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Suspended sediment dynamics for June storm events in the urbanized River Tame, UK

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Abstract Few studies of urban water quality storm-event dynamics have been conducted at the sub-catchment scale, though most models assume a "first-flush", positive hysteresis response. This paper reflects on the appropriateness of the first-flush model for summer (June) storms, using high-resolution flow, turbidity and water quality data from the highly urbanized River Tame headwater system, central England. Discharge responded very quickly to storm precipitation, and turbidity events exceed 500 FTU 60 times per annum. However, "first-flush" responses were rare, and turbidity normally peaked after the flow maximum, leading to anticlockwise hysteresis, reinforced by lengthy turbidity "tails". This suggests limited sediment exhaustion. Many responses probably relate to triggering of Combined Sewer Overflows and/or Waste Water Treatment Works, which occur late in storms when capacities are exceeded, and is consistent with concurrent ammonia increases and DO decreases. Prolonged turbidity responses can raise suspended solids loads above predicted levels, increase ecological stress, and lead to complications for sediment budget studies. A re-examination of the first-flush model is overdue.

Key words hysteresis; storm event; suspended sediment; suspended solids; turbidity; urban river; water quality

INTRODUCTION

Elevated turbidity and suspended solids concentrations can indicate upstream erosion and sediment delivery problems, and have important ecological impacts through light suppression, reduced BOD levels, elevated exposure to contaminants (e.g. Chebbo *et al.*, 2001), and impacts on macroinvertebrates and fish (Schleiger, 2000). However, urban river solids transport is still poorly understood, and few published high-resolution data sets on storm-event turbidity *dynamics* exist (cf. Ellis, 1979; Lawler *et al.*, 2006), which are crucial for process inference and model inputs, calibration and validation (e.g. Lawler, 2005a; Old *et al.*, 2003, 2005).

The "first-flush", positive hysteresis idea has long been the accepted suspended sediment storm-response model, especially in small and/or urbanized basins. This paper aims to test the first-flush model using high-resolution water quality data sets for summer 2001 storm events for a heavily urbanized headwater stream system of the River Tame in central England (Fig. 1). The study helps to address scalar research gaps, because it is focused at the neglected *sub-catchment* scale, and builds on the useful studies at small scales such as individual sewer pipes (e.g. Arthur & Ashley, 1998), or larger "lumped-catchment" scales. Sub-catchments are small enough to allow intensive monitoring, and are less affected by spatial precipitation differences, but are sufficiently large, representative and integrative of both hydrological and hydraulic systems to enable potential upscaling to whole catchments, and testing of catchment models. Also, to understand sediment pollution events at downstream locations, we need to understand how suspended solids are first generated in upstream headwater sub-catchments then transmitted downstream. Headwater responses can additionally provide early-warning of pollution problems downstream. This study focuses on a very heavily urbanized sub-catchment, which suffers little complicating upstream "rural" influences.

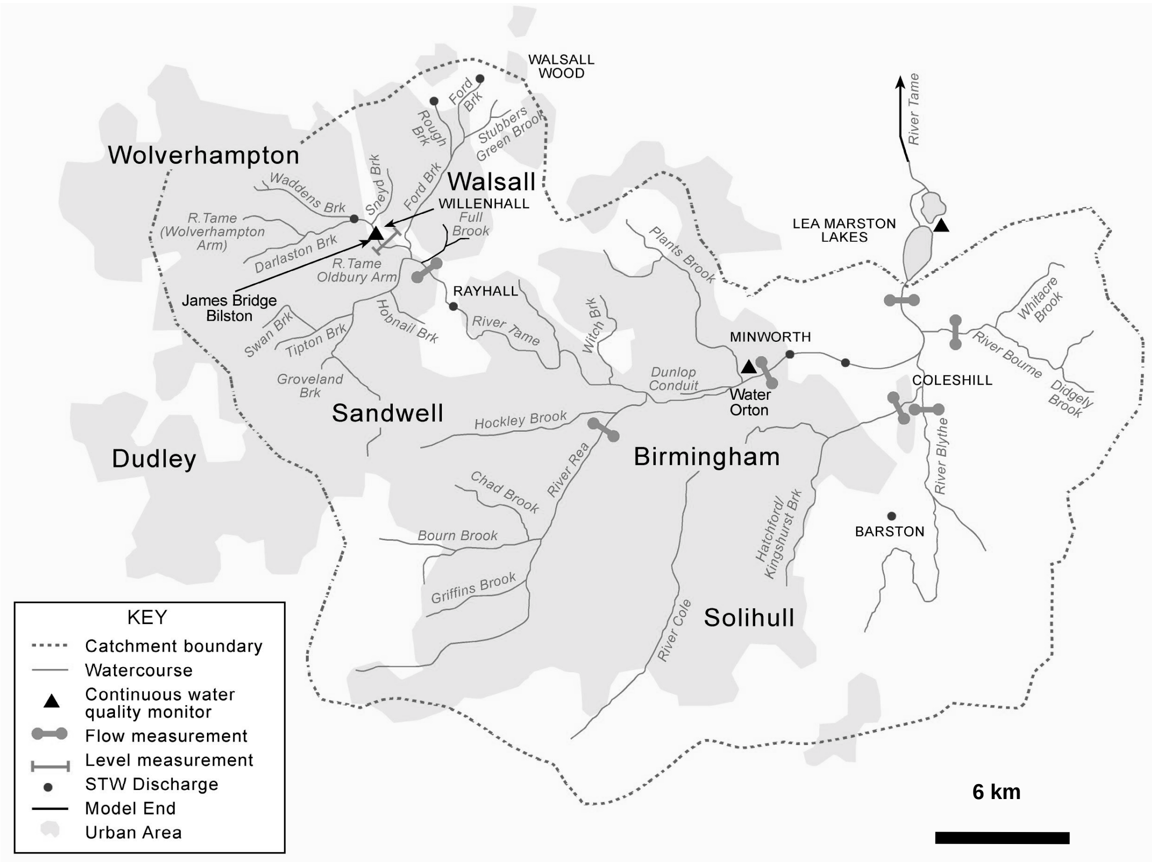

Fig. 1 The Tame catchment showing the James Bridge monitoring station in the headwater basin to the northwest (WwTW, Waste Water Treatment Works; STW, Severn–Trent wastewater) (after Crabtree *et al.*, 1999).

STUDY AREA AND METHODS

Study sub-catchment

The study sub-catchment is the urbanized upper River Tame, West Midlands, UK (Fig. 1). Measurements are drawn from the UK Environment Agency river flow and automatic water quality monitoring station at James Bridge (UK National Grid Reference SO 990 975), where the basin area is 57 km^2, and station altitude is 113.3 m above UK Ordnance Datum. There is one wastewater treatment works (WwTW) in the sub-catchment, at Willenhall, 1.5 km upstream of James Bridge. The Tame is the most urbanized basin in the UK (appox. 42% urban). The catchment contains residential areas and factories, and railway, canal and major motorway networks, including the M6 to the east of James Bridge, and has a long history of coal mining and metal-based industry. The upstream end of one of the Tame tributaries, the Darlaston Brook, intercepts mine shafts. The polluted Upper Tame places it in the worst water quality category of RE5 (River Ecosystem 5: highly polluted). The Tame also periodically receives effluents from WwTWs, Combined Sewer Overflows (CSOs) and industrial sites (Crabtree *et al.*, 1999).

Methods

The automatic water quality monitoring station at James Bridge generated 15-minute data on discharge, turbidity, electrical conductivity (EC), water temperature, pH, DO and ammonia (NH_3N). River water samples were pumped up from a near-bank intake to a measurement facility housing the detectors. The instrumentation system was cleaned at weekly intervals. Turbidity was monitored *in-line* with a pHOX 750M absorptiometric turbidity head, and so was less affected by snagged debris than *in-stream* sensors (Mitchell *et al.*, 2003). Turbidity was measured using a red LED: optics were automatically wiped clean five times per hour. Zero drift was checked approximately weekly. Monthly end-point calibrations were performed with deionized water and a liquid turbidity standard of 500 FTU (Formazin Turbidity Units: Lawler, 2005b). Basin precipitation data at 15-min resolution were used from Willenhall, to the north of James Bridge.

RESULTS

Though turbidity is a key water quality variable *per se*, it shows a very reasonable relationship here with suspended solids concentration (r^2 = 66.5%). Figures 2 and 3 show the typical features of the summer 2001 flow and water quality response to precipitation events. Flow response is characteristically fast in the urbanized Upper Tame: discharge reacts to precipitation in less than an hour, rise-times are <1 h , and events are generally over within 12 hours. Turbidity response is similarly rapid and significant and, although suspended solid concentrations are low in absolute terms (e.g. Lawler *et al.*, 2003; Old *et al.*, 2005), turbidities are high. Indeed, turbidity peaks exceeded 500 FTU on 60 occasions in the year ending April 2002. The first-flush, positive hysteresis concept has long been an accepted suspended solids storm-event response model, especially in small and/or urbanized basins (e.g. Lee *et al.*, 2002). It is defined here as a tendency for: (a) turbidity peak to lead the flow peak; (b) higher concentrations on the rising limb for a given river discharge; giving rise to (c) positive, clockwise hysteresis loops in flow-turbidity relationships (e.g. Walling, 1974; Williams, 1989). This is often ascribed to sediment exhaustion effects, in which limited stores of available sediment are entrained early in the hydrograph, leaving little for later transport, despite competent discharge, velocity or shear stress (e.g. Walling, 1974; Wotling & Bouvier, 2002).

However, in the summer 2001 June–August period, as for spring events (Lawler *et al.*, 2006), “first-flush” effects were rarely documented. Instead, turbidity peaks tended to *lag* the flow peak slightly; also evident were long recessional-limb turbidity

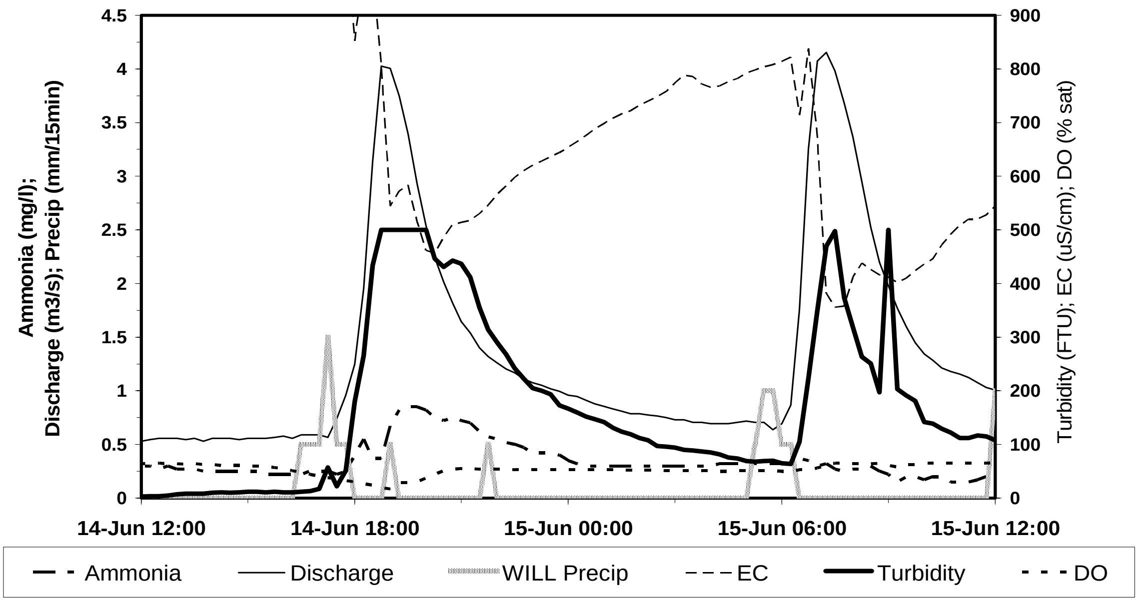

Fig. 2 Turbidity and water quality response during successive storm events on the River Tame at James Bridge, 14–15 June 2001 (WILL precip., Willenhall precipitation).

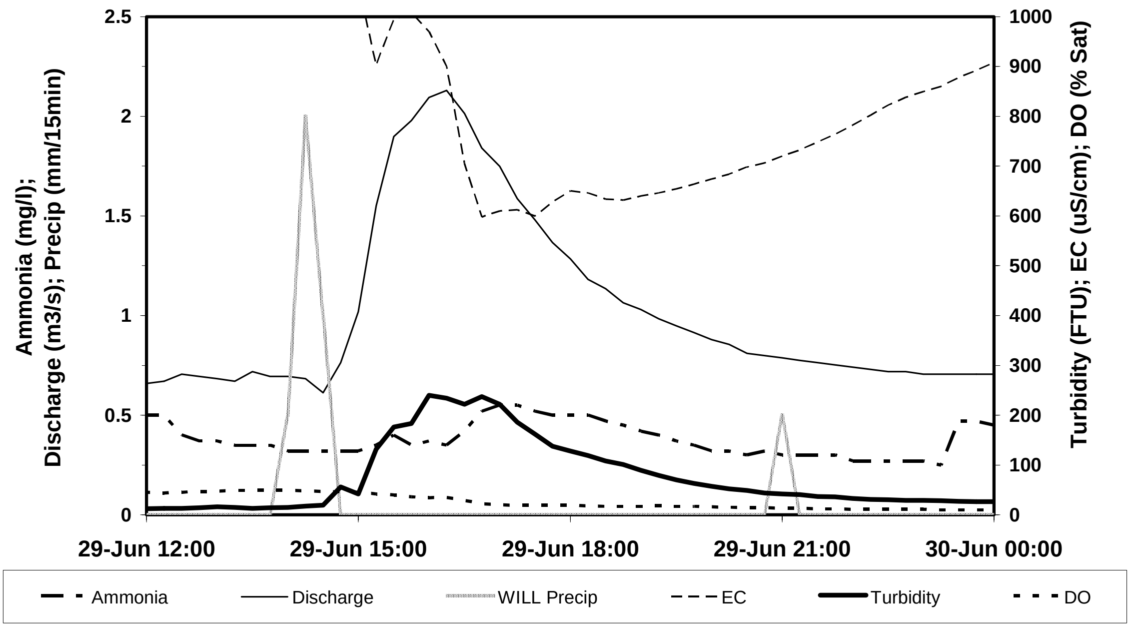

Fig. 3 Turbidity and water quality response for the River Tame at James Bridge, storm event of 29 June 2001 (WILL precip., Willenhall precipitation).

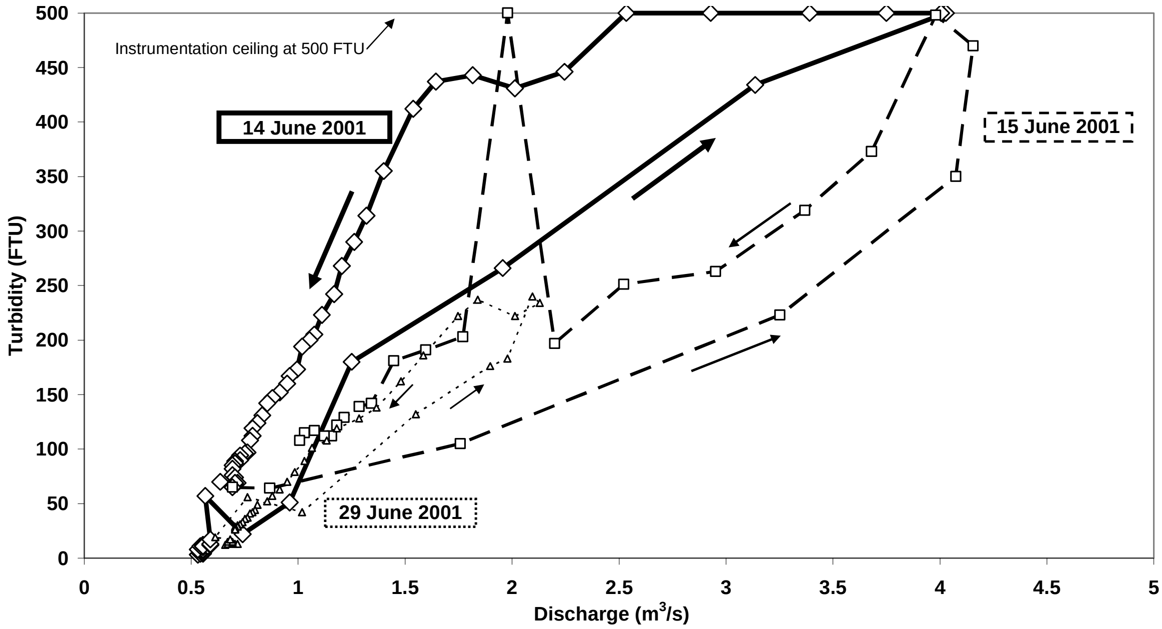

Fig. 4 Hysteresis plots of discharge against turbidity for June 2001 events.

"tails"—termed FLITEs (Falling LImb Turbidity Extensions) by Lawler *et al.* (2006) (Figs 2 and 3). This produces strongly negative, *anticlockwise* hysteresis in the flow-turbidity relationship (e.g. Fig. 4), inconsistent with the "first-flush" model and sediment exhaustion ideas.

DISCUSSION

Anticlockwise hysteresis is unusual in small or urban systems (but see Old *et al.*, 2003), and existing models of sediment accumulation between storms (e.g. EPA-SWWP)—followed by entrainment early in the storm (e.g. Akan & Houghtalen, 2003)—do not explain the patterns revealed here, or for spring events, analysed using a new dimensionless, hysteresis index, HI_{mid} proposed by Lawler *et al.* (2006). Mechanisms currently being explored to guide future modelling and monitoring efforts include CSO and WwTW spills, sediment sources from mine drainage and road surfaces, and biofilm mediation of bed sediment entrainment.

Inputs from CSO and Waste Water Treatment Works (WwTW)

Turbid waters could be input from the CSOs and the WwTW, when their capacities are exceeded late on in storms (e.g. Baker *et al.*, 2003). There are 14 storm sewer overflows in the sub-catchment, and surcharging may partly explain the delayed turbidity responses. Higher ammonia concentrations are often associated with spills from CSOs (e.g. Mulliss *et al.*, 1997). In the 14 June storm (Fig. 2), ammonia rises and falls with the discharge and turbidity responses. DO also falls (Fig. 2). Figure 5 shows the strength of the association between turbidity and ammonia responses though the 14

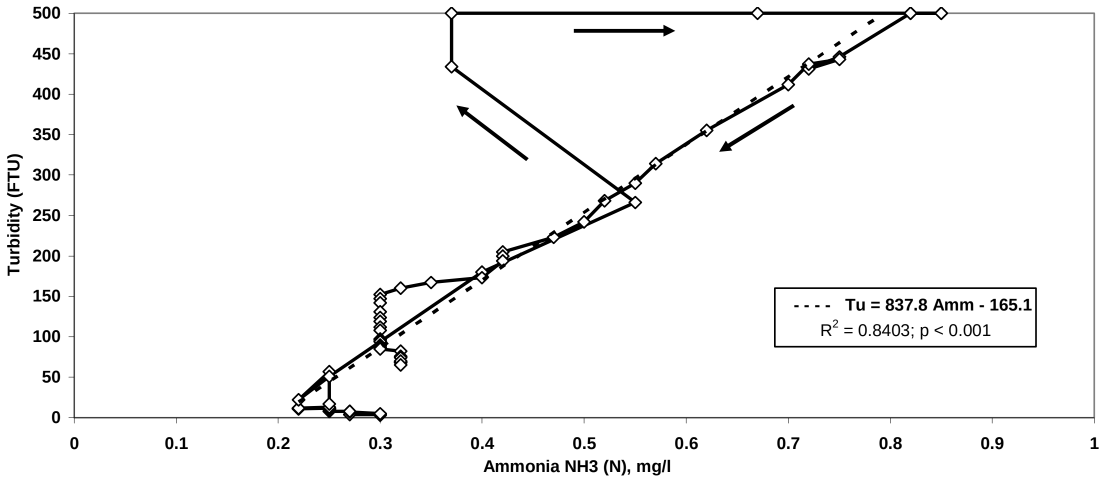

Fig. 5 Hysteresis plot of ammonia against turbidity for the storm event of 14 June 2001.

June storm (r^2 = 84%; $p < 0.001$), and strongly suggests that CSO/WwTW inputs were an important control of turbidity dynamics. Clearly, these anthropogenic turbidity components would have implications for sediment budget studies in urbanized (or even intensively stocked) catchments.

Negative hysteresis was also found in the flow-turbidity relationship for the 29 June storm (Figs 3–4). Similarly, a clear ammonia increase and DO decrease was also observed for the later stages of the event, when CSOs/WwTWs might surcharge. Interestingly, as converse support for the argument, the ammonia spike appears to be *absent* on a *clockwise* hysteresis event on 16 August 2001, when turbidity peaked *ahead* of the flow peak in a rare example of consistency with the first-flush model (Lawler, in preparation). The picture is complex, however, because an ammonia spike was absent for the compound 15 June event, despite clear anticlockwise turbidity hysteresis: this is possibly because the shorter and less intense rainstorm may have failed to trigger the CSOs (Fig. 2).

Other sediment sources and biofilm impacts

Other processes, therefore, are being explored, which may also be important. For example, distal sediment sources could influence delayed turbidity responses. Abandoned mines in the headwaters have been pinpointed as a source of turbid waters (Severn Trent Water Authority, 1976). However, waters emerging from mine shafts might be expected to raise EC values, but EC levels drop during storm events (Figs 2–3). Dust from road networks could also be a significant sediment source (e.g. Carter *et al.*, 2003), and in winter storms after road de-icer applications strong stream EC *rises* confirm the hydraulic connection between roads and the Tame channel. However, given the proximity of arterial routes to the Tame, some delay mechanism (e.g. gully pot sediment detention) may be needed to link these to turbidity delays.

Biofilms can suppress particle entrainment from mudbanks (e.g. Black *et al.*, 2001), and its operation on the Tame River bed, where biofilms are well developed

(Gainswin, 2004), is currently being explored with a conceptual Biofilm Adhesion of Sediment Supplies (BASS) model (Lawler, in preparation). Biofilms may subdue entrainment early in the hydrograph, but once broken up in the higher shear stresses of peak flows, they could allow sediment release on the falling limb to produce the characteristic delayed turbidity "rush" in the later stages of storms (e.g. Figs 2 and 3).

CONCLUSIONS

The main findings of this study are:

(1) Turbidity is a reasonably reliable guide to suspended solids concentrations in the Upper Tame, and turbidity responds rapidly and significantly to the flashy urban storm runoff regime, underlining the need for high-resolution monitoring (Lawler, 2005a).
(2) Clear departures from the "first-flush" model exist for June summer storm turbidity responses as for spring events (Lawler *et al.*, 2006): for most events, turbidity peaked *after* the flow maximum and, for a given discharge, higher turbidities were found on the hydrograph *falling* limb. There was little evidence of sediment exhaustion. This is not consistent with existing models of sediment accumulation between storms (e.g. EPA-SWWP)—followed by entrainment early in the storm (e.g. Akan & Houghtalen, 2003).
(3) One explanation for delayed turbidity responses is late-event triggering of CSOs. Concurrent ammonia increases and DO decreases are consistent with inputs from sewerage systems.
(4) However, because negative flow-turbidity hysteresis was found in the *absence* of an ammonia spike, other processes may be influential. Thus, current work is focusing not only on the operation of storm- and waste-water systems and the character of the suspended solids load as a basis for source ascription and dynamics, but also on the roles of bed sediment resuspension, biofilm mediation of sediment entrainment, and sediment inputs from major roads in the basin.
(5) Such anthropogenic waste components in the turbidity signal have implications for sediment budget studies in urbanized (or even intensively stocked) catchments.
(6) Prolonged elevated turbidity levels, linked to more sustained supplies of fine material than has generally been assumed for urban rivers, increase suspended solids yields above predicted levels, but also extend periods of light suppression, BOD impact and suspended particle effects on organisms and habitats. Such systems may be even more ecologically hazardous than previously thought, and this needs to be explored further. However, such headwater basins provide useful early warning systems for sediment and sediment-associated pollution events downstream.

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