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Hursh CR and Brater EF (1941) Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow. *Transactions, American Geophysical Union* 22: 863–871

T.P. Burt
University of Durham, UK

W.T. Swank
USDA Forest Service, USA

I Context

The Coweeta Hydrologic Laboratory was established in 1934 (originally known as the 'Coweeta Experimental Forest'). A symposium to celebrate its 75th anniversary in 2009 was an opportunity to acknowledge that some of the world's most important long-term research in forest hydrology and ecology has been conducted there (Swank and Vose, 2009).

To understand the reasons why Coweeta was established, one must understand something of the social, economic and political circumstances at the time. It was concern about soil erosion, flood control and sustained flow of rivers, as well as future timber supplies, that led to the establishment of the first forest reserves (soon to become 'national forests') from the public domain lands of the American West (Douglass and Hoover, 1988). The Weeks Act of 1911 provided the basis for national forests in the East, primarily to protect forest and water resources in the headwaters of navigable rivers. At this time, little was known about the influence of forests on catchment hydrology and interest was at a high level in 1926 when Charles R. Hursh, an ecologist, joined the five-man staff of the newly established Appalachian Forest Experiment Station. Hursh identified the need to understand the relationship between forests and streamflow where erosion was of minor importance. Only then was it possible to show how patterns of runoff and erosion would change when the tree cover was removed. Hursh searched for suitable areas in the Appalachian Mountains where comprehensive studies of forest influence could be made. His site criteria were: a complete headwater drainage basin with well-developed stream networks, perennial flow, high rainfall, deep soils and complete forest cover. The Coweeta basin was selected in 1931 and, following a major programme of construction and surveying, the Coweeta Experimental Forest was

Corresponding author:
Department of Geography, University of Durham, South Road, Durham DH1 3LE, UK
Email: t.p.burt@durham.ac.uk

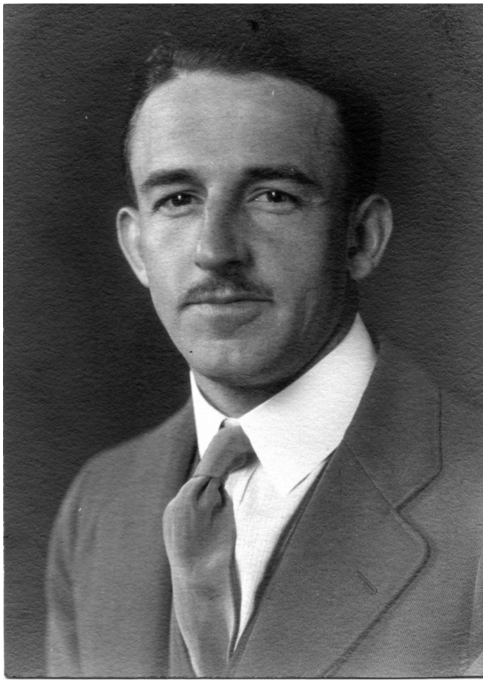

Figure 1. Charles Hursh
Source: Reproduced with permission from the Coweeta Hydrologic Laboratory archive

finally approved on 28 March 1934 (Douglass and Hoover, 1988).

II The authors

Charles R. Hursh (1895–1988; Figure 1) was born in Jonesboro, Illinois. He received a BS from the University of Missouri and a PhD from the University of Minnesota. His first goal at the Appalachian Forest Experiment Station was to define the characteristics of the soil, water and climate of forests and of abandoned agricultural land. He foresaw the need for complete instrumentation of catchments in order to provide continuous measurements of precipitation, groundwater levels and stream discharge. By 1932, Hursh had studied the various needs of the mountain and Piedmont regions of the southeastern USA and had prepared a comprehensive analysis of catchment problems and an approach to solving them (Swank, 1991). The indefatigable Hursh utilized manpower and funds from various federal relief programmes of the 1930s, notably the Civilian Conservation Corps, to enable the infrastructure at Coweeta to be constructed (instrumentation, access roads and buildings).

As the founding Director of the Coweeta Hydrologic Laboratory, Hursh pioneered a number of research themes, most notably the role of vegetation in controlling water yield. While not inventing the practice of paired catchment experiments as a means of conducting field experiments in hydrology – these had been first used in the USA at Wagon Wheel Gap, Colorado (Bates and Henry, 1928) – Hursh established their use as the standard approach. He envisaged three phases to the work: an initial period of standardization when two basins would be compared; a second phase of experimentation when one of the basins would be 'treated' (eg, clear-cutting); and a third phase in which new methods of managing forests for water and other resources would be developed and tested (Douglass and Hoover, 1988). However, Hursh's interests clearly extended beyond water budgets and there was a series of publications dealing with subsurface flow processes, including the paper reviewed here. He was perhaps proudest of his research on vegetation of highway road banks to control erosion. In later years, he worked as a consultant across the USA and in France, Japan, Turkey and Kenya. In 1953 he received the prestigious Nash Conservation Award from American Motors. Hursh published over 125 papers, an enormous output for the time; these have stood the test of time and form the basis of important concepts in hydrological science today. Moreover, the plans he implemented at Coweeta have, with few modifications, continued to guide research methodology there for over 75 years.

Ernest F. Brater (1912–2003) was born in Saginaw, Michigan. He received an undergraduate degree in Civil Engineering from the University of Michigan and, upon completion, began employment as an Assistant in Forest

Influence Investigation at the Appalachian Forest Experiment Station, USDA Forest Service in Asheville, North Carolina. Under the tutelage of Professor Chester O. Wisler at the University of Michigan and Dr Charles Hursh, he conducted his PhD research on the application of the unit hydrograph principles to small watersheds (Brater, 1937). He was the first graduate student (that number now stands at 275) to complete a postgraduate degree based upon work at Coweeta. Subsequently, he joined the faculty in Civil Engineering at the University of Michigan where he served with distinction for 50 years (CEE, University of Michigan Newsletter, 2003). He conducted important research on the efforts of urbanization on storm water runoff and in the field of coastal engineering. He co-authored two books: *Handbook of Hydraulics* with H.W. King and *Hydrology* with C.O. Wisler. He received the Stephen Attwood award in 1971 for ‘extraordinary achievement in teaching and research’; he retired from the University in 1982.

III Hursh’s ideas on catchment hydrology

Between the two world wars, Robert Elmer Horton, a hydraulic engineer, published extensively on overland flow and erosion. Horton emphasized the importance of the process of infiltration; in his view, rain which failed to infiltrate the soil was the sole cause of overland flow and erosion. It followed that surface runoff would be the only contributor to the storm hydrograph and would accrue more or less uniformly from all parts of the basin. Two serious deficiencies were soon recognized in Horton’s approach. The first problem was that calculations of surface runoff only held good for very small areas, such as runoff plots, and that overland flow was evidently not widespread across drainage basins. Second, it soon became recognized, by Charles Hursh and others, that storm runoff contained water with a subsurface origin, as well as the infiltration excess identified by Horton; this ‘other’ water could enter the stream either as subsurface stormflow (also called throughflow or interflow) or as return flow, water which had infiltrated upslope and then seeped back to the surface further down the slope (Burt, 2008). Notwithstanding these issues, Horton’s ideas came to dominate hydrology for several decades.

While Hursh’s work was primarily concerned with forested catchments, he was also interested in what happened when forest was removed and the land used for agriculture. Working with scientists like Ernest Brater and Marvin Hoover, Hursh shaped current concepts of forest hydrology, including water quality. A conceptual diagram produced by Hursh in 1938 (Figure 2) illustrates the hydrological cycle and instrumentation at Coweeta, showing that Hursh was able to integrate his own view of hydrological processes on forested slopes with Horton’s ideas for agricultural land. Hursh identified the dominance of subsurface stormflow in forested catchments: indeed, it was he who first used the term ‘subsurface-stormflow’ (Hursh, 1936). His sketch also suggests the importance of the water table in near-stream zones, presaging John Hewlett’s *Variable Source Area* concept.

IV The paper itself

> To evaluate the effects of different land-management practices on the water economy of small drainage-areas, it is essential that the stream hydrograph obtained from small drainage-areas be separated into ground-water flow and the several components of storm-flow as accurately as the data permit.

The purpose is clear from this opening sentence: to infer stormflow processes from a graphical analysis of storm hydrographs. However, this was not simply an exercise in geometry, and the use of well records to corroborate the results of hydrograph separation anticipates studies of hillslope hydrological processes in the 1970s (see Kirkby, 1978, for example).

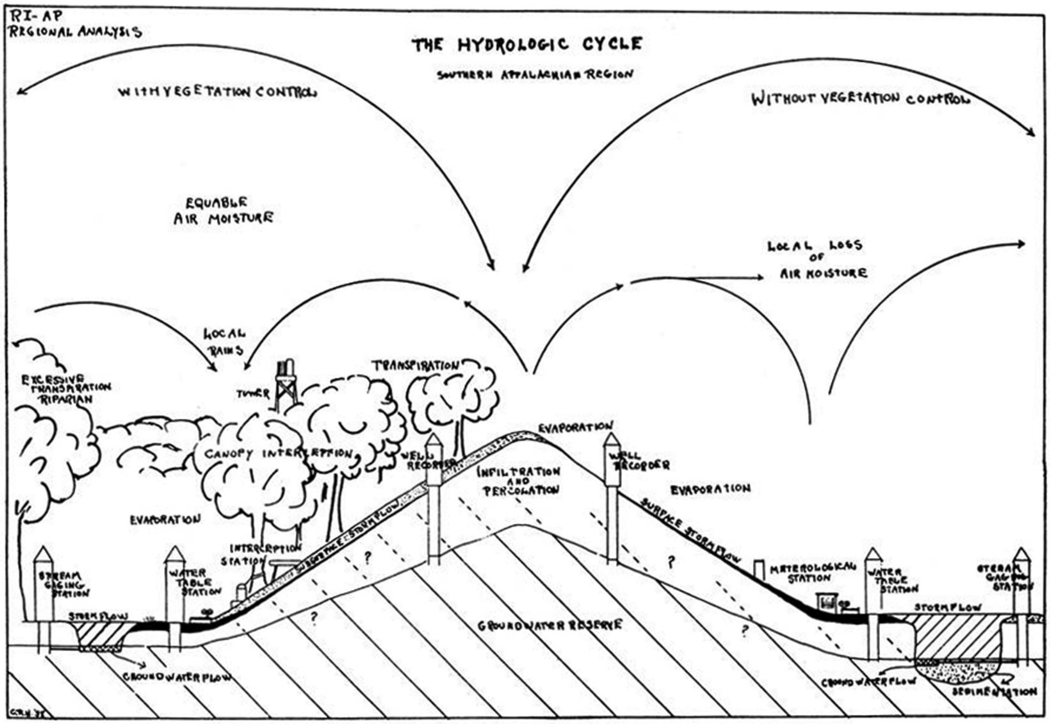

Figure 2. Conceptual diagram developed by C.R. Hursh in 1938 of the hydrological cycle and instrumentation of water balance studies at Coweeta
Source: Reproduced with permission from the Coweeta Hydrologic Laboratory archive

Hursh and Brater's first achievement is important in itself, but often overlooked given the main thrust of their paper: they provide the first evidence of the contribution of direct channel precipitation to stormflow. The paper begins with an analysis of a storm hydrograph (their Figure 1) in which almost all the storm discharge is generated by precipitation falling directly into the channel itself. A caveat of this analysis is that the length of the stream channel used in the computations was overestimated by about 20%. Nevertheless, channel precipitation would still have been the dominant component of this particular storm hydrograph. Apart from a small amount of rain falling just after the main storm, the total input was 0.54 in (13.7 mm) in 25 minutes, equivalent to an average intensity of 1.29 in (32.8 mm) per hour; the maximum 5-minute intensity was 1.68 in (42.8 mm) per hour. These intensities, while impressive enough, are still too low to generate infiltration-excess overland flow on the permeable forest soils at Coweeta.

Given that 'surface storm-runoff as overland flow has not been observed on this drainage-area', Hursh and Brater naturally turned their attention to subsurface stormflow. Their investigation of two further storm hydrographs (their Figures 3 and 4, reproduced here as Figures 3 and 4), where rainfall intensities are not nearly so intense (average intensities: 0.38 in (9.8 mm) and 0.19 in (4.9 mm) per hour), provides new understanding of near-stream hydrological processes. Their analysis shows that only a 'minor portion of the total [storm] flow' is channel precipitation; almost all must be subsurface stormflow therefore. They differentiate two types of response: water 'in close enough proximity to the stream to contribute a significant amount

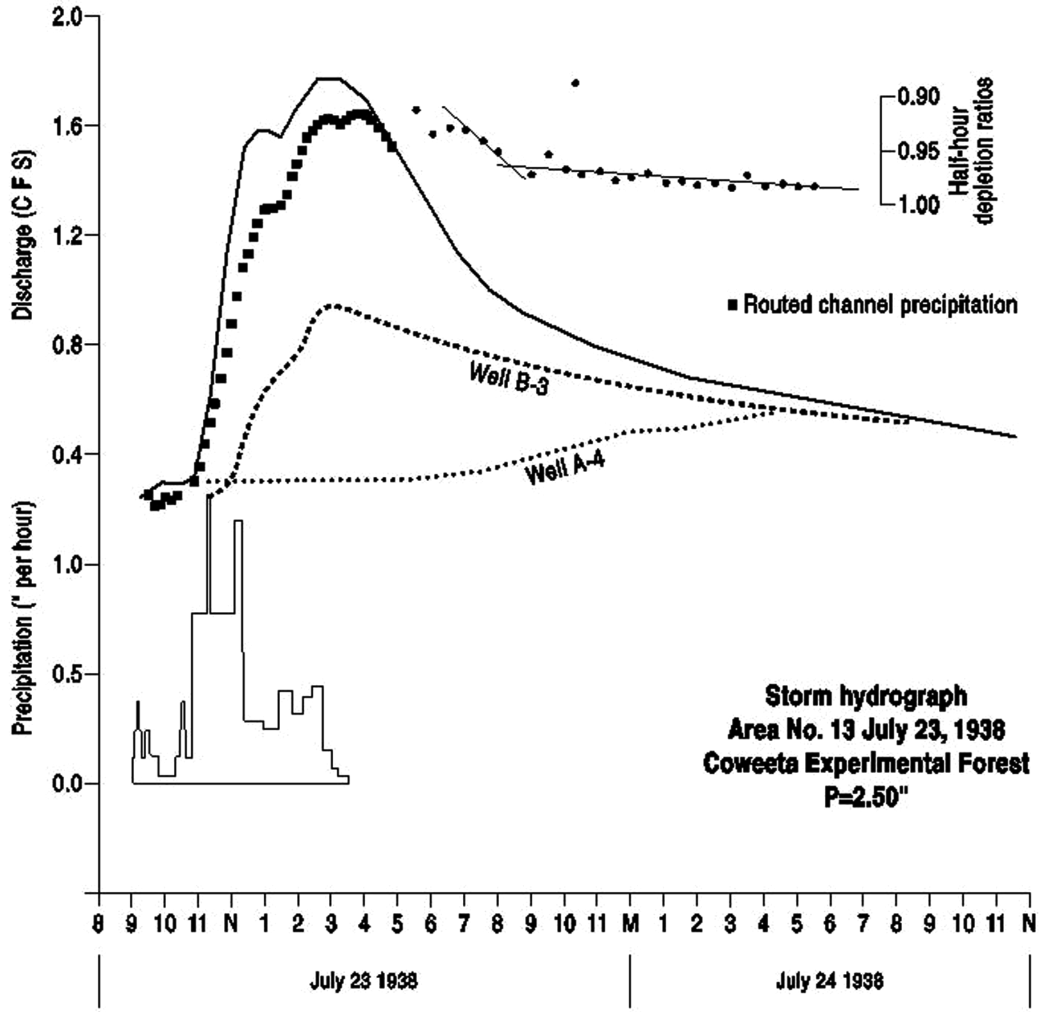

Figure 3. Analysis of the 23 July 1938 storm hydrograph for Watershed 13 at Coweeta
Source: Reproduced by permission of the American Geophysical Union; Hursh and Brater (1941): Figure 3

of percolated water during the period of the storm' and water draining from further upslope that takes longer to reach the stream and so supports the gradual recession in stream discharge after the storm hydrograph. Of course, there is only a single reservoir of soil providing the slope drainage, so their division is arbitrary; nevertheless, they are able to separate near-stream sources that contribute to 'stormflow' and more distant sources that sustain 'baseflow'. They identify the role of water table slope adjacent to the stream in controlling discharge rate (cf. Weyman, 1973) and emphasize the importance of 'rounded bottom ravines' (Well J-1) as potentially importance source areas for subsurface stormflow (cf. Anderson and Burt, 1978). The use of well records to support the graphical analysis is a crucial contribution, providing a bridge between hydrograph separation analysis and process inference. Well A-4 is about 600 ft ($\sim$ 200 m) from the stream and was known to rise slowly after rainfall; its slow recession matches the seasonal depletion curve for the stream and matches the 'traditional'

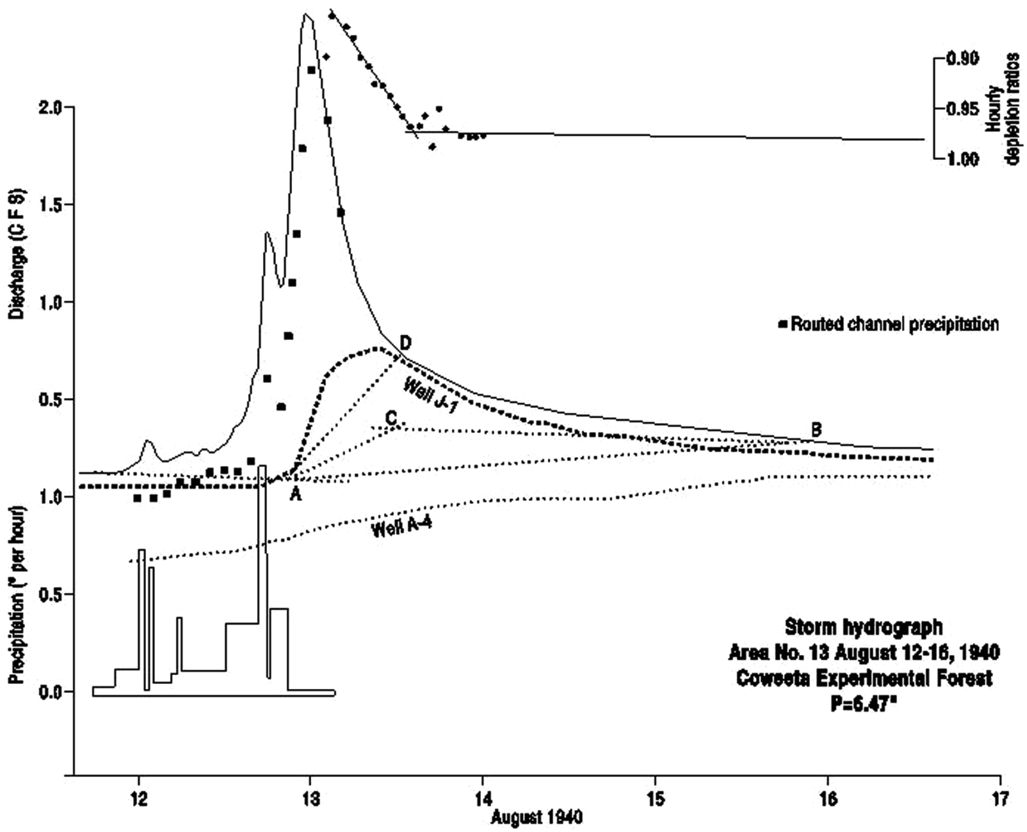

Figure 4. Analysis of the 12–16 August 1940 storm hydrograph for Watershed 13 at Coweeta
Source: Reproduced by permission of the American Geophysical Union; Hursh and Brater (1941): Figure 4

hydrograph separation (line AB on Figure 4). Wells B-3 and J-1 follow the storm hydrograph much more closely and are used to develop new ways of separating different elements of the subsurface stormflow response (lines AC and AD on Figure 4).

At the end of their paper, Hursh and Brater review likely sources of stormflow at Coweeta, arranged in the order in which they might contribute to the storm hydrograph:

(1) channel precipitation;
(2) contributions from areas of shallow water table in close proximity to the stream;
(3) water moving through porous soil horizons close to the surface and under high hydraulic gradient;
(4) storm seepage along natural drainage lines that exist in valleys and ravines infilled with colluvium;
(5) drainage from areas of temporarily high water table on steep slopes.

Of course, more recent research has added greatly to our understanding of the complexity of stormflow generation in time and space, but this is a perceptive list given the date of publication and emphasizes that Hursh's understanding was ahead of his time. Discussing the development of the research programme at Coweeta, Hursh (1932, quoted in Douglass and Hoover, 1988) stated that 'the purpose of the streamflow and erosion study in its broader sense is to determine the principles underlying the relation of forest and vegetative cover to the supply and distribution of meteorological water'. His 1938 drawing of the hydrological cycle shows that he had a clear understanding of the partition of hillslope runoff under differing land-use conditions, with subsurface stormflow dominating under forest cover and surface stormflow after clearance. His work with Ernest Brater on stormflow hydrographs deepened his understanding of subsurface stormflow generation, as well as indicating complexity and the need for further studies.

V Impact

Research at Coweeta laid the foundation for an alternative model of storm runoff generation on hillslopes. At the same time as Horton was publishing on infiltration and surface runoff, Hursh, Brater and others were becoming increasingly aware that overland flow was not being generated on forest slopes in sufficient quantities to account for stormflows from low-order streams (Hibbert and Troendle, 1988). In effect, Hursh and Brater (1941) described the process which 20 years later became known as the *Variable Source Area* concept (Burt, 2008). John Hewlett's (1961) account of processes operating within the steep headwater catchments at Coweeta is the first full description of that concept:

> When rain falls on porous forest soil, it enters the ground and either begins to migrate to the nearest stream or is held as 'retained water' by the soil particles ... Where it sinks in near a stream and consequently can contribute more to immediate rises in streamflow, it generally will move faster than if it enters the drier slopes and ridges above ... Rainfall influence in producing immediate runoff obviously diminishes with distance from the stream channel ... Under prolonged and heavy rainfall, the stormflow-contributing area contiguous to the stream channels may grow wider and wider, depending on the nature and depth of the earth mantle. (Hewlett, 1961)

Originally, Hewlett only emphasized the importance of lower slopes for generating subsurface stormflow, but the link between soil saturation and production of overland flow from limited parts of the slope (which would vary in extent within storms and seasonally) was soon recognized. Where the soil profile becomes totally saturated, for example in hillslope hollows, saturation-excess overland flow is produced by a combination of return flow (exfiltration of soil water) and direct runoff (resulting from rain falling on to a saturated surface). Hewlett's *Variable Source Area* model thus involved a significantly different mechanism from that described by Horton. At first, the concept was not well known, but eventually it has become an accepted alternative to the Hortonian model of stormflow generation (McDonnell, 2009). The influence of Charles Hursh, in particular his 1941 publication with Ernest Brater, is plain to see.

Finally, an indirect link may be drawn between Hursh and Brater's interest in the nature of water making up the storm hydrograph and contemporary studies of stream solute dynamics and catchment biogeochemistry. In the early 1970s, an important development at Coweeta was research on nutrient cycling (Swank *et al*., 2002). One outcome was the concept of nutrient spiralling, which was based on research carried out at Coweeta by Jack Webster for his PhD (Webster and Patten, 1979), complementing the river continuum concept (Vannote *et al*., 1980). The near-stream zone has become a focus for the study of links between flow paths and stream water chemistry (Burt and Pinay, 2005; Cirmo and McDonnell, 1997) using a variety of tracers, such as naturally occurring isotopes and rare earth elements. Quantification of biogeochemical fluxes at the terrestrial-aquatic interface in small catchments with different land uses and land covers is a major challenge for current catchment research. An understanding of flow paths on hillslopes, a theme pioneered by Hursh and Brater (1941), is fundamental to its progress.

References

Anderson MG and Burt TP (1978) The role of topography in controlling throughflow generation. *Earth Surface Processes* 29: 331–334.

Bates CG and Henry AJ (1928) Forest and streamflow experiments at Wagon Wheel Gap, Colorado. Washington, DC: USDA. *Weather Bureau Monthly Weather Review* Supplement 30.

Brater EF (1937) An application of the unit hydrograph principle to small watersheds. PhD dissertation, University of Michigan, 56 pp.

Burt TP (2008) Valley-side slopes and drainage basins. I: Runoff and erosion. In: Burt TP, Brunsden D, Chorley RJ, Cox NJ and Goudie AS (eds) *The History of the Study of Landforms or the Development of Geomorphology. Volume 4: Quaternary and Recent Processes and Forms (1890–1965) and the Mid-Century Revolutions*. London: The Geological Society, 325–352.

Burt TP and Pinay G (2005) Linking hydrology and biogeochemistry in complex landscapes. *Progress in Physical Geography* 29(3): 297–316.

Cirmo CP and McDonnell JJ (1997) Linking the hydrologic and biogeochemical controls of nitrogen transport in near-stream zones of temperate-forested catchments: A review. *Journal of Hydrology* 199: 88–120.

Civil and Environmental Engineering (CEE), University of Michigan Newsletter (2003) Ernest F. Brater, obituary, p. 22.

Douglass JE and Hoover MD (1988) History of Coweeta. In: Swank WT and Crossley DA (eds), *Forest Hydrology and Ecology at Coweeta*. Ecological Studies 66. New York: Springer, 17–31.

Hewlett JD (1961) Watershed management. In: *Report for 1961 Southeastern Forest Expt. Sta*. Asheville, NC: USDA Forest Service, 62–66.

Hibbert AR and Troendle CA (1988) Streamflow generation by variable source areas. In: Swank WT and Crossley DA (eds), *Forest Hydrology and Ecology at Coweeta*. Ecological Studies 66. New York: Springer, 111–27.

Hursh CR (1936) Storm water and absorption. *Transactions, American Geophysical Union* 17: 301–302.

Kirkby MJ (ed.) (1978) *Hillslope Hydrology*. Chichester: Wiley.

McDonnell JJ (2009) Hewlett, J.D. and Hibbert, A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. In Sopper, W.E. and Lull, H.W., editors, *Forest hydrology*, New York: Pergamon Press, 275–90. *Progress in Physical Geography* 33(2): 288–293.

Swank WT (1991) Contribution to *Opportunities in the Hydrologic Sciences*, Committee on Opportunities in the Hydrologic Sciences, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Academy Press, Washington, DC, 176–177. Available at: http://www.nap.edu/openbook.php?record_id=1543

Swank WT and Vose JM (2009) Long-term forest ecosystem research: A programmatic view. Commentary. *Journal of Forestry* 107(7): 335–336.

Swank WT, Meyer JL, and Crossley DA Jr (2002) Long-term ecological research: Coweeta history and perspectives. In: Barrett GW and Barrett TL (eds) *Holistic Science – The Evolution of the Georgia Institute of Ecology (1940–2000)*. New York: Taylor and Francis, 143–163.

Vannote RL, Minshall GW, Cummins KW, Sedell JR, and Cushing CE (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37(1): 130–137.

Webster JR and Patten BC (1979) Effects of watershed perturbation on stream potassium and calcium dynamics. *Ecological Monographs* 49(1): 51–72.

Weyman DR (1973) Measurements of downslope flow of water in a soil. *Journal of Hydrology* 20: 267–84.