

## Increasing Evapotranspiration from the Conterminous United States

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### ABSTRACT

Recent research suggests that evapotranspiration (ET) rates have changed over the past 50 years; however, some studies conclude ET has increased, and others conclude that it has decreased. These studies were indirect, using long-term observations of air temperature, cloud cover, and pan evaporation as indices of potential and actual ET. This study considers the hydrological cycle more directly and uses published precipitation and stream discharge data for several large basins across the conterminous United States to show that ET rates have increased over the past 50 years. These results suggest that alternative explanations should be considered for environmental changes that previously have been interpreted in terms of decreasing large-scale ET rates.

### 1. Evapotranspiration and the hydrologic budget

Controversy continues over whether potential evaporation rates are increasing (e.g., Manabe 1997; Szilagyi et al. 2002) or decreasing (e.g., Peterson et al. 1995; Roderick and Farquhar 2002) and over trends in actual evaporation (Ohmura and Wild 2002). Evaporation or evapotranspiration (ET) trends can be identified for a large portion of the United States by using published data and assuming that the balance among precipitation, streamflow, and ET dominates the terrestrial hydrological budget on annual and longer time scales. The other terms in a watershed budget are surface, vadose zone, and groundwater losses and net storage, which are generally considered to be substantially smaller than the fluxes considered over annual time periods (e.g., Hornberger et al. 1998).

Figure 1 shows the 1950–2000 time series of the annual (water year, October–September) basin-area-average precipitation derived from monthly U.S. Climate

Division data (Guttman and Quayle 1996) and U.S. Geological Survey stream discharge (USGS 2003) over six large basins in the conterminous United States: the Mississippi, Columbia, Colorado, Susquehanna, Sacramento, and three adjacent Southeast Rivers (Fig. 2). Both annual precipitation and stream discharge exhibit positive linear trends over the period considered, with precipitation having increased more rapidly and statistically significantly than discharge. Figure 3 more clearly shows that the difference between precipitation and streamflow has been generally increasing over the past 50 yr. Using these data as estimates of water inputs to and outputs from the continent, the most probable explanation to reconcile the hydrologic budget is increased actual ET rates.

Mechanistically, the anticipated increase in soil moisture, as a result of increased precipitation, would lead to greater actual ET under nonpotential conditions because the soil water matric potential would be generally increased. As a result, the number and duration of periods with soil moisture low enough to significantly restrict ET are expected to have decreased, and, overall, soil water would be held less tightly by the soil on average. Milly and Dunne (2001) reported similarly increasing ET over the Mississippi basin, and it is unclear

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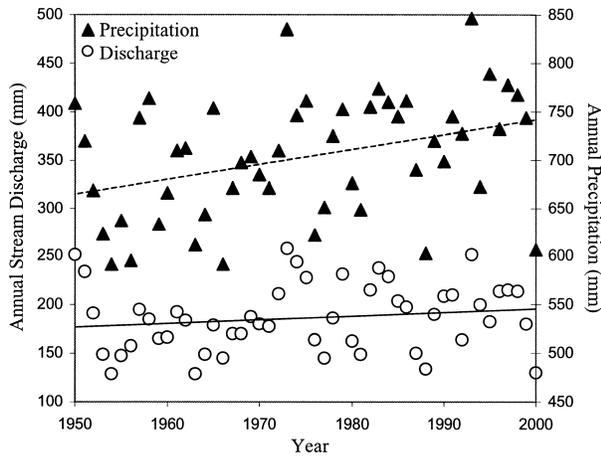


FIG. 1. Comparison of 1950–2000 trends in annual U.S. precipitation (Guttman and Quayle 1996) and stream discharge (USGS 2003) from six large U.S. basins: Mississippi, Columbia, Colorado, Susquehanna, Sacramento, and Southeast. Data were area-weighted averaged. Triangles are annual precipitation data, and circles are annual discharge data. Lines are 50-yr regressions: precipitation slope =  $1.49 \text{ mm yr}^{-1}$  ( $p = 0.0113$ ) and discharge slope =  $0.39 \text{ mm yr}^{-1}$  ( $p = 0.2408$ ).

why this work has not been more widely cited. Several studies have noted the increasing trends in both precipitation and streamflow over much of North America (Lettenmaier et al. 1994; Lins and Michaels 1994; Karl et al. 1996; Karl and Knight 1998; Hamelet and Lettenmaier 1999; Kunkel et al. 1999; Neal et al. 2002; McCabe and Wolock 2002); however, the relevance of these trends to evaporation has not been widely discussed. Interestingly, this study did not find ubiquitous increases in streamflow or precipitation (Table 1).

Although slight variations in Figs. 1 and 3 may be achieved by considering slightly longer, shorter, or shifted periods, the relative trends remain consistent. The increasing trend in “precipitation – discharge” in Fig. 3 persists when the Mississippi is removed from [slope =  $0.76 \text{ mm yr}^{-1}$  ( $p = 0.0177$ )] and when the St. Lawrence is added to [slope =  $1.02 \text{ mm yr}^{-1}$  ( $p = 0.0039$ )] the analysis. Because the Great Lakes and part of Canada compose most of the St. Lawrence basin, this latter watershed was outside the scope of this brief study, that is, the conterminous United States, and therefore was not included in the figures. The slopes of the linear regressions for individual basin data all showed increasing differences between precipitation and discharge, however, the increased sampling variability on these smaller scales resulted in the basin-by-basin trends of calculated ET (precipitation – discharge) being statistically significant (5% level) only for the Mississippi and Colorado watersheds (Table 1).

We should explicitly reiterate here that our analysis assumed long-term equilibrium in the hydrological budget’s storage terms, and it should be noted that the observed trends in the fluxes are small relative to the magnitudes of storage terms within the budget. Inclusion of



FIG. 2. Locations and extents of the watersheds used in this study. The Southeast basins include the Savannah, Altamaha, and Apalachicola watersheds.

the storage terms may lead to more precise estimates in ET trends. For example, groundwater over much of the United States has been decreasing because of overdraft; thus, including this storage change into our analysis would increase the apparent ET trend. On the other hand, some of these watersheds may have water removed from the basins, as in the case of the Susquehanna, the headwaters of which supply New York City, and the impact of these fluxes on net storage might lower our estimated ET trend. Also note that the ET trend,  $\sim 55\text{-mm}$  increase over 50 years, is relatively small as compared with estimates of annual surface storage variability, which is on the order of hundreds of millimeters per year (e.g., Ropelewski and Yarosh 1998; Maurer et al. 2002); however, the ubiquity of the apparent ET trend

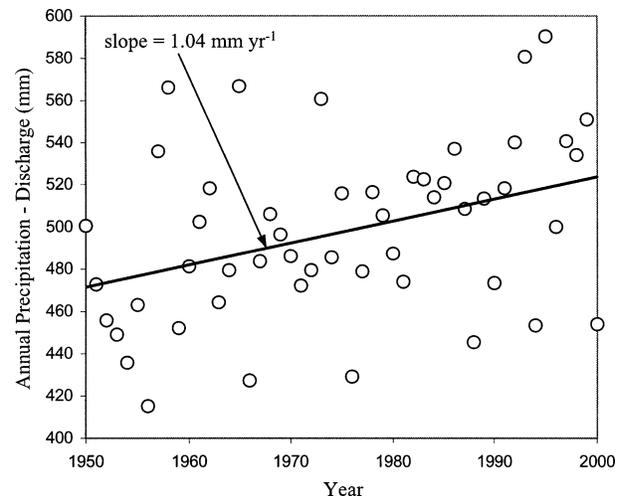


FIG. 3. Trend (1950–2000) in the difference between annual precipitation (Guttman and Quayle 1996) and stream discharge (USGS 2003) for six large U.S. basins: Mississippi, Columbia, Colorado, Susquehanna, Sacramento, and Southeast. Data were area-weighted averaged. Circles are annual data, and solid line is 50-yr linear regression ( $p = 0.0064$ ).

TABLE 1. Individual regression slopes of annual stream discharge, precipitation, and evapotranspiration (i.e., precipitation – discharge) for each of the basins used in this study over the period 1950–2000. Here ID is identifier number.

Basin (area/USGS ID)	Stream discharge (mm yr <sup>-1</sup> )	Precipitation (mm yr <sup>-1</sup> )	Evapotranspiration (mm yr <sup>-1</sup> )
Mississippi (2 964 227 km <sup>2</sup> /07289000)	0.65 ( $p = 0.1292$ )	1.76 ( $p = 0.0169$ )	1.10 ( $p = 0.0079$ )
Columbia (613 824 km <sup>2</sup> /14105700)	-0.54 ( $p = 0.1216$ )	-0.15 ( $p = 0.7164$ )	0.39 ( $p = 0.4396$ )
Colorado (488 210 km <sup>2</sup> /09429490)	-0.06 ( $p = 0.1516$ )	1.46 ( $p = 0.0046$ )	1.52 ( $p = 0.0075$ )
Southeast basins* (105 282 km <sup>2</sup> /*)	0.63 ( $p = 0.2997$ )	1.44 ( $p = 0.3979$ )	0.81 ( $p = 0.4565$ )
Susquehanna (67 313 km <sup>2</sup> /01576000)	0.60 ( $p = 0.4187$ )	1.68 ( $p = 0.2207$ )	1.08 ( $p = 0.1396$ )
Sacramento (55 040 km <sup>2</sup> /11425500)	0.09 ( $p = 0.9381$ )	1.96 ( $p = 0.5028$ )	1.86 ( $p = 0.3380$ )
St. Lawrence** (773 885 km <sup>2</sup> /04264331)	0.80 ( $p = 0.0012$ )	1.23 ( $p = 0.0317$ )	0.43 ( $p = 0.3811$ )

\* The Southeast basins include the Apalachicola (USGS ID 02358000), Savannah (USGS ID 02198500), and Altamaha (USGS ID 02226000) watersheds.

\*\* The analyses in this study used only land-based U.S. precipitation data; thus, because a large portion of the St. Lawrence basin is in Canada and is composed of the Great Lakes, this basin was not included in the figures.

shown here is difficult to reconcile as a 50 year increase in surface storage.

## 2. Discussion

These data do not reconcile the debate regarding trends in potential ET, although the conclusion that actual ET has increased over a large part of the United States is consistent with Brutsaert and Parlange's (1998) explanation for the widely observed decreases in pan evaporation from several locations around the world (Peterson et al. 1995; Chattopadhyay and Hulme 1997; Quintana-Gomez 1997). In short, Brutsaert and Parlange (1998) noted that evaporation from a pan decreases when the surrounding landscape's humidity rises in response to increased regional ET. Lawrimore and Peterson (2000) also observed this inverse relationship between pan evaporation and actual evaporation for different parts of the United States. Pan evaporation data have also been used to argue that potential ET has decreased as a result of decreased surface solar radiation (Peterson et al. 1995; Roderick and Farquhar 2002) resulting from increased cloudiness and atmospheric aerosols (Stanhill and Cohen 2001; Cohen et al. 2002). However, investigations of potential ET trends need to consider more of the system's complexity (Milly and Dunne 2001). For example, decreased atmospheric transmissivity of solar radiation because of clouds implies increased downward atmospheric longwave radiation (e.g., Crawford and Duchon 1999), which would mitigate the effect of reduced solar radiation on potential ET.

The increased ET trend could include effects from human activities, which have the potential to alter substantially the hydrological cycle, especially irrigation (e.g., Kondolf and Vorster 1993; Kendy et al. 2003). Unfortunately, "undisturbed" systems are not widely

available. However, anecdotal evidence from largely undisturbed, nonglacial southeast Alaskan streams, in which long-term streamflow has been relatively stable while precipitation has increased (Neal et al. 2002), suggests that increases in actual ET are at least in part climatological rather than the result of human redistribution of water. Milly and Dunne (2001) showed that increased ET in the Mississippi had both climatological and anthropogenic dimensions. Inclusion in the hydrologic balance of generally decreasing groundwater over much of the United States would yield larger ET changes than indicated in Fig. 1 because the decreasing ground water levels are largely attributed to overdraft such that the pumped water is redistributed on the land where it is susceptible to ET. It would be informative to study the hydrological cycle in more detail than is done in this broad-brush study to determine more precisely how the pieces of the hydrological cycle fit together. For example, are the largest observed increases in annual rainfall coincident with the periods of highest actual ET?

## 3. Conclusions

Mounting evidence suggests that the hydrological cycle is accelerating over the conterminous United States (cf. Fig. 3) and, thus, probably over North America as a whole. This study used direct measures of annual precipitation and stream discharge, the two largest components of the watershed hydrological budget, and found evidence of increasing rates of actual ET throughout large portions of the conterminous United States over the past 50 years. There is some evidence of similar ET trends over the former Union of Soviet Socialist Republics (Golubev et al. 2001), and it would be interesting to know if these trends are global, including over the oceans.

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