Springer

# Dear Author

Here are the proofs of your article.

- You can submit your corrections **online** or by **fax**.
- For **online** submission please insert your corrections in the online correction form. Always indicate the line number to which the correction refers.
- Please return your proof together with the permission to publish confirmation.
- For **fax** submission, please ensure that your corrections are clearly legible. Use a fine black pen and write the correction in the margin, not too close to the edge of the page.
- Remember to note the journal title, article number, and your name when sending your response via e-mail, fax or regular mail.
- **Check** the metadata sheet to make sure that the header information, especially author names and the corresponding affiliations are correctly shown.
- **Check** the questions that may have arisen during copy editing and insert your answers/corrections.
- **Check** that the text is complete and that all figures, tables and their legends are included. Also check the accuracy of special characters, equations, and electronic supplementary material if applicable. If necessary refer to the *Edited manuscript*.
- The publication of inaccurate data such as dosages and units can have serious consequences. Please take particular care that all such details are correct.
- Please **do not** make changes that involve only matters of style. We have generally introduced forms that follow the journal's style.
  Substantial changes in content, e.g., new results, corrected values, title and authorship are not allowed without the approval of the responsible editor. In such a case, please contact the Editorial Office and return his/her consent together with the proof.
- If we do not receive your corrections **within 48 hours**, we will send you a reminder.

**Please note**

Your article will be published **Online First** approximately one week after receipt of your corrected proofs. This is the **official first publication** citable with the DOI. **Further changes are, therefore, not possible.**

After online publication, subscribers (personal/institutional) to this journal will have access to the complete article via the DOI using the URL:

`http://dx.doi.org/10.1007/s10040-008-0339-5`

If you would like to know when your article has been published online, take advantage of our free alert service. For registration and further information, go to: http://www.springerlink.com.

Due to the electronic nature of the procedure, the manuscript and the original figures will only be returned to you on special request. When you return your corrections, please inform us, if you would like to have these documents returned.

The **printed version** will follow in a forthcoming issue.

To: Carla Lucero for Springer
E-mail: M.Lucero@spi-bpo.com
Fax: +1-703-5621873
SPi
SPi Building, Sac-sac Bacong,
Oriental Negros 6216
Philippines

Re:

**Hydrogeology Journal DOI 10.1007/s10040-008-0339-5**

Fine scale variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions

**Malcolm · Soulsby · Youngson · Tetzlaff**

## Permission to publish

I have checked the proofs of my article and

- ❑ I have **no corrections.** The article is ready to be published without changes.
- ❑ I have **a few corrections.** I am enclosing the following pages:
- ❑ I have made **many corrections.** Enclosed is the **complete article.**

**Date / signature:** ______________________________________________

# Metadata of the article that will be visualized in OnlineFirst

| | | | |
|---|---|---|---|
| 1 | Article Title | **Fine scale variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions** | |
| 2 | Journal Name | Hydrogeology Journal | |
| 3 | Corresponding Author | Family Name | **Malcolm** |
| 4 | | Particle | |
| 5 | | Given Name | **I. A.** |
| 6 | | Suffix | |
| 7 | | Organization | Fisheries Research Services Freshwater Laboratory |
| 8 | | Division | |
| 9 | | Address | P.O. Box 101, Pitlochry AB11 9DB, Scotland, UK |
| 10 | | e-mail | I.A.Malcolm@MARLAB.AC.UK |
| 11 | Author | Family Name | **Soulsby** |
| 12 | | Particle | |
| 13 | | Given Name | **C.** |
| 14 | | Suffix | |
| 15 | | Organization | University of Aberdeen |
| 16 | | Division | School of Geosciences |
| 17 | | Address | Elphinstone Road, Aberdeen AB24 3UF, Scotland, UK |
| 18 | | e-mail | |
| 19 | Author | Family Name | **Youngson** |
| 20 | | Particle | |
| 21 | | Given Name | **A. F.** |
| 22 | | Suffix | |
| 23 | | Organization | Fisheries Research Services Freshwater Laboratory |
| 24 | | Division | |
| 25 | | Address | P.O. Box 101, Pitlochry AB11 9DB, Scotland, UK |
| 26 | | e-mail | |
| 27 | Author | Family Name | **Tetzlaff** |
| 28 | | Particle | |
| 29 | | Given Name | **D.** |
| 30 | | Suffix | |
| 31 | | Organization | University of Aberdeen |
| 32 | | Division | School of Geosciences |
| 33 | | Address | Elphinstone Road, Aberdeen AB24 3UF, Scotland, UK |
| 34 | | e-mail | |
| 35 | | Received | 20 January 2008 |

| | | | |
|---|---|---|---|
| 36 | Schedule | Revised | |
| 37 | | Accepted | 19 June 2008 |

38 Abstract

There is increasing realisation of the importance of groundwater–surface water (GW–SW) interactions in understanding freshwater ecology. A study that assessed the influence of local GW–SW interactions on shallow (<250 mm) hyporheic water quality at two contrasting salmon spawning locations in Scotland, UK is reported. At a groundwater-dominated site, continuous logging sensors revealed that hyporheic dissolved oxygen (DO) concentrations changed rapidly in response to changing hydrological conditions. Low volume (25 ml) spot samples revealed fine-scale spatial variability (<0.05 m) consistent with a vertically shifting boundary layer between source waters. At a surface-water-dominated location, hyporheic water was typically characterised by high DO and electrical conductivity values, characteristic of surface water. Small reductions in DO at this site are hypothesised to be associated with short residence hyporheic discharge. A comparison between in-situ (logging DO sensor data) and ex-situ (small volume sampling) methods revealed good agreement, potentially allowing deployment of the two methods in stratified sampling programmes. This study demonstrates that hyporheic water quality varies over fine spatial and temporal scales and that future studies need to design sampling strategies that consider the scales appropriate to both the ecology and the hyporheic processes of interest.

**Résumé:** En écologie, l'importance des interactions entre eau de surface et eau souterraine (GW–SW) est de plus en plus reconnue. Une étude sur l'influence des interactions locales eau de surface – eau souterraine sur la qualité de la partie superficielle (<250 mm) de l'eau hyporhéique à deux stations différentes de frayère à saumon localisées en Ecosse, Royaume Uni, est décrite ici. Sur un site dominé par les eaux souterraines, des sondes de mesures en continu montrent que la concentration en oxygène dissous (OD) de la zone hyporhéique change rapidement en réponse à la variation des conditions hydrologiques. Des échantillons ponctuels de faible volumes (25 ml) indiquent une variabilité spatiale à petite échelle (<0.05 m) correspondant à une variation verticale des sources d'eau. Pour le site dominé par les eaux de surface, l'eau hyporhéique est caractérisée par des valeurs élevées en oxygène dissous et conductivité, typique des eaux de surface. On suppose que les faibles diminutions d'oxygène dissous à ce site sont associées à des flux rapides des eaux hyporhéiques. Il existe une bonne adéquation entre les méthodes in-situ (sondes d'OD) et ex-situ (échantillons de faible volume), habilitant potentiellement l'utilisation de ces deux méthodes pour les programmes d'échantillonnage stratifié. Cette étude a montré que la qualité de l'eau hyporhéique varie à une faible échelle spatiale et temporelle et de futures études sont nécessaires afin de définir des stratégies d'échantillonnage prenant en compte l'échelle des études écologiques et des processus hyporhéiques.

**Resumen:** Existe una conciencia creciente de la importancia de las interacciones aguas subterráneas-aguas superficiales en el entendimiento de la ecología de las aguas dulces. Se informan los resultados de un estudio que evalúa la influencia de las interacciones entre aguas subterráneas y aguas superficiales locales sobre la calidad de aguas hiporreicas someras (<250 mm) en dos sitios de desove de salmones en Escocia, Reino Unido. En un sitio con predominio de aguas subterráneas, las medidas de sensores continuos revelan que las concentraciones de oxígeno disuelto hiporreico (OD) cambian rápidamente en respuesta al cambio en las condiciones hidrológicas. Las muestras puntuales de bajo volumen (25 ml) indican una variabilidad a escala fina (<0.05 m) que es consistente con una capa límite vertical y cambiante entre las fuentes de agua. En un sector dominado por aguas superficiales, el agua hiporreica típicamente se correspondió con altos valores de OD y conductividad eléctrica, característicos de las aguas superficiales. Se especula que las pequeñas reducciones de OD en este sitio podrían asociarse con descargas hiporreicas de corto tiempo de residencia. Una comparación entre métodos in-situ (datos de sensores de monitoreo de OD) y ex-situ (muestreo de pequeños volúmenes) demuestra una buena concordancia, y potencialmente permite la utilización de los dos métodos en programas de muestreos estratificados. Este estudio demuestra que la calidad del agua hiporreica varía en escalas finas de espacio y tiempo, y que los estudios futuros necesitan diseñar estrategias de muestreo que consideren las escalas adecuadas tanto para los procesos ecológicos de interés como los hiporreicos.

**Resumo:** Existe uma percepção crescente da importância das interacções águas subterrâneas-água superficial para a compreensão da ecologia dos cursos de água doce. Apresenta-se neste artigo um estudo de avaliação da influência daquelas interacções na qualidade da água de zonas hiporreicas a reduzida profundidade (<250 mm) em dois locais, com características contrastantes, de desova de salmão na Escócia, Reino Unido. Num primeiro local, em que predomina o fluxo de água subterrânea, a monitorização contínua revelou que a concentração de Oxigénio Dissolvido (OD) na zona hiporreica se alterava rapidamente em resposta a variações das condições hidrológicas. Amostras de água de volume reduzido (25 ml) mostram uma variabilidade espacial a escala reduzida (<0.05 mm) consistente com variações na posição vertical entre fontes de água (superficial e subterrânea). Num segundo local, em que predomina a influência das águas superficiais, a água da zona hiporreica era tipicamente caracterizada por valores elevados de Oxigénio Dissolvido (DO) e de condutividade eléctrica, característicos de águas superficiais. Pequenas reduções no valor de DO neste local são atribuídas a tempos de residência reduzidos das águas subterrâneas nas zonas hiporreicas. Uma comparação entre métodos in-situ (sensores de DO) e ex-situ (amostras de reduzido volume) demonstram uma boa concordância entre aquelas metodologias, potenciando a utilização de ambos os métodos em programas de amostragem em zonas estratificadas. Este estudo demonstra que a qualidade da água de zonas hiporreicas varia em escalas temporais e espaciais reduzidas e que estudos futuros devem considerar estratégias de amostragem adaptadas às escalas apropriadas para os processos ecológicos e para os processos da zona hiporreica a estudar.

| | | |
|---|---|---|
| 39 | Keywords separated by ' - ' | Groundwater–surface-water relations - Hydrochemistry - Oxygen - Hyporheic - UK |
| 40 | Foot note information | |

# Fine scale variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions

**I. A. Malcolm · C. Soulsby · A. F. Youngson · D. Tetzlaff**

**Abstract** There is increasing realisation of the importance of groundwater–surface water (GW–SW) interactions in understanding freshwater ecology. A study that assessed the influence of local GW–SW interactions on shallow (<250mm) hyporheic water quality at two contrasting salmon spawning locations in Scotland, UK is reported. At a groundwater-dominated site, continuous logging sensors revealed that hyporheic dissolved oxygen (DO) concentrations changed rapidly in response to changing hydrological conditions. Low volume (25ml) spot samples revealed fine-scale spatial variability (<0.05m) consistent with a vertically shifting boundary layer between source waters. At a surface-water-dominated location, hyporheic water was typically characterised by high DO and electrical conductivity values, characteristic of surface water. Small reductions in DO at this site are hypothesised to be associated with short residence hyporheic discharge. A comparison between in-situ (logging DO sensor data) and ex-situ (small volume sampling) methods revealed good agreement, potentially allowing deployment of the two methods in stratified sampling programmes. This study demonstrates that hyporheic water quality varies over fine spatial and temporal scales and that future studies need to design sampling strategies that consider the scales appropriate to both the ecology and the hyporheic processes of interest.

**Keywords** Groundwater–surface-water relations · Hydrochemistry · Oxygen · Hyporheic · UK

Received: 20 January 2008 / Accepted: 19 June 2008



I. A. Malcolm (✉) · A. F. Youngson
Fisheries Research Services Freshwater Laboratory, P.O. Box 101, Pitlochry, AB11 9DB, Scotland, UK
e-mail: I.A.Malcolm@MARLAB.AC.UK

C. Soulsby · D. Tetzlaff
School of Geosciences,
University of Aberdeen,
Elphinstone Road, Aberdeen, AB24 3UF, Scotland, UK

## Introduction

With increasing research focus on groundwater–surface water (GW–SW) interactions, there is a growing realisation of the complex spatio-temporal dynamics exhibited by physical, chemical and biological characteristics in the hyporheic zone (Dahm et al. 2006; Malcolm et al. 2008). In particular, the chemical characteristics of the hyporheic zone, as the important interface between groundwater and surface water, are known to vary spatially at scales ranging from centimetres to kilometres (Wondzell and Swanson 1996; Brunke and Gonser 1997; Boulton et al. 1998; Soulsby et al. 2001; Malcolm et al. 2004; Malcolm et al. 2005; Poole et al. 2006) and temporally at scales ranging from storm event (sub-hourly) to inter-annual (Wondzell and Swanson 1996; Fraser and Williams 1998; Malcolm et al. 2004; Malcolm et al. 2006; Arntzen et al. 2006).

It is widely accepted that there is a need for improved characterisation of the hyporheic environment in order to enhance understanding of hyporheic ecology (Palmer 1993; Fowler and Death 2001; Brunke et al. 2003; Boulton and Hancock 2006; Poole et al. 2006). Furthermore, it has long been recognised that sampling of the hyporheic zone poses particular problems in terms of protocols and methodology (Palmer 1993). However, it is also becoming increasingly clear that one of the central challenges for hyporheic zone research is to sample at temporal and spatial resolutions that are appropriate to both the hyporheic processes of interest and the related ecology (Palmer 1993; Youngson et al. 2005; Grimm et al. 2006; Malcolm et al. 2006). Previous studies of the hyporheic zone have often employed sampling methods that operate at coarse temporal and spatial scales. Moreover, these often involve abstraction of large water samples that integrate over an indeterminate volume of streambed, with unknown recharge or equilibration times. This potentially risks failing to characterise important fine scale spatio-temporal variability and may result in a mis-match between the (large) spatial scales characterised by hyporheic water quality sampling and the (smaller) scales often required to adequately characterise and understand the environment experienced by the hyporheos (Palmer 1993; Malcolm et al. 2008). While the importance of hyporheic sampling methodology has been highlighted for invertebrates (Fraser and Williams 1997; Hunt and Stanley 2000; Scarsbrook



 DOI 10.1007/s10040-008-0339-5

and Halliday 2002), the issue of water quality sampling has not been addressed in a similar way. In fact, the issue has been overlooked to the extent that in many cases the important details of sampling and sample volumes are not reported (e.g. Bernier-Bourgault and Magnan 2002; Bowen and Nelson 2003; Greig et al. 2005) making interpretation of data and comparison between studies difficult.

Traditional hyporheic sampling methods typically involve water sampling under negative pressure from standpipes (Ringler and Hall 1975), piezometers (Curry and Noakes 1995; Baxter and Hauer 2003; Olsen and Townsend 2003), incubators (Soulsby et al. 2001; Malcolm et al. 2003a, b) and temporary (Mermillod-Blondin et al. 2000) or fixed (Youngson et al. 2005) sampling tubes, inserted to specified depths in the streambed (ex-situ). These methods have a number of potential problems, including direct connection between the streambed and surface water or atmosphere, and the creation of preferential flow paths such that surface water is drawn down into the streambed during sampling. However, these methods benefit from potentially high spatial coverage and relatively low cost. In-situ measurements (e.g. Malcolm et al. 2006), using water quality probes, have the benefit of providing high-resolution temporal data with minimal sampling disturbance, but financial constraints often dictate that replicated sampling at fine spatial resolution is impractical. These applications are relatively scarce (few chemical determinants can be accurately measured this way) and individual probes are parameter specific. Furthermore, there is the potential that in-situ monitoring can reflect highly localised conditions that are not more generally representative of the hyporheic zone at a given location and scale and that results are not comparable with traditional ex-situ methods.

In the context of salmon embryo survival, previous work by the authors has demonstrated that traditional sampling methods have often failed to adequately characterise both the temporal dynamics (Malcolm et al. 2006) and spatial variability (Malcolm et al. 2005; Youngson et al. 2005) of the hyporheic zone in a way that is biologically meaningful. Salmon ova are deposited in open gravel structures called redds, constructed from streambed gravels during a process known as spawning. Egg burial depths are typically between 0.05 and 0.3 m beneath the streambed (DeVries 1997). Survival is dependant on complex interactions of physical, chemical and biological processes which are reviewed in detail elsewhere (Malcolm et al. 2008). Critically, however, survival depends on the delivery of adequate oxygen to meet the needs of developing embryos, and thus, is often influenced by the local nature of GW–SW interactions where groundwater is characterised by reducing conditions.

This paper examines the hydroecological importance of sampling at appropriate spatio-temporal scales and compares the results of in-situ sampling with low volume, finely stratified, ex-situ sampling methods, using a case study of salmon embryo survival at two heavily utilised spawning locations with contrasting GW–SW interactions. Inter-site differences are discussed in the context of local hydrological controls. The importance of sampling method and resolution are discussed with reference to previous work investigating salmon embryo survival in field settings. Specifically this study aims to: (1) characterise hyporheic hydrochemistry at fine temporal and spatial resolution during the period of time between salmon spawning and embryo hatch; (2) use natural tracer methods to infer the influence of local GW–SW interactions on streambed DO; (3) assess the implications for embryo survival and (4) compare in-situ and ex-situ sampling methods and assess the implications for sampling strategy in future studies of the hyporheic zone

## Materials and methods

The work was carried out at the Girnock Burn catchment, a 31-km$^2$ sub-catchment of the River Dee in northeast Scotland, UK (Fig. 1). Detailed characteristics about the catchment are given elsewhere: Tetzlaff et al. (2007a) describe the general hydrology and dominant runoff processes; 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 GW–SW interactions, whilst Malcolm et al. (2005) consider their implications for hyporheic water quality and salmon embryo 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, contributing 25–30% of annual runoff. The catchment is largely dominated by heather (*Calluna*) moorland (ca. 95%), though the lower catchment has mixed forest cover of pine (*Pinus*) and birch (*Betula*). Rainfall is around 1,100 mm per annum, with a mean annual runoff of around 700 mm.

Two sites with contrasting GW–SW interactions and a long and documented history of salmon spawning were selected for detailed monitoring of hyporheic chemistry and assessment of the mortality of salmon ova (Fig. 1). Both sites were previously included in catchment scale studies of hyporheic hydrochemistry (Malcolm et al. 2005) and embryo survival and performance (Youngson et al. 2005) using traditional broad scale ex-situ sampling procedures. Each site comprised a riffle ca. 10 m long. In the upper catchment, the reach containing site 7 (S7) was examined in detail by Malcolm et al. (2004). The site is characterised by strong groundwater upwelling which often results in marked groundwater influence on the hyporheic chemistry. The reach containing site 16 (S16) was investigated by Malcolm et al. (2002, 2003b) using hydrometric, tracer and thermal data which indicated that the hyporheic zone was dominated by surface water at this site.

At each site, novel methods for measuring hyporheic water quality and embryo survival were employed. High resolution DO and temperature data were obtained between 04 November 2005 and 11 April 2006, from the stream and an artificially constructed redd at depths of 150 and 250 mm in the hyporheic zone using Aandera 4175 shallow water (rated to 300 m) DO optodes with analogue converters



 DOI 10.1007/s10040-008-0339-5

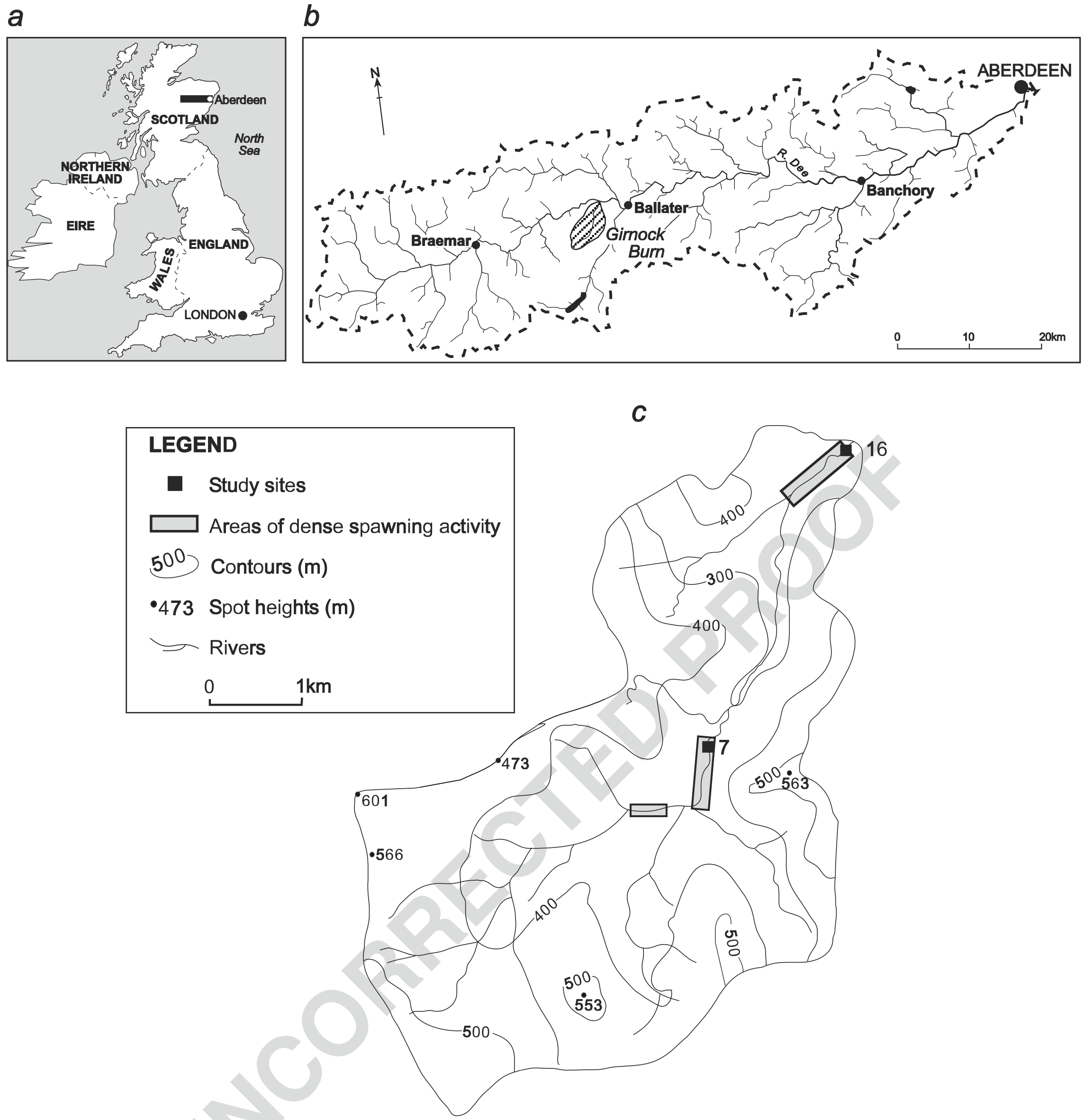



**Fig. 1** Location maps showing **a** the position of the River Dee catchment within the UK, **b** the position of the Girnock Burn within the River Dee catchment and **c** the location of study site 7 (*7*) and site 16 (*16*) within the Girnock Burn catchment

(Fig. 2). These were connected to Campbell dataloggers programmed to sample DO (per cent saturation) and temperature at 30 second intervals and log average values over 15 min. Prior to installation, DO optodes were cross-calibrated in the laboratory at a range of $O_2$ concentrations and temperatures showing agreement to within 1% $O_2$ saturation and 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. Data integrity was generally good, with the exception of two short periods early in the monitoring period at S16.

These high temporal resolution measurements were supplemented with high-spatial-resolution spot samples of DO, electrical conductivity and temperature from within vertically stratified incubation chambers (Fig. 2). The incubation chambers were adapted from those described by Youngson et al. (2005). Briefly, they comprised stacking 25-mm-high plastic containers, 42 mm in diameter, regularly perforated with 6 mm holes. When screwed together, the containers formed a cylindrical column 250 mm long. The top chamber was filled with stream gravel to exclude daylight. Each subsequent container was lined with a 1-mm plastic mesh and contained 20 water-hardened salmon eggs taken from a single male and female mating to exclude parental effects. Fish were obtained from the Fisheries Research Services (FRS) Girnock trap facility. A control group of eggs was held in surface water at the Girnock incubator facility. The control accounted for hyporheic affects on survival and performance by maintaining oxygen concentrations near saturation for the entire incubation period between spawning and hatch.

In November 2005 (spawning time in the Girnock Burn), the cylindrical arrays were placed into pre-prepared

 DOI 10.1007/s10040-008-0339-5

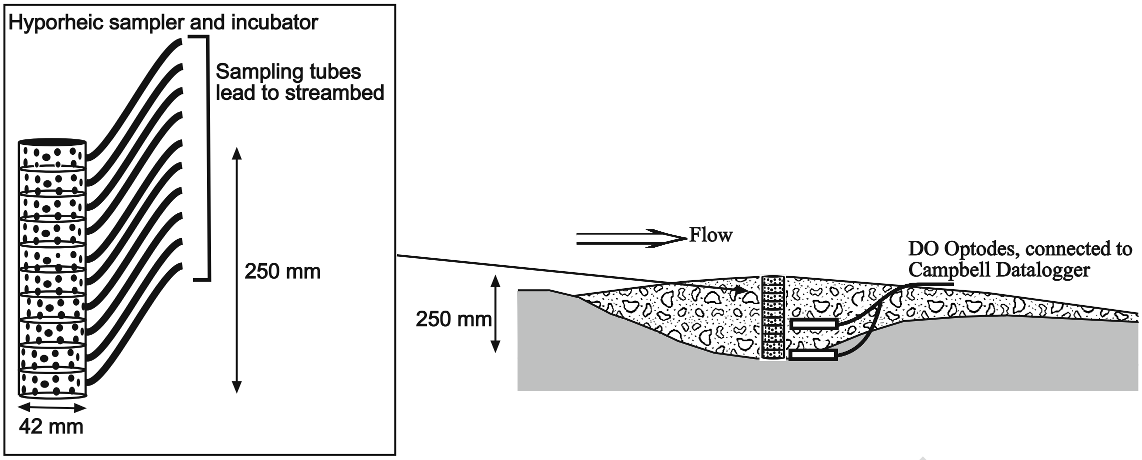


**Fig. 2** Sampler design and installation within an artificially constructed redd



inserts within artificial redds, constructed at locations used by spawners in previous years. The insert was then withdrawn from around the cylinder and any resulting gaps were filled with surrounding gravel material (>4 mm). This resulted in egg chambers at depths of 25, 50, 75, 100, 125, 150, 175, 200, 225 and 250 mm beneath the streambed. A narrow diameter (4 mm i.d.) Nalgene tube led from each chamber to the streambed. During sampling, a volume equivalent to that held in the sampling tube was discarded and a sample (25 ml) approximately equivalent to that held in the containers (container volume-ova volume) collected to characterise water quality in the immediate vicinity of the ova. When not used for sampling a small plastic plug prevented direct connection between sampler and surface water. DO and temperature were measured using a 2-mm-diameter DO micro-sensor and thermistor connected to a Pre-Sens Fibox3 oxygen meter. The manufacturer stated reporting resolution for DO varies from 0.05% Sat. at 1% Sat. to 0.5% Sat. at 100% Sat. Accuracy is stated as ±1% Sat. at 100% Sat. to ±0.15% at 1% Sat. The reporting resolution for temperature is 0.2°C with an accuracy of ±1°C. Electrical conductivity was measured using a Hannah HI 9033 portable conductivity meter, reporting resolution 0.1 µS/cm, accuracy ±2 µS/cm (0–200 µS/cm range). Spot samples were collected at approximately fortnightly intervals where discharge and icing conditions permitted ($n$=7). Spot samples were compared with continuously logged data from the same depth to assess the comparability of methods. The chambers were excavated from the stream bed on the day of the last sample collection on 11th April 2006. Live and dead eggs were counted to provide percentage survival rates.

## Results

### Temporal variability in hyporheic conditions

*Spawning–hatch (in-situ sampling)*

The 2005–2006 spawning to hatch period (ca. November–April in the Girnock catchment) was relatively dry with only four moderate flow events over 3 $m^3/s$ (cumecs; Fig. 3). Stream temperatures at S7 and S16 were broadly similar. Early November was characterised by declining stream temperatures, with frequent icing events throughout the winter, before warming once more during March. The last icing period in early March corresponded to a prolonged period of late winter snowfall, whose subsequent melt resulted in a period of moderately elevated flows.

Previous hydrochemical and hydrometric work at the study sites indicated contrasting GW–SW interactions, with the hyporheic zone of S7 being influenced by variable contributions of groundwater (Malcolm et al. 2004), while S16 was dominated by surface water (Malcolm et al. 2005). These differences in GW–SW interactions were reflected in different hyporheic temperature and DO characteristics between the sites. At S16, streambed temperatures were slightly moderated, showing less variable temperatures than surface water, with differences being most apparent at greater depths and during freezing periods (Fig. 3). At S7, stream and shallow hyporheic water (150 mm) exhibited similar temperature characteristics. However, hyporheic water at 250 mm initially exhibited similar temperatures, with moderation of temperature extremes increasing over time. This is consistent with increasing groundwater influence, where groundwater is typically characterised by more stable temperatures which are higher than surface water during winter months (Hannah et al. 2004). Differences in stream and hyporheic temperatures for the entire period where data were available at both sites are summarised in Figs. 4a and b. Only the 250 mm depth sampler at S7 (S7–250) exhibited a notably different thermal regime, showing some temperature moderation.

DO concentrations at S16 remained close to saturation in both the stream and hyporheic water for the majority of the study period, although small and short-lived gradients were observed, particularly in the final months on the study (Fig. 3). Between October and the end of February, DO at 150 mm was often lower than that at 250 mm. Much of this variability can be explained by the moderated (generally higher) temperatures in the streambed, which affect calculated saturation values, i.e. there is no change in oxygen


DOI 10.1007/s10040-008-0339-5

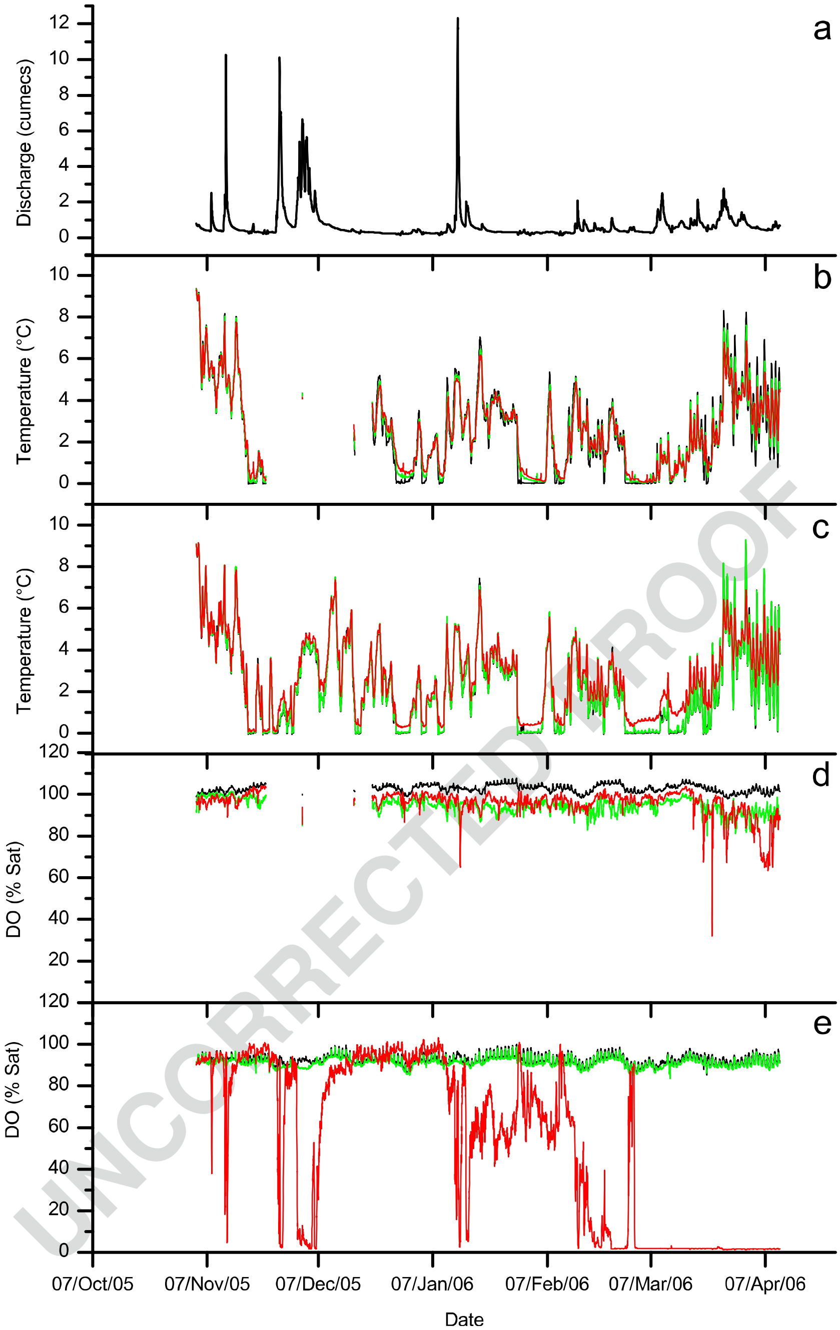




**Fig. 3** **a** Girnock Burn discharge; temperature at **b** S16 and **c** S7; and dissolved oxygen at **d** S16 and **e** S7, for the period between salmon spawning and embryo hatch. *Black lines* show surface water, *green lines* show hyporheic water at 150 mm, *red lines* show hyporheic water at 250 mm

concentration (mg/L), but small differences in temperature change expected saturation values. Over the course of the study, five periods of notable DO reductions were observed where levels dropped below 70%. Four of these periods were observed during the final month of the study.

At S7 DO concentrations in stream and shallow (150 mm) hyporheic water remained at or near saturation throughout the study. However, at 250 mm, concentrations were characterised by a dynamic response, varying between 0 and 100% saturation, often varying markedly over short periods in response to hydrological events. Typically, DO levels fell on the recession limb of storm hydrographs shortly after peak discharge in agreement with observations from previous years (Malcolm et al. 2004, 2006). DO concentrations tended to recover in the aftermath of events. Recovery times varied depending on event magnitude and antecedent catchment wetness, which are thought to influence water table elevation in the adjacent hillslopes at this site (Malcolm et al. 2004, 2006). Between January and the end of February, DO recoveries were only partial. In the final stage of the study from March onwards, DO levels failed to exhibit any response recovery. Inter-site


DOI 10.1007/s10040-008-0339-5

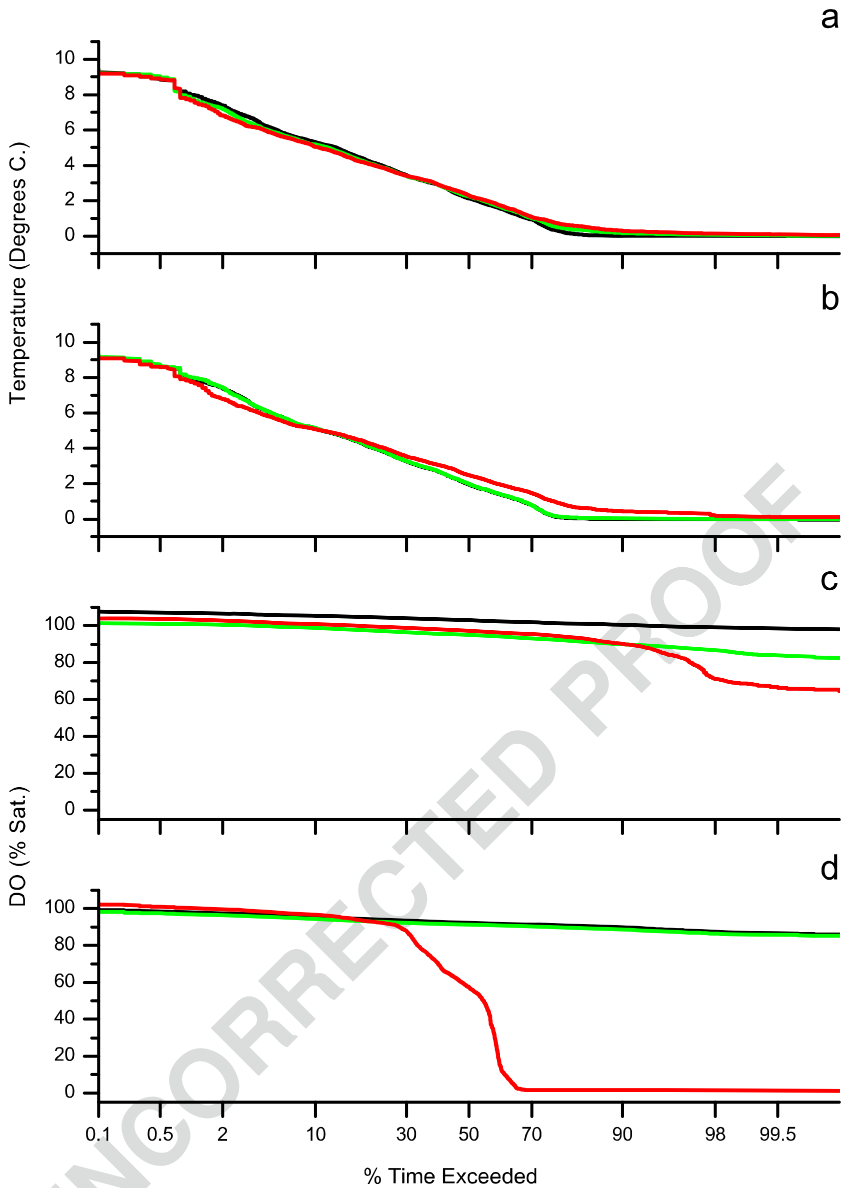




**Fig. 4** Temperature at **a** S16 and **b** S7, and dissolved oxygen at **c** S16 and **d** S7; duration curves for the period between spawning and embryo hatch. *Black lines* show surface water, *green lines* show hyporheic water at 150 mm, *red lines* show hyporheic water at 250 mm

differences in DO are summarised in the duration curves shown in Fig. 4c and d. At S16 DO was always above saturation in surface water and at, or near saturation at 150 mm. DO at 250 mm was near to saturation for the majority of the study dropping below 80% sat. for less than 3% of the time. At S7 DO concentrations were close to saturation in surface water and at 150 mm for the entire study period. However, at 250 mm DO concentrations were near to saturation for only ~30% of the time, which is comparable to the time spent at 0% saturation.

*Event responses (in-situ sampling)*

Event responses varied between sites, depending on event magnitude and antecedent conditions. Three contrasting event responses were identified: (1) DO response identified only at S7, (2) DO response observed at both sites, and (3) DO response observed at S16 with S7 characterised by constant low DO at 250 mm.

On the 10 November 2005, a complex double-peaked hydrograph was accompanied by mirrored declines in DO concentrations at S7–250, punctuated by a short period of saturated DO at the main event peak (Fig. 5e). Falling DO concentrations on the recession limb were followed by fairly rapid recovery. At S16, only a very slight decline in DO was observed at 250 mm on the recession limb following the main event peak. Temperatures in the stream and hyporheic zone were similar at both sites, though small differences at S7–250 were associated with the event peak.

Figure 6 shows a later event (12 January 2005) where hyporheic DO concentrations declined at 250 mm at both S7 and S16. On the rising limb of the hydrograph and at


DOI 10.1007/s10040-008-0339-5

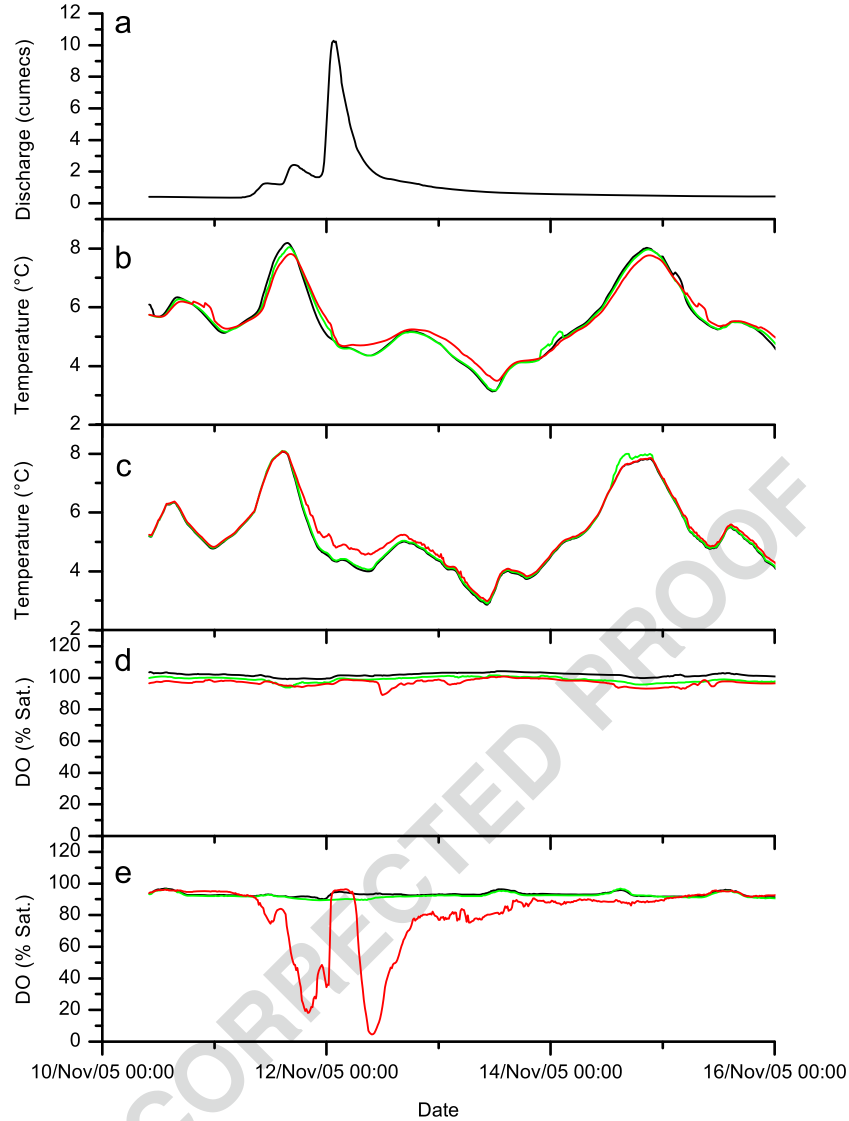


**Fig. 5** Event based (November 2005) oxygen and temperature responses showing: **a** discharge; temperature at **b** S16 and **c** S7; and dissolved oxygen at **d** S16 and **e** S7. *Black lines* show surface water, *green lines* show hyporheic water at 150 mm, *red lines* show hyporheic water at 250 mm



the event peak, DO levels in stream water, S16 (150, 250 mm) and shallow hyporheic water at S7 (150 mm) were close to saturation. In contrast, at S7–250, DO levels declined on the rising and falling limb of the hydrograph, with elevated DO levels during peak flow (Fig. 6e). At S16–250, DO concentrations exhibited a small decrease in DO on the recession, which was considerably lagged relative to that at S7. Following the event, DO concentrations at both S7–250 and S16–250 recovered to near saturation within 3 days. Temperature data from S16 (Fig. 6b), shows moderation of warmer pre-event and cooler post-event water. S7–250 exhibited distinct stratification from surface and shallow hyporheic water on the recession limb, while temperatures at S7–150 were identical to those of surface water (Fig. 6c).

Towards the end of the monitoring period (22 March 2006), S7–250 was consistently characterised by near-zero DO concentrations for almost a month (Fig. 3e). However, during this period, S16 exhibited a series of unusual, moderate and occasionally prolonged reductions in DO that appeared to be associated with only minor hydrological events in the Girnock Burn (Fig. 7d). Temperature data from S16 showed a moderated temperature gradient with depth that also showed a lagged response (Fig. 7b). At S7, temperatures in the stream and at 150 mm closely tracked, while temperature at 250 mm exhibited marked thermal moderation.

### Fine scale spatial variability in hyporheic water quality (ex-situ sampling)

The continuous water quality monitors provide data of excellent temporal resolution, but only provide relatively coarse spatial information on hyporheic water quality. The integrated embryo survival chambers and samplers facil-


DOI 10.1007/s10040-008-0339-5

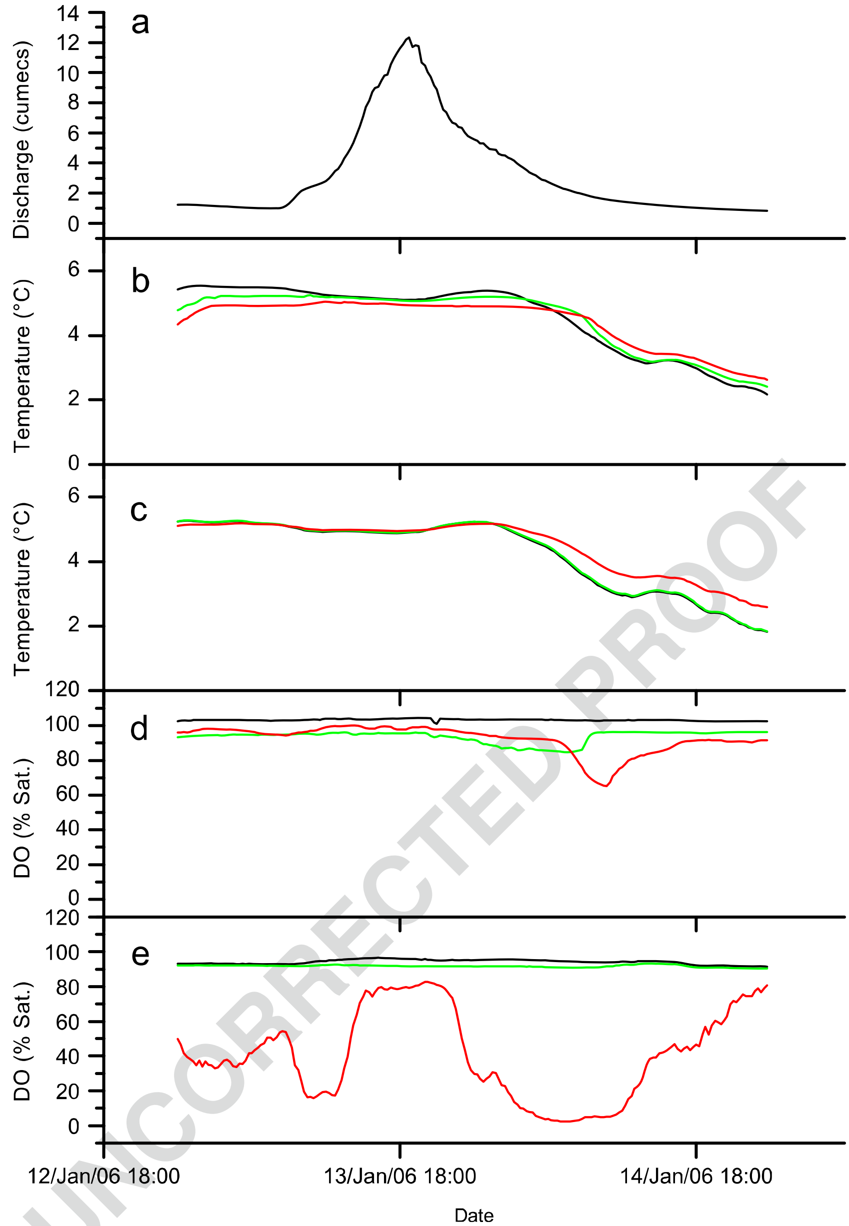




**Fig. 6** Event based (January 2006) oxygen and temperature responses showing: **a** discharge; temperature at **b** S16 and **c** S7; and dissolved oxygen at **d** S16 and **e** S7. *Black lines* show surface water, *green lines* show hyporheic water at 150 mm, *red lines* show hyporheic water at 250 mm

itated collection of water samples at 25 mm vertical resolution (25–250 mm) which revealed the fine-scale spatial variability of hyporheic water quality with depth, although at the expense of temporal resolution (Fig. 8). Additionally, spot samples allowed the collection of electrical conductivity data (Fig. 8a, b) as an indicator of source water provenance (Youngson et al. 2005). Electrical conductivity and DO saturation at S16 were relatively uniform with depth over the entire study period indicating a common source water. By contrast, depth-related stratification of both DO and conductivity was apparent at S7 over much of the study and appeared to increase over time. Differences in conductivity and DO were consistent with an increasing groundwater influence with depth (Malcolm et al. 2005). Higher conductivity values indicative of longer residence water were generally associated with lower DO. Stratification gradients at S7 were steep, with DO varying from nearly 100% saturation to <10% over distances of only 50 mm. Gradients in DO appeared to be more consistent with depth than those exhibited by electrical conductivity and it is possible that this inconsistency reflected mixing between samples collected from adjacent depths despite very low volumes.

### A comparison of in- and ex-situ sampling methods

A comparison of the spot sample DO data, with continuous data from the optodes located at approximately

 DOI 10.1007/s10040-008-0339-5

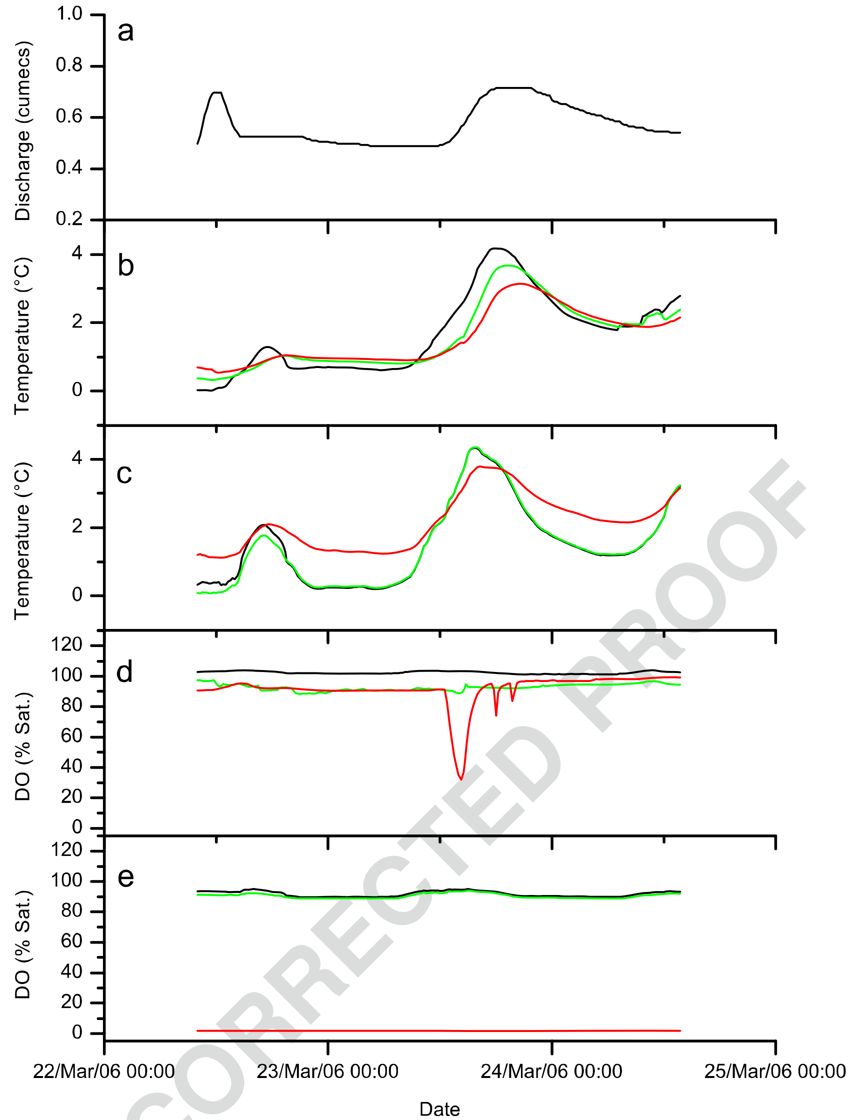


**Fig. 7** Event based (March 2006) oxygen and temperature responses showing: **a** discharge; temperature at **b** S16 and **c** S7; and dissolved oxygen at **d** S16 and **e** S7. *Black lines* show surface water, *green lines* show hyporheic water at 150 mm, *red lines* show hyporheic water at 250 mm



the same depth, reveals that the two methods were generally comparable for a given sampling occasion (Fig. 9). The two methods also produced broadly similar patterns of variability, although very few low DO spot samples were obtained due to the coarse sampling frequency. Given the fine-scale spatial variability of DO revealed by the spot sampling, difficulties locating equipment with a high degree of spatial precision beneath the streambed and complexities associated with cross-calibration of seven independent measuring units, it is not surprising that the two methods did not provide exactly the same DO values. However, a paired *t*-test ($n$=26) revealed that there was no significant difference between the data obtained using the two methods ($P$=0.27).When comparing the methods, it is clear that each has merit. The loss of temporal resolution is evident in the spot samples, while the continuous data lacks potentially important fine scale spatial resolution.

### Embryo survival

In 2003–2004 and 2004–2005 embryo survival at controls held at the Girnock Burn was 100%. During the 2005–2006 spawning season, unusually high mortality of fertilised ova occurred. The reasons for this mortality are unclear, but appeared to affect many groups of ova reflecting reduced viability in general or unknown procedural problems during adult stripping or fertilisation. Survival in the control group was 70%, although across the incubator as a whole it was on average closer to 50%. Given this background, interpretation of ova survival at S7 and S16 is difficult and it is possible that variability between sites and depths reflected random sampling from a variably impacted group of fertilised ova at the project outset. Embryo survival in the streambed incubators varied from 0–60% (Table 1) and for the most part did not show clear patterns that could be associated with environmental variation. Nevertheless, at S7, complete


DOI 10.1007/s10040-008-0339-5

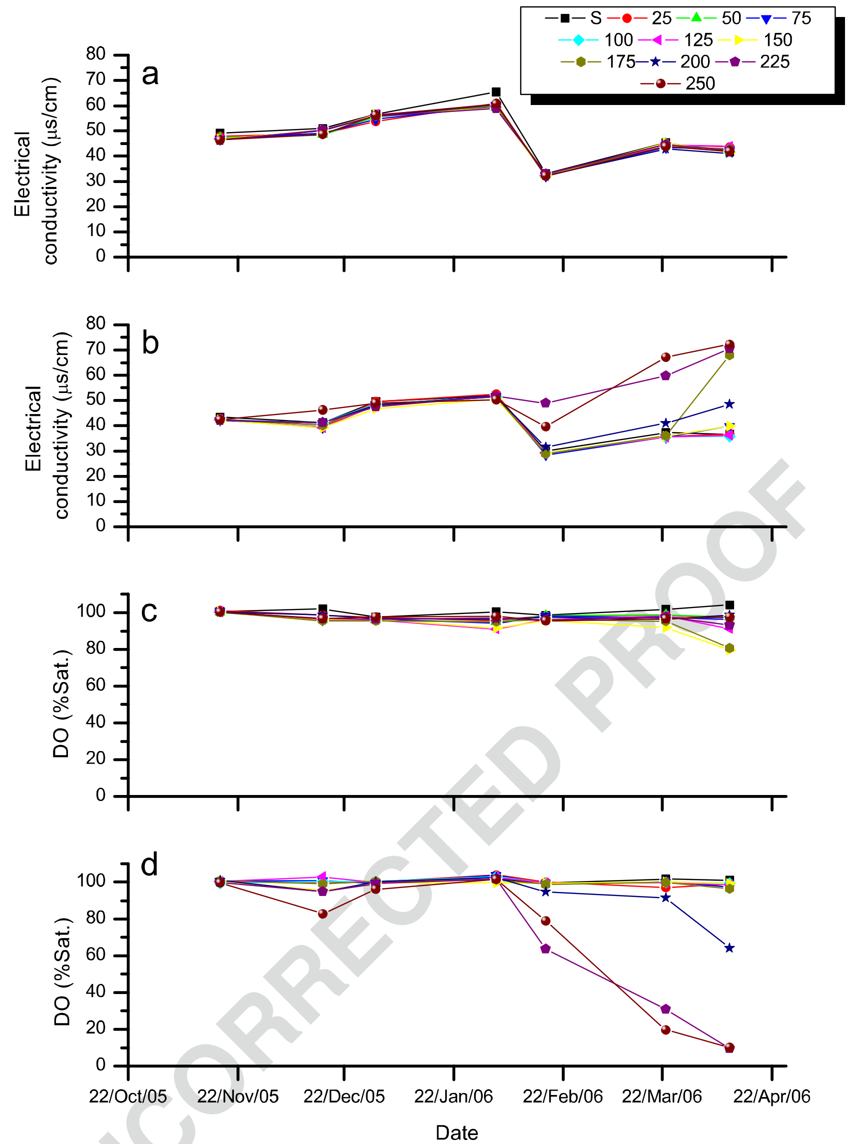




**Fig. 8** Temporal and spatial variability of electrical conductivity at **a** S16 and **b** S7 and dissolved oxygen at **c** S16 and **d** S7 in surface (*S*) and hyporheic water at depths ranging from 25–250 mm (see *legend*), separated at 25-mm intervals. Approximately fortnightly sampling occasions are shown as points

ova mortality was observed across the depth range 200–250 mm. These mortalities are consistent with the sharp DO concentration gradients observed at S7 for these depths (Fig. 8). In contrast, survival at S16 was generally higher than at S7, especially in the lower hyporheic zone, though even here, survival at 250 mm was only 25%.

## Discussion

### *Influence of local GW–SW interactions on fine scale spatio-temporal variability of hyporheic water quality*

At S7, DO concentrations varied spatially and temporally in a manner that was consistent with changing groundwater contributions to the hyporheic zone. Low DO was associated with higher electrical conductivities, thought to be associated with increased residence times. Groundwater influence was associated with steep DO gradients (distances of ca. 0.05 m), which shifted vertically over time. This is contrary to the common conceptual understanding of a broad hyporheic mixing zone containing groundwater and surface water (e.g. Malard et al. 2002) and is more consistent with a temporally shifting sharp boundary between groundwater and surface water, with limited mixing. DO concentrations changed rapidly in response to hydrological events (Malcolm et al. 2006). The exact form of the response varied with antecedent conditions and discharge magnitude. In general, dry, low flow periods were characterised by high DO, while low DO was observed during periods of wet antecedent conditions, later in the winter, and the recession limb of hydrological events where water table levels are high.

At S16, where surface water dominated the hyporheic zone, DO concentrations in the stream bed were compa-

 DOI 10.1007/s10040-008-0339-5

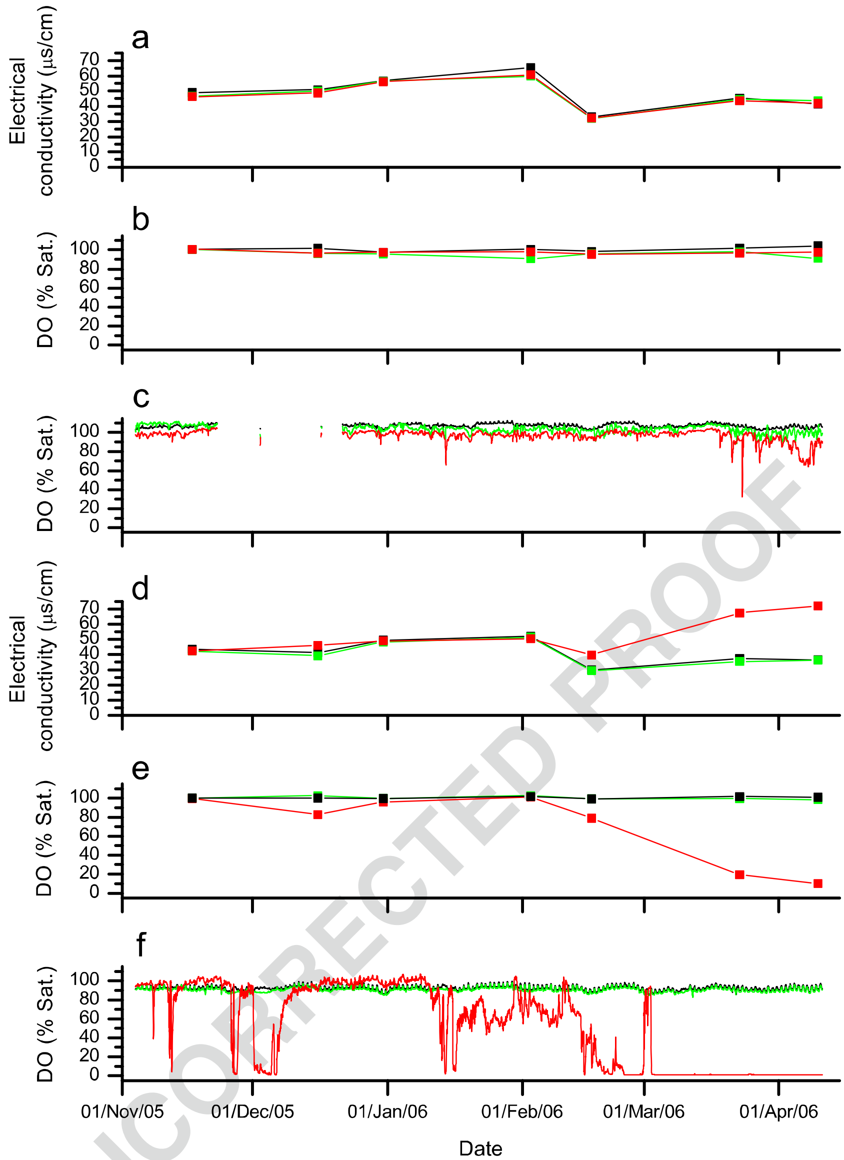




**Fig. 9** A comparison of ex-situ spot sample data (ca. fortnightly) with in-situ continuous (15 min) data for comparable depths. Plots show: **a** S16 electrical conductivity spot samples, **b** S16 dissolved oxygen spot samples, **c** S16 continuous dissolved oxygen, **d** S7 electrical conductivity spot samples, **e** S7 dissolved oxygen spot samples, and **f** S7 continuous dissolved oxygen. *Black lines* show surface water, *green lines* show hyporheic water at 150 mm, *red lines* show hyporheic water at 250 mm. *Symbols* denote spot-sampling occasions

**Table 1** Percentage embryo survival for depths ranging from 25–250 mm at site 7 (*S7*) and site 16 (*S16*)

| Depth (mm) | % survival | |
|---|---|---|
| | S7 | S16 |
| 25 | 40 | 35 |
| 50 | 25 | 40 |
| 75 | 55 | 50 |
| 100 | 60 | 60 |
| 125 | 40 | 40 |
| 150 | 40 | 45 |
| 175 | 40 | 55 |
| 200 | 0 | 45 |
| 225 | 0 | 45 |
| 250 | 0 | 25 |

rable with stream water and consequently near saturation for the majority of the monitoring period, although low DO episodes were observed towards the end of the study. Reductions in DO were not associated with increased electrical conductivity and thus appear unlikely to be associated with intrusion of groundwater. On excavation, the incubation chambers were found to be entirely free of sediment, and therefore it also seems very unlikely that reductions in DO were associated with intrusion of fine sediment to the redd environment. It is possible that changing DO levels reflected changing short residence (hours to days) hyporheic dynamics at the site associated with changing bed morphology during the study period. High flows over the winter led to the development of a substantial gravel bar immediately upstream of the

 DOI 10.1007/s10040-008-0339-5

monitoring site. It is possible that hyporheic exchange passing through the bar feature, re-emerged on the downstream side under certain flow conditions (Tonina and Buffington 2007) and that DO could have been stripped from the water during transit (Claret et al. 1997). Under these circumstances the residence time would be too short for substantial changes to more conservative water quality parameters but DO could be reduced. Alternatively, it is possible that low DO episodes reflected discharge of hyporheic water from the River Dee as S16 lies at the bottom of the Girnock catchment, within course gravel sediments associated with the Dee floodplain. It is therefore possible that high flows from the River Dee, entering an abandoned channel adjacent to the Girnock Burn, could have altered local hyporheic dynamics resulting in discharge of Dee water or displacement of Girnock floodplain water through S16 (Rodgers et al. 2004; Poole et al. 2006).

### *Implications for hyporheic sampling*

Palmer (1993) identified a number of key challenges for hyporheic zone research. These included the need to conceptualise hyporheic zone boundaries through understanding of inter-site heterogeneity and the development of methods to sample the hyporheic environment at small spatial scales that could be calibrated and quantified in terms of spatial extent. This study combined adaptations of recently documented hyporheic sampling methodologies (Youngson et al. 2005; Malcolm et al. 2006) to identify fine scale spatial and temporal differences in hyporheic chemistry and embryo survival at two salmon spawning locations with contrasting GW–SW interactions.

While in-situ methods revealed important temporal variability, the stratified incubators and ex-situ sampling method provided valuable information on the spatial variability of water quality, embryo survival and also provided supporting hydrochemical data. For the depths and times for which data could be compared (150 and 250 mm), the two methods showed good agreement (no significant difference between methods), indicating that in-situ measurements did not reflect unrepresentative micro-scale (mm's) conditions and, more importantly, that the two methods generated comparable data and therefore could be deployed in a stratified sampling programme to give both high resolution spatial and temporal data in future expanded studies.

### *Implications for hydro-ecological studies of the hyporheic zone*

Previous studies of the hyporheic environment have often used large or unspecified sample volumes and infrequent sampling intervals. These water quality data are then often related to hyporheic ecology such as invertebrate communities (Boulton et al. 1997; Mermillod-Blondin et al. 2000; Fowler and Death 2001) or salmonid embryo survival without fully considering the spatial and temporal scales of the water quality sampling, the variability of the hyporheic environment or the scales relevant to the ecology. Table 2



**Table 2** Comparison of hyporheic oxygen sampling methods and frequencies for studies investigating salmonid embryo survival

| Authors | Water sampling method (DO measurement method) | Sample volume | Sample depth (m) | Sample frequency |
|---|---|---|---|---|
| Malcolm et al. 2006 | In-situ (Aanderaa DO optode) | NA | 0.15, 0.3 | 30 s, averaged every 15 min |
| Groves and Chandler (2005) | Buried incubators with sampling tubes and piezometers. (flow-through cell and YSI DO electrode) | 3× dead volume discarded sample volume for measurement unknown | 0.25 | Monthly |
| Greig et al. (2005) | Standpipe (YSI 250 DO electrode) | Not stated | Not stated | Weekly to fortnightly |
| Youngson et al. (2005) | Sealed flexible hyporheic sampling tubes (Hannah DO electrode) | Dead volume discarded 200 ml sample | 0.2–0.3 | Fortnightly |
| Bernier-Bourgault and Magnan (2002) | Sampling pipe installed on sampling date (YSI 57 DO electrode) | Not stated | 0.05–0.15 | Not stated |
| Bowen and Nelson (2003) | Variable depth hyporheic sampling pipes (unspecified multi-parameter meter including DO electrode) | Not stated | 0.3, 0.46 | 2 samples, 1 month apart |
| Ingendahl (2001) | Flexible sampling tube (portable DO electrode) | 60 ml discarded 60 ml sample | 0.1, 0.2, 0.3 | Fortnightly |
| Peterson and Quinn (1996) | Sampling tube (titration) | Dead volume discarded 185 ml sample | Variable, depending on egg burial depth | Weekly to fortnightly |
| Sowden and Power (1985) | Mini-piezometer (YSI 54 DO electrode) | 150 ml sample | 0.15 | Approximately monthly |
| Ringler and Hall (1975) | Standpipe (titration) | 60 ml | 0.25 | 3 samples per week |
| Coble (1961) | Standpipe (not stated) | 37 ml | 0.25 | Not stated |

 DOI 10.1007/s10040-008-0339-5

shows a comparison of hyporheic studies, where the research focus was to understand salmonid embryo survival. It can be seen that sample depths generally reflect the reported range of egg burial depths (DeVries 1997). However, the number of reported depths is typically only 1–3 (relatively coarse) and the sampling methods and volumes are highly variable or are not clearly specified. This effectively means that, depending on streambed characteristics and equilibration times, individual studies will be reporting hyporheic water quality for highly variable, but generally poorly delineated volumes of extracted streambed water that are unlikely to reflect the environmental conditions experienced by the hyporheos, in this case salmonid embryos. If the temporal variability of hyporheic water quality and the general inadequacy of sampling frequency is also considered, then it is unsurprising that the results of field (Sowden and Power 1985; Rubin and Glimsater 1996; Ingendahl 2001) and laboratory (Alderdice et al. 1958; Silver et al. 1963) based studies of salmonid embryo survival are not in good agreement. Disparities in the apparent findings of these approaches probably reflect the controlled nature of laboratory experiments and problems with adequately characterising an environment that is as temporally and spatially highly variable and inaccessible as the hyporheic zone.

### Implications for salmonids

At S7, there was a sharp transitional gradient in hyporheic water quality over distances of <0.05 m which was reflected in the total mortality of embryos at greater depths. In recent years there has been frequent discussion of the benefits of greater burial depth to avoid washout or overcutting by later arriving female fish (Steen and Quinn 1999). Since larger fish generally bury their eggs deeper (Crisp and Carling 1989; DeVries 1997; Steen and Quinn 1999), there has been debate as to whether larger fish are favoured in locations where scour or super-imposition are likely to be problematic. However, the results of this study show that burial depth can also impact on survival where reduced hyporheic water quality is associated with groundwater upwelling. Moreover, very small (0.025 m) differences in burial depth can have a potentially very large impact on survival. Therefore, in terms of spawning, there may be a careful tradeoff to be made between avoiding scour on the one hand and avoiding hypoxia of developing embryos on the other.

Much salmon-focussed research to date has focussed on the sediment component of hyporheic dynamics. This has led to proposals for fine sediment water quality standards under legislation such as the Water Framework Directive and Habitats Directive (Naden et al. 2002) of the European Union. It has also led to the development of simplified tools (Alonso et al. 1996; Wu 2000) which do not consider the full range of hyporheic processes relevant to an understanding of embryo survival. This paper has highlighted both the importance of appropriate sampling methods and a holistic understanding of hyporheic processes, which includes understanding of local GW–SW interactions for understanding hyporheic ecology.

### Future research

This study lasted only for 1 year, focussing on a particular aspect of hyporheic ecology over a relatively short, but ecologically relevant time period. The issues highlighted in relation to the spatial and temporal scale of sampling are clear. However, further work is required to assess the influence of local GW–SW interactions on other aspects of the ecology and to characterise and understand the influence of antecedent conditions on catchment hydrology (e.g. Tetzlaff et al. 2007b) and the effect that this has on GW–SW interactions at longer temporal scales.

**Acknowledgements** The authors would like to acknowledge staff from the Environment and Resources Groups at FRS Freshwater Laboratory for field assistance during this project and the Scottish Environment Protection Agency (SEPA) for the provision of discharge data.



### References

Alderdice DF, Wickett WP, Brett JR (1958) Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs. J Fish Res Board Can 15(2):229–249

Alonso CV, Theurer FD and Zachmann DW (1996) Sediment intrusion and dissolved oxygen transport model: SIDO. Technical report 5, USDA, NSL, Oxford, MI

Arntzen EV, Geist DR, Dresel PE (2006) Effects of fluctuating river flow on groundwater/surface water mixing in the hyporheic zone of a regulated, large cobble bed river. River Res Appl 22:937–946

Baxter CV, Hauer FR (2000) Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). Can J Fish Aquat Sci 57:1470–1481

Bernier-Bourgault I, Magnan P (2002) Factors affecting redd site selection, hatching, and emergence of brook charr, *Salvelinus fontinalis*, in an artificially enhanced site. Environ Biol Fish 64:333–341

Boulton AJ, Foster JG (1998) Effects of buried leaf litter and vertical hydrological exchange on hyporheic water chemistry and fauna in a gravel-bed river in northern New South Wales, Australia. Freshw Biol 40:229–243

Boulton AJ, Hancock PJ (2006) Rivers as groundwater-dependent ecosystems: a review of degrees of dependency, riverine processes and management implications. Aust J Bot 54:133–144

Boulton AJ, Scarsbrook MR, Quinn JM, Burrell GP (1997) Land-use effects on the hyporheic ecology of five small streams near Hamilton, New Zealand. New Zeal J Mar Freshw 31:609–622

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

Brunke M, Gonser T (1997) The ecological significance of exchange processes between rivers and groundwater. Freshw Biol 37:1–33

Brunke M, Hoehn E, Gonser T (2003) Patchiness of river-groundwater interactions within two floodplain landscapes and diversity of aquatic invertebrate communities. Ecosystems 6:707–722

Claret C, Marmonier P, Boissier JM, Fontvieille D, Blancs P (1997) Nutrient transfer between parafluvial interstitial water and river water: influence of gravel bar heterogeneity. Freshw Biol 37:657–670

Coble DW (1961) Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos. Trans Am Fish Soc 90:469–474

Crisp DT, Carling PA (1989) Observations on the siting, dimensions and structure of salmonid redds. J Fish Biol 34:119–134

Curry RL, Noakes DLG (1995) Groundwater and the selection of spawning sites by brook trout (*Salvelinus fontinalis*). Can J Fish Aquat Sci 52:1733–1740


DOI 10.1007/s10040-008-0339-5

Dahm CN, Valett HM, Baxter CV, Woessner WW (2006) Hyporheic zones. In: Hauer FR, Lamberti GA (eds) Methods in stream ecology. Academic, San Diego, CA, pp 119–142

DeVries P (1997) Riverine salmonid egg burial depths: review of published data and implications for scour studies. Can J Fish Aquat Sci 54:1685–1698

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

Fraser BG, Williams DD (1997) Accuracy and precision in sampling hyporheic fauna. Can J Fish Aquat Sci 54:1135–1141

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

Greig SM, Sear DA, Carling PA (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. Sci Total Environ 344:241–258

Grimm NB, Baxter CV, Crenshaw CL (2006) Surface–subsurface interactions in streams. In: Hauer FR, Lamberti GA (eds) Methods in stream ecology. Academic, San Diego, CA, pp 761–782

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. River Res Appl 21:469–483

Hannah D, Malcolm IA, Soulsby C, Youngson AF (2004) Heat exchanges and temperature behaviour within a salmon spawning stream in the Cairngorms, Scotland. River Res Appl 20:1–18

Hunt GW, Stanley EH (2000) An evaluation of alternative procedures using the Bou-Rouch method for sampling hyporheic invertebrates. Can J Fish Aquat Sci 57:1545–1550

Ingendahl D (2001) Dissolved oxygen concentration and emergence of sea trout fry from natural redds in tributaries of the River Rhine. J Fish Biol 58:325–341

Malard F, Tockner K, Dole-Olivier MJ, Ward JV (2002) A landscape perspective of surface–subsurface hydrological exchanges in river corridors. Freshw Biol 47:621–640

Malcolm IA, Soulsby C, Youngson A (2002) Thermal regime in the hyporheic zone of two contrasting salmonid spawning streams: ecological and hydrological implications. Fish Manage Ecol 9(1):1–10

Malcolm IA, Soulsby C, Youngson AF, Petry J (2003a) Heterogeneity in ground water–surface water interactions in the hyporheic zone of a salmonid spawning stream. Hydrol Process 17:601–617

Malcolm IA, Youngson AF, Soulsby C (2003b) Survival of salmonid eggs in gravel bed streams: effects of groundwater–surface water interactions. River Res Appl 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. Hydrol Process 18:1543–1560

Malcolm IA, Soulsby C, Youngson AF, Hannah DM (2005) Catchment scale controls on groundwater–surface water interactions in the hyporheic zone: implications for salmon embryo survival. River Res Appl 21:977–989

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

Malcolm IA, Greig S, Youngson AF, Soulsby C (2008) Hyporheic influences on spawning success In: Sear D, DeVries P, Greig S (eds) Salmon spawning habitat in rivers: physical controls, biological responses and approaches to remediation. American Fisheries Society, Bethesda, MD

Mermillod-Blondin F, Chatelliers MCD, Marmonier P, Dole-Olivier MJ (2000) Distribution of solutes, microbes and invertebrates in river sediments along a riffle–pool–riffle sequence. Freshw Biol 44:255–269

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

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

Naden P, Smith B, Jarvie H, Llewellyn N, Matthiessen P, Dawson H, Scarlett P, Hornby D (2002) Life in UK rivers: methods for the assessment and monitoring of siltation in SAC rivers. Part 1: summary of available techniques. CEH, Wallingford, UK, 133 pp

Olsen DA, Townsend CR (2003) Hyporheic community composition in a gravel-bed stream: influence of vertical hydrological exchange, sediment structure and physiochemistry. Freshw Biol 48:1363–1378

Palmer MA (1993) Experimentation in the hyporheic zone: challenges and prospectus. J N Am Benthol Soc 12(1):84–93

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

Poole GC, Stanford JA, Running SW, Frissell CA (2006) Multiscale geomorphic drivers of groundwater flow paths: subsurface hydrologic dynamics and hyporheic habitat diversity. J N Am Benthol Soc 25(2):288–303

Ringler NH, Hall JD (1975) Effects of logging on water temperature and dissolved oxygen in spawning beds. Trans Am Fish Soc 1:111–121

Rodgers P, Soulsby C, Petry J, Malcolm I, Gibbins C, Dunn S (2004) Groundwater–surface water interactions in a braided river: a tracer-based assessment. Hydrol Process 18:1315–1332

Rubin JF, Glimsater C (1996) Egg-to-fry survival of the sea trout in some streams of Gotland. J Fish Biol 48:585–606

Scarsbrook MR, Halliday J (2002) Detecting patterns in hyporheic community structure: Does sampling method alter the story? New Zeal J Mar Freshw 36:443–453

Silver SJ, Warren CE, Doudoroff P (1963) Dissolved oxygen requirements of developing steelhead trout and Chinook salmon embryos at different water velocities. Trans Am Fish Soc 92 (4):327–343

Soulsby C, Malcolm IA, Youngson AF (2001) Hydrochemistry of the hyporheic zone in salmon spawning gravels: a preliminary assessment in a small regulated stream. Regul River 17:651–665

Soulsby C, Tetzlaff D, Van den Bedem N, Malcolm IA, Bacon PJ, Youngson AF (2007) Inferring groundwater influence on streamwater in montane catchments from hydrochemical surveys of springs and seeps. J Hydrol 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. Trans Am Fish Soc 114:804–812

Steen RP, Quinn TP (1999) Egg burial depth by sockeye salmon (*Oncorhynchus nerka*): implications for survival of embryos and natural selection on female body size. Can J Zool 77:836–841

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

Tetzlaff D, Soulsby C, Bacon PJ, Youngson AF, Gibbins CN, Malcolm IA (2007b) Connectivity between landscapes and riverscapes: a unifying theme in integrating hydrology and ecology in catchment science? Hydrol Process 21:1385–1389

Tonina D, Buffington JM (2007) Hyporheic exchange in gravel bed rivers with pool-riffle morphology: laboratory experiments and three-dimensional modeling. Water Resour Res 43, W01421. doi:10.1029/2005WR004328

Wondzell SM, Swanson FJ (1996) Seasonal and storm dynamics of the hyporheic zone of a 4th-order mountain stream, I: hydrologic processes. J N Am Benthol Soc 15(1):3–19

Wu F-C (2000) Modelling embryo survival affected by sediment deposition into salmonid spawning gravels: application to flushing flow prescriptions. Water Resour Res 36(6):1595–1603

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. Can J Fish Aquat Sci 61:2278–2287

Springer

# AUTHOR QUERY FORM

Dear Author,

During the preparation of your manuscript for typesetting, some questions have arisen. These are listed below. Please check your typeset proof carefully and mark any corrections in the margin of the proof or compile them as a separate list.

**Bibliography**
**Queries and/or remarks**

| Location in Article | Query / remark |
|---|---|
| Reference citations | Boulton et al. 1998; Malcolm et al. In press; Bowen and Nelson 2002; Olson and Townsend 2003; Malcolm et al. 2002 were cited in the text but no information found in the reference list. |
| | Reference citation Grimm et al. 2006 was changed to Grim et al. 2006. Please check. |
| | Please provide citations for references Malcolm et al. 2008; Olsen and Townsend 2003; Boulton and Foster 1998. |
| | Please check provided city and country for affiliation 1. |

Thank you for your assistance