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Comment on "Solute specific scaling of inorganic nitrogen and phosphorus uptake in streams" by Hall et al. (2013)

R. González-Pinzón[1], J. Mortensen[1], and D. Van Horn[2]

[1]Department of Civil Engineering, University of New Mexico, Albuquerque, New Mexico 87131, USA
[2]Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131, USA

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Correspondence to: R. González-Pinzón (gonzaric@unm.edu)

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Hall et al. (2013) presented a synthesis on 969 nutrient tracer experiments conducted primarily in headwater streams (generally < 4th order streams), with discharges $< 200\,\mathrm{L\,s^{-1}}$ for $\sim 90\,\%$ of the experiments, and used a scaling method to test the hypothesis that nutrient demand is constant with increasing stream size (i.e., along a river continuum). Nutrient uptake length, S_w (L), was correlated with specific discharge, Q/w ($\mathrm{L^2\,T^{-1}}$), and nutrient uptake demand, v_f ($\mathrm{L\,T^{-1}}$):

$$S_w = \frac{Q/w}{v_f}, \tag{1}$$

$$S_w \propto (Q/w)^a, \tag{2}$$

where Q ($\mathrm{L^3\,T^{-1}}$) is stream discharge, w (L) is stream width, and a is a scaling exponent. The transport model considered by Hall et al. (2013) to derive S_w corresponds to that used by Runkel (2007) to derive uptake length Case I, S_w^I (cf. Table 1 in Runkel, 2007). This transport model is limited to the simplest representation of nutrient uptake in open channel flow, including only advection and first-order reaction kinetics. A real-world example of this scenario is a straight, impervious-channel where flow is uniform and mixing due to dispersion and transient storage does not occur.

Hall et al. (2013) used the power law correlation presented in Eq. (2) to test the hypothesis that nutrient uptake demand, v_f ($\mathrm{L\,T^{-1}}$), is constant across stream orders. In their hypothesis testing, the existence of a constant nutrient uptake demand (constant v_f) is implied by a scaling exponent $a = 1$ (isometric scaling), whereas a scaling exponent $a \neq 1$ (allometric scaling) would imply the reverse. Note that in this context, the existence of a constant nutrient uptake demand would be useful to scale and predict nutrient uptake in stream ecosystems.

Assuming wide-rectangular channel geometry, as implicitly assumed by Hall et al. (2013) also (i.e., the channel cross-section area is $A = w \cdot h$; in ($\mathrm{L^2}$)), and following Case I in Runkel (2007), the relationship S_w vs. Q/w can be rearranged to yield

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u/K_c vs. $u \cdot h$:

$$S_w = u/K_c, \tag{3}$$

$$\frac{Q}{w} = \frac{uA}{w} = \frac{u(w \cdot h)}{w} = u \cdot h, \tag{4}$$

where u is the mean channel velocity ($\mathrm{L\,T^{-1}}$), K_c is the first-order uptake rate constant ($\mathrm{T^{-1}}$), and h (L) is mean stream depth. Note that in u/K_c vs. $u \cdot h$, each side of the proportion shares the common variable u. Therefore, an increase in u will increase both sides of the proportion. If a meaningful, significant correlation exists between S_w and Q/w, there should be a significant correlation between the underlying parameters $1/K_c$ vs. h. However, if there is not a corresponding correlation in both of these cases, then the correlation between S_w and Q/w would be falsely influenced by the presence of u in both products.

Spurious correlations can result from the use of ratios or products that share a common factor (Benson, 1965, Kenney, 1982) and are more likely when working with complex variables and dimensional analysis. The relationship from Hall et al. (2013) that we deem spurious is analogous to that of Model II presented by Benson (1965) for the spurious correlation of products sharing a common factor (i.e., $X_1 \cdot X_2$ vs. $X_3 \cdot X_2$; where $X_1 = 1/K_c$, $X_2 = u, X_3 = h$, cf. Table 2 in Benson, 1965). As shown by Benson (1965), the correlation of complex variables (i.e., S_w and Q/w) is dependent on the coefficients of correlation and variation of the three original component variables. Due to the presence of a common factor in the scaling relationship proposed by Hall et al. (2013), we hypothesize that it is a spurious correlation (u influences both S_w and Q/w) that may be mechanistically irrelevant for scaling in-stream nutrient uptake.

To test our hypothesis, we propose a null condition in which we remove the common variable u from the scaling relationship and compare the correlation with that of the original scaling relationship (i.e., we compare $1/K_c$ vs. h and S_w vs. Q/w). This analysis was performed using the dataset published by Tank et al. (2008), another meta-analysis of nutrient addition experiments which was included in the Hall et al. (2013)

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meta-analysis. This dataset was chosen because it reports values for S_w, Q, w, and h for nutrient experiments with NH_4 and NO_3 (SRP not included), even though these values were not reported for all the studies ($n = 143$ for NH_4, $n = 210$ for NO_3). The dataset published by Hall et al. (2013) does not include values of h, hence we were not able to use it for our analysis.

Assuming rectangular channel geometry, we calculated mean stream velocity as $u = Q/(w \cdot h)$. This allowed us to produce values for the relationship $1/K_c$ vs. h, by dividing S_w and Q/w by u (cf. Eqs. 3 and 4). By doing so, we were able to evaluate the scaling relationship with and without the common term u to compare the coefficient of determination, r^2, for both relationships. Results of this analysis are shown for NH_4 and NO_3 in Figs. 1 and 2.

Our results show that $1/K_c$ vs. h are weakly correlated ($r^2_{(NH_4)} = 0.029$, $p_{(NH_4)} = 0.042$; $r^2_{(NO_3)} = 0.036$, $p_{(NO_3)} = 0.0057$). However, the correlations S_w vs. Q/w are higher ($r^2_{(NH_4)} = 0.161$, $p_{(NH_4)} < 0.00001$; $r^2_{(NO_3)} = 0.151$, $p_{(NO_3)} < 0.00001$), i.e., r^2 is improved by 452 and 317 % for NH_4 and NO_3, respectively. These findings suggest that the correlation S_w vs. Q/w is spurious because it is driven by the shared velocity (u) term, rather than by an inherent correlation between the inverse of the nutrient uptake rate constant ($1/K_c$) and stream depth (h). The correlations shown in Figs. 1 and 2 are comparable to those reported by Hall et al. (2013). However, we note that the r^2 values do not match because of different datasets (we were limited by the number of studies reporting all parameters S_w, Q, w, h), and our aggregation of reference and altered streams. Regardless, our analysis shows that the inclusion of the parameter u falsely improves the correlation of the investigated relationships.

The mechanism producing spurious correlation in the dataset by Hall et al. (2013) can be viewed more clearly using three arbitrary and uncorrelated variables to represent the relationship between $X_1 \cdot X_2$ and $X_3 \cdot X_2$. We gathered mean daily values for specific conductance (X_1, $\mu S\,cm^{-1}$) in the Potomac River (DC) (USGS, 2008a), turbidity (X_2, FNU) in the Little Arkansas River (KS) (USGS, 2008b), and temperature

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(X_3, °C) in the Rio Grande (NM) (USGS, 2008c) for the year 2008. First, we isolate the common factor X_2 and plot X_1 vs. X_3, as shown in Fig. 3 ($r^2 = 0.020$, $p = 0.012$). As expected, there is no statistically significant correlation between these water quality parameters. However, when we incorporate the turbidity (X_2) from a remote location by plotting $X_1 \cdot X_2$ vs. $X_3 \cdot X_2$ ($n = 313$), we find a positive correlation (Fig. 4) with a drastic improvement in r^2 ($r^2 = 0.846$, $p < 0.00001$). Despite the evident correlation in this relationship, the result is mechanistically irrelevant. Analogous to this case example where the correlation is driven by X_2 (turbidity), the correlation S_w vs. Q/w seems to be driven by u (recall $S_w = u/K_c$ and $Q/w = u \cdot h$). Thus, our findings suggest that the results produced by Hall et al. (2013) regarding the isometric scaling ($a = 1$) of NH_4, and allometric scaling ($a > 1$) of NO_3 and SRP, resulted from an unintentional spurious correlation of S_w vs. Q/w.

In addition to scaling nutrient uptake length with specific discharge, Hall et al. (2013) also provide a method for scaling nutrient uptake with stream length using several parameters including the scaling exponent a obtained from the analysis of the scaling relationship shown in Eq. (2). Our findings have implications for these results as well. While Hall et al. (2013) commented that their results for scaling uptake with stream length was most influenced by b (hydraulic geometry exponent), their analysis still relies on the spurious correlation S_w vs. Q/w not only for parameter a, but also for their subsequent derivations (cf. Eqs. 3–10 in Hall et al., 2013). Therefore, we also find those results debatable.

1 Concluding remarks

The majority of nutrient addition experiments have been performed in headwater streams because they are more experimentally tractable (Tank et al., 2008). Consequently, the dearth of empirical evidence of nutrient processing in large rivers limits our understanding of the role of these rivers in nutrient processing at the catchment scale. While advances are being made toward performing nutrient addition experiments in large rivers (Tank et al., 2008; Covino et al., 2010), the need to understand and quantify nutrient export from these systems has driven the development and use of scaling relationships. This motivated the work by Hall et al. (2013) and their results after correlating S_w vs. Q/w for a large dataset of field nutrient experiments suggest that uptake demand (v_f) for NH_4 is relatively constant across stream orders, whereas that for soluble reactive phosphorous (SRP) and NO_3 declines with increasing specific discharge. Here, we demonstrated that these conclusions are subject to debate due to unintentional spurious correlations present in their scaling relationships.

We also suggest that S_w should be used with extreme caution to scale nutrient uptake because, even though its magnitude can be directly estimated from relatively simple field measurements (cf. Eqs. 2–3 in Runkel, 2007), its mechanistic interpretation strongly depends on the type of model assumed to describe the real-world system (cf. Table 1 in Runkel, 2007). This is because the same estimate of the magnitude of S_w may be arbitrarily used to co-estimate or constrain the magnitude of parameters describing different (arbitrary) sets of processes (see Cases I–IV in Runkel, 2007). Finally, when a model describing a given set of processes is chosen to interpret how nutrient uptake scales along a river continuum, the main assumption is that such processes operate analogously along the continuum. For example, if the model of advection-decay chosen by Hall et al. (2013) to interpret S_w across stream orders were correct, our analysis presented in Figs. 1 and 2 would suggest that headwater streams tend to have higher nutrient uptake rate coefficients, which might be mechanistically supported by their higher ratio of benthic area to cross-sectional area. However, this (biased) analysis would not provide insight into how mass-transfer processes between the main-channel and transient storage zones may control nutrient uptake and retention along the river continuum. Paradoxically, increasing the complexity of the transport models used to derive S_w (e.g., Cases II–IV in Runkel, 2007) does not necessarily improve the mechanistic understanding gained on how nutrient uptake scales along the river continuum because such models are poorly constrained, i.e., the number of parameters introduce more degrees of freedom than the data collected (from field and remote measurements) can constrain (Kirchner, 2009).

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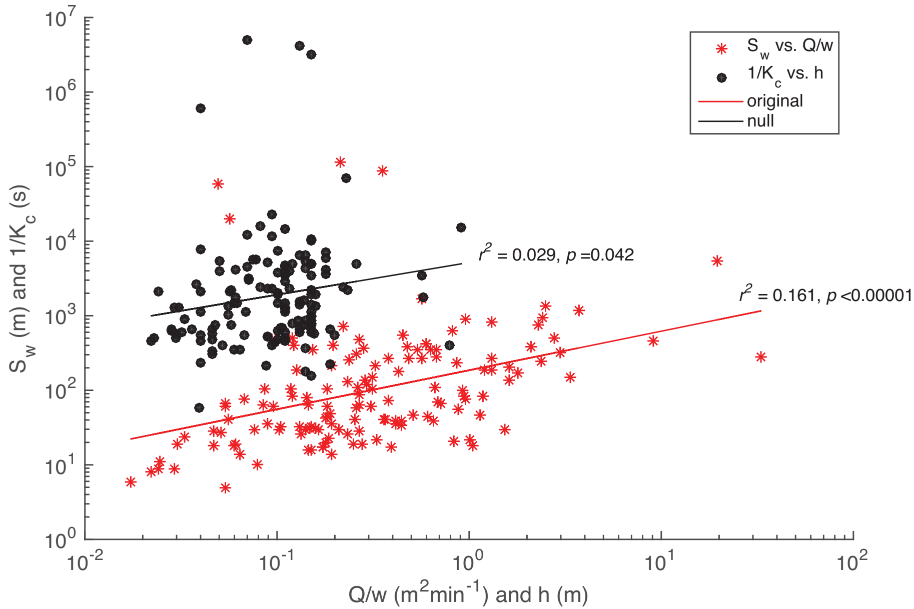

Figure 1. NH_4 scaling relationship with and without shared velocity term. The original relationship is represented by S_w vs. Q/w and the null condition by $1/K_c$ vs. h.

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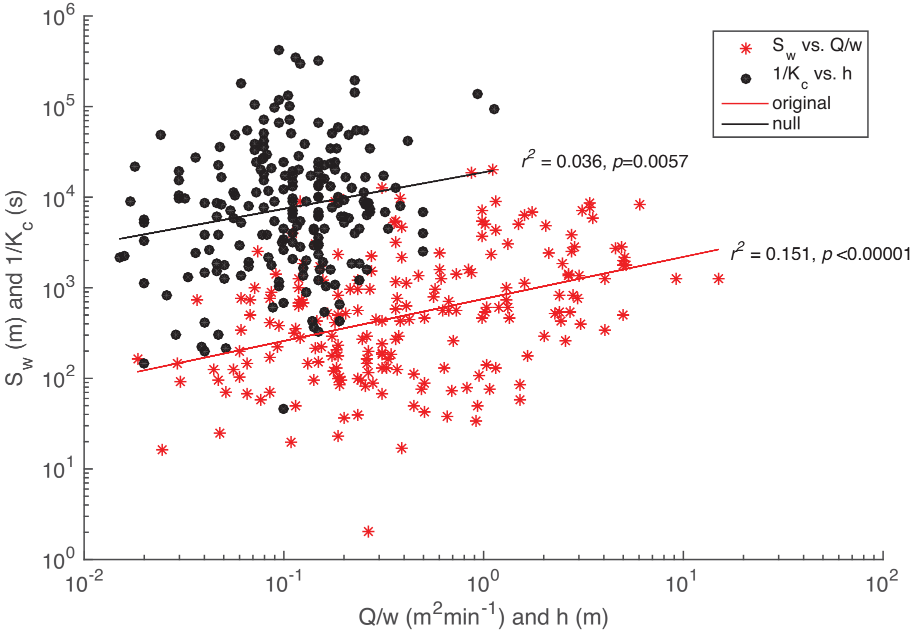

Figure 2. NO_3 scaling relationship with and without shared velocity term. The original relationship is represented by S_w vs. Q/w and the null condition by $1/K_c$ vs. h.

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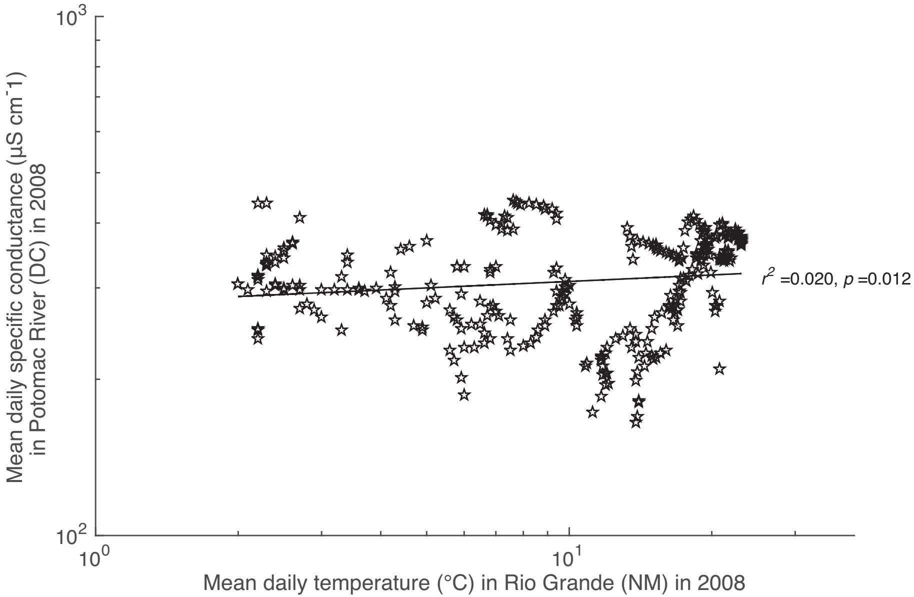

Figure 3. Synthetic data correlation, type X_1 vs. X_3, without common parameter, X_2. There is a weak correlation between these water quality parameters.

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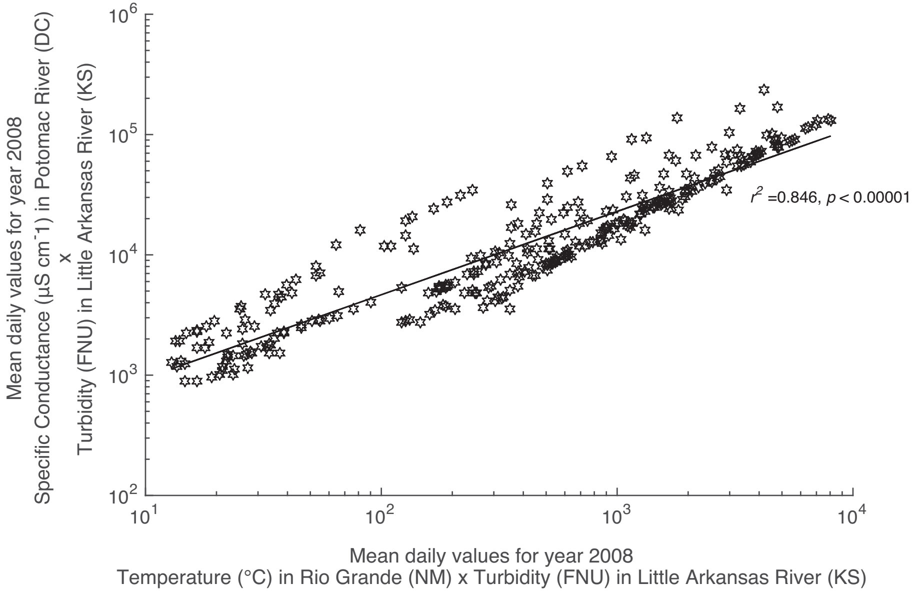

Figure 4. Synthetic data correlation, type $X_1 \cdot X_2$ vs. $X_3 \cdot X_2$, with common parameter X_2. This spurious correlation results simply because X_2 is common to both quantities.

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