On the Ratio of Evaporation to Precipitation[1]

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ABSTRACT

The evaporation ratio ϵ is defined as the ratio of the evaporation actually occurring under natural conditions over a given area to the precipitation falling on that area. Data drawn from a variety of sources are used to obtain simple climatological estimates of ϵ. The mean value of ϵ over all the world's land surfaces is probably near 0.65, with individual continents ranging from 0.60 for North America to 0.87 for Australia. For the United States, ϵ averages about 0.73, with local ϵ values ranging from near 1.0 in the southwestern deserts to essentially zero in the Pacific Northwest coastal slopes and in portions of Maine. A chart depicting the generalized pattern of ϵ over the United States east of the Rocky Mountains is presented.

1. Introduction

The purpose of the following discussion is to assemble into one note a number of reference data pertaining to the ratio between actual evaporation and precipitation. If, for any given land area and time interval, we divide the actual evaporation by the precipitation, the quotient may be usefully designated as the *evaporation ratio,* ϵ, for that area and time. The magnitude of ϵ is of interest in a number of hydrometeorological considerations. It should be stressed that all remarks made here pertain not to evaporation rates from free water surfaces as estimated by evaporimeter measurements nor to theoretical estimates of potential evapotranspiration, as developed particularly by Thornthwaite, but to *actual* evaporation as determined by those many factors that operate upon soil and plant moisture to cause parts of the moisture to escape into the atmosphere.

To have available information on climatoligical mean values of ϵ is important in various kinds of water budget studies and in applied meteorological studies concerned with efforts to influence runoff yields from given watersheds. The writer has recently found it necessary to gather data pertaining to ϵ and the complementary quantity $1\text{-}\epsilon$ (which may, in absence of appreciable storage, be termed the *runoff ratio* ρ) while analyzing hydrometeorological problems associated with plans aimed at increasing runoff yields from central Arizona mountain watersheds through modification of the natural vegetation cover. In Arizona, as in other arid regions, ϵ is so near unity, even for those higher-altitude areas yielding most of the useful runoff, that proposals to influence runoff can be quite misleading if careful allowance is not made for heavy evaporative losses. In the following, several types of data concerning geographical variation of the quantities ϵ and ρ will be discussed from a climatological viewpoint.

2. Method of estimation

Over short periods of time and in small drainage areas, transient water storage in the form of surface detention or slowly percolating ground water or even divergence in the gross flux of water can be large enough to render invalid the assertion that total precipitation P must equal total runoff plus total evaporation. When, however, we deal with annual mean values based on a number of years of record, as will be the case in all of the present remarks, storage effects become insignificant in all but very exceptional cases; thus, it becomes possible to infer the value of ϵ from information concerning just mean runoff, mean precipitation and drainage areas.

Useful reference data on runoff for the United States are to be found in a variety of publications of the U. S. Geological Survey, notably in that agency's *Water Supply Papers*. Most of the estimates of ϵ to be given here involve runoff data from such sources. Most of the precipitation data used are taken from published U. S. Weather Bureau records.

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TABLE 1. Annual mean water balance data (from Budyko [2]).

Continent	P(in)	ϵ	ρ
Europe	23	0.60	0.40
Asia	24	0.64	0.36
North America	26	0.60	0.40
South America	53	0.64	0.36
Africa	26	0.76	0.24
Australia	18	0.87	0.13
All land areas	28	0.65	0.35

3. Some mean values of ϵ and ρ

Meyer [1] estimated total runoff to the oceans from all the world's continent's as 7×10^3 mi^3 and continental precipitation as 35×10^3 mi^3, whence his figures imply $\epsilon = 0.20$, $\rho = 0.80$. However, Meyer's mean land precipitation was incorrect, being 40 inches, the Meinardus estimate for the entire globe including the oceans. Also, his runoff estimate is probably low. Budyko [2] summarizes what appears to be magnitudes arrived at by considerably more-careful analyses.[2] For all *land* areas, the Russian studies have given 28 inches for annual average precipitation, 10 inches for average depth-equivalent of runoff, and 18 inches for evaporation. A runoff of 10 inches over all land areas implies a world total of 9×10^3 mi^3, noticeably larger than the estimate of Meyer and still larger than an estimate of 6×10^3 mi^3 given more recently by Fox [3]. From Budyko's data, we infer annual global means of $\epsilon = 0.65$, $\rho = 0.35$. These will be accepted here as probably the best now available. In table 1 are presented, for climatological reference purposes, values of ϵ and ρ derived from Budyko's precipitation, evaporation, and runoff estimates for individual continents. The arid character of much of Australia and Africa is clearly reflected in these values.

In a study of the water balance of an area comprising most of North America for a time period of a single year, 1949, Benton and Estoque [4] obtained estimates of 27 inches for P, and 7 inches for runoff, whence $\epsilon = 0.74$, $\rho = 0.26$, a distinctly higher ϵ and lower ρ than Budyko presents as a long-term average for North America; but Budyko includes Mexico and Central America in what he terms "North America," so the two estimates are not directly commensurate on either geographic or temporal basis.

[2] Budyko's monograph also contains some interesting discussions of theoretical relations between the runoff ratio and other climatic variables.

For just the area of the United States, reasonably reliable estimates of mean annual ϵ and ρ are obtainable from standard precipitation data plus runoff data for rivers flowing into the surrounding oceans and for those carrying water across the Canadian and Mexican borders. By using U. S. Geological Survey data presented by Wrather [5] for the major segments of the national boundaries, one obtains the effective mean runoff depths that have been summarized in table 2 for their intrinsic climatological interest. It may be well to point out here that runoff is only measured in streams of such size that it is tolerably correct to say that, once a molecule of water has reached such a stream via overland flow or seepage, it suffers only slight additional chance of being lost to the atmosphere via evaporation before it can reach the sea. It is this fact that makes it meaningful to speak of a continuous two-dimensional field of variable runoff depths over such large areas as the United States and to regard *streamgaged* runoff deep in continental interiors as measures of water that, to good approximation, flows *in toto* to the distant sea. Wrather gives data suggesting that the latter statement is true to within an error of less than five per cent for the United States as a whole.

It is of interest to note that the Mississippi basin, though it contributes 35 per cent of total United States annual runoff, occupies 41 per cent of the total area; *i.e.*, its mean runoff is below the United States average. From other data given by Wrather, it can be shown that 85 per cent of all the United States runoff originates on only that 38 per cent of the total area characterized

TABLE 2. Annual runoff from major United States drainage areas (expressed in inches of depth averaged over each watershed).

Source	Drainage area (thousands of mi²)	Runoff (in)
North Atlantic slope basins	149	19
South Atlantic slope and eastern Gulf of Mexico basins	285	15
Mississippi River basin	1,250	7
Hudson Bay basins	48	1
St. Lawrence River basin	130	15
Western Gulf of Mexico basins	320	2
Colorado River basin	246	1
Great Basin	215	0
Pacific slope basins in California	117	9
Columbia River basin and coastal streams in Oregon and Washington	362	18
United States	3,022	8

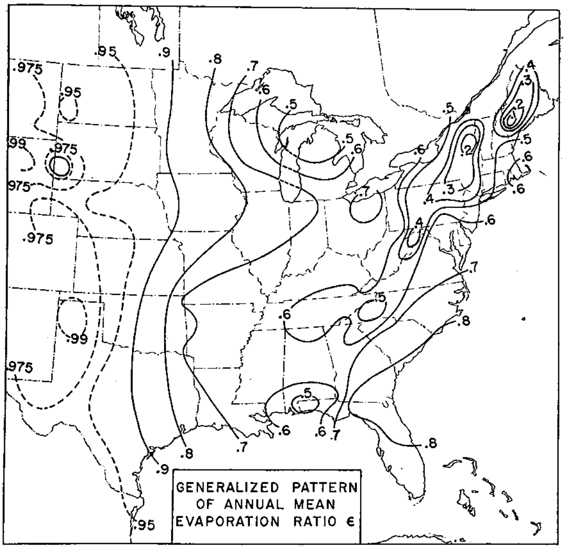

Fig. 1. Generalized pattern of annual mean evaporation ratio ϵ for the eastern United States.

by mean runoff depths in excess of 10 inches per yr. Fully 40 per cent of total runoff depths is derived from that 11 per cent of the country characterized by local runoff of over 20 inches per yr. For 53 per cent of the area of the country, the yield runoff from local precipitation is equal to or less than 5 inches per yr.

Dividing the generally accepted mean annual value of precipitation P for the United States, 30 inches per yr, into the mean total peripheral runoff of 8 inches per yr obtained from table 2 yields $\rho = 0.27$ and hence $\epsilon = 0.73$ as the mean annual United States runoff and evaporation ratios. By comparing these with the Budyko values for all of North America (table 1), we see that the United States is above the North American average with respect to percentage of received precipitation that evaporates back into the atmosphere before it can reach the oceans, a climatologically quite reasonable result of the fact that large areas of the continent lie so far poleward as to reduce the mean continental evaporation ratio well below that for just the United States alone. Mexico and Central America must tend to counteract the above trend, but their combined area is too small to be of dominant influence over Canada and Alaska.

Considering only the Mississippi River basin, Benton, Blackburn, and Snead [6] found P to average about 30 inches per yr, the same as the entire United States average, and runoff to be 7 inches per yr (in agreement with table 2), whence, for this basin alone, $\epsilon = 0.77$, $\rho = 0.23$. The evaporation ratio averages as high as 0.77 over the Mississippi basin *in spite of* the influence of the humid eastern portions of the basin and *because of* the dominant influence of the western portions (*cf.* fig. 1 below). Seasonal variations of ϵ are of climatological interest, so it should be noted that Benton and coworkers found a range from about 0.30 in winter to about 0.85 in summer, in agreement with earlier estimates of Horton.

Values of ϵ for an area of size comparable to that of the Mississippi basin but lying at a higher latitude can be derived from a water-balance study of the European USSR which Drozdov has carried out [2, p. 230] by using the same type of aerological approach employed by Benton and coworkers. Drozdov's analysis indicates a mean annual evaporation of 11.6 inches, a mean precipitation of 19.2 inches, and hence $\epsilon = 0.60$ for the year as a whole in European Russia. Monthly ϵ-values are also obtainable from Drozdov's data. The lowest monthly mean is 0.16 for December; the highest is May's 1.31 (3.0 inches evaporation as compared with only 2.3 inches of precipitation, the extra 0.7 inches presumably being supplied by evaporation of over-winter snow storage). The summer half-year April-September exhibits a mean ϵ of 0.85, while the winter half-year October-March averages 0.22. By comparing the Mississippi basin seasonal values cited above from Benton *et al.*, one notes close similarity in summer, but lower ϵ in winter in European Russia, which is climatologically consistent with the general principle that latitudinal climatic gradients tend to be more significant in winter than in summer in middle latitudes.

The meteorological values governing ϵ (*e.g.*, radiation receipts, humidity, winds, *etc.*) vary from year to year and hence so must ϵ itself. As a consequence, then, of fluctuations in the general circulation over periods of a number of years, ϵ can also fluctuate in a way that may assume a hydrometeorological significance in some contexts. Useful indication of the order of magnitude of fluctuations in the value of ϵ accompanying such short-term climatic fluctuations can be derived from data reported by Hoyt and others [7]. In table 3 are listed the minimum and maximum 10-yr moving average values of ϵ (designated as ϵ') for six basins in the eastern and midwestern United States. Individual yearly values of ϵ vary, of course, through considerably greater ranges than those shown for ϵ'.

To give further information on the way ϵ and its complement ρ vary within some of the larger

TABLE 3. Extrema of decadal moving average ϵ' (after Hoyt *et al.*).

Drainage basin	Number of years of record	Area (mi²)	Minimum ϵ'	Maximum ϵ'
Red River above Grand Forks, North Dakota	53	25,500	0.92	0.97
Mississippi River above Keokuk, Iowa	57	119,000	0.73	0.80
Merrimack River above Lawrence, Massachusetts	56	4,500	0.49	0.56
James River above Cartersville, Virginia	36	6,200	0.58	0.65
Tennessee River above Chattanooga, Tennessee	54	22,000	0.45	0.56
Chattahoochee River above West Point, Georgia	39	3,600	0.55	0.62

United States drainage units already discussed, the generalized ϵ-pattern of fig. 1 has been prepared for the area east of the Rocky Mountains. (The mountainous West involves so complex a pattern as to require much more detailed analysis than was within the scope of this note). By plotting runoff isolines from a chart of mean annual runoff [8, p. 225] upon a chart of mean annual precipitation [9, p. 711], values of ϵ could be readily computed at as many points as were needed to delineate the field of ϵ. The runoff data were for the period 1921 to 1945, whereas the P data were for the period 1898 to 1938, the closest time-match available from among several published charts of the two required quantities. The extrema of ϵ' over periods of four or five decades, as shown in table 3, afford a crude estimate of the magnitude of error introduced by using disparate time-periods. Clearly the errors will not be so great as to conceal the broad pattern of ϵ which fig. 1 is intended to display. In preparing fig. 1 values of ϵ for 47 individual basins, computed from data given by Lee [10] were used as cross-checks, supplemented in certain areas by values computed from more-recently-published runoff summaries. Except for details in small areas of the mountainous parts of the eastern states, fig. 1 is probably a fairly representative portrayal of the distribution of ϵ in the eastern United States.

As pointed out earlier, the Mississippi basin is seen to contain appreciable east-west gradients of ϵ, ϵ varying from values near 0.5 on the Appalachian slopes of lower temperature, higher prevailing humidities, and steeper mean drainage slopes to values above 0.99 in the high plains areas where virtually all precipitated water is reevaporated into the atmosphere from soil or vegetation before it can move into a permanent watercourse. It is interesting to note the similarity between the eastward protrusion of the $\epsilon = 0.7$ isoline into northern Indiana and the outlines of the "prairie peninsula" or "prairie wedge" [11, p. 329] whose existence has long interested students of mid-western ecology. The lowest evaporation ratios of fig. 1 occur in western Maine where ϵ is below 0.1 for parts of the Androscoggin watershed, and almost all water falling as precipitation flows off to the ocean.

Since fig. 1 does not extend to the Pacific coast where climatic conditions are such that, at least at higher latitudes, very low ϵ values would be expected, data for a number of smaller coastal streams and mountain tributary streams in Oregon and Washington were used to estimate local ϵ values. The Quinault and Hoh Rivers of the Washington coastal slope of the western Olympic Peninsula, each having drainage areas of about 200 sq mi, are typical. Their basin mean annual runoffs are 142 and 131 inches, respectively. To within the somewhat doubtful accuracy of the precipitation data available, the mean annual runoff to the Pacific from these and similar coastal streams of the area was found equal to (in some cases *higher* than!) the published precipitation values for the areas in question; *i.e.*, $\epsilon = 0$ and $\rho = 1.0$, approximately. These Pacific Northwest coastal watersheds, and similar counterparts in Maine, may be vividly contrasted with watersheds ("vaporsheds" would be more apt) of the Southwest. The Santa Cruz River flows ephemerally past Tucson, Arizona, carrying an average runoff from the 2200 mi² watershed above Tucson that represents only 0.6 per cent of the estimated total precipitation over that area [12], whence $\epsilon = 0.994$ for this drainage area. In the still more arid desert basins of western Arizona and southeastern California, ϵ cannot depart sensibly from unity. Even in the forested Mogollon Plateau region (altitude 6000 to 7000 ft msl) from which all of the runoff used in central Arizona irrigation agriculture is derived, the annual mean of ϵ is about 0.90. In winter, this falls to perhaps 0.85, but in summer it rises slightly above 0.95, whence the nearly one-half of the year's total precipitation that falls in summer is almost entirely consumed by evapotranspirational losses before the water can, by overland flow or seepage, reach a watercourse whose effective surface/volume ratio is low enough to permit most of its flow to reach a reservoir. The high ϵ-values typical of arid regions stand as intrinsic obstacles to easy amelioration of the aridity through any prospective cloud-modification efforts or watershed-modification efforts that may be considered for these regions that have the most pressing need for just such efforts.

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REFERENCES

1. Meyer, A. F., 1942: Runoff, Ch. 11 of *Hydrology* (ed. by O. E. Meinzer). New York, McGraw-Hill, 712 pp.
2. Budyko, M. I., 1956: *The heat balance of the earth's surface.* Transl. by N. A. Stepanova, U. S. Wea. Bur. Off. of Tech. Serv., Washington, 259 pp.
3. Fox, C. S., 1951: *Water.* London, Technical Press, Ltd., 148 pp.
4. Benton, G. S., and M. A. Estoque, 1954: Water-vapor transfer over the North American continent. *J. Meteor.*, **11**, 462–477.
5. Wrather, W. E., 1952: A summary of the water situation with respect to annual runoff in the United States, in *The physical and economic foundation of natural resources,* Pt. II. Interior and Insular Affairs Comm., House of Representatives, U. S. Congress, Washington, pp. 36–41.
6. Benton, G. S., R. T. Blackburn and V. O. Snead, 1950: The role of the atmosphere in the hydrologic cycle. *Trans. Amer. geophys. Union,* **31**, 61–73.
7. Hoyt, W. G., and others, 1936: *Studies of relations of rainfall and runoff in the United States.* U. S. Geol. Survey Water-Supply Pap. 772, Washington, 301 pp.
8. Linsley, R. K., M. A. Kohler and J. L. H. Paulhus, 1949: *Applied hydrology.* New York, McGraw-Hill, 689 pp.
9. U. S. Dept. of Agr., 1941: *Climate and man.* Yearbook of Agr., 1941, Washington, U. S. Govt. Print. Off., 1248 pp.
10. Lee, C. H., 1942: Transpiration and total evaporation, Ch. 7 of *Hydrology* (ed by O. E. Meinzer). New York, McGraw-Hill, 712 pp.
11. Trewartha, G. T., 1954: *An introduction to climate.* New York, McGraw-Hill, 395 pp.
12. Schwalen, H. C., and R. J. Shaw, 1957: *Water in the Santa Cruz Valley.* Bull. 288, Agr. Exp. Sta., Univ. Ariz., 119 pp.

ABOUT OUR MEMBERS

Henry C. Alberts, formerly liaison engineer for the Cook Research Laboratories, recently accepted the position of director of marketing for the northeastern United States, National Company, Inc., Malden, Mass.

Milo J. Andre has left Nuclear Products, Atlanta, and is now associated with the Climatic Center, USAF, Washington, D. C.

Dr. *James K. Angell* and *Donald H. Pack,* Weather Bureau research meteorologists, conducted a project last summer at the Nevada Proving Grounds. Thirteen constant level balloons were tracked for distances up to 30 miles, providing data of great interest for the study of air flow in mountainous terrain.

Niels C. Beck has been appointed assistant director at the Armour Research Foundation, Illinois Institute of Technology, Chicago. Mr. Beck has recently returned to Chicago after directing an ARF project in Burma for four years.

Dr. *George S. Benton,* professor of meteorology at Johns Hopkins University, was named chairman of the newly created department of mechanics in 1960. Prof. Benton had formerly been acting chairman of the civil engineering department at Johns Hopkins.

Dr. *Lloyd V. Berkner* has resigned as president of Associated Universities, Inc., to assume the post of president of the Graduate Research Center, Dallas. An expanding scope of activities for the center and the development of large-scale research facilities in the area are foreseen by the Trustees.

Prof. *J. A. Bjerknes* of the University of California and Prof. *M. Bossolasco,* University of Genoa, were among the delegates to the IUGG meeting in Helsinki last July who visited the Vaisala factory. Prof. *Vilho Vaisala* gave some forty guests a short account of recent developments in the Vaisala Sounding System.

The new vice president of the Commission for Maritime Meteorology, WMO, is Vice Admiral *C. V. Bunnag* of the Meteorological Department, Royal Thai Navy.

The Texas Academy of Science has been conducting a 1960–1961 Visiting Scientist Program, sponsored by the National Science Foundation, designed to improve the status of science and mathematics throughout the State by making scientists available for talks to senior and junior high schools. Among those participating in the program and their subjects are: Prof. *L. A. Colquitt,* mathematics, Texas Christian University; Prof. *Guy A. Franceschini,* marine science, Texas A. and M. College; Prof. *Kenneth H. Jehn,* meteorology, University of Texas; Prof. *Vance E. Moyer,* meteorology, University of Texas; and Prof. *Dale F. Leipper,* marine science, Texas A. and M. College.

Earl L. Davis left the Aero-Space Division, Boeing Airplane Company, Seattle, on 1 January to join the Weather System Division of the Travelers Insurance Companies, Hartford.

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