Water-Quality Trends in the Nation's Rivers

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Water-quality records from two nationwide sampling networks now permit nationally consistent analysis of long-term water-quality trends at more than 300 locations on major U.S. rivers. Observed trends in 24 measures of water quality for the period from 1974 to 1981 provide new insight into changes in stream quality that occurred during a time of major changes in both terrestrial and atmospheric influences on surface waters. Particularly noteworthy are widespread decreases in fecal bacteria and lead concentrations and widespread increases in nitrate, chloride, arsenic, and cadmium concentrations. Recorded increases in municipal waste treatment, use of salt on highways, and nitrogen fertilizer application, along with decreases in leaded gasoline consumption and regionally variable trends in coal production and combustion during the period appear to be reflected in water-quality changes.

IN THE PAST 15 YEARS MAJOR CHANGES HAVE OCCURRED IN various factors influencing the water quality of rivers in the United States. Prominent among these has been the expenditure of more than \$100 billion for the control of "conventional" pollutants, especially oxygen-demanding wastes from municipal and industrial point sources (*1*). Needed additional municipal sewage treatment plants alone are estimated to cost \$118 billion through the end of the century (*2*). However, recent assessments suggest that nonpoint-source pollution, that is, pollution from diffuse sources such as urban and agricultural runoff, may prevent achievement of national water-quality goals even after complete implementation of planned point-source controls (*3*). Significant changes in nonpoint-source pollution have occurred in recent years as a result of changes in agricultural practice, including large increases in fertilizer use, implementation of soil conservation measures, and greatly increased regulation of animal feedlot runoff. Changes in mine reclamation practices and regional shifts in the level of both surface and underground mining activities also have influenced nonpoint-source pollution (*4*). Finally, changing rates of emission to the atmosphere of a variety of combustion products (for example, lead, cadmium, and oxides of sulfur and nitrogen) have influenced the chemical quality of precipitation over large regions of the United States (*5*). In sum, economic and political changes of the 1970s and 1980s have had potentially far-reaching effects on the water quality of rivers and have increased the need for nationwide assessment of water-quality trends. This article presents recent trends in selected aspects of the water quality of U.S. rivers on the basis of data from approximately 380 sampling stations in two nationwide monitoring networks.

A major difficulty in assessing the effects of pollution control programs and other influences on national and regional water quality has been the problem of obtaining reliable information on water-quality trends for a representative sample of the nation's rivers (*6*). To date, information on trends in water quality has come from two primary sources. First, there have been numerous intensive studies of selected rivers with historically severe water-quality problems (*7*). Although intensive studies have led to a greatly increased understanding of the processes that affect water quality, such investigations have been discontinuous in time for all but a few well-studied rivers (*8*). Thus, they do not provide a representative picture of nationwide trends. A second source of information on water-quality trends has been monitoring data. State and local governments monitor various aspects of water quality at more than 60,000 locations nationally, but major differences among localities in the methods and objectives of monitoring have precluded a comprehensive analysis of this body of data. Instead, recent assessments (*9–11*) have taken the form of nationwide surveys of state and local environmental officials who were questioned on their knowledge and opinions of changes in water quality in general. Such surveys have the advantage of drawing on locally gathered chemical and ecological information, but they have the serious disadvantages of generality and subjectivity. In sum, the need remains to assess national trends in a manner that is geographically representative, yet specific in terms of chemical and biological measures of water quality.

During the 1970s, several federal programs for nationally consistent water-quality data collection were established as an adjunct to state and local monitoring. These programs have provided data for several general summaries of water-quality conditions (*12*) but only recently have accumulated sufficient data for a comprehensive study of long-term trends. The trend information presented here is taken from a recent statistical summary of records for about 30 regularly sampled water-quality variables from more than 300 river locations for the period from 1974 to 1981 (*13*). An analysis of the causes of trends was undertaken by using ancillary data on the basin characteristics and pollution sources upstream of each sampling station (*14*). Because consistent methods were applied at a large number of sites, the results of these analyses differ in several respects from the results that have emerged from other studies in recent years. First, they permit a more detailed and objective assessment of the effects on water quality of point-source pollution controls imposed during 1974 to 1981. Second, they show evidence of several previously unknown, or poorly documented, trends in the water quality of rivers stemming from nonpoint-source factors. These include (i) trends in suspended sediment and nutrient concentrations in relation to changes in agricultural activity, (ii) trends in various components of salinity, and (iii) trends in toxic trace-element concentrations in relation to changes in atmospheric deposition of trace elements.

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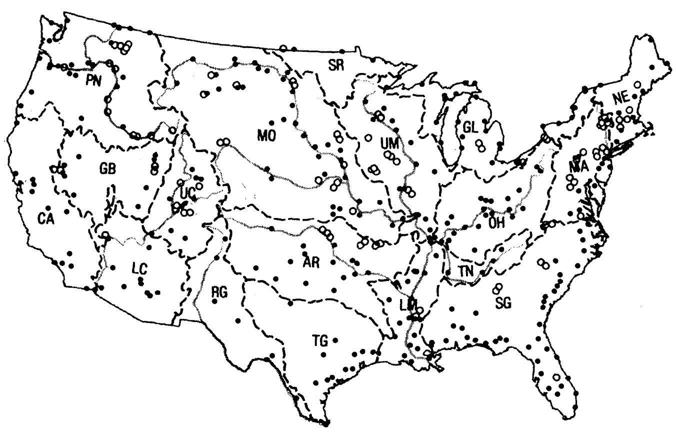

Fig. 1. The locations of sampling stations in NASQAN (solid symbols) and the NWQSS (open symbols) in the conterminous United States. Regional drainage basins are outlined with dashed lines and are abbreviated as follows: New England, NE; Mid-Atlantic, MA; Southeast-Gulf, SG; Tennessee, TN; Ohio, OH; Great Lakes, GL; Upper Mississippi, UM; Lower Mississippi, LM; Texas-Gulf, TG; Arkansas-Red, AR; Missouri, MO; Souris-Red-Rainy, SR; Rio Grande, RG; Lower Colorado, LC; Upper Colorado, UC; Great Basin, GB; California, CA; Pacific Northwest, PN. The largest U.S. rivers are shown as solid gray lines. Most NASQAN stations lie on tributaries to these rivers and most NWQSS stations lie on still smaller rivers and in the vicinity of selected urban and agricultural areas.

Analysis and Interpretation of Water-Quality Trends

Table 1 presents a summary of water-quality trends at 388 sampling stations in the National Stream Quality Accounting Network (NASQAN) and the National Water Quality Surveillance System (NWQSS). These stations, collectively referred to as "network" stations (Fig. 1), provide a representative picture of water-quality conditions in U.S. rivers larger than those of stream order 6 (*15*). Details of network design, sampling procedures, and laboratory methods are given elsewhere (*16*). The statistical procedures used to produce Table 1 have also been described elsewhere (*17*). Trend analyses were conducted by using the Seasonal Kendall test (*17*), which is intended for monthly water-quality time series with potentially large seasonal variability. Because the test is nonparametric, outliers, missing values, or values defined as "less than" the laboratory detection limit (Table 1) present no computational or theoretical problem in its application. With the exception of trace constituents, water-quality records were flow-adjusted before trend testing in order to eliminate streamflow variation as a potential cause of a trend (*17*). Also, we conducted a review of laboratory methods to identify changes in procedures that might result in trend artifacts. Records subject to methods changes were eliminated before trend testing.

Table 1. Statistical summary of water-quality conditions and trends from 1974 to 1981 at NASQAN and NWQSS sampling stations in the conterminous United States. Sampling was monthly for common constituents and quarterly for trace elements. Chemical concentrations refer to the dissolved form of the constituent unless stated otherwise. Mean concentrations denoted as (<) are estimated to be less than the laboratory detection limit. Laboratory detection limits (in micrograms per liter) for trace elements were as follows: arsenic, 1; cadmium, 2; chromium, 2; lead, 2; iron, 10; manganese, 10; mercury, 0.1; selenium, 1; and zinc, 2. Mean concentrations of trace elements were computed as the average of "minimum" and "maximum" estimates of the mean. Minimum and maximum estimates of the mean were obtained by assigning a value of 0 and the detection limit, respectively, to "less-than" values in the record. Trend slopes for common constituents are summarized as the median slope among stations showing a significant ($P < 0.1$) trend and are expressed as the annual percentage change in mean concentration at the station. Reliable slope estimates for trace elements could not be obtained because of the frequent occurrence of "less-than" values in those records.

Water-quality measure	No. of stations	Station-mean concentration percentiles*			Trends in concentration†			
					Increases		Decreases	
		25th	50th	75th	No. of stations	Median slope (% year^{-1})	No. of stations	Median slope (% year^{-1})
Common constituents								
*p*H	290	7.3	7.8	8.1	70	0.8	54	−0.8
Alkalinity as $CaCO_3$	289	42.0	104.3	161.8	18	2.3	75	−2.8
Sulfate as SO_4	289	10.5	39.9	116.9	78	3.7	38	−3.2
Nitrate, total as N‡	383	0.20	0.41	0.89	116	6.7	27	−8.7
Phosphorus, total as P‡	381	0.06	0.13	0.29	43	7.4	50	−8.1
Calcium	289	15.8	38.2	66.8	23	1.8	79	−2.7
Magnesium	289	3.9	11.2	21.7	48	2.6	41	−2.9
Sodium	289	6.8	18.3	68.9	100	3.7	27	−3.7
Potassium	289	1.5	2.8	4.9	66	2.4	39	−3.2
Chloride	289	6.7	14.9	53.3	101	3.3	34	−5.5
Suspended sediment	276	18.4	66.8	193.2	43	10.7	39	−17.4
Fecal coliform bacteria‡	305	92	355	1222	16	11.1	45	−34.5
Fecal streptococcal bacteria‡	295	173	488	1501	9	14.0	67	−32.0
Dissolved oxygen‡	369	8.7	9.8	10.5	63	2.3	41	−2.4
Dissolved-oxygen deficit‡	353	0.4	1.0	1.5	41	14.9	58	−19.7
Trace elements								
Arsenic	293	<1	1	3	62		11	
Cadmium	285	<2	<2	<2	48		6	
Chromium	161	9	10	10	12		2	
Lead	292	3	4	6	7		66	
Iron	293	36	63	157	27		21	
Manganese	286	11	24	51	30		19	
Mercury	199	0.2	0.2	0.3	7		2	
Selenium	211	<1	<1	1	4		23	
Zinc	288	12	15	21	18		32	

*Concentrations are expressed as milligrams per liter for common constituents and micrograms per liter for trace elements, except as follows: *p*H (standard units) and fecal bacteria (colonies per 100 ml). †Trends in concentration were flow adjusted for common constituents. ‡Denotes constituents sampled at both networks. Other constituents were sampled only at NASQAN stations.

Table 1 shows that numerous, and sometimes large, changes occurred nationally in the concentrations of several constituents (for example, nitrate, chloride, and sodium) during the period from 1974 to 1981. For some constituents the trends are predominantly in one direction (for example, decreases in lead and in fecal streptococcal bacteria), but for others the trends are more evenly divided between increases and decreases (for example, total phosphorus and suspended sediment). Various potential causes exist for trends in most constituents. For example, changes in fertilizer use, atmospheric deposition, and municipal waste treatment can each be identified as the major cause of nitrate trends in specific basins (Fig. 2). In interpreting the causes of water-quality trends at network stations, we relied on information from various sources. First, through literature review we identified major sources of specific chemical and biological constituents, noting previous reports of regional trends. Second, we investigated statistical associations among the water-quality trends and between the water-quality trends and various hydrologic characteristics of the basins upstream of the sampling stations (*18*). Finally, we tested statistical associations between the observed trends and related data (Table 2) describing population, land use, and known pollution sources in the basins upstream of the sampling stations (*19*). Point sources within the conterminous United States (*2, 20, 21*) (Table 2) could be identified by river-reach number (*15*) and located as a function of channel distance from the sampling stations. Industrial and agricultural land-use information was available either by cataloging unit (*22*) or by county (Table 2), and it was aggregated to the basin level through digitization of the drainage area above the stations.

Effects of Point-Source Controls on Water Quality

In the decade after the passage of the Clean Water Act (CWA) in 1972, municipal loads of biochemical oxygen demand (BOD) decreased an estimated 46% (*9*) and industrial BOD loads decreased at least 71% nationally (*23*). These achievements in point-source pollution control are particularly impressive since population and the inflation-adjusted gross national product (GNP) increased 11 and 25%, respectively, during the same period. Industrial sources currently contribute about one-third of the total point-source BOD load nationwide (*21*), and it is likely that much of the decline in industrial loads took place slightly earlier (mid-1970s) than the decline in municipal loads (*24*). Federal expenditures for the upgrading of municipal facilities under the Construction Grants Program reached a maximum in 1980 (*25*) and totaled $35 billion from 1972 to 1982 (*9*).

Trends in dissolved oxygen deficit (DOD). Over the period from 1974 to 1981, decreases in DOD (that is, improvements in dissolved oxygen conditions) outnumbered increases at network stations by a ratio of about 3 to 2 (Table 1). Decreases in DOD occurred frequently in the New England, Mid-Atlantic, Ohio, and Mississippi regional basins, while increases were most frequent in the Southeast. In view of the large reductions in BOD loads that occurred during the period, one might suspect that the greater frequency of DOD decreases over increases reflects the success of point-source control efforts. Many case studies (*7, 26*) have documented local decreases in stream DOD after improvements were made at waste-treatment facilities. Moreover, nationwide assessments (*9, 23*) based on surveys of state and local pollution-control personnel suggest that widely visible improvements in water quality have occurred that are attributable to point-source BOD reductions occurring in the decade after enactment of CWA. According to these surveys, water-quality improvements reported by state officials for the period from 1972 to 1982 extended to approximately 13% of the river miles studied. A more conservative estimate, however, comes from modeling studies (*27*), which indicate that point-source BOD reductions comparable to those achieved by 1982 would result in detectable DOD changes in only about 7% of river miles nationwide.

Comparing the observed trends in DOD at network stations with various measures of upstream BOD loads leads to a still lower assessment of the effects of point-source controls on nationwide dissolved oxygen levels. There is a moderately significant ($P = 0.045$) statistical association between DOD trends and static measures such as the ratio of point- to nonpoint-source BOD loads

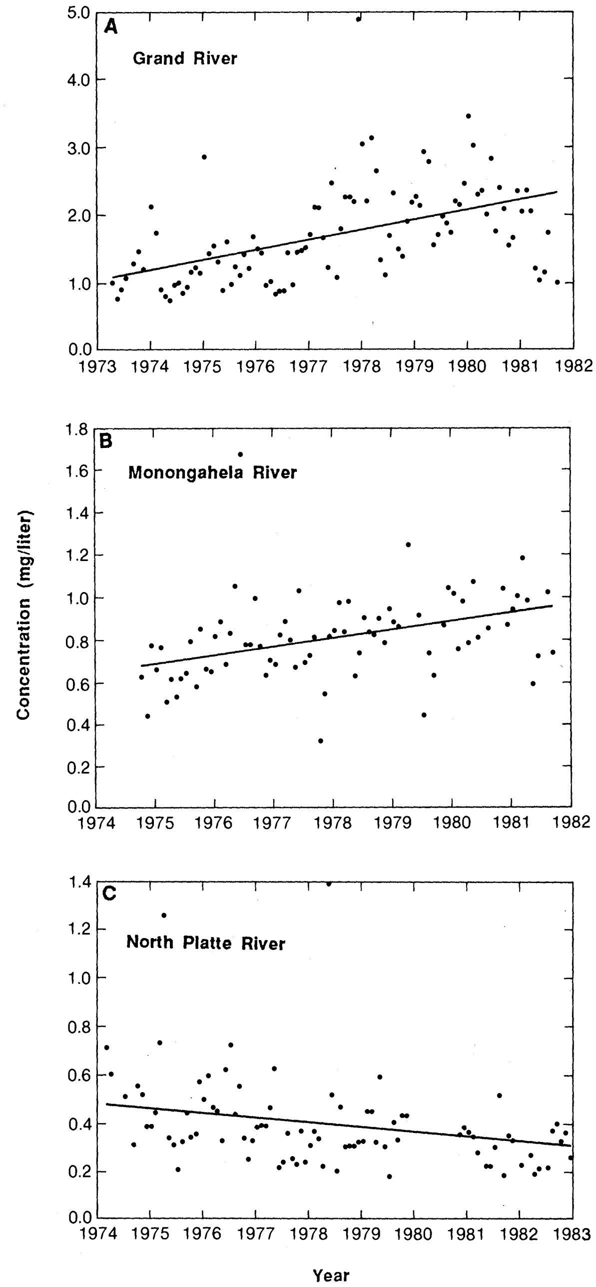

Fig. 2. Trends in total nitrate concentrations in U.S. rivers (1974 to 1981) have resulted from a variety of causes. (**A**) The Grand River (MI) drains intensively cultivated land and received increased inputs of nitrogen fertilizer throughout the 1970s. (**B**) The Monongahela Basin (PA) is largely forested and received increased atmospheric deposition of nitrate during the 1970s. (**C**) Point-source loads of nitrogen to the North Platte River (NE) decreased significantly during the late 1970s as a result of improved municipal waste treatment.

Table 2. Ancillary data used in the interpretation of NASQAN and NWQSS trend results.

Database and reference	Description
U.S. Census of Population (*61*)	Population in the United States summarized for approximately 400,000 block groups and enumeration districts* identified by latitude and longitude.
EPA river-reach file (*15*)	Numeric listing of approximately 67,000 stream reaches† (950,000 km) arranged systematically to provide hydrologic linkages among major U.S. rivers.
EPA Industrial Facility Discharge File (*20*)	Estimated flow from approximately 54,000 industrial and municipal facilities having EPA permits; identified by permit number in the National Pollution Discharge Elimination System (NPDES) and by river-reach number.
EPA Needs Survey (*2*)	Includes estimates of flow and BOD concentrations in the effluent discharged from approximately 30,000 publicly owned sewage treatment plants identified by NPDES permit number and river-reach number.
RFF Environmental Data Inventory (*21*)	Estimates of BOD, nutrient, and toxic-metal loads discharged to U.S. streams and lakes from approximately 32,000 industrial and municipal waste treatment facilities and discharged in the runoff from major land types (urban, cropland, pastureland, rangeland, and forest land); identified by NPDES permit number, cataloging unit, and river-reach number.
National Resources Inventory (*36*)	Estimates of sheet and rill erosion for approximately 800,000 sample plots, aggregated by county and identified according to land use (cropland, pastureland, rangeland, and forest land).
U.S. Census of Agriculture (*33*)	Census of farm operators including county-based estimates of crop, forest, pasture, and range acreage, agricultural chemical and fertilizer use, and inventories and sales of livestock and poultry.
U.S. gasoline consumption (*56*)	Annual consumption of leaded and unleaded gasoline by state and annual lead content of leaded gasoline.
U.S. road salt application (*43*)	Annual quantities of salt applied to roads and highways, aggregated by state.
NADP wet deposition chemistry (*59*)	Isopleth maps of the United States, giving annual estimates of wet deposition for major dissolved ions.
Air emissions of sulfur and nitrogen oxides (*40*)	Based on quantities and chemical composition of consumed fuels, by state and year.
U.S. coal production (*46*)	Surface and underground coal production by county.

*Block groups and enumeration districts are census units consisting of 800 to 1000 people. †A reach is a segment of stream channel extending from one tributary junction to another. Average stream-reach length is approximately 15 km.

(*21*) upstream of the stations (Table 2). Decreases in DOD occurred more frequently than expected where point sources were dominant, and increases where nonpoint sources were dominant. There was also a slight tendency for DOD decreases to occur more frequently where the industrial contribution to total point-source BOD load was large, a finding that is consistent with evidence (*24*) that major increases in industrial treatment preceded the surge in construction and upgrading of municipal waste treatment facilities under the Construction Grants Program. No significant relation was found, however, between trends in DOD and changes in BOD loads from municipal treatment plants within 160 km upstream of the stations. Reducing the distance over which BOD loads were summed in computing load changes gave progressively higher numerical significance levels, but even at the apparent maximum at 50 km, χ^2 results showed little sign of association between load changes and DOD trends. Additional steps to specifically consider low-flow conditions and dilution and reaeration effects (*28*) gave even lower significance levels. Stratifying the stations to consider only those with high average DOD levels or those close to large point-source loads gave the most nearly significant results, but even these were unconvincing.

Overall, these results provide weak evidence that the distribution of trends in DOD reflects the effects of point-source BOD reductions. The inability to demonstrate a relation between observed DOD trends and recorded changes in municipal BOD loads seems surprising in view of the magnitude of change in loads that has occurred and the number of case studies demonstrating local effects of increased treatment. The poor correlation with municipal load changes might be explained, in part, by a greater effect of industrial load changes, but a more likely explanation is that the effects of municipal BOD reductions do not generally extend to the location of network stations (*29*). This possibility is supported by the fact that test results improve systematically with decreasing distance between the stations and municipal sources and with stratification of the network to focus on stations more heavily influenced by point sources.

As a sample of nationwide water-quality conditions, network stations are moderately biased toward higher point-source loads (*30*), suggesting that the effects of increased treatment should be somewhat more observable at these stations than in the nation's rivers in general. Therefore, the inability to clearly demonstrate the effects of increased municipal treatment on DOD trends at network stations, although not inconsistent with case studies showing local improvements from plant upgrading, does appear to be at odds with other recent assessments citing more far-reaching effects. Statistically, load reductions appear to explain observed improvements in dissolved oxygen at less than 2% of all stations (that is, 5% of stations showing an improving trend) (*31*). Given the bias of network stations toward higher point-source loads, the effects of BOD-load reductions on DOD levels among all stream reaches (Table 2) are probably somewhat smaller.

The statistical association between municipal BOD reductions and the occurrence of "no trend" in DOD at network stations was considerably stronger than the association to decreasing DOD trends. It has been suggested (*9*) that maintenance of constant water quality during a period of rising population and GNP represents a significant achievement for pollution control efforts to date. Accordingly, evidence indicates that municipal BOD reductions in some basins compensated for rising nonpoint-source BOD loads, resulting in roughly constant levels of DOD. Statistically, load reductions may have led to maintenance of dissolved-oxygen concentrations (that is, no trend) at as many as 5% of all stations (*31*).

Fecal bacteria. In contrast to the relatively infrequent occurrence of DOD trends, decreases in fecal coliform (FC) and fecal streptococcal (FS) bacteria were widespread during the study period. Decreases in FS bacteria were especially common in parts of the Gulf Coast, central Mississippi, and the Columbia basins (Fig. 3A), and decreases in both forms of bacteria were frequent in the Arkansas-Red Basin and along the Atlantic Coast. There is a significant association in the occurrence and direction of trends in the two types of bacteria, suggesting common causes for the trends in many cases.

Because both municipal and agricultural sources of fecal bacteria were the object of pollution control efforts during the 1974 to 1981 period (*1*, *32*), it is of interest to know whether the observed decreases in fecal bacteria counts are more strongly associated with point-source or nonpoint-source changes. As with DOD, decreases in aquatic bacteria counts have been linked in case studies to improvements in sewage treatment during the study period (*26*). A major emphasis of the Construction Grants Program has been the achievement of secondary treatment as a minimum standard, which has led to the establishment of centralized collection and treatment of municipal wastes for the first time in many communities (*1*). Increased control of animal wastes in feedlot and other agricultural runoff (*32*) also occurred during the late 1970s with the objective of reducing stream bacteria counts.

Several lines of evidence suggest that the widespread decreases in fecal bacteria at network stations are traceable to improved municipal waste treatment and the less frequent increases in FC counts are associated with livestock wastes. Tests of association between fecal bacteria trends and various measures of change in sewage treatment (*2*) in network basins indicate that point sources are more important than nonpoint sources in explaining observed decreases. In particular, decreases in both forms of bacteria are associated with increases in the fraction of municipal effluent receiving secondary (or higher) levels of treatment within 50 km of network stations. Despite increased control of agricultural runoff, however, FC increases are positively associated with cattle population density as well as feedlot activity in the basins (*33*).

Trends in Nonpoint Sources of Suspended Sediment and Nutrients

Recent assessments suggest that nonpoint-source pollution may prevent achievement of national water-quality goals even after complete implementation of planned point-source controls (*3*). Suspended sediment (SS) and nutrients from agricultural sources are cited as the most damaging nonpoint-source pollutants national-

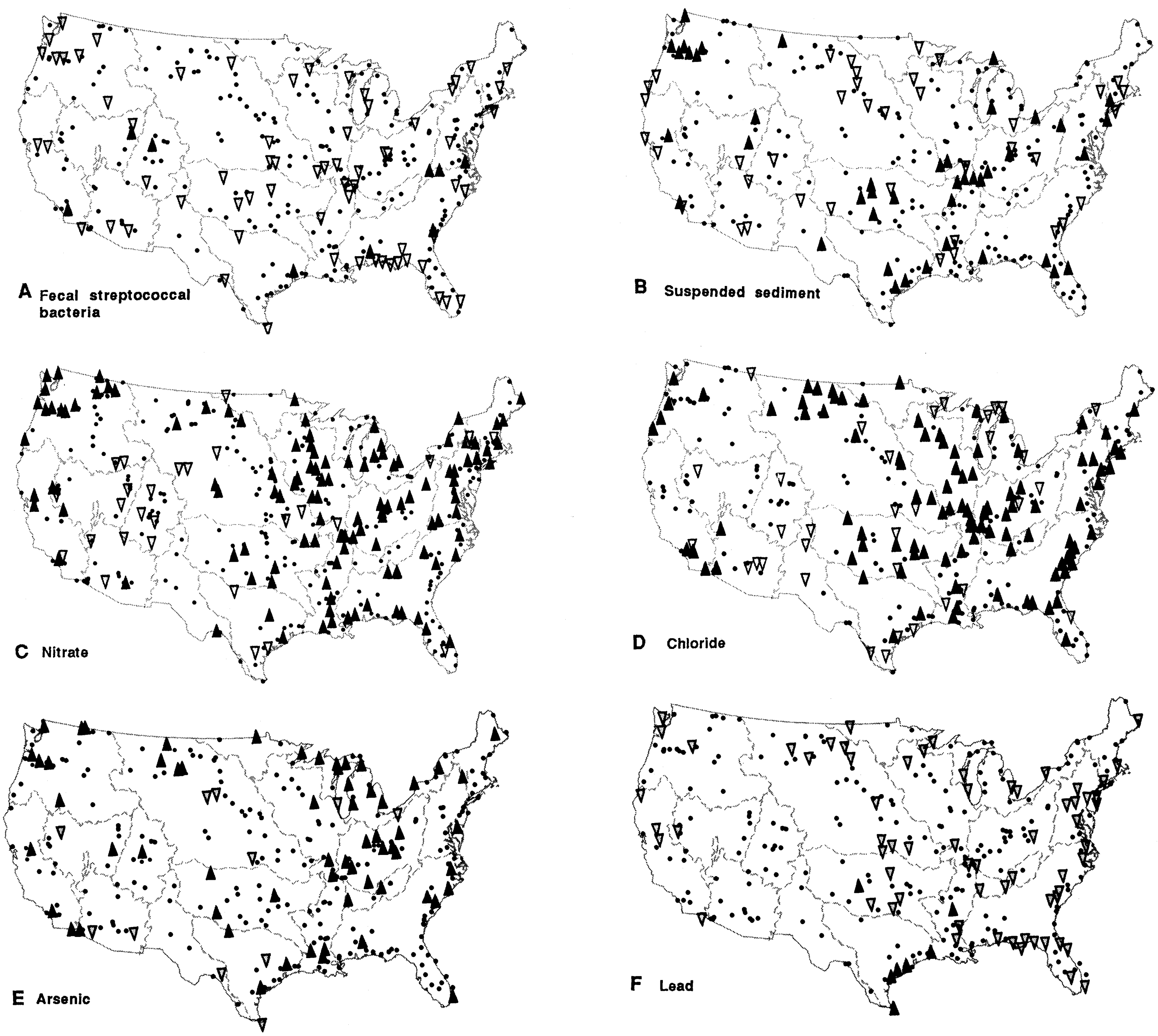

Fig. 3. Trends in the flow-adjusted concentrations of six common water-quality constituents at NASQAN and NWQSS stations from 1974 to 1981 (▲, increase; ▽, decrease; and ●, no trend). Regional drainage basins are outlined with dashed lines. (**A**) Fecal streptococcal bacteria, (**B**) suspended sediment, (**C**) nitrate, (**D**) chloride, (**E**) arsenic, and (**F**) lead.

ly (*11*). One source (*34*) estimates the cost of the hydrologic impacts of soil erosion and related nutrients on aquatic ecosystems at roughly \$3.5 billion annually. Despite the widely acknowledged severity of nonpoint-source pollution, however, little information has been available on long-term trends in the specific measures of water quality most affected by nonpoint sources. Of particular interest are the possible effects on SS and nutrient concentrations of large increases in agricultural activity during the 1970s. Fertilizer application rates increased 68% between 1970 and 1981 in association with rapidly increasing farm production (*35*). Indeed, the long-term history of fertilizer use has been one of nearly continuous increase in nitrogen and phosphorus application rates up to 1981 (*35*). The extent to which these and other changes in agricultural practice are reflected in trends in SS, phosphorus, and nitrogen concentrations in the nation's rivers has been largely a matter of conjecture because of the lack of systematic long-term studies.

Analysis of network data indicates that, from 1974 to 1981, nitrogen concentrations followed a distinctly different pattern of trends, both in frequency and geographic distribution, from those of phosphorus and SS. Likely reasons for the difference can be seen in relations between the trend results and various nonpoint-source characteristics of network basins.

Suspended sediment. Nationwide trends in SS concentrations (Fig. 3B) occurred with only moderate frequency and were nearly equally divided between increases and decreases. Increasing SS concentrations occurred in basins in which the predominant forms of land use have historically been associated with high rates of soil erosion (for example, logging in the Columbia and agriculture in the Arkansas-Red and Mississippi basins). We tested the association between SS trends and erosion rates for specific land-use categories by using detailed erosion rate estimates (*36*) from the U.S. Department of Agriculture National Resources Inventory (Table 2). Trends in SS were not significantly associated with estimates of total basin soil erosion, but SS increases were significantly related to the fraction of total soil erosion contributed by cropland in the basin and to the absolute magnitude of cropland erosion in the basin. By contrast, SS trends were not associated with erosion rates on either forest land, pastureland, or rangeland.

Factors other than soil erosion played an important role in SS trends in certain basins. Many streams in the Columbia Basin carried increased sediment loads after the eruptions of Mount St. Helens during 1980 and 1981 (*37*). Also, declining concentrations have been reported for several locations in the Missouri River basin and have been clearly traced to the effects of reservoir construction throughout the basin during the 1950s and 1960s (*38*). However, tests of association between SS trends and the fraction of the drainage basin located upstream of reservoirs were not significant, indicating that construction and operation of reservoirs were not major factors in the nationwide occurrence of trends.

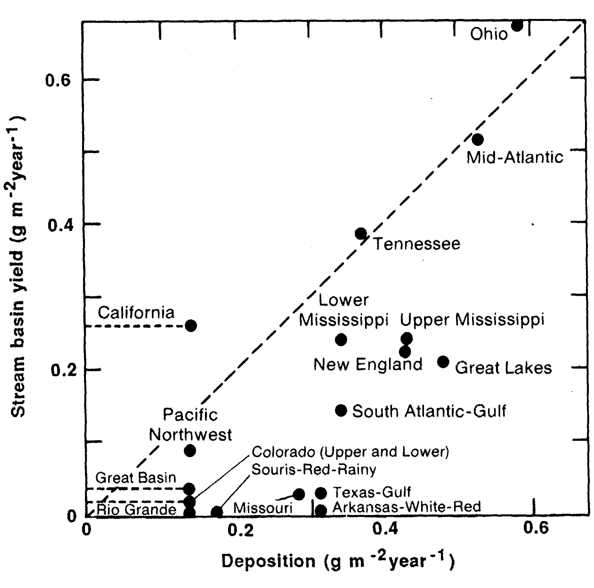

Fig. 4. Median yield of nitrate at network monitoring stations in relation to the atmospheric deposition rate of nitrate for the 18 water resources regions of the conterminous United States.

Total phosphorus. Trends in total phosphorus (TP) concentrations followed a pattern similar to that of SS with the exception that decreases in TP occurred frequently in the Great Lakes and Upper Mississippi regions. Decreases in TP in the Great Lakes region resulted, in part, from point-source reductions achieved in the region in the late 1970s (*39*). Several lines of evidence suggest that observed TP decreases stem generally from point-source reductions, while observed increases in TP result from nonpoint-source increases. Tests of association between TP trends and various measures of point-source phosphorus loads upstream of network stations are significant mainly because of the frequent coincidence of TP decreases with large point-source loads (*21*). Conversely, evidence for the importance of nonpoint sources in relation to increasing trends lies in significant associations between TP increases and various measures of agricultural land use (*33*), including fertilized acreage and cattle population density. Additional evidence for the importance of nonpoint sources is provided by a significant association between TP and SS trends.

Total nitrate. In contrast to SS and TP, increasing trends in total nitrate (TN) concentrations were extremely frequent and widespread, outnumbering decreases 116 to 27 out of a total of 383 stations (Fig. 3C). Increasing trends were most frequent east of the 100th meridian. Increases in TN were strongly associated with several measures of agricultural activity (*33*), including fertilized acreage as a percentage of basin area, livestock population density, and feedlot activity.

In addition to agricultural runoff, atmospheric deposition has become a major source of nitrate in surface waters, especially in forested basins of the East and northern Midwest (Fig. 4). Few nitrate deposition records exist for the years before 1980, but those that do (*5*), together with emission estimates of nitrogen oxides (*40*), show a general pattern of increasing rates during the 1974 to 1981 period. Consistent with this trend, TN increases at network stations were strongly associated with high levels of atmospheric nitrate deposition (*14*) (particularly in the Ohio, Mid-Atlantic, Great Lakes, and Upper Mississippi basins).

Point-source loads of nitrogen declined in many basins during the late 1970s as a result (directly or indirectly) of improvements in waste treatment (*7*), but the magnitude of change nationally is poorly documented. Trends in TN at network stations are only weakly associated with changes in the fraction of municipal effluent receiving secondary or higher levels of treatment (*2*) within 50 km upstream of the stations. Similar tests for distances up to 160 km, as well as tests involving changes in the fraction of municipal effluent receiving either advanced secondary or tertiary treatment, were not significant. In sum, TN trends appear more related to nonpoint sources than to point sources, and, in particular, atmospheric deposition may have played a large role in the frequent occurrence of TN increases in midwestern and eastern basins.

Given the large increases in fertilizer application rates that occurred before and during the 1974 to 1981 period, it is not surprising that trends in both TP and TN (especially increasing trends) show strong associations to measures of agricultural activity. Despite the importance of agricultural sources, however, distinct differences exist in the trend patterns for TP and TN. Phosphorus trends (along with SS trends) occurred with only moderate frequency and were largely confined to the major mid-continent basins. In contrast, nitrate trends (especially increasing trends) occurred with high frequency and were widely distributed from the Farm Belt eastward. The differences in nitrogen and phosphorus trend patterns appear to be the result of three factors. First, atmospheric deposition seems to have played a large role in the high frequency of nitrate trends, especially among forested basins in the Midwest and East. Second, the low frequency of, and strong association between, phosphorus and SS trends suggests that anticipated increases in phosphorus concentrations resulting from the rise in agricultural activity in the 1970s have been moderated or delayed by the temporary storage of sediment-bound phosphorus in stream channels. Because nitrate transport in rivers is much less dependent on the movement of suspended sediment than phosphorus transport (*34*), the observed pattern of nitrogen trends more fully reflects the effects of increased agricultural activity than the phosphorus trend pattern. Finally, point-source control efforts during the study period were focused much more heavily on phosphorus than on nitrogen because phosphorus was considered more limiting to eutrophication in freshwater ecosystems (*39*). The results of this policy difference are observable both in the greater ratio of phosphorus decreasing trends to increasing trends and in the stronger association of phosphorus decreasing trends to point-source loads.

Perhaps the greatest consequence of the differences in nitrogen and phosphorus trend patterns is seen in recent changes in the delivery of nutrients to coastal areas (Table 3). Nitrate loads to East Coast estuaries, the Great Lakes, and the Gulf of Mexico have increased significantly, while phosphorus loads to coastal areas have changed little or have even declined. (Exceptions to the pattern are the Gulf Coast and Pacific Northwest basins where phosphorus loads to estuaries have increased in association with substantial increases in sediment loads.) There is increasing concern over the problem of eutrophication in estuaries, and debate has arisen over the need for nutrient controls in tributary basins (*3*). Increased delivery of nitrate to estuaries is of particular concern because of the tendency for nitrogen to be limiting to eutrophication in many estuarine environments (*41*).

Trends in Salinity

One striking feature of the trends in Table 1 is the high frequency of increasing trends among dissolved substances that contribute to salinity in natural waters. Increasing trends in chloride (Fig. 3D), sulfate, and sodium are numerous both in relation to the frequency of decreasing trends as well as in absolute terms. The magnitude—an average increase of 30%—and wide distribution of these trends represent a significant increase in the salinity of the nation's rivers during the 1974 to 1981 period.

From analyses of concurrent changes in basin conditions, it seems likely that several factors have been responsible for the general pattern of salinity increase. First, chloride trends were moderately correlated with basin population changes during the study period, reflecting the fact that human wastes are a major source of chloride in many populated basins (*42*). Second, salt use on highways increased nationally by a factor of more than 12 between 1950 and 1980 (*43*) and stands out as a likely cause of sodium and chloride trends in basins where rates of highway salt use have become a significant contributor to total stream salinity (*44*). Increasing sodium and chloride concentrations were significantly associated with high rates of highway salt use and with large increases in its use (especially in the Ohio, Tennessee, lower Missouri, and Arkansas-Red basins). Although irrigated agriculture has a large influence on the salinity of certain western rivers (*45*), chloride trends were not significantly correlated with changes in irrigated acreage nationally (*33*). Finally, increases in sulfate were especially frequent in the Missouri, Arkansas, and Tennessee basins and were highly correlated with changes in surface coal production from 1974 to 1981 (*46*). Sulfate trends were not significantly correlated with underground coal production in the basins, however.

In contrast to much of the rest of the nation, salinity clearly decreased in the Upper Colorado Basin during the 1974 to 1981 period. Decreases in chloride concentrations in the Colorado drainage are noteworthy in view of the history of salt problems in the basin. These decreases have been recently traced, in part, to salinity control efforts and, in part, to the temporary effects of reservoir filling during the early 1970s (*47*).

Table 3. Recent changes in the delivery of nutrients to coastal areas of the United States reflect major differences in the trend patterns for nitrogen and phosphorus in rivers.

Region	Change in load, 1974–1981	
	Total nitrate (%)	Total phosphorus (%)
Northeast Atlantic Coast	32	−20
Long Island Sound/New York Bight	26	−1
Chesapeake Bay	29	−0.5
Southeast Atlantic Coast	20	12
Albemarle/Pamlico Sound	28	0
Gulf Coast	46	55
Great Lakes	36	−7
Pacific Northwest	6	34
California	−5	−5

Trends in Trace Elements

Recent trends in toxic element concentrations in surface waters have remained largely unknown despite rapidly increasing knowledge of the potential sources of toxic substances in aquatic systems (*48*). Network water-quality records show frequent increasing trends in the dissolved forms of two potentially toxic trace elements, arsenic (Fig. 3E) and cadmium. The dissolved forms of trace elements are of particular concern because they are more readily incorporated into potable water supplies than nondissolved forms (*49*). Increasing trends in arsenic and cadmium concentrations occurred with greatest frequency in basins in the northern Midwest, and evidence suggests that increased atmospheric deposition of fossil-fuel combustion products was the predominant cause of the trends in both elements. The major environmental sources of arsenic and cadmium include fossil-fuel combustion, primary metals manufacturing, pesticides, herbicides, and phosphate-bearing commodities such as fertilizers and detergents (*50*). Fossil-fuel combustion, the largest source of both elements, introduces arsenic and cadmium into the aquatic environment both through atmospheric deposition of combustion products and in the runoff from fly-ash storage areas near power plants and nonferrous smelters (*50*).

Evidence favoring atmospheric deposition over terrestrial sources as the predominant cause of the arsenic and cadmium trends lies in several factors. First, statistical associations between deposition rates and arsenic and cadmium trends are highly significant (*14*), whereas associations between the trends and the number of power plants, nonferrous smelters, and other industrial sources upstream of the stations (*21*) are not significant. Similarly, arsenic and cadmium

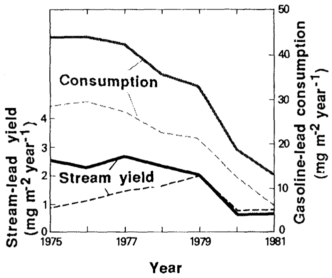

Fig. 5. Changes in mean rates of gasoline-lead consumption and lead yield (dissolved) in streams in NASQAN drainage basins. The level and rate of decrease of gasoline-lead consumption over the study period are greater among basins where stations show significant decreases in stream-lead concentration (solid lines) than in basins where stations do not show such decreases (dashed lines).

trends are not significantly related to basin herbicide use (*33*), basin fertilizer use (*33*), irrigated acreage (*33*), or municipal effluent-flow rates upstream of the stations (*2*). Finally, sedimentary evidence from Adirondack lakes indicates that increasing atmospheric deposition of arsenic and cadmium has occurred since the 1950s (*51*).

In contrast to arsenic and cadmium, decreases in dissolved lead concentrations greatly outnumbered increases at network stations (Fig. 3F); these decreases occurred frequently along the East and West coasts and on tributaries to the Missouri and Mississippi rivers. The few increases in lead that did occur were clustered along the Texas-Gulf Coast and in the Lower Mississippi Basin. Evidence of declining environmental lead levels has accumulated rapidly in recent years (*52–54*), and the decline has been widely attributed to decreased consumption of leaded gasoline (*55*). Both the consumption rate and lead content of fuels have declined in all of the 50 states since the mid-1970s (*56*), resulting in a 67% drop in nationwide gasoline-lead consumption between 1975 and 1981 (Fig. 5). Gasoline lead is recognized as the major source of environmental lead (*57*), although its distribution in aquatic systems is perhaps the least well known. Declines in airborne lead have been reported for many U.S. cities (*52*), whereas declines in lead concentrations in bulk precipitation (*53*), rivers (*54*), and lake sediments (*55*) have been reported only at selected sites.

Given the general decline in the major source of environmental lead, the geographic pattern of changes in aquatic lead concentrations is of interest. Decreases in lead concentrations in streams were significantly associated with both the level and rate of decline in gasoline-lead consumption (*56*) in network basins during the study period. Nevertheless, significant declines in stream lead did not occur in all basins, including some with large urban and suburban populations (for example, the Ohio and Great Lakes basins), despite at least moderate declines in gasoline-lead consumption in all basins. Thus, in addition to gasoline consumption, unknown factors pertaining to the solubility and transport of lead in network basins (*48, 58*) seem to have influenced the observed pattern of trends.

Conclusions

Analysis of network water-quality records for the years from 1974 to 1981 leads to an assessment of the effects of point-source pollution controls imposed during the 1970s that differs from previous studies. While the emphasis of both private and public control efforts during that period was on dissolved oxygen conditions, the clearest evidence of water-quality improvements attributable to point-source controls is found in declining fecal bacteria counts and, to a lesser degree, in decreased TP concentrations. The weak association found between DOD trends and recorded changes in municipal BOD loads suggests that previous assessments have overestimated the spatial extent of dissolved oxygen improvements.

Trends in the concentrations of nitrate in rivers followed a distinctly different geographic pattern than those of phosphorus and SS over the study period. Nitrate increases occurred nearly three times more often than phosphorus increases, resulting in rises of from 20 to 50% in the delivery of nitrate to Atlantic Coast estuaries, the Gulf of Mexico, and the Great Lakes. Although increases in both nitrogen and phosphorus in rivers can be traced, in part, to agricultural sources upstream of the sampling stations, atmospheric deposition of nitrogen contributed greatly to the observed pattern of nitrate increases. The contribution of atmospheric nitrogen to surface water nutrient budgets deserves wider recognition in future assessments.

Flow-adjusted salinities have increased significantly in most regional drainage systems as a result of increasing trends in the concentrations of several dissolved constituents. Historical trends in the nationwide use of highway salt have been a factor in the regional pattern of sodium and chloride increases, and changes in surface coal production have similarly influenced the pattern of sulfate trends. Declining salinity levels in the Colorado River are a noteworthy exception to the general pattern of salinity increases.

Increases in dissolved arsenic and cadmium concentrations occurred frequently at network stations, especially in basins in the industrial Midwest. When the known locations of specific industrial and agricultural sources of arsenic and cadmium are considered, atmospheric deposition is favored over terrestrial sources as the predominant cause of the trace element trends. This conclusion is also supported by the results of lake sediment analyses in regions with high deposition of fossil-fuel combustion products (*51*).

Dissolved lead concentrations decreased at many network stations but failed to decrease at some despite significant declines in gasoline-lead consumption in the basins. Since lead consumption has decreased uniformly across the nation, continued monitoring of the geographic pattern of dissolved lead trends may provide additional insight into factors governing the transport of lead in large basins.

More intensive forms of monitoring are needed to better assess the policy implications of recent water-quality trends. Most urgent, perhaps, is the need for more detailed information on trace element trends and their relation to fossil-fuel combustion. Quantifying this relation requires expanding the scope of existing national programs for atmospheric deposition monitoring (*59*), which are currently focused on acidic effects and do not include trace element measurements. More detailed information is also needed to assess the ecological implications of large increases in nitrate in rivers. The number and magnitude of nitrate trends in comparison to those of phosphorus and SS suggest that nitrogen delivery to coastal areas will be of critical relevance in the growing debate over nonpoint-source pollution controls (*3*) as well as emission controls on nitrogen oxides. In contrast to trace element deposition, existing programs for monitoring nitrogen deposition are probably adequate, and the need, instead, is for more intensive investigation of the hydrochemical and ecological processes involved in nitrogen transport in basins dominated by various kinds of land use. The national water-quality monitoring networks are currently ill-suited for such specialized investigations. Many network basins are large and heterogeneous, and the factors affecting water quality are complex. Additional long-term water-quality sampling in smaller, more homogeneous basins would increase the ability to distinguish terrestrial from atmospheric influences and would establish the time scales of nitrogen transport from land to water.

Additional sampling in selected smaller basins would also improve the ability to determine the effects of changes in point-source pollution. Although the effects of improved sewage treatment on dissolved oxygen levels appear to be more localized than previously thought, it is possible that the ecological and social benefits of water-quality improvements have been large in proportion to their spatial extent. Individual case studies (*7*) have demonstrated local effects of point-source pollution controls, but they do not provide an adequate national sample on which to base an assessment of the benefits of pollution abatement programs. It has been argued (*60*) that the availability of water-quality information is not commensurate with the large public and private expenditures that have been made for point-source controls. Thus, in designing water-quality monitoring programs for the future, we should recognize the growing number of both point- and nonpoint-source issues that our economic and political systems must address.

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