Algal community diversity in relation to water source in an alpine stream

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ABSTRACT
Aquatic ecosystems are often used to evaluate climate and land use change. However, these ecosystems are frequently sensitive to minute changes in water source. In this study the influence of groundwater on the benthic algal community within a single stream reach of Opabin Creek, British Columbia, was examined. Diatom diversity declined downstream of lower-temperature, higher electrical conductivity groundwater. Across the stream, a distance of several metres, mixing of groundwater was mirrored by gradations in algal communities.

RÉSUMÉ
L'utilisation des écosystèmes aquatiques dans les lignes de partage alpestres pour évaluer les changements dans le climat et l'utilisation de la terre exige un compréhension amélioré de leurs sensibilités aux facteurs tels que la source et les voies d'eau. Dans cette étude, l'influence de la décharge d'eaux souterraines sur la communauté d'algues benthique dans un section simple du ruisseau Opabin, en Colombie Britannique, a été examinée. La diversité de diatomée a diminué en aval de la décharge des eaux souterraines avec une plus basse température et une conductivité électrique plus élevée. À travers le ruisseau, une distance de plusieurs mètres, un gradient dans les propriétés de l'eau à cause du mélange des eaux souterraines a été reflétée par une gradation dans la communauté d'algues.

1 INTRODUCTION

The effects of changes in climate and land use on mountain hydrology have important implications for water resources, power generation and wildlife habitat, both locally and in surrounding lowlands serviced by mountain rivers or groundwater. Changing climatic patterns may influence the balance of water inputs (rain, snow melt, glacier melt, condensation) and outputs (evaporation, transpiration, sublimation, river runoff, groundwater outflow). Land use may influence water transport and storage within watersheds, as well as transpiration losses. Effects on the hydrology may include changes in the magnitude and seasonality of stream flows (Barnett et al., 2005), in reservoir storage and to water quality, including temperature, chemistry and dissolved nutrients.

Aquatic ecosystems in alpine environments may act as sensitive indicators to such hydrologic changes (Hauer et al., 1997, 2007; Rott et al., 2006). The benthic algal community may be an especially useful indicator as it provides much of the foundation for alpine stream foodwebs and due to the relative ease in sample collection. They can also be highly sensitive to water quality changes. For example, diatoms can be influenced by even small (0.3 pH units) pH changes in lakes and have, in fact, been used to estimate the pH history of lakes, based on lake bed fossils (Renberg and Hellberg, 1982). In addition, Rott et al. (2006) noted a considerable reduction in algal diversity with a greater portion of glaciation within a catchment, though the threshold for the glaciation effect differed between algal groups. Benthic algae assemblages are also known to differ between different types of streams, such as those dominated by glacial melt or sourced by groundwater springs (Ward, 1994; Robinson and Kaweka, 2005; Rott, et al., 2006, Brown, et al., 2006, Brown, et al., 2007). For example, massive *Hydrurus* growths of short duration have been associated with cold and high-flow glacial streams (Uehlinger et al., 1998, Robinson, et al., 2002). In addition, greater species richness has been noted for streams that serve as outlets to lakes (Hieber et al., 2002).

Field studies in mountainous areas over the past decade have shown that the groundwater contribution to high-elevation streams (Campbell et al., 1995; Ward et al., 1999; Michel et al., 2000; Sueker et al. 2000; Liu et al., 2004; Huth et al., 2004) and lakes (Clow et al., 2003; Gurrieri and Furniss, 2004; Hood *et al.*, 2006; Roy and Hayashi, 2008a) is often substantial. Differences in the groundwater contribution to streams have been linked to spatial variability in aquatic habitats. For example, Ward et al. (1999) noted differences in hydrological and chemical properties between what they classified as groundwater channels and other types of channels of the Val Roseg flood plain in the Swiss Alps, with additional changes in the channel system characteristics over time. These spatial and temporal differences were associated with a wide variation of habitats within the flood plain. Also, Robinson and Kawecka (2005) showed that within primarily glacial-fed streams and lakes, longitudinal gradients along lake chains affect diatom assemblages. This was likely partly a result of groundwater contributions. However, they noted that the interaction of lake chains with landscape features can make it difficult to separate out the effects of lake inlets, outlets, chemical changes and water sources.

While much of the previous research on alpine aquatic ecosystems has focused on comparing streams of different types (e.g. Ward, 1994; Brown et al., 2003), the influence of groundwater discharge at the reach-scale and below has received much less attention. However, it may lead to greater heterogeneity in stream conditions, which may affect biodiversity and community resiliency to change. Thus, in this study, the effect of groundwater discharge from a large spring to a single alpine lake-outlet stream was evaluated, with a focus on changes in diatom and benthic macroalgal assemblages both along the short stream reach and across the stream near the discharge location.

2 STUDY SITE

This study was conducted in the alpine zone of the Opabin sub-basin, which is part of the Lake O'Hara watershed (Hood *et al.* 2006) in the Canadian Rockies, British Columbia, Canada (latitude 51 ° 21'N; longitude 116 ° 20'W). The site is at an elevation of approximately 2220 m.a.s.l., with average annual temperature and precipitation estimated as -1℃ and around 1000-1200 mm respectively (J. Hood, personal communication). A few small glaciers, including Opabin Glacier, are located at the south end of the sub-basin and are surrounded by an intermixed proglacial moraine-talus debris field (Fig. 1).

The bedrock is primarily composed of thickly bedded quartzite and quartzose sandstone, with interbedded shales, of the Cambrian Gog Group. Carbonate rocks of the Mt. Whyte, Cathedral, Stephen and Eldon Formations are found at the summits of most of the surrounding peaks (Lickorish and Simony, 1995; Price et al., 1980), and this material is also present in the talus and moraine debris.

Hungabee Lake is disconnected from the moraine-talus field and is the source of the Hungabee outlet stream, which flows towards a moraine ridge that makes up the far end of the proglacial moraine-talus field (Fig. 1). The stream fans out at the moraine's rocky edge and then flows westward along it until entering a small pond (Fig. 1). Groundwater discharges along the edge of the pond over a length of about 30 m at the base of the moraine. Location GW3 is in the middle of this discharge zone, and generally represents the average properties across it (Roy and Hayashi, 2008b). Part of this water is likely sourced from Opabin Lake (Roy and Hayashi, 2008b), which abuts the proglacial moraine further up-valley (Fig. 1). The discharge area may be considered a large spring. The stream exiting the pond is referred to as upper Opabin Creek (UOC).

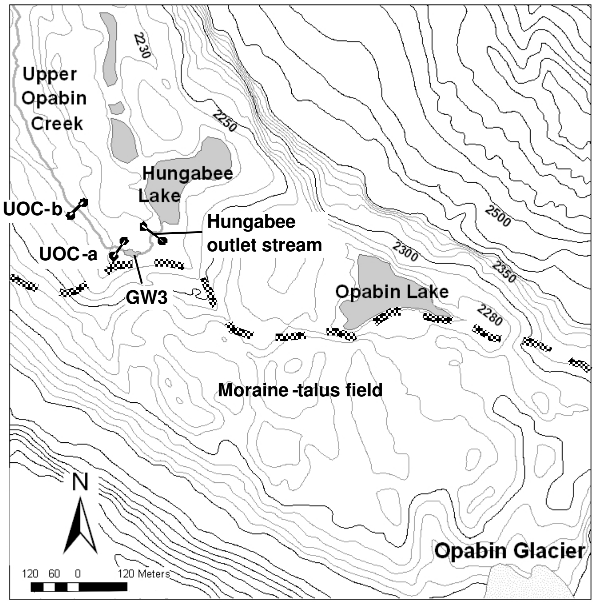

Figure 1. Map of the study site and surrounding area, with monitoring and sampling locations indicated.

3 METHODOLOGY

Algae samples and stream measurements were collected between 25 May and 4 October, 2006. Stream discharge was measured for the Hungabee outlet stream and two positions on upper Opabin Creek: UOC-a, at the outlet of the pond, and UOC-b, about 100 m downstream. Discharge was calculated using the area-velocity method from manual measurements made using a hand-held propeller flow meter (Global Water FP101) with an estimated uncertainty of 4-9 % (Hood *et al.*, 2006). Continuous stream stage measurements were obtained for the Hungabee outlet stream and UOC-b location using pressure transducers (Geokon, 4500AL/V) placed in stilling wells and connected to data loggers (Campbell Scientific, CR10X). Thus, a stage-discharge rating curve was developed for these two locations to calculate continuous stream discharge. The root-mean-squared (RMS) error values associated with the rating curves represented 12% and 9 % of average flow for the Hungabee outlet stream and UOC-b location, respectively.

Algal samples were collected from the five sites listed below (see also Figure 1) on 6 June, 25 July, 9 August, 23 August, and 19 September of 2006.

1. Hungabee outlet stream, depths of 0-20 cm
2. GW3, the centre of the groundwater discharge area, depths of 0-40 cm
3. UOC-a East, which was water flowing along the east side of UOC-a, at depths of 3-10 cm
4. UOC-a Middle, which was water from the center of UOC-a, at depths of 15-35 cm

5. UOC-a West, which was water from the west side of UOC-a, at depths of 5-20 cm

The first two locations can be considered as representing the two source waters for upper Opabin Creek. The last three provide a cross-section of the stream exiting the pond (Fig. 1) where the two sources come together.

To characterize benthic algal assemblages, algae was collected by placing a 24 x 36 mm template on three randomly selected rocks and scraping each rock for 20 s. The resulting material was stored in a cooler with ice during transport to the laboratory, where it was preserved in 10% formalin for later identification. Identification of algae to genus was by light microscopy at 400X, and diatoms were identified to species by light microscopy at 1000X. For each algal sample, all larger algae were identified, and two subsamples were taken for diatom identification. The first 25 diatoms viewed in each subsample were identified to species using, initially, Wehr, et al. (2003), then Patrick and Reimer (1966) and the online resource SilicaSecchiDisk (Silver, 2008), so that 50 diatoms were identified from each sample. To avoid bias in diatom identification, all sample collection vials were coded in the field, and the person identifying the diatoms was not present in the field and only given access to the code after all diatoms were identified. Shannon's index of Diversity and Shannon's index of Evenness were calculated for the diatom species only, by the method described in Bowden, et al., 2007.

Water temperature, pH and electrical conductivity (EC) were measured at water sample locations using hand-held meters. Measured EC values were standardized to 25℃ (Hayashi, 2004).

4 RESULTS AND DISCUSSION

Stream discharge measurements for 2006 are plotted in Figure 2. The discharge of upper Opabin Creek reached 0.8 $m^3 s^{-1}$ during peak snow melt and declined to about 0.1 $m^3 s^{-1}$ in late September; a similar pattern was noted in 2005 (Roy and Hayashi, 2008b). Meanwhile, discharge of the Hungabee outlet stream barely surpassed 0.05 $m^3 s^{-1}$ during peak spring flows, and remained below 0.01 $m^3 s^{-1}$ for the remainder of the summer. The difference between the two hydrographs illustrates the large contribution of groundwater from the discharge area to upper Opabin Creek throughout the summer field season.

The electrical conductivity (EC) and temperature of the discharging groundwater were much higher and lower, respectively, than that of the Hungabee outlet stream (Fig. 3). The groundwater likely attained more dissolved minerals from the carbonate materials found in the moraine around Opabin Glacier (Fig. 1), and potentially longer travel times through the subsurface. The pH was consistently about 8.2. The large variation in EC across the stream has been attributed to the presence of multiple distinct groundwater systems (Roy and Hayashi, 2008b). The low and constant groundwater temperature may indicate contact with buried ice or loss of heat to deep subsurface materials. The Hungabee outlet stream water reflects the properties of its source lake, which is shallow and fed by streams and groundwater associated with more inert quartzite and shale materials. The pH ranged from 6.9 to 7.6. Lake outlet streams tend to have higher temperatures than other types of streams (Heiber et al., 2002).

Water properties EC and temperature varied across the stream at the UOC-a location between those of the Hungabee outlet stream and the highest values measured for the groundwater discharge (Fig. 3). There were only minor differences in pH, with most readings around 8.2, except for values between 6.9 and 7.8 for UOC-a East through June and early July. This gradation of properties indicates that mixing of the two sources is incomplete exiting the pond. Stream water at UOC-a East was more similar to the Hungabee outlet stream, especially in the early summer. This may be due to higher flows of the Hungabee outlet stream (early summer), preventing the encroachment of mixing groundwater at the east side of the stream bank. Meanwhile, the stream water at UOC-a West and UOC-a Middle appear to be largely dominated by groundwater.

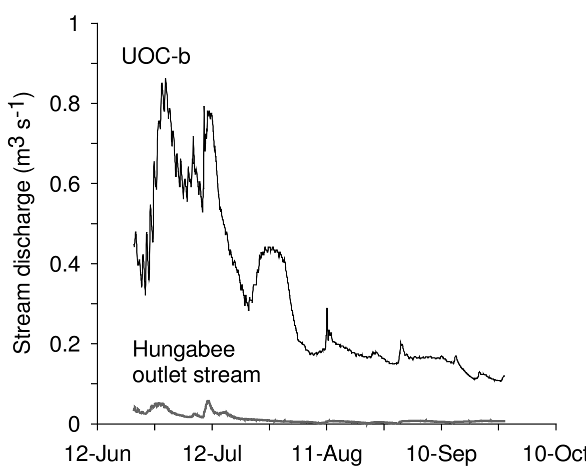

Figure 2. Stream discharge measurements from the 2006 field season for upper Opabin Creek, location UOC–b (Fig. 1), and the Hungabee outlet stream.

A total of 1,252 diatom frustules were examined and identified to the lowest practical taxonomic level, resulting in identification of 49 different species. Only eight other algal/cyanobacterial genera were noted to be present. These included the Cyanobacteria ('blue-green algae') *Anabaena*, *Lyngbya* and *Oscillatoria*, the thallic Chrysophycean (golden) alga *Hydrurus*, the green algal desmids *Cosmarium* and *Closterium*, and the filamentous green algae *Oedogonium* and *Spirogyra*.

The algae at the Hungabee outlet stream site differed from the algae at the groundwater discharge site, GW3. At Hungabee outlet, the dominant green filamentous algae was *Oedogonium sp.*, and the dominant diatom was *Tabellaria flocculosa* (Table 1). Neither of these organisms was found at any other site. Species richness, diversity and equitability were also highest at the Hungabee outlet location (Table 1), which is consistent with the observations by Hieber et al. (2001, 2002), who reported greater diversity for alpine streams that exit lakes. Conversely, the chrysophycean alga *Hydrurus foetidus* was found at all other sites except Hungabee outlet. A massive bloom of *H. foetidus* occurred downstream of the UOC-a location in late August, encompassing the whole width of the stream to UOC-b. *This chrysophyte* is frequently dominant in cold streams, and commonly found in alpine streams (Rott, et al., 2006, Wellnitz and Rader, 2003, Hieber, et al., 2001). Although it is reported to be often associated with glacially-fed streams (Hieber, et al., 2001), in this system it was associated with groundwater discharge from the moraine-talus field (Fig. 1).

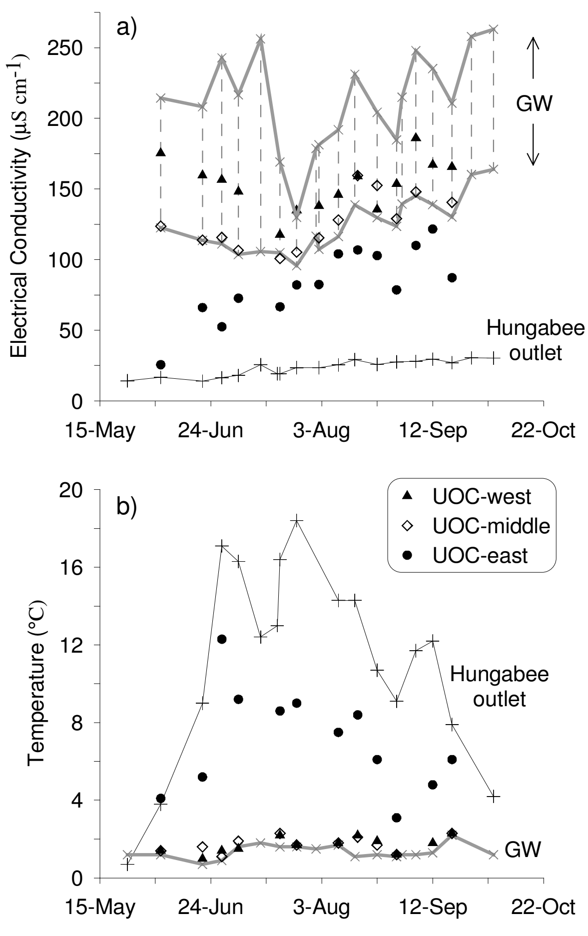

Figure 3. 2006 stream and groundwater data for a) electrical conductivity (EC), and b) water temperature. Note the large spatial variation in EC for the groundwater spring, while temperature was spatially consistent.

At the UOC-a site (Fig. 1), downstream of the groundwater discharge area, the algal community varied substantially across the stream. The East side sampling location exhibited the greatest diversity and equitability (Table 1), while the Middle location had the lowest values. In comparing the assemblage of species at these sites to the source waters, the East location was more similar to the Hungabee outlet stream, while the Middle and West location were more similar to GW3. In fact, regression analysis of Shannon's index of diversity for all five sampling locations showed a significant negative correlation ($p=0.001$; R^2 of 0.370) with EC, which can be considered a rough proxy for the proportion of groundwater in the stream. That is, where EC was lowest, diversity was highest, and vice versa. An exception to the trend of negative correlation of EC with diatom diversity was the Middle location. Despite its lower EC than the West location, it is likely that this stream water was predominantly groundwater, similar in composition to the GW3 location (Fig. 3a). This site also had relatively high stream velocities and was consistently dominated by the diatom *Diatoma hiemale,* which is known to favor high velocity streams (Sabater and Roca, 1990). There was no significant correlation between EC and Shannon's index of equitability ($p=0.044$; R^2 of 0.165), though the values were higher for Hungabee outlet and UOC-a East (Table 1).

In addition to the spatial variation described above, there were also temporal changes in algal assemblages in the mixing zone that may relate to changes in the contribution of groundwater. For example, *H. foetidus* did not appear at the UOC-a East location until late in the season, when the EC was approaching values similar to GW3. Similarly, the diatom *Diatoma vulgare* became the predominant diatom late in the season at UOC-East, -Middle, and -West (Fig. 3a).

These differences in alga community between source waters (i.e. Hungabee outlet stream and GW3) and the changes along this stream reach suggest that the discharge of groundwater to the stream is altering its algal community. In fact, it appears to be reducing the diversity of benthic algae downstream compared to upstream conditions.. Also of note, the substantial differences in algal assemblages across the stream in the mixing area of the two source waters (UOC-a), seemingly linked to the proportion of groundwater to original stream water, occurred over a distance of only a few meters. This shows that diatom and algal compositions are extremely sensitive to mixing of waters with different properties.

The diversity of diatoms found at the five sites in Opabin Creek is roughly in line with diatom diversity reported elsewhere. In a soft-water Wisconsin lake, diatom diversity was reported as between 2.77 and 3.85 (Hagerthey and Kerfoot, 2005), in springs in the Pyrnees mountains, diversity was reported as between 3.1 and 0.8, depending on several factors including pH and water velocity (Sabater and Roca, 1990). In Antarctic Tres Hermanos lake, diatom diversity was reported as between 1.0 and 2.8 (Unrein and Vinocur, 1999). In this study, the diversity for five sampling locations varied between 0.9 and 2.08 (Table 1), and the diversity for the entire stream reach was 1.28, which is on the low end, but well within, the ranges reported in the other studies.

Table 1. Predominant macroalgae and predominant and common diatoms in each reach of Opabin Creek from June through September 2006. Diatoms are in order from most to least common. The number in parentheses indicates the percentage of the total diatoms at that site accounted for by the species shown. Numbers do not add up to 100 as minor species (<5%) are not shown. Shannon's diversity index and Shannon's index of equitability are used to indicate diversity and evenness of diatom species only.

	Hungabee Outlet	UOC-a East	UOC-a Middle	UOC-a West	GW3
Predominant macroalga	*Oedogonium sp.*	*Oscillatoria sp.*	*Hydrurus foetidus*	*Hydrurus foetidus*	*Oscillatoria sp.*
Common macroalga / cyanobacteria	*Oscillatoria sp.*	-	*Oscillatoria sp.*	*Oscillatoria sp.*	*Hydrurus foetidus*
Number of diatom species (Species Richness)	62	45	24	32	21
Predominant diatom	*Tabellaria flocculosa* (24)	*Diatoma vulgare* (21)	*Diatoma hiemale* (59)	*Cymbella minuta* (53)	*Cymbella minuta* (66)
Common diatom	*Cymbella minuta* (14)	*Cymbella minuta* (20)	*Cymbella minuta* (20)	*Achnanthes lanceolata* (9)	*Navicula rhynchocephala* (9)
Common diatom	*Fragilaria capucina* (10)	*Achnanthes lanceolata* (18)	*Diatoma vulgare* (8)	*Diatoma vulgare* (9)	*Meridion circulare* (7)
Common diatom	*Navicula sp.* (6)	*Gomphonema olivaceoides* (5)	-	*Diatoma hiemale* (8)	*Navicula sp.* (5)
Common diatom	*Achnanthes lanceolata* (10)	-	-	*Fragilaria pinnata* (6)	-
Shannon diversity	2.08	1.60	0.73	1.06	0.9
Shannon equitability	0.85	0.68	0.39	0.62	0.53

5 CONCLUSIONS

Groundwater discharge dramatically changed the physical and chemical conditions of the stream, creating much higher flows, with greater velocities, and altering the stream water properties (e.g. higher EC, lower temperature, higher pH). Thus, the discharge resulted in increased longitudinal variation in stream properties. Because discharge occurred only along one side of the stream, there was also a gradient in the stream properties across the stream as a result of incomplete mixing of the two water sources. The gradient across the stream changed seasonally, a result of changing relative contributions of the two water sources.

The periphytic algal communities were distinctly different between the two water sources (i.e. lake outlet stream versus large groundwater spring). The groundwater discharge to the stream resulted in a change in the downstream algal community, including reduced algal diversity, but also a strong gradation in community structure across the stream in the mixing zone. These changes were strongly correlated with the stream water properties noted above. Thus, the algal community at this site displayed a strong sensitivity to changes in water source, in this case, the discharge of groundwater with much higher electrical conductivity, higher pH and lower temperatures than measured upstream. The changes occurred at the reach-scale and sub-reach (metre) scale. This suggests that the locations of groundwater discharge may affect the in-stream patchiness or transitions of benthic algae communities in alpine watersheds, and perhaps the supported invertebrate populations as well. These findings also have implications for algal sampling protocols in ecology studies. Finally, this sensitivity to groundwater discharge suggests that these benthic algal communities may be useful indicators of climate and land-use changes that affect mountain hydrology.

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