Physical and chemical extremes of the urban river environment: Bradford Beck, UK

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INTRODUCTION

Urban rivers are being increasingly recognised as valuable resources. In addition to their primary role of draining urban areas, they are often ecologically diverse, aesthetically pleasing, the foci for urban regeneration schemes and sinks for controlled wastewater discharges. Currently, many urban rivers in the UK suffer from water quality problems which are compounded by their extremely rapid hydraulic responses to precipitation events. Despite their importance for in-stream ecology (Jarvie and Neal, 1998), the physical and chemical characteristics of urban rivers remain poorly understood. This paper attempts to address the dearth of data and scientific understanding to aid future environmental management. High resolution data from a network of sites in the heavily urbanised Bradford catchment in the UK are analysed. Specifically, the objectives are: (1) to present time series of flow and water quality from a network of sites along Bradford Beck; and (2) to identify and account for spatial and temporal variations of flow and water quality (suspended sediment concentration, SSC, temperature and specific conductance) along Bradford Beck and consider their ecological significance.

STUDY AREA AND METHODOLOGY

Research was undertaken in the small (58 km^2), steep, heavily urbanised (population: ~259,000) catchment of Bradford Beck (West Yorkshire, UK). As shown in Figure 1, the downstream point of the study catchment was Shipley Weir [National Grid Reference (NGR): SE151375]. Mean annual rainfall (1983 to 1995) for the catchment is 915 mm and mean river flow in the

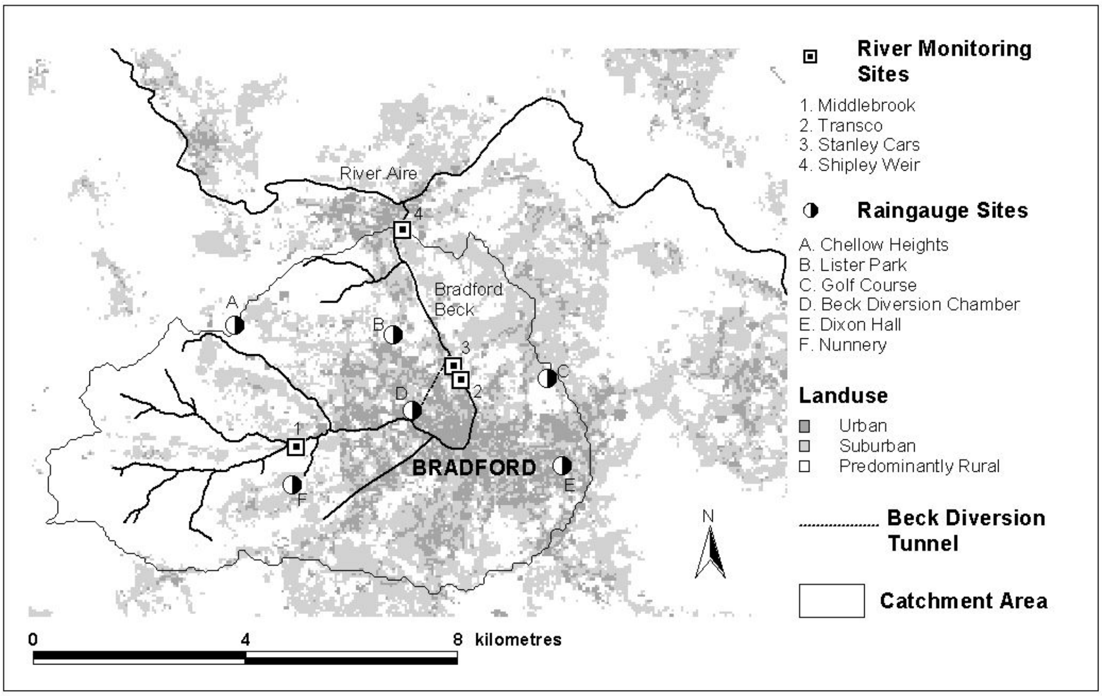

Fig. 1 Bradford Beck study area.

Bradford Beck at Shipley Weir is 0.65 m^3 s^{-1} (Centre for Ecology and Hydrology, 2003).

The river channel is in a relatively 'natural' state in the upper western part of the catchment but elsewhere it has been culverted. The heavily urbanised and industrialised city of Bradford lies in the centre of the catchment, close to the confluence of the Bradford Beck and the River Aire. Water quality of Bradford Beck is poor and is a result of a combination of urban pollution sources including surface water runoff, drainage from contaminated land and intermittent discharges from the sewage system. Bradford has a 'combined' sewer system, whereby foul sewage and surface runoff enter the same drainage structure. The system is hydraulically overloaded following extensive development of the urban area. During intense rainstorms the capacity of the system is often exceeded and sewers overflow into nearby watercourses via Combined Sewer Overflows (CSOs).

Site selection

Monitoring was undertaken as part of the Urban Regeneration and the Environment (URGENT) UK NERC research programme (Leeks, 2002). This paper concentrates on data collected between 20 June 2000 and 19 June 2001 from a network of six raingauges installed throughout the catchment and four key sites along the main channel of the Bradford Beck where river flow and water quality were monitored (Figure 1). Urban drainage networks are often complex, and therefore considerable effort was invested in selecting representative sites. The most upstream site was at Middlebrook (NGR SE129329). This site was above the urban area and monitored flow and water quality from the predominantly rural part of the catchment. The river was monitored at two sites in highly urbanised central Bradford, downstream of the city centre. The Transco site (NGR SE162344) was upstream, and the Stanley Cars site (NGR SE162345) was downstream of the largest CSO in the Bradford catchment. During flood conditions a proportion of the flow in Bradford Beck bypasses the Transco and Stanley Cars sites because it is diverted through the Beck Diversion Tunnel (Figure 1). The catchment outlet was monitored at Shipley Weir (NGR SE151374). Flow and water quality data from this site provided an aggregation of all upstream inputs.

Discharge and water quality monitoring

Stage, velocity, turbidity, water temperature and specific conductance were monitored automatically at 15 minute intervals or less. Regular bottle sampling during storms, and at set times, was undertaken to determine suspended sediment concentration (SSC). Stage and velocity were monitored because they were needed in the determination of discharge. Turbidity was included because it can be calibrated against water samples to produce a continuous record of SSC. Water temperature was measured because it is an important quality of in-stream physical habitat. Specific conductance provided a widely used surrogate for solute concentration. The latter may be indicative of ecologically harmful pollution events caused by, for example, surface water and CSO discharges to the river.

Discharges were determined from stage, velocity and channel profile data by multiplying flow area by velocity. At Middlebrook, Transco and Stanley Cars, stage and velocity were monitored at 5 minute intervals by Starflow ultrasonic Doppler flowmeters (model 6526B). These discharge data were calibrated to those estimated by dilution gauging and current metering. Discharge data, at 15 minute frequency, for Shipley Weir from 1984 to present were provided by the Environment Agency (North East Region), who operate a weir at this site.

Turbidity was monitored, at all four sites, using Analite sensors (model 195/4/30). These nephelometric turbidity sensors were chosen because they are able to measure a wide range of turbidity values (0-1000 FTU), have wipers for lens cleaning, are not affected by ambient light, are insensitive to variations in river water temperature (0-25 °C) and have linear calibration characteristics. Turbidity readings were recorded at 15 minute frequency.

Water samples were taken for SSC determination to enable the calibration of the turbidity record. Manual water samples (~500 ml) were taken at all sites using a USGS DH 48 sampler at fortnightly intervals. EPIC wastewater 1011 samplers (Montec Manchester) were used to take automatic samples (~500 ml). EPIC samplers were either triggered on a set time frequency (usually daily) or river stage basis to preferentially sample during high flow events (Evans *et al*., 1997; Wass and Leeks, 1999). SSC values were determined from water samples by filtration.

Turbidity was calibrated to SSC in two stages (Old *et al*., 2003). Firstly, the raw output from the turbidity sensor (mV) was calibrated to Formazin Turbidity Units (FTU), and secondly, the FTU record was calibrated to SSC values determined from water samples collected throughout the study period. Preliminary simple linear relationships between SSC and FTU were used. Reasonable relationships were obtained at each site (r^2 values ranged from 0.5 to 0.8; sample numbers ranged from 160 and 445). However, linear models may underestimate SSC during periods of high flow when coarser particles may be in suspension (e.g. Old *et al*., 2003; Wass and Leeks, 1999).

At Middlebrook, Transco and Stanley Cars water temperature was measured using Unidata Starflow instruments positioned in the centre of the channel and secured to the channel bed. At Shipley Weir water temperature was monitored using a Hydrolab DataSonde3 multiprobe fixed to the channel bank.

Specific conductance was monitored at all sites using a Hydrolab DataSonde3 multiprobe, fixed to the channel bank. A single point, specific conductance calibration was undertaken using a 720 µS cm^{-1} standard. The calibration was checked by measuring a 1413 µS cm^{-1} standard.

RESULTS

Time series data for flow, SSC, water temperature and specific conductance are presented in Figures 2 to 5. Key results are summarised in Table 1.

River flow

The high total rainfall and maximum intensity over the monitoring period resulted in high annual total and peak discharges from the Bradford catchment. This is clear when discharge statistics for Shipley Weir are considered for the period 1984 to 2001 (see Old *et al*., 2003). Total discharge for the 12 month study period ranked second after the 12 month period January 1986 to January 1987. Maximum discharge and standard deviation ranked fourth illustrating that flows varied significantly over the monitoring period.

Discharge in Bradford Beck is very flashy with more than 35% of the total annual discharge volume at Middlebrook, Stanley Cars and Shipley Weir occurring in just 10% of the year. River flow becomes increasingly flashy in a downstream direction with 9% of annual discharge volume at Middlebrook and 12% of discharge at Shipley Weir occurring in just 1% of the year.

The seasonality of peak discharges also changed in a downstream direction (Figure 2). The five highest peak discharges (from individual flow peaks) occurred during the winter half of the year at Middlebrook. However, at Stanley Cars and Shipley Weir four out of the five highest peak discharges occurred in the summer half of the year. The rates of flow rises were also found to be considerably higher in the urbanised part of the catchment. The maximum discharge rise in a 15 minute period was 1.4 m^3 s^{-1} at Middlebrook compared to 34 m^3 s^{-1} and 32 m^3 s^{-1} at Shipley Weir and Stanley Cars, respectively.

Suspended sediment concentrations (SSC values)

It is clear from Figure 3 that SSC values were highly variable at all sites throughout the year June 2000 to June 2001. Mean SSC values were estimated in two ways: (1) using only recorded data (61% Middlebrook, 67% Stanley Cars and 69%

Table 1. Temporal and spatial variations in river water flow and quality in Bradford Beck (20 June 2000 to 19 June 2001)

		Site			
		Middlebrook	*Transco*	*Stanley Cars*	*Shipley Weir*
Maximum discharge rise in 15 mins (m^3 s^{-1})		1.4	-	32	34
Mean SSC (mg l^{-1})	Only recorded data (% of year)	41 (61)	-	39 (67)	29 (69)
	Complete year with infilled data	41	-	43	39
80 mg l^{-1} SSC exceedance times (%)	Only recorded data (% of year)	10.5 (61)	-	12.4 (67)	8.5 (69)
	Complete year with infilled data	11.1	-	11.7	10.2
Measured peak SSC mg l^{-1}	Sampled	2270	1809	1543	1864
	Turbidity derived	1496	1535	1096	1247
*Median water temperature		6.95	8.6	9	8.55
*Standard deviation of water temperature (°C)		3.1	2.1	2.1	2.9
**Median specific conductance (µS cm^{-1})		444	1021	1009	666
**Standard deviation of specific conductance (µS cm^{-1})		171	401	460	237
**Maximum recorded specific conductance (µS cm^{-1})		2810	7034	8595	3422

Note:
* Based on contiguous data from all sites (77% of year 20 June 2000 to 19 June 2001)
** Based on contiguous data from all sites (35% of Year 20 June 2000 to 19 June 2001)

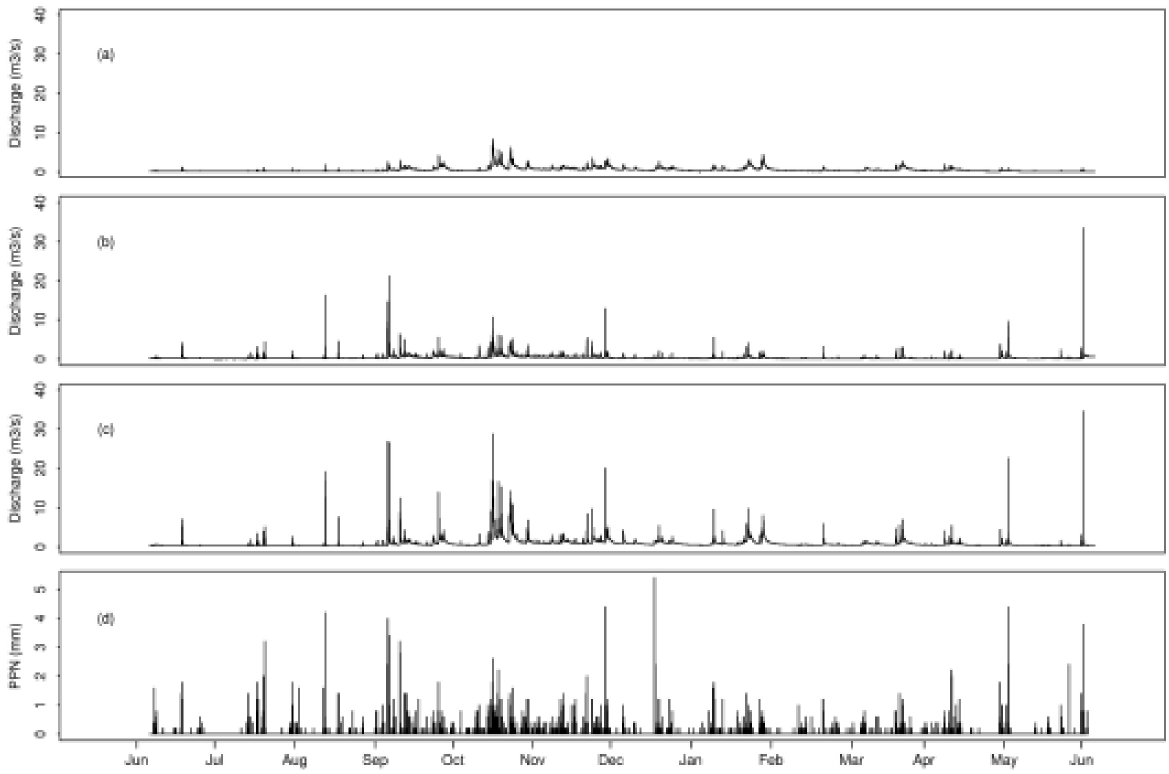

Fig. 2 River flow data

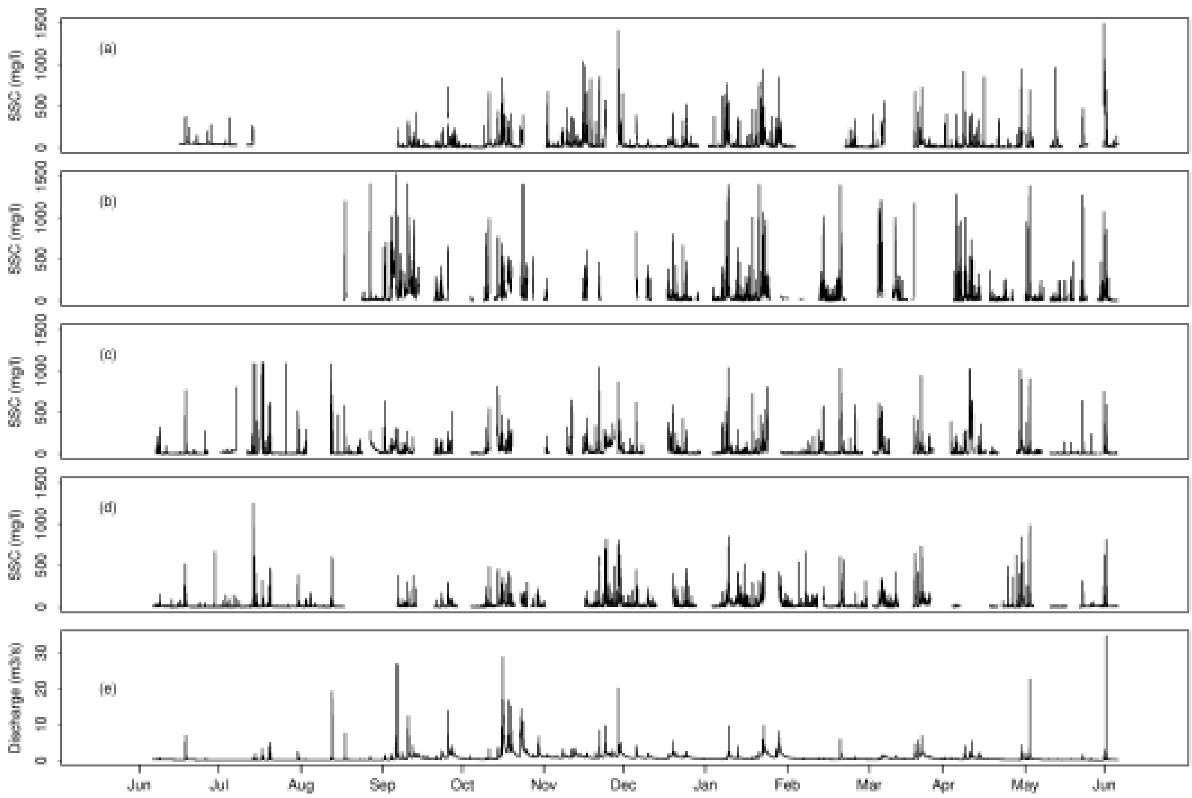

Fig. 3 suspended sediment data

Shipley Weir); and (2) using data for the complete year with low and high flow infilling (based on Old *et al*., 2002). Mean SSC values ranged from 29 mg l^{-1} (Shipley Weir) to 41 mg l^{-1} (Middlebrook), based only on recorded data, and from 39 mg l^{-1} (Shipley Weir) to 43 mg l^{-1} (Stanley Cars), based on the complete year of infilled data. Peak SSC of more than 1500 mg l^{-1} (sampled) and 1000 mg l^{-1} (turbidity derived) were recorded at all sites (Figure 3).

Water temperature

As expected, water temperature followed a seasonal cycle reaching a summer maximum at all sites (Figure 4). Water temperature and its variation along Bradford Beck was considered using data from 77% of the year, when measurements were available simultaneously from all four monitoring sites (Table 1). Median water temperature ranged from 7.0ºC at Middlebrook to 9.0ºC at Stanley Cars (Table 1). There was a 1.6ºC rise in median water temperature from Middlebrook (most upstream site) to Shipley Weir (most downstream site). However, the highest median water temperature occurs in the centre of the catchment at Stanley Cars. Recorded water temperatures ranged from a minimum of 0.7ºC (Middlebrook) to a maximum of 17.5ºC (Shipley Weir). Standard deviations of water temperature measurements were 3.1ºC at Middlebrook, 2.1ºC at Transco, 2.1ºC at Stanley Cars and 2.9ºC at Shipley Weir. Therefore, water temperature is generally higher and less variable in the heavily urbanised part of the catchment.

Specific conductance

The specific conductance of water in Bradford Beck, at all four sites during the monitoring period, is presented in Figure 5 and Table 1. Specific conductance and its variation along Bradford Beck was studied using data from 35% of the year when measurements were simultaneously available from all four sites (Table 1). Median specific conductance ranged from 444 µS cm^{-1} at Middlebrook to 1021 µS cm^{-1} at Transco. Median values are considered because they are not unduly influenced by extreme values. Standard deviation of specific conductance ranged from 171 µS cm^{-1} at Middlebrook to 460 µS cm^{-1} at Stanley Cars (Table 1). Maximum recorded specific conductance ranged from 2810 µS cm^{-1} at Middlebrook to 8595 µS cm^{-1} at Stanley Cars (Table 1). Therefore, solute concentrations were highest and most variable in the heavily urbanised central part of the catchment. Higher values of specific conductance were recorded during winter than summer at all sites.

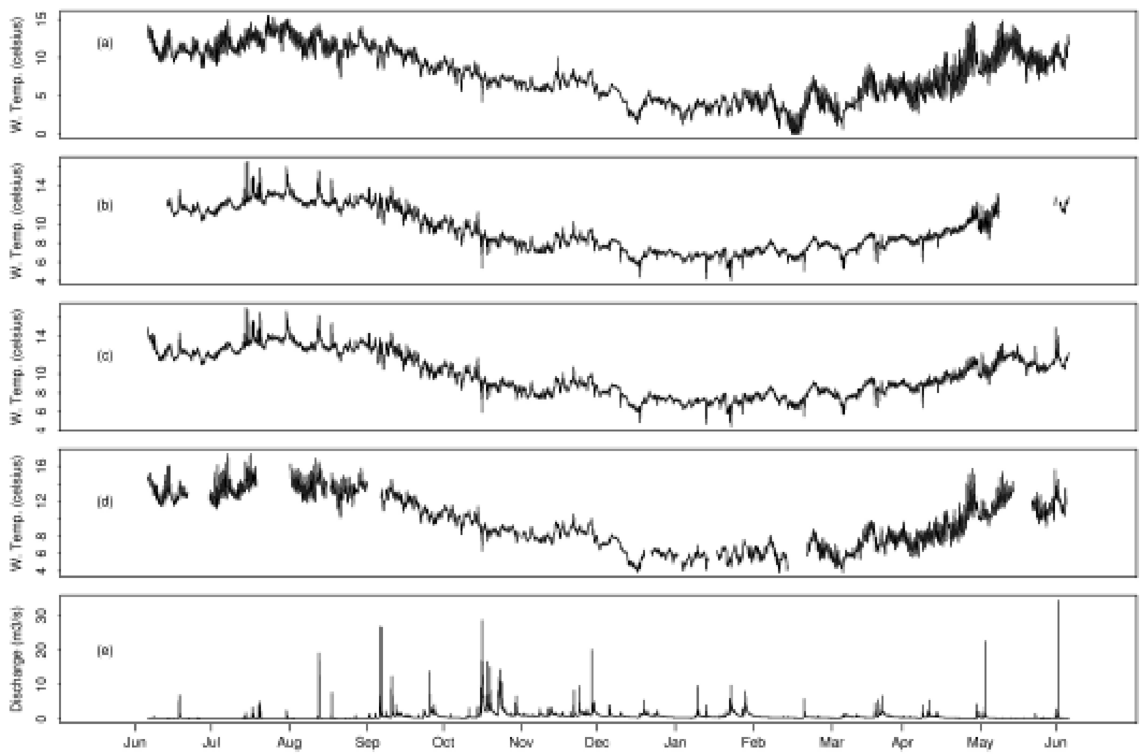

Fig. 4 Water temperature data

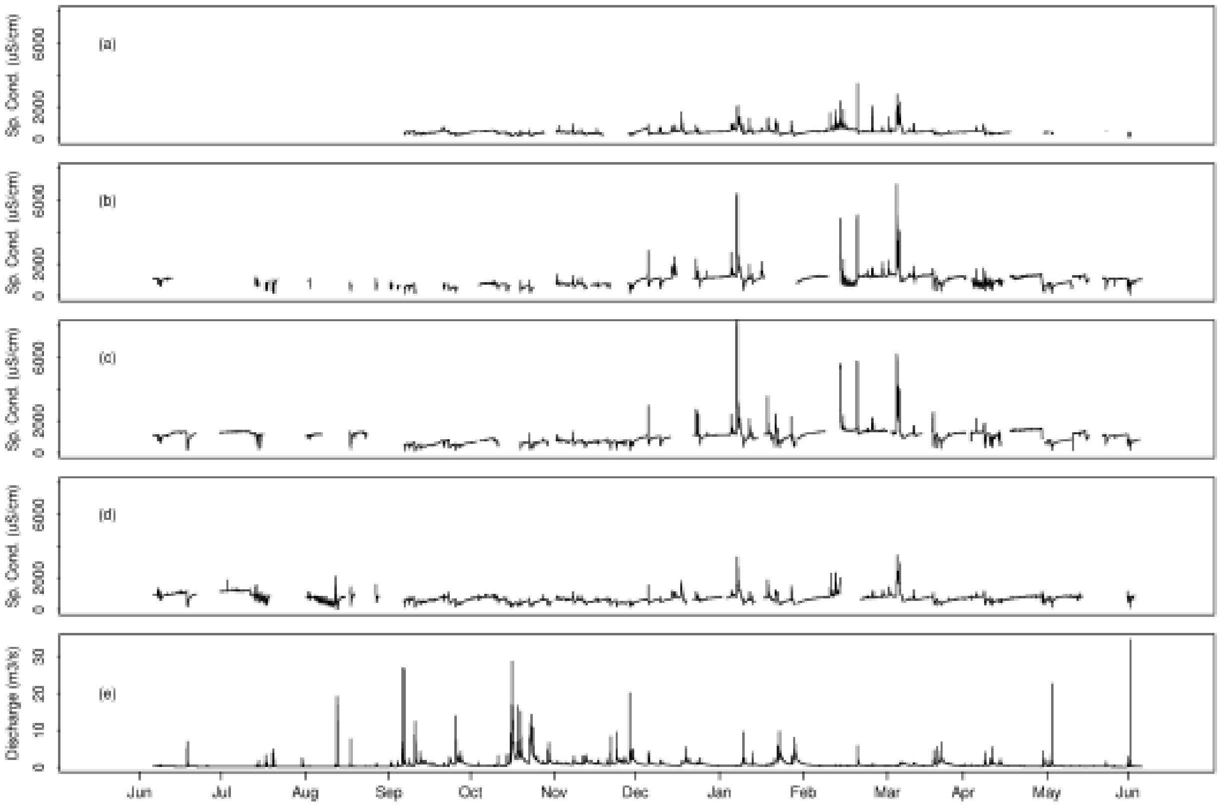

Fig. 5 Specific conductance data

DISCUSSION

Data have been presented for river flow and water quality monitored continuously at a network of four sites in the heavily urbanised Bradford catchment between June 2000 and June 2001. The results illustrate the spatial and temporal dynamics of river water flow, SSC, temperature and specific conductance. The identified patterns can be linked to the high level of urbanisation in the Bradford catchment.

River flow

The flashy regime of Bradford Beck may be attributed to its small size, steep gradient and large proportion of urban cover. Its increasingly flashy nature, in a downstream direction (Figure 2), most likely reflects the increasingly urbanised nature of the catchment and therefore more efficient generation of runoff in response to rainfall.

There was also a clear downstream change in the seasonality of peak discharges (Figure 2). Highest peak discharges, of discrete events, generally occurred in winter at Middlebrook and in summer at Shipley Weir. The highest annual discharges in the rural part of the catchment usually occur in winter when the ground is sufficiently wet to generate runoff. In summer runoff is limited because most rainfall is either intercepted by vegetation or infiltrates the soil. However, in the urbanised part of the catchment, the impervious surfaces and efficient drainage structures mean that surface runoff is generated throughout the year and highest discharges occur at times of greatest rainfall intensity which are often produced by convective summer rainstorms. The highest rate of discharge rise was observed at Shipley Weir downstream of central Bradford. This reflects the efficient routing of surface runoff through the urban drainage networks. The high peaks and rapid rises of flows in Bradford Beck in the urbanised part of the catchment may be damaging to fish populations where there are no refuges in which they can survive. Booker (2003) simulated high flow hydraulic conditions of two reaches of the River Tame, Birmingham, and compared these to published maximum sustainable swimming speeds of fish. It was concluded that poor physical habitat at high flows is a possible limiting factor for fish in urban river channels.

Suspended sediment concentration (SSC)

Bradford Beck was observed to have an extremely flashy regime in terms of its SSC (Figure 3). Estimated mean SSC values (from recorded data) at Middlebrook, Stanley Cars and Shipley Weir ranged from 29 mg l^{-1} to 41 mg l^{-1}. These are comparable to those that have been reported for other UK rivers (22 to 58 mg l^{-1}:Wass and Leeks, 1999). However, the maximum sampled SSC values of >1500 mg l^{-1}, which were recorded at all sites, are high when compared to SSC values of storm samples taken in other Yorkshire (UK) river systems (typically below 600 mg l^{-1}; Wass and Leeks, 1999). The high peak SSC values at Middlebrook are due, at least in part, to the near bed sampling of coarse sediment particles from turbulent flow (Old *et al*., 2003). However, the high peak SSC values in the urbanised part of Bradford Beck result, at least in part, from mobilisation of fine sediment accumulations from the channel bed by river flow, and contributions of sediment from combined sewer overflows and surface water drains.

Although transient high values of SSC are a natural phenomenon, to which ecological systems adapt, they may have adverse ecological effects when they are anthopropogenically enhanced. The SSC values observed in Bradford Beck are likely to have significant ecological implications. Many researchers have reported the adverse effects of high SSC values on aquatic flora, invertebrates and fish (e.g. Harbor, 1999; Crabtree, 1989; Newcombe and MacDonald, 1991; Marks and Rutt, 1997). Alabaster and Lloyd (1980) suggest that SSC values above 80 mg l^{-1} are likely to have adverse effects on fish. This threshold is exceeded at Middlebrook, Stanley Cars and Shipley Weir for more than 10.2% of the time, when considering the complete year including infilled data (June 2000 to June 2001), and for over 8.5% of the time when considering only measured data. These exceedance times are significantly higher than those published for the River Tweed and River Teviot in Scotland, 1994–1997 (1.7% and 2%, respectively: Bronsdon and Naden, 2000), and are likely to be a limiting factor for fish and other species, especially if the periods of exceedance are sustained for significant lengths of time. Furthermore, the particle size and quality of the suspended sediment may be important. Suspended sediment is likely to be contaminated in the urban environment (e.g. Old *et al*., 2004).

Water temperature

Water temperature had higher median values and was less variable in the heavily urbanised part of the catchment (Transco and Stanley Cars). The high median water temperatures may be produced by runoff being warmed through contact with the urban fabric, relatively warm CSO and effluent discharges and the Beck being warmed and insulated from the cold as it flows through long culverted sections. The small variability of water temperature is probably a result of the Beck being largely culverted and insulated from air temperature extremes. Water temperature variability is greatest at Middlebrook (standard deviation of 3.1ºC) because the channel is exposed to the atmosphere and its small discharge means that its water temperature can respond quickly to air temperature changes. These downstream changes in the dynamics of river water temperature may have implications for particularly temperature sensitive organisms.

Specific conductance

In the heavily urbanised part of the catchment (Transco and Stanley Cars) solute concentrations reached highest maximum values (>7000 μS cm^{-1}) and were most variable (standard deviations >400 μS cm^{-1}) (Figure 5). Median values of specific conductance were highest (>1000 μS cm^{-1}) at Transco and Stanley Cars (Table 1). These maximum and median concentrations are very high when compared to those reported from other UK river systems (e.g. Jarvie and Neal, 1998; Christmas and Whitton, 1998). High and variable solute concentrations in the Bradford Beck in central Bradford are consistent with solute inputs being greatest in this part of the catchment. Furthermore, dilution of solutes in the urbanised part of the Beck is limited during high flows because a proportion of the upstream flow is routed through the diversion tunnel and bypasses this part of the Beck (Figure 1). The major solute inputs are likely to include effluent discharges, sewage inputs from CSOs, unauthorised trade discharges and surface runoff. Highest specific conductivities were recorded during winter at all sites. Very high conductivities were recorded when small amounts of runoff were generated subsequent to cold periods during which roads were salted. Times of road salting in the Bradford Metropolitan District and specific conductance and stage of water in Bradford Beck at Stanley Cars are presented in Figure 6 for a cold period (17 January to 12 February 2001). During a period of heavy road salting (20 January 2001) a small rise in river stage corresponded to extremely high specific conductance (>8000 μS cm^{-1}) in the Beck. Similarly, Peters and Turk (1981) attributed chemical pollution ($NaCl$) of the Mohawk River in New York to road salting. The pulses of high solute concentration that have been identified in Bradford Beck may have important implications for ecology and water quality. There is evidence that high concentrations of $NaCl$ in river water, resulting from road salting, have adverse effects on fish, invertebrates and microflora and increase the abundance of bacteria (as reviewed by Canadian Government, 2001).

High concentrations of $NaCl$ in river water are also likely to adversely affect other chemical aspects of water quality. High Cl concentrations often enhance the release of metals (e.g. cadmium, copper and zinc) from sediments by competing for particulate binding sites and/or producing soluble chloride salts (Hares and Ward, 1999; Warren and Zimmerman, 1994). This may be a significant problem in Bradford Beck, as

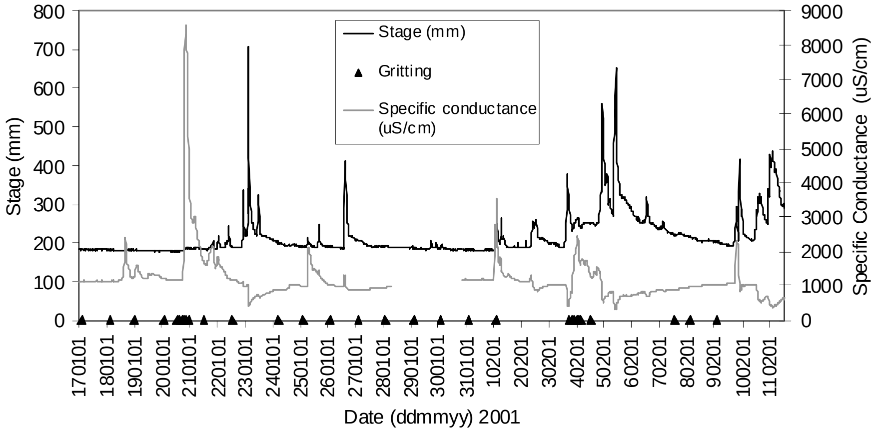

Fig. 6 Times of road salting in the Bradford Metropolitan District and specific conductance and stage of water in Bradford Beck at Stanley Cars

research has shown that channel bed sediments in the urbanised part of the catchment are highly contaminated with metals (Old *et al*., 2004). In addition, road salt itself may directly contribute to the metal pollution of a river because it contains contaminants such as copper, zinc and cadmium (Maltby *et al*., 1995, cited in Canadian Government, 2001). The detailed chemistry of the river water is likely to be highly important for ecology but its determination was beyond the scope of the current study.

CONCLUSION

Knowledge of spatial and temporal variations of key physical and chemical characteristics of urban rivers is vital for their effective management, restoration and monitoring. The current study enabled the elucidation of variations in river flow, suspended sediment concentration, water temperature and solute concentration for a period of a year at four sites throughout the highly urbanised Bradford catchment. River flows became increasingly flashy, with larger peaks in the urbanised part of the catchment. This is likely to limit the availability of suitable habitat for fish. Mean SSC values upstream, within and downstream of highly urbanised central Bradford were comparable to those observed in other UK rivers, although the peak values were considerably higher. The duration of potentially ecologically harmful SSC values (>80 mg l^{-1}) was also high at these sites, which may restrict the suitability of the river for fish. Solute concentrations were highest and most variable in the urbanised part of the catchment. The high pulses of solute rich water are also likely to have adverse ecological effects and reduce the quality of river water by enhancing the mobilisation and solubility of metals in contaminated bed sediments. However, the most ecologically harmful conditions are likely to occur when high discharges, suspended sediment and solute concentrations occur simultaneously. The current research has illustrated that the water flow and quality in Bradford Beck are strongly affected by the high level of urbanisation in the catchment. The ecological potential of the Beck is likely to be limited by its flow and suspended sediment and solute concentrations. It is evident that an ecological restoration project must adopt a multi-disciplinary approach that considers the dynamics of both flow and water quality.

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