7-1-2017

Reply to Comment by Fred L. Ogden et al. on "Beyond the SCS-CN Method: A Theoretical Framework for Spatially Lumped Rainfall-Runoff Response"

Mark Bartlett
Duke University

Anthony J. Parolari
Marquette University, anthony.parolari@marquette.edu

Jeffrey McDonnell
University of Saskatchewan

Amilcare Porporato
Duke University

Published version. *Water Resources Research*, Vol. 53, No. 7 (July 2017): 6351-6354. DOI.

AGU PUBLICATIONS

Water Resources Research

REPLY

10.1002/2017WR020456

This article is a reply to a comment by *Ogden et al.* [2017], doi:10.1002/2016WR020176.

Key Points:

- Fit for purpose is a key factor in hydrological modeling
- The SCS-CN method is generalized to provide a family of semidistributed models
- Moving forward requires linking model types to different hydrogeographic settings

Correspondence to:
A. Porporato,
Amilcare@duke.edu

Citation:
Bartlett, M. S., A. J. Parolari, J. J. McDonnell, and A. Porporato (2017), Reply to comment by Fred L. Ogden et al. on "Beyond the SCS-CN method: A theoretical framework for spatially lumped rainfall-runoff response," *Water Resour. Res.*, *53*, 6351–6354, doi:10.1002/2017WR020456.

Received 20 JAN 2017
Accepted 12 JUN 2017
Accepted article online 21 JUN 2017
Published online 28 JUL 2017

Reply to comment by Fred L. Ogden et al. on "Beyond the SCS-CN method: A theoretical framework for spatially lumped rainfall-runoff response"

M. S. Bartlett[1], A. J. Parolari[1], J. J. McDonnell[2,3], and A. Porporato[1]

[1]Department of Civil and Environmental Engineering, Duke University, Durham, North Carolina, USA, [2]Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [3]School of Geosciences, University of Aberdeen, Aberdeen, UK

Abstract Though Ogden et al. list several shortcomings of the original SCS-CN method, fit for purpose is a key consideration in hydrological modelling, as shown by the adoption of SCS-CN method in many design standards. The theoretical framework of *Bartlett et al.* [2016a] reveals a family of semidistributed models, of which the SCS-CN method is just one member. Other members include event-based versions of the Variable Infiltration Capacity (VIC) model and TOPMODEL. This general model allows us to move beyond the limitations of the original SCS-CN method under different rainfall-runoff mechanisms and distributions for soil and rainfall variability. Future research should link this general model approach to different hydrogeographic settings, in line with the call for action proposed by Ogden et al.

We thank Ogden and colleagues [*Ogden et al*., 2017, hereinafter referred to as O&C] for their interest in our work and for generating community discussion on the curve number (SCS-CN) method. We largely concur with their assessment of the SCS-CN method as well as with their generic call for future research directions. Indeed, the development of hydro-geographically appropriate dynamic models, multiscale model capabilities, and improved data collection for specific research questions is what much of our own past work has focused on [e.g., *McDonnell et al*., 2007; *Porporato et al*., 2015].

Here in response to O&C, we first address the SCS-CN method and whether or not it makes sense to continue discussions of its use and usefulness; we then reply to their specific criticism at the end of this response. As pointed out by their comment, the empirical SCS-CN method is simple and works well for small agricultural watersheds, but has significant shortcomings for other undisturbed watershed types, specifically forested watersheds. Of course, the original formulation has little in the way of any process underpinning, as they correctly note. But then, so might be said of the rational method that has been around for 100 years longer than the curve number [*Mulvaney*, 1851] and we would not want to throw that away. Both are important components of current design standards, such as TR55 [*Cronshey*, 1986], and other models. Again, fit for purpose is a key factor in any hydrological modeling.

It is true that our work with the curve number was motivated by its limitations and aimed to extend its applicability [*Bartlett et al*., 2016a]. But, more broadly and more importantly, our goal is to explore a theoretical underpinning to this method that was perhaps hitherto unnoticed. As detailed in a subsequent paper [*Bartlett et al*., 2016b], we have described a family of semidistributed models, of which the SCS-CN method is just one. Other models described by this framework include event-based versions of the Variable Infiltration Capacity (VIC) model [*Liang et al*., 1994] and TOPMODEL (Topography-based hydrologic MODEL) [*Beven and Kirkby*, 1979]. The resulting general model indeed allows us to go beyond the original SCS-CN method and apply it to situations where the original method fails. That theory also paved the way for a nonstatic application of the framework and a calculation of the antecedent moisture conditions as linked to ecohydrological and climate considerations [*Bartlett et al*., 2016c].

So, we are motivated not so much by breathing new life into the curve number, but by exploring the generality and power of treating the rainfall-runoff processes at a point as a joint distribution of runoff, rainfall, soil moisture, and potentially other watershed variables. This runoff distribution characterizes the spatial variability of runoff, as well as the fraction of the watershed with specific rainfall-runoff mechanisms. Based on this distribution, the average (unit area) runoff, the so-called "runoff curve," follows as a function of rainfall and moisture status on a unit area basis.

In comparison to the original SCS-CN method, the new runoff curve provides a much improved representation of runoff in forested watershed areas [see *Bartlett et al*., 2016a, Figure 9 and Table 2]. This runoff curve fixes the large error that was previously rectified by unrealistically increasing the maximum potential retention with increasing rainfall [*Tedela et al*., 2011]. While this new runoff curve may be considered a refinement of the original SCS-CN method, the overall framework is not. The framework provides for a continuum of models that are akin to, but yet different than the SCS-CN method. In this sense, the framework opens a path that moves beyond the original SCS-CN method. To start, the framework provides a previously missing characterization of runoff spatial variability (via the joint distribution of runoff with other watershed variables)—a key development that O&C call for. Furthermore, the framework shows that the same canonical runoff curve represents both common semidistributed models and the SCS-CN method, i.e.,

$$\overline{Q}=\overline{R}F_t(\overline{S},\overline{R})+\overline{R}(1-F_t(\overline{S},\overline{R}))P_I. \tag{1}$$

where average (unit area) runoff $\overline{Q}$ is a function of the average antecedent potential retention, $\overline{S}$, average rainfall $\overline{R}$, the prethreshold runoff index P_I, and the fraction of area with threshold-excess runoff, $F_t(\overline{S},\overline{R})$ [see *Bartlett et al*., 2016b, equation (10)]. This expression of equation (1) differs for each model expression of $F_t(\overline{S},\overline{R})$ (e.g., VIC, TOPMODEL, etc.), which results from a unique distribution of watershed properties.

Thus, as mentioned by O&C, moving forward will require adapting models to specific problems and linking model types to different hydrogeographic settings, all of which will require extensive data acquisition. However, O&C do not recognize the compatibility of their call with our framework, which accommodates different runoff mechanisms (including threshold-type runoff resulting from different hydrologic connections to the stream [e.g., *Hewlett and Hibbert*, 1967; *Tromp-van Meerveld and McDonnell*, 2006a, 2006b; *McGuire and McDonnell*, 2010]) as well as different data-derived distributions for describing soil and rainfall variability. Indeed, we are intrigued by the fact that previous process-based rainfall-runoff research may be converging on the idea that all runoff processes are "the same," i.e., all threshold like via filling, spilling, loss along the flow path and ultimately connectivity of saturated areas [*McDonnell*, 2013; *Ameli et al*., 2015; *Bartlett et al*., 2016b]. If true, this could lead to interesting developments for dynamic and multiscale models and new guidance for what data to collect in the field.

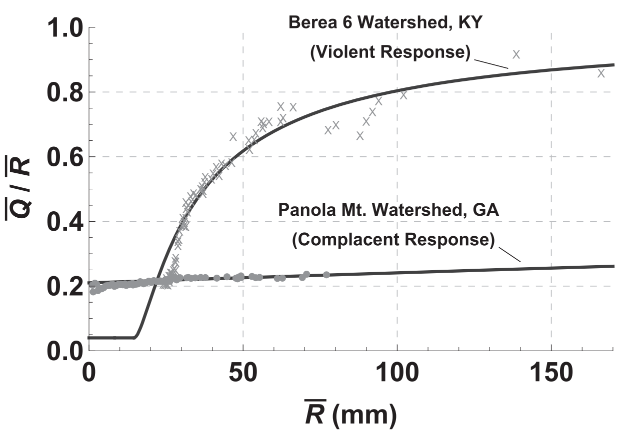

Figure 1. Comparison of rank-order data to the SCS-CNx method for the complacent response of (a) the Panola Mountain Watershed (gray dots, data from the U.S. Geological Survey) and (b) the violent response of the Berea 6 watershed (crosses) [*Hawkins*, 1993]. Model fit minimizes the root-mean-square error (RMSE). For the Panola watershed, RMSE = 0.0074 for $\overline{S}$ = 1931 mm, P_I=0.21, and μ = 0; and for the Berea 6 watershed, RMSE = 0.076 for $\overline{S}$= 20 mm, P_I=0.04, and μ=0.07. Note that the SCS-CN initial abstraction—a fraction μ of $\overline{S}$—abstracts rainfall before an effective value, i.e., $\overline{R}_t=\overline{R}-\frac{\mu\overline{S}}{1-P_I}$, produces a threshold-excess response at any watershed point.

Regarding the specific criticism of O&C, our responses are as follows:

C1–C5 and C7: A specific response to these points is made difficult by the fact that they, when correct, apply generically to most spatially implicit rainfall-runoff models. We only note that (i) obtaining data for the parameter distributions of our model is no more difficult than gathering the data (e.g., soil hydraulics) desired by O&C in their call to action, (ii) including rainfall intensity is certainly possible (as also stated in *Bartlett et al*. [2016a]) and work is in progress to implement the time compression approximation [e.g., *Rigby and Porporato*, 2006; *Liu et al*., 1998] in this framework, (iii) capturing discontinuity of the rainfall field and systematic spatial nonuniformities is possible through mixed distributions [e.g., *Sivapalan et al*., 1997], and (iv) accommodating (nonrandom) heterogeneity is feasible as demonstrated by the framework adaptation to TOPMODEL [*Bartlett et al*., 2016b].

C6: O&C incorrectly state that our approach relies on an assumption of stationarity, which is never mentioned in our work. In fact, subsequent work [*Bartlett et al*., 2016c] has successfully applied the model to seasonal and time-varying conditions. Regarding equations (14) and (15) of *Bartlett et al*. [2016a], they provide a threshold description of runoff supported by detailed process work from the field [e.g., *Hewlett and Hibbert*, 1967; *Tromp-van Meerveld and McDonnell*, 2006a,b; *McGuire and McDonnell*, 2010]. In lieu of equations (14) and (15), the theoretical framework allows for approximations to Richards equation solutions (e.g., time compression approximation) or other approaches that include the rainfall rate, as already mentioned.

C8: O&C provide the unsubstantiated claim that the SCS-CNx method does not capture nonstandard (violent and complacent) rainfall-runoff behaviors found in rank order-data [e.g., *Hawkins*, 1993]. Indeed, as shown in Figure 1, our extended model well captures these behaviors, without additional empirical equations adjusting the CN parameter to the rainfall amount [e.g., *Hawkins*, 1993]. In this comparison, we consider the SCS-CNx method with the SCS-CN concept of an initial abstraction threshold—a fraction μ of $\overline{S}$ that abstracts rainfall prior to any threshold-excess response at a point.

C9: This comment is especially surprising since O&C themselves invoke *Hawkins* [1993] who used rank-order data in support of their earlier arguments (see C1 and C8). To be absolutely clear, the model by *Bartlett et al*. [2016a] respects causality. As in *Hawkins* [1993], we use the rank-order data to extract an expected rainfall-runoff response [see *Bartlett et al*., 2016a, Appendix D]. The rank-order data are just one route for data comparison. We also may compare event-based models like the SCS-CN method to the joint distribution of average rainfall and runoff for many events, as was demonstrated by *Bartlett et al*. [2015].

To conclude, the scientific process is an ongoing one of finding and sharing evidence to support, disprove, or revise hypotheses, theories, and models. Under this light, it is certainly useful for O&C to acknowledge how the SCS-CN model originated, but it is also scientifically relevant for us to provide new physical justification and/or qualification to that model, so that our understanding and predictive capabilities are extended.

Acknowledgments
This work was partially funded through the USDA Agricultural Research Service through cooperative agreement 58-6408-3-027, the National Science Foundation through grants CBET-1033467, EAR-1331846, FESD-1338694, EAR-1316258, and the Duke WISeNet grant DGE-1068871. We kindly thank the editor A. Montanari and reviewer S. Orlandini for their comments and effort. Processed data are available by email from the corresponding author.

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