

RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

The watershed-ecosystem approach

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As a graduate student, I studied circulation and mixing in lakes, but was fascinated by the numerous biological, geological and chemical (biogeochemical) interactions in lakes. I also had investigated the interactions and interconnections between catchments (watersheds), airsheds and lakes by releasing ¹³¹I into the depths of a meromictic (permanently stratified) lake in northern Wisconsin and then tracing its transport via emerging, flying adult midges (*Chaoborus* spp.) to the lake's shoreline and drainage basin (Hasler & Likens, 1963; Likens, 1962). The surprising finding about this connection (i.e., uphill transport of chemicals, sensu Leopold, 1949), provided my first direct insight into the existence and importance of these vital and interesting biogeochemical interactions and connections (air-land-water interactions).

I began to study these interactions more formally when I moved to Dartmouth College in 1961 and initiated the Hubbard Brook Ecosystem Study (HBES) with Herb Bormann, Noye Johnson and Bob Pierce in 1963. Establishing boundaries for these ecosystems gave quantitative meaning to these studies. Likewise, the mass balance approach of the HBES (Watershed Ecosystem Concept - WEC) (Bormann & Likens, 1967; Likens et al., 2021) applied to watershed-ecosystems of the Hubbard Brook Experimental Forest (HBEF) in the White Mountains of NH, with carefully defined boundaries, provided a potent opportunity to combine hydrology and chemistry and obtain quantitative information on flux of nutrients into and out of adjacent watersheds. The WEC also enabled us to do experimental manipulations at large, catchment scales (an experiment [experimental manipulation] is one of the most powerful tools in science). Our USDA Forest Service partners in the HBES contributed continuous, quantitative, hydrologic data on precipitation amount and streamflow amount to this team effort. Moreover, the ability to do long-term (currently 57+ years and counting for the HBES) integrated biogeochemical and hydrological monitoring at a secure site, coupled with long-term, integrated ecosystem research, provided biogeochemical insights that were not available, or very difficult to obtain, otherwise (e.g., Bormann & Likens, 1967; Likens, 2013). Because of the large scale, watershed manipulation results also had management relevance

(e.g., forestry practices, acid rain mitigation, role of organic debris dams in streams: Bormann & Likens, 1967; Bormann & Likens, 1979; Holmes & Likens, 2016; Likens & Bilby, 1982; Likens, 2010). The role of biology in these air-land-water interactions was demonstrated on many levels. An interesting biogeochemical example was the concentration and transport of dispersed, vital nutrients like calcium and phosphorus to ridge tops in moose antlers (Leopold's "uphill transport") in these watershed-ecosystems (Likens, 2013).

We initiated the WEC in 1963 (Bormann & Likens, 1967) using paired watershed-ecosystems at the HBEF (43°56'N, 71°45'W). A paired watershed approach does not provide a strict "control" needed in experimental studies (Likens, 1985), but does give critical reference information during whole watershed, experimental manipulations. Because these HBEF watersheds were relatively watertight regarding deep seepage (Bormann & Likens, 1967; Juang, 1966; Likens, 2013; Likens et al., 1967), mass balances could be done quantitatively. The difference between input of cations in precipitation and output in stream water also gave conservative, reasonable estimates of geochemical weathering at the watershed scale (Likens, 2013; Likens et al., 1967).

Combining quantitative hydrology (precipitation and streamflow) with quantitative chemistry of precipitation and stream water enabled calculation of Net Hydrologic Flux (NHF). The strong effect of hydrology on NHF was demonstrated frequently in analyses of biogeochemical mass balances in these watershed-ecosystem studies (e.g., Likens et al., 1967; Likens et al., 2021). For example, drought and rewetting are major factors in accumulation, transport, and transformation of solutes in stream water (Likens et al., 2021). Quantitative mass balances represent the biogeochemical connection between small watershed-ecosystems and the larger biospheric systems of the Earth and help to identify the relevant connections pertinent to management intervention (Bormann & Likens, 1967). For example, streamwater outputs of phosphorus and nitrogen from a catchment may represent the major inputs of these critical nutrients for a receiving lake (e.g., Likens & Bormann, 1974).

Whole watershed experimentation (such as the addition of the mineral, Wollastonite [CaSiO₃], to Watershed 1 and removal of trees

in Watersheds 2, 4 and 5; see, Holmes & Likens, 2016 for review of experiments and pertinent references) at the HBEF has provided important opportunities to test major questions in forestry management, acid rain impact, to validate simulation models, etc. Importantly, the watershed/catchment scale is large enough to be management relevant. The HBEF is one of several experimental watershed sites operated by the USDA Forest Service, including the H. J. Andrews Experimental Forest in Oregon and the Coweeta Hydrological Laboratory in North Carolina. These unique sites offer exceptional opportunities for long-term research, monitoring and large-scale experimentation in catchment hydrology, biogeochemistry and ecology, and development and validation of simulation models (e.g., at Hubbard Brook: Federer, 1974; Gbondo-Tugbawa et al., 2001; Holmes & Likens, 2016; Likens, 2013).

Acid rain was discovered at Hubbard Brook in June 1963 (Holmes & Likens, 2016; Likens et al., 1972). The phenomenon is thought to have started in eastern North America in the mid-1950s (Likens et al., 2020, 2021). Therefore, the HBES was initiated at the peak of acidification in the late 1960s-early 1970s (Likens et al., 2021), providing an important disturbance at the time, but the arc of impact lasted over many decades. Because of federal legislation in Clean Air Act Amendments of 1970 and especially 1990, emissions of SO₂ and to lesser extent NO_x, have been markedly reduced. As a result, the acidity of precipitation at HBEF currently is some 80% lower than it was at peak values in the early 1970s (Likens et al., 2020). However, it required 18 years of continuous monitoring to show statistically that a downward trend in acidity was occurring (Likens, 1989). Because of the marked decline in acidity of precipitation and depletion of base cations (calcium, magnesium, potassium, sodium) in soils from long-term acidification, both precipitation and stream water are now showing extreme dilution at the HBEF (Likens & Buso, 2012). Long-term studies like this indicate that novel insights may be unique to the length of recorded measurements and provide a powerful reminder of how important long-term studies and monitoring can be.

Numerous legacies of past disturbance such as forest harvest, severe wind and ice storm damage, and insect outbreaks are layered and embedded in the ecosystems being studied (e.g., Holmes & Likens, 2016; Likens et al., 2021; Likens & Buso, 2010). How they interact and affect current and future conditions of structure and function in ecosystems should be an important part of the planning in future studies and in manipulation experiments. For example, the special role of climate change, regarding hydrologic changes (droughts and storms), on biogeochemistry requires careful study and attention to changes in flow, evapotranspiration and water storage.

The ecosystem approach contributes to integrated assessment and comprehensive management assessments. It is important to recognize, however, the need to evaluate complexity and uncertainty when using the WEC in the study of catchments. Overall, the WEC is a powerful tool in the ecologist's, ecosystem scientist's and hydrologist's scientific toolbox. Designated catchments/watersheds, such as the HBEF, are special systems for integrated, long-term study of

hydrology and biogeochemistry, have been important in developing national policy (e.g., air pollution, forestry management), and need to be sustained, strengthened, elaborated and supported into the future. Designated experimental ecosystems (watersheds and lakes) offer even greater opportunities for important research and monitoring of natural and disturbed systems because of the opportunities provided to do hydrological and biogeochemical experimentation/manipulation at large, management-relevant scales.

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REFERENCES

- Bormann, F. H., & Likens, G. E. (1967). Nutrient cycling. *Science*, 155, 424–429.
- Bormann, F. H., & Likens, G. E. (1979). *Pattern and process in a forested ecosystem* (p. 253). Springer-Verlag: New York.
- Federer, C. A. (1974). A soil-plant-atmosphere model for transpiration and availability of soil water. *Water Resources Research*, 15, 555–562.
- Gbondo-Tugbawa, S. S., Driscoll, C. T., Aber, J. D., & Likens, G. E. (2001). Evaluation of an integrated biogeochemical model (PnET-BGC) in a northern hardwood forest ecosystem. *Water Resources Research*, 37, 1057–1070.
- Hasler, A. D., & Likens, G. E. (1963). Biological and physical transport of radionuclides in stratified lakes. In V. Schultz & A. W. Klement, Jr. (Eds.), *Radioecology* (pp. 463–470). American Institute of Biological Sciences and Reinhold Publ. Corp.
- Holmes, R. T., & Likens, G. E. (2016). *Hubbard Brook: The story of a forest ecosystem* (p. 271). Yale University Press.
- Juang, F. (1966). *The geochemical cycle of chlorine in the Hubbard Brook Watershed, New Hampshire* (M.S. thesis). Dartmouth College, Hanover, NH, p. 71.
- Leopold, A. (1949). *A sand county almanac* (p. 226). Oxford University Press.
- Likens, G. E. (1962). *Transport of radioisotopes in lakes* (Ph.D. thesis). University of Wisconsin, Madison, WI, p. 209.
- Likens, G. E. (1985). An experimental approach for the study of ecosystems. *Journal of Ecology*, 73, 381–396.
- Likens, G. E. (1989). Some aspects of air pollution effects on terrestrial ecosystems and prospects for the future. *Ambio*, 18, 172–178.
- Likens, G. E. (2010). The role of science in decision-making: Does evidence-based science drive environmental policy? *Frontiers in Ecology and the Environment*, 8, e1–e8.
- Likens, G. E. (2013). *The biogeochemistry of a forest ecosystem* (3rd ed., p. 208). Springer-Verlag New York.
- Likens, G. E., & Bilby, R. E. (1982). Development, maintenance and role of organic-debris dams in New England streams. In F. J. Swanson, R. J. Janda, T. Dunne, & D. W. Swanston (Eds.), *Sediment budgets and routing in forested drainage basins* (pp. 122–128). USDA Forest Service. General Technical Report PNW-141.
- Likens, G. E., & Bormann, F. H. (1974). Linkages between terrestrial and aquatic ecosystems. *Bioscience*, 24, 447–456.
- Likens, G. E., Bormann, F. H., & Johnson, N. M. (1972). Acid rain. *Environment*, 14, 33–40.
- Likens, G. E., Bormann, F. H., Johnson, N. M., & Pierce, R. S. (1967). The calcium, magnesium, potassium, and sodium budgets for a small-forested ecosystem. *Ecology*, 48, 772–785.
- Likens, G. E., & Buso, D. C. (2010). Long-term changes in streamwater chemistry following disturbance in the Hubbard Brook Experimental Forest, USA. *Verhandlungen des Internationalen Verein Limnologie*, 30, 1577–1581.
- Likens, G. E., & Buso, D. C. (2012). Dilution and the elusive baseline. *Environmental Science and Technology*, 46, 4382–4387.

- Likens, G. E., Buso, D. C., Bernhardt, E. S., & Rosi, E. (2021). *A century of change: Reconstructing the biogeochemical history of Hubbard Brook*. *Hydrological Processes*. Special Issue. Submitted.
- Likens, G. E., Butler, T. J., Claybrooke, R., Vermeylen, F., & Larson, R. (2020). Long-term monitoring of precipitation chemistry in the U.S.: Insights into changes and condition. *Atmospheric Environment*, 245, 118031.

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