Reply to comment by Richard M. Iverson on "Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding"

David R. Montgomery
Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA

William E. Dietrich
Department of Earth and Planetary Science, University of California, Berkeley, California, USA

Received 29 October 2003; revised 1 December 2003; accepted 3 December 2003; published 9 March 2004.

INDEX TERMS: 1824 Hydrology: Geomorphology (1625); 1815 Hydrology: Erosion and sedimentation; 1829 Hydrology: Groundwater hydrology; 1875 Hydrology: Unsaturated zone; 1860 Hydrology: Runoff and streamflow

Citation: Montgomery, D. R., and W. E. Dietrich (2004), Reply to comment by Richard M. Iverson on ''Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding,'' *Water Resour. Res.*, *40*, W03802, doi:10.1029/2003WR002815.

[1] *Iverson* [2004] has offered a useful commentary on our paper, and we appreciate this opportunity to offer corrections and to raise some important questions. The issue he raises deals with a subsidiary part of the paper, and none of our primary conclusions are affected by these corrections.

[2] *Iverson* [2000] proposed a useful scaling argument for understanding the relative role in pore pressure development during a rainstorm of lateral flow from upslope contributing areas versus slope normal flow. He suggests that the ratio A/D_0 "approximates the minimum time necessary for strong lateral pore pressure transmission from the area A to the point (x, y, H)," whereas H^2/D_0 "approximates the minimum time necessary for strong slope-normal pore pressure transmission from the ground surface to depth H." Iverson argues that A must be approximated by "some readily measurable property" and states that A is "the area enclosed by the upslope topographic divide and hypothetical flow lines that run normal to topographic contours and bound the region that can contribute surface runoff to point (x, y)." Iverson defines D_0 as the "maximum characteristic diffusivity" given by the ratio of saturated conductivity (K_{sat}) to C_0, the minimum value of $C(\psi)$ defined as "the change in volumetric water content per unit change in pressure head" (i.e., $C(\psi) = d\theta/d\psi$, where θ is the volumetric water content and ψ is pressure head). Iverson introduces D_0 to give a useful "reference time" and argues that comparison of these two timescales demonstrates that the "slope-normal" component must control slope instability because it delivers a pore pressure response much quicker. We argued in this article, and in our previous reports on our study site [*Torres et al.*, 1998; *Montgomery and Dietrich*, 2002] that rapid pore pressure response that controls both slope instability and general hydrologic response is driven by vertical flow, not lateral flow. Hence there is no disagreement between Iverson and us on this important finding. We both agree, too, that the lateral flow contribution is, nonetheless, important in that it affects the "propensity for landsliding" [*Iverson*, 2000] because it strongly influences the pore pressure field antecedent to a burst of rain that could initiate a landslide.

[3] Iverson correctly points out that we miscalculate D_0. Instead, we mistakenly calculated the dimensionally equivalent transmissivity (saturated conductivity times depth), which we often use in subsurface runoff modeling. There is no point in clarifying how we arrived at our estimated timescales for site response, as they were based on an erroneous definition and are simply wrong. Old habits sometimes blind one, and we are thankful that Iverson caught this foolish mistake.

[4] There are, however, some issues in regard to the application of Iverson's scaling ratios to the Coos Bay data that are worth reviewing. In his comment, Iverson argues that an effective depth-averaged $d\theta/d\psi$ for the wet region ($\theta > 0.2$) of the soil-water retention curve of Coos Bay soil is about 0.1 m^{-1}. The soil water retention curves of Coos Bay soils are strongly nonlinear, such that while not "at saturation" small changes in ψ require large changes in θ as the pressure head nears zero, but before the soil reaches saturation. *Torres et al.* [1998, Figure 5] show that soil tensions were nearly all less than -0.1 m in response to irrigation, and a median value of about -0.03 m typified the pressure head for wet conditions. The values of $d\theta/d\psi$ for the change in ψ between -0.1 and a "hinge" beyond which $d\theta/d\psi$ increases greatly as ψ approaches 0 for the six soil water retention curves reported by *Torres et al.* [1998] for CB1 range from 0.1 to 0.7 m^{-1}, or up to seven times the value assumed by Iverson. For winter conditions when landslides are most likely, ψ will be near zero and the soil moisture retention curves for CB1 [*Torres et al.*, 1998] show that $d\theta/d\psi$ may be even larger. This means that D_0, assuming K_{sat} of 10^{-4} m s^{-1}, is from 10^{-3} m^2 s^{-1} to a value of 1.4×10^{-4} m^2 s^{-1}, 7 times smaller than assumed by *Iverson* [2000, Table 1]. Using these values of D_0, H^2/D_0 ranges from about 20 min to 1.9 hr for a 1 m thick soil, and from 1.1 to 7.8 hr for a 2 m thick soil due to the squared dependency on soil depth.

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[5] What is the timescale of observed response at CB1? We have four observations. First, in our paper, we reported the lag from peak of rainfall to peak pore pressure response for piezometers at our site (Figure 16); the mean of these data was 3.4 hours with values varying between 5 min and 3.6 hours for piezometers installed less than 1 m deep, 2.5 to 6.5 hours for piezometers between 1 and 2 m deep, and from 1.8 to 9.9 hours for piezometers deeper than 2 m below the ground surface. Second, as noted by *Torres et al.* [1998], a spike of rainfall occurred after a period of experimental rainfall in which the soils were in the near-zero pressure head state typical of winter conditions. They found that the piezometers typically showed a spike response 1.5 hours later and the discharge peaked 2.5 hours after the rainfall spike. Third, during the storm event that caused CB2 to fail [*Montgomery et al.*, 2002] the piezometric response at CB1 nearest the channel head was about 3 hours after the destabilizing burst of rainfall. Finally, the landslide that occurred in CB1 itself in 1996 initiated one hour after the peak rainfall (D. R. Montgomery et al., manuscript in preparation, 2004). This gross agreement between calculated values of H^2/D_0 and the observed timescale of piezometric response is encouraging.

[6] In assessing the value of A/D_0, *Iverson* [2000] used $A = 100\ \mathrm{m}^2$, while in our paper we argued that the total drainage area of our catchment, 860 m^2, was the more appropriate scale. In his comment, Iverson offers a helpful explanation for the basis of his selection of 100 m^2. Nonetheless, our observations of the lateral timescale of site response are derived from the observed runoff response at the weir draining an area of 860 m^2. While we find Iverson's argument reasonable for selecting a possible drainage area for where a landslide might occur, we point out that our assessment of A/D_0 is for observations for which we are obliged to use the entire drainage area. While it is obvious that A varies with topographic position, the data on reported timescales for the response of CB1 to both irrigation and natural rainfall come from a weir installed at the channel head at the base of CB1. The use by Iverson of A equal to 100 m^2, and D_0 set to $10^{-3}\ \mathrm{m}^2\ \mathrm{s}^{-1}$ leads to a calculated response time of one day which he states in his comment is "in accord with observations at the site." Clearly, somewhere on the slope there will be an $A = 100\ \mathrm{m}^2$ and therefore a predicted lateral response time of 1 day. The pertinent question is whether that is the location for which the observations of CB1 response time can be reasonably compared. We can agree that something like one day is a reasonable estimate for the response time of CB1, as the response time to steady state for our experiment 2 (wet initial conditions having followed experiment 1 and three times the rainfall rate) was about 1 day [*Montgomery et al.*, 1997]. However, if we use the values of $D_0 = 10^{-3}\ \mathrm{m}^2\ \mathrm{s}^{-1}$ to $1.4 \times 10^{-4}\ \mathrm{m}^2\ \mathrm{s}^{-1}$ arrived at by using $d\theta/d\psi = 0.1$ to $0.7\ \mathrm{m}^{-1}$, as supported by tensiometric data, and K_{sat} of $10^{-4}\ \mathrm{m\ s}^{-1}$, then A/D_0 is just over 1 day to 8 days for an area of 100 m^2 and about 10 to 70 days for an area of 860 m^2. Because observations for the timescale for the lateral response of CB1 are based on the response of the weir at the base of the catchment, which has a drainage area of 860 m^2, the agreement between the site response and the timescale for lateral diffusive pressure response predicted by A/D_0 is not as close as implied by Iverson based on his selection of a drainage area for a location well upslope of the weir where response was measured.

[7] *Iverson* [2000] selected the square root of A as the length scale for the lateral transport distance and divided A by the diffusivity term to estimate a timescale for pore pressure diffusion. He is careful to draw the distinction between pressure diffusion and water flow. If the value of A/D_0 for the channel head where a response time of about 1 day is recorded is as long as 10 to 70 days, then lateral pore pressure diffusion does not appear to govern the site response time. One possibility is that the lateral flow response is dominated by the advective response at our site. Others [i.e., *Humphrey*, 1982; *Iida*, 1984] have noted that for simple Darcy flow parallel to the topographic gradient the travel time from the drainage divide to the point of interest gives a timescale of full subsurface flow response to a steady rainfall. Hence, for these simplifying assumptions (in which the unsaturated response is ignored) the travel time is approximately $L/(p^{-1}K_{sat} \sin\alpha)$, in which L is the length scale of the basin (along the slope), and the denominator is the Darcy pore velocity in which α is the topographic gradient and p is the effective porosity. Following Iverson's scaling argument that $A^{-0.5}$ is the appropriate length scale for the lateral flow contribution, we suggest the ratio of $A^{-0.5}/K_{sat}$ may serve as an appropriate advective timescale for lateral flow. For the Coos Bay site, this ratio is $(860\ \mathrm{m}^2)^{-0.5}/10^{-4}\ \mathrm{m\ s}^{-1}$ or 3.4 days, a value reasonably close to the observed findings.

[8] We understand that the primary point of Iverson's argument is that the vertical response time is much shorter than the lateral, and as noted above, on this issue we agree and have shown field evidence to emphasize this point. If the absolute value of the two ratios is not important, only their relative values, then dividing H^2/D_0 by A/D_0 leads to the dimensionless ratio of H^2/A, a ratio independent of soil-water retention properties of the site. For shallow landslides even short distances from the drainage divide, this ratio will be small, indicating dominance of vertical infiltration. If the two ratios are intended, however, to give some insight about the actual timescale of the vertical and lateral response of CB1, then based on our Coos Bay data H^2/D_0 seems useful, particularly when not close to saturation. The proposed lateral response timescale of A/D_0, however, does not appear to predict observed response times for the CB1 catchment, suggesting that lateral advective response may be a more significant control on site response than the lateral diffusive pressure component.

[9] **Acknowledgments.** We thank Iverson for the opportunity to rectify our incorrect calculations and elaborate on the application of his proposed scaling ratios.

References

Humphrey, N. F. (1982), Pore pressures in debris failure initiation, M.S. thesis, 169 pp., Univ. of Wash., Seattle.

Iida, T. (1984), A hydrological method of estimation of the topographic effect on the saturated throughflow, *Trans. Jpn. Geomorph. Union*, *5*, 1–12.

Iverson, R. M. (2000), Landslide triggering by rain infiltration, *Water Resour. Res.*, *36*, 1897–1910.

Iverson, R. M. (2004), Comment on "Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding" by David R. Montgomery, William E. Dietrich, and John T. Heffner, *Water Resour. Res.*, *40*, doi:10.1029/2003WR002077, in press.

Montgomery, D. R., and W. E. Dietrich (2002), Runoff generation in a steep, soil-mantled landscape, *Water Resour. Res.*, *38*(9), 1168, doi:10.1029/2001WR000822.
Montgomery, D. R., W. E. Dietrich, R. Torres, S. P. Anderson, J. T. Heffner, and K. Loague (1997), Piezometric response of a steep unchanneled valley to natural and applied rainfall, *Water Resour. Res.*, *33*, 91–109.
Montgomery, D. R., W. E. Dietrich, and J. T. Heffner (2002), Piezometric response in shallow bedrock at CB1: Implications for runoff generation and landsliding, *Water Resour. Res.*, *38*(12), 1274, doi:10.1029/2002WR001429.
Torres, R., W. E. Dietrich, D. R. Montgomery, S. P. Anderson, and K. Loague (1998), Unsaturated zone processes and the hydrologic response of a steep unchanneled catchment, *Water Resour. Res.*, *34*, 1865–1879.

W. E. Dietrich, Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA.
D. R. Montgomery, Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA. (dave@geology.washington.edu)