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# SEASONAL AND INTER-ANNUAL VARIABILITY IN HYPORHEIC WATER QUALITY REVEALED BY CONTINUOUS MONITORING IN A SALMON SPAWNING STREAM

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## ABSTRACT

Over a 3.5 year period, levels of dissolved oxygen (DO) saturation were continuously monitored in surface waters and at depths of 150 and 300 mm in the hyporheic zone of a riffle in a montane stream where Atlantic salmon spawn. Throughout this period, DO in surface waters remained close to 100% saturation, but exhibited daily variations related to $CO_2$ cycling driven by diurnal patterns of respiration and photosynthesis. However, in the hyporheic zone, variations were much more dynamic over storm event, seasonal and inter-annual timescales. At 300 mm, DO saturation was generally close to 100% during summer low flows, though levels occasionally fell during warm periods which appeared to be related to diffusion gradients caused by benthic respiration. Such DO decreases at low flows were much more common and marked at 150 mm. During wetter conditions, DO saturation at 300 mm fell to zero for prolonged periods; this is consistent with increased fluxes of groundwater discharging through the hyporheic zone. During the wettest periods this also affects DO saturation at 150 mm. However, during hydrological events, hyporheic water quality is 're-set' as head reversals cause streamwater ingress which results in transient periods of re-oxygenation, which end during the hydrograph recession. This is consistent with stream-ward hydraulic gradients being re-established in riparian ground water as the stream stage falls. The connectivity between groundwater and streamwater through the hyporheic zone is driven by climatic conditions and is reflected in marked inter-annual variability in water quality characteristics. In some cases, this variability may have implications for the ecology of the hyporheic environment—including the survival of salmon eggs—particularly if oxygen levels are affected. Copyright © 2009 John Wiley & Sons, Ltd.

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## INTRODUCTION

Recent technological innovation now allows *in situ* monitoring of water quality over prolonged periods in the hyporheic zone without disturbance to the stream bed (Malcolm *et al.*, 2006, 2009). Such high resolution monitoring has revealed previously unrealized variability in hyporheic water quality at a range of spatial scales, and over temporal scales varying from individual hydrological events to periods of several months (e.g. Malcolm *et al.*, 2009). This variability has often been missed or ignored in hyporheic studies where logistical constraints dictate that monitoring normally involves sampling at relatively coarse (i.e. weekly or monthly) temporal scales. Importantly, there are very few data sets that examine hyporheic water quality over periods in excess of a few months; and none published (that we are aware of) extending over several years. Thus, while major advances have been made in understanding short-term and event-based variability in hyporheic water quality (Malcolm *et al.*, 2004; Fritz and Arntzen, 2007; Hanrahan, 2008; Nyberg *et al.*, 2008), there is very limited information on seasonality and inter-annual variability in hyporheic processes. This limitation often restricts the inferences that can be made over the precise nature of many physical, chemical and ecological processes that characterize the hyporheic environment and their relative importance at different temporal scales. As research effort has expanded

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dramatically in recent years and sampling methodologies have improved, it is becoming increasingly apparent how complex these processes are and how dynamic the hyporheic zone is. One of the major remaining research challenges is to characterize hyporheic dynamics at a fine temporal resolution over longer time periods to assess the nature of seasonal and inter-annual variability.

Hyporheic water quality is an important control on many in-channel ecological processes ranging from biogeochemical cycling (Boulton *et al*., 1998; Duff and Triska, 2000; Storey *et al*., 2004), to the structure of macroinvertebrate communities (Fraser and Williams, 1998; Fowler and Death 2001; Storey and Williams, 2004). A particularly important area where the link with the ecology has been shown to be important is the issue of low dissolved oxygen (DO) in the hyporheic zone (Boulton *et al*., 1998; Malard and Hervant, 1999). A matter of particular concern that has been intensively studied is the effect of low DO on salmon embryo survival in spawning gravels (Sowden and Power, 1985; Peterson and Quinn 1996; Rubin and Glimsater 1996; Ingendahl, 2001; Malcolm *et al*., 2003; Youngson *et al*., 2004; Greig *et al*., 2006). Salmon embryos spend a substantial period in the hyporheic zone between spawning and hatch and transient periods of de-oxygenation have been cited as being responsible for lethal or sub-lethal effects which may affect recruitment to populations (Youngson *et al*., 2004; Malcolm *et al*., 2008). Proximal causes have been identified as including periods when de-oxygenated groundwater is discharging through the stream bed (Malcolm *et al*., 2003); *in situ* consumption of oxygen as a result of respiration stimulated by infiltration of fine organic sediments (Greig *et al*., 2006), and reduced permeability of stream gravels after spawning due to an influx of fine sediments (Zimmerman and Lapointe, 2005) inhibiting the removal of the potentially toxic products of metabolism (Shumway *et al*., 1964).

This paper reports the results of almost 4 years of continuous hyporheic water quality monitoring at an intensively studied site in the Girnock Burn, a montane Atlantic salmon spawning stream in northeast Scotland. The site in question has been identified as one with dynamic groundwater-surface water interactions where transient connectivity of hillslope groundwater causes discharge of de-oxygenated water through the hyporheic zone (Malcolm *et al*., 2004, 2006). The aim of the paper is to examine the nature of these dynamics over a prolonged period of time. The specific objectives are to: (1) examine the annual and inter-annual temporal variability of hyporheic water quality over a 40 month period using continuous water quality monitoring of DO and temperature; (2) establish the seasonal variations of hyporheic water quality in relation to antecedent and prevailing hydrological conditions using fine resolution data and (3) assess the nature and importance of inter-annual variability in hyporheic water quality during the critical winter/early spring period (November–April) when salmon eggs are typically in the hyporheic zone.

## STUDY AREA AND METHODS

The work was carried out at the Girnock catchment, a 31 km$^2$ sub-catchment of the river Dee in Northeast Scotland (Figure 1 and Table I). Detailed characteristics about the catchment are given elsewhere: Tetzlaff *et al.* (2007, 2008) describe the general hydrology; Moir *et al.* (2002, 2004) describe the distribution of salmon spawning sites and their hydraulic and sedimentary characteristics; Soulsby *et al.* (2007) outline the catchment scale groundwater-surface water interactions, whilst Malcolm *et al.* (2005) consider their implications for salmon spawning and Youngson *et al.* (2004) assess the resulting effects on embryo development and survival.

Briefly the catchment drains a montane area underlain by granitic and metamorphic rocks. Groundwater drains through fractures in these rocks and various glacial and paraglacial drifts which cover much of the catchment and contributes 25–30% of annual runoff (Soulsby *et al*., 2007). The land use is largely heather (*Calluna*) moorland; though the lower catchment has mixed forest cover of pine (*Pinus*) and birch (*Betula*). Rainfall is around 1100 mm per annum, with a mean annual runoff of around 700 mm.

One 55 m long pool-riffle reach with a long history of salmon spawning that has been intensively researched (see Moir *et al*., 2005), was selected for detailed monitoring of hyporheic chemistry over several years. The site was examined in detail by Malcolm *et al.* (2004) and is characterized, at times, by strong groundwater upwelling which often results in marked groundwater influence on the hyporheic chemistry in salmon redds. The groundwater is strongly reducing and the low DO levels have been implicated in poor embryo survival at this site (Malcolm *et al*., 2005).

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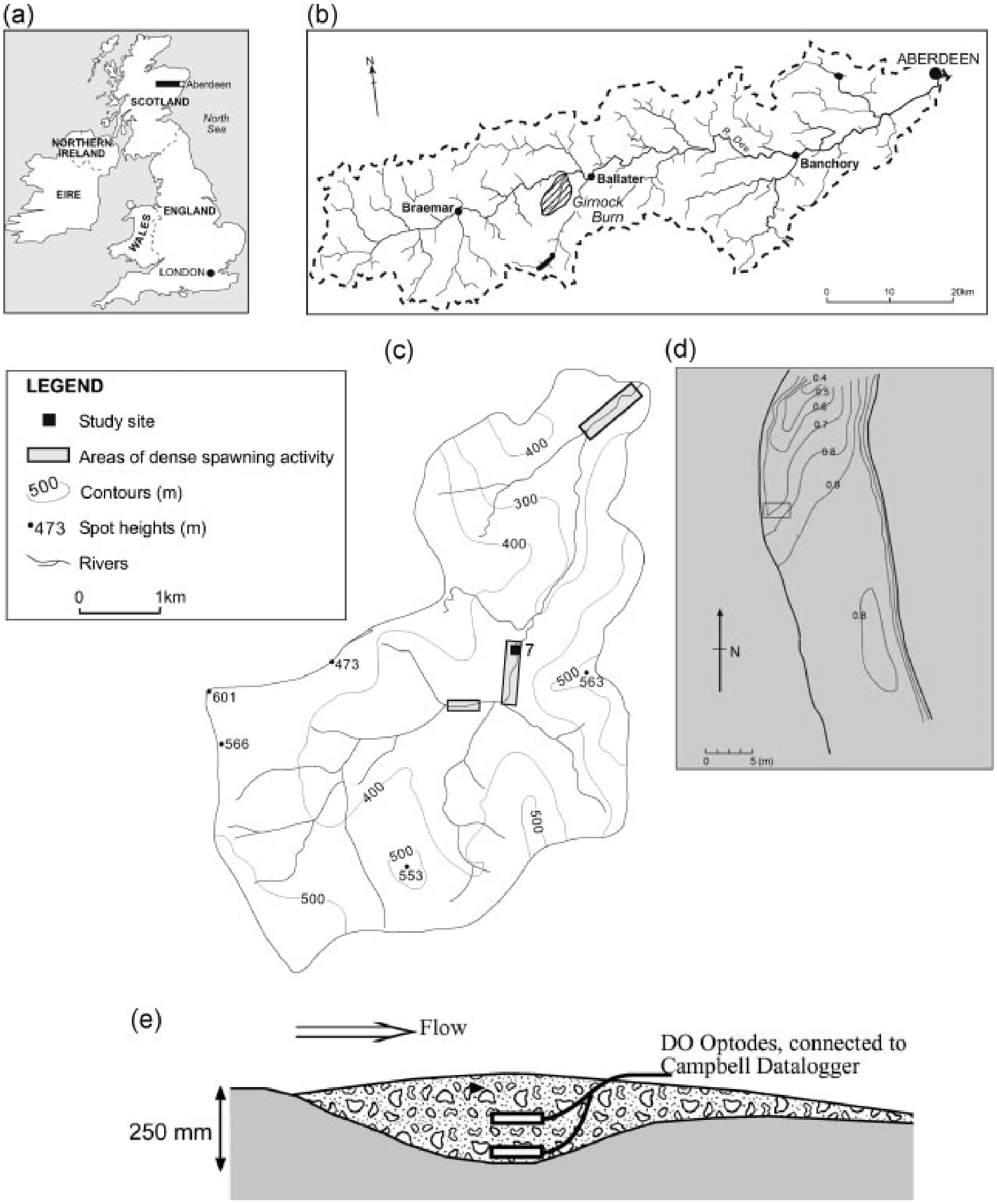

Figure 1. Location of (a) the study area, (b) the Dee and Girnock catchments, (c) the study site, (d) the location of sampling equipment (marked by rectangle) in plan view and (e) equipment installation in cross section

Continuous monitoring of hydraulic head and water quality in the hyporheic zone for short periods has shown that transient changes in chemistry are synchronous with changes in hillslope groundwater—channel connectivity (Malcolm *et al*., 2004, 2006, 2009). This has shown that wet periods are characterized by strong stream-ward hydraulic gradients and the chemistry of the hyporheic zone is strongly reducing and reflects that of groundwater. This reverses during storm events where the rise in river stage appears to be more rapid than the riparian groundwater response, and the chemistry of hyporheic zone then temporarily reflects that of the stream. On the hydrograph recession, stream-ward hydraulic gradients strengthen and reducing conditions are re-established.

Instrumentation was installed in the shallow hyporheic zone at a known spawning location within the study reach (Figure 1d) and at depths appropriate to the distribution of eggs buried by Atlantic salmon (100–300 mm)

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Table I. Characteristics of the Girnock catchment and the spawning reach investigated.

| | |
|---|---|
| Girnock catchment | |
| Climate | Mean precipitation = 1100 mm year$^{-1}$: Mean annual temperature = 8°C |
| Discharge (m$^3$ s$^{-1}$) | Mean = 0.5: $Q_{95}$ = 0.04: $Q_{10}$ = 1.01 |
| Dominant soils (% cover) | Peaty gleys (60%): Podzols (24%): Rankers (9%): Peat (4%) |
| Dominant geology (% cover) | Granite (51%): Schists (34%) |
| Water quality parameters (mean) | pH = 7.3: DOC 4.7 mg L$^{-1}$: $NO_3$–N <0.04 mg L$^{-1}$ |
| Channel typology (% main channel length) | Step pool/plane bed (92%): Pool-riffle (8%) |
| Study reach | |
| Physical characteristics | 9 m wide: 55 m long: 0.0092 m m$^{-1}$ gradient |
| Sedimentary characteristics | $D_{50}$ = 43.4 mm: $D_{84}$ = 104 mm: 12% fines |
| Hydraulic conductivity of Stream gravels | $10^{-4}$ m s$^{-1}$ |

(Figure 1e). However, the purpose of this study was to capture long-term variability in hyporheic water quality rather than simulate the transient physical architecture of actual redds. Instrumentation comprised high temporal resolution DO and temperature measurements in the stream and at depths of 150 mm (100–150 mm) and 300 mm (250–300 mm) in the hyporheic zone using logging Aandera™ 3830 DO optodes (Malcolm *et al*., 2006). These were connected to Campbell™ dataloggers programmed to sample DO (per cent saturation) and temperature at 30 s intervals and log average values over 15 min. It was recognized that two optodes provided a relatively coarse spatial sampling of the hyporheic zone at this site, a limitation reflecting budgetary constraints. However previous work had shown that the location where they were installed was broadly representative of sites several metres upstream and downstream (Malcolm *et al*., 2004), and previous spot sampling at 50 mm depth intervals in the hyporheic showed that 150 and 300 mm depths reflected the most important variability in water quality experienced by salmon embryos (Malcolm *et al*., 2009).

Prior to installation, DO optodes were cross-calibrated in the laboratory at 0 and 100% saturation and showed agreement to within 1% saturation. Temperatures were compared over the range 2–25°C and found to be within 0.1°C. Previous work in the same catchment (Malcolm *et al*., 2006) had shown that *in situ* installation for the period between spawning and egg hatch (ca. 5 months) without re-calibration provided excellent data quality. The optodes were installed in November 2004, and generally downloaded at monthly intervals, but were taken out for re-calibration in May 2006 and October 2007. Although instruments were found to maintain their precision, sensor foils were changed as a precautionary approach before re-burial.

## RESULTS

### *Annual and inter-annual temporal variability*

Figure 2a shows the hydrological variability of the Girnock Burn during the monitoring period. The hydrological years (October–September) of 2004/2005 and 2005/2006 are characteristic of the Girnock's longer-term, average hydrological regime. Usually frequent spates occurring during the autumn and winter (October–March), with spring and early summer (May–July) being drier with the lowest flows. However, summers in Scotland can also be very wet and the hydrological year 2006/2007 had a wet summer with only a very brief spring low flow period.

The DO concentrations in the water column remained close to 100% throughout the study period (Figure 2b). Diurnal variability is apparent throughout the year, with daytime maxima and night time minima, though this was most marked in the summer. This reflects the usual daytime net production of $O_2$ through photosynthesis from algae and macrophytes on the stream bed and the consumption during the night time due to respiration. Patterns of oxygen variability at the 150 and 300 mm depths contrasted markedly. Through the initial phases of monitoring, DO levels at 150 mm were close to saturation, in common with streamwater, and also exhibited comparable diurnal fluctuations (Figure 2c). In the summer of 2005, drawdown to <80% saturation was common, and in extreme cases <20%. During the early winter of 2005/2006 levels again were close to 100% and similar to streamwater. Again, there were examples of transient drawdown to <80% in the summer of 2006. However, in the winter of 2006/2007 there were prolonged periods of low (i.e. <50% saturation) DO levels. These were more marked and extended in the

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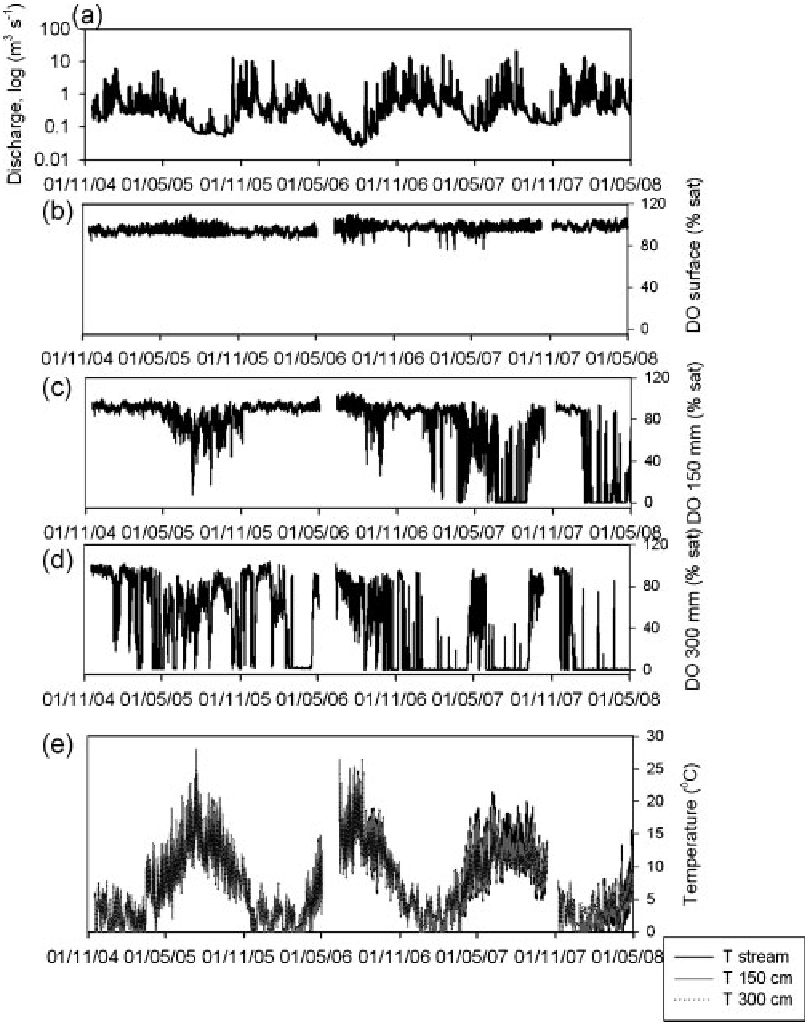

Figure 2. Long-term high resolution data of (a) discharge, (b) dissolved oxygen levels in the stream and at depths of (c) 150 and (d) 300 mm and (e) temperatures

wet summer of 2007. These recovered to near surface water concentrations in an unseasonably dry autumn in 2007, though levels dropped again in the wetter winter of 2007/2008.

The variability of DO levels at 300 mm was more marked than that at 150 mm (Figure 2d). At the start of monitoring in the autumn of 2004, DO levels were close to 100% saturation and comparable to those in the stream or at 150 mm. However, in the wetter winter conditions, transient declines in DO to 0% saturation were frequent. Oxygen concentrations increased and were generally higher in the summer of 2005, though there were still occasional low levels. In the winter of 2005/2006, periods of low DO became more frequent and a prolonged period of drawdown was evident in spring 2006 before an apparent recovery to higher concentrations during the summer. In the winter of 2006/2007, there were repeated periods of transient low DO where concentrations dropped to 0% saturation. This led to a prolonged period of low DO in the late winter where DO only occasionally rose above 0% saturation. Concentrations increased in late April, only to lead to another comparable period of low DO in the wet summer of 2007. The dry autumn of 2007, corresponded with increasingly high DO levels that again approached 100% saturation, before the wetter winter of 2007/2008 again produced periods of transient DO drawdown, and subsequently prolonged periods of DO close to 0% saturation.

Temperatures showed less marked variability than DO (Figure 2e). Temperatures in the stream and both depths in the hyporheic zone follow expected seasonal patterns (Hannah *et al.*, 2008). As anticipated, temperatures in the

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open water column exhibited the most marked variation ranging from 0°C in the winter to highs above 25°C in the summers of 2005 and 2006 (Figure 2e). The cool, wet summer of 2007 was apparent as stream temperatures only occasionally exceeded 20°C. Temperature variation was increasingly damped at depths of 150 and 300 mm (Figure 2e). The damping at 300 mm was particularly evident in the summer of 2007.

### *Seasonal variability—wet periods*

The short-term dynamics in hyporheic water quality become more apparent when the data are plotted for individual months. Figure 3 shows the DO dynamics during four contrasting wet months as exemplars of the main types of conditions that were observed. January 2005 was the first major wet period of the winter (cf. Figures 2, 3a). In the first three events, hyporheic DO exhibits no response at 150 or 300 mm depths. Subsequently, the responses to events at 300 mm become somewhat more complex, DO levels fall below 40% saturation on the recession limb of the fourth event. Thereafter, event peaks resulted in increased hyporheic DO, with subsequent depression early on the recession limb, followed by later recovery to higher levels. Temperatures during this period are relatively low (<6°C) in the water column and streambed (Figure 4a) and in general oscillations are in phase although temperatures at 300 mm were increasingly attenuated and lagged in comparison to the main stream during low DO periods.

Figure 3b shows the DO dynamics 3 months later in April 2005. This followed wetter periods in February and March and shows the catchment in a greater state of antecedent wetness. Throughout April, DO remained close to 100% saturation in the stream and at 150 mm depths. Initially some small-scale variability at 300 mm was evident, though this appeared to relate to accentuated, regular diurnal variations rather than hydrological change. In the first and second events, decreases in DO at 300 mm were apparent on the hydrograph recession before values 'bottomed out' at 0% saturation just after the peak of the third event. This remained low for 5 days, then began to recover. However, the very small fourth and fifth events of April resulted in slight increases in DO on the rising limb, followed by reductions on the early recession and subsequent increases late on the recession. The larger sixth event of the month again resulted in DO saturation bottoming out close to 0% for a prolonged period of several days before fully recovering on the 24th April. Two final events in the last week of April again brought DO down to zero, despite very transient higher DO levels at the peak of the final event. The temperatures in April exhibited much more marked diurnal variability due to the increases in levels of incoming short wave radiation compared to December. Although temperature at 150 mm was similar to surface water, temperature at 300 mm exhibited marked thermal moderation (Figure 4b).

In March 2006 antecedent conditions in the catchment were very wet and two very small events on the first two days resulted in DO levels falling to zero and remaining there for the rest of the month (Figure 3c), this was despite the stream and upper 150 mm remaining near 100% saturation. After these first two precipitation events, there were several days of late winter snow, when a substantial snowpack began to accumulate. Melt commenced on the 7th March, but was very gradual as temperatures remained low (Figure 4c). Diurnal flow variability in relation to snowmelt was increasingly evident through the latter half of the month though this was punctuated by colder periods with re-freezing causing abrupt decreases in night-time flows. Temperatures at 300 mm, again exhibited substantial thermal moderation and were generally higher, especially during freezing periods.

A more extreme period of catchment saturation and associated high flow occurred in the exceptionally wet summer of 2007. During this period DO at 300 mm was close to 0% saturation for over 2 months and for the first time in over 3 years, DO saturation was also exceptionally low at 150 mm (Figure 2). This is evident in the plot for July 2007 where with the exception of occasional spikes of increased DO at the peak of storm events, DO at both 150 and 300 mm flat line at 0% saturation (Figure 3d). DO increases associated with hydrological events were greater and more frequent at 150 mm than those observed at 300 mm. It is also apparent from the temperature plots at this time that water at 300 mm is up to 5°C cooler than that of surface waters, diurnal variations were much more muted and clear gradients were observed between surface water and 300 mm, with 150 mm exhibiting intermediate temperatures (Figure 4d).

The nature of some of these dynamics in hyporheic DO saturation become more clear when changes are plotted in relation to flow (Figure 5). As an example, in Figure 5a the changes during the major event on 10th April 2005

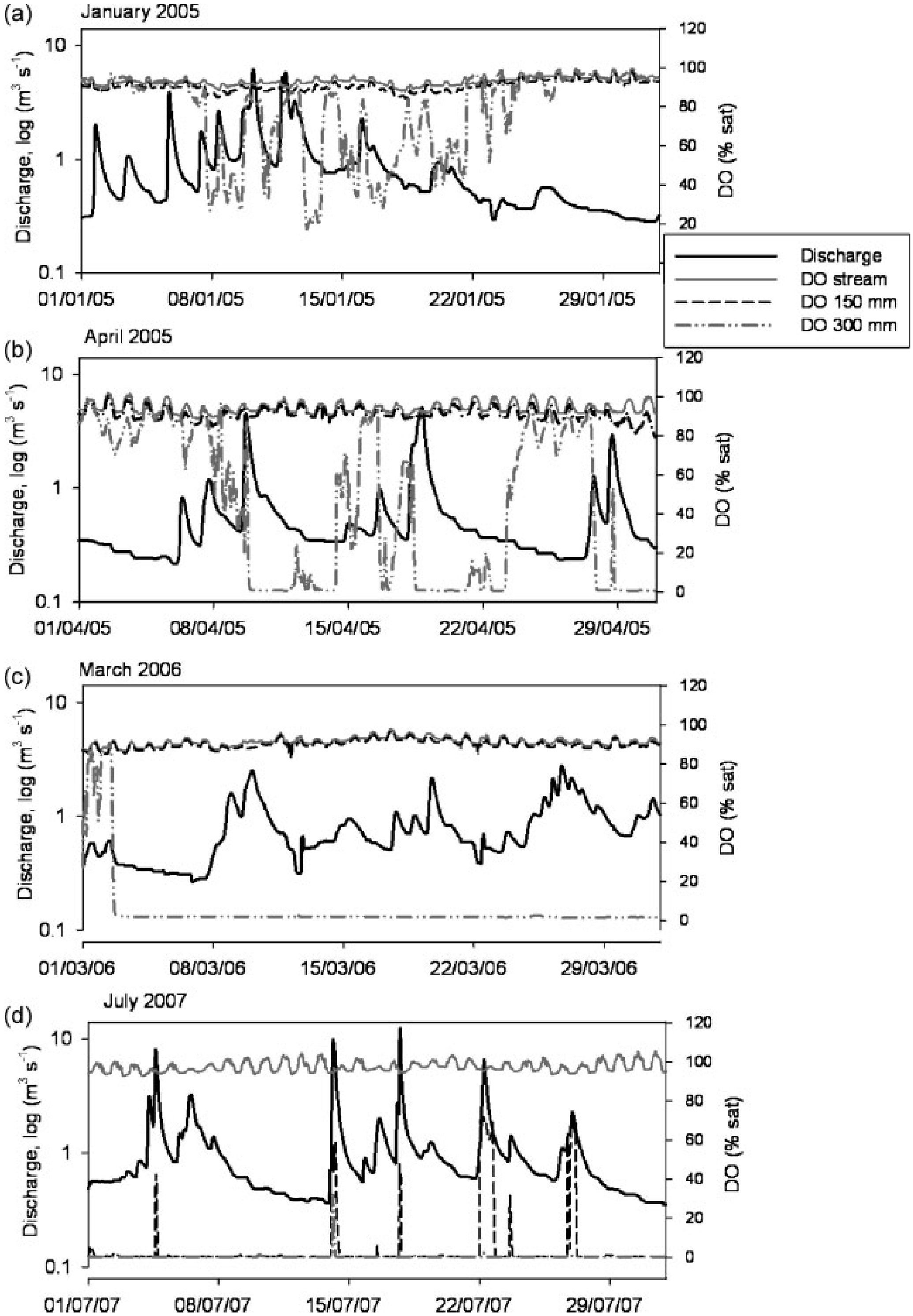

Figure 3. Dissolved oxygen dynamics in the stream and hyporheic zone during four wet periods

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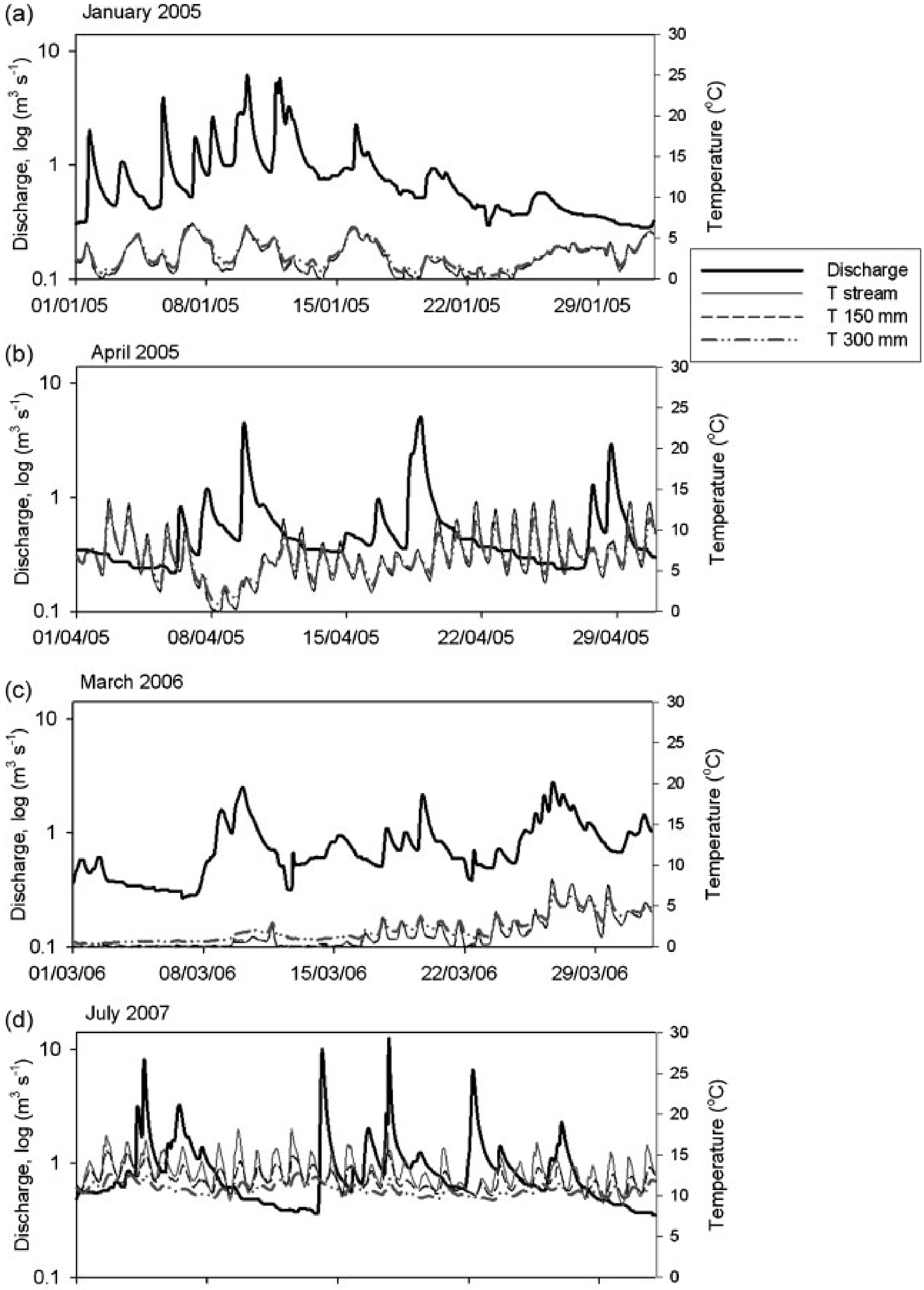

Figure 4. Temperature dynamics in the stream and hyporheic zone during four wet periods

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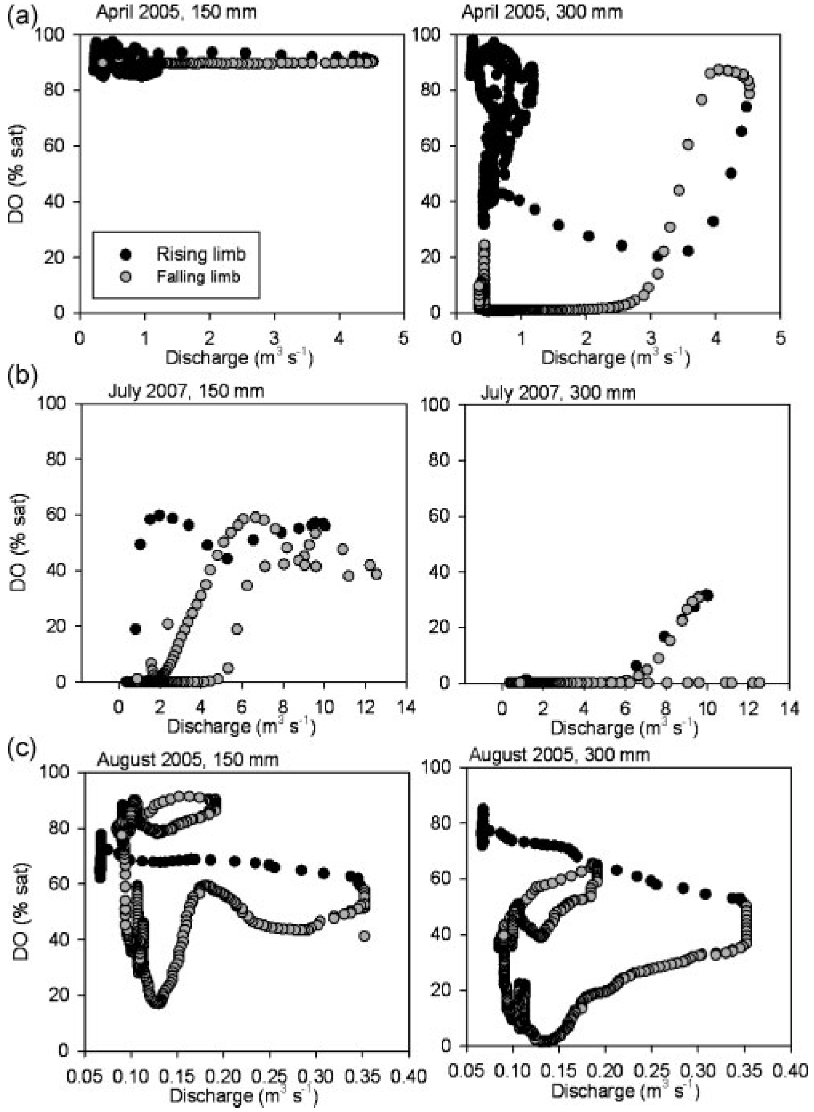

Figure 5. Changing DO saturation in relation to flow during selected wet periods in (a) April 2005 and (b) July 2007; and a dry period event in (c) August 2005

(cf. Figure 3b) are shown. DO saturation stays close to 100% throughout the event at 150 mm, but the hysteresis at 300 mm is clear, with DO increasing to above 80% on the rising limb of the hydrograph, but declining to 0% on the recession in a matter of a few hours and remaining there.

Figure 5b shows an example of an even wetter period during two large events following the 13th July 2007 (cf. Figure 3d). At the start of this sequence of events, DO saturation was at 0% at both 150 and 300 mm. On the rising limb of the event, DO at 150 mm increases to around 60%, but declines soon on the recession. There is a short, transient increase at 300 mm to above 50% but values soon fall back to 0%.

### *Seasonal variability—dry periods*

The very different nature of DO dynamics during drier periods is evident from Figure 6. In May 2005 at the start of the dry season, surface and shallow hyporheic (150 mm) DO were close to 100% saturation, with marked diurnal

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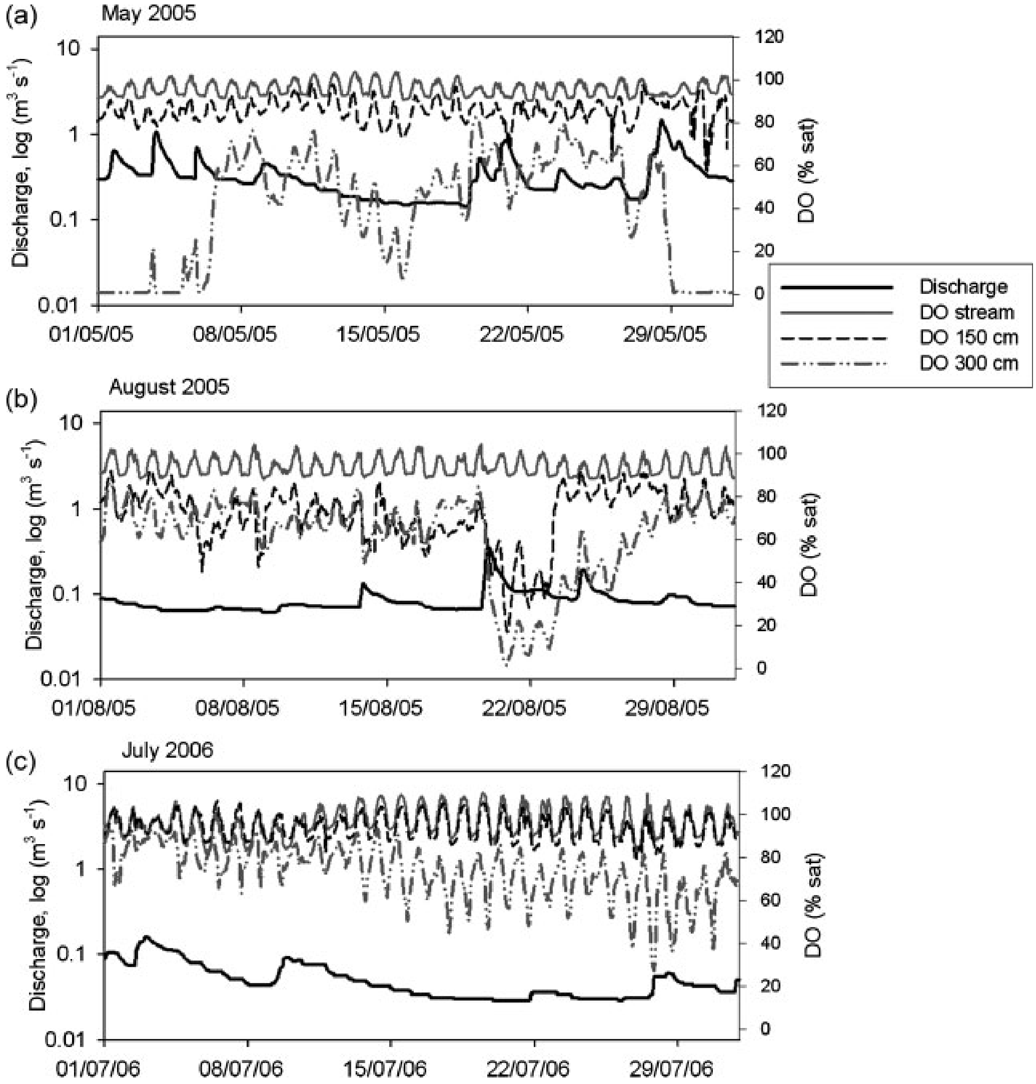

Figure 6. Dissolved oxygen dynamics in the stream and hyporheic zone during three dry periods

variability. DO at 300 mm was initially at 0% saturation, but increased as flows declined (Figure 6a). This was followed by a period of declining DO characterized by distinct diurnal variation that was amplified over that seen in surface water and at 150 mm. Small events on the 20th and 21st May resulted in DO increases close to 80%, before a further small event at the end of the month caused a decline on the recession to 0%, where levels remained for a few days. Stream temperatures during this period showed marked, diurnal fluctuations which were as great as 10°C; hyporheic temperatures tracked stream temperature though some damping of daily temperature extremes was observed at 300 mm (Figure 7a).

By August of the same summer, flows had declined to $<0.1\,m^3\,s^{-1}$ (Figure 6b). Streamwater DO exhibited diurnal variation by around 15% fluctuating close to 100% saturation. The two hyporheic optodes showed similar diurnal oscillations although at lower concentrations and with greater amplitude, fluctuating between around 50 and 90% of saturation. A small hydrological event (ca $0.5\,m^3\,s^{-1}$) on 20th August caused a marked decline in hyporheic DO at both 150 and 300 mm, though diurnal variations remained evident and DO saturation recovered within a few days at 150 mm and within a week at 300 mm. Temperatures during this period were similar to May, with diurnal variations being marked, in phase and slightly damped in the hyporheic zone at 300 mm (Figure 7b).

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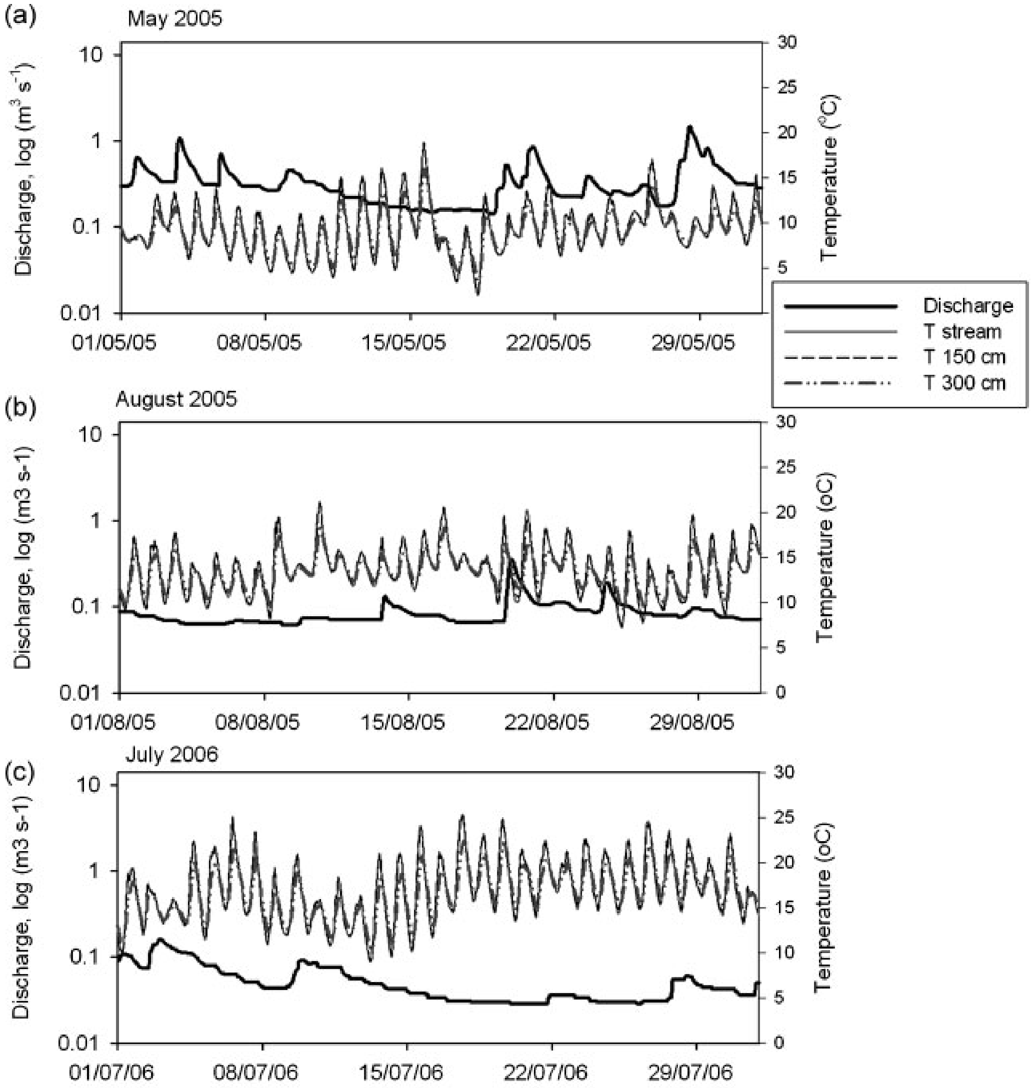

Figure 7. Temperature dynamics in the stream and hyporheic zone during three dry periods

The lowest flows during the 3.5 year monitoring period occurred in July 2006 (Figure 6c). At this time water depths were exceptionally low across the channel, with substantial areas of exposed sediments. Here DO levels in the stream and at 150 mm in the hyporheic zone exhibited high amplitude diurnal fluctuations around the 100% level. At 300 mm the diurnal fluctuations were considerably more marked with increasing diurnal amplitude and time lag, and reducing DO levels towards the end of the month. Although slightly damped at 300 mm, hyporheic temperatures tracked those of streamwaters with diurnal ranges exceeding 10°C (Figure 7c).

An example of the response of DO saturation in relation to flow in a small, dry period event starting on 19th August 2005 (cf. Figure 6b) is shown in Figure 5c. The nature of the response is markedly different to the wet period responses exemplified in Figure 5a and b. DO is at 80% saturation at the start of the event at both 150 and 300 mm; it then declines slightly as flows increase, before declining more abruptly on the recession limb and then recovering again.

### *Inter-annual variability in water quality: implications for salmonid spawning success*

The temporal variability in hyporheic water quality observed in this study, both intra- and inter-annually, has important implications for ecological processes within river systems. This can be demonstrated by examining inter-

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annual variability in water quality conditions over the winter periods when salmonid embryos are typically incubating within river gravels. Figure 8 provides duration curves of flow and water quality parameters, summarizing data for the critical period from mid-November to late April. This corresponds to the period when salmon eggs would be present in the hyporheic zone at this site prior to emergence of juvenile fish in the spring. In general, flows during this period have increased in each successive year of monitoring from 2004/2005 to 2007/

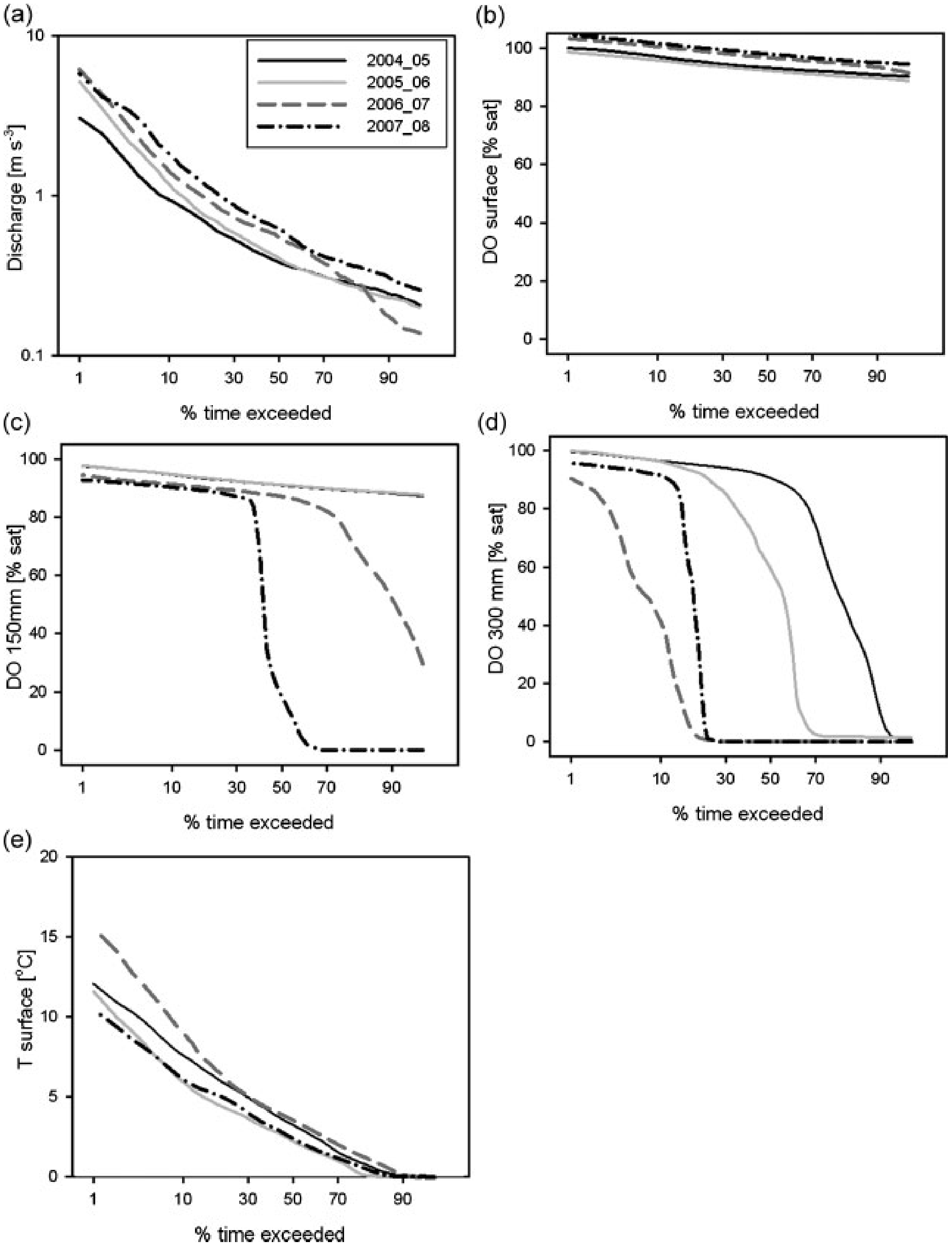

Figure 8. Exceedence curves for spawning period (mid November–end of April) during the period for (a) discharge, (b) stream DO, (c) DO at 150 mm, (d) DO at 300 mm and (e) stream temperatures

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2008 (Figure 8a) whilst the cooler winters of 2005/2006 and 2007/2008 contrast with the mild winter 2006/2007 in particular (Figure 8e). Whilst streamwater DO remained near 100% saturation in each year (Figure 8b), inter-annual differences in hyporheic water quality which were evident in Figure 2, become increasingly apparent (Figure 8c and d). At 150 mm, in 2004/2005 and 2005/2006 DO was above 85% saturation throughout the November–April period. However, in 2006/2007, per cent saturation was below 85% for approximately 30% of the time, and in 2007/2008 this extended to over 60% of the time, with concentrations as low as 0% for about 30% of the time.

Similar inter-annual variability was evident at 300 mm, but the effects were even more marked. In 2003/2004, DO levels were <10% saturation for around 20% of the time. This increased to around 40% of the time in the following year, but was for more than 70% of the time in the wetter years of 2006/2007 and 2007/2008. For salmon embryos developing in the hyporheic zone at this site, marked inter-annual variability in hydrology could lead to markedly different water quality conditions, particularly in terms of the levels of oxygenation, depending upon the amount and timing of precipitation.

## DISCUSSION

The broad scale variability in hyporheic water quality at this site—as shown in Figure 2—primarily reflects the degree to which hillslope groundwater is connected to the stream channel. Antecedent and prevailing hydrological conditions influence the strength of this connectivity, which in turn determines the amount of groundwater discharge through the hyporheic zone (e.g. Soulsby *et al.*, 1998, 2000). This discharge largely determines the level of oxygenation in the stream sediments (Figure 9).

During wet periods (Figure 9a), stream-ward hydraulic gradients result in strong groundwater dominance in hyporheic zone; usually this is evident from 0% DO saturation at 300 mm, but in extremely wet conditions, reducing conditions are also evident for prolonged periods at 150 mm (e.g. Figure 3c, d). Although this had been shown in previous work (e.g. Malcolm *et al.*, 2006, 2009), the data presented here have shown how these periods of de-oxygenation can last for a number of successive month in wet periods. This groundwater influence is also evident in thermal buffering during wet periods which results in warmer temperatures at 300 mm depths in the winter and cooler temperatures during summer wet periods (Figure 4). This is consistent with theoretical studies that have shown that strong groundwater fluxes through the stream bed can effectively shuts off short residence hyporheic exchange by limiting streamwater infiltration (Cardenas and Wilson, 2006).

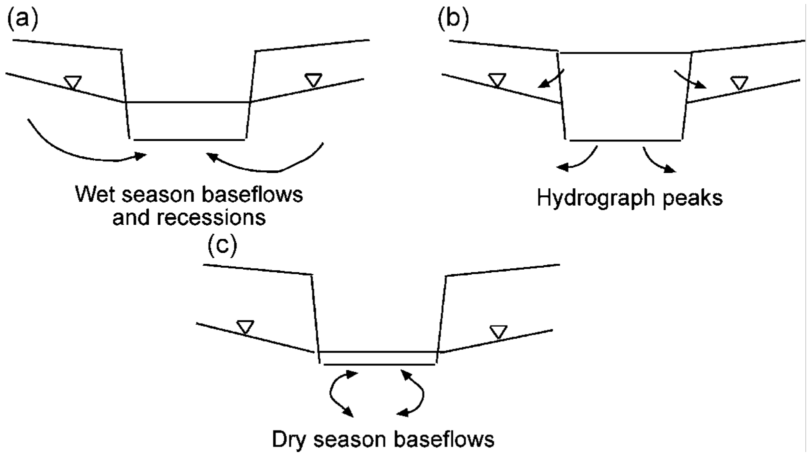

Figure 9. Conceptual model of groundwater—surface water interactions at the study site showing (a) groundwater dominance during wet season recessions and baseflows—under such conditions, low DO saturation has the potential to adversely affect salmon embryos; (b) head reversals at hydrograph peaks where streamwater influx and re-oxygenation of the hyporheic zone occurs and (c) surface water—shallow hyporheic exchange during dry period baseflows—under such conditions during the winter, hyporheic DO saturation will be close to 100% and suitable for salmon embryo development

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These prolonged periods of reducing conditions are punctuated by hydraulic reversals at event peaks (Figure 9b), when high stream stages reverse local hydraulic gradients resulting in transient periods of streamwater downwelling which re-oxygenate the hyporheic zone and homogenize stream bed temperatures (e.g. Figure 3a, b). Similar reversals have been reported previously by the authors (Malcolm *et al*., 2004, 2006) and more recently have been reported in relation to studies of high stream stage associated with hydro-peaking in regulated rivers (Fritz and Arntzen, 2007; Hanrahan, 2008). However, in the Girnock, on the recession limb of larger events as stream stage falls, groundwater flux increases and the DO saturation and thermal characteristics of the hyporheic zone diverge from those of streamwater (Figure 5a). Although in this longer-term monitoring, continuous logging of hydraulic head in the hyporheic zone was precluded by logistical constraints (particularly loss and damage to equipment during high flows and icing events), shorter periods of head monitoring (Malcolm *et al*., 2004), along with other tracers of groundwater influence such as alkalinity (Malcolm *et al*., 2005) have been consistent with this conceptual model shown in Figures 9a and 9b.

Dry periods appear to result in weak groundwater connectivity at the site, presumably as hillslope groundwater levels have declined and hydraulic gradients are very low (Figure 9c). At such times the water quality of the hyporheic zone appears to reflect a greater surface water influence (Figure 6). DO levels in the hyporheic zones can exhibit marked diurnal variability which may be out of phase with variations in streamwater. This may infer *in situ* consumption of oxygen in the hyporheic zone as a result of respiration by the hyporheos or diffusion gradients drawing down hyporheic DO as a result of benthic respiration (Figure 6a, c). During the summer periods when water levels are low, and algal growth reduces stream bed roughness, low water velocities may also contribute to limit hyporheic exchange via turbulent processes (Packman and Salehin, 2003). However, the DO drawdown may also be accentuated by marked diurnal variations in temperature which will affect the solubility of $O_2$ and the resulting degree of saturation.

There is also evidence of *in situ* consumption of oxygen during and after small hydrological events following dry periods (Figures 5c and 6b). Such occurrences are rare and appear to follow low flows that in the Girnock can result in extensive algal growth on the stream bed. Increased shear stresses as velocities increase can dislodge in-channel vegetation causing a flux of organic material that can infiltrate into the stream bed downstream where subsequent decomposition is likely to cause oxygen drawdown (Whitman and Clark, 1982; Soulsby *et al*., 2001). However, the fine sediment fraction in the Girnock tends to be restricted to relatively coarse sands (Moir *et al*., 2002). Thus, *in situ* oxygen consumption caused by fine organic sediments seems to be restricted to such specific conditions at the Girnock, rather than at some other sites where it is a major cause of de-oxygenation (Greig *et al*., 2006; Malcolm *et al*., 2008).

The results of this investigation have demonstrated the importance of prevailing and antecedent hydrological conditions in regulating groundwater—surface water interactions and hyporheic water quality. As a result there are marked seasonal and inter-annual differences in hyporheic processes and consequently water quality. There are ecological implications of such variability, as the life cycles of individual organisms utilizing the hyporheic zone will be adapted to the average range of conditions. Nevertheless, extremes—which are only effectively captured with continuous monitoring—can be important. For example, the prospects for the development and survival of salmon embryos at the study site will be strongly influenced by the inter-annual variability in water quality conditions shown in Figure 8. Developing salmon embryos can endure low DO for short periods (Alderdice *et al*., 1958; Silver *et al*., 1963), particularly at the start of the incubation period when oxygen demand is relatively low, due to low stream temperature and low respiratory mass (Hamor and Garside, 1976; Malcolm *et al*., 2008). In drier years, such as 2004/2005, the well-oxygenated conditions in the hyporheic zone are more likely to maintain $O_2$ availability at levels above those required for survival. In contrast in 2006/2007, it is probable that survival levels would be very low given the anoxic conditions at both shallow and deeper levels in the hyporheic zone. Obviously, this has consequences for juvenile recruitment, and high mortalities can occur in periods when groundwater influence on the hyporehic zone is marked (Youngson *et al*., 2004). In contrast, drier periods of weaker groundwater flux produce more conductive water quality for embryo survival (Malcolm *et al*., 2009). The impact of such inter-annual variability of fry emergence and population dynamics is currently unknown, but is now an important research priority at this site.

This study has revealed that inter-annual variability in hyporheic conditions can be marked and potentially has important consequences for stream ecology and for future hyporheic studies. Evidence of such inter-annual

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variability has only been possible at this site as a result of high temporal resolution monitoring over a prolonged period of several years. Recent hydrological studies elsewhere in the Scottish highlands (e.g. Hrachowitz *et al*., 2009) have suggested that at least 5 years of data are needed to reasonably capture the variability in hydrological and hydrochemical conditions that are characteristic of the site. The data presented here, suggest that similar time periods may be needed to adequately characterize the dynamics of the hyporheic zone. Of course this highlights the need for caution in avoiding the over-interpretation of the results from the usual short-term investigations in hyporheic studies which rarely extend beyond one or two seasons.

## REFERENCES

Alderdice D, Wickett F, Brett JR. 1958. Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs. *Journal of the Fisheries Research Board of Canada* **15**(2): 229–249.

Boulton AJ, Findlay S, Marmonier P, Stanley EH, Valett HM. 1998. The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics* **29**: 59–81.

Cardenas MB, Wilson JL. 2006. The influence of ambient groundwater discharge on exchange zones induced by current-bedform interactions. *Journal of Hydrology* **331**: 103–109.

Duff JH, Triska FJ. 2000. Nitrogen biogeochemistry and surface-subsurface exchange in streams. In *Streams and Ground Waters*, Jones JB, Mulholland PJ (eds). Academic press: California.

Fowler RT, Death RG. 2001. The effect of environmental stability on hyporheic community structure. *Hydrobiologia* **445**: 85–95.

Fraser BG, Williams DD. 1998. Seasonal boundary dynamics of a groundwater/surface-water ecotone. *Ecology* **79**(6): 2019–2031.

Fritz BG, Arntzen EV. 2007. Effect of rapidly changing river stage on uranium flux through the hyporheic zone. *Groundwater* **45**(6): 753–760.

Greig SM, Sear DA, Carling PA. 2006. A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. *Hydrological Processes* **21**(3): 323–334.

Hamor T, Garside ET. 1976. Developmental rates of embryos of Atlantic salmon, *Salmo salar* L., in response to various levels of temperature, dissolved oxygen, and water exchange. *Canadian Journal of Zoology* **54**: 1912–1917.

Hannah DM, Malcolm IA, Soulsby C, Youngson AF. 2008. A comparison of forest and moorland stream microclimate, heat exchanges and thermal dynamics. *Hydrological Processes* **22**: 919–940.

Hanrahan TP. 2008. Effects of river discharge on hyporheic exchange flows in salmon spawning areas of a large gravel-bed river. *Hydrological Processes* **22**: 127–141.

Hrachowitz M, Soulsby C, Tetzlaff D, Dawson JJC, Dunn SM, Malcolm IA. 2009. Using long-term data sets to understand transit times in contrasting headwater catchments. *Journal of Hydrology* DOI:10.1016/j.jhydrol.2009.01.001

Ingendahl D. 2001. Dissolved oxygen concentration and emergence of sea trout fry from natural redds in tributaries of the River Rhine. *Journal of Fish Biology* **58**: 325–341.

Malard F, Hervant F. 1999. Oxygen supply and the adaptations of animals in groundwater. *Freshwater Biology* **41**: 1–30.

Malcolm IA, Youngson A, Soulsby C. 2003. Survival of salmonid eggs in gravel bed streams: effects of groundwater—surface water interactions. *River Research and Applications* **19**: 303–316.

Malcolm IA, Soulsby C, Youngson AF, Hannah DM, McLaren IS, Thorne A. 2004. Hydrologica influences on hyporheic water quality: implications for salmon egg survival. *Hydrological Processes* **18**: 1543–1560.

Malcolm IA, Soulsby C, Youngson AF, Hannah DM. 2005. Catchment scale controls on groundwater -surface interactions in salmon spawning gravels. *Rivers Research and Application* **21**: 977–989.

Malcolm IA, Soulsby C, Youngson AF. 2006. High frequency logging technologies reveal state dependant hyporheic process dynamics: implications for hydroecological studies. *Hydrological Processes* **20**: 615–622.

Malcolm IA, Soulsby C, Youngson AF, Tetzlaff D. 2009. Fine scale spatial and temporal variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions. *Hydrogeology Journal* DOI:10.1007/s10040-008-0339-5

Malcolm IA, Youngson AF, Greig S, Soulsby C. 2008. Hyporheic influences on spawning success. In *Salmon Spawning Habitat in Rivers: Physical Controls, Biological Responses and Approaches to Remediation*, Sear DA, DeVries P (eds). American Fisheries Society; 225–248.

Moir H, Soulsby C, Youngson AF. 2002. The hydraulic and sedimentary controls on the availability of Atlantic salmon spawning habitat in the river system NE Scotland. *Geomorphology* **45**: 291–308.

Moir HJ, Gibbins CN, Soulsby C, Webb J. 2004. Linking catchment geomorphic characteristics to the spatial pattern of discharge use by spawning salmon in two Scottish upland streams. *Geomorphology* **60**: 21–35.

Moir H, Gibbins C, Soulsby C, Youngson A. 2005. Validation of PHABSIM predictions for simulating salmon spawning habitat. *Rivers Research and Application* **21**: 1021–1034.

Nyberg L, Calles O, Greenberg L. 2008. Impact of short-term regulation on hyporheic water quality in a boreal river. *River Research and Applications* **24**: 407–419.

Packman AI, Salehin M. 2003. Relative roles of stream flow and sedimentary conditions in controlling hyporheic exchange. *Hydrobiologia* **494**: 291–297.

Peterson NP, Quinn TP. 1996. Spatial and temporal variation in dissolved oxygen in natural egg pockets of chum salmon, in Kennedy Creek, Washington. *Journal of Fish Biology* **48**: 131–143.

Rubin JF, Glimsater C. 1996. Egg-to-fry survival of the sea trout in some streams of Gotland. *Journal of Fish Biology* **48**: 585–606.

Shumway DL, Warren CE, Doudoroff P. 1964. Influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. *Transactions of the American Fisheries Society* **93**: 342–356.

Silver SJ, Warren CE, Doudoroff P. 1963. Dissolved oxygen requirements of developing steelhead trout and chinook salmon embryos at different water velocities. *Transaction of the American Fisheries Society* **92**(4): 327–343.

Soulsby C, Chen M, Ferrier RC, Jenkins A, Harriman R. 1998. Hydrogeochemistry of shallow groundwater in a Scottish catchment. *Hydrological Processes* **12**: 1111–1127.

Soulsby C, Malcolm R, Helliwell RC, Ferrier RC, Jenkins A. 2000. Isotope hydrology of the Allt a' Mharcaidh catchment, Cairngorm mountains, Scotland: implications for hydrological pathways and water residence times. *Hydrological Processes* **14**: 747–762.

Soulsby C, Malcolm IA, Youngson AF. 2001. The hydrochemistry of the hyporheic zone in salmon spawning gravels: a preliminary assessment in a small regulated stream. *Regulated Rivers* **17**: 651–665.

Soulsby C, Tetzlaff D, van den Bedem N, Malcolm IA, Bacon PJ, Youngson AF. 2007. Inferring groundwater influences on streamwater in montane catchments from hydrochemical surveys of springs and streamwaters. *Journal of Hydrology* **333**(2–4): 199–213.

Sowden TK, Power G. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. *Transactions of the American Fisheries Society* **114**: 804–812.

Storey RG, Williams DD. 2004. Spatial responses of hyporheic invertebrates to seasonal changes in environmental parameters. *Freshwater Biology* **49**(11): 1468–1486.

Storey RG, Williams DD, Fulthorpe RR. 2004. Nitrogen processing in the hyporheic zone of a pastoral stream. *Biogeochemistry* **69**(3): 285–313.

Tetzlaff D, Soulsby C, Waldron S, Malcolm IA, Bacon PJ, Dunn SM, Lilly A. 2007. Conceptualisation of runoff processes using GIS and tracers in a nested mesoscale catchment. *Hydrological Processes* **21**: 1289–1307.

Tetzlaff D, Gibbins CN, Bacon PJ, Youngson AF, Soulsby C. 2008. Influence of hydrological regimes on the pre-spawning entry of Atlantic salmon (*Salmo Salar L.*) into an upland river. *Rivers Research and Application* **24**: 528–542.

Whitman RL, Clark WJ. 1982. Availability of dissolved oxygen in interstitial waters of a sandy creek. *Hydrobiologia* **92**: 651–658.

Youngson AF, Malcolm IA, Thorley JL, Bacon PJ, Soulsby C. 2004. Long-residence groundwater effects on incubating salmonid eggs: low hyporheic oxygen impairs embryo development and causes mortality. *Canadian Journal of Fisheries and Aquatic Sciences* **61**: 2278–2287.

Zimmerman AE, Lapointe M. 2005. Intergranular flow velocity through salmonid redds: sensitivity to fines infiltration from low intensity sediment transport events. *River Research and Applications* **21**: 865–881.

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