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Groundwater – surface water interactions in upland Scottish rivers: hydrological, hydrochemical and ecological implications

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SYNPOSIS

Contrary to previous hydrogeological assumptions, we now know that drift deposits and fracture systems in crystalline rocks can constitute important aquifers in the Scottish highlands and other montane environments. Groundwater from these aquifers usually has an important influence on the hydrology, hydrochemistry and ecology of upland river systems. Tracer-based research in the Girnock burn catchment in the Cairngorms revealed that groundwater comprises at least 30% of annual runoff. Groundwater often enters stream channels via drift deposits in valley bottom areas, which appear to be fed from recharge areas on the catchment interfluves. A range of groundwater sources exist in the catchment reflecting the complex solid and drift geology. These account for spatial differences in stream hydrochemistry and the spatial delineation of groundwater discharges to rivers and riparian zones. Areas where groundwaters enter the stream channel directly can have profound ecological implications. Most obvious are low rates of salmonid egg survival where chemically reduced groundwater discharges through the hyporheic zone. However, it is argued that only further research will reveal the full significance of groundwater-surface water interactions to the ecological status of Scottish rivers.

INTRODUCTION

Recent research has dispelled the long standing myth of Scottish hydrology that groundwater is insignificant in catchments in the Highlands (Marsh and Anderson, 2002). We now know that drift deposits and fracture systems in hard rocks form important aquifers that can substantially influence the hydrology, hydrochemistry and hydroecology of surface waters (Brunke and Gonser, 1997; Cook et al., 1991; Edmunds and Savage, 1991; Soulsby et al., 1998, 1999, 2000). This influence is most obviously evident at the local scale of the hyporheic zone – the transitional zone between groundwater and surface water – that fringes the stream channel (Malcolm et al., 2004a). However, the influence of groundwater in these headwater areas often extends downstream along the main stem of many of Scotland's major river systems (Soulsby et al., 2002a, 2003).

Unfortunately groundwater – surface water (GW-SW) interactions in upland environments remain poorly understood (Shand et al., 1999a). The traditional reliance on surface water for public supplies in Scotland has limited major drilling and geophysical investigations in the Highlands (Robins, 1990). Nevertheless, recent work with geochemical and isotopic tracers has given some interesting insights into the processes which are occurring (Shand et al., 1999b; Kirchner et al., 2000; 2001; Robins, 2002; Soulsby et al., 2000, 2004; Rodgers et al., 2004). These also provide guidance for the detailed investigations that will be needed to understand GW-SW interactions and maintain and enhance the ecological status of water bodies as required by the EU Water Framework Directive (Triska et al., 1993; Soulsby et al., 2002b).

This paper reports some results from interdisciplinary investigations in an upland catchment in the eastern Cairngorms which is drained by the Girnock Burn - an important Atlantic salmon (*Salmo salar*) spawning stream (Potter and Dare, 2003). These investigations have sought to understand some of the major influences of GW-SW interactions on river flows, surface water chemistry and the functioning of aquatic ecosystems (Malcolm et al., 2002, 2003, 2004a; Hannah *et al.*, 2004; Youngson et al. 2004). The original motivation behind these investigations arose from salmon population studies which identified lower levels of juvenile fish recruitment to the stream than were expected from the numbers of spawning female fish. It was hypothesised that high levels of egg mortality might explain this discrepancy, and one line of inquiry was that there may be toxic effects in areas where chemically reduced groundwater discharges into the stream channel (Hansen, 1975; Peterson and Quinn, 1996; Youngson et al., 2004). Previous studies have tested this hypothesis (Malcolm et al., 2002, 2003, 2004a; Youngson et al. 2004) and they have also contributed to an overall re-appraisal of the significance of groundwater on flows in the Girnock which is synthesised in this paper. Specifically, the paper seeks to: (a) examine the influence of groundwater on the quantity and quality of streamflows in the Girnock Burn; (b) characterise the spatial and temporal dynamics of GW-SW interactions at a range of scales; and (c) examine some of the ecological implications for salmonid populations and freshwater ecosystems in these areas. Future research needs are also highlighted.

STUDY AREA

The Girnock Burn drains a catchment of ca. 30 km^2 (Figure 1a). The catchment characteristics are summarised in Table 1. Briefly, the stream drains a moorland-covered catchment which has some small areas of forestry on the lower hillslopes (Figure 1d). The main economic activity in the catchment is the management of moorlands for the shooting of red deer (*Cervas elaphus*) and grouse (*Lagopus lagopus*) - land use and activities common to much of the Scottish highlands. The geology is complex; granite dominates the western half of the catchment, and metamorphic bedrock ranging from calcareous schists to serpentenite dominate the east (Figure 1b). The bedrock is covered by a complex array of drift deposits in the valley bottom: low permeability glacial drift is most common, resulting in extensive coverage of gleyed soils fringing the stream channel (Figure 1c).

River flows in the Girnock are measured at Littlemill, a short distance upstream from the confluence with the river Dee. Annual precipitation is around 1100 mm with annual runoff about 700 mm (Table 1). The gleyed and peaty soils give the Girnock a very responsive hydrological regime. Figure 2 shows flow and temperature duration curves for the Girnock in comparison to the Allt a' Mharcaidh in the western Cairngorms. It is clear that the Girnock is much flashier, with higher discharge rates during storm events and lower specific discharges during low flows. This suggest a lower groundwater influence than in the Mharcaidh where groundwater contributions to annual streamflow can be as high as 55% (Soulsby et al., 1998; 2004). The lower groundwater influence for the Girnock also appears to be reflected in the less moderated thermal regime which is prone to much colder winter and warmer summer temperatures (Hannah et al., 2004; Malcolm et al*,* 2004c).

The Girnock Burn has been an important site for monitoring salmonid populations since 1967 (Youngson and Hay, 1996). A critical stage of the salmon life cycle sees adult fish spawning in gravel bed rivers like the Girnock (Potter and Dare, 2003). This involves female fish making redds, or nests, up to 0.3 m in depth in the streambed. This depth penetrates the transitional hyporheic zone between groundwater and surface water (Williams, 1989). Eggs are laid in these locations by females and fertilized by male fish. The eggs need to survive from spawning (typically in late October to late November) to the hatch and emergence of juvenile fish in April and May, respectively. To do so, they require a continuous throughput of clean water which delivers oxygen to the developing embryos and removes waste products which they excrete (Sowden and Power, 1985).

Spawning occurs throughout the main stem of the Girnock Burn over a distance of ca. 9 km (Moir et al., 1998). Detailed redd counts since 1969 and observation of radio-tagged fish have shown that spawning activity is focused in areas of relatively low gradient where larger geomorphological units of suitable streambed sediments accumulate and appropriate hydraulic conditions prevail (Moir et al., 2002). Around 50% of spawning occurs at just four locations (Figure 1a). Elsewhere, spawning sites tend to occur on isolated patches of suitable sized gravel (Webb et al., 2001). The number of spawning females entering the stream is counted at the fish traps at Littlemill and recruitment levels are known from subsequent electrofishing of juveniles. Over the monitoring period, the number of female fish entering the Girnock for spawning each year has averaged 125, but has ranged between 6 and 293.

MONITORING AND METHODS

Hydrological understanding of the Girnock has emerged from a number of different studies over recent years. Full details of the methods used in these investigations are reported in the original journal articles and only brief details salient to this paper are reported here. Despite the emphasis on fisheries, river flows in the Girnock have been recorded at a natural rated section at Littlemill since 1969. As part of a wider hydrochemical investigation in the Dee catchment, water samples were collected from the Girnock at fortnightly intervals between May 1996 and May 1997: these were analysed for major cations and anions, as well as nutrients (Smart et al., 1998). Spawning sites have been identified and characterised in terms of their hydraulics and sedimentary characteristics at different flows (Moir et al., 1998, 2002; Gibbins et al., 2002). More recently, egg survival studies have been carried out between November 2002 and April 2003 at 10 sites (Figure 1a), sub-sampled from 16 that had been previously monitored for surface water chemistry and hyporheic (at 200-300mm depth) chemistry (Malcolm et al., 2004b). The main focus was on measuring Gran alkalinity and dissolved oxygen concentrations. This was because Gran alkalinity closely approximates acid neutralising capacity (ANC) which is a conservative tracer with proven utility in the UK uplands as it differentiates between acidic soil waters and more alkaline groundwaters (Neal et al., 2001). Obviously, dissolved oxygen provides an indicator of the influence of chemically-reduced groundwater. At the 10 sites where egg survival studies were carried out, 30cm long egg chambers were inserted into the streambed. These were partitioned into 5cm long sub-chambers where fertilised eggs were inserted at the start of the investigation and survival and embryo performance assessed at hatch time in March (see Youngson et al., 2004 for full details).

More focused process studies were carried out at sites 5, 7and 16 (Figure 1a): In these, groundwater – surface water interactions in the hyporheic zone were investigated using multi-proxy approaches and equated to egg survival rates. Piezometers in the stream bed were used to measure head, and hyporheic and stream waters were also sampled for hydrochemical analysis – again mainly Gran alkalinity and dissolved oxygen levels (Malcolm et al., 2003, 2004a). In addition, temperature loggers were used to establish thermal profiles (Malcolm et al., 2002; Malcolm *et al.,* 2004a; Hannah et al., 2004).

Spatial surveys of stream chemistry were also carried out under average (Q_{55}) and high (Q_9) flow conditions in April 2002 and January 2004 respectively. On each occasion approximately 60 samples were collected. In addition, spatial surveys in early 2004 have characterised the hydrochemistry of springs and seeps discharging into the Girnock Burn in order to identify groundwater discharge areas. Again Gran alkalinity was used as a tracer of geochemical weathering reactions and dissolved oxygen to assess the redox status of the groundwater.

SURFACE WATER HYDROLOGY AND HYDROCHEMISTRY

Table 2 shows that the hydrochemistry of the Girnock is broadly typical of a Cairngorm stream with calcareous rocks in the catchment (cf. Soulsby et al., 1997). The pH of stream water is well buffered, but storm flows are acidic with low alkalinity levels (Figure 3a). Other weathering-derived species (base cations and SiO_2) also decline at high flows which is a characteristic feature of upland streams when there is a dilution of groundwater-dominated baseflows by soil water-dominated storm runoff which is enriched in Total Organic Carbon (TOC) (Soulsby and Dunn, 2003). Up until c.0.5 cumecs, alkalinity declines linearly with flows, implying simple mixing of higher alkalinity groundwater sources and acidic soil waters. At flows above this, low alkalinity soil water dominance is clear and comparable to upland sites elsewhere (cf Soulsby et al., 2003).

These relationships can be used as a basis for a chemically-based hydrograph separation using simple mixing models for conservative tracers to estimate the groundwater contributions to flows (see Wade et al., 1999 for details). Groundwater end member chemistry for the hydrograph separation is estimated from low flow stream water chemistry. This gives an integrated measure of groundwater chemistry at the catchment scale, which although simplistic, at least provides a conservative assessment of the minimum contribution that groundwater makes to annual flows. The results in Figure 3b show that, assuming a catchment-averaged groundwater chemistry equivalent to the average of the 3 or 6 lowest flows sampled, around 28-32% respectively of streamflows over the hydrological year are derived from groundwater. This groundwater contribution is relatively low and similar to other flashy headwater catchments elsewhere in the Cairngorms (Soulsby et al., 2003, 2004).

Spatial surveys of catchment hydrochemistry revealed that the chemistry at the catchment outfall is underpinned by much more complex variability (Figure 4).

Samples collected under average (Q_{55}) flow conditions in April 2002 showed that the stream chemistry – indexed by Gran alkalinity – was spatially variable, with geology having a clear influence (Figure 4a). Low alkalinity drainage waters come from granitic areas (upper Girnock), higher alkalinity waters come from serpentinite (in the case of the East Burn) and other base-rich rocks such as the calcareous schists (in the lower catchment) or diorite/amphibolite areas (around the South Burn). Samples collected in high flows (Q_9) in January 2004 showed a similar pattern, but much lower alkalinities and a weakening of the geological influence by low alkalinity soil waters (Figure 4b). The results of the spatial survey indicate that the groundwater in the catchment, which contributes to high alkalinity baseflows, represents a complex range of sources which mix to supply streamflow. This is consistent with the findings of Smart et al. (2001) who found that variations in the geochemistry of riparian geology – ie the local geology adjacent to the stream channel - provided a powerful predictor of differences in stream water chemistry at a range of spatial and temporal scales throughout the Dee catchment.

GROUNDWATER - SURFACE WATER INTERACTIONS IN THE HYPORHEIC ZONE

Catchment scale

The 2002/2003 spatial survey of downstream changes in stream and hyporheic chemistry at the sites shown in Figure 1a revealed, as anticipated, an increase in streamwater alkalinity as geological boundaries are crossed and substantial drainage is received from areas underlain by different geological units (Figure 5). The hyporheic chemistry, however, revealed interesting and somewhat complex patterns. Some sites (3, 9, 10, 14, 16) have hyporheic waters that are very similar to stream water in terms of Gran alkalinity and dissolved oxygen concentrations. Others – most notably sites 4, 5, 6, 7, 8 and 11 - have particularly marked differences in terms of both alkalinity and dissolved oxygen. The remaining sites have less obvious, but still substantial hydrochemical differences.

These patterns are consistent with groundwaters of variable chemistry mixing to differing degrees with surface waters in the hyporheic zone in different parts of the catchment. The alkalinity of hyporheic waters at sites 2 and 4 are respectively c.50% and 150% greater than stream waters, implying longer residence times and greater weathering reactions in the granitic catchment headwaters. However, the change was even greater at site 5, probably reflecting the influence of more base rich solid geology of the calcareous schists and serpentenite on groundwaters in the lower catchment. At each of these sites, residence time studies indicated freely moving hyporheic waters (Youngson, unpublished data), thus quasi-stagnant zones appeared not to be responsible for the chemical differences. This remained evident at sites 6, 7 and 8. At sites 5 and 7 dissolved oxygen levels were also notably depressed. In general groundwater influences tended to decline downstream of site 7.

Reach scale

The spatial variability in hyporheic chemistry indicated by Figure 5 has substantial ecological implications. In particular, the most strongly groundwater-influenced sites were found to have the poorest rates of egg survival (Table 3). Egg survival was low at all depths below 5 cm at site 7, presumably as a result of the low oxygen levels in the hyporheic zone (Malcolm et al., 2004a). Low egg survival rates were also observed at depth (30 cm) at sites 6 and 13. Elsewhere, mortality was high in the upper 5 cm, presumably as a result of mechanical shock initiated by sediment transport processes on the stream bed (Moir et al., 2002). Such findings provided an impetus to investigate selected sites in more detail (Table 4).

Initial detailed investigations on the interactions between groundwater discharge points and embryo survival focused on Site 7 (see Malcolm et al., 2004a for full details). This site is located along a riffle that is a key spawning site in the Girnock. Hydrometric and hydrochemical data indicated a streamward groundwater flux apart from during high flows where, in some places the hydraulic gradient was reversed and stream water ingressed into the hyporheic zone. Table 4a shows data for stream chemistry and hyporheic chemistry at depths of 15 and 30 cm for three sites at the head (1), run (2) and tail (3) of the riffle. Only the 15 cm sampler at site 1 at the head of the riffle had a hyporheic chemistry similar to stream water. At all other sites the alkalinity increased with depth and was much higher than in the stream, whilst dissolved oxygen levels decreased with depth (Table 4).

The hyporheic samplers were located in streambed gravels which overlay a sand/silt layer at depths of ca. 50 cm. Hydraulic conductivity measurements using falling head slug tests indicated typical rates of 0.9 m/d in the sand/silt layer and 17 m/d in the upper stream gravels. It was concluded that groundwater flux rates through the stream bed were probably quite low, but sufficient to have a substantial influence on hyporheic chemistry. Also, apart from at the very lowest flows, alkalinities at 30 cm in site 7 were greater than stream samples collected here, or at Littlemill.

Site 5 was located at another spawning riffle. Here a longer stretch of channel constitutes a plane bed reach of the river where spawning is common. Hydraulic head measurements revealed a streamward flux vector, and chemistries collected from 9 hyporheic samplers at depths of 20-30 cm revealed a marked spatial variation in hyporheic chemistry (Table 4b). Here hyporheic water at 20 cm below the stream channel was markedly different in chemical composition and in some locations very different from observed stream chemistries in terms of alkalinity and dissolved oxygen levels. Again, at this site, fluvial gravels were underlain by finer silt-clay deposits.

A contrast was observed at Site 16 where temperatures and chemistries (see Malcolm et al, 2002) suggested downwelling stream of stream water into the hyporheic zone; hyporheic chemistries that were virtually identical to stream water. At this site, no clear streamward hydraulic gradient was evident and hydrochemical data from replicate hyporheic samplers at depths of 15 and 30 cm suggested that stream waters freely exchanged with hyporheic waters. This site was on an area of alluvium where the Girnock flows towards the river Dee, thus there was no stream-ward hydraulic head driving groundwater towards the stream channel.

The spatial difference in the degree of groundwater influence in hyporheic chemistry is clear from Table 4, with sites like 5 and 7 being characterised by groundwater upwelling and sites like 16 being characterised by streamwater downwelling. These differences appear to be related to catchment geomorphology as well as geology (Baxter and Hauer, 2000; Malcolm et al, 2004b). Sites 5 and 7, for example are both upstream of morainic deposits in the valley bottom that are perpendicular to the main down valley axis. This obstruction to the channel network appears to create sedimentation basins which allow gravel riffles to develop which have hydraulic conditions well-suited to spawning. However, they may well contribute to enhanced groundwater upwelling in these areas, probably as a result of over-burden pressures on the underlying sediments. This raises a number of issues in relation to site selecton by salmonids (Baxter and Haur, 2000), as it seems that the fish are unable to identify areas of groundwater upwelling which adversely affect embryo development and survival, or they prioritise site selection on the basis of sedimentary and hydraulic conditions.

GROUNDWATER DISCHARGE: DEEP & SHALLOW SOURCES

This range of investigations has been instructive in indicating the nature of GW-SW interactions in the Girnock. Clearly the imprint of geology is apparent on surface water chemistries, even at higher flows, suggesting important hydrological contributions from groundwater sources. However, insights into groundwater discharges directly into the stream channel were spatially restrictive; and whilst it is clear that groundwater is generally in connection with the stream channel and discharges directly, elsewhere, it emerges on hillslopes in springs and seeps. To gain a broader perspective on groundwater discharge areas, spatial hydrochemical surveys of springs and seeps in the catchment were undertaken. Figure 6 shows that these exhibited a wide range of chemical characteristics. Low alkalinity springs and seeps appear to reflect drainage from shallow soils overlying impermeable drifts. In contrast, other high alkalinity springs suggest longer residence times and / or interactions with more weatherable base-rich rocks.

Figure 6 shows the changes in stream chemistry in the section of the Girnock between sites 4 and 7 near to the points where the major tributaries of the South and East Burn enter the main stem (see Figure 1a) and where a key spawning area is located . Stream water alkalinity increases in this area (see Figure 4) as the geology – and hence chemistry of groundwater inputs – together with significant flows from the tributaries buffer the waters from the granitic headwaters. The alkalinity of some springs is very high and similar to the alkalinity of deeper hyporheic waters reported in Table 4, indicating that some groundwater sources are chemically distinct.

However, this creates an apparent paradox in the way that groundwater sampled in valley bottom has chemistry very distinct from what is generally observed in the stream. Also, there seems to be an inconsistency in how groundwater in low conductivity drift can respond over the time scale of a hydrological event and provide a significant flux to stream water as inferred by the hydrograph separations in Figure 3b and measured head data (see Malcolm et al., 2004a).

It is useful to differentiate between groundwater in the drift and that emerging from springs on the catchment hillslopes as shown in Figure 6. The drift in the valley bottom is often characterised by compacted glacial till, though in places it may be more freely draining morainic or fluvio-glacial deposits. The valley bottom seems to act as a discharge area, with springs emerging in lower slopes where the slowly permeable, saturated drift appears to inhibit lateral drainage. In places this saturation appears to result in the exfiltration (or return flow) of lower Gran alkalinity (< 100 μeq l^{-1}) soil waters. The chemistry of other higher Gran alkalinity (> 200 μeq l^{-1}) springs suggests that its origin is groundwater in fracture systems in the bedrock. Tracer studies using ^{18}O isotopes in other upland catchments in the UK have suggested that the mean residence times of water draining shallow soil layers may be less than 2 months. In contrast, deeper waters from drifts and fracture systems may be well over 10 years old (Soulsby et al., 2000; Shand et al., 2004). Such differences in residence times and flow paths would help explain the differences in chemistry of groundwater sources.

To explain the physical processes underpinning this re-emergence of groundwater, the most likely hypothesis appears to be that the upper hillslopes which are not drift-covered act as groundwater recharge zones. Although there may be some re-emergence of groundwater on the hillslope springs, deeper movement in the fracture zones may provide a mechanism for the response of groundwater in the drift as rapid recharge through the fracture zone can initiate a head response in the valley bottom (Shand et al., 2004). This is shown in Figure 7, which presents a conceptual model of the groundwater flow paths in the valley bottom area around sites 5- 7. However, there is clearly a need to develop tentative conceptual models such as this into a broader understanding of groundwater in the catchment context.

ECOLOGICAL SIGNIFICANCE

In the Girnock studies outlined above, the ecological implications of the GW-SW interactions were targeted at understanding the significance of reducing groundwater in causing salmon egg mortality. There is clear evidence that spawning selection in areas of groundwater upwelling can at best compromise embryo development and at worst cause high mortality rates (see Table 3 and Youngson et al., 2004). However, this is only one aspect of stream ecology, and it is reasonable to assume that GW-SW interactions affect other components of aquatic ecosystems. Thus, patch dynamics in freshwater ecosystems, such as variability in macroinvertebrate communities may reflect patchiness in groundwater discharge sites (Fowler and Death, 2001). Clearly there are implications for primary and secondary production that occur in these areas whose importance we are only beginning to appreciate (White and Hendricks 2000; Baker et al., 2000). As hyporheic zones can have an important role as thermal refugia in river systems, understanding these ecological implications must be a major priority in view of climate change predictions of warming stream temperature in the Scottish Highlands.

IMPLICATIONS

The data presented here provide only a rough sketch of the role of groundwater in the hydrological functioning of the Girnock Burn. On the one hand, the role of groundwater is very simple, but it is underpinned by a very complex suite of processes. We currently understand these processes only in a very basic way. There is a need for more detailed integrated studies, involving drilling programmes which explore the ways in which shallow and deep groundwater flow systems interact and how this water is discharged into streams. Only then will the ways in which groundwater influences the hydrology and hydrochemistry of upland streams be understood (cf Kirchner, 2003). This will then provide a basis for further understanding the role of GW – SW interactions in sustaining the ecological status of upland streams and their sensitivity to environmental change. Upland catchments are affected by numerous land use activities; traditional forestry, land drainage, and river regulation operations may have fundamentally changed the nature of GW-SW interactions. At the present time extensive construction of wind farms, with associated road infrastructure and deep excavation of turbine bases may be having a similar impact on water flow paths and residence time distributions.

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LIST OF TABLES

Table 1 Characteristics of the Girnock catchment.

Topographic range [m]	230-862
Catchment area [km^2]	30.3
Dominant Geology	Granite, Schist, Gneiss
Dominant Soil Types	Gleys, Peaty Podzols, Peat
Dominant Land Use	Moorland (80%), Coniferous woodland (10 %), Montane (10%)
Rainfall [mm year^{-1}]	1100
Q_{50} [m^3 s^{-1}]	0.5
Q_{95} [m^3 s^{-1}]	0.04
Q_{10} [m^3 s^{-1}]	1.01
Mean annual flow [m^3 s^{-1}]	17.9
Peak flow recorded [m^3 s^{-1}]	100.1

Table 2. Hydrochemistry of Girnock burn from fortnightly samples collected between 1996 and 1997 (n=28) and showing storm flow chemistry (mean of 2 highest flows sampled) and baseflow chemistry (mean of the 3 lowest flows).

	Low Flow	High Flow	Mean
PH	7.9	5.8	7.3
Alkalinity [µeq l^{-1}]	599.7	30.0	315.9
Ca^{2+} [mg l^{-1}]	7.9	2.5	4.8
Mg^{2+} [mg l^{-1}]	2.8	0.9	1.7
Na^{+} [mg l^{-1}]	6.3	3.7	5.0
K^{+} [mg l^{-1}]	1.1	0.6	0.7
Cl^{-} [mg l^{-1}]	6.9	6.3	6.7
SO_4^{2-} [mg l^{-1}]	4.1	6.0	4.9
NO_3-N [mg l^{-1}]	<0.05	<0.05	<0.05
SiO_2 [mg l^{-1}]	13.1	5.5	9.7
TOC [mg l^{-1}]	1.8	12.4	4.7

Table 3. Proportion of ova (n=20) surviving to the eyed stage at sub-set of sampling locations.

Depth below streambed (mm)	Site									
	2	3	4	6	7	9	10	12	13	16
50	0	0	1.0	0.65	1.0	0	0	1.0	0	0
100	1.0	0.95	1.0	1.0	0	0.95	1.0	1.0	1.0	1.0
150	1.0	0.95	1.0	1.0	0	1.0	1.0	1.0	1.0	1.0
200	1.0	1.0	1.0	1.0	0	1.0	1.0	1.0	1.0	1.0
250	1.0	0.95	0.9	1.0	0	1.0	1.0	0.95	1.0	1.0
300	1.0	0.95	1.0	0	0	0.95	1.0	1.0	0	1.0

Table 4. Surface water and hyporheic chemistry at 3 study areas.

a. Site 7: Means and standard deviations (bracketed) of stream and hyporheic chemistry (Gran alkalinity, dissolved oxygen and conductivity) at 15 and 30 cm depths at the (1) head, (2) run and (3) tail of a riffle.

Site 7		Alk [μeq l^{-1}]	DO [mg l^{-1}]	Cond. [μS cm^{-2}]
	Stream	150 (22)	11.7 (1.1)	328 (8.2)
	H_{15} (1)	166 (66)	10.7 (1.0)	35.3 (7.2)
	H_{30} (1)	207 (30)	8.3 (1.5)	44.2 (5.7)
	H_{15} (2)	268 (30)	3.6 (2.1)	60.7 (11.8)
	H_{30} (2)	233 (59)	3.0 (1.7)	60.3 (7.6)
	H_{15} (3)	285 (115)	7.6 (2.3)	50.5 (13.7)
	H_{30} (3)	513 (91)	2.8 (1.7)	81.0 (8.9)

b. Site 5: Chemical composition of stream and hyporheic (20 cm depth) chemistry of spawning riffle 30 m long in 10 m wide reach of the Girnock, July 2003.

		Alk [μeq l^{-1}]	DO [mg l^{-1}]	Cond. [μS cm^{-2}]
Site 5	Stream	473	12.1	36
	5A	475	5.4	80.4
	5B	535	11.7	36.9
	5C	559	11	38.5
	5D	505	8.8	41.2
	5E	534	11.7	36.3
	5F	553	12	36.7
	5G	490	10.5	50.7
	5H	635	10.8	51.6
	5I	1112	10	72.2

Site 16. Mean and standard deviation (bracketed) of stream and hyporheic chemistry at 15 and 30cm depths in spawning riffle. 2 sites were monitored within the riffle – upstream (up) and downstream (down).

		Alk [mg l^{-1}]	DO [mg l^{-1}]	Cond. [μS cm^{-2}]
Site 16	Stream	8 (3)	12.0	54 (9)
	H_{15} (up)	9 (4)	11.7 (1.3)	54 (8)
	H_{30} (up)	9 (3)	11.2 (1.2)	54 (8)
	H_{15} (down)	10 (4)	11.5 (1.1)	56 (8)
	H_{30} (down)	10 (5)	11.3 (1.2)	54 (7)

LIST OF FIGURES

Figure 1

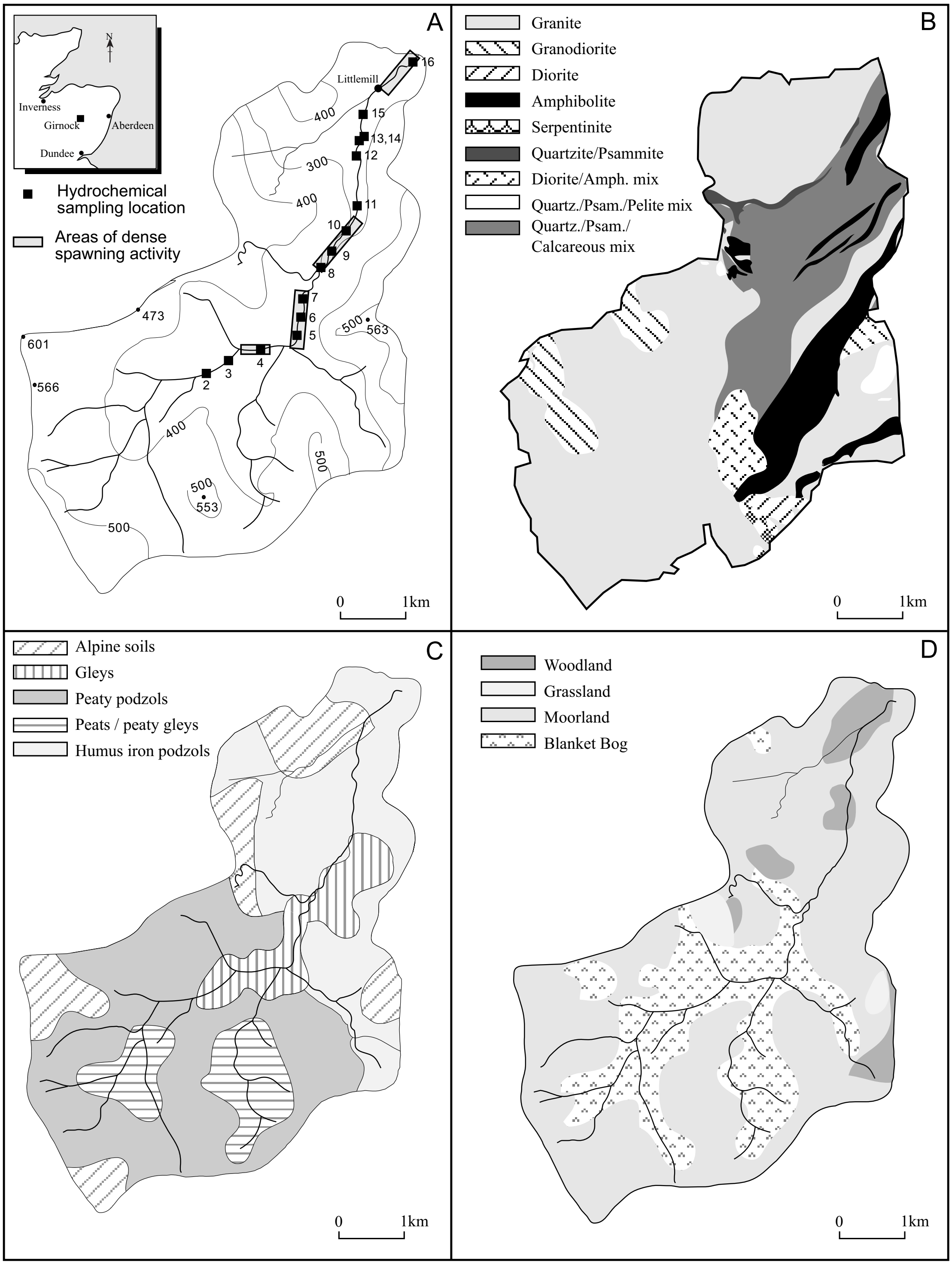

A
N
Inverness
Girnock
Aberdeen
Dundee
Hydrochemical sampling location
Areas of dense spawning activity
Littlemill
1
2
3
4
5
6
7
8
9
10
11
12
13,14
15
16
300
400
500
473
601
566
563
553
0 1km
B
Granite
Granodiorite
Diorite
Amphibolite
Serpentinite
Quartzite/Psammite
Diorite/Amph. mix
Quartz./Psam./Pelite mix
Quartz./Psam./ Calcareous mix
0 1km
C
Alpine soils
Gleys
Peaty podzols
Peats / peaty gleys
Humus iron podzols
0 1km
D
Woodland
Grassland
Moorland
Blanket Bog
0 1km

Figure 2

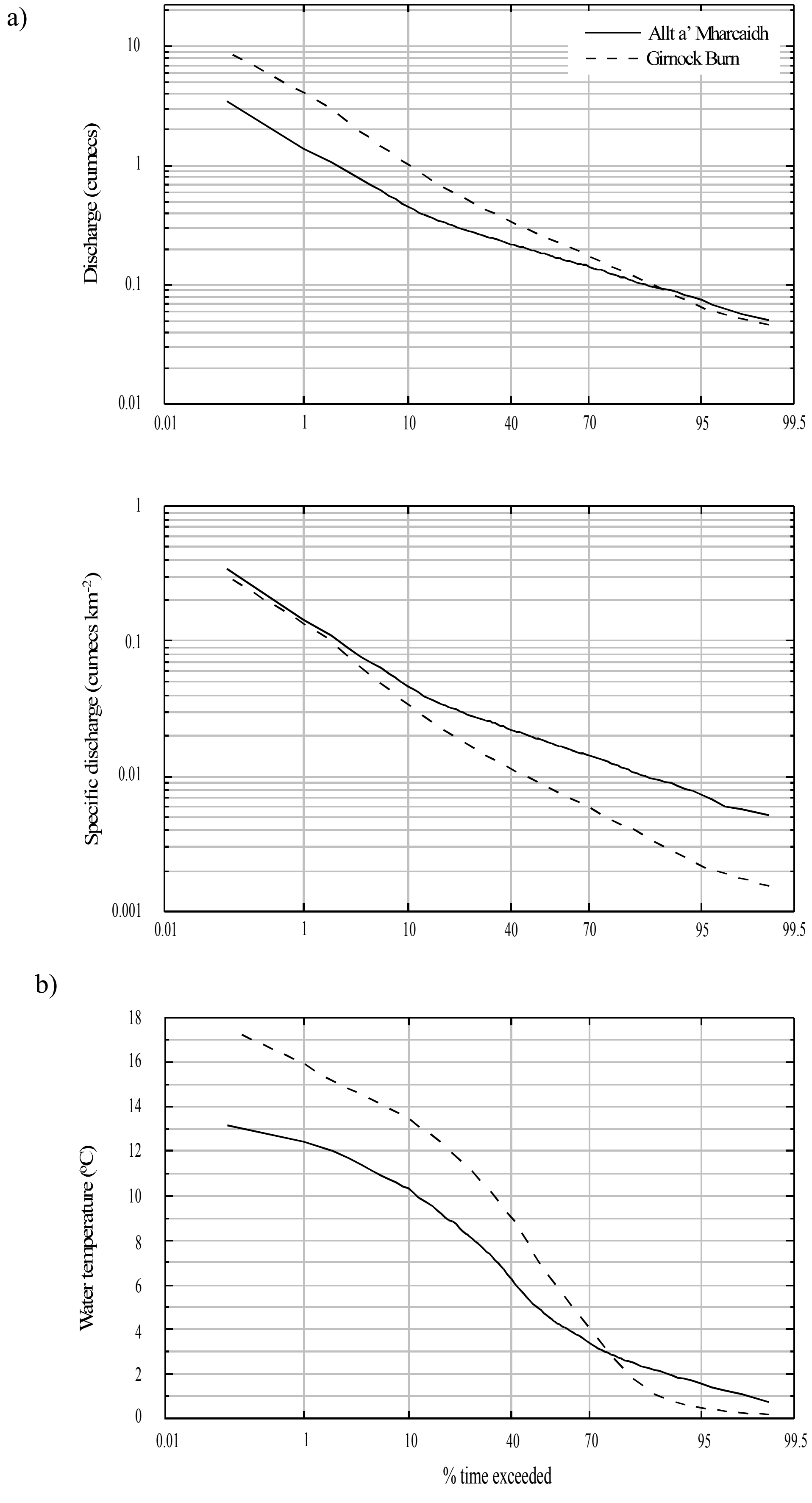
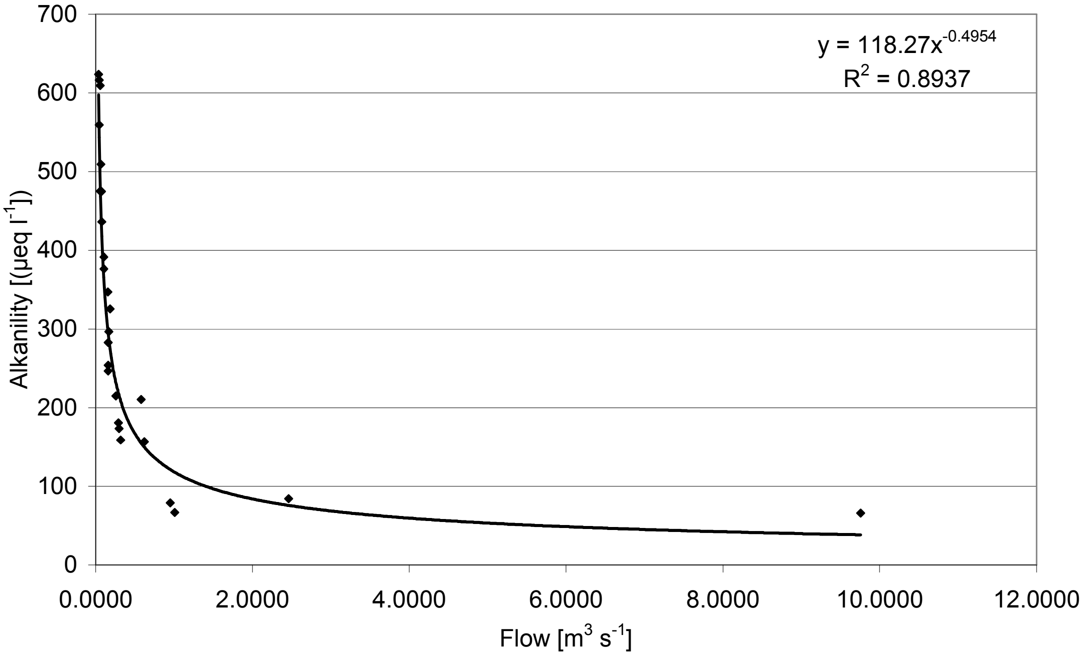

a)
Allt a' Mharcaidh
Girnock Burn
Discharge (cumecs)
10
1
0.1
0.01
0.01
1
10
40
70
95
99.5
Specific discharge (cumecs km^{-2})
1
0.1
0.01
0.001
0.01
1
10
40
70
95
99.5
b)
Water temperature (°C)
18
16
14
12
10
8
6
4
2
0
0.01
1
10
40
70
95
99.5
% time exceeded

Figure 3

a)


y = 118.27x$^{-0.4954}$
R^2 = 0.8937
Alkanility [(μeq l^{-1}])
Flow [m^3 s^{-1}]
0
100
200
300
400
500
600
700
0.0000
2.0000
4.0000
6.0000
8.0000
10.0000
12.0000

b)

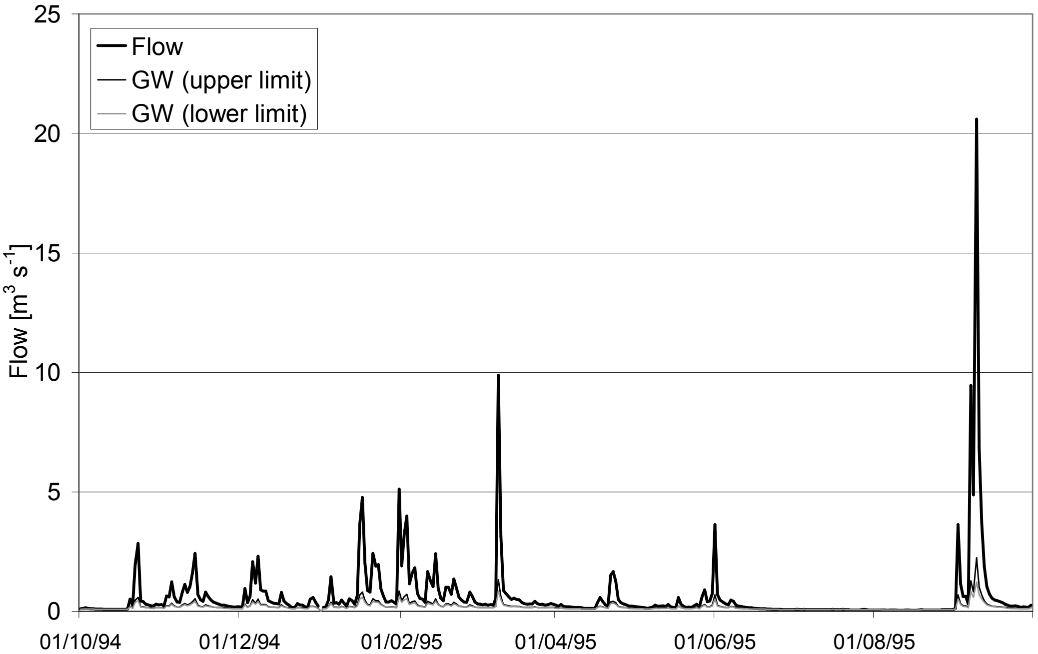

Flow
GW (upper limit)
GW (lower limit)
Flow [m^3 s^{-1}]
0
5
10
15
20
25
01/10/94
01/12/94
01/02/95
01/04/95
01/06/95
01/08/95

Figure 4

a) b)

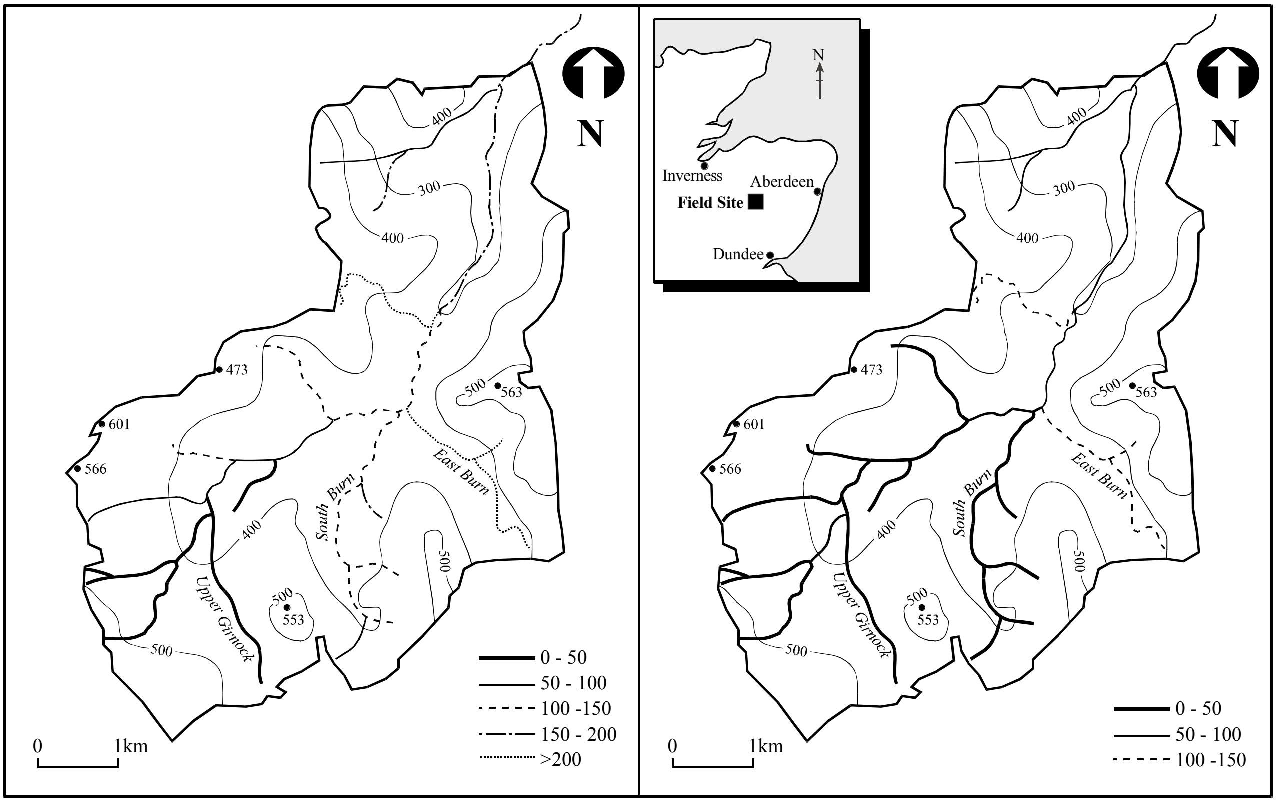
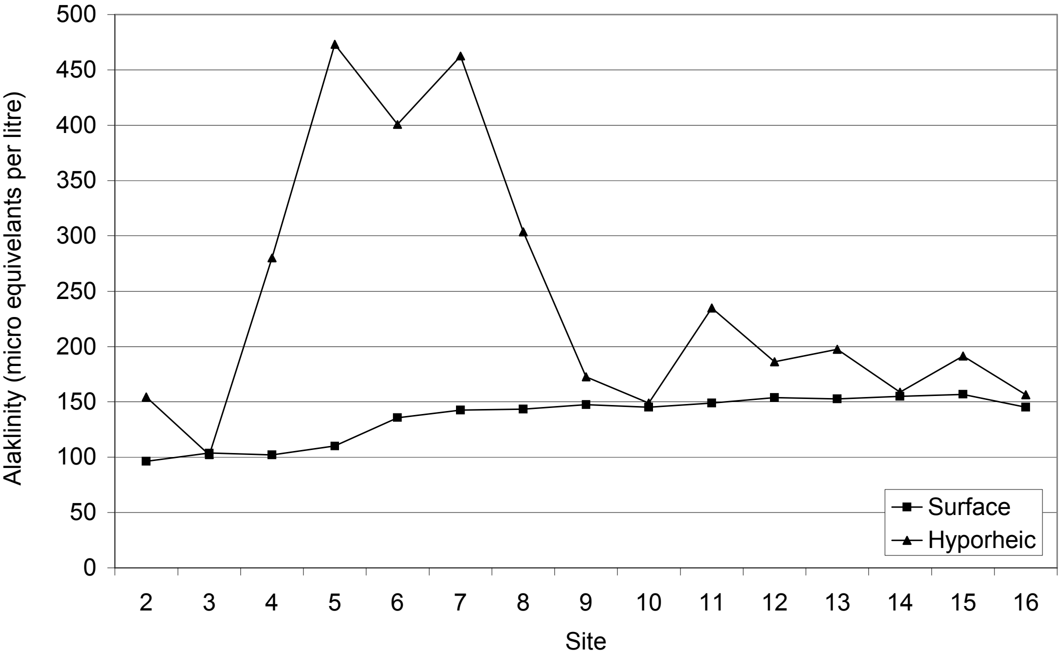

N
400
300
400
473
601
566
500
563
South Burn
East Burn
400
Upper Girnock
500
553
500
500
0 1km
0 - 50
50 - 100
100 -150
150 - 200
>200
N
Inverness
Aberdeen
Field Site
Dundee
N
400
300
400
473
601
566
500
563
South Burn
East Burn
400
Upper Girnock
500
553
500
500
0 1km
0 - 50
50 - 100
100 -150

Figure 5

a)


Alaklinity (micro equivelants per litre)
0
50
100
150
200
250
300
350
400
450
500
Site
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Surface
Hyporheic

b)

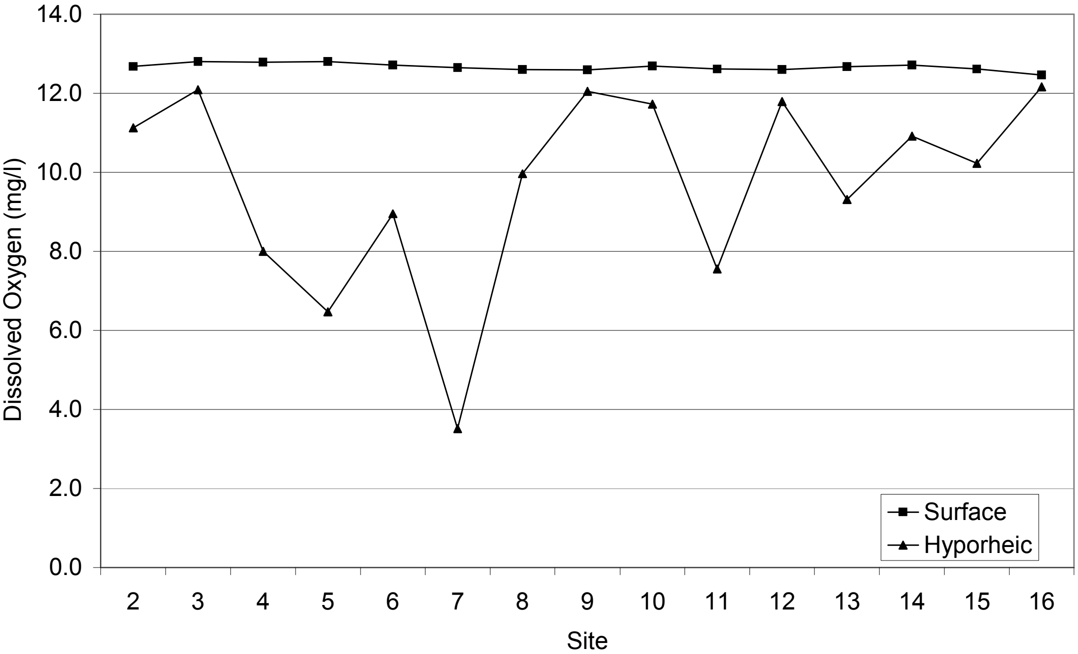

Dissolved Oxygen (mg/l)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Site
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Surface
Hyporheic

Figure 6

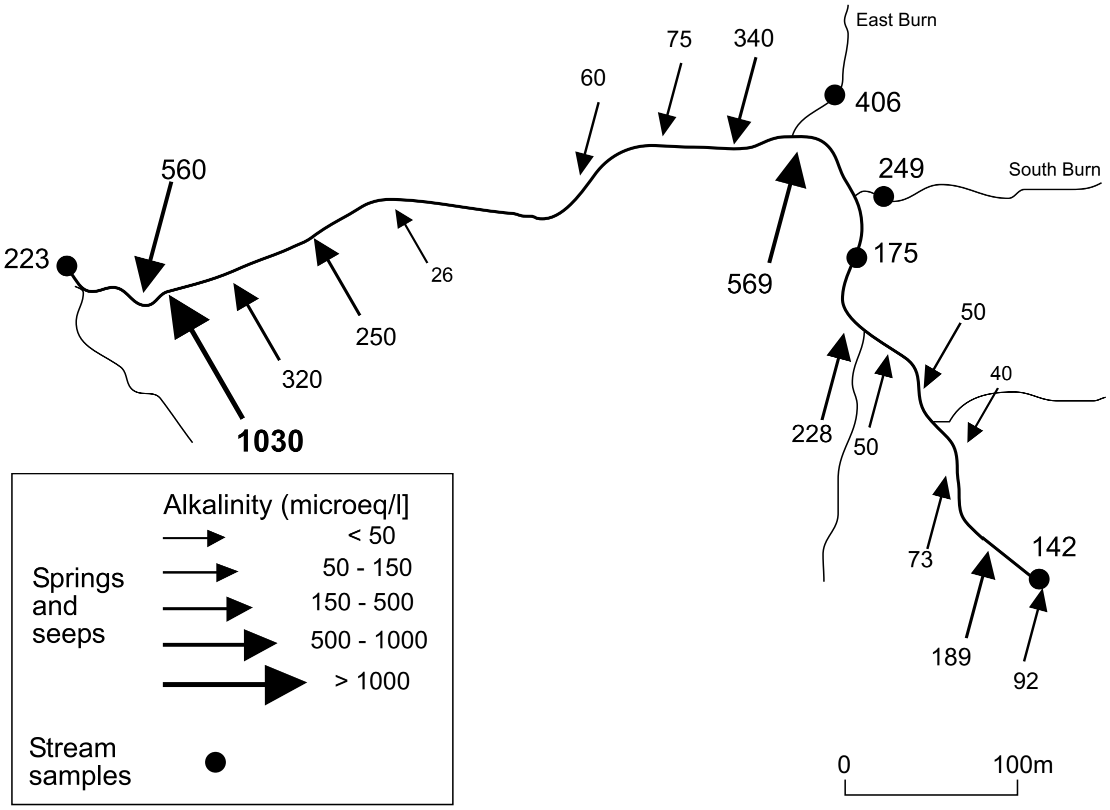
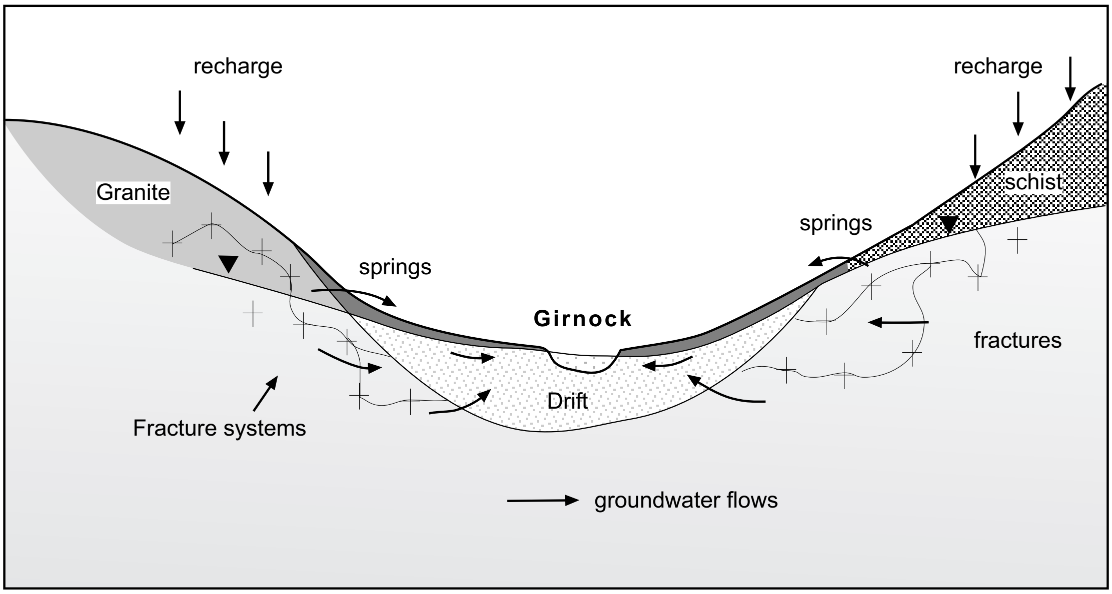

East Burn
South Burn
75
340
60
406
560
249
223
26
569
175
250
50
320
40
1030
228
50
73
142
189
92
Alkalinity (microeq/l)
< 50
50 - 150
150 - 500
500 - 1000
> 1000
Springs and seeps
Stream samples
0
100m

Figure 7


recharge
recharge
Granite
schist
springs
springs
Girnock
fractures
Drift
Fracture systems
groundwater flows