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Correcting whole-stream estimates of metabolism for groundwater input

Robert O. Hall Jr.[1] and Jennifer L. Tank[2]*
[1]Department of Zoology and Physiology, University of Wyoming, Laramie, WY 82071, USA
[2]Department of Biological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA

Abstract

Open-channel metabolism is commonly measured in streams, but these measurements may be strongly biased by small inputs of low-O_2 groundwater seeping into the study reach that will appear to increase community respiration (CR), but decrease gross primary production (GPP). We developed a new equation that considers groundwater inputs when calculating metabolism. When streamwater O_2 concentrations are much higher than groundwater O_2 concentrations, a small amount of groundwater input can substantially bias CR. For example, a 200-m, 100-L s^{-1} stream reach that increases in discharge by only 5% may overestimate CR by twofold. Unlike CR, the degree of bias for GPP is unaffected by O_2 concentration in groundwater, therefore it is easily calculated as a function of groundwater flux into the study reach. We applied this new correction for a cowpasture spring stream in Wyoming that increased in discharge by 50% over our study reach. Uncorrected CR was –18.8 g O_2 m^{-2} d^{-1} and GPP was 11.6 g O_2 m^{-2} d^{-1} in the spring stream; corrected CR was –11.4 g O_2 m^{-2} d^{-1} and GPP was 16.2 g O_2 m^{-2} d^{-1}. Our modeling and data show that ecosystem metabolism estimates are extremely sensitive to groundwater inputs, even inputs that are difficult to measure by using mass-balance of tracers. The largest unknown is the concentration of O_2 in groundwater when correcting CR. We suggest that investigators attempt to correct for the impact of groundwater on any stream where the inflows are detectable.

Howard T. Odum (1956) introduced the open-channel method of measuring metabolism in rivers almost 50 years ago, and it has recently been improved to increase its accuracy, precision, and ease of use. For example, using tracer gases we can empirically measure reaeration rates for particular rivers (Wanninkhof et al. 1990; Marzolf et al. 1994; Young and Huryn 1998), and automated recording oxygen meters are both precise and affordable. Consequently, this method has been recently applied to answer several questions about the relationship between metabolism and other metrics of stream ecosystem function (Young and Huryn 1999; Mulholland et al 2001; Hall and Tank 2003). Although the whole-stream metabolism technique is now easier to use, there are potential for errors when using this method (McCutchan et al. 1998). Recently McCutchan et al. (2002) addressed how groundwater inputs could bias estimates of metabolism. For example, substantial low-O_2 groundwater inputs into a reach will appear to increase community respiration (CR) and may strongly bias both CR and gross primary production (GPP) estimates.

Although a groundwater correction for metabolism is necessary, we do not believe that the approach supplied by McCutchan et al. (2002) appropriately corrects metabolism measurements for the effect of groundwater, and we supply an alternate method for correcting both GPP and CR estimates in streams with significant groundwater inflow. We demonstrate how much this correction alters estimates of metabolism for a strongly gaining spring stream in Wyoming, and we propose a potential threshold of groundwater input after which one needs to correct metabolism estimates in order to accurately calculate whole-stream metabolism.

Materials and procedures

Calculating groundwater-corrected metabolism—McCutchan et al. (2002) start with the following equation to describe oxygen

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*E-mail: bhall@uwyo.edu

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Table 1. Variables and units

Variable	Description	Units
m	Mass of oxygen in reach	g O_2
m_0	Mass of oxygen in reach at time 0	g O_2
m_t	Mass of oxygen in reach at time t	g O_2
Q_g	Groundwater discharge into study reach	m^3 min^{-1}
Q_s	Downstream discharge	m^3 min^{-1}
A	Reach area	m^2
z	Mean stream depth	m
k	Reaeration rate of O_2	min^{-1}
t	Time	min
Δt	Travel time of reach	min
C_g	O_2 concentration of groundwater	g O_2 m^{-3}
C_t	O_2 concentration of streamwater at time t	g O_2 m^{-3}
C_0	O_2 concentration of streamwater at time 0	g O_2 m^{-3}
C_{tD}	O_2 concentration of streamwater during day	g O_2 m^{-3}
C_{tN}	O_2 concentration of streamwater during night	g O_2 m^{-3}
S	Saturation concentration of oxygen	g O_2 m^{-3}
M	Metabolism	g O_2 m^{-2} min^{-1}
CR_u	Uncorrected community respiration	g O_2 m^{-2} min^{-1}
G	Groundwater O_2 correction term	g O_2 m^{-2} min^{-1}
CR_c	Corrected community respiration	g O_2 m^{-2} min^{-1}
NDM_u	Uncorrected net daytime metabolism	g O_2 m^{-2} min^{-1}
GPP_u	Uncorrected gross primary production	g O_2 m^{-2} min^{-1}
GPP_c	Corrected gross primary production	g O_2 m^{-2} min^{-1}
B	bias	

dynamics in a stream. Variable definitions and units are in Table 1.

$$\frac{dm}{dt} = C_g Q_g + MA + k(SAz - m) \tag{1}$$

This equation can be solved using an Euler approximation since O_2 data are collected on a discrete basis to give

$$m_t = m_0 + \left[C_g Q_g + MA + k(SAz - m_t)\right]\Delta t \tag{2}$$

Dividing both sides of the equation by reach volume (Az) and substituting C_t for (m_t/Az) and C_o for (m_o/Az) to get concentration and then solving for metabolism (M) gives the following equation:

$$M = z\left[\frac{C_t - C_0}{\Delta t} - k(S - C_t)\right] - C_g \frac{Q_g}{A} \tag{3}$$

We suggest that Eq. 3 is incorrect because the groundwater correction term ($C_g \frac{Q_g}{A}$) goes to 0 as C_g becomes 0, when in fact, if groundwater O_2 concentration (C_g) is 0, then the largest groundwater correction needs to be made because lowest O_2 groundwater will most strongly affect estimates of stream metabolism.

We believe that Eq. 1 needs to be modified to include fluvial fluxes of oxygen; missing from Eq. 1 is both the O_2 flux from upstream and the flux downstream. The open-channel oxygen method is essentially a short-term oxygen budget where one measures flows of oxygen into and out of a stream reach (Fig. 1). If there is no groundwater input, then discharge upstream and downstream cancel out, and only O_2 concentration is considered. With substantial groundwater inputs, it is necessary to account for fluxes measured as discharge × concentration. Additionally, we consider only O_2 concentration because the mass of oxygen will not really change from upstream to downstream, but the concentration will change. An equation that contains fluvial O_2 fluxes, where $Q_s - Q_g$ = upstream discharge, is (Fig. 1):

$$\frac{dC}{dt} = \frac{C_g Q_g}{Az} + (Q_s - Q_g)\frac{C}{Az} - Q_s \frac{C}{Az} + \frac{M}{Z} + k(S - C) \tag{4}$$

Q_s cancels to give

$$\frac{dC}{dt} = \frac{C_g Q_g}{Az} - \frac{Q_g C}{Az} + \frac{M}{Z} + k(S - C) \tag{5}$$

The term $-\frac{Q_g C}{Az}$ represents a loss of O_2 concentration in the reach that is a function of the dilution rate of the stream reach (1/t) times the concentration of O_2 in the streamwater.

Again, solving using the Euler approximation gives

$$C_t = C_0 + \left[\frac{C_g Q_g}{Az} - \frac{Q_g C}{Az} + \frac{M}{z} + k(S - C)\right]\Delta t \tag{6}$$

Rearranging gives the equation used to calculate groundwater-corrected metabolism.

$$M = z\left[\frac{C_t - C_0}{\Delta t} - k(S - C)\right] - (C_g - C)\frac{Q_g}{A} \tag{7}$$

The groundwater correction term, G, ($(C_g - C_t)\frac{Q_g}{A}$) gets more negative as C_g becomes lower than C_t, thus making more of a correction to instantaneous metabolism estimates via a net increase in metabolism (M). This equation is the same as Eq. 6 in McCutchan et al. (2003), however their equation is presented without derivation.

Estimating bias—We estimate bias for CR as

$$B_{CR} = \frac{CR_u}{CR_c} \tag{8}$$

where CR_c is corrected community respiration (calculated from Eq. 7) and CR_u is uncorrected community respiration. Given that $CR_c = CR_u - G$, this bias is estimated as

$$B_{CR} = \frac{CR_u}{CR_u - G} \tag{9}$$

where CR_u is uncorrected community respiration. Based on Eq. 9, we can estimate relative bias for CR for varying values of $C_g - C_t$, CR_u, and Q_g/A.

We calculate bias differently for GPP because unlike CR, bias for GPP does not depend on C_g, but only Q_g/A because C_g

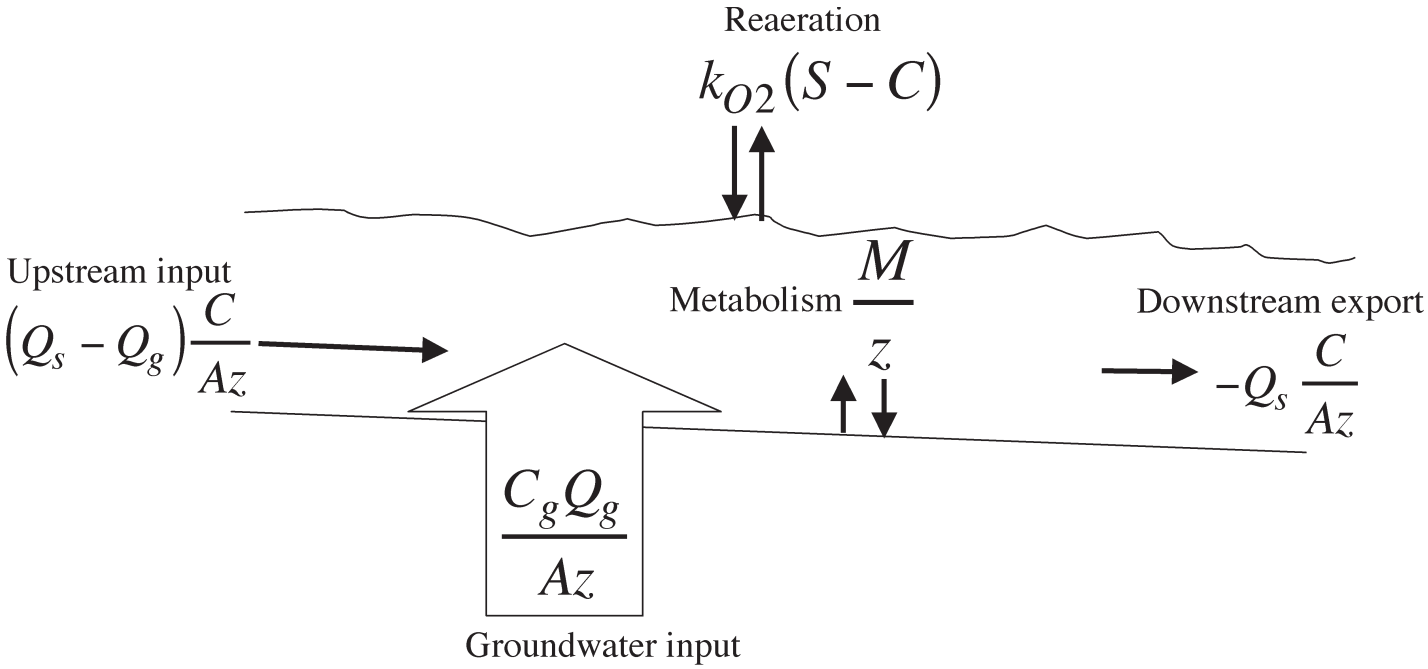

Fig. 1. Schematic of an oxygen budget for a stream reach, which corresponds to Eq. 4. Oxygen flux into and out of the reach is measured as concentration times discharge, though note that stream discharge cancels from the final equation. k_{O2} is calculated from a tracer gas releases (e.g., SF_6 or propane). Groundwater discharge is estimated based on dilution of a conservative tracer. Groundwater O_2 concentration is estimated based on a reach-scale budget where groundwater inputs are high (*see* text for details).

cancels out of the equation (*see* below). Also, it is difficult to simply calculate bias for daily GPP because it is integrated through time, but we can easily calculate bias for instantaneous GPP. Given that GPP is the difference between net daytime metabolism (NDM) and CR, groundwater-corrected GPP is calculated as

$$GPP_c = \left(NDM_u - \left(C_g - C_{tD}\right)\frac{Q_g}{A}\right) - \left(CR_u - \left(C_g - C_{tN}\right)\frac{Q_g}{A}\right) \quad (10)$$

where C_{tD} is the O_2 concentration during the day at the time interval measured, and C_{tN} is the average of the nighttime oxygen concentrations.
Eq. 10 simplifies to

$$GPP_c = NDM_u - CR_u + \left(C_{tD} - C_{tN}\right)\frac{Q_g}{A} \quad (11)$$

Note that C_g cancels from the equation, so that corrected GPP depends on the flux of groundwater into the reach and not the concentration of oxygen in that groundwater. Bias for GPP is thus calculated following Eq. 9 and Eq. 11 as

$$B_{GPP} = \frac{NDM_u - CR_u}{NDM_u - CR_u + \left(C_{tD} - C_{tN}\right)\frac{Q_g}{A}} \quad (12)$$

A field test—We provide an example of a groundwater correction of metabolism in a stream for which we measured open-channel metabolism during July 2003. Giltner Spring Creek is a gaining spring stream located in irrigated cow pasture on the Snake River Ranch in Wilson, Wyoming, USA. Most of the stream flow is derived from return flows from flood irrigation that last most of the summer. Shallow groundwater seeps into this stream throughout its length. Discharge at the top of the 180-m reach was 107 L s^{-1} and was 144 L s^{-1} at the bottom of the reach, therefore Q_g was 37 L s^{-1}. Given a 180-m study reach (mean width 5.7 m, area 1026 m^2), Q_g/A was 3.08 m d^{-1}. Riparian vegetation is pasture grasses with sparse willows, and with stable, grass-covered banks. The stream bottom is carpeted by macrophytes and filamentous algae. We chose an 180-m study reach that minimized groundwater input. This study reach was just downstream of an area of high groundwater input, where stream discharge doubled over 125 m.

We measured metabolism for 2 consecutive days following methods we have used previously on nearby streams (Hall and Tank 2003). Briefly, we measured O_2 concentrations and stream temperature at 10-min intervals at the top and bottom of Giltner Spring Creek using Hydrolab recording O_2 meters. We measured travel time as the time it took for a salt injection (*see* below) to reach 50% of its plateau concentration at the downstream station. We estimated reaeration rates of O_2 by bubbling in sulfur hexafluoride (SF_6), a tracer gas, for 90 min in conjunction with a NaCl injection (Wanninkhof et al. 1990; Hall and Tank 2003). We sampled SF_6 by equilibrating 45 mL water with 15 mL air in 28 syringe-collected water samples along a 550-m reach, and we measured it on a gas chromatograph with an electron capture detector (Cole and Caraco 1998). We corrected these SF_6 concentrations for dilution using the decline in Cl^- concentrations (*see* below), and we converted k_{SF6} to k_{O2}, based on the ratio of their Schmidt numbers (1.4) following Wanninkhof et al. (1990). Reaeration was low in Giltner spring (k_{02} at 20°C was 32 d^{-1}).

We measured Q_g as part of the SF_6 addition by continuously pumping NaCl as a conservative tracer in Giltner Spring. We added this solute 220-m above the metabolism reach, which ensured good mixing. Prior to the solute addition we collected 5 filtered water samples within each of three locations along the 180-m metabolism reach and 55-m upstream of the metabolism reach for measurement of ambient Cl^-. We also measured background electrical conductivity every 25 m. We then injected NaCl and following a plateau in conductivity measured conductivity and collected filtered water samples at each location. We measured Cl^- using ion chromatography and subtracted background Cl^- from plateau Cl^- for each point. Discharge at the top and bottom of the metabolism reach was measured by mass balance of the added chloride, and Q_g was calculated by difference.

Estimation of C_g can be difficult, but in Giltner Spring, there was a discrete area of groundwater input just above our study reach; we monitored oxygen concentrations at night above and below the groundwater inputs, which corresponded to a 55-m reach with 5.6 min of travel time. Groundwater inputs were large there (Q_g/A = 16 m d^{-1}). Given the drop in O_2 concentration along the reach during night (1.5 mg O_2 L^{-1}), an estimated CR of –11.4 g O_2 m^{-2} d^{-1} (based on our corrected value described below), and k_{02} at 20°C, we solved for C_g using Eq. 6. Using an estimated CR to calculate C_g is a circular analysis in that we are trying to estimate the true CR based on C_g. However in the case of the short reach that we used to estimate C_g, O_2 concentrations were much more driven by groundwater inputs than they were by metabolism.

Metabolism was calculated from field data using Eq. 7 using a two-station technique, where C_0 was the upstream O_2 concentration, and C_t was the downstream O_2 concentration. C was measured as the average value of C_t and C_0 (Young and Huryn 1998). We estimated CR as the average of the nighttime respiration values and GPP as the area under the curve of the diel increase in net metabolism.

Assessment

Controls of degree of correction—Bias for CR strongly increases with increasing difference between groundwater and streamwater O_2 concentrations, and with increasing vertical velocity of groundwater (Q_g/A) (Fig. 2). Bias = 2 means that uncorrected CR is twice as high as uncorrected, while B = 1.2 means that the uncorrected estimate is 20% higher than corrected. For example, when C_g is 8 mg O_2 L^{-1} less than C_t, CR_u is 10 g O_2 $m^{-2}d^{-1}$, and Q_g/A is 0.5 m d^{-1}, then the uncorrected metabolism estimate will be 1.7 times the corrected estimate, a substantial bias.

GPP is also biased; however, this bias is not a function of C_g, but rather the difference between day and night oxygen concentrations and groundwater discharge. Increasing Q_g/A and increasing difference between day and night oxygen concentration increase corrected GPP relative to uncorrected GPP (Fig. 2B).

To what degree are literature estimates of metabolism biased? We measured Q_g/A from some of our own data (Hall and Tank 2003) as the fractional decline in conservative tracer injected for 90 min into 11 streams. We estimated the fractional decline as (1 – background-corrected concentration of tracer at the downstream station/the background-corrected upstream concentration). This fractional decline was multiplied by stream discharge to estimate Q_g. Despite small increases in discharge along the study reach, Q_g/A was high enough (e.g., 0.2 m d^{-1}) in several of the streams to bias the metabolism estimate, provided C_g was very low (Fig. 2, Fig. 3). Mean Q_g/A was 0.45 m/d. However, we do not know what C_g was for any of these streams, so we can only estimate a maximum bias if we assume C_g = 0 mg O_2 L^{-1}. Estimates of Q_g/A from Hall and Tank (2003) correspond with those reviewed by McCutchan et al. (2002) where the mean for positive Q_g/A was 1.09 m d^{-1} and ranged from 0.04 to 4.1 m d^{-1}. Measures of Q_g/A from 8 streams across the US (data from Mulholland et al. 2001 and Webster et al. 2003) averaged 0.33 m d^{-1} and ranged from 0 m d^{-1} to 0.71 m d^{-1}. Groundwater inflow from Hall and Tank (2003) was not substantially different from those in other studies suggesting that the potential for bias is high even if groundwater accrual is low along the study reach.

We can, however, measure bias of GPP for the estimates in Hall and Tank (2003) because it is independent of C_g. Range of instantaneous bias was 0.72 to 1.01, with a mean of 0.95. This estimated instantaneous bias for our streams is not the same as the actual bias, because the estimated bias is only for the part of the day when instantaneous GPP is highest, and not the integrated value of GPP. Bias for integrated GPP was closer to 1 than that estimated from the NDM peak during the day, and ranged from 0.88 to 1.09. Taken together, we suggest that the GPP estimates from Hall and Tank (2003) were not substantially biased, and that bias for GPP is probably small in studies with low Q_g/A.

Application of the correction—High groundwater input gave Q_g/A of 3.08 m d^{-1}. This value was particularly high, relative to other studies (e.g., Mulholland et al. 2001), and required a substantial correction. Groundwater O_2 was 1.3 mg O_2 L^{-1}, close to anoxic, which will further increase bias (Fig. 2). Although we estimated CR to calculate C_g, in the case of the short reach that we used to estimate C_g, O_2 concentrations were much more driven by groundwater inputs than they were metabolism because Q_g/A was 5 times higher in this upstream reach than the metabolism reach. Indeed C_g was not particularly sensitive to varying metabolism. Using the corrected value of CR (–11.4 g O_2 m^{-2} d^{-1}), C_g was 1.3 mg O_2 L^{-1}, while using the uncorrected value (–18.8 g O_2 m^{-2} d^{-1}), the estimate of C_g increased to only 1.8 mg O_2 L^{-1}.

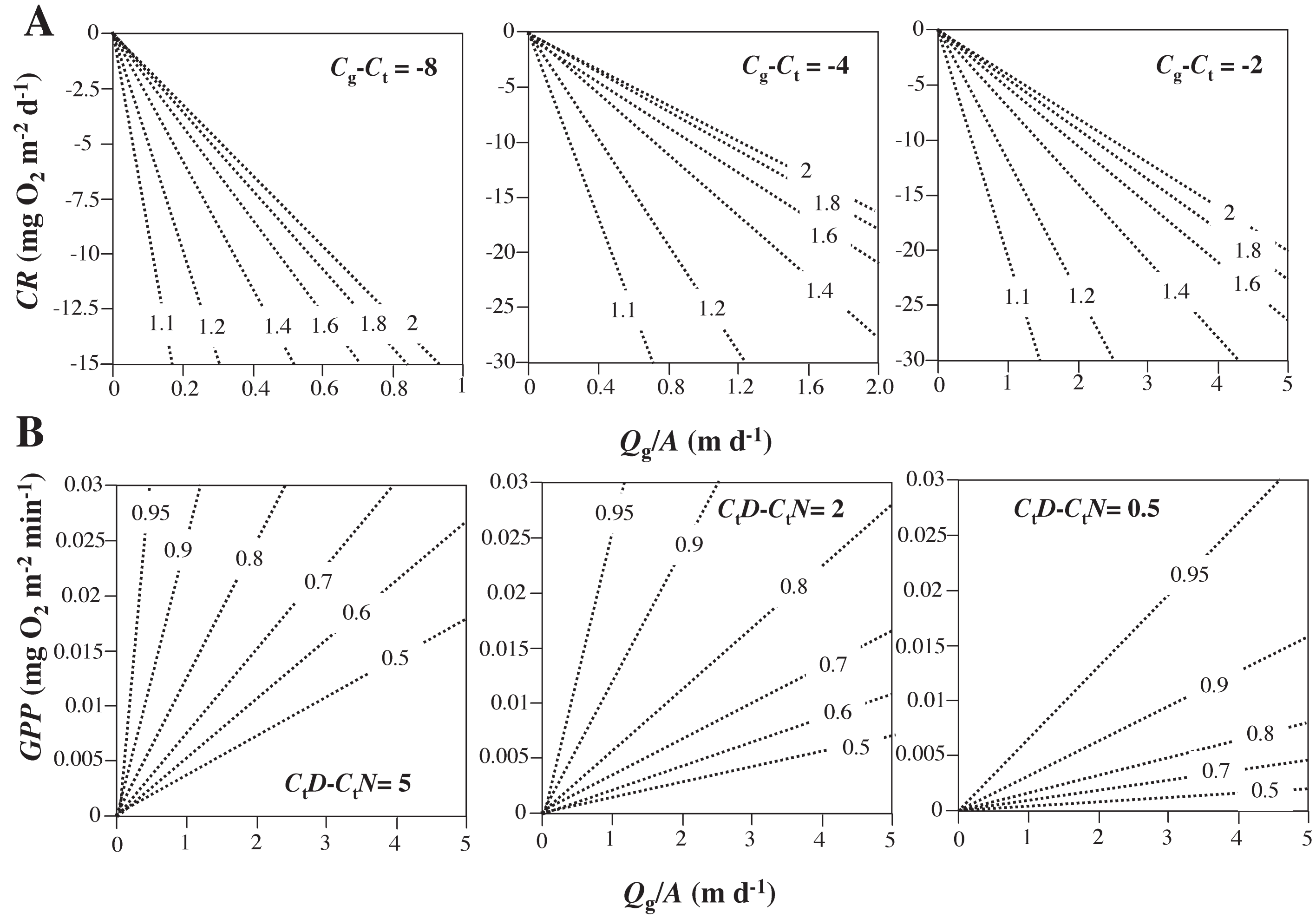

Fig. 2. (A) Estimating the ratio of corrected to uncorrected CR as a function of uncorrected CR, groundwater input, and difference in oxygen concentration between groundwater and streamwater. Given measured groundwater flow into the reach expressed as a vertical velocity, Q_g/A (*x* axis) and uncorrected CR (*y* axis), bias corresponds to the dotted lines, which here ranges from 1.1 to 2. Each panel represents decreasing difference between groundwater and streamwater oxygen concentration (i.e., $C_g - C_t$). (B) Estimating the ratio of corrected to uncorrected gross primary production (GPP) as a function of uncorrected GPP, groundwater input, and difference in oxygen concentration between day and night. Given measured groundwater flow into the reach expressed as a vertical velocity, Q_g/A (*X* axis) and uncorrected instantaneous GPP (*Y* axis), bias corresponds to the dotted lines, which here ranges from 0.5 to 0.95. Each panel represents decreasing difference between day and night streamwater oxygen concentration (i.e., $C_tD - C_tN$).

Giltner Spring Creek had high metabolism, but these rates were strongly biased by the groundwater inputs. Uncorrected CR was 1.6 times corrected CR (Table 2, Fig. 4). Also, CR is constant through the night following correction rather than drifting downward. As the stream got colder through the night, C_{tN} drifted from 3.6 mg O$_2$/L to 3.9 mg O$_2$/L, which made G more negative later in the night and flattened out the CR values. GPP was also biased; uncorrected values were about 0.7 of the corrected values (Table 2, Fig. 4). This bias dramatically altered interpretation of the carbon balance for this ecosystem. Before correction GPP/CR was 0.6 and after it was 1.4, indicating a strongly autotrophic ecosystem during the 2 d.

Discussion

We show how groundwater inputs to a stream reach can potentially bias metabolism, and we provide a new mathematical correction for this bias and demonstrate its application in the field. Even when groundwater inputs appear to be low (e.g., 5% decline in tracer concentration along a reach) these groundwater inputs may be high enough to warrant a substantial correction in the metabolism estimates. We purposely chose a reach with low groundwater inputs. Very high groundwater inputs such as the short reach upstream of our metabolism reach (with Q_g/A of 16 m d^{-1}) will have an oxygen budget dominated by

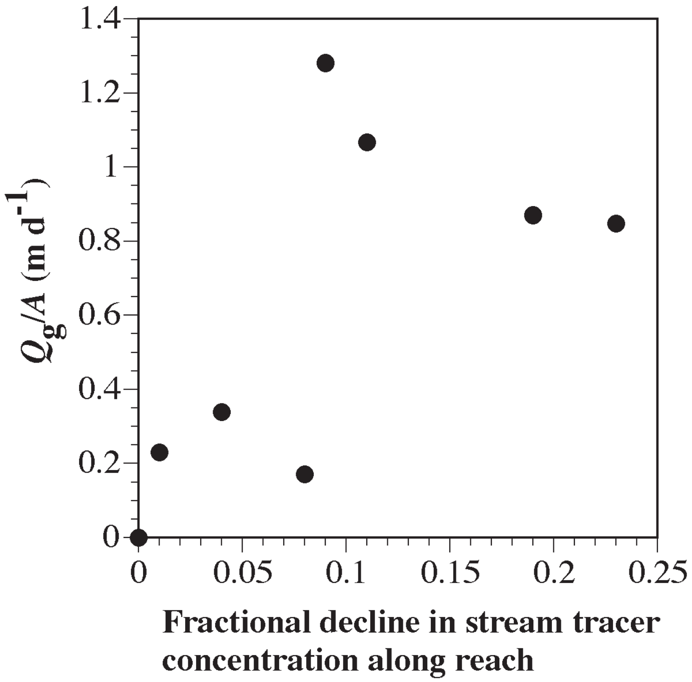

Fig. 3. Q_g/A can be large when conservative tracer concentrations decline only slightly along a stream reach. Data are from streams in Hall and Tank (2003), and the decline in conservative tracer was estimated using Cl^- injections into streams in short-term (90 min) solute additions. Fractional concentration was estimated as (1 – background-corrected concentration of tracer at the downstream station/background-corrected upstream concentration).

Table 2. Groundwater corrected and uncorrected metabolism estimates in Giltner Spring Creek during 2 consecutive days

	Metabolism		
	Uncorrected g O_2 m^{-2} d^{-1}	Corrected g O_2 m^{-2} d^{-2}	Bias
Community respiration			
Day 1	–19.3	–11.8	1.63
Day 2	–18.3	–11.0	1.66
Gross primary production			
Day 1	11.4	16.0	0.71
Day 2	11.7	16.4	0.71

hydrologic fluxes rather than biological ones, which makes quantifying metabolism more difficult.

It is possible that previous estimates of respiration may be biased because of groundwater input, but this bias is impossible to verify given that we do not know C_g from any of these studies. Measuring C_g may not always be easy, groundwater sampled from wells must represent the groundwater that is flowing into the stream. For example, the spatial scale of hyporheic water exchange can affect this groundwater correction because an upwelling zone may be well-oxygenated streamwater that enters the study reach with very little contribution from anoxic groundwater. For example, upwelling zones into Sycamore Creek, Arizona, are oxic with mean O_2 concentration of 3.9 mg O_2 L^{-1} (Jones et al. 1995). Addition-

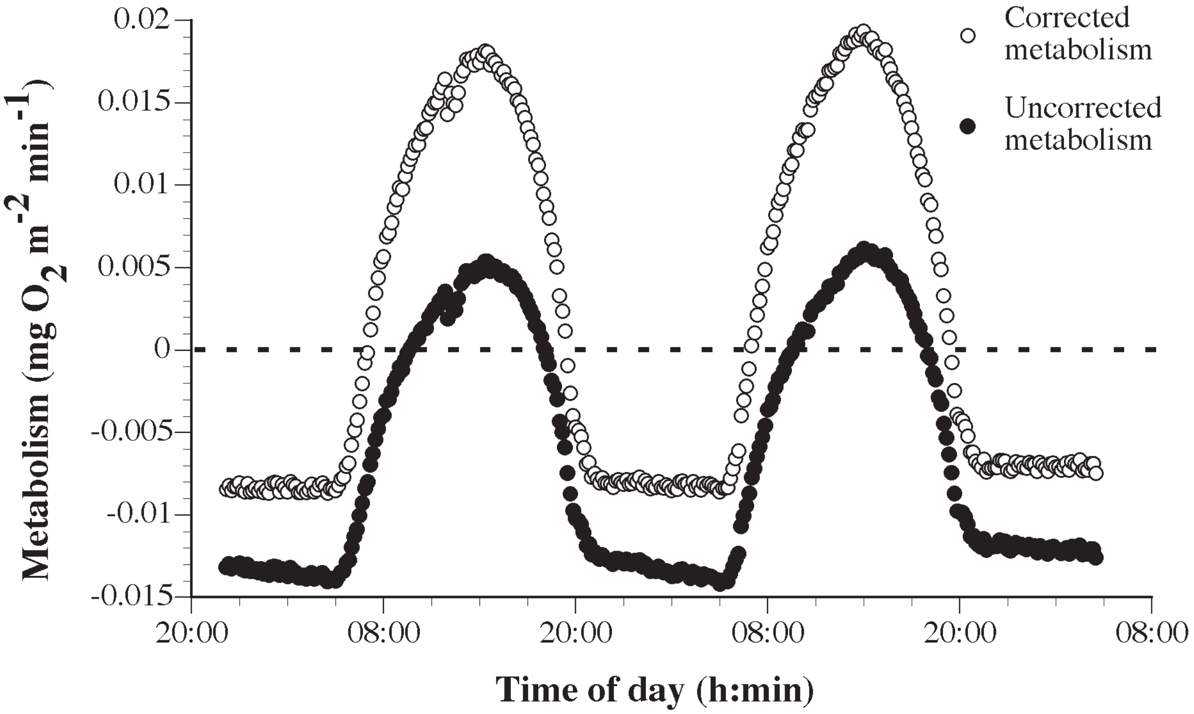

Fig. 4. Metabolism correction is large for Giltner Spring Creek. Data are instantaneous measurements of metabolism during 2 d. Area under the diel excursion represents GPP while nighttime metabolism is scaled to 24 h to measure CR.

ally, if one is interested in whole-stream (i.e., surface and hyporheic respiration, *see* Fellows et al. 2001), upwelling of hyporheic water within the reach should not be corrected, but rather is part of the desired estimate. However, it may be challenging to distinguish hyporheic upwelling water from groundwater, especially given that hyporheic water may be a mixture of stream and new groundwater. Thus, correcting metabolism estimates for groundwater requires finding where new water enters the reach and measuring its oxygen concentration at that point. Oxygen concentration can be measured in wells, but in many streams it will be necessary to understand the local hydrology to ensure the measured groundwater is indeed that which is diluting the streamwater, and not simply stagnant groundwater adjacent to the stream or hyporheic water on a temporary detour from the stream channel. In the case of Giltner Spring, it was relatively simple to back calculate C_g because so much groundwater entered the stream within a short reach upstream of our metabolism reach. This technique may work for other spring streams that have high, and often discrete, groundwater inputs.

A central finding of our results, contrary to McCutchan et al. (2002), is that GPP is also biased, albeit the bias appears smaller than that for CR. Unlike CR, this bias increases the magnitude of GPP. Because estimating GPP involves a relative change in oxygen concentration, it has been considered to be less error-prone than CR estimates (McCutchan et al. 1998), yet here we show that estimates of GPP can be biased. However, it is fortunate that we are able to estimate this bias without hard-to-get values for C_g, and that the bias appears smaller than that for CR. Estimates of bias for GPP from Hall and Tank (2003) were ca. 10% in either direction (one stream had CtD < CtN), which is likely much smaller than those for CR if C_g is very low. Bias was also lower for GPP than CR in Giltner Spring Creek. Estimating bias of daily GPP based on uncorrected GPP is more difficult than that for respiration because instantaneous GPP varies throughout the day, and daily GPP is integrated. Integrated GPP is less biased than what one would estimate from using instantaneous values because we chose the highest NEP value to calculate instantaneous bias, which maximizes the difference between CtD and CtN. Integrated GPP adds NEP across a range of mostly smaller values so integrated bias is less.

Giltner Spring was highly autotrophic the 2 d that we measured it and had high GPP, typical of some spring streams (Odum 1957; Minshall 1978; Cushing and Wolf 1984). Open-canopy spring streams have high GPP, probably because of stable hydrology and temperature combined with high nutrient and light input. Additionally spring streams are typically autotrophic, which is less commonly observed in studies that measure GPP and CR using the open-channel method (Young and Huryn 1999; Mulholland et al. 2001; Hall and Tank 2003). It is possible that we are misinterpreting the degree of autotrophy in streams when groundwater inputs are high. In the case of Giltner Spring Creek, correcting for groundwater inputs strongly affected whether we consider this stream to be autotrophic or heterotrophic during the measurement days.

Comments and recommendations

Acceptable bias will vary among investigators, depending on how they use and interpret their metabolism estimates. Gross primary production should be corrected for groundwater inputs with every metabolism estimate, because only groundwater flow data are required for empirically estimating reaeration and because error for measuring GPP is small (McCutchan et al. 1998). We suggest $B > 1.3$ should be corrected for community respiration given that error in measuring CR can be ± 30% given medium rates of reaeration (e.g., 20-60 d^{-1}) (McCutchan et al. 1998). Given low CR and high difference in O_2 between streamwater and groundwater, then a low groundwater input of ca. 0.2 m d^{-1} could equal this threshold. However, this bias is only large for CR if groundwater oxygen concentrations are low, thus it is important to measure oxygen concentrations, which cannot always be assumed to equal 0. We recommend measuring groundwater O_2 concentration and coupling it to tracer-derived measures of groundwater discharge to accurately measure CR.

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