SEASONAL AND REGIONAL CHARACTERISTICS OF U.S. STREAMFLOW TRENDS IN THE UNITED STATES FROM 1940 TO 1999

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Abstract: J. R. Mather (1981) observed that runoff (streamflow) constitutes a significant phase of the hydrologic cycle. He also noted that it takes at least 15–25 years of systematic observations to characterize statistically the spatial and temporal patterns in streamflow. With this in mind, a recent assessment of temporal trends in streamflow (Lins and Slack, 1999) is updated to encompass the 60-year period 1940–1999, using data from 435 climate-sensitive stream-gauging stations and expanded to include regional and seasonal characteristics. The previously documented pattern of increasing discharge in the low to moderate range of flows is corroborated, with this pattern being most pronounced in the central two-thirds of the U.S. and to a lesser extent in the eastern coastal regions and in the Great Basin. Relatively few trends are observed in the annual maximum flow. No systematic shift in the timing of the annual minimum, median, or maximum flow is detected in any region on a monthly time scale. The observed increases in low to moderate streamflows, typical of the warm and transitional seasons, are consistent with documented trends in warm and transition season precipitation, and indicate that natural U.S. surface water supply has increased without a concomitant increase in flooding. [Key words: streamflow, trends, seasonal changes, regional patterns.]

INTRODUCTION

A recent assessment of long-term changes in streamflow for the United States found significant increases in low to moderate flows across broad sections of the country (Lins and Slack, 1999; hereafter referred to as LS99). Gauge records from 30 to 40 percent of 395 stations nationwide revealed increases in annual minimum to median flows during the period 1944 to 1993. Substantially fewer stations (4 percent) recorded increases in the annual maximum discharge, the category that includes (but is not limited to) floods, while 5 percent indicated decreases in the maximum. Discharge decreases were documented in LS99 across the entire range of flows in the Pacific Northwest and in parts of the Southeast.

Confirmation and elaboration of these results were presented most recently by McCabe and Wolock (2002) who, in addition to finding a significant increase in low to median streamflow, also found that this increase occurred as a step change around 1970 rather than as a gradual trend. Douglas et al. (2000) added more geographic detail by performing a regional analysis of flood- and low-flow trends for the period 1939 to 1988. Using a regional test statistic, they found no evidence of trends in flood flows, but did find upward trends in low flows in the Ohio, North-Central, and Upper Midwest regions. Congruent results were also reported for Canada (Zhang et al., 2001), where investigators analyzed a database of streamflow

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from a climate-sensitive (i.e., minimally affected by human activities) network of gauges covering the years 1947 to 1996. Their major findings were that annual maximum streamflow had decreased across southern Canada, particularly southern British Columbia, and that annual minimum flows had decreased there as well. Minimum flows were observed to have increased in northern British Columbia and in the Yukon Territory. Significantly, the reported decreases in southern British Columbia for all streamflow percentiles agree perfectly with the LS99 findings for the contiguous Pacific Northwest region of the U.S. Thus, several independent investigations have produced a similar picture of streamflow changes during the past half-century across much of North America: statistically significant trends in minimum flows at numerous stream gauges that tend upward in many regions and downward in the northwest U.S.–southwest Canada border area; and relatively few trends in flooding and high flows, with no regionally coherent pattern of increases and a clear pattern of decreases in the western border area of the U.S. and Canada.

These studies have been possible because the United States and Canada have systematically gauged rivers and streams for more than a century, and have hundreds of stations with record lengths of 30 to 60 years. Mather (1981) noted the necessity of such long records for valid statistical characterization of spatial and temporal variability. However, despite increasing numbers of stream gauges over the years, many smaller catchments are not gauged, which confounds hydroclimatic analysis. Mather saw the climatic water budget as a means for dealing with this situation and demonstrated that streamflow computed from the climatic water budget correlates closely with measured streamflow in the same basin. This finding makes the water budget a useful tool for studying hydrologic characteristics *and their changes over time* in ungauged basins. Despite the practicality of using the climatic water budget for hydrologic trend assessment, no broad-scale studies have done so to date. The imperative for doing so clearly exists, given the need for testing hypotheses associated with the water-resource implications of climatic change, particularly in regions of the world where few stream gauges exist. In their 1992 paper evaluating the average annual global water balance, Legates and Mather provided a basis for performing a global assessment of runoff trends.

Herein, however, we utilize observed streamflow data to update and expand the trend results reported in LS99. Our objectives are to assess runoff trends in the conterminous United States for the 60-year period 1940–1999, across the entire range of measured discharges (from minimum to maximum); to characterize the regional distribution of these trends by water-resources region; to identify seasonal shifts in the timing of minimum, median, and maximum flows within each water-resources region; and to explain the observed pattern of runoff trends in terms of previously reported trends in U.S. precipitation.

DATA AND METHODS

Values of daily mean streamflow for 435 stations from the U.S. Geological Survey's Hydro-Climatic Data Network (HCDN) are analyzed herein. These data update those used by Lins and Slack (1999) through water year 1999. The HCDN is a collection of USGS stream gauges identified expressly to provide an account of the effect of climatic variation over a watershed. The ability to do so is conditioned on the absence of confounding anthropogenic factors that diminish the climate signal. Each station in the HCDN has been reviewed by the USGS and deemed in conformance with several qualifying criteria, one of which being "unimpaired basin conditions." This criterion specifies that "there should be no overt adjustment of 'natural' streamflow, such as flow diversion or augmentation, regulation of the streamflow by some containment structure, or reduction of base flow by extreme ground-water pumping, nor should the degree of human activity in the watershed, such as changes in land use during the period of record, be so large as to significantly affect the value of monthly mean discharge (computed on the basis of the daily mean discharge) at the station" (Slack and Landwehr, 1992, p. 6). With respect to land use, a station located within a developed basin could be included within the HCDN if it had not undergone substantial change in its land-cover condition during the period of record. In other words, a basin need not be "pristine" for inclusion. However, a station in a basin that has undergone a substantial land-cover change, such as from forest to agriculture to urban, either gradually or abruptly, would not be included. The use of HCDN stations avoids a number of interpretive problems associated with "dirty" data, or what Mather (1991, p. 270) refers to as "human modification of both climatic and hydrologic factors."

Following publication of LS99, a question arose as to the size and character of the basins gauged at HCDN sites. The concern was that HCDN basins were primarily small headwater catchments, like those in the USGS Hydrologic Benchmark Network (Cobb and Biesecker, 1971), and therefore had only local rather than broader-scale hydro-climatic significance. A comparison of the size distribution of HCDN basins with the 57 Benchmark basins, and with more than 17,000 basins gauged by the USGS during the past century, revealed that the HCDN basins are representative of the full suite of basins gauged by USGS. More than 75 percent of the HCDN basins are between 500 and 5,000 km^2, which agrees well with the set of 17,000+ basins for which 64 percent have areas between 500 and 5,000 km^2. In contrast, 93 percent of the Benchmark basins are less than 500 km^2. Thus, basin size does not appear to be a concern in using the HCDN to evaluate regional and national hydro-climatic patterns and trends.

As in LS99, we test for trends using the nonparametric Mann–Kendall test. Results are summarized by water-resources region (U.S. Water Resources Council, 1970) and by streamflow percentile, from the annual minimum (based on daily means; Q_0) to the annual median (daily mean; Q_{50}), to the annual maximum (daily mean; Q_{100}). Seasonal shifts in the timing of the Q_0, Q_{50}, and Q_{100} flows for each water-resources region are determined using seasonal subseries graphs (Cleveland, 1985). These plots depict, for each flow percentile and water-resources region, the mean number of stream gauges reporting their Q_0 (Q_{50}, Q_{100}) value in each month over the 60-year period of record, along with decadal variations (for 1940–1949, 1950–1959, 1960–1969, 1970–1979, 1980–1989, 1990–1999) above and below the mean. From the graphs, it is possible to interpret decade-to-decade changes in the occurrence of the Q_0 (Q_{50}, Q_{100}) flow within each month, and whether or not one month became more or less dominant through time relative to an adjacent month.

Fig. 1. Water-resources regions of the conterminous United States (after U.S. Water Resources Council, 1970).

REGIONAL PATTERNS AND TRENDS

A total of 434 stations in the 18 water-resources regions of the conterminous U.S. (Fig. 1), and 1 coastal station in southeastern Alaska were evaluated for trends between 1940 and 1999. Test results are summarized by region and percentile in Table 1. The most obvious general result is that, within each region, more stations experienced trends in the low to moderate percentiles of flow than in the upper percentiles, with the fewest trends occurring in the Q_{100} (annual maximum) category. Increasing trends dominated, although the proportion of increasing to decreasing trends was lowest in the annual maximum flow (Fig. 2). These patterns are consistent with those first reported in LS99.

The strongest and most pronounced pattern of runoff trends occurred in the central two-thirds of the nation, including the Great Lakes, Ohio Valley, Tennessee, Upper Mississippi, Lower Mississippi, Souris-Red-Rainy, Missouri, Arkansas-White-Red, Texas-Gulf, and Rio Grande water-resources regions. The pattern was dominated by increasing streamflow at all percentiles except the Q_{100}. In the Upper Mississippi region, for example, more than 70 percent of the gauges reported runoff increases in all but the Q_{90} (47 percent up) and Q_{100} (14 percent up) flows. No runoff decreases were detected except in the Q_{100}, with 11 percent reporting downward trends. Nearly identical results were observed in the Ohio Valley and Great Lakes regions, as well as in those regions to the west and south where there was a lower density of stream gauges. Thus, nearly 50 percent of the area of the conterminous United States exhibited a clear and unambiguous pattern of increasing runoff at all but the highest percentiles of discharge between 1940 and 1999.

Table 1. Number of Stations Having Trends in Annual Percentiles of Daily Streamflow, 1940–1999, with an Attained Significance Level at or below 0.05, by Water-Resources Region

Water resource region	Number of stations	Trend direction	Stations with trend by percentile										
			Q_0	Q_{10}	Q_{20}	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{100}
New England	19	Up	6	9	8	12	7	8	5	4	1	0	3
		Dn	1	0	0	0	0	0	0	0	0	0	0
Mid-Atlantic	49	Up	10	8	10	8	14	10	7	5	2	1	5
		Dn	0	0	0	0	0	0	0	0	0	0	0
South Atlantic–Gulf	62	Up	9	8	7	9	10	10	10	5	4	3	8
		Dn	15	7	4	3	1	1	1	1	1	1	2
Great Lakes	15	Up	10	9	10	11	13	13	12	9	7	1	1
		Dn	0	0	0	0	0	0	0	0	0	0	0
Ohio Valley	45	Up	29	26	27	28	31	30	26	21	12	8	5
		Dn	0	0	0	0	0	0	0	0	0	0	3
Tennessee	10	Up	2	2	3	5	5	6	8	8	6	2	0
		Dn	0	0	0	0	0	0	0	0	0	0	0
Upper Mississippi	57	Up	49	50	52	51	50	51	48	44	41	27	8
		Dn	0	0	0	0	0	0	0	0	0	0	6
Lower Mississippi	5	Up	2	4	4	4	4	3	1	1	0	0	2
		Dn	0	0	0	0	0	0	0	0	1	0	0
Souris-Red-Rainy	6	Up	4	4	4	3	3	3	2	2	1	1	1
		Dn	0	0	0	0	0	0	0	0	0	0	0
Missouri	31	Up	18	21	20	19	17	16	14	12	10	8	2
		Dn	1	0	0	0	0	0	0	0	0	0	1
Arkansas-White-Red	17	Up	11	8	11	12	10	10	10	9	3	3	0
		Dn	1	0	0	0	0	0	0	0	0	0	0
Texas-Gulf	21	Up	12	10	14	15	15	14	14	13	11	10	3
		Dn	1	2	1	1	1	1	1	1	0	0	2
Rio Grande	7	Up	4	5	5	5	5	5	5	3	0	0	0
		Dn	0	0	0	0	0	0	0	0	0	0	1
Upper Colorado	3	Up	1	1	2	2	1	1	1	0	0	0	0
		Dn	1	1	1	0	0	0	0	0	0	0	0
Lower Colorado	3	Up	1	2	3	2	1	1	1	1	1	1	1
		Dn	0	0	0	0	0	0	0	0	0	0	0
Great Basin	8	Up	2	4	3	2	2	3	2	2	0	0	0
		Dn	0	0	0	0	0	0	0	0	0	0	0

(*table continues*)

Table 1. (Continued)

Water resource region	Number of stations	Trend direction	Stations with trend by percentile										
			Q_0	Q_{10}	Q_{20}	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{100}
Pacific Northwest	52	Up	2	3	2	2	3	3	3	1	0	0	4
		Dn	8	1	1	0	0	0	0	0	0	0	0
California	24	Up	2	2	1	0	0	0	0	0	0	0	0
		Dn	5	1	1	1	0	0	0	0	0	0	0
Alaska	1	Up	1	1	1	0	0	0	0	0	0	0	0
		Dn	0	0	0	0	0	0	0	0	0	0	0
All regions (total)	435	Up	175	177	187	190	191	187	169	140	99	65	43
		Dn	33	12	8	5	2	2	2	2	2	1	15

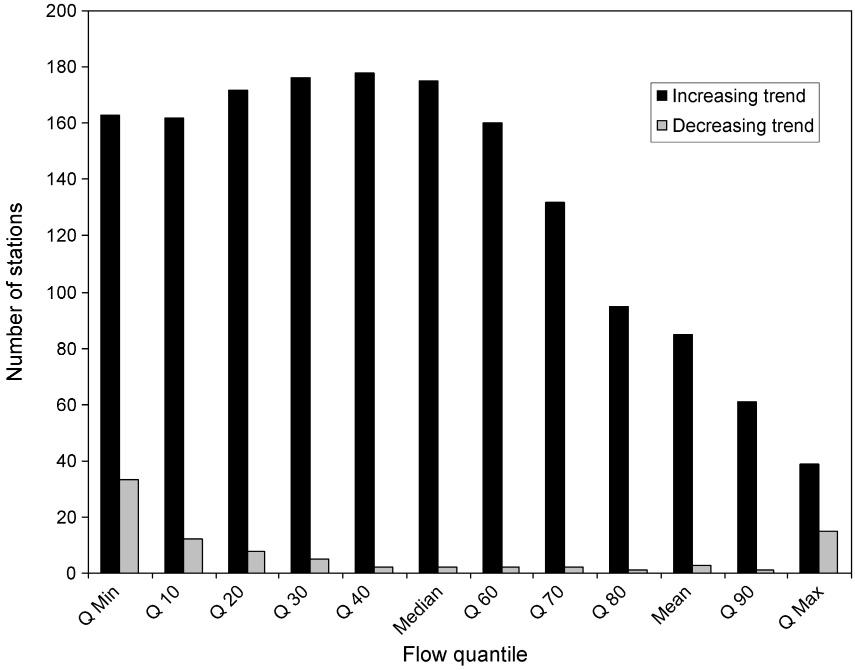

Fig. 2. Number of U.S. stream gauges, out of a total of 435, with statistically significant (attained significance level ≤ 0.05) trends for the 60-year period 1940–1999.

In the eastern coastal regions, namely New England, the Mid-Atlantic, and the South Atlantic–Gulf, and in the Great Basin region in the West, a very similar distribution of trends occurred, both in trend direction and distribution across percentiles. The primary difference between the patterns in these regions and those in the central part of the country was that trends were detected at fewer stations. The South Atlantic–Gulf region, however, displayed some notable differences. Although it exhibited the same general pattern of more stations having trends in the lower to middle percentiles that in the higher percentiles, it also experienced more downtrends. The annual minimum flow, for example, had more downtrends than uptrends. Most of the downtrending gauges were located in Georgia. It was also the only water-resources region to have at least one station exhibiting a decreasing trend in each of the 11 percentiles evaluated. Finally, it tied with the Upper Mississippi region for having the most stations (8; 13 percent) reporting an increase in the annual maximum flow. Half of these occurred in southern Virginia.

Compared to the eastern and central parts of the country, the Pacific Northwest and California regions had relatively few trends. As in the South Atlantic–Gulf region, California and the Pacific Northwest both had more decreasing than increasing trends in the annual minimum flow. Moreover, although at least some runoff increases occurred in most flow percentiles in the Pacific Northwest, all of the increases in California occurred in the lower-flow part of the regime between Q_0 and Q_{20}. The Upper and Lower Colorado regions, while having a pattern of trends consistent with those observed in the water-resources regions of the central U.S., had too few stations to emphasize or from which to draw strong conclusions.

SEASONAL PATTERNS AND SHIFTS

The U.S. streamflow regime has strong seasonal characteristics that, for the annual minimum, median, and maximum flows, are illustrated in Figure 3. The graphs in the figure depict the average number of stream gauges nationwide having their Q_0, Q_{50}, and Q_{100} flow in each month of the year during the 60-year period 1940–1999 as a horizontal line, with the departures from that number for each of the six constituent and consecutive decades (1940–1949, 1950–1959, 1960–1969, 1970–1979, 1980–1989, 1990–1999) plotted as vertical lines above and below the mean.

The seasonal distribution of annual maximum (Q_{100}) flows appears in the top graph. The peak month for Q_{100} flows is March, followed closely by April and then May. A steep decline in Q_{100} flows occurs between June and July, and their occurrence remains low though the warm season and into November. A gradual increase then takes place, with a major increase coming between February and the March peak. Close inspection of the decade-to-decade variations within and between months, particularly during the critical winter to spring transition when annual maximum flows are most frequent, indicates no systematic nationwide shift or trend in the timing of their occurrence. There is, however, considerable interdecadal variability both within and between the winter and early spring months. So, for example, during the decades 1950–1959 and 1980–1989 there were more annual maximum flows in April than in March.

Annual median flows (middle graph) exhibit a more complicated pattern, with a broad primary maximum in the autumn to winter transition season (December peak) and a broad secondary maximum in the spring to summer transition season (May peak). High interdecadal variability is observed in the Q_{50} flow of some months, particularly January, May, and July. However, no systematic shift is evident in the season of either the primary or secondary Q_{50} maximum nationwide.

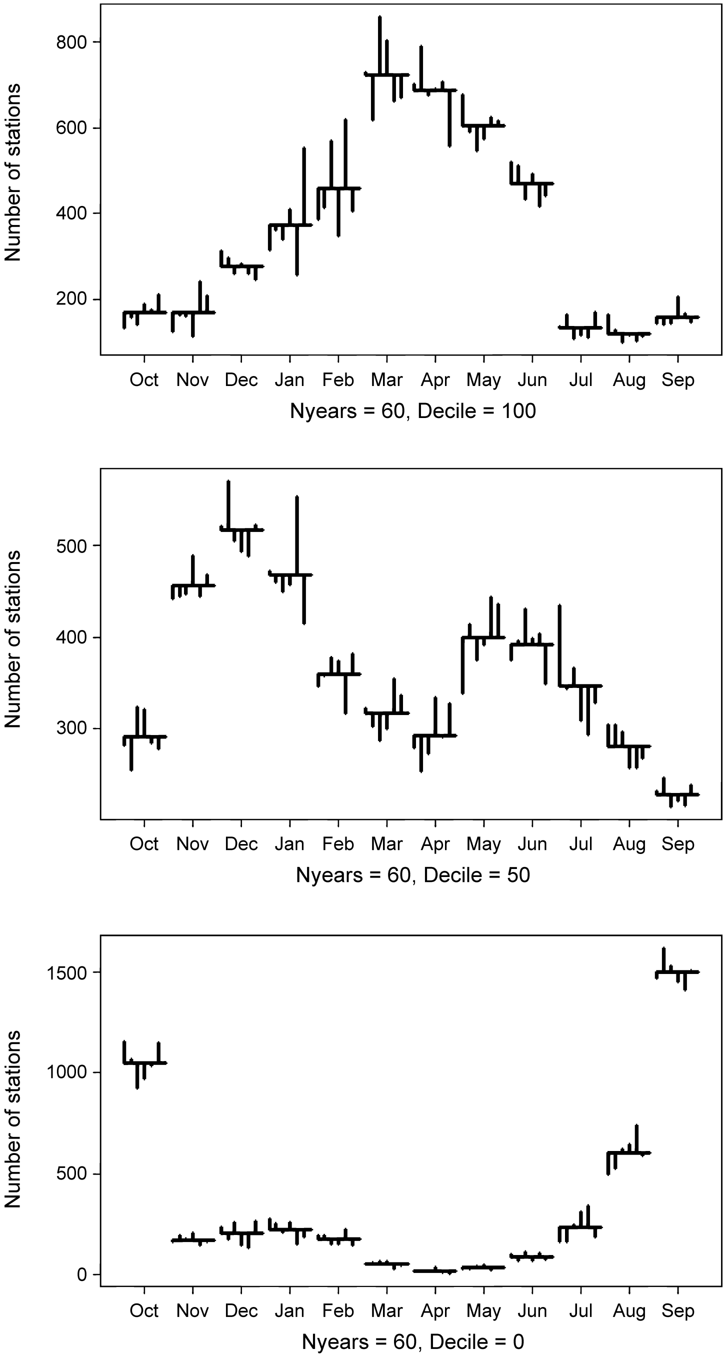

Fig. 3. Seasonal subseries plots depicting the average number of stream gauges nationwide having their Q_{100} (top), Q_{50} (middle), and Q_0 (bottom) flow, by month, for the 60-year period 1940–1999 (horizontal lines), and for the six constituent and consecutive decades (vertical lines).

Table 2. Shifts in the Timing of Annual Maximum, Median, and Minimum Streamflow, 1940–1999, by Water-Resources Region

Water-resource region	Number of stations	Month(s) of most frequent occurrence, and timing shifts (Δ) for Q_0	Q_{50}	Q_{100}
New England	19	Sep (No Δ)	Dec (No Δ)	Apr (No Δ)
Mid-Atlantic	49	Sep (No Δ)	Jan (No Δ)	Mar (No Δ)
South Atlantic–Gulf	62	Sep (No Δ)	May (No Δ)	Mar (No Δ)
Great Lakes	15	Sep (No Δ)	Nov–Dec (No Δ)	Apr (No Δ)
Ohio Valley	45	Sep (No Δ)	May–Jun (No Δ)	Mar (No Δ)
Tennessee	10	Sep (No Δ)	May (No Δ)	Mar (No Δ)
Upper Mississippi	57	Sep (No Δ)	Nov (No Δ)	Mar (No Δ)
Lower Mississippi	5	Sep (No Δ)	May (No Δ)	Mar (No Δ)
Souris-Red-Rainy	6	Feb (No Δ)	Nov (No Δ)	Apr (No Δ)
Missouri	31	Sep (No Δ)	Nov (No Δ)	Jun (No Δ)
Arkansas-White-Red	17	Sep (No Δ)	Jan (No Δ)	May (No Δ)
Texas-Gulf	21	Sep (No Δ)	Jan–Mar–Apr (No Δ)	May (No Δ)
Rio Grande	7	Sep (No Δ)	Oct (No Δ)	May (No Δ)
Upper Colorado	3	Feb (No Δ)	Oct (No Δ)	May (No Δ)
Lower Colorado	3	Jul (No Δ)	Nov (No Δ)	Mar (No Δ)
Great Basin	8	Sep (No Δ)	Jan–Feb (No Δ)	May (No Δ)
Pacific Northwest	52	Sep (No Δ)	Nov (No Δ)	May (No Δ)
California	24	Sep–Oct (No Δ)	Jun (No Δ)	Feb (No Δ)
All regions (total)	434	Sep (No Δ)	Dec (No Δ)	Mar (No Δ)

The annual minimum streamflow (bottom graph) has the most pronounced and unambiguous seasonal characteristic. The overwhelming majority of stream gauges in the U.S. experience their minimum flow in late summer and early autumn, with the largest number of Q_0 flows occurring in September. Very few minimum flows are observed during the winter and spring seasons. Interdecadal variability within months is low, and no systematic seasonal shift is evident.

A more detailed regional summary of seasonal patterns is presented in Table 2. Although most regions reflect the patterns exhibited in the national aggregate presented in Figure 3, there are a few exceptions. For example, the largest number of annual minimum flows in the Souris-Red-Rainy and Upper Colorado regions occur in February (as a result of ice effects), and in July for the Lower Colorado region. The Upper Colorado and Rio Grande regions both have most of their median flows in October, rather than during the primary winter transition or summer transition months. Most annual maximum flows occur during February in California, shortly ahead of the spring peak nationwide, and during June in the Missouri region, just after the national peak. Significantly, none of the 18 water-resources regions in the conterminous United States experienced a shift in the month(s) of most frequent Q_0, Q_{50}, and Q_{100} flows during the 1940–1999 period. However, interdecadal variability within the months of most frequent low, mid, and high flows was often high.

DISCUSSION

These results further reinforce the findings of LS99 and Douglas et al. (2000) regarding low and high streamflow trends, as well as earlier works by Lettenmaier et al. (1994) and Lins and Michaels (1994) regarding trends in monthly mean flows. In combination, these studies present a consistent and compelling picture of how and where streamflow has changed during the 20th century in the United States. That said, there are several elements of the present study that require explanation and elaboration in light of several recent investigations.

One element involves the issue of spatial correlation of streamflow records, raised most recently by Douglas et al. (2000), but also by Lettenmaier et al. (1994). Douglas and her collaborators found that the cross-correlation of flow records dramatically reduced the effective number of samples available for trend assessment. They noted, for example, that although there was no evidence of regional trends in flood flows when cross-correlation was taken into account, two-thirds of the regions would have had significant increases in flood flows had cross-correlation not been considered. We agree that accounting for spatial correlation is a necessary consideration when attempting to derive a single regional characterization of trend. However, a weakness in using a statistic such as the regional average Kendall's S ($\bar{S}_m$; Douglas et al., 2000), which sums the individual S-statistics (S_k) computed for the record from each stream gauge within the region, is that opposing trends within a region cancel each other. It is possible, therefore, that in the South Atlantic–Gulf region, where we found an increasing trend in the annual minimum flow at 9 of 62 stream gauges and a decreasing trend at 15 of 62 gauges, Kendall's $\bar{S}_m$ may have produced a "no trend" result. To avoid any such cancellation effects, we summarize separately the number of stations having statistically significant increasing and decreasing trends in comparison to the total number of stations within each region (Table 1). Thus, by not evaluating regional trends using a single test statistic, we avoid the need to explicitly account for cross-correlation. Analysts interested in making summary assessments of region-wide trends based on our results should, however, be mindful of the potential effects of spatial cross-correlation.

Another element relates to the consistency and timing of runoff and precipitation trends. Although we did not explicitly test for monthly or seasonal streamflow trends, it is possible to infer from Figures 2 and 3 at what times during the year the trends in the various streamflow percentiles occurred. For example, most of the 435 gauge records that we tested had their annual minimum flow in August, September, and October (Fig. 3). It is reasonable to assume, then, that trends in annual minimum flow must be occurring primarily during these months. Thus, by comparing the extent and direction of trends in the Q_0, Q_{50}, and Q_{100} flows with documented trends in seasonal precipitation, it should be possible to assess how trends in the latter affected the former.

Karl and Knight (1998) documented seasonal and annual trends in precipitation frequency and intensity for the nine conterminous U.S. climate regions between 1910 and 1996. They found statistically significant increases in precipitation in the spring (March–May), summer (June–August), and autumn (September–November) seasons, but not in winter (December–February). The total observed increase in annual precipitation amounted to 81 mm per century, and was approximately evenly divided among the spring (23 mm), summer (24 mm), and autumn (29 mm) seasons. The remaining 5 mm came during winter. Karl and Knight noted further that the increase stemmed primarily from heavy and extreme daily precipitation events. Per Karl et al. (1995), they defined heavy and extreme precipitation as rates greater than 50.8 mm per day.

The timing of these seasonal precipitation increases closely correspond with the observed streamflow increases. That is, the rainfall increases in late summer and early autumn (August to October) were exactly coincident with the months when most U.S. streams and rivers experience their annual minimum flow (Fig. 3). The Q_0 increased at 37 percent of the stations sampled herein. Similarly, rainfall increases in the late spring, early summer, and late autumn (May, June, November) coincided with three of the six months when most streams have their Q_{50} flow. Forty percent of the 435 stations had an increase in their median streamflow. Thus, the preponderance of streamflow increases across the lower half of the discharge distribution are reflective of the observed increase in warm-season precipitation. Moreover, it is consistent with Karl and Knight's (1998) observation that the proportion of total precipitation derived from daily events exceeding 50.8 mm increased relative to lower rainfall rates. Events in the 50–75 mm per day range generally do not produce high flows or floods except, perhaps, under rare circumstances when antecedent conditions have been anomalously wet and basin-wide soil moisture is at or near saturation. A review of annual flood information compiled by USGS (Perry et al., 2000) indicates that precipitation rates typically associated with significant flooding are on the order of 75 mm per hour, 425 mm in 8 hours, 125–400 mm per day, 250–350 mm in two days, 425–500 mm in three days, and even larger amounts over two- to four-week periods. This raises serious questions about the efficacy of using subjective terms such as "very heavy" and "extreme" to characterize a 50.8 mm per day precipitation event. From a hydrological perspective, by generating increases in low to average flows, such events appear to be moderate and beneficial. With respect to the issue of global climate change, these findings provide evidence that an enhancement of the hydrological cycle has occurred. However, contrary to the popular hypothesis that such an enhancement will manifest itself by an increase in the frequency and intensity of extreme events (i.e., floods and droughts), the evidence indicates that the opposite has occurred; the supply of water has increased, while the range between low flows and high flows has gotten smaller.

Finally, although we report that none of the 18 water-resources regions in the conterminous United States experienced a shift in the month(s) of most frequent Q_0, Q_{50}, and Q_{100} flows during the 1940–1999 period, other investigators have reported shifts in the timing of annual peak streamflows during the spring season; particularly in regions where the annual streamflow regime is dominated by the melting of mountain snowpacks in spring. Dettinger and Cayan (1995) and Stewart et al. (2004), for example, report a shift in the timing of springtime snowmelt toward earlier in the year in the western United States during the second half of the 20th century. Using the "center of volume" of each year's streamflow hydrograph, that is, the midpoint in plots of day-to-day values of streamflow during each year, they found that the mid-point in the annual flow volume was arriving one to three weeks earlier in 2000 than in 1948. The largest shifts appear most consistently in the Pacific Northwest and the Sierra Nevada of California. Similarly, Hodgkins et al. (2003) studied changes in the timing of the center of volume at 27 rural, unregulated streamflow gauges in New England and found a shift toward earlier center of volume dates by up to two weeks, primarily during the last 30 years. The differences in results between these studies and the present investigation are attributable to differences in temporal resolution. The current study evaluated timing shifts using monthly mean values, whereas the other analyses evaluated shifts in daily values. The reported daily shifts, primarily from 5 to 20 days, are as yet too short to be reflected in monthly averages. Thus, the results are not contradictory.

CONCLUSION

Streamflow increased in all water-resources regions of the conterminous U.S. between 1940 and 1999. The pattern of increases was most pronounced in the central two-thirds of the nation and, to a lesser extent, in the eastern coastal regions and in the Great Basin. Decreases in the annual minimum flow were observed in Georgia and the Pacific Northwest; although the later had relatively few trends in comparison to other regions, as did California. Within each region, more stations experienced trends in the low to moderate percentiles of flow than in the upper percentiles, with the fewest trends occurring in the annual maximum. Although the minimum, median, and maximum flow exhibit strong seasonal characteristics and relatively high interdecadal variability, no systematic shift in the timing of their occurrence was detected. The observed pattern of runoff trends is consistent with previously documented precipitation trends. Increases in low to moderate streamflow have resulted from increases in warm season precipitation at or just above 50.8 mm per day. These results indicate that the natural supply of U.S. surface water increased during the 20th century, and did so without a concomitant excess water (flood) penalty. They also support a belief articulated by Mather (1991, p. 271) that hydroclimatology "has now reached a maturity in which it can offer possible solutions to many water resources problems." We agree, and believe that the coupling of measured runoff (where data are available) and computed runoff (where data are unavailable) is the next logical step in fulfilling Mather's vision of hydroclimatic analysis.

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REFERENCES

Cleveland, W. S. (1985) *The Elements of Graphing Data*. Monterey, CA: Wadsworth Advanced Book Program.

Cobb, E. D. and Biesecker, J. E. (1971) *The National Hydrologic Bench-Mark Network*. Washington, DC: U.S. Government Printing Office, *U.S. Geol. Surv. Circ. 460-D.*

Dettinger, M. D. and Cayan, D. R. (1995) Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *Journal of Climate*, Vol. 8, 606–623.

Douglas, E. M., Vogel, R. M., and Kroll, C. N. (2000) Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology*, Vol. 240, 90–105.

Hodgkins, G. A., Dudley, R. W., and Huntington, T. G. (2003) Changes in the timing of high river flows in New England over the 20th century. *Journal of Hydrology*, Vol. 278, 242–250.

Karl, T. R. and Knight, R. W. (1998) Secular trends of precipitation amount, frequency, and intensity in the USA. *Bulletin of the American Meteorological Society*, Vol. 79, 231–241.

Karl, T. R., Knight, R. W., and Plummer, N. (1995) Trends in high-frequency climate variability in the twentieth century. *Nature*, Vol. 377, 217–220.

Legates, D. R. and Mather, J. R. (1992) An evaluation of the average annual global water balance. *The Geographical Review*, Vol. 2, 253–267.

Lettenmaier, D. P., Wood, E. F., and Wallis, J. R. (1994) Hydro-climatological trends in the continental United States, 1948–88. *Journal of Climate*, Vol. 7, 586–607.

Lins, H. F. and Michaels, P. J. (1994) Increasing U.S. streamflow linked to greenhouse forcing. *Eos, Transactions of the American Geophysical Union*, Vol. 75, 281, 284–285.

Lins, H. F. and Slack, J. R. (1999) Streamflow trends in the United States. *Geophysical Research Letters*, Vol. 26, 227–230.

Mather, J. R. (1981) Using computed stream flow in watershed analysis. *Water Resources Bulletin*, Vol. 17, 474–482.

Mather, J. R. (1991) A history of hydroclimatology. *Physical Geography*, Vol. 12, 260–273.

McCabe, G. J. and Wolock, D. M. (2002) A step increase in streamflow in the conterminous United States. *Geophysical Research Letters*, Vol. 29, 2185–2188.

Perry, C. A., Aldridge, B. N., and Ross, H. C. (2000) *Summary of Significant Floods in the United States, Puerto Rico, and the Virgin Islands, 1970–1989*. Reston, VA: U.S. Geological Survey, *U.S. Geological Survey Water-Supply Paper 2502*.

Slack, J. R. and Landwehr, J. M. (1992) Hydro-Climatic Data Network: A U.S. Geological Survey Streamflow Data Set for the United States for the Study of Climate Variations, 1874–1988. Reston, VA: U.S. Geological Survey, *U. S. Geological Survey Open-File Report 92-129*.

Stewart, I. T., Cayan, D. R., and Dettinger, M. D. (2004) Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario. *Climatic Change*, Vol. 62, 217–232.

U.S. Water Resources Council (1970) *Water Resources Regions and Subregions for the National Assessment of Water and Related Land Resources*. Washington, DC: Author.

Zhang, X., Harvey, K. D., Hogg, W. D., and Yuzyk, T. R. (2001) Trends in Canadian streamflow. *Water Resources Research*, Vol. 37, 987–998.