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Estimating effective specific yield in inundated conditions: a comment on a recent application

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Water level fluctuation (WLF) methods have been widely used to estimate phreatophyte water use in groundwater settings since the pioneering work of White (1932). However, applications in surface waters have been rare because of methodological constraints, particularly the availability of high-resolution water level sensors and appropriate representation of specific yield (S_y) for inundated systems, where rapid interactions between open water and adjacent groundwater can influence the effective S_y (McLaughlin and Cohen, 2013). In a recent paper in *Ecohydrology*, Carlson Mazur *et al.* (2013) provided results from one of the few studies to successfully apply a WLF method in inundated conditions to simultaneously measure evapotranspiration (ET) and groundwater flow rates. The authors used two approaches to estimate S_y for flooded conditions; one approach was site-specific whereas the other can be more generally applied. The purpose of this technical note is to discuss both approaches, emphasize the intent and limited appropriateness of the site-specific methodology and provide guidance to other researchers applying WLF methods in surface water systems.

On a per unit area basis, S_y represents the ratio of a water input (rain) or ouput (ET) to the induced water level change, and this parameter is required to infer ET and groundwater flux rates from diurnal water level variation (i.e. WLF methods). Values of soil S_y for groundwater systems, where small inputs and outputs can create large water level changes, range from 0.01 to 0.40 (Loheide *et al.*, 2005). In contrast, S_y for flooded conditions is often assumed to be constant, regardless of flooding depth, and equal to 1·0 (Mitsch and Gosselink, 2007). However, biovolume displacement (i.e. volume taken up by inundated living and dead vegetation) and rapid lateral equilibration with adjacent non-inundated areas can reduce the effective S_y that controls water level variation observed in the inundated system; failure to account for these effects can lead to large errors in ET and groundwater flow rates estimated with WLF methods (Hill and Neary, 2007; McLaughlin and Cohen, 2013).

Differences in S_y between non-inundated and inundated areas (i.e. soil $S_y \approx 0{\cdot}2$ vs open water $S_y \approx 1$, less biovolume displacement) create differential water level responses to ET. The larger water level declines experienced in non-inundated areas, in turn, create a gradient that enables lateral flow out of the inundated area; the reverse holds true following rain events, wherein rapid responses in non-inundated areas create flow towards inundated areas. If this lateral equilibration is rapid (i.e. << sub-daily timescales), then the effective S_y of a system integrates the S_y of flooded areas with soil S_y of equilibrating non-inundated areas. Sumner (2007) investigated the role of this mechanism in a large wetland system where soil microtopography reduced S_y of flooded conditions. McLaughlin and Cohen (2013) also explored this mechanism but in small circular depressional wetlands where adjacent exposed regions created stage-dependent variation in S_y. Water table monitoring across inundated and non-inundated wetland areas not only supported the mechanism but also indicated that the extent of equilibrated area varied across sites.

Rapid lateral equilibration can result in stage-dependent variation in the effective S_y of an inundated system, but accounting for this effect with a mechanistic equation requires detailed topographic information and a well-constrained areal extent of rapid equilibration. Similar to McLaughlin and Cohen (2013), Carlson Mazur *et al.* (2013) applied an alternative approach to empirically

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estimate S_y as a function of stage using ratios of rain to induced rise, an approach widely used in groundwater studies (e.g. Schilling, 2007). Additionally, the authors estimated a composite S_y using a modified version of the method developed by Hill and Neary (2007), who used a weighted average of S_y between inundated and non-inundated areas. However, Carlson Mazur *et al.* (2013) had limited topographic information for their system. Therefore, in their revised method, the authors replaced lateral equilibration with vertical equilibration, calculating the composite S_y by applying $S_y = 1$ to the inundated *depth* as a proportion of total *depth* (inundated depth plus soil substrate depth to an impermeable confining unit) and applying soil S_y to the proportional substrate *depth* (Carlson Mazur *et al.*, 2013):

$$S_{yc} = S_{yw}\left(\frac{D_w}{D_w + D_s}\right) + S_{ys}\left(\frac{D_s}{D_w + D_s}\right) \tag{1}$$

where S_{yc} is the composite specific yield, S_{yw} is the specific yield of surface water and equal to 1·0, S_{ys} is soil specific yield, D_w is inundated depth and D_s is depth of the soil substrate. Concordance between this calculated composite S_y function and the empirically derived function (via rain-to-rise ratios) supported the approach.

Although the concordance between the two approaches used by Carlson Mazur *et al.* (2013) is empirically compelling, it is a fortuitous coincidence, and their approach to calculating S_y using depth proportions does not apply in general. Such an approach implicitly assumes that *vertical* water equilibration reduces the S_y of flooded conditions. In fact, vertical equilibration between open water and the saturated soil beneath it does not reduce the S_y of flooded conditions. In the extreme case, where the total ET flux from an inundated wetland is supplied by belowground water loss (i.e. no evaporation or transpiration of standing water above the soil surface), the decline in soil water will be the ET loss divided by soil S_y. This decline, however, would be rapidly equilibrated by a downward flux of the requisite volume of overlying surface water to fill the deficit (depleted water in soil voids). As an example, for an ET rate of 2 mm and a soil S_y of 0·2, the decline in soil water level would be 10 mm (Figure 1). However, a surface water level decline of only 2 mm is required to fill the 10-mm deficit because the water is entering the soil, which has a specific yield of 0·2. Thus, the water level decline in the substrate is equal to ET/soil S_y, whereas the deficit equilibrated with standing water remains equal to the depth of ET. In short, the decline in the standing water level is simply the ET rate (assuming that open water $S_y = 1$), and the effective S_y of flooded systems with solely vertical (no lateral) equilibration is equal to open water S_y, regardless of the source of the ET flux or the proportion of flooding depth to soil substrate depth (Figure 1).

Carlson Mazur *et al.* (2013) provide a valuable contribution to WLF method applications by addressing several methodological considerations, including determining empirical estimates of S_y with ratios of rain to induced rise. Using these empirical estimates, the authors found that their approach to calculate a composite S_y using depth proportions was appropriate in their ridge-and-swale wetland complex. However, this was a site-specific coincidence, and applying the same logic in other systems may result in large errors. The likely source of the coincidence is that lateral equilibration with inter-wetland

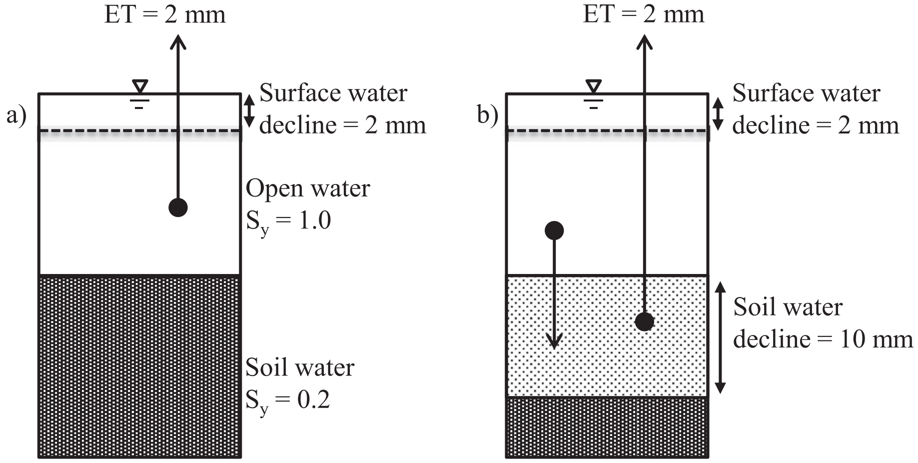

Figure 1. Under inundated conditions, evapotranspiration (ET) results in equal surface water decline regardless of whether the flux is supplied by (a) standing water or (b) soil water. Dots and arrows show source location and direction of flow, respectively. (a) In the absence of lateral equilibration, an ET flux of 2 mm supplied by standing water results in a 2-mm surface water decline due to open water S_y of 1.0 (decline = ET flux/open water S_y). (b) In contrast, an equal flux entirely supplied by soil water creates a 10-mm decline in soil water level due to a soil S_y of 0.2 (decline = ET/soil S_y). However, the net result is still a 2-mm surface water level decline because the deficit (depleted water in soil voids) is 2 mm (soil water decline × soil S_y), and this is instantaneously equilibrated with standing water ($S_y = 1.0$).

dunes occurs with a ratio of dune area to wetland area similar to the observed ratio of soil depth to water depth. Thus, the use of this relationship to calculate composite S_y is only appropriate if it happens to hold true for other systems as well, and this would need to be confirmed prior to use.

Applying WLF methods in surface water systems allows assessment of the influences and implications of ET and groundwater flow rates at high spatial and temporal resolution but critically requires an accurate understanding of the mechanisms that regulate S_y in inundated conditions and correct approaches to account for those mechanisms. While rapid lateral equilibration may largely control the stage-dependent variation in S_y, applying mechanistic models to account for this may result in errors without the detailed topographic mapping and cross-wetland well transects to make analysis of equilibration attainable (McLaughlin and Cohen, 2013). Considering the large variation among systems in lateral equilibration area, as well as other factors that affect $\mathrm{S_y}$ of flooded conditions (e.g. soil S_y, biovolume displacement), the empirical approach of determining S_y with ratios of rain-to-rise, as performed by Carlson Mazur *et al.* (2013), may be the most effective and general approach. However, a robust rain and stage dataset (>20 moderate to large storms) is needed for accurate inferences of stage to S_y relationships, and the method may not be applicable in sites with substantial overland flow (McLaughlin and Cohen, 2013).

In summary, the effective S_y of inundated systems is driven by the extent of equilibration with adjacent non-inundated areas, and accurate estimates of stage-dependent variation in S_y are critical to understand the interactions between atmospheric fluxes (rain and ET), WLFs and surface water budgets. Whereas mechanistic equations relating stage and S_y may be developed, their parameterization requires detailed topography and long-term hydrologic monitoring to identify the appropriate area of equilibration. The empirical rain-to-rise approach also requires an investment in site-specific data collection but is an integrative measure of system response that is likely less prone to error. Both approaches to estimate S_y require additional monitoring but are necessary when applying WLF methods in flooded conditions.

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