



A reference data set of hillslope rainfall-runoff response, Panola Mountain Research Watershed, United States

H. J. Tromp-van Meerveld,¹ A. L. James,² J. J. McDonnell,^{3,4} and N. E. Peters⁵

Received 26 June 2007; revised 19 November 2007; accepted 21 January 2008; published 24 June 2008.

[1] Although many hillslope hydrologic investigations have been conducted in different climate, topographic, and geologic settings, subsurface stormflow remains a poorly characterized runoff process. Few, if any, of the existing data sets from these hillslope investigations are available for use by the scientific community for model development and validation or conceptualization of subsurface stormflow. We present a high-resolution spatial and temporal rainfall-runoff data set generated from the Panola Mountain Research Watershed trenched experimental hillslope. The data set includes surface and subsurface (bedrock surface) topographic information and time series of lateral subsurface flow at the trench, rainfall, and subsurface moisture content (distributed soil moisture content and groundwater levels) from January to June 2002.

Citation: Tromp-van Meerveld, H. J., A. L. James, J. J. McDonnell, and N. E. Peters (2008), A reference data set of hillslope rainfall-runoff response, Panola Mountain Research Watershed, United States, *Water Resour. Res.*, 44, W06502, doi:10.1029/2007WR006299.

1. Introduction

[2] Although hillslope-scale experimental studies of rainfall-runoff behavior in humid regions date back to the early work of Hoover and Hursh [1943], subsurface stormflow remains a poorly understood and poorly conceptualized runoff process. While there have been scores of studies in different climate, topographic and geological settings (see Weiler *et al.* [2005] and Beven [2006] for reviews), few of these data sets are available for use by the scientific community/wider public. Some surface processes can be identified such as infiltration excess overland flow from infiltration tests and saturation excess overland flow from labor-intensive mapping of saturated areas. In contrast, subsurface stormflow is a runoff enigma—it is very difficult to observe and seemingly different at locales with contrasting driving conditions. Part of this enigma relates to the extreme difficulty in acquiring subsurface stormflow data—intensive site investigations, such as a hillslope trench and internal water level measurements, are a precondition for defining internal controls on flow generation.

[3] In this data note, we present a high-resolution spatial and temporal rainfall-runoff data set generated from the Panola Mountain Research Watershed (PMRW) experimental trenched hillslope, henceforth called the PMRW hillslope. This data set has provided new insights into the role of subsurface topography in hillslope-scale runoff generation

[McDonnell *et al.*, 1996; Freer *et al.*, 1997, 2002], the role of hillslope subsurface stormflow in stream runoff generation [Burns *et al.*, 2001], the link between subsurface stormflow and solute flushing [Burns *et al.*, 1998; Burns, 1999], the identification of threshold responses [Peters *et al.*, 2003; Tromp-van Meerveld and McDonnell, 2006a], the fill-and-spill theory [Tromp-van Meerveld and McDonnell, 2006b], the link among soil depth, soil moisture, and plant transpiration [Tromp-van Meerveld and McDonnell, 2006c], and new modeling approaches to describe subsurface stormflow emergent behavior [Lehmann *et al.*, 2007].

[4] Although the PMRW hillslope data set has been extensively analyzed, to date, there has been only limited efforts focused on the intercomparison of hillslope hydrologic response from different climate, topographic and geological settings worldwide [e.g., Uchida *et al.*, 2005]. Further, the use of hillslope data sets to examine model structural development, parameter identification, testing of process descriptions, evaluation of data and model uncertainties and assessments of model performance remains an open and active area of research in which many scientific questions remain.

[5] In this data note, we provide a description of the PMRW hillslope data set for the period January to June 2002, during which rainfall-runoff response was monitored at the permanently excavated trench face and during which detailed, high-resolution internal hydrologic measurements were made. This data set is the first of its kind to be made available. These data are available in the auxiliary material¹ and as online data files at <http://www.sfu.ca/PanolaData/>.

2. Physical Description

[6] PMRW is in the Panola Mountain State Conservation Park, in the Piedmont of Georgia, USA (84°10'W, 33°37'N)

¹Department of Geography, Simon Fraser University, Burnaby, British Columbia, Canada.

²Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, North Carolina, USA.

³Water Resources Section, Delft University of Technology, Delft, Netherlands.

⁴On leave from Department of Forest Engineering, Oregon State University, Corvallis, Oregon, USA.

⁵U.S. Geological Survey, Atlanta, Georgia, USA.

located 25 km southeast of Atlanta. Studies began at the PMRW in 1985 as part of the USGS Acid Rain Thrust Program [Huntington *et al.*, 1993]. In 1991, the 41-ha forested watershed became one of five Water, Energy and Biogeochemical Budgets (WEBB) sites, focusing research on the movement of water and solutes within a small forested watershed and the effects of anthropogenic and environmental change [Lins, 1994].

[7] Climate at the PMRW is humid continental to subtropical with a long growing season, warm temperatures and high rates of evapotranspiration (ET) during summer. Air temperature averages 15.2°C annually and the average monthly temperatures range from 5.5°C during January to 25.2°C during July [NOAA, 1991]. Peters *et al.* [2003] report that during water years (October through September) 1986 to 2001, annual precipitation averaged 1220 mm and ranged from ~760 to 1580 mm; less than 1% of the precipitation occurred as snow; annual runoff averaged 377 mm and ranged from ~150 to 700 mm; and annual water yield averaged 30% and ranged from 16% to 50%. Winter frontal systems provide long, typically low intensity rainstorms in contrast to short, intense convective thunderstorms in spring and summer. PMRW is covered with a mixed deciduous/coniferous forest [Carter, 1978; Cappellato, 1991]; the oldest deciduous trees are ~130 years old and the oldest coniferous trees are ~70 years old (N. E. Peters, unpublished data, 1995). The PMRW hillslope is predominantly deciduous.

[8] The PMRW hillslope was established in 1995 with the excavation of a 1.5-m-wide, 20-m-long trench, at the base of a 48–50-m-long hillslope to examine active hydrologic pathways delivering water to the ephemeral stream channel 30 m downslope [McDonnell *et al.*, 1996]. Depth of the sandy-loam soils [Zumbuhl, 1998; McIntosh *et al.*, 1999] on the hillslope ranges from 0 to 1.86 m [Freer *et al.*, 2002] and are underlain by 320 Ma old Panola granite [Higgins *et al.*, 1988; Crawford *et al.*, 1999] with highly irregular subsurface topography (referred herein as bedrock topography). A detailed hillslope description can be found in work by Burns *et al.* [1998] and Freer *et al.* [1997, 2002]. Additional soil description on the PMRW hillslope and adjacent hillslopes can be found in work by McIntosh *et al.* [1999] and provided in the auxiliary material. Soil macropores are described by Burns *et al.* [1998], Freer *et al.* [2002], and Uchida *et al.* [2005]. A summary of soil and bedrock characteristics including bulk density, porosity, and saturated hydraulic conductivity from McIntosh *et al.* [1999], White *et al.* [2002] and Tromp-van Meerveld *et al.* [2007] is available as descriptive auxiliary material in the HTML. A summary of hillslope process description is also available in the HTML.

3. Data Description

[9] The following data set provides description of the PMRW hillslope and its hydrologic response during the period of January through June 2002. During this period, PMRW was dry with slightly more frequent but smaller rainstorms compared to the 1989–2001 period. Selected additional data from the Panola watershed at the 10 ha and 41 ha scales are currently being reviewed for inclusion in USGS' National Water Information System (NWIS), which provides public access (N. E. Peters, personal communication, 2007).

3.1. Hillslope Digital Elevation Model (DEM)

[10] A 1 × 1 m DEM of ground-surface elevation and bedrock topography interpolated from a 2 × 2 m total station survey [Zumbuhl, 1998; Burns *et al.*, 1998; Freer *et al.*, 1997, 2002] describes the relatively planar surface and highly irregular bedrock topography. Data are stored in Table S1. The local planar coordinate system is used to describe the location names of water table recording wells and soil moisture content measurements described in subsequent sections. Tromp-van Meerveld *et al.* [2006b, Figure 2] show maps of instrument locations, upslope contributing area calculated on the basis of both surface and bedrock topography and soil depth.

3.2. Rainfall-Runoff Data

[11] Detailed rainfall-runoff data were collected from the hillslope from January through June 2002. During this period, 23 discrete rainstorms were recorded ranging in magnitude from 5 to 68 mm, with three rainstorms exceeding 50 mm. The data collection is described by Tromp-van Meerveld and McDonnell [2006a, 2006b]. Stormflow delivered at the trench face via matrix and macropore flow (trench flow) was monitored from the 10 individual 2-m trench sections (Data Set S1) and five macropores [see Tromp-van Meerveld and McDonnell, 2006a, Figure 1]. Trench flow, sectional trench flow and macropore flow are reported in L 15 min⁻¹. Rainfall was recorded using three instrument types: (1) tipping-bucket rain gauges, (2) weighing-bucket gauge and (3) standard gauges. These rainfall data series were combined to yield one rainfall time series for the watershed.

3.3. Water Table Data

[12] Observations of the transient water table that forms at the soil-bedrock interface were collected using a spatial grid of 135 crest-stage gauges (Table S2) and a smaller set of individually instrumented continuous recording wells (Data Set S2). The crest-stage gauges record the maximum rise of the water table generated at the soil-bedrock interface during a defined period of time, typically associated with a rainstorm; pieces of floating cork rise within the gauge and stick on a wooden rod at the maximum water table elevation above the bedrock surface in each gauge. The locations of the 135 crest-stage gauges are shown by Tromp-van Meerveld and McDonnell [2006c, Figure 2]. Spatial maps of maximum water table elevation are available for 17 periods.

[13] A series of 29 water table recording wells provides additional temporal information on the dynamics of the development and decline of transient saturation within the hillslope (Table S3 and Data Set S2). The 29 recording wells are located along two downslope transects and within a bedrock hollow [Tromp-van Meerveld and McDonnell, 2006b, Figure 2]. Recording wells were instrumented with capacitance rods (TruTrack, New Zealand), which measured water table height greater than 7.5 cm above the soil-bedrock interface. Extensive saturation at the bedrock surface, as recorded by crest-stage gauges and water table wells, only occurred during the two largest rainstorms. These rainstorms (6 February 2002 and 30 March 2002) are described by Tromp-van Meerveld and McDonnell [2006b].

3.4. Soil Moisture Data and Soil Moisture Retention Curves

[14] In addition to the observations of water table development, the 2002 PMRW hillslope data set quantifies the relative state of wetness of the hillslope. Soil moisture content was measured with the Aqua-pro radio frequency sensor (Aqua-pro Sensors, Reno, Nevada) over a 4 m × 4 m grid of the hillslope (64 locations) described by *Tromp-van Meerveld and McDonnell* [2006c]. The moisture distributions can also be evaluated with respect to the tree distribution on the hillslope [*Tromp-van Meerveld and McDonnell*, 2006c, Figure 12]. The data records provided herein include 67 individual surveys from February 2002 to June 2002 at depths of 5, 15, 30, and 50 cm below the soil surface as well as profile average soil moisture (Data Sets S3–S6). Integration of the detailed spatial soil moisture data for each x–y soil profile was performed to provide an estimate of relative average hillslope state of wetness [see *Tromp-van Meerveld and McDonnell*, 2006c]. These estimates are provided in Data Set S7.

[15] Moisture retention curves were generated in the laboratory for six 569 cm³ soil cores collected at depths of 15, 40 and 70 cm (H. J. Tromp-van Meerveld, unpublished data, 2003). These previously unpublished data are provided in Table S4.

4. Conclusions

[16] Studies of the trenched experimental hillslope at the Panola Mountain Research Watershed provide a strong reference data set with which to test diverse modeling approaches and process descriptions of rainfall-runoff response. The data set, available in the auxiliary material, encompasses a 6-month period from January through June 2002, and includes high-resolution spatial and temporal internal measurements of subsurface stormflow. We hope that with the noted availability of this PMRW data set, other researchers will be encouraged to publish similar data sets for future intercomparisons. We ultimately hope that through an analysis of these data sets, new subsurface stormflow theories will evolve, deriving new concepts based on classification of dominant behaviors from different geohydroclimatic settings.

Appendix A: Data Files

[17] The following is a brief description of the data files.

[18] Table S1 includes the PMRW hillslope DEM with x, y, z coordinates of ground surface, bedrock elevation topography, and corresponding soil depth. Additional text file with information on local planar coordinate system is also provided.

[19] Data Set S1 includes precipitation, flow from individual 2-m trench sections (matrix plus macropore flow) and total trench flow for the period of January through June 2002. Additional text file with information on rainfall-runoff data collection methods is also provided.

[20] Table S2 includes surface maps (x, y coordinates) of maximum water table rise for 17 periods. Additional text file with information on water table maps is also provided.

[21] Data Set S2 includes water table elevations for 29 recording wells, expressed in cm above the 7.5 cm blanking depth of capacitance rods (e.g., 1 cm recorded water table

elevation = 8.5 cm actual water table elevation). A value of –1 indicates a water table elevation < 7.5 cm. Additional text file with information on water table elevation data collection is also provided.

[22] Table S3 includes water table recording well identification corresponding to local x, y planar coordinate system.

[23] Data Sets S3–S7 include 67 spatial surveys of soil moisture content collected at depths of 5, 15, 30, and 50 cm and profile average soil moisture (in % Aqua-pro sensor units). Additional text file with information on survey data collection is also provided.

[24] Table S4 includes volumetric soil moisture content and corresponding matric potentials for six site-specific soil cores.

[25] **Acknowledgments.** The authors would like to thank Martin Tromp for his assistance in the field during the 2002 field season. We are grateful to Jim Freer and Doug Burns for construction of the excavated trench in 1995–1996; Keith Beven, Rick Hooper, and Carol Kendall for their contributions to the original experimental design; Al Zumbuhl for the collection of the DEM and soil depth data; Brent Aulenbach for database assistance; and the staff of the Georgia Department of Natural Resources Panola Mountain State Park for their ongoing logistical support. Finally, we would like to thank the numerous students, postdoctoral researchers, and colleagues who have worked with us at Panola. The collection of the field work for the 2002 season was funded in part by NSF grant EAR-0196381 and the U.S. Geological Survey's Water, Energy and Biogeochemical Budgets Program (WEBB). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

References

- Beven, K. (2006), Searching for the holy grail of scientific hydrology: $Q_t = H(\bar{S}, R, Df)A$ as closure, *Hydrol. Earth Syst. Sci.*, *10*, 609–618.
- Burns, D. A. (1999), The hydrochemistry of stormflow in a forested Piedmont catchment, Ph.D. dissertation, 193 pp., Coll. of Environ. Sci. and For., State Univ. of N. Y., Syracuse.
- Burns, D. A., R. P. Hooper, J. J. McDonnell, J. E. Freer, C. Kendall, and K. Beven (1998), Base cation concentrations in subsurface flow from a forested hillslope: The role of flushing frequency, *Water Resour. Res.*, *34*(12), 3535–3544, doi:10.1029/98WR02450.
- Burns, D. A., R. P. Hooper, J. J. McDonnell, N. E. McDonnell, J. E. Peters, J. E. Freer, C. Kendall, and K. Beven (2001), Quantifying contributions to storm runoff using end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA), *Hydrol. Processes*, *15*, 1903–1924, doi:10.1002/hyp.246.
- Cappellato, R. (1991), Acidic atmospheric deposition and canopy interactions of adjacent deciduous and coniferous forests in the Georgia piedmont, Ph.D. thesis, Emory Univ., Atlanta, Ga.
- Carter, M. E. B. (1978), A community analysis of the piedmont deciduous forest of Panola Mountain State Conservation Park, M. S. thesis, 126 pp., Emory Univ., Atlanta, Ga.
- Crawford, T. J., M. W. Higgin, R. F. Crawford, R. L. Atkins, J. H. Medlin, and T. W. Stern (1999), Revision of stratigraphic nomenclature in the Atlanta, Athens, and Cartersville 30 × 60 quadrangles, Georgia, *Bull. B-130*, Ga. Geol. Surv., Atlanta, Ga.
- Freer, J. E., J. J. McDonnell, K. J. Beven, D. Brammer, D. A. Burns, R. P. Hooper, and C. Kendall (1997), Topographic controls on subsurface stormflow at the hillslope scale for two hydrologically distinct small catchments, *Hydrol. Processes*, *11*, 1347–1352, doi:10.1002/(SICI)1099-1085(199707)11:9<1347::AID-HYP592>3.0.CO;2-R.
- Freer, J. E., J. J. McDonnell, K. J. Beven, N. E. Peters, D. A. Burns, R. P. Hooper, and B. Aulenbach (2002), The role of bedrock topography on subsurface storm flow, *Water Resour. Res.*, *38*(12), 1269, doi:10.1029/2001WR000872.
- Higgins, M. W., R. L. Atkins, T. J. Crawford, R. F. Crawford III, R. Brooks, and R. Cook (1988), The structure, stratigraphy, tectonostratigraphy and evolution of the southernmost part of the Appalachian orogen, *U. S. Geol. Surv. Prof. Pap.*, *1475*, 173 pp.
- Hoover, M. D., and C. R. Hursh (1943), Influence of topography and soil depth on runoff from forest land, *Eos Trans. AGU*, *24*, 693.
- Huntington, T. G., R. P. Hooper, N. E. Peters, T. D. Bullen, and C. Kendall (1993), Water, energy, and biogeochemical budgets investigation at

- Panola Mountain Research Watershed, Stockbridge, Georgia—A research plan, *U.S. Geol. Surv. Open File Rep.*, 93–55.
- Lehmann, P., C. Hinz, G. McGrath, H. J. Tromp-van Meerveld, and J. J. McDonnell (2007), Rainfall threshold for hillslope outflow: An emergent property of flow path connectivity, *Hydrol. Earth Syst. Sci.*, 11, 1047–1063.
- Lins, H. F. (1994), Recent directions taken in water, energy and biogeochemical budgets research, *Eos Trans. AGU*, 75, 433, doi:10.1029/94EO01063.
- McDonnell, J. J., J. E. Freer, R. P. Hooper, C. Kendall, D. A. Burns, K. J. Beven, and N. E. Peters (1996), New method developed for studying flow in hillslopes, *Eos Trans. AGU*, 77, 465, doi:10.1029/96EO00306.
- McIntosh, J., J. J. McDonnell, and N. E. Peters (1999), Tracers and hydro-metric study of preferential flow in large undisturbed soil cores from the Georgia Piedmont, USA, *Hydrol. Processes*, 13, 139–155, doi:10.1002/(SICI)1099-1085(19990215)13:2<139::AID-HYP703>3.0.CO;2-E.
- NOAA (1991), *Local climatological data, annual summary with comparative data, 1990, Atlanta, Georgia*, 6 pp., Asheville, N.C.
- Peters, N. E., J. Freer, and B. T. Aulenbach (2003), Hydrologic dynamics of the Panola Mountain Research Watershed, Georgia, USA, *Ground Water*, 41(7), 973–988, doi:10.1111/j.1745-6584.2003.tb02439.x.
- Tromp-van Meerveld, H. J., and J. J. McDonnell (2006a), Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope, *Water Resour. Res.*, 42, W02410, doi:10.1029/2004WR003778.
- Tromp-van Meerveld, H. J., and J. J. McDonnell (2006b), Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis, *Water Resour. Res.*, 42, W02411, doi:10.1029/2004WR003800.
- Tromp-van Meerveld, H. J., and J. J. McDonnell (2006c), On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale, *Adv. Water Resour.*, 29, 293–310, doi:10.1016/j.advwatres.2005.02.016.
- Tromp-van Meerveld, H. J., N. E. Peters, and J. J. McDonnell (2007), Effect of bedrock permeability on subsurface stormflow and the water balance of a trenched hillslope at the Panola Mountain Research Watershed, Georgia, USA, *Hydrol. Processes*, 21, 750–769, doi:10.1002/hyp.6265.
- Uchida, T., H. J. Tromp-van Meerveld, and J. J. McDonnell (2005), The role of lateral pipe flow in hillslope runoff response: An intercomparison of non-linear hillslope response, *J. Hydrol.*, 311(1–4), 117–133.
- Weiler, M., J. J. McDonnell, H. J. Tromp-van Meerveld, and T. Uchida (2005), Subsurface stormflow, in *Encyclopedia of Hydrological Sciences*, vol. 3, edited by M. G. Anderson, pp. 1719–1732, John Wiley, Hoboken, N. J.
- White, A. F., A. E. Blum, M. S. Schulz, T. G. Huntington, N. E. Peters, and D. A. Stonestrom (2002), Chemical weathering of the Panola granite: Solute and regolith elemental fluxes and the weathering rate of biotite, in *Water-Rock Interactions, Ore Deposits, and Environmental Geochemistry: A Tribute to David A. Crerar*, edited by R. Hellmann and S. A. Wood, *Spec. Publ. Geochem. Soc.*, 7, 37–59.
- Zumbuhl, A. (1998), Spatial modeling of soil depth and landscape variability in a small forested catchment, M. S. thesis, State Univ. of N. Y., Syracuse.
-
- A. L. James, Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695, USA. (april_james@ncsu.edu)
- J. J. McDonnell, Department of Forest Engineering, Oregon State University, Corvallis, OR 97331, USA.
- N. E. Peters, U.S. Geological Survey, Atlanta, GA 30360, USA.
- H. J. Tromp-van Meerveld, Department of Geography, Simon Fraser University, Burnaby, BC, Canada V5A 1S6.