AGU PUBLICATIONS

Water Resources Research

REPLY

10.1002/2017WR021021

This article is a reply to a comment by *Ma and Zhang* [2017], doi:10.1002/2017WR020892.

Key Points:

- The complementary relationship can be rescaled using the maximum potential evaporation rate, which occurs when the surface is totally dry
- The behavior of the formulation may not be realistic when wind speeds are very low
- We argue that assumptions behind the CR are not met when the daily wind speed is very low

Correspondence to:
R. Crago,
rcrago@bucknell.edu

Citation:
Crago, R., R. Qualls, J. Szilagyi, and J. Huntington (2017), Reply to comment by Ma and Zhang on "Rescaling the complementary relationship for land surface evaporation", *Water Resour. Res.*, *53*, doi:10.1002/2017WR021021.

Received 1 MAY 2017
Accepted 7 JUN 2017
Accepted article online 21 JUN 2017

Reply to comment by Ma and Zhang on "Rescaling the complementary relationship for land surface evaporation"

Richard Crago[1], Russell Qualls[2], Jozsef Szilagyi[3,4], and Justin Huntington[5]

[1]Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, Pennsylvania, USA, [2]Department of Biological Engineering, University of Idaho, Moscow, Idaho, USA, [3]Department of Hydraulic and Water Resources Engineering, Budapest University of Technology and Economics, Budapest, Hungary, [4]Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA, [5]Division of Hydrologic Sciences, Desert Research Institute, Reno, Nevada, USA

Abstract Ma and Zhang (2017) note a concern they have with our rescaled Complementary Relationship (CR) for land surface evaporation when daily average wind speeds are very low (perhaps less than 1 m/s). We discuss conditions and specific formulations that lead to this concern, but ultimately argue that under these conditions, a key assumption behind the CR itself may not be satisfied at the daily time scale. Thus, careful consideration of the reliability of the CR is needed when wind speeds are very low.

1. Introduction and Discussion

We would like to thank N. Ma and Y. Zhang for opening up a conversation on the rescaled Complementary Relationship (CR) proposed in *Crago et al*. [2016, hereinafter C16]. The CR relates E (actual regional evaporation) to E_{pa} (potential evaporation—estimated here with the *Penman* [1948] equation) and E_{p0} (regional wet-surface evaporation—estimated with the *Priestley and Taylor* [1972] equation). C16 introduced E_{pads}, "the value E_{pa} would have if the regional surface was devoid of all moisture." We are pleased that Ma and Zhang agree with the need to adjust the boundary conditions for $y = E/E_{pa} = 0$ and to rescale the CR, as suggested in C16. We agree with them that E_{pads} could be defined using a version of Penman's equation. We also agree that there are situations in which equation (3) given by Ma and Zhang could result in $E_{pads} < E_{p0}$, so that $x_{min} = E_{p0}/E_{pads} > 1$, which falls outside the physically valid range.

The use of the *Penman* [1948] equation to estimate E_{pads} fits well with the definition given above, because E_{pa} itself is calculated with the Penman equation. *Szilagyi et al*. [2017, hereinafter S17] suggested that the temperature used to estimate E_{pads} using this method should be T_d, the air temperature that would result from adiabatic drying to a humidity of zero. S17 obtained excellent results with the rescaled CR in this way. We also note that the definition of E_{pads} might be best met if the same temperature and humidity measurement height is used to estimate E_{pa} and E_{pads}.

The behavior of x_{min} displayed in Figure 1 of the Comment appears to be correct. Use of the Penman equation will reduce or eliminate values of $x_{min} > 1$. The extent to which nonphysical values of x_{min} will occur depends in part on the wind function chosen for the drying power term in Penman's equation. Use of the wind function originally suggested by *Penman* [1948], that is, $f(u) = a(b + cu)$, where a, b, and c are constants and u is wind speed (usually at 2 m height), avoids $x_{min} > 1$ because the wind function remains greater than zero even as $u \to 0$. Wind function formulae based on Monin-Obukhov Similarity (MOS) Theory result in $f(u) \to 0$ when $u \to 0$. In this limiting case, MOS Theory results in the second term of Penman's equation equaling zero, so that $E_{pads} = (1/\alpha)E_{p0}$, where α is the Priestley and Taylor parameter. Since $\alpha > 1$ for saturated regions [e.g., *Brutsaert*, 2005], this results in $x_{min} > 1$. The MOS wind function could conceivably be modified by replacing all values of u less than u_{min} with u_{min}, where u_{min} is a parameter, to prevent $f(u) = 0$ and $x_{min} > 1$.

However, we suggest caution using any CR in the limit as $u \to 0$. In this situation, there is no shear-driven turbulence. At the same time, at the daily time step, stability is assumed to be neutral, so there is no buoyancy-driven turbulence either. With minimal turbulence, the lower atmosphere would be disconnected from the properties of the surface. This violates an assumption of the CR, namely, that the lower atmosphere is well-adjusted to the moisture status of the surface in the region. Furthermore, under these same conditions, $x = E_{p0}/E_{pa}$ can exceed 1.0, thus exceeding the theoretical limit postulated for example, by *Brutsaert* [2015]. Therefore, rather than seeing nonphysical values of x_{min} as a mathematical problem to be solved, we see them as a sign that the CR is unlikely to be reliable under those conditions.

Acknowledgments
No data were used in writing this reply.

References

Brutsaert, W. (2005), *Hydrology: An Introduction*, 605 pp., Cambridge Univ. Press, New York.

Brutsaert, W. (2015), A generalized complementary principle with physical constraints for land-surface evaporation, *Water Resour. Res.*, *51*, 8087–8093, doi:10.1002/2015WR017720.

Crago, R., J. Szilagyi, R. Qualls, and J. L. Huntington (2016), Rescaling the complementary relationship for land surface evaporation, *Water Resour. Res.*, *52*, 8461–8470, doi:10.1002/2016WR019753.

Ma, N., and Y. Zhang (2017), Comment on "Rescaling the complementary relationship for land surface evaporation" by R. Crago et al., *Water Resour. Res.*, *53*, doi:10.1002/2017WR020892.

Penman, H. L. (1948), Natural evaporation from open water, bare soil and grass, *Proc. R. Soc. London, Ser. A*, *193*(1032), 120–145, doi:10.1098/rspa.1948.0037.

Priestley, C. H. B., and R. J. Taylor (1972), On the assessment of surface heat flux and evaporation using large-scale parameters, *Mon. Weather Rev.*, *100*(2), 81–92, doi:10.1175/1520-0493(1972)100 < 0081:OTAOSH > 2.3.CO;2.

Szilagyi, J., R. Crago, and R. Qualls (2017), A calibration-free formulation of the complementary relationship of evaporation for continental-scale hydrology, *J. Geophys. Res. Atmos.*, *122*, 264–278, doi:10.1002/2016JD025611.