Characterising the Hyporheic Environment and Inferring Groundwater-Surface Water Interactions with Continuous Monitoring of Dissolved Oxygen Using Optical Sensors

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1. INTRODUCTION

The recent development of optical chemical sensors that facilitate continuous, accurate *in-situ* measurement of dissolved oxygen concentrations (Optodes) have revolutionised our ability to monitor the hydrochemistry of the hyporheic zone; an important ecological and biogeochemical hot spot in streams. Furthermore, when combined with traditional hydrometric approaches, Optodes have provided valuable insights into the dynamic nature of local groundwater – surface water exchange, which have major ecological implications, most notably in spawning habitats.

Salmonids deposit their eggs in open gravel structures - known as redds - to depths of up to 300mm in the hyporheic zone where consistently high streambed oxygen levels are essential for survival. Recent studies have shown that the discharge of chemically reduced groundwater characterised by low dissolved oxygen (DO) concentrations can adversely affect embryo survival and performance. It has long been recognised that the inaccessable, complex and dynamic nature of the hyporheic zone poses particular problems in terms of sampling protocols and methodology. Previous field-based studies of hyporheic DO and embryo survival have employed low frequency sampling strategies that often involve abstraction (*ex-situ* sampling) of large water volumes integrating over an indeterminate volume of streambed, with unknown recharge or equilibration times. This potentially risks failing to characterise important high resolution 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 (in this example salmonid ova). *In-situ* measurements (e.g. Malcolm *et al*., 2006) have the benefit of providing high resolution temporal data with minimal sampling disturbance, but financial constraints often dictate that sampling at fine spatial resolution is impractical. Furthermore, there are concerns 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. Combining variations of traditional (*ex-situ*) hyporheic sampling methods with hydrometric data and modern sensor technology allows improved characterisation of the hyporheic environment and understanding of the processes controlling oxygen concentrations; a pre-requisite for understanding hyporheic ecology.

This poster reports the findings of a two year study of hyporheic dynamics in an upland salmon spawning stream in Scotland. Hyporheic dynamics are characterised using hydrometric and streambed water quality data. The hydro-ecological importance of sampling at appropriate temporal and spatial resolutions is demonstrated using high temporal resolution (15-minute) optode data. Comparability between traditional *ex-situ* sampling methods and optode data is demonstrated through method comparison. The ecological importance of the findings is discussed with reference to salmonid embryo survival.

Our specific objectives are:
1. To characterise hyporheic hydrochemistry at fine temporal and spatial scales during the period of time between salmon spawning and embryo hatch;
2. To use high resolution hydrometric data together with streambed optode data to infer the influence of local GW-SW interactions on DO;
3. To assess the hydro-ecological importance of sampling at appropriate temporal and spatial scales;
4. To compare *in-situ* and *ex-situ* sampling methods and thereby assess inter-comparability;
5.To assess the ecological importance of the findings of this study in the context of salmonid embryo survival.

2. STUDY AREA, DATA AND METHODS

- Study site: Girnock Burn catchment, a montane, 30km² sub-catchment of the river Dee in North East Scotland (Fig. 1).
- Geology: granitic and metamorphic rocks
- Groundwater drains through bedrock fractures and various glacial and paraglacial drifts, which cover much of the catchment, contributing 25-30% of annual runoff.
- Annual rainfall: ca. 1100mm per annum; mean annual runoff ca. 700mm.

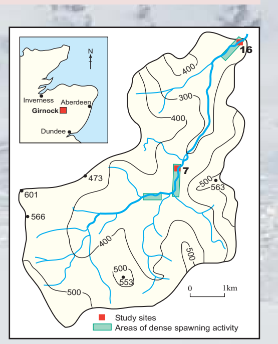

Figure 1: Map of Girnock Burn showing study locations, Sites 7 and 16, and areas of major spawning activity.

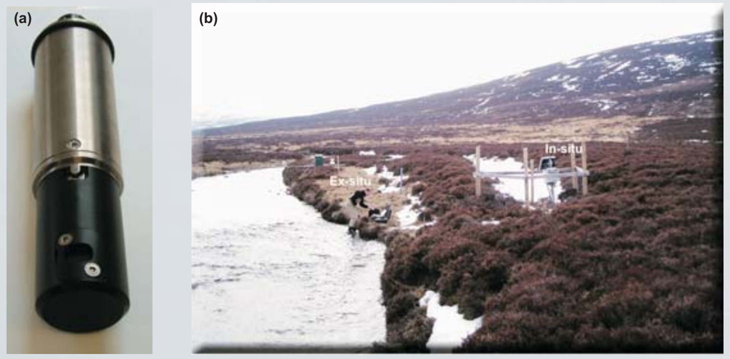

Plate 1: (a) Plate 1 Aanderaa™ DO Optode with analogue converter;
(b) Installation in the field.

- Year 1 (2004-05), single groundwater influenced site studied (S7). Year 2 (2005-06), two contrasting sites were monitored (upwelling groundwater (S7) and downwelling surface water (S16))
- At each site: Aanderaa™ 3830 optodes (Plate 1a) with 0-5V analogue converters (connected to Campbell™ CR23x dataloggers) recorded DO levels (%sat) and temperature in stream and in hyporheic water at depths of 150 and 250mm in stream bed; 30 second sampling, average values ogged at 15 minute intervals
- At spawning time vertically stratified cylindrical arrays (seperated every 25mm) were inserted into pre-prepared inserts within artificial redds immediately adjacent to optodes giving egg burial depths of 25, 50, 75, 100, 125, 150, 175, 200, 225 and 250mm beneath the streambed.
- Small volume (25ml) spot samples taken from each of the egg chambers provided high spatial resolution assessment of DO, electrical conductivity and temperature from within vertically stratified incubation chambers (Fig. 2) using traditional *ex-situ* sampling. This also allowed comparisonof *in-situ* versus *ex-situ* measurements
- *Ex-situ* measurement of DO and temperature using a 2mm diameter DO (optode) micro-sensor and thermistor connected to a Pre-Sens™ Fibox3 oxygen meter
- In year 1 local GW-SW interactions were assessed using hydraulic head data obtained from piezometers at depths of 38 and 70cm using Eijkelkamp™ Diver pressure transducers with integrated loggers and thermistors
- Chambers and optodes excavated from the stream bed at estimated hatch time; live and dead eggs were counted to provide percentage survival rates.

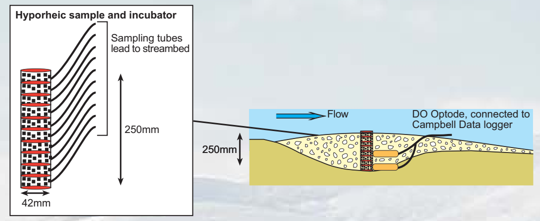

Figure 2: Sampler design and installation.

3. RESULTS

3.1 Hyporheic dynamics

- Study of S7, groundwater influenced site, during 2004-05. Changes in DO are plotted in relation to discharge and hydraulic gradient (Fig. 3)
- Early period characterised by negative hydraulic gradients and high streambed oxygen concentrations
- Following catchment re-wetting, increasingly positive hydraulic gradient (upwelling) results in low DO episodes.
- Hydraulic gradient exhibited consistent patterns of event based response: at event peak hydraulic gradient became increasingly negative; on recession limb increasingly positive hydraulic gradients
- Changes in hydraulic gradient: result from changes in the relative differences in stream stage and riparian water table elevation
- Although patterns of hydraulic gradient were consistent among events, the magnitude of gradients and changes in hyporheic water quality were variable
- Follow up work in 2005-06 allowed comparison of DO at sites with contrasting GW-SW interactions. At S16 (Fig. 6b) hyporheic zone dominated by surface water inputs throughout study and consequently characterised by high DO throughout. S7 (Fig. 6d) was again characterised by temporally variable GW inputs and rapidly changing hyporheic DO concentrations.
- 2005-06: method developed to obtain vertically stratified samples at fine spatial scales (25mm resolution) from egg stacks using small volume samples (Fig. 4)
- Data obtained from SW dominated (S16) and groundwater influenced (S7) sites
- S16 characterised by vertical homogeneity of DO in spot samples (Fig. 4a)
- S7 characterised by temporally variable DO that on occasion shows fine scale vertical stratification across distances of ca. 2.5-5.0mm (Fig. 4b). Indicates shifting boundary layer between GW and SW rather than broad hyporheic mixing zone.

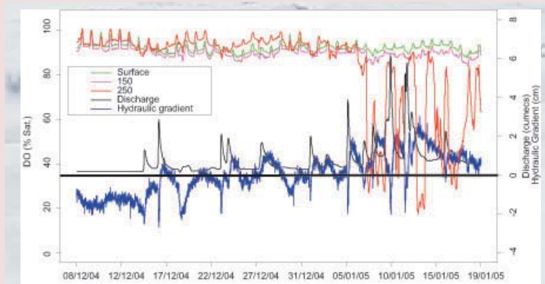

Figure 3: S7-DO concentrations in surface and hyporheic water (150 and 250mm) relative to discharge and hydraulic gradient. Streamward gradients are indicated where hydraulic gradient exceeds 0 (solid line).

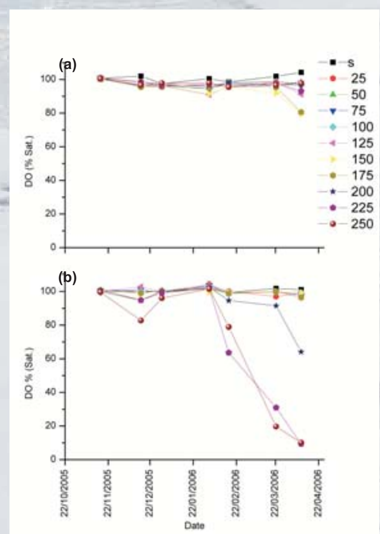

Figure 4: Temporal and spatial variability of dissolved oxygen at S16 (a) and S7 (b) in surface and hyporheic water at depths ranging from 25-250 mm, separated at 25mm intervals as revealed by approximately fortnightly sampling.

3.2 The importance of sample resolution in characterising hyporheic water quality

- Continuous hyporheic water quality data (300mm) were used to demonstrate theeffect of traditional sampling strategies using 100 random repeat samples (Fig. 5)
- 15 minutes time series data to show loss of information and resulting uncertainty that would have occurred had samples been collected at daily,weekly, fortnightly or monthly intervals that are common in hyporheic studies (Fig. 5).
- Coarser sampling frequencies miss much of the variability and extremes in hyporheic DO, particularly biologically important low DO episodes
- Fine scale spatial variability of hyporheic water quality (Fig. 4) demonstrates problems of using large volume samples to characterise the small scale hyporheic environment experienced by hyporheos.
- Biological inferences made on the basis of low spatio-temporal resolution sampling have the potential to be highly misleading

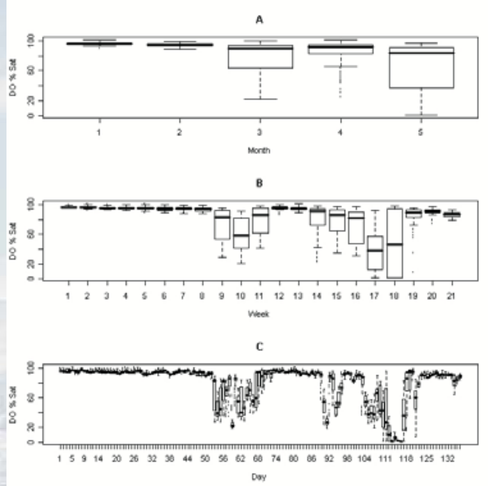

Figure 5: The effect of sampling frequency on observed hyporheic DO concentrations at 250mm.

3.3 Comparison of *ex-situ* and *in-situ* measurements

- Spot samples of DO were compared with continuous data from the optodes at Sites 7 and 16 (Fig. 6)
- Two methods generally comparable for a given sampling occasion and depth
- Optodes were not providing unrepresentative micro-scale data
- Optodes at S7 show threshold like behaviour in terms of groundwater connectivity

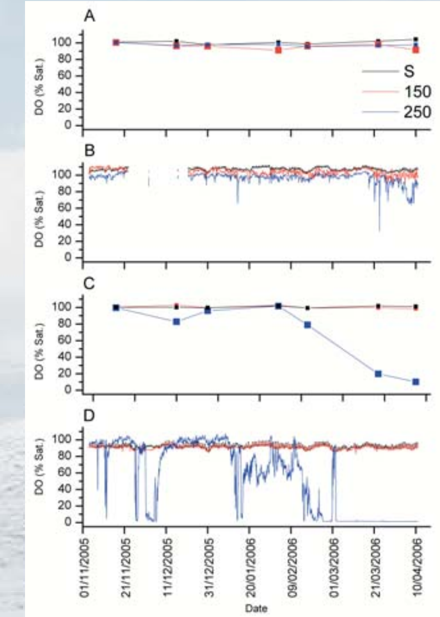

Figure 6: A comparison of spot and continuous DO data at S16 (A, B) and S7 (C,D). Data is shown for depths where comparable continuous and spot samples were available.

Table 1 Frequency of hyporheic oxygen sampling in previous studies of salmon spawning habitat. Where sampling frequency has not been explicitly stated, it is derived from figures or sample numbers in a specified period.

Author	Sampling Method (Measurement method)	Sample Volume	Sample depth (m)	Sample Frequency
Malcolm *et al.*,2006	*In-situ* (Aanderaa DO optode)	N/A	0.15, 0.3	30 seconds, averaged every 15 minutes
Groves and Chandler (2005)	Burried incubators with sampling tubes and piezometers. (Flow-through cell and YSI DO electrode)	3* dead volume discard 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 discard 200ml sample	0.2 - 0.3	Fortnightly
Bernier-Bourgault and Marmonier (2002)	Sampling pipe inseted on sampling date (YSI 57 DO electrode)	Not stated	0.05 - 0.15	Not stated
Bowen and Nelson (2002)	Variable depth hyporheic sampling pipes (Unspecified multi-parameter meter including DO electrode)	Not stated	0.3, 0.46	2 occasions, one month apart
Ingendahl (2001)	Flexible sampling tube (Portable DO electrode)	60ml discard 60ml sample	0.1, 0.2, 0.3	Fortnightly
Peterson and Quinn (1996)	Sampling tube (titration)	Dead volume discard 185ml sample	Variable, depending on egg burial depth	Weekly to fortnightly
Sowden and Power (1985)	Mini-piezometer (YSI 54 DO electrode)	150ml sample	0.15	Approximately monthly
Ringler and Hall (1975)	Standpipe (titration)	60ml	0.25	3* per week
Coble (1961)	Standpipe (not stated)	37ml	0.25	Not stated

5. CONCLUSION

- Previous hydro-ecological studies: varying sampling strategies that are generally of much lower resolution than is required to characterise the hyporheic environment (Table 1)
- Typical sampling strategies include weekly, fortnightly, monthly or in some cases only single samples
- Optical-chemical sensors revealed rapidly changing GW-SW interactions and associated hyporheic DO concentrations in a way that traditional *ex-situ* sampling at weekly or fortnightly intervals could not
- Previous hydro-ecological studies typically sample a large water volume, which equates to a large but indeterminate volume of streambed
- Use of DO micro-sensor allowed small volume water samples to be obtained that show high spatial variability not previously realised through tradition *ex-situ* sampling
- Fine resolution *ex-situ* measurements were comparable with data obtained from the *in-situ* optodes demonstrating that the methods could be used together in stratified sampling programme and that optodes were not characterising an unrepresentative micro-environment
- Additional information gained was found to be fundamentally important to identify nature and significance of frequency and magnitude of changes in hyporheic processes, including changes in GW-SW interactions and water quality and to hydroecological interpretation
- Hyporheic DO varied depending on local GW-SW interactions
- Similar hydrological events revealed variable hyporheic responses depending on antecedent conditions (state-dependant)
- Need to re-assess the biological interpretations of previous water quality studies of the hyporheic zone as they do not adequately characterise the temporal and spatial variability of hyporheic water quality and thus do not characterise the environment experience by the hyporheos.

REFERENCES

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