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Hydrological influences on hyporheic water quality: implications for salmon egg survival

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Abstract:

The spatial and temporal variability of groundwater–surface-water (GW–SW) interactions was investigated in an intensively utilized salmon spawning riffle. Hydrochemical tracers, were used along with high-resolution hydraulic head and temperature data to assess hyporheic dynamics. Surface and subsurface hydrochemistry were monitored at three locations where salmon spawning had been observed in previous years. Temperature and hydraulic head were monitored in three nests of three piezometers located to characterize the head, the run and the tail-out of the riffle feature. Hydrochemical gradients between surface and subsurface water indicated increasing GW influence with depth into the hyporheic zone. Surface water was characterized by high dissolved oxygen (DO) concentrations, low alkalinity and conductivity. Hyporheic water was generally characterized by high levels of alkalinity and conductivity indicative of longer residence times, and low DO, indicative of reducing conditions. Hydrochemical and temperature gradients varied spatially over the riffle in response to changes in local GW–SW interactions at the depths investigated. Groundwater inputs dominated the head and tail of the riffle. The influence of SW increased in the area of accelerating flow and decreasing water depth through the run of the riffle. Temporal GW–SW interactions also varied in response to changing hydrological conditions. Gross changes in hyporheic hydrochemistry were observed at the weekly scale in response to changing flow conditions and surface water inputs to the hyporheic zone. During low flows, caused by freezing or dry weather, hyporheic hydrochemistry was dominated by GW inputs. During higher flows hyporheic hydrochemistry indicated that SW contributions increased. In addition, high-resolution hydraulic head data indicated that rapid changes in GW–SW interactions occurred during hydrological events. The spatial, and possibly the temporal, variability of GW–SW interactions had a marked effect on the survival of salmon ova. It is concluded that hyporheic dynamics and their effect on stream ecology should be given increased consideration by fisheries and water resource managers. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS hydrology; hydrochemistry; hyporheic; groundwater; salmon; ova

INTRODUCTION

Assessments of the freshwater fisheries resources of Scotland suggest that many populations of Atlantic salmon (*Salmo salar*) are in a state of decline (Youngson *et al*., 2002). Recent changes are generally attributed to poor marine survival (Friedland *et al*., 2000), probably in response to changing climate patterns in the North Atlantic (Otterson *et al*., 2001). Faced with declining marine survival, fisheries management has refocused on reducing exploitation and maximizing smolt production from the freshwater environment. In the latter case, an understanding of the major causes of mortality in freshwater is a prerequisite for the management of salmon spawning populations and their progeny.

Recruitment to salmon populations in upland Scottish streams is often lower than would be anticipated on the basis of returning female numbers and estimated egg deposition (Malcolm, 2002). Salmon eggs are

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deposited in nests known as 'redds', in the upper 0·3 m of gravel bed streams during the late autumn and early winter (Mills, 1989). The developing eggs spend 4–6 months incubating in the gravel before they emerge in spring as free-swimming fish. The period of time between spawning and emergence accounts for a large, yet highly variable proportion of lifetime mortality (Peterson and Quinn, 1996). The survival and development of salmon embryos during the incubation period is dependent on a complex interaction of environmental factors within the redd. These include, water delivery rate (Sowden and Power, 1985; Curry *et al*., 1995; Peterson and Quinn, 1996), temperature (Crisp, 1988; Elliott and Hurley, 1998), gravel composition (Witzel and MacCrimmon, 1981; Chapman, 1988; Olsson and Persson, 1988) and, critically, dissolved oxygen (DO) concentrations (Peterson and Quinn, 1996; Malcolm *et al*., 2003b). In the past, investigations of in-redd survival have focused on the role of fine sediment in reducing interstitial water velocity and infiltration of oxygenated surface water (e.g. Chapman, 1988). However, a number of field-based investigations have suggested that the link between sediment size characteristics, DO and in-redd survival 'should not be accepted uncritically' (Peterson and Quinn, 1996, p. 140), and that other environmental factors may contribute to in-redd mortality (Sowden and Power, 1985; Peterson and Quinn; 1996; Ingendahl, 2001).

Over the past 20 years, the temporal and spatial variability of groundwater–surface-water (GW–SW) interactions has received increasing attention. The potential for long-residence, chemically reduced groundwater to reduce DO levels in the hyporheic zone is of particular interest (Hill and Lymburner, 1998; Fowler and Death, 2001; Malard *et al*., 2002). This has led to the publication of several comprehensive reviews of hyporheic processes (White, 1993; Brunke and Gonser, 1997; Winter, 1995; Boulton *et al.* 1998; Dahm *et al*., 1998; Malard and Hevant, 1999; Jones and Mulholland, 2000). Within this broad literature, an area of particular ecological interest is the influence of GW–SW interactions on the survival and development of salmonid embryos (Sowden and Power, 1985; Soulsby *et al*., 2001; Malcolm *et al*., 2003b).

Hyporheic water quality is regulated by local (reach scale) and regional (catchment scale) GW–SW interactions and the relative contribution of these two water sources (Fraser and Williams, 1998), which in turn is strongly affected by extreme flows and changing hydrological conditions (Soulsby *et al*., 2001; Malcolm *et al*., 2003). In general, surface water in upland spawning streams is of high quality, with DO concentrations that are at, or near saturation (>10 mg L^{-1}). In contrast, long-residence groundwater is often less well oxygenated, with reducing conditions causing DO concentrations to fall to potentially lethal levels. Field-based investigations of egg mortality suggest that survival rates are trivial below mean DO concentrations of between 4·3 mg L^{-1} (Sowden and Power, 1985) and 9 mg L^{-1} (Rubin and Glimsater, 1996). Malcolm *et al.* (2003b) reported negligible survival where mean DO $<7·6$ mg L^{-1}. Differences in reported critical values probably reflect differences in methods (including sampling frequency), salmonid species and water temperature (Malcolm, 2002) between studies. Sublethal effects are associated with lesser reductions in DO (Shumway *et al*., 1964; Hausle and Coble, 1976; Malcolm *et al*., 2003b) and these are likely to reduce fitness in later life (Mason, 1969; Einum and Fleming, 2000).

The relative contribution of groundwater and surface water to the hyporheic zone varies both spatially (Boulton *et al*., 1998; Winter *et al*., 1998; Malard and Hervant, 1999; Malcolm *et al*., 2003) and temporally (Soulsby *et al*., 2001; Malcolm *et al*., 2003). Spatial variability occurs locally according to channel morphology (Vaux, 1962, 1968; Thibodeaux and Boyle, 1987; Baxter and Hauer, 2000; Malard *et al*., 2002; Worman *et al*., 2002) and riparian–stream linkages (Wondzell and Swanson, 1996; Soulsby *et al*., 1998) and regionally according to geology and catchment topography (Stanford and Ward, 1993; Brunke and Gonser, 1997; Boulton *et al*., 1998; Dahm *et al*., 1998; Wroblicky *et al*., 1998; Baxter and Hauer, 2000; Malard *et al*., 2002). Temporal variability occurs in response to seasonal controls on catchment hydrology (Wondzell and Swanson, 1996; Fraser and Williams, 1998) and, importantly, to short-term changes in catchment flow paths in response to high and low flow extremes (Malcolm *et al*., 2003). During high flows the hyporheic environment can be dominated by downwelling stream water as hydraulic head in the stream exceeds that of the surrounding water table (Soulsby *et al*., 2001). During low flows, which can occur during the critical winter months as surface water freezes, groundwater has an increasingly dominant effect on hyporheic water quality and has the potential to have a serious impact on the survival and development of salmonid embryos.

This paper reports the findings of an intensive investigation of GW–SW interactions across a salmon spawning riffle with a documented history of intense utilization. The study site was located in a semi-pristine upland catchment where spawning distributions and returning adult numbers have been monitored since the late 1960s. Specifically this paper aims to (i) characterize local GW–SW interactions across the study site using hydrochemical tracers, supported by temperature and hydraulic head data and (ii) investigate the effects of temporally and spatially variable GW–SW interactions on the survival of salmon embryos.

FIELD SITE

Glen Girnock is a semi-natural upland catchment draining part of the Lochnagar massif into the Aberdeenshire Dee (Figure 1). The catchment ranges in altitude from approximately 230 m at the confluence with the Dee, to 862 m at the summit of Caisteal na Caillich draining a total area of approximately 30·3 km^2. The geology of upper Glen Girnock is largely composed of igneous rocks (granite and diorite) with metamorphosed Dalradian rocks, primarily schists and gneisses in the lower catchment. In parts of the catchment, metamorphosed calcareous rocks and serpentinite are also present (Soulsby *et al*., 2001). The solid geology is overlain by a variety of glacial and glacio-fluvial sediments. The dominant soil types include peats, podzols and gleys, with significant areas of brown forest soils on the more steeply sloping areas of the lower catchment. The soils are derived from local granitic and igneous rock parent material in the south and west of the catchment, various glacial drift deposits in the north and east, and glacio-fluvial sands and gravels in the extreme north, at the confluence with the Dee. Land use is dominated by heather (*Calluna*) moorland, with some small areas of commercial and semi-natural forestry in the lower catchment (Moir, 1999). A detailed description of the sedimentary characteristics of Girnock spawning gravels is provided elsewhere (Moir *et al*., 2002). Briefly, the gravels have a geometric mean diameter (d_g) of 9·98 mm, are strongly coarse-skewed, and have a low fine sediment content (<2 mm), contributing 12% to the total sediment mass (Moir, 1999; Moir *et al*., 2002).

The Girnock Burn receives approximately 1100 mm of precipitation annually, with up to 25% falling as snow (Warren, 1985). Air temperatures historically have been highly variable. For example, Moir (1999) reported maximum and minimum temperatures of 31 °C and −27 °C respectively at Littlemill (Figure 1) during 1995. Highest temperatures are usually recorded between June and July, and lowest temperatures recorded between December and February. A gauging station operated by Scottish Environmental Protection Agency (SEPA) was installed at Littlemill in 1969 and provides 15-min resolution discharge data. The Burn has a mean discharge of *c*. 0·5 m^3 s^{-1}. However, mean daily flow can vary between <0·01 m^3 s^{-1} in the summer and >23 m^3 s^{-1} during floods in the winter.

The Fisheries Research Services (FRS) Freshwater Laboratory has monitored Atlantic salmon production using adult and smolt traps located at Littlemill since 1966. As part of this work, accurate redd maps (<1 m resolution) are constructed on an annual basis to identify spawning distributions. The hydrological and physical controls on salmon spawning are described in some detail elsewhere (Gibbins *et al*., 2002; Moir *et al*., 2002). However, the most consistently used areas of intensive spawning are identified in Figure 1. The most frequently and heavily utilized areas are situated below the Girnock trap, and in two main accumulations of spawning gravel in the upper catchment (Figure 1). Opportunistic spawning also takes place less frequently at locations where small lenses of gravel have collected (Webb *et al*., 2001). These locations are numerous, often transient and scattered throughout the catchment. The chosen study reach was located at one of the three main spawning areas, in an area of open ground immediately upstream of a channel constriction, where the stream cuts through a relict terminal moraine. Between 1986 and 1988, this section of stream and the 100 m above it, accounted for approximately 22% of total spawning activity in the Girnock Burn (Hamish Moir, personal communication).

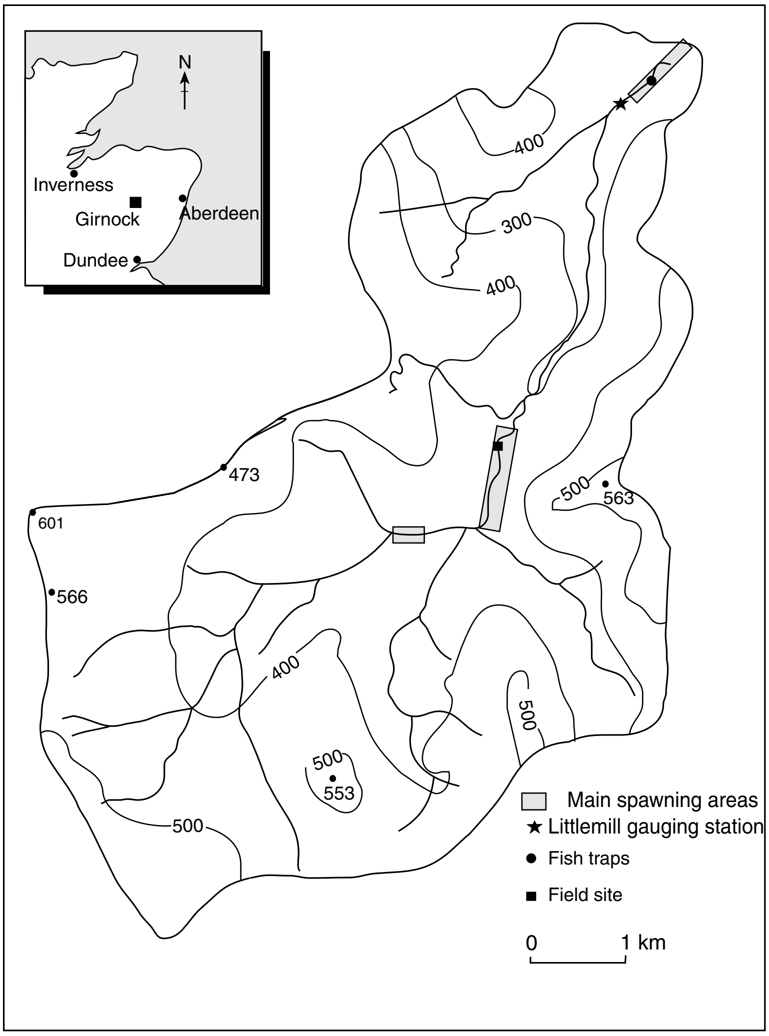

Figure 1. Map showing the location of the Girnock Burn, main spawning areas and fieldsite. Elevations are expressed as metres above sea level

METHODS

In November 2001, three artificial redds, each containing four hyporheic samplers (Figure 2) of the type described by Malcolm *et al.* (2003b), were constructed at known spawning locations in the study reach (Figure 3). Hyporheic samplers were buried in pairs to depths of approximately 150 mm and 300 mm. Spawning sites were identified on the basis of detailed field notes and photographs from previous years. The choice of sites corresponded with an area of accelerating flow below the head of the riffle (Redd 1) and two further locations moving progressively downstream towards the tail of the riffle (Redds 2 and 3). The position of the artificial redds relative to historical spawning patterns is shown in Figure 3.

At installation, 50 fertilized (water hardened) salmon eggs were incorporated into each hyporheic sampler (200 eggs per redd), in order to evaluate the relationship between environmental conditions and mortality. Numerous small diameter perforations in the hyporheic samplers prevented incidental extraction of eggs or hatching juveniles from the apparatus, while maintaining connectivity between samplers and the hyporheic

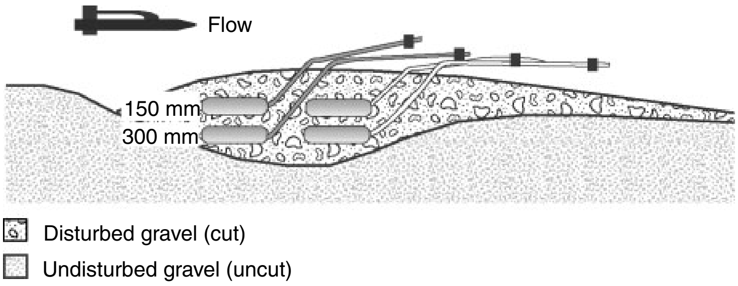

Figure 2. Vertical cross-section through artificial redd and hyporheic samplers

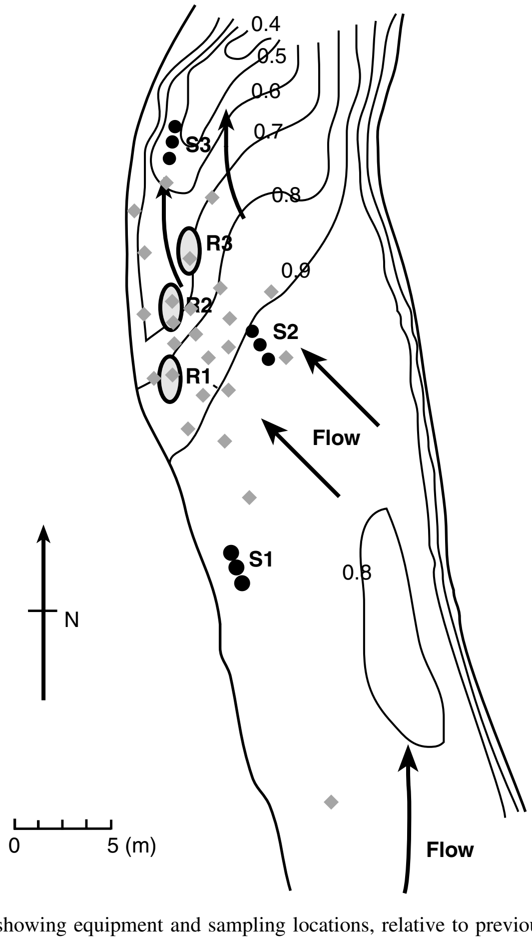

Figure 3. The Girnock Burn field site showing equipment and sampling locations, relative to previous spawning locations (1991–1999 ♦), streambed topography (0·1 m intervals) and direction of water movement: S (●) denotes the site of a piezometer nest; R denotes an artificial redd location

zone. Water samples (250 ml) were collected from each hyporheic sampler over a period of approximately 2 min using a hand-held vacuum pump and clean polyethylene bottles. The resulting samples were analysed for DO and conductivity in the field using Hanna HI9142 and HI9033 portable meters respectively, before being returned to the laboratory for determination of Gran alkalinity by titration (Neal, 2001). Gran alkalinity and electrical conductivity are hydrochemical tracers that are indicative of weathering processes. Consequently, they are useful indicators of residence time over short distances where differences in geology and land use are likely to have a negligible effect on water quality. The DO generally reflects the residence time and redox status of water.

Three nests of piezometers were installed across the spawning riffle in order to characterize hydraulic head and consequently hyporheic flowpaths (Figure 3). Nests were installed at the head of the riffle (site 1), in an area of decreasing depth and increasing velocities through the run (site 2), and on the tail at the head of a downstream pool (site 3). Each nest comprised three piezometers, located to depths of approximately 0·3, 0·5 and 0·7 m below the streambed at the time of installation. Installation was accomplished with the aid of a specially designed driver, disposable drive points and a sledgehammer. Piezometers were constructed from 0·032 m i.d. Durapipe™. The lower end was sealed and the bottom 0·12 m regularly perforated with 5 mm holes. A fine plastic mesh was used to shield the perforations and prevent excessive intrusion of sediment. Piezometer location and elevation were surveyed in late February using a Leica™ TC705 total station (reported accuracy 2 mm). Eijkelkamp™ Diver pressure transducers with integrated loggers and thermistors provided 15-min resolution temperature and head data from each of the piezometers. The hydraulic conductivity of bed sediments was determined at each piezometer location using pump tests and the Hvorslev method as described by Dahm and Vallet (1996).

Although the authors acknowledge the difficulties associated with monitoring hyporheic conditions, it was felt that the combination of hydraulic head, temperature and hydrochemical data provided a robust combination of techniques with which to characterize GW–SW interactions at the study site.

RESULTS

Hydraulic conductivity of streambed sediments

Hydraulic conductivities ranged from 1×10^{-5} to 6×10^{-4} m s^{-1} and generally decreased with depth (Figure 4). At the upstream end of the riffle (S1, Figure 3) hydraulic conductivities remained high ($>2 \times 10^{-4}$ m s^{-1}) to depths of approximately 0·7 m. However, conductivities decreased sharply at shallower depths further down the riffle. Order of magnitude declines in conductivity were observed at depths approximately of 0·7 m and 0·5 m at S2 and S3 respectively.

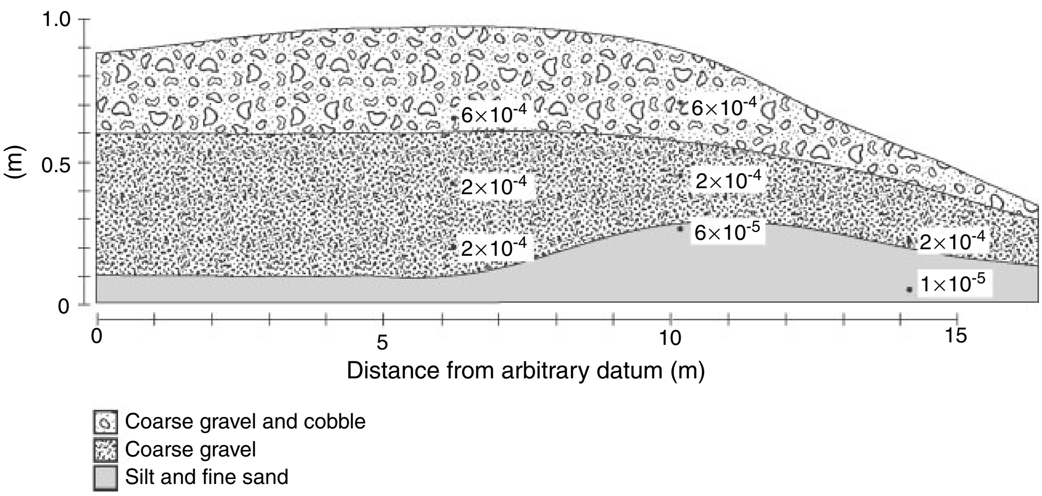

Figure 4. Longitudinal cross-section through spawning riffle showing the spatial variability of hydraulic conductivity (m s^{-1}). Conductivity values presented at location of determination

Spatial variability of groundwater–surface-water interactions

All three artificial redds exhibited chemical gradients with depth into the streambed for the measured determinands. The DO concentrations decreased with depth, whereas conductivity and alkalinity increased. Table I shows the mean and standard deviation of DO, electrical conductivity and alkalinity measurements in surface water and hyporheic water in Redds 1–3. For clarity, 150 mm and 300 mm replicates have been combined to give average measurements for a given depth in each of the artificial redds. The strength of gradients and changes with depth differed markedly between redds. Redd 1 exhibited the weakest gradients. Redd 2 exhibited strong gradients between surface water and shallow hyporheic water (150 mm), although gradients were smaller to 300 mm (DO and conductivity), and directionally inconsistent (alkalinity decreased between 150 and 300 mm). Redd 3 showed the clearest patterns of water chemistry gradients with depth into the streambed.

Between redd differences in hyporheic hydrochemistry suggested that the relative contribution of groundwater and surface water varied spatially across the riffle. These observations were supported by temperature data from the three logging piezometer sites (Figure 5), which formed part of a larger study of heat exchange and temperature at the site (Hannah *et al*., in press). Temperature data can be used to infer the nature of GW–SW interactions (White *et al*., 1987; Silliman and Booth, 1993; Evans *et al*., 1995). Groundwater typically exhibits a stable thermal profile whereas surface water is characterized by marked diurnal and seasonal temperature fluctuations. Because of the close proximity of the three piezometer sites the thermal properties of bed sediments were assumed to be uniform. Consequently, differences in hyporheic thermal regime probably were the result of differences in local GW–SW interactions. Figure 5 shows mean diurnal temperature cycles for piezometer sites 1–3 at depths of approximately 0·3, 0·5 and 0·7 m below the streambed (actual depths indicated on figure) between 15 April 2002 and 30 April 2002. The amplitude of diel temperature signals in surface water was high at this time and differences in thermal regime between sites were pronounced.

The amplitude of surface water temperature signals was dampened considerably with depth into the hyporheic zone at all three piezometer locations (Figure 5). However, marked intersite differences were apparent. At site 1 (Figure 5A), located at the head of the riffle (Figure 3), diel temperature signals were absent at depths of >0·49 m, and the amplitude of the signal at 0·33 m was low, indicating that the influence of surface water at this site, and at the depths investigated was insubstantial. Site 3 (Figure 5C), located at the downstream riffle–pool transition (Figure 3) exhibited similar patterns to site 1, and was probably characterized by similarly low levels of surface water influence at depth. Site 2 (Figure 5B), located in an area of accelerating flow and decreasing water depth adjacent to R1 (Figure 3) contrasted strongly with sites 1 and 2. Although there was no clear diel temperature signal at 0·69 m depth, there were clear signals at 0·33 and 0·49 m. The amplitude of the signal decreased with depth and exhibited a lag of approximately seven time steps (105 min) between 300 and 500 mm. It is therefore concluded that whereas sites 1 and 3 were dominated by groundwater there was a marked surface water influence to depths of between 0·51 and 0·69 m at site 2.

Table I. Mean and standard deviation of hydrochemical determinands in stream and hyporheic water of Redds 1–3

Determinand	Statistic	Surface	R1 150 mm	R1 300 mm	R2 150 mm	R2 300 mm	R3 150 mm	R3 300 mm
DO	Mean	11·7	10·7	8·3	3·6	3·0	7·6	2·8
(mg L^{-1})	Standard deviation	1·1	1·0	1·5	2·1	1·7	2·3	1·7
Conductivity	Mean	32·8	35·3	44·2	60·7	60·3	50·5	81·0
(μs)	Standard deviation	8·2	7·2	5·7	11·8	7·6	13·7	8·9
Alkalinity	Mean	150	166	207	268	233	285	513
(μeq L^{-1})	Standard deviation	77	66	30	88	59	115	91

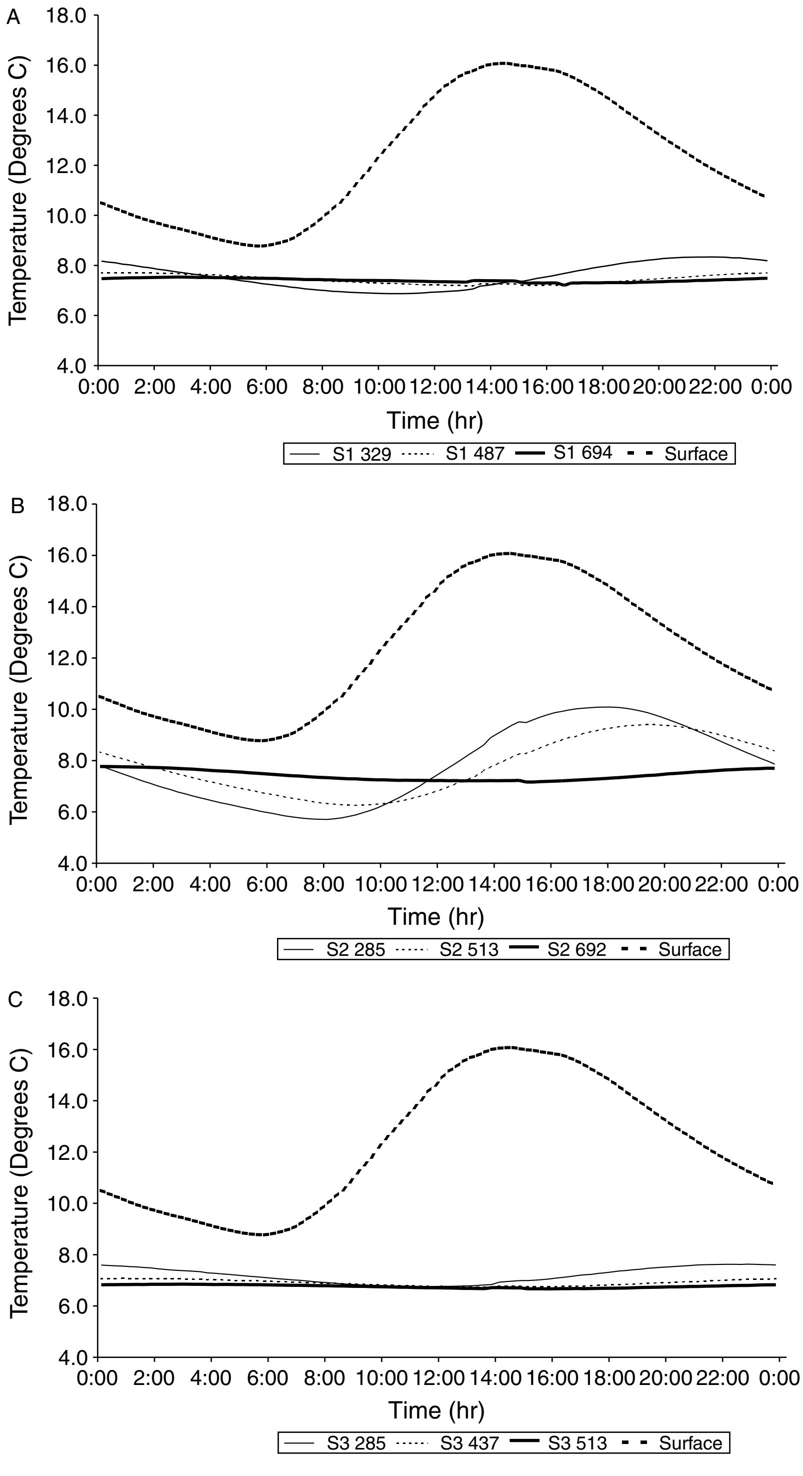

Figure 5. Mean daily temperature cycle at piezometer sites 1–3 (A–C) between 15 April 2002 and 30 April 2002. Values denote depth beneath streambed at time of survey (28 February 2002)

Temporal variability of groundwater–surface-water interactions

In addition to clear spatial variability, the hydrochemistry of individual redds also exhibited distinct temporal changes in response to changing hydrological conditions of high and low flows. Figure 6 shows the temporal variability of DO in stream and hyporheic water in Redds 1 to 3 during the period between spawning (late November) and hatch in the following spring (early April). The DO concentrations in Redd 1 exhibited clear gradients between surface and hyporheic waters throughout the study period. Gradients were most apparent between the end of January and mid-March when DO concentrations in deeper hyporheic water (300 mm) dropped to their lowest levels. Concentrations in upper hyporheic water (150 mm) were similar to, and closely tracked, those of surface water. The DO concentrations remained above 5 mg L^{-1} in all samplers during the monitoring period.

Hyporheic conditions in Redds 2 and 3 contrasted strongly with those in Redd 1, with markedly lower DO concentration and patterns of variability that were more clearly associated with changes in hydrological conditions. In Redd 2, DO concentrations initially declined with depth into the streambed and exhibited clear stratification. However, from the 12 November 2001 onwards hyporheic DO concentrations tracked each other closely and appeared to be influenced by flow. Hyporheic DO concentrations declined throughout December, partly in response to receding flows and extreme low temperatures, which caused the stream to partially freeze. By 31 December 2001, DO concentrations had fallen to 0·25 mg L^{-1} at 300 mm depth and 0·4 mg L^{-1} at 150 mm. The accuracy of discharge estimates at this time are unknown as ice can affect stage measuring, but direct observations indicated that flow was probably less than that indicated by SEPA discharge data (0·34 m^3 s^{-1}) and probably closer to recorded values in mid-April (*c*. 0·15 m^3 s^{-1}). The DO concentrations in hyporheic waters rose in response to increasing stream discharge throughout January and early February before declining once more between February and April in response to declining flows, interrupted only by a small increase on 20 March.

As in Redd 2, hyporheic DO concentrations in Redd 3 appeared to be related to flow and patterns of variability were similar between the two redds. However, DO concentrations in Redd 3 decreased with depth and showed clear stratification throughout the monitoring period. In general high flow periods were characterized by rising hyporheic DO concentrations, whereas low flows were characterized by declining DO concentrations.

Figure 7 shows the temporal variability of electrical conductivity in Redds 1 to 3. The conductivity of stream water responded predictably to changes in discharge. High flow periods were characterized by low conductivity surface water in response to increased surface runoff (short residence water). Low flow periods and periods of declining baseflow were characterized by higher conductivities, presumably because the relative contribution of groundwater to stream flow increased. The conductivity of shallow hyporheic water (150 mm) in Redd 1 closely tracked that of surface water indicating a probable surface origin (Figure 7A). The conductivity of deeper hyporheic water (300 mm) remained fairly constant, although it increased slightly throughout the monitoring period. Clear differences were observed between deeper samplers and shallow samplers/surface water as the conductivity of surface water and shallow hyporheic water declined in response to increasing stream flow throughout much of January and early February. Differences between samples once again decreased in March and April in response to the increasing contribution of groundwater to stream runoff. It is not thought that these changes in hydrochemistry reflected differences in surface water contribution to the deeper hyporheic samplers, as conductivity measurements in the deeper samplers remained relatively constant. Rather, it is thought that the conductivity of surface water more closely resembled that of hyporheic water during low flow periods when groundwater contributions dominate stream flow.

In Redd 2 (Figure 7B) the conductivity of stream and hyporheic water exhibited clear stratification throughout the monitoring period. Stratification between stream and hyporheic water increased between 5 and 19 November 2001 after which differences remained relatively stable. Initial stratification with depth decreased following 31 December 2001 after which samples from 150 and 300 mm exhibited similar characteristics.

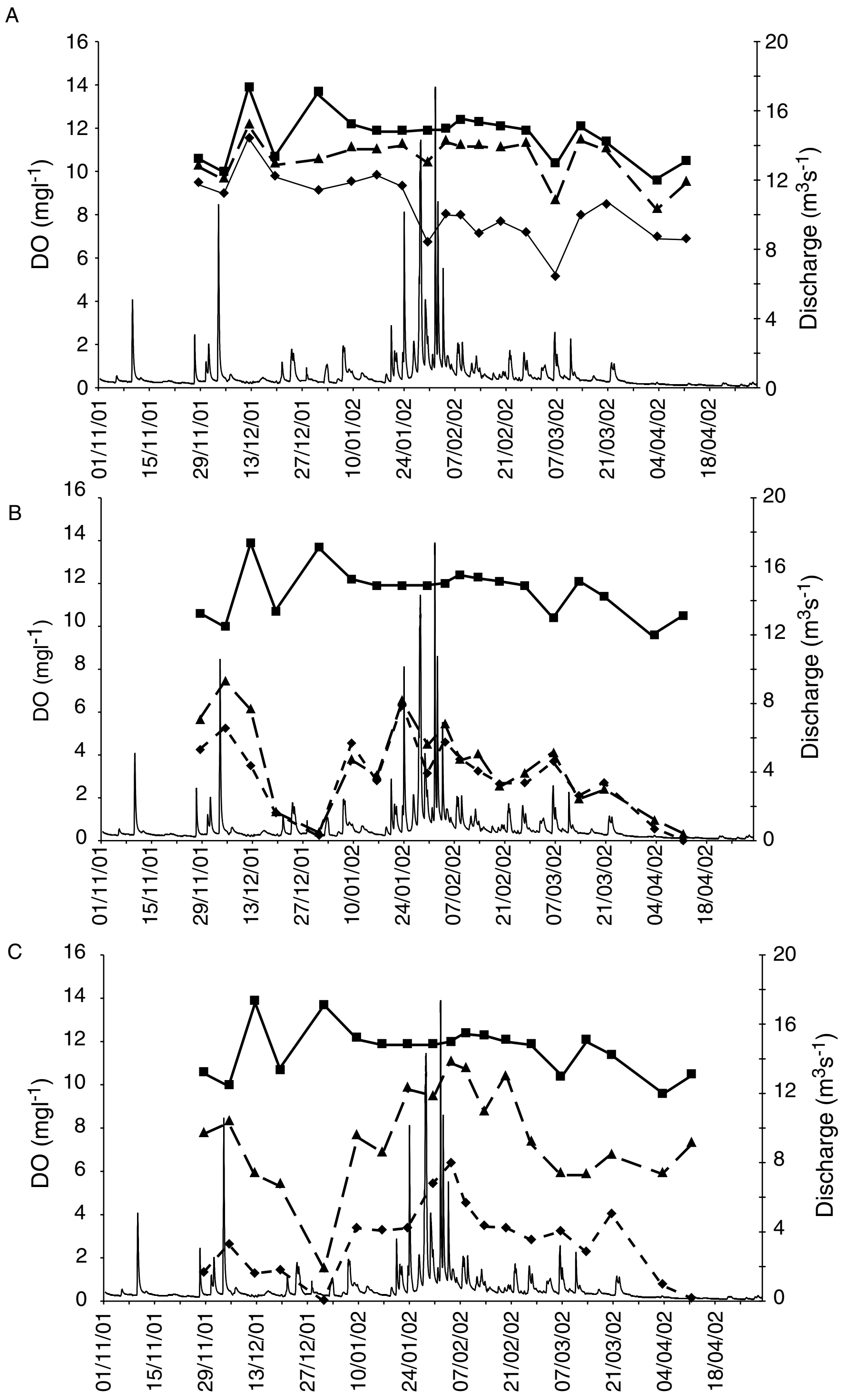

Figure 6. Temporal variability of DO at Redds 1–3 (A–C): surface water (■), 150 mm (▲), 300 mm (♦) and discharge (—)

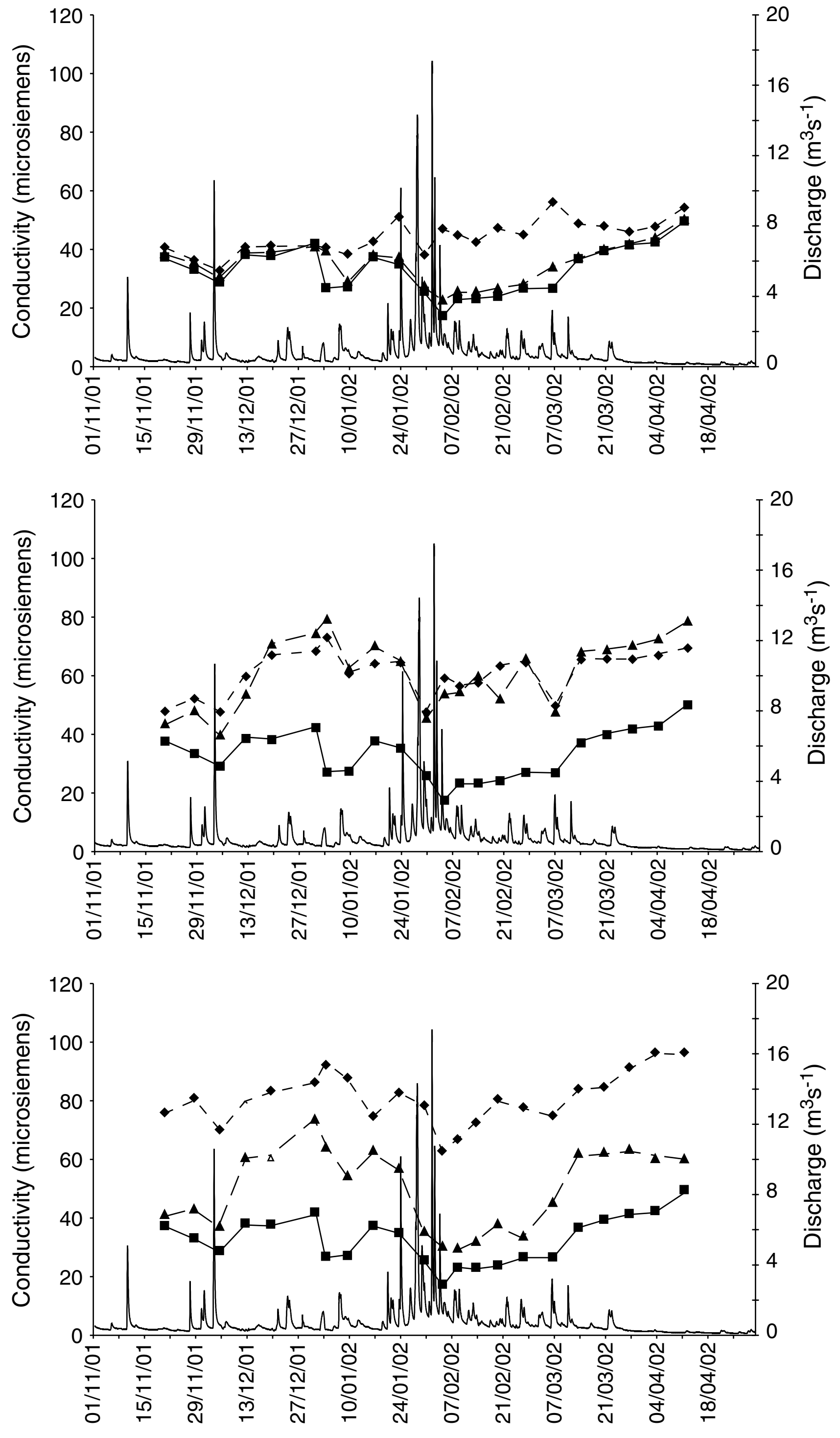

Figure 7. Temporal variability of conductivity at Redds 1–3 (A–C): surface water (■), 150 mm (▲), 300 mm (♦) and discharge (—)

Redd 3 (Figure 7C) exhibited clear stratification between samplers throughout the monitoring period. The conductivity of deeper hyporheic water was typically twice that of surface water while exhibiting similar patterns of variability. The conductivity of shallow hyporheic water was far more variable, approaching that of surface water during periods of high flow, and deeper hyporheic water during low flows. This probably reflects decreasing surface water influence and increasing groundwater contributions during baseflows and increasing surface water influence during high flows.

Figure 8 shows the temporal variability of Gran alkalinity in Redds 1–3. Alkalinity exhibited similar patterns of variability to conductivity. Surface water alkalinity followed predictable trends, increasing during baseflows as groundwater contributions increased and declining during high flow periods when contributions from short residence near-surface pathways increased. In Redd 1 the alkalinity of shallow hyporheic water (150 mm) closely tracked that of surface water, indicating surface water influence. Deeper hyporheic water exhibited fairly stable alkalinity concentrations that were similar to surface water during baseflow periods and higher than surface water during high flow periods when surface water alkalinities declined.

Hyporheic water in Redds 2 and 3 showed a clear response to changing hydrology. In Redd 2, alkalinity levels in hyporheic water were higher than those of stream water and concentrations at 150 and 300 mm depth were generally similar. However, during low flow periods between 19 and 31 December 2001 and 13 March and 11 April 2002 alkalinity levels at 150 mm exceeded those at 300 mm. These patterns may reflect the contribution of different source waters to the hyporheic zone at variable depths or alternatively that some heterogeneity existed in streambed deposits. Patterns of variability in hyporheic water generally tracked those of surface water, indicating the importance of surface water in the hyporheic gravels.

Alkalinity concentrations in Redd 3 exhibited consistently clear stratification with depth. Alkalinity concentrations of deeper hyporheic water (300 mm) were typically four times that of surface water. Patterns of variability were similar in surface and deeper hyporheic water, with rising alkalinities during low flow periods and falling alkalinities during higher flows. Alkalinities at 150 mm were more variable than those in surface water and at 300 mm depth. During the low flow period between 12 December 2001 and 16 January 2002 alkalinities at 150 mm approached those at 300 mm, indicating an increasing groundwater influence. During the period of higher flow between 23 January and 19 February 2002 the alkalinities of shallow water approached those of surface water, indicating the increasing dominance of the latter.

Short duration, flow-induced changes in GW–SW interactions

Weekly stream and hyporheic water samples revealed something of the gross changes in GW–SW interactions in response to changing hydrological conditions. However, these broad trends were punctuated by shorter period signals in these data. It is possible that much of this variability can be explained by rapidly changing hydrological flow paths during flood events. Although safety considerations prevented hyporheic chemistry sampling during large events, 15-min resolution hydraulic head data from the three piezometer nests provided information on changing GW–SW interactions and an explanation for short-term variability of hyporheic hydrochemistry. Figure 9 shows hydraulic head data for piezometer nests 1–3 (Figure 3) during a hydrological event with a peak discharge of $17{\cdot}4\ m^3\ s^{-1}$ between 1 and 2 February 2002. At the head of the riffle (S1, Figure 3), pre-event hydraulic heads indicated a dominant flux of water from the streambed to the stream (Figure 9A) with water flowing from a higher hydraulic head at 0·694 m to a lower head at 0·329 m. Hydraulic heads converged late on the ascending limb of the hydrograph, indicating that lateral movement of water through the riffle became the dominant direction of flow. On the descending limb of the hydrograph a streamward gradient was re-established as head increased with depth. At S2, located centrally in the run of the riffle, pre-event hydraulic head data indicated a small streamward gradient (Figure 9B). This gradient was cancelled out early on the rising limb of the event as hydraulic heads converged. Hydraulic gradients were reversed at high stream stage indicating that the dominant direction of flow shifted so that water moved from the stream to the bed. Small streamward gradients were re-established late on the recession limb. Head data from S3 (Figure 3), located at the tailout of the riffle, indicated that the dominant direction of flow was from the stream to the bed throughout the event. Differences in head declined on

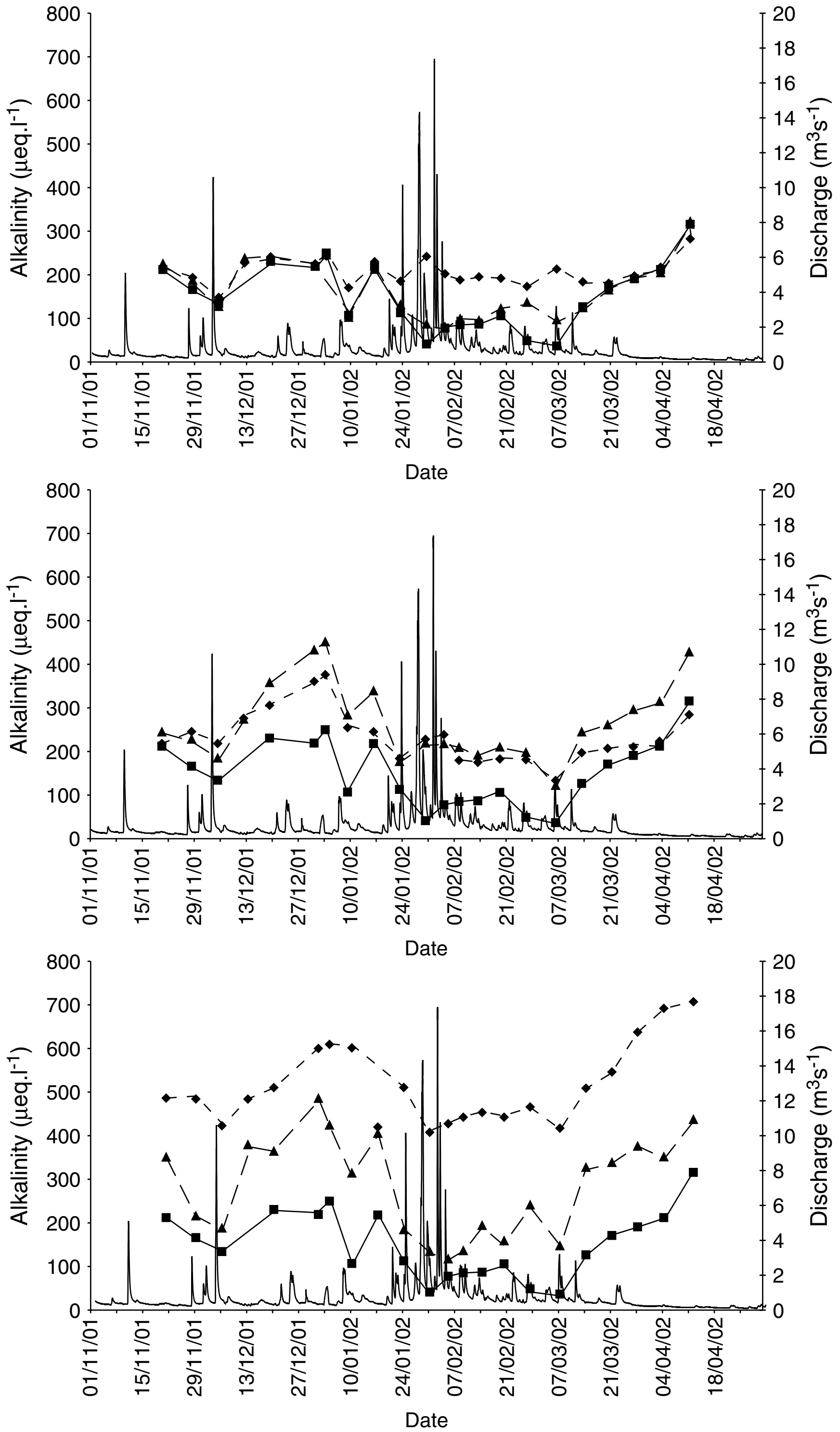

Figure 8. Temporal variability of alkalinity at Redds 1–3 (A–C): surface water (■), 150 mm (▲), 300 mm (♦) and discharge (—)

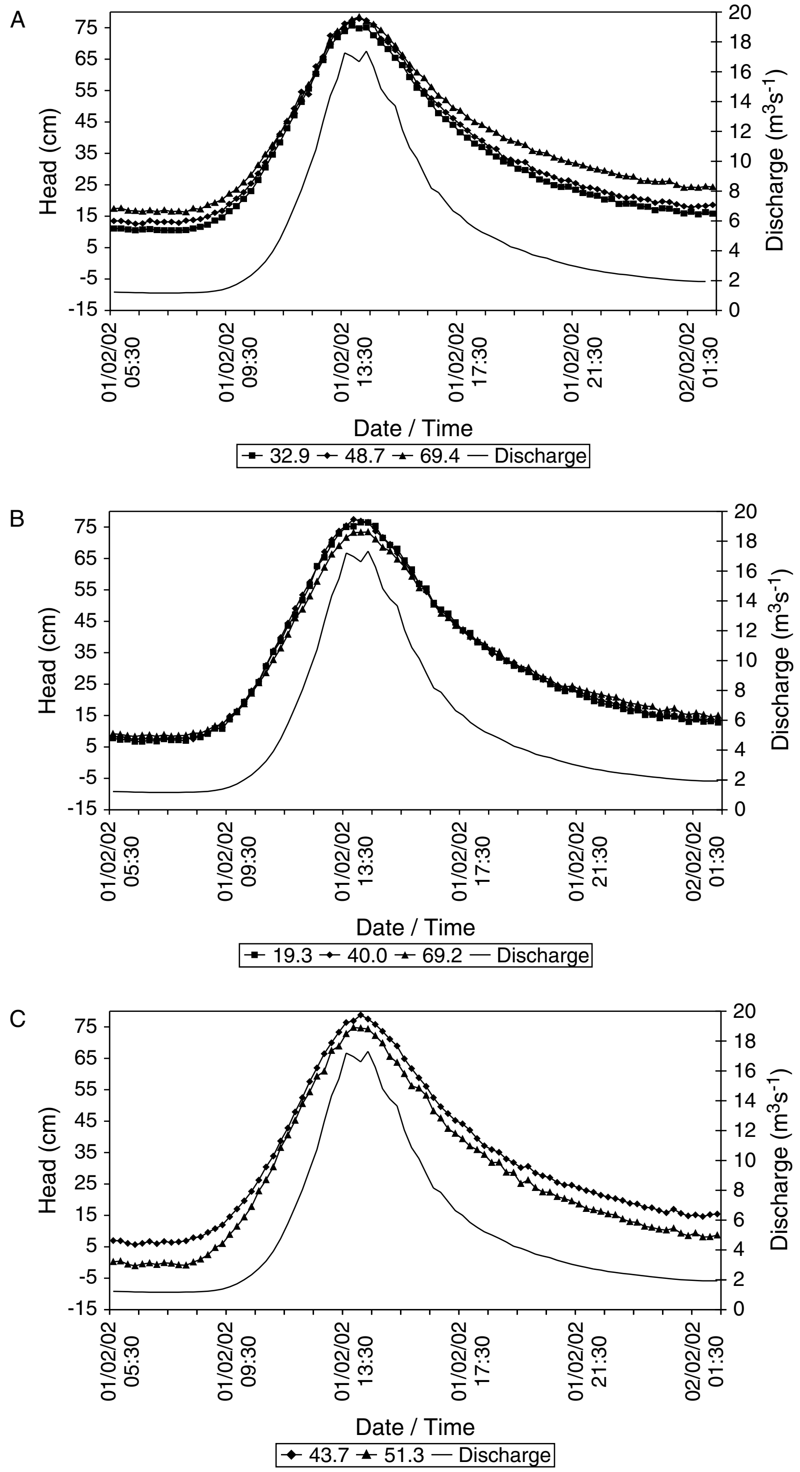

Figure 9. Stream discharge and hydraulic head relative to streambed reference point in piezometer nests S1–S3 (A–C) during a single hydrological event (01–02 February 2002)

the ascending limb, indicating that the bedward flux may have been reduced at this time. Unfortunately no data were available from shallow depths during this event as ice flows had previously sheared the durapipe piezometer.

The short duration changes in hydrological flowpaths, identified here using high-resolution head data, are likely to effect hyporheic hydrochemistry. Consequently, the time that water samples are taken relative to the various stages of hydrological events (e.g. ascending limb, peak and recession) is likely to affect observed hydrochemistry. The magnitude of changes in hyporheic hydrochemistry during extreme high-flow events is as yet unknown as safety considerations constrain hyporheic sampling.

Water quality and salmon survival

The spatial variability, and potentially the temporal variability, of GW–SW interactions had a marked effect on the success of developing salmon embryos. Longer residence groundwater is often characterized by low DO (Freeze and Cherry, 1979), which is detrimental to the survival and development of salmon embryos (Sowden and Power, 1985; Rubin and Glimsater, 1996; Malcolm *et al*., 2003b). Table II shows survival rates from hyporheic samplers located at 150 mm and 300 mm depths in Redds 1–3. Of the three sites investigated, only Redd 1, where the surface water influence was greatest, exhibited non-trivial rates of survival to hatch time. Even at this location high rates of surviving embryos were present only within the shallow hyporheic samplers (150 mm), whereas survival rates in deeper hyporheic samplers (300 mm) were low (2% and 10%). In Redds 2 and 3, where hydrochemistry suggested a strong groundwater influence, no embryos survived to hatch time.

DISCUSSION

This study has shown that for depths appropriate to spawning salmon (100–300 mm), water quality can be highly variable at fine spatial scales (<1 m), depending on local GW–SW interactions. Hydrochemical data, together with stream and hyporheic temperatures, indicate that groundwater was the dominant control on hyporheic water quality at the head and tail of a riffle heavily used by spawning salmonids. These observations are contrary to those published elsewhere, which suggest that surface water should dominate the head of the riffle (Vaux, 1962, 1968), and probably reflect the influence of valley constriction (Stanford and Ward, 1993; Baxter and Hauer, 2000) and streambed stratigraphy (Triska *et al*., 1989; Harvey and Bencala, 1993; Vallett *et al*., 1996; Brunke and Gonser, 1997) over local geomorphology in determining local GW–SW interactions at the study location.

Surface-water influence was most apparent at shallow depths and in the area of accelerating flow and decreasing surface water depth through the run of the riffle (S2 and R1, Figure 3). This was probably a response to surface-water infiltration, caused by local changes in bed morphology and consequently changes in water pressure at the bed (Vaux, 1962, 1968). In areas of groundwater dominance, 100% mortality was observed. Even in areas with a substantial surface-water influence, high rates of survival were apparent only at shallow depths (150 mm).

In addition to distinct spatial variability, hyporheic hydrochemistry responded temporally to changes in hydrological regime. Hydrochemical data indicate that during periods of low flow, caused by extreme cold

Table II. Percentage embryo survival in Redds 1–3: US and DS denote upstream and downstream samplers respectively; 150 and 300 denote depth (mm) of samplers below the streambed

	US 150	US 300	DS 150	DS 300
Redd 1	100	10	100	2
Redd 2	0	0	0	0
Redd 3	0	0	0	0

temperatures and streambed icing, or by a prolonged period of low rainfall, the influence of groundwater in the hyporheic zone increased. In addition to gross changes in hyporheic hydrochemistry, 15-min resolution hydraulic head data indicate that subtle changes in hyporheic hydrochemistry over short time periods probably could be explained by rapidly changing GW–SW interactions in response to hydrological events. At the head of the riffle, streamward head gradients experienced during pre- and post-event low flows were absent during the rising limb of events. In the run of the riffle, streamward gradients during pre- and post-event low flows were reversed under high flows. Consequently the time of sampling, for example, on the ascending or descending limb of an event, probably had a substantial effect on the observed hyporheic hydrochemistry.

Under low flow conditions, increased GW influence caused hyporheic DO concentrations to fall to $<0{\cdot}1$ mg L^{-1}, creating conditions beyond those that can be tolerated by developing salmon embryos. In some circumstances, chronic intermediately low DO can cause mortality (Alderdice *et al.*, 1958; Garside, 1966). However, for the extreme conditions observed here ($<0{\cdot}1$ mg L^{-1}), a single short episode would probably be enough to cause complete mortality within redds.

Salmon spawning habitat exhibits a high degree of geographical spread and environmental variability. Historically, studies investigating salmon embryo mortality in the redd environment have focused on the effects of fine sediment deposition, and the occlusion of oxygenated surface water from the hyporheic environment (Olsson and Person, 1986; Chapman, 1988; Rubin and Glimsater, 1996). However, recent studies have shown that in so-called degraded streams, with high fine-sediment (<2 mm) concentrations, rates of in-redd mortality are often low, although highly variable (Malcolm *et al.*, 2003b). The Girnock Burn represents an upland environment regarded as 'pristine', with an open gravel structure and low fine sediment concentrations and a conventional appreciation would predict a high degree of spawning success. Indeed, in some areas of the Girnock Burn 100% survival has been observed (Malcolm *et al.*, 2003b). More generally, however, embryo mortality appears not to be dependent on fine sediment concentration but to associate strongly with local GW–SW interactions.

This study highlights a series of concerns for fisheries and water resource managers. It is apparent that even in so-called 'pristine' upland spawning locations survival between spawning and hatch can be low. The site used in this study historically has been of major importance as a spawning location. Populations of salmon are now in decline throughout Scotland (Youngson *et al.*, 2002), to the point where returning adult numbers may become insufficient to adequately stock rivers and streams. Those managing salmon populations may wish to consider the use of hatchery facilities to eliminate groundwater effects and associated mortality over the period before hatch.

For those managing water resources, it is worth noting that episodes of low water quality (low DO) were as a result of declining surface water influence in the hyporheic zone in response to low flow conditions. In future water managers ought to consider the effects of anthropogenic influences such as impoundment, abstraction and irrigation on GW–SW interactions and the effects that this can have on stream ecology. Hyporheic hydrochemistry is likely to have an impact on interstitial fauna of species other than salmonids. Invertebrates use the hyporheic zone as a refuge from temperature extremes, floods and droughts, and as a nursery habitat (Brunke and Gonser, 1997). The distribution of invertebrates in the hyporheic zone is highly patchy (Brunke and Gonser, 1997; Boulton *et al.*, 1998) and much of the variability in distribution can be explained by physico-chemical gradients (Malard and Hervant, 1999; Franken *et al.*, 2001), which are spatially and temporally variable. This variability is expected to have an impact on the hyporheos, with potential effects on local species diversity (Ward and Tockner, 2001).

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