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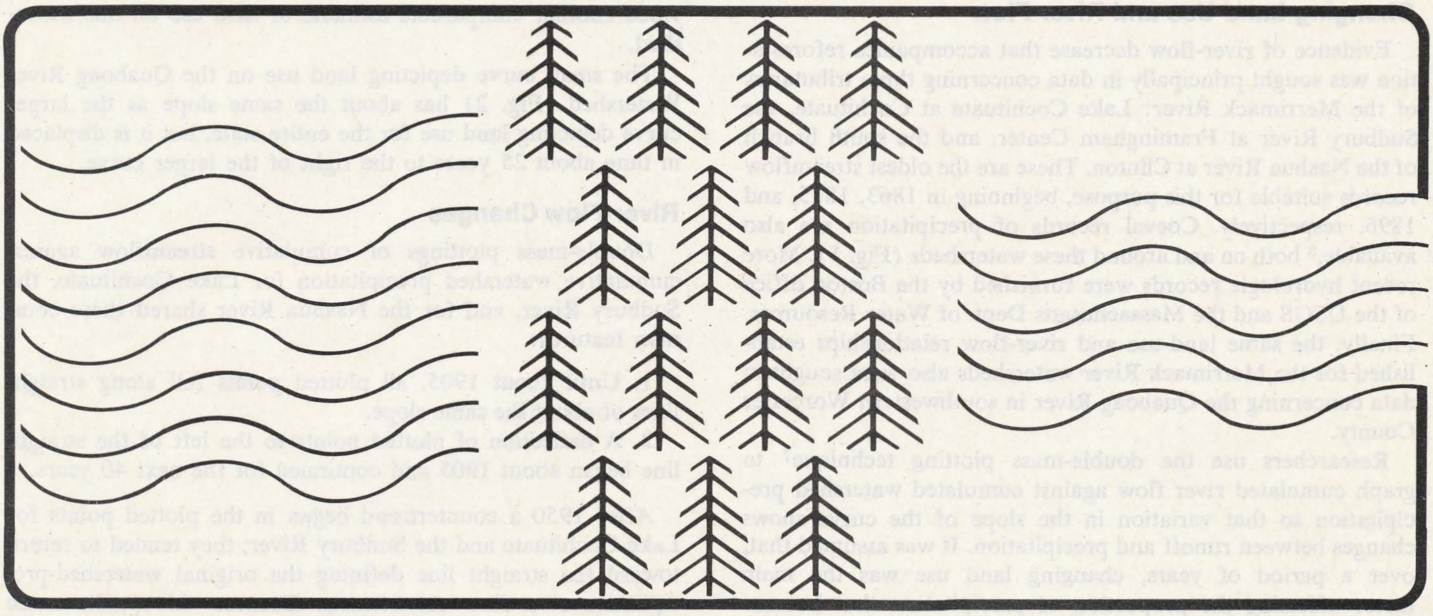
Shifting Land Use and the Effects on River Flow in Massachusetts



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A paper contributed to and selected by the JOURNAL, authored by James H. Patric, proj. leader, Wtr. Mgt. Res., Timber and Watershed Lab., Parsons, W. Va., and Ernest M. Gould, forest economist, Harvard Forest, Petersham, Mass.*

A century ago, land formerly cleared for agriculture in Massachusetts began reverting to forest. It was thought that decreasing streamflow contributed to the decline of water power as the prime energy source in Massachusetts. Some further speculation concerns hydrologic effects of urbanization and of the 1938 hurricane on flow in these streams.

It is generally accepted that streamflow increases after forest cutting and decreases as the forest regrows.[1] Reflection on this theme leads to speculation about streamflow levels in Massachusetts where, from settlement until the mid-nineteenth century, perhaps 80 per cent of the land had been cleared at one time or another for farming.[2]

Beginning about 100 years ago, much of this farmland began to revert to forest, and this process has continued up to the present time. About 65 per cent of the state is now forested.

Did streamflow increase as forests were cleared for farming? Has streamflow decreased as trees reclaimed unused farmland? A complete lack of hydrologic data disallows consideration of the former question; a few useful records do pertain to the latter.

The oldest streamflow record in the US was observed in 1848 on the Merrimack River at Lowell, Mass.[3] It concerned, however, only flow for that period of each work day when mills operated. Other organizations in Massachusetts began to collect streamflow records thereafter, usually at places where the water supply and demand were critical. Thus in 1863, Boston's Metropolitan District Com. (MDC) began collecting both streamflow and precipitation data along those tributaries of the Merrimack River that, until completion of the Quabbin Reservoir, were to supply most of that city's water. The year 1909 marked the beginning of systematically collected streamflow records in Massachusetts, with the State and the USGS[4,5] co-

*Research on which this article was based was completed while the senior author was temporarily assigned as Bullard Fellow at Harvard Univ., Cambridge, Mass.

operating for that purpose. Thus, most river-flow records for Massachusetts begin well into the twentieth century. Even though precipitation is more easily measured, systematically collected records of it before 1900 are also scarce.

With full reliance on the Quabbin Reservoir, urban development has proceeded unrestricted along tributaries of the Merrimack River that formerly supplied water to Boston. Framingham and its environs, for example, occupy virtually all of the Lake Cochituate watershed and much of the Sudbury River drainage. Here, effects of changing land use on streamflow can be surmised. Progressively urbanizing watersheds show trends of increasing hydrologic response and annual runoff.[6]

Changing Land Use and River Flow

Evidence of river-flow decrease that accompanies reforestation was sought principally in data concerning three tributaries of the Merrimack River: Lake Cochituate at Cochituate, the Sudbury River at Framingham Center, and the south branch of the Nashua River at Clinton. These are the oldest streamflow records suitable for this purpose, beginning in 1863, 1875, and 1896, respectively. Coeval records of precipitation are also available,[3] both on and around these watersheds (Fig. 1). More recent hydrologic records were furnished by the Boston office of the USGS and the Massachusetts Dept. of Water Resources. Finally, the same land-use and river-flow relationships established for the Merrimack River watersheds also were sought in data concerning the Quaboag River in southwestern Worcester County.

Researchers use the double-mass plotting technique[7] to graph cumulated river flow against cumulated watershed precipitation so that variation in the slope of the curve shows changes between runoff and precipitation. It was assumed that, over a period of years, changing land use was the main factor affecting the proportion of precipitation that became river flow. But first, the comparability of precipitation records inside and near each watershed was checked by plotting cumulative precipitation in the watershed against cumulative precipitation around it. Mean values of rainfall were used, based on similar numbers of rain-gage records. The points of such plottings fell along straight lines, showing reasonably similar rainfall on and around the watersheds. This similarity was gratifying in view of the region's sparse rainfall record before 1900. Given watershed precipitation representative of that around it, cumulative river-flow data could be plotted against cumulative watershed precipitation. Change in slope of this double-mass plotting line was interpreted as decreased or increased river flow resulting from changed land use.

Land-Use Changes

Land use unquestionably has changed in Massachusetts (Fig. 2). Data for the years 1900–1940 were published by the National Resources Planning Bd.,[8] and subsequent figures were published by Ferguson and Howard[9] and by Lull.[10] The plotted points for 1870 and 1890 depart considerably from the eye-fitted trend line through these data, but this probably reflects the different definitions of farm and forest land used for census for those years. Despite these minor and probably meaningless discrepancies, the available data show a near-doubling of forest land in Massachusetts between 1900 and 1940. The reversion from farm to forest in Middlesex and Worcester counties, containing the entire watersheds for these streams, differed little in timing or extent from the rest of the state.[2]

The Quaboag River Watershed is different, however; it is of special interest because reversion from farm to forest lagged behind the rest of the state.[2] Three independent estimates of land use confirm this lag:

1. The Census of 1930 includes a special report concerning minor civil divisions, permitting computation of weighted average land use for all towns composing the Quaboag River Watershed.
2. A similar weighted average was computed for the same towns, based on aerial photographs taken about twenty years later.[11] However, it was necessary to normalize the photographic data to the 1950 Census report before all of these estimates of land use were comparable.
3. A summary of Soil Conservation Dist. farm plans* provided another comparable estimate of land use on this watershed.

The small curve depicting land use on the Quaboag River Watershed (Fig. 2) has about the same slope as the larger curve depicting land use for the entire state, but it is displaced in time about 25 years to the right of the larger curve.

River-Flow Changes

Double-mass plottings of cumulative streamflow against cumulative watershed precipitation for Lake Cochituate, the Sudbury River, and for the Nashua River shared these common features:

1. Until about 1905, all plotted points fell along straight lines of about the same slope.
2. A deflection of plotted points to the left of the straight line began about 1905 and continued for the next 40 years.

After 1950 a countertrend began in the plotted points for Lake Cochituate and the Sudbury River; they tended to return toward the straight line defining the original watershed-precipitation–river-flow relationship. Because this performance was consistent, an average precipitation–river-flow relationship was plotted for these streams (Fig. 3). Maximum leftward deflection for these plotting points suggests decreased river flow totaling almost 60 in. from 1905–1950, an average flow loss accompanying reforestation of about 1.5 in./year. Rapid decrease of farmland (or increase of forest) began in Massachusetts about 1910, apparently coinciding in time with declining river flow (Fig. 2).

Maximum leftward deflection of double-mass plotting points for Lake Cochituate and the Sudbury River occurred aound 1950. Subsequently they tended to return to the right, toward the line calculated by linear regression that defined the original precipitation–river-flow relationship. This increased flow effect was most pronounced at Lake Cochituate, the smallest and most urbanized watershed, and probably has been little influenced by agriculture or afforestation since 1950. Instead, it probably reflects urbanization.

During the past century, and particularly since WW II, Cochituate and Framingham have evolved from rural crossroads communities to suburban centers replete with interstate highways, miles of paved streets, shopping plazas, and acres of roofs. These impervius surfaces increased overland flows during storms and correspondingly decreased soil moisture storage and evaporative losses between storms. The net effect is more flashy streams with increased annual flow.[6]

Double-mass plotting of cumulative streamflow against

*Watershed work plan for watershed protection and flood prevention, Upper Quaboag River. Mimeographed report on file at the State Office, US Soil Conservation Svce., Amherst, Mass. (1961)

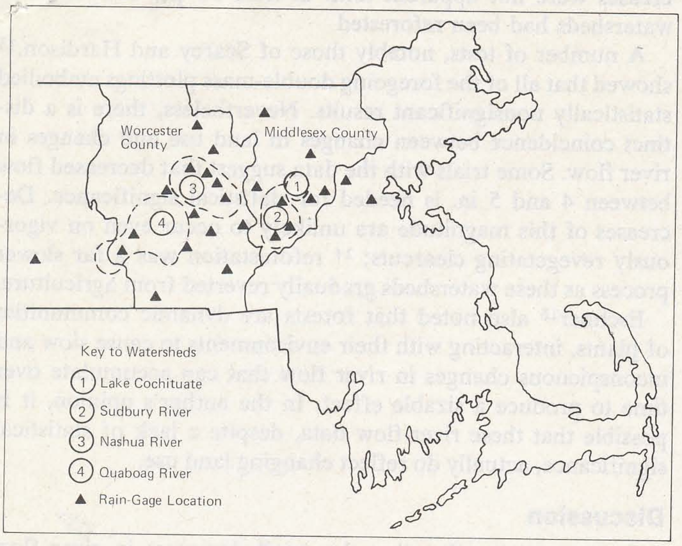

Fig. 1. Locations in Massachusetts of Watersheds and Rain Gages

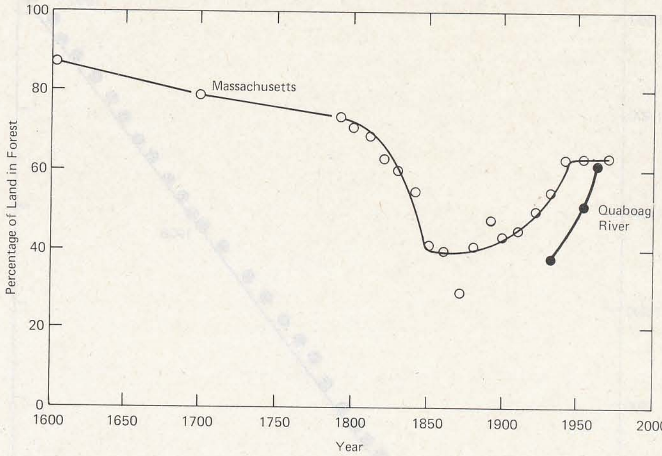

Fig. 2. Land-Use Change in Massachusetts and on the Quaboag River Watershed

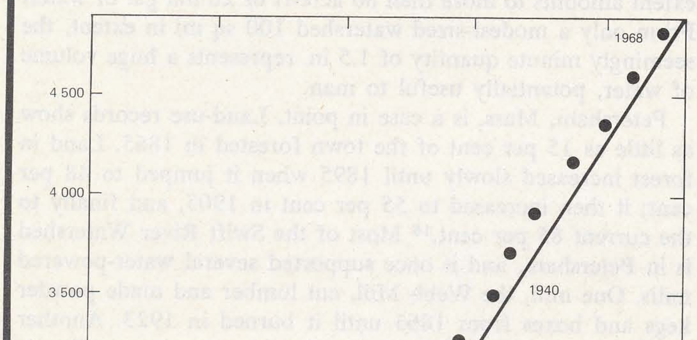

Fig. 3. Double-Mass Plotting of Average Flow in Lake Cochituate and the Sudbury River Against Precipitation on Their Watersheds

Points are plotted at five-year intervals to avoid cluttering record

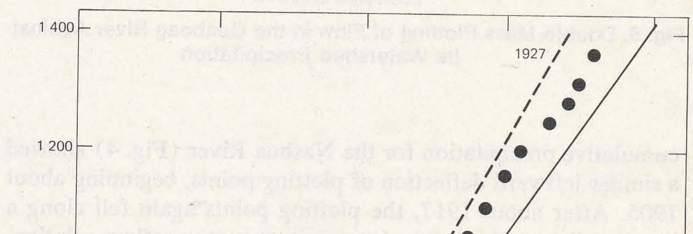

Fig. 4. Double-Mass Plotting of Flow in the Nashua River Against Precipitation on its Watershed

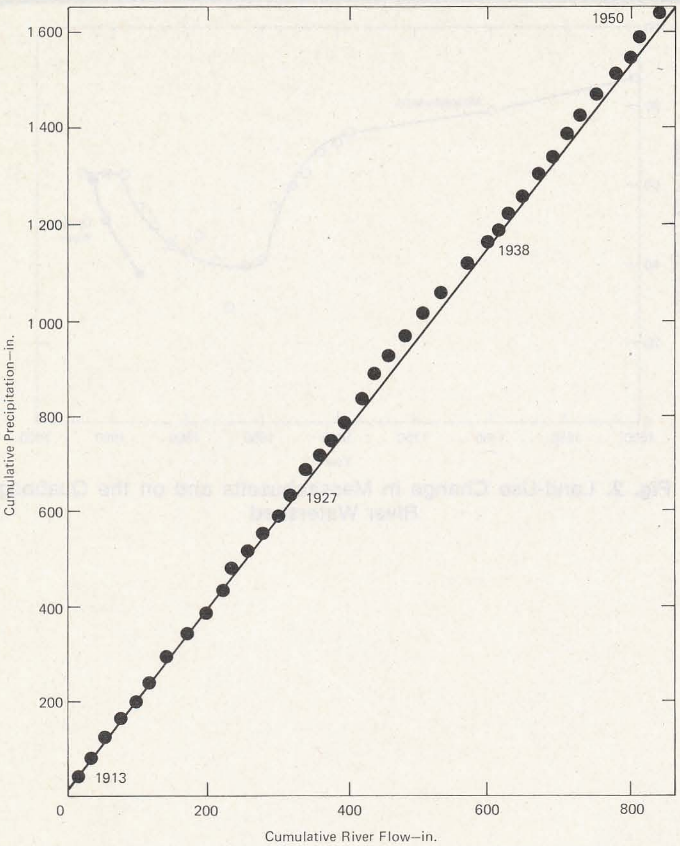

Fig. 5. Double-Mass Plotting of Flow in the Quaboag River Against its Watershed Precipitation

cumulative precipitation for the Nashua River (Fig. 4) showed a similar leftward deflection of plotting points, beginning about 1905. After about 1917, the plotting points again fell along a line parallel to the original precipitation–streamflow relationship. Presumably, reversion of farmland to forest had halted temporarily, perhaps in response to the higher prices for farm products that accompanied and followed WW I. Urbanization has not been widespread on this watershed; and the leftward deflection of plotting points resumed after 1930, possibly reflecting the considerable decrease in farming that accompanied the Great Depression. It appears that flow in this river has averaged almost 2 in. less since 1905 than before that year.

A like trend of diminishing river flow accompanying afforestation shows in the double-mass plotting for the Quaboag River (Fig. 5). There are two points of special interest on this plotting:

1. Leftward deflection from the original precipitation–river-flow relationship began between 20 and 25 years later than on the Merrimack River tributaries, seemingly reflecting the delayed reforestation shown in Fig. 2

2. For a few years after 1938, the plotting points fell closer to a line defining the original precipitation–river-flow relationship, presumably an effect of the New England hurricane. Forest destruction by that storm, severe enough to increase flow in the Merrimack and Connecticut Rivers,[12] may have reversed the trend of diminishing flow in this Connecticut River tributary.

The plotting point for 1940 in Fig. 3 suggests a similar hurricane effect on the Merrimack River tributaries. It seems that flow in the Quaboag River has averaged about 1 in. less since 1927 than before that year. For all of these rivers, flow decreases were not apparent until at least 50 per cent of their watersheds had been reforested.

A number of tests, notably those of Searcy and Hardison,[13] showed that all of the foregoing double-mass plottings embodied statistically nonsignificant results. Nevertheless, there is a distinct coincidence between changes in land use and changes in river flow. Some trials with the data suggest that decreased flow between 4 and 5 in. is needed for statistical significance. Decreases of this magnitude are unlikely to occur even on vigorously revegetating clearcuts; [14] reforestation was a far slower process as these watersheds gradually reverted from agriculture.

Eschner[15] also noted that forests are dynamic communities of plants, interacting with their environments to cause slow and inconspicuous changes in river flow that can accumulate over time to produce a sizable effect. In the author's opinion, it is possible that these river-flow data, despite a lack of statistical significance, actually do reflect changing land use.

Discussion

Some may question that the small decreases in river flow noted in this article can in fact have any real influence on human activity. Such doubts are best dispelled by considering such flow losses on a watershed scale. For example, 1.5 in. of streamflow lost annually from a tiny watershed 1 sq mi in extent amounts to more than 80 acre-ft or 26 mil gal of water. From only a modest-sized watershed 100 sq mi in extent, the seemingly minute quantity of 1.5 in. represents a huge volume of water, potentially useful to man.

Petersham, Mass. is a case in point. Land-use records show as little as 15 per cent of the town forested in 1865. Land in forest increased slowly until 1895 when it jumped to 48 per cent; it then increased to 55 per cent in 1905, and finally to the current 85 per cent.[16] Most of the Swift River Watershed is in Petersham, and it once supported several water-powered mills. One mill, the Webb Mill, cut lumber and made powder kegs and boxes from 1863 until it burned in 1923. Another water-powered sawmill took its place but was soon discontinued. Some people recall that the Webb Mill had enough water to run 10 hr a day even in the summer into the first decade of the 1900s. By the early 1920s, however, running time was down to a half day when the trees were transpiring at full force. Research in New Hampshire[17] suggests that reforestation will cause maximum decreases in the summertime.

A broader significance is apparent when one remembers that the New England industrial revolution was firmly based on water power. In the early 1800s, the factory system began to absorb significant amounts of labor; this raised the demand for farm products, stimulated land clearing, and increased runoff for the mills. At this stage, the industry–river–farm–forest systems worked together to foster regional development. Later, western competition depressed New England farming; but manufacturing continued and took up much of the employment slack. Before the ensuing afforestation could greatly affect river flow, most mills had shifted to other forms of power. Presently, urban demands for water are straining runoff capabilities; but greater streamflow from built-up areas is unlikely to satisfy these needs, especially for uncontaminated water.

One may ask if a flow decrease of 1.5 in/year is realistic in view of research. Conceptually, this question has been answered simply and conclusively:

If agricultural cropland or grassland is afforested, the subsequent reduction in water yield will be proportional to the evapotranspiration differences between the original cover and that of the forest which replaces it.[1]

The answer in terms of actual amounts of water, however, is not so definite.

The insurmountable difficulty of answering quantitatively stems from the multitude of simultaneous activities on populated watersheds, each influencing evapotranspiration in a different way. Research provides some answers, but usually from single-use watersheds. Hibbert[18] postulated streamflow decreases of 0.084 in./year for every 1 per cent of the watershed afforested. North Carolina streams decreased 3–6 in. in flow during the first year of forest regrowth after clearcutting.[14] Decreased flow at substantially lesser rates continued for the 3–16 years needed to reestablish preclearcutting evapotranspiration.

Hay-cutting reduced evapotranspiration to 50 per cent of potential rates, and about a month of grass regrowth was needed to reestablish water use at near-potential rates.[19] Streamflow increases averaging 1 in./year accompanied declining vigor of grass.[20] Thus, some events (forest- and hay-cutting, grazing, and tillage) tend to increase streamflow, and others (tree and grass regrowth, brush invasion of pastures, and crop fertilization) tend to decrease it. In the balance, streamflow from 1910 to 1950, averaging 1–2 in./year less than flow at the peak of land clearing for agriculture, seems well within the realm of possibility.

A remark concerning the streamflow record for Lake Cochituate[5] suggests that the discovery of altered flow is not an unprecedented discovery:

Records subsequent to the 1938 water year have been found to be in error on the basis of a precipitation-runoff study of the original data and comparison with records for nearby stations. Records for the water years 1951–58 are not published herein,* and all published records since 1938 should not be used.

It is interesting to speculate on why these records were considered erroneous; two causes are known that could have contributed to this evaluation:

1. The New England hurricane of 1938 destroyed vast areas of forest, measurably increasing flow of the Connecticut and Merrimack rivers for three years thereafter.[12] Double-mass plotting of precipitation and streamflow also showed post-hurricane streamflow increases in tributaries of these rivers.

2. The authors' results further suggest that urbanization effects on streamflow must have begun about 1950, probably adding to the uncertainty expressed by the USGS, concerning the accuracy of this record.

Thus, it seems possible that the error perceived in their study may in fact be evidence of real but gradual changes in the post-1938 precipitation–runoff relationship for Lake Cochituate.

Conclusions

The authors' data suggest a three-stage precipitation–streamflow relationship accompanying the shift from farm to forest to urban-dominated landscapes in central Massachusetts:

1. Maximum annual flows probably occurred when 60 per cent or more of the land was farmed. Hydrologic data are unavailable for quantifying streamflow during the peak farming period.

2. When less than 60 per cent of their watershed was farmed, annual flow in these rivers averaged 1.5 in. less than flow during the peak farming period.

3. Increasing annual flow accompanied urbanization, beginning about 1950. Apparently, greater proportions of the rainfall were diverted to overland flow, with correspondingly decreased evaporative losses. Even though the annual water yield increased during urbanization, streams probably tended to unwanted flashiness caused by lack of infiltration opportunity during storms.

*Streamflow records for Lake Cochituate from 1951 to 1968 were furnished by Prof. G. R. Higgins, Engr. Dept., Univ. of Massachusetts, Amherst, Mass.

References

1. DOUGLASS, JAMES D. & SWANK, WAYNE T. Streamflow Modification Through Management of Eastern Forests. USDA Forest Svce. Res. Ppr. SE-94, Asheville, N. C. (1972).
2. BLACK, JOHN DONALD & WESCOTT, GEORGE WILLIAM. *Rural Planning of One County*. Harvard Univ. Press, Cambridge, Mass. (1959).
3. KNOX, C. E. & SOULE, R. M. Hydrology of Massachusetts: Part 1, Summary of Streamflow and Precipitation Records. USGS Wtr. Sply. Ppr. 1105, Washington, D. C. (1949).
4. Compilation of Records of Surface Waters of the United States Through September 1950. Part 1-A. North Atlantic Slope Basins, Maine to Connecticut. USGS Wtr. Sply. Ppr. 1301, USGS, Washington, D. C. (1954).
5. Compilation of Records of Surface Waters of the United States, October 1950 to Sep. 1960. Part 1-A. North Atlantic Slope Basins, Maine to Connecticut. USGS Wtr. Sply. Ppr. 1721, Washington, D. C. (1964).
6. LULL, HOWARD W. & SOPPER, WILLIAM E. Hydrologic Effects, from Urbanization of Forested Watersheds in The Northeast. USDA Forest Svce. Res. Ppr. NE-146, Washington, D. C. (1969).
7. ANDERSON, HENRY W. Detecting Hydrologic Effects of Changes in Watershed Conditions by Double-Mass Analysis. *Trans. Amer. Geophy. Union*, 36:1:119 (1955).
8. BALDWIN, HENRY I. *Forestry in New England*. Natural Resources Planning Bd., Boston, Mass. (1942).
9. FERGUSON, ROLAND H. & HOWARD, MILFORD C. The Timber Resources in Massachusetts. Northeastern Forest Exp. Sta, Upper Darby, Pa. (1956).
10. LULL, HOWARD W. A Forest Atlas of the Northeast. USDA Forest Svce. Northeastern Forest Exp. Sta., Upper Darby, Pa. (1968).
11. MACCONNELL, WILLIAM P. & GARVIN, LESTER E. Cover Mapping a State from Aerial Photographs. Photogrametry Engrg., (Sept. 1956). pp. 702–707.
12. PATRIC, JAMES H. River Flow Increases in Central New England After the Hurricane of 1938. *Jour. Forestry*, 72:1:21 (1974).
13. SEARCY, JAMES K. & HARDISON, CLAYTON H. Double-Mass Curves. Manual of Hydrol.: General Surface-Water Techniques. USGS Wtr. Sply. Ppr. 1541-B Washington, D. C. (1960).
14. SWANK, W. T. & HELVEY, J. D. Reduction of Streamflow Increases Following Regrowth of Clearcut Hardwood Forests, in Symp. on the Results of Research on Representative and Experimental Basins. (1970) pp. 346–360.
15. ESCHNER, ARTHUR R. Effects of Long-Term Protection Policy on Water Yields. Municipal Watershed Mgmt. Symp. Proc. Pubn. 446, Univ. of Massachusetts, Amherst, Mass. (Nov. 9–10, 1965). pp. 8–15.
16. RAUP, H. M. & CARLSON, R. E. The History of Land Use in the Harvard Forest. Harvard Forest. Bull. No. 20, Petersham, Mass. (1941).
17. PIERCE, R. S., ET AL. Effect of Elimination of Vegetation on Stream Water Quantity and Quality. IASH–UNESCO, Symp. on Results of Research on Representative and Experimental Basins, Wellington, New Zealand. (Dec. 1970).
18. HIBBERT, ALDEN R. Forest Treatment Effects on Water Yield, in *Intl. Symp. on Forest Hydrol.*, Pergamon Press, London (1967). pp. 527–543.
19. MUSTONEN, SEPPO, & MCGUINESS, J. L. Lysimeter and Watershed Evapotranspiration. *Wtr. Resources Res.*, 3:4:989 (1967).
20. HIBBERT, A. R. Water Yield Changes After Converting a Forested Catchment to Grass. *Wtr. Resources Res.*, 5:3:634. (1969).

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