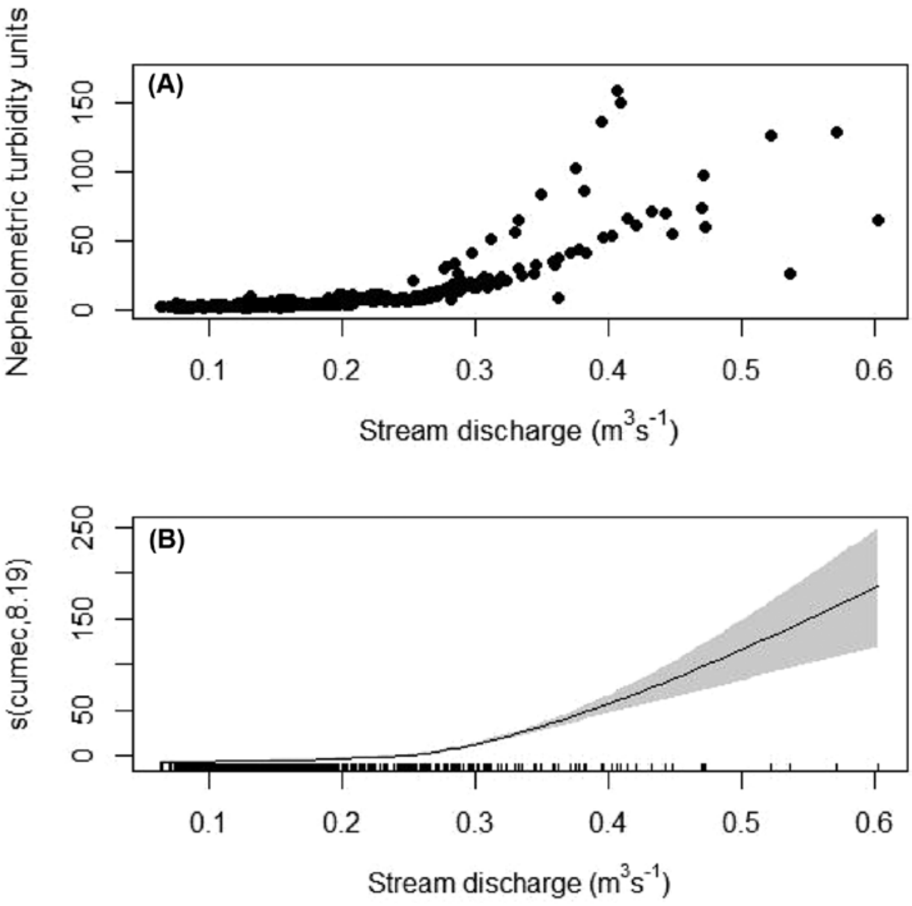

Figure 6. (A) Nephelometric turbidity units (NTU) versus stream discharge for 1–28 February 2018; (B) Smoother for a generalised additive model with NTU as the response variable and stream discharge ($m^3 s^{-1}$ = cumec) as the independent variable. The Y-axis units represent the centred linear predictor of the model. The estimated degrees of freedom are also given in the Y-axis title.

variance can be tolerated because a continuous estimate of the concentration of suspended solids overcomes the problem of infrequent sampling, which is the greatest source of error in the estimation of stream sediment loads. In this work, turbidity measurements were recorded at a frequency of every 15 min over several months, therefore providing an excellent opportunity to investigate cattle access impacts.

Sediment input to streams is a natural occurrence and crucial to sustaining good ecological diversity, biota dynamics and biogeochemical and geomorphological processes in river systems (Lake *et al.*, 2007; Horowitz, 2008). Typically, sediment transport in headwater streams is episodic (Lewis *et al.*, 2001), and in Ireland this follows a seasonal pattern, with significant loads occurring in the wettest months (Bruen *et al.*, 2017). Wetter months are associated with high streamflow events that typically have a scouring effect on watercourses, flushing fine sediment from the stream bed – an effect that has a range of impacts on stream biota (Blasczak *et al.*, 2019). This study quantified the effect of cattle access on turbidity levels in a small stream in Ireland. Access by cattle resulted in frequent but short-lived increases in turbidity that were significantly related to the numbers of cattle entering the water.

The abrupt short-lived increases in turbidity which we reported here are likely due to the disturbance of existing bed sediment by cattle, rather than any introduction of new fine material to the stream, although the soil surrounding cattle access points will generally be highly eroded (O'Callaghan *et al.*, 2019), and this effect can be seen in the example study images in Figure 2. One of the only other studies to use a similar combination of remote cameras and in-stream sensors was that of Terry *et al.* (2014) from the Pow Beck catchment (UK). They reported no statistical relationship between stream-suspended sediment and cattle feet in the stream, but found that 57.9% of the instances when stream concentrations were above 25 mg/L could be attributed to cattle presence. However, that study used one downstream nephelometer only, while our study design with two nephelometers allowed for the upstream-to-downstream differences to be assessed.

Stream locations where livestock access the water are associated with decreases in vegetation cover, and increased erosion of soil material (O'Callaghan *et al.*, 2019). In contrast to any flushing effect in higher flows, the increases in turbidity related to cattle access in our study occurred during low flows, and were all short-lived, indicating that the disturbed material settled again rapidly. However, although flows were low, this material would have been displaced over short distances downstream, an effect that could explain the higher concentrations of resuspendable sediment reported by O'Sullivan *et al.* (2019a) downstream of this study site and other cattle access points. Deposition of this resuspended sediment can have impacts on sediment-sensitive aquatic macroinvertebrates (Jones *et al.*, 2012a, 2012b).

The application of automated sensor and camera technology can be especially useful where livestock are being monitored, as the presence of observers can result in alterations in behaviour (Poulopoulou *et al.*, 2019; Wurtz *et al.*, 2019). Camera technology is now becoming more commonly used in agriculture generally, for example, in Precision Livestock Farming, where the aim is usually to gather information on animal health or for herd management (Wurtz *et al.*, 2019). Here, we used cameras to provide data on cattle use of the stream for drinking, combined with sensors to quantify changes in stream turbidity. This dual use of automated technology ensured that livestock behaviour was not impacted by the presence of humans. Nevertheless, there were challenges related to the use of cameras in the study. In particular, while the images allowed for quantification of cattle numbers and duration of stream access, it was not possible to assess how often cattle defecated into the water, especially when many animals were grouped together. Direct defecation was observed and would have contributed to turbidity and to the unexplained data in the relationship with cattle numbers. An additional source of variability would have been the extent of any in-stream movement by individual animals, which also could not be quantified.

In Ireland, cattle graze outdoors during the spring to autumn months (generally April to October/November) and are housed over the winter months. The cattle grazing period (and associated potential access to watercourses) coincides with the growing season for most stream biota; thus, increases in turbidity (even short-lived) can have potential negative impacts on freshwater ecosystems.

Agri-environment policies that incentivise cattle exclusion from watercourses can help improve the ecological quality of watercourses in the short- and long-term. The fourth Nitrates Action Programme of the Nitrates Directive requires that farms with a grassland stocking rate over 170 kg N/ha must prevent cattle from accessing watercourses. Kilgarriff *et al.* (2020) highlighted that targeting cattle exclusion measures to medium- and high-intensity farms is more cost-effective (in terms of reduction of faecal deposition to watercourses) relative to farms with lower livestock densities. However, this study highlights the localised impact cattle access can have on turbidity. A localised impact such as increased sedimentation of the hyporheic zone, for example, can give rise to increased ingress of fine sediment, clogging and collimation of interstices, reductions in interstitial dissolved oxygen and in turn impacting ecological communities (Kibichii *et al.*, 2015).

It should also be noted that fencing and cattle exclusion alone may not be sufficient to restore the ecological condition of impacted watercourses. Future policy could consider multiple mitigation measures that interact with one another. For example, fencing to exclude cattle could be coupled with targeted riparian buffer management to yield other environmental benefits in relation to biodiversity and carbon sequestration, thereby achieving maximum environmental improvements. Such an approach could be facilitated under future Common Agricultural Policy, whereby the quantity of a mitigation measure could be incentivised under Pillar 1 payments, but the performance (linked with targeting and management) of associated measures could be incentivised under Pillar 2 payments (i.e. results-based approaches).

Conclusions

This study involved the combined use of camera technology and *in situ* sensors for the measurement of turbidity to assess the impact of cattle entering a stream. A direct relationship was found between cattle access to streams and water column turbidity levels. Real-time data showed that the changes in the maximum turbidity level could be equivalent in magnitude to those associated with high flows. It also showed, however, that these changes in turbidity were short-lived and that therefore their effects would likely be restricted to the site and the area immediately downstream. While the current study was undertaken at a single site and has produced useful new insights, we suggest that this approach could be extended to more sites allowing assessment under differing hydrological, sedimentological and agricultural conditions, therefore contributing to evidence-based agricultural policy in Ireland and more globally in agricultural systems.

Acknowledgements

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