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High-frequency logging technologies reveal state-dependent hyporheic process dynamics: implications for hydroecological studies

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Abstract

This paper presents a novel method for assessing hyporheic water quality dynamics using advances in sensor technology. High-resolution (15 min) dissolved oxygen (DO) and hydraulic head data were combined to assess groundwater–surface water (GW–SW) interactions in the hyporheic zone. DO concentrations varied at fine temporal and spatial scales, depending on the relative contributions of GW and SW. The effect of sample frequency on observed patterns of variability was assessed with reference to studies of the ecology of salmon spawning habitat. Conventional approaches fail to capture the full range of temporal variability in hyporheic water quality and demonstrate the need to reassess the interpretations of previous studies of the hyporheic zone. © Crown Copyright 2006. Reproduced with the permission of Her Majesty's Stationery Office. Published by John Wiley & Sons, Ltd.

Key Words hydrology; hyporheic; oxygen; ecology; salmon; redd; chemistry

Introduction

In recent years there has been increased recognition of the importance of the hyporheic zone to the hydroecological functioning of river systems (Hancock *et al.*, 2005). Associated with this has been an increase in hyporheic zone research and consideration of its importance in legislation such as the Water Framework Directive of the European Union. It is now clear that the physical and chemical characteristics of the hyporheic zone can affect a wide range of hydroecological processes, including nutrient processing (McKnight *et al.*, 2004), microbial (Findlay *et al.*, 2003) and invertebrate communities (Storey and Williams, 2004).

One area of particular interest in hyporheic research has been the influence of hyporheic processes on the reproductive success of gravel spawning fish (Malcolm *et al.*, 2003a, 2004; Groves and Chandler, 2005). Salmonids deposit their eggs in open gravel structures (known as redds) to depths of up to 300 mm in the hyporheic zone. Embryo survival and performance between spawning and emergence, a period that may be in excess of 5 months, is strongly influenced by the delivery of sufficient oxygen to meet the requirements of developing embryos (Malcolm *et al.*, 2003b). Historically, fisheries scientists have viewed the streambed (i.e. the hyporheic zone) in overly simplistic terms, often assuming the stream itself to be the only source of water to the redd.

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This led research to focus primarily on the role of fine sediment in determining hyporheic oxygen supply, and thus embryo survival. However, a number of field-based studies have now demonstrated that the link between sediment size characteristics, streambed oxygen and embryo survival is not clear (Sowden and Power, 1985; Peterson and Quinn, 1996), and there is increasing realization of the importance of groundwater–surface water (GW–SW) interactions in determining hyporheic water quality (Groves and Chandler, 2005). In particular, recent studies have shown that the discharge of chemically reduced (low dissolved oxygen (DO)) groundwater may adversely affect embryo performance in the hyporheic zone (Youngson *et al.*, 2005) and that GW–SW interactions can be highly dynamic, changing rapidly over the period of a single hydrological event (Malcolm *et al.*, 2004).

Although hydrologists have inferred the nature of GW–SW interactions from fine-resolution monitoring of hillslope flowpaths (Haria and Shand, 2004; Vidon and Hill, 2004), there have been few studies using similar resolution hydrometric data to assess exchange processes directly in the hyporheic zone (Geist, 2000; Malcolm *et al.*, 2004). Even rarer are investigations combining high-resolution hydrochemical and hydrometric data to characterize GW–SW interactions in the hyporheic zone. Kirchner *et al.* (2004) highlighted the potential of high-frequency water quality monitoring for understanding the links between hydrology and stream chemistry, noting that most hydrochemical studies are based on data collected at weekly or monthly intervals, sometimes with more frequent sampling during individual hydrological events. Such approaches miss much of the variability observed with continuous water quality monitoring and fail to identify temporally variable event responses that result from rapidly changing hydrological conditions. These problems are exacerbated in hyporheic studies, where it is necessary for equipment to remain buried in the streambed for prolonged periods without maintenance or recalibration, where water velocities are generally low and where physical access during hydrological events is often dangerous or impossible. These constraints have dictated that, to date, very little high-resolution hydrochemical data have been collected in hyporheic studies, despite awareness that a number of key water quality parameters (which have a demonstrable effect on hyporheic ecology) vary dynamically over time and space. Within the last year, new technology has allowed high-resolution hyporheic oxygen measurements to be made *in situ* using optical probes that exhibit long-term stability, do not consume oxygen during measurement and do not require a flow of water past the sensor to obtain accurate readings.

In this paper we present data collected using this new technology to assess the variability of dissolved oxygen at fine temporal scales in the hyporheic zone of salmon spawning gravels in an upland stream. Our specific objectives are to: (i) characterize the temporal and spatial variability of DO concentrations in an artificial salmon redd; (ii) assess the influence of GW–SW interactions in determining this variability; (iii) evaluate the contribution that continuous water quality data can make in improving our understanding of hyporheic dynamics and ecological response.

Site Description

Detailed descriptions of the field site are available elsewhere (Malcolm *et al.*, 2004). Briefly, Glen Girnock is a semi-natural upland catchment in Scotland (Figure 1). It ranges in altitude from $\sim$230 to 862 m, and drains 30·3 km^2. The geology is dominated by igneous rocks (granite) with metamorphosed rocks, including calcareous schists and serpentinite elsewhere (Soulsby *et al.*, 2005). The solid geology is overlain by a variety of glacial sediments that form the parent material for soils, which include peats, podzols, gleys and brown forest soils. Land use is dominated by heather (*Calluna*) moorland. The Girnock receives approximately 1100 mm of precipitation annually and a gauging station provides 15 min resolution discharge data at Littlemill (Figure 1). The burn has a mean discharge of $\sim$0·5 m^3 s^{-1}, varying between $<$0·01 m^3 s^{-1} in the summer and $>$23 m^3 s^{-1} during floods. FRS Freshwater Laboratory has monitored Atlantic salmon populations since 1966 and produce redd maps ($<$1 m resolution) to identify spawning distributions. Spawning gravels are characterized by a geometric mean diameter (dg) of 9·98 mm and are strongly coarse-skewed, with a low fines content ($<$2 mm), contributing 12% to the sediment mass (Moir *et al.*, 2002). The area chosen for the study is one of three main spawning areas in the catchment, accounting for $\sim$22% of total spawning activity in the Girnock Burn between 1986 and 1988

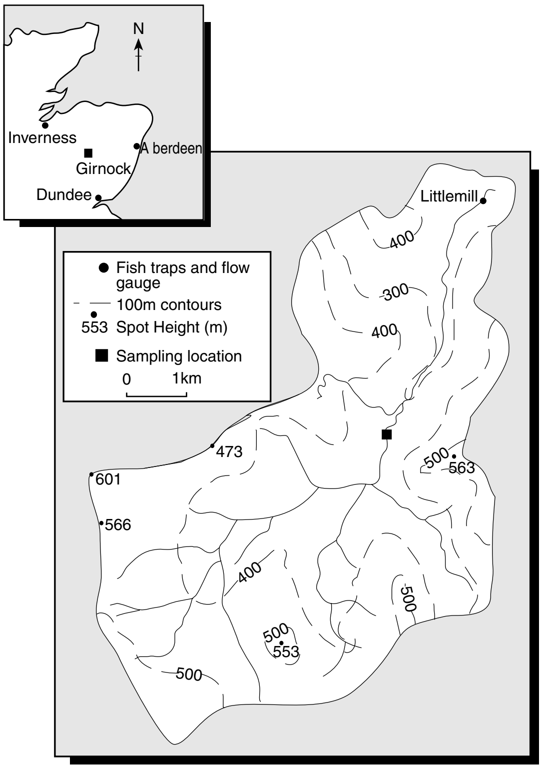

Figure 1. Topographic map of the Girnock Burn catchment showing the location of the sampling site, SEPA flow gauge and FRS fish traps

(Gibbins *et al*., 2002). Previous work at this site identified temporally variable GW–SW interactions using logging piezometers combined with traditional hydrochemical sampling methods (Malcolm *et al*., 2004).

Methods

In November 2004 (spawning time), an artificial redd incorporating two Aanderaa™ DO optodes was constructed in a location used by spawning salmon in previous years. Aanderaa™ 3830 optodes with analogue converters (0–5 V) were connected to a Campbell™ CR23X datalogger and programmed to sample DO (per cent saturation) and temperature at 1 min intervals, recording instantaneous and average measurements every 15 min from surface water and 150 and 300 mm depths in the hyporheic zone (i.e. in the artificial redd). Prior to deployment, DO optodes were cross-calibrated over a 3 week period in the laboratory at a range of oxygen concentrations and temperatures and showed excellent agreement between sensors (within 1% oxygen saturation and 0·1 °C). The manufacturers report that the typical time required between sensor calibrations is approximately 1 year and, therefore, in excess of the duration of the study.

The nature of local GW–SW interactions at the site was assessed using hydraulic head data measured at depths of 38 and 70 cm using piezometers containing Eijkelkamp™ Diver pressure transducers with integrated loggers and thermistors, as described by Malcolm *et al.* (2004). The direction of water movement is inferred using the difference in head between the two piezometers, with positive values indicating a streamward hydraulic gradient and negative values a gradient towards the bed. Owing to technical difficulties, head data were only available for the period 16 November 2004–19 January 2005.

Results and Discussion

Figure 2 shows the temporal variability in stream and hyporheic DO (150 and 300 mm) plotted relative to discharge for the period between spawning and egg hatch. Throughout this period the DO saturation in stream and shallow hyporheic water (150 mm) remained high; typically, this was between 90 and 100%, varying in response to diurnal shifts in the balance between respiration and photosynthesis. DO at 300 mm initially exhibited similar patterns; but, in early January, the DO response became more dynamic in association with a series of hydrological events. Low DO periods were associated with increased catchment wetness in mid January, and between mid February and mid March. These periods were characterized by highly variable conditions, with DO typically falling below 40% saturation on the recession limb of individual hydrographs. Prolonged base flow periods between late January and early February, then again in late March were associated with the re-establishment of high DO levels, comparable to those found in surface water.

Figure 3 focuses on the period between early December and mid January, when reductions in DO at 300 mm were first observed as the catchment responded to a prolonged period of increased precipitation. Changes in DO are plotted relative to discharge and differences in hydraulic head between depths of 38 and 70 cm in the hyporheic zone. Hydraulic gradient data indicate increasingly positive streamward

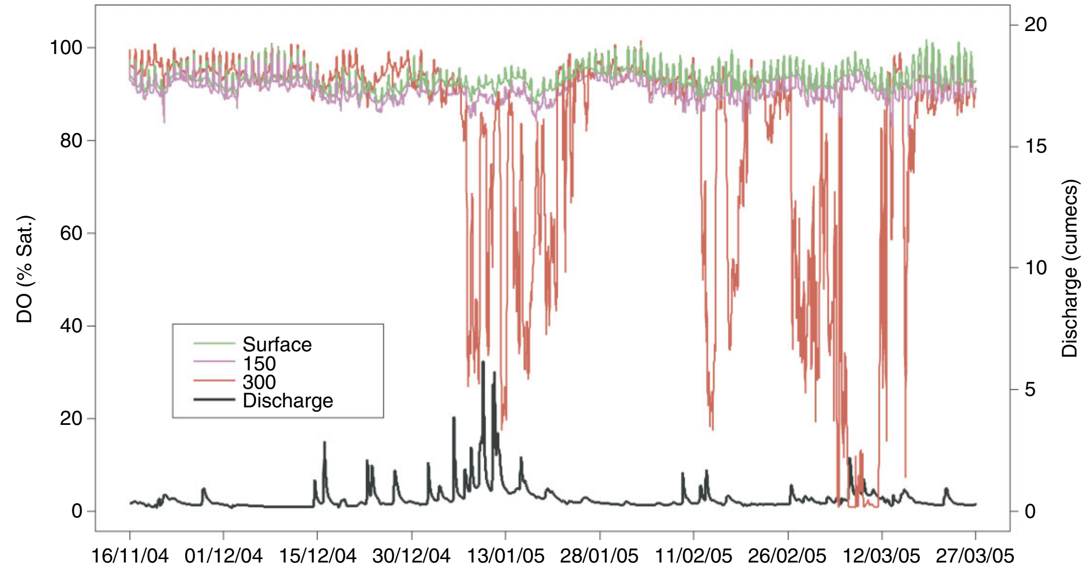

Figure 2. DO concentrations in surface water and at depths of 150 and 300 mm in the hyporheic zone between spawning and hatch. Discharge is shown on the secondary *y* axis

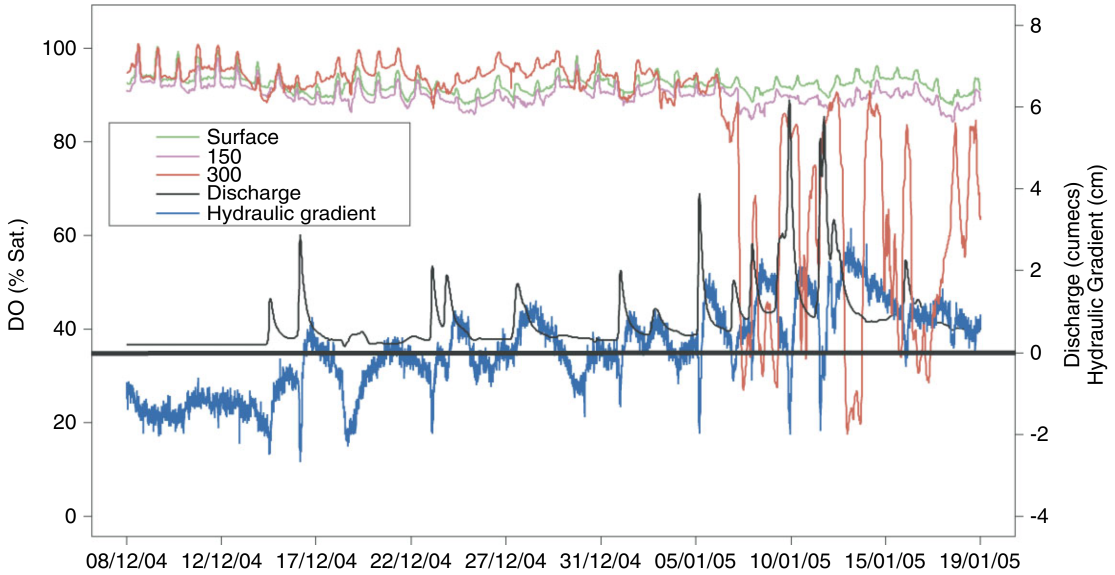

Figure 3. DO concentrations in stream and hyporheic water (150 and 300 mm), relative to discharge and hydraulic gradient. Streamward gradients are indicated where the difference in head between 70 and 38 cm exceeds unity, as indicated by the solid horizontal line

hydraulic gradients as the frequency and magnitude of hydrological events increased. This is consistent with increased water table elevation in response to groundwater recharge.

In general, the event-scale changes in hydraulic gradient followed a consistent pattern (Malcolm *et al.*, 2004). At the event peak, the hydraulic gradient became increasingly negative, presumably in response to increased stream stage relative to riparian water table elevation resulting in a stream water flux into the bed. On the recession limb, increasingly positive hydraulic gradients were established, which

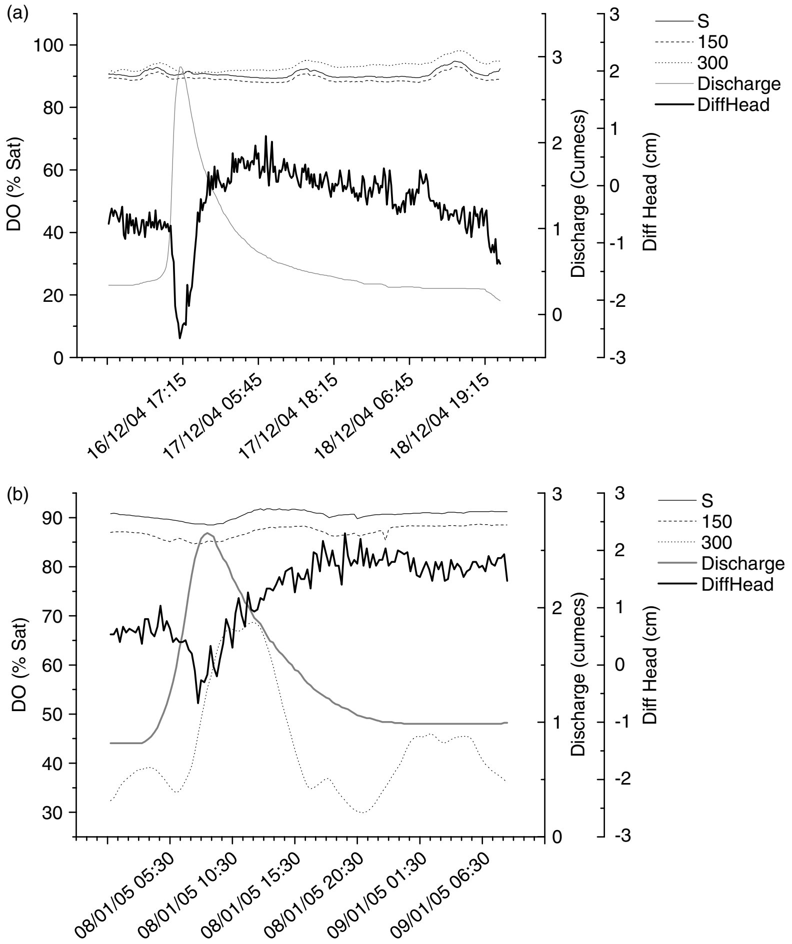

Figure 4. Event-based variability in DO concentration relative to discharge and hydraulic gradient as indicated by the difference in hydraulic head between 38 and 70 cm piezometers. Events of similar magnitude are shown (a) before and (b) after catchment rewetting

were assumed to result from increasing riparian groundwater levels and reductions in stream stage (Malcolm *et al.*, 2004). Although patterns of hydraulic flux were consistent between events, the magnitude of gradients and changes in hyporheic water quality were variable. Prior to 6 January, small event-based occurrences of positive hydraulic gradient were not associated with changes in hyporheic DO levels, as shown in Figure 4a. However, following catchment rewetting and the establishment of increasingly positive hydraulic gradients, events of similar magnitude were associated with rapidly changing hyporheic DO concentrations. This is shown in Figure 4b, where low DO concentrations associated with the recession limb of a previous event increased rapidly in response to increasing stream stage and negative hydraulic gradients, before declining on the recession limb as positive gradients were re-established.

Owing to the difficulties associated with hyporheic sampling (as outlined above), previous hydroecological studies have failed to identify the nature and significance of the frequency and magnitude of changes in hyporheic processes, including changes in GW–SW interactions and water quality. This has resulted in widely varying sampling strategies that are generally of much lower resolution than is required to characterize the hyporheic environment. For example, the focus of many investigations has been the influence of hyporheic DO levels on exposed organisms such as salmonid embryos (Table I). In such studies,

Table I. Frequency of hyporheic oxygen sampling for studies of salmonid spawning habitat. Where sampling frequency has not been stated explicitly, it has been derived from figures or numbers of samples in a specified period

Study	Sampling frequency
Youngson *et al.* (2005)	Fortnightly
Groves and Chandler (2005)	Monthly
Malcolm *et al.* (2004)	Weekly
Bowen and Nelson (2003)	1–3 monthly (three occasions over 5 months)
Malcolm *et al.* (2003a)	Weekly (with more frequent event-based monitoring)
Niepagenkemper and Meyer (2002)	Monthly/bi-monthly
Ingendahl (2001)	Fortnightly
Peterson and Quinn (1996)	Weekly–fortnightly
Rubin and Glimsater (1996)	Approximately fortnightly
Curry and Noakes (1995)	Single sample, 24 h after samplers deployed
Curry *et al.* (1995)	Monthly–bi-monthly (strategic to developmental stage of embryos)
Sowden and Power (1985)	Approximately monthly

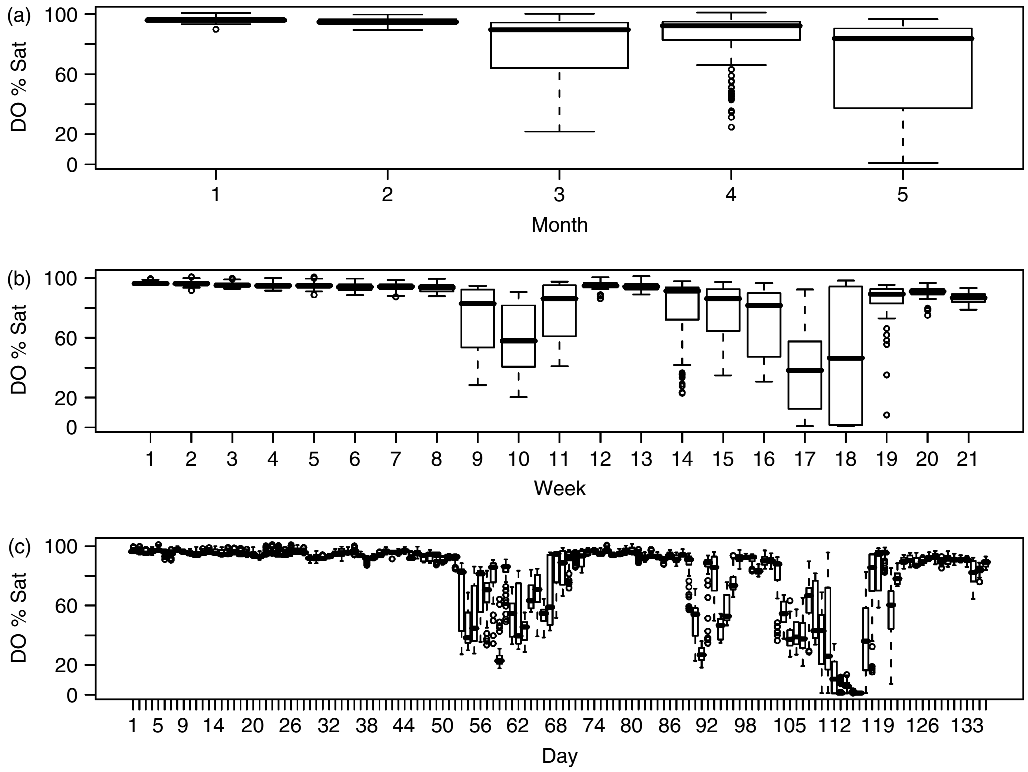

Figure 5. Box plots showing the influence of sample frequency on observed patterns of DO variability based on 100 random samples of continuous DO data at specified intervals: (a) monthly; (b) weekly; (c) daily

hyporheic sampling frequencies typically include weekly, fortnightly, monthly or, in some cases, only single samples. These sampling frequencies are long in comparison with the hydrochemical response times identified in the current study and, as such, risk missing biologically important low DO episodes. Figure 5 uses the continuous hyporheic water quality data (300 mm) collected in this study (Figure 2) to demonstrate the effect of monthly, weekly, or daily sampling strategies using 100 random repeat samples. At monthly sampling intervals, there is a high risk of missing most of the variation in hyporheic DO concentrations. At weekly intervals, the general trends of longer duration are observed, but extreme values are underestimated; with daily sampling, more of the variability is observed, but sampling fails to capture extreme low values, which prevail for short periods. We conclude, therefore, that any biological inferences made on the basis of low-resolution sampling have the potential to be highly misleading.

Implications

The data presented here show that at the Girnock Burn study site hyporheic DO exhibits fine-resolution temporal and spatial dynamics, which vary depending on the relative contributions of GW and SW. GW–SW interactions respond to antecedent hydrological conditions, prevailing stream stage and water table elevation. Thus, hyporheic water quality can vary at different time scales ranging from seasonal to individual events. Moreover, events of similar magnitude can produce marked differences in hyporheic water quality due to the state dependence associated with antecedent conditions. To date, much of the variability in hyporheic water quality parameters (in this case DO) has probably been underestimated owing to technological limitations on the resolution and timing of sampling in hyporheic studies. These difficulties have been overcome, and there is now a need to reassess the biological interpretations of previous water quality studies of the hyporheic zone.

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References

Bowen MD, Nelson SM. 2003. Environmental variables associated with a chinook salmon redd in Deer Creek, California. *California Fish and Game* **89**(4): 176–186.

Curry RA, Noakes DLG. 1995. Groundwater and the selection of spawning sites by brook trout (*Salvelinus fontinalis*). *Canadian Journal of Fisheries and Aquatic Sciences* **52**: 1733–1740.

Curry RA, Noakes DLG, Morgan GE. 1995. Groundwater and the incubation and emergence of brook trout (*Salvelinus fontinalis*). *Canadian Journal of Fisheries and Aquatic Sciences* **52**: 1741–1749.

Findlay SEG, Sinsabaugh RL, Sobczak WV, Hoostal M. 2003. Metabolic and structural response of hyporheic microbial communities to variations in supply of dissolved organic matter. *Limnology and Oceanography* **48**: 1608–1617.

Geist DR. 2000. Hyporheic discharge of river water into fall chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. *Canadian Journal of Fisheries and Aquatic Science* **57**: 1647–1656.

Gibbins C, Moir H, Webb J, Soulsby C. 2002. Assessing discharge use by spawning Atlantic salmon habitat: a comparison of discharge electivity indices and PHABSIM simulations. *River Research and Applications* **18**: 383–395.

Groves PA, Chandler JA. 2005. Habitat quality of historic Snake River fall chinook salmon spawning locations and implications for incubation survival. Part 2: intra-gravel water quality. *Rivers Research and Applications* **21**: 469–483.

Hancock PJ, Boulton AJ, Humphreys WF. 2005. Aquifers and hyporheic zones: towards an ecological understanding of groundwater. *Journal of Hydrogeology* **13**: 98–111.

Haria AH, Shand P. 2004. Evidence for deep sub-surface flow routing in forested upland Wales: implications for contaminant transport and stream flow generation. *Hydrology and Earth System Sciences* **8**: 334–344.

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.

Kirchner JW, Feng X, Neal C, Robson AJ. 2004. The fine structure of water-quality dynamics: the (high-frequency) wave of the future. *Hydrological Processes* **18**: 1353–1359.

Malcolm IA, Soulsby C, Youngson A, Petry J. 2003a. Heterogeneity in ground water–surface water interactions in the hyporheic zone of a salmonid spawning stream. *Hydrological Processes* **17**: 601–617.

Malcolm IA, Youngson A, Soulsby C. 2003b. 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. Hydrological influences on hyporheic water quality: implications for salmon egg survival. *Hydrological Processes* **18**: 1543–1560.

McKnight DM, Runkel RL, Tate CM, Duff JH, Moorhead DL. 2004. Inorganic N and P dynamics of Antarctic glacial meltwater streams as controlled by hyporheic exchange and benthic autotrophic communities. *Journal of the North American Benthological Society* **23**: 171–188.

Moir HJ, Soulsby C, Youngson AF. 2002. Hydraulic and sedimentary controls on the availability and use of Atlantic salmon (*Salmo salar*) spawning habitat in the River Dee system, north-east Scotland. *Geomorphology* **45**: 291–308.

Niepagenkemper O, Meyer EI. 2002. Messungen der Sauerstoffkonzentration in Flusssedimenten zur Beurteilung von potentiellen Laichplätzen von Lachs und Meerforelle. In *Veröffentlichungen des Landesfischereiverbandes Westfalen und Lippe e.V. (Hrsg.)*, 2. Bitter und Loose.

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.

Soulsby C, Malcolm IA, Youngson AF, Tetzlaff D, Gibbins CN, Hannah DM. 2005. Groundwater–surface water interactions in upland Scottish rivers: hydrological, hydrochemical and ecological implications. *Scottish Journal of Geology* **41**: 39–49.

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**: 1468–1486.

Vidon P, Hill AR. 2004. Landscape controls on the hydrology of stream riparian zones. *Journal of Hydrology* **292**: 210–228.

Youngson AF, Malcolm IA, Thorley JL, Bacon PJ, Soulsby C. 2005. 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.