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Water quality trends in the Delaware River Basin (USA) from 1980 to 2005

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Abstract In 1940, the tidal Delaware River was "one of the most grossly polluted areas in the United States." During the 1950s, water quality was so poor along the river at Philadelphia that zero oxygen levels prevented migration of American shad leading to near extirpation of the species. Since then, water quality in the Delaware Basin has improved with implementation of the 1961 Delaware River Basin Compact and 1970s Federal Clean Water Act Amendments. At 15 gages along the Delaware River and major tributaries between 1980 and 2005, water quality for dissolved oxygen, phosphorus, nitrogen, and sediment improved at 39%, remained constant at 51%, and degraded at 10% of the stations. Since 1980, improved water-quality stations outnumbered degraded stations by a 4 to 1 margin. Water quality remains good in the nontidal river above Trenton and, while improved, remains fair to poor for phosphorus and nitrogen in the tidal estuary near Philadelphia and in the Lehigh and Schuylkill tributaries. Water quality is good in heavily forested watersheds (>50%) and poor in highly cultivated watersheds. Water quality recovery in the Delaware Basin is coincident with implementation of environmental laws enacted in the 1960s and 1970s and is congruent with return of striped bass, shad, blue crab, and bald eagle populations.

Keywords Water quality · Watersheds · Rivers/streams · Environmental regulations

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Introduction

In 1940, the Interstate Commission on the Delaware River Basin called the tidal Delaware River at Philadelphia "one of the most grossly polluted areas in the United States" (INCODEL 1940). By the 1950s, the urban estuary was noted as one of most polluted rivers in the world with zero oxygen levels during the summer (Dale 1996). American shad were unable to migrate through the anoxic barrier at Philadelphia leading to near extirpation of the species with genetic origins in the basin (Chittendon 1974). In 1973, a USEPA study concluded that the Delaware Estuary would never achieve fishable designated uses (USEPA 2000a).

Since then, environmental laws have led to water quality recovery in the Delaware Basin. In

1961, JFK signed the first ever Federal-state water compact creating the Delaware River Basin Commission (DRBC 2004). In 1972, Congress passed the Clean Water Act which led to amendments in 1977 and 1987 (Cech 2003). Phosphate detergent bans by New York in 1973 and Pennsylvania in 1990 along with a 1994 halt on manufacture prompted sizable phosphorus declines in basin streams (Litke 1999). In 1986, Congress added the Delaware Estuary to the National Estuary Program as one of only 28 nationally significant estuaries in the United States. By 2005 after over $250 million invested in wastewater treatment plants, dissolved oxygen at Philadelphia exceeded 5 mg/l, the fishable water quality standard in the tidal river. Migratory shad and striped bass have returned to the river in numbers not recorded since the early twentieth century (PDE 2002). The bald eagle, a protected species that relies on a fish-laden diet, returned to the cleaner waters of the Delaware Basin in growing numbers, even nesting in South Philadelphia in March 2007 (Associated Press 2007). By 2010, examination of 100 years of dissolved oxygen (DO) data indicates the Delaware Estuary has experienced one of the most dramatic improvements of water quality of any river worldwide (Sharp 2010).

In 2006, the Delaware River Basin Commission and Partnership for the Delaware Estuary gathered a land grant university consortium from the Basin states to collect water quality and environmental data for State of the Basin and State of the Estuary reports (DRBC 2008a) and PDE (2008). The University of Delaware in association with Cornell University, Pennsylvania State University, and Rutgers University examined water quality trends from 1980 to 2005 at 15 monitoring stations along the Delaware River and its largest tributaries.

Objectives

This article reports on water quality trends in the Delaware Basin as measured by dissolved oxygen, phosphorus nitrogen, and total suspended sediment from 1980 to 2005, an era of environmental action that coincided with recovered water quality. Our research objectives are to evaluate water quality trends along 15 monitoring stations and determine whether watershed management programs have resulted in improved or preserved water quality along the Delaware River and tributaries. Water quality trends were detected using the nonparametric flow-weighted Seasonal Kendall test for statistical significance supplemented by examination of time series scatterplots and boxplots illustrating the 25th, 50th (median), and 75th percentiles of the sample. We compared water quality changes with watershed influences such as stream flow, seasonality, land use, and point source pollutants.

Study location

The Delaware is the longest un-dammed river east of the Mississippi, extending 330 miles (529 km) from the Catskill Mountains in New York to the mouth of the Delaware Bay (DRBC 2004). The river is fed by 216 tributaries, the largest being the Schuylkill and Lehigh Rivers in Pennsylvania (Fig. 1). The basin contains 13,539 square miles (34,660 km^2), draining parts of Pennsylvania (51% of the basin), New Jersey (23%), New York (18%), and Delaware (8%). The Delaware Basin is covered by 55% forest, 26% agriculture, 4% wetlands, and 15% urban land.

The Delaware Basin is underlain by five physiographic provinces including the mountainous Appalachian plateau north of the Delaware Water Gap (Fig. 2), Valley and Ridge, and New England and Piedmont provinces north and west of the Fall Line through Trenton, Philadelphia, and Wilmington (USGS 2004). The flat Coastal Plain is south of the Delaware Estuary and below the Fall Line in southern New Jersey and Delaware.

More than 7.5 million people live in the Delaware Basin. Nearly 15 million people (5% of the nation's population) rely on the waters of the Basin for drinking and industrial use, but the watershed drains only 0.4% of the continental USA. Over seven million people in New York City and northern New Jersey live outside the basin and receive drinking water from the Delaware Basin. New York City withdraws 50% of its drinking water from three reservoirs located in the headwaters of the Delaware. By 2010, population in the

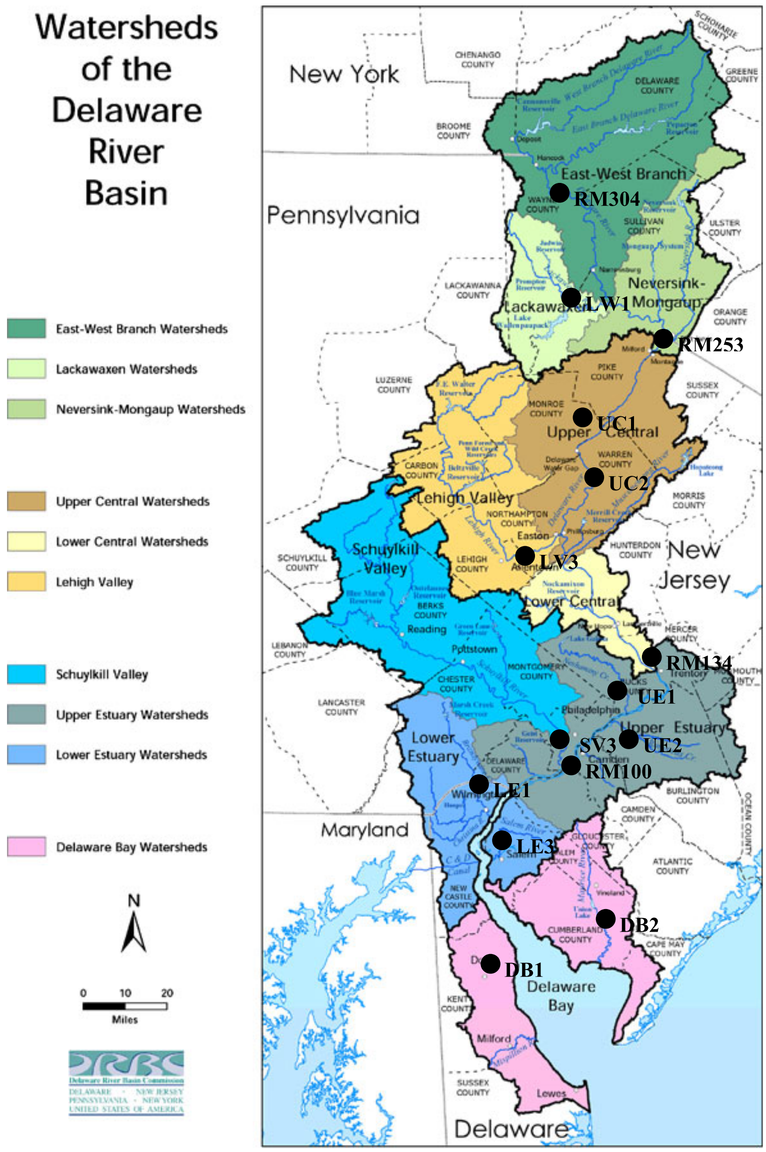


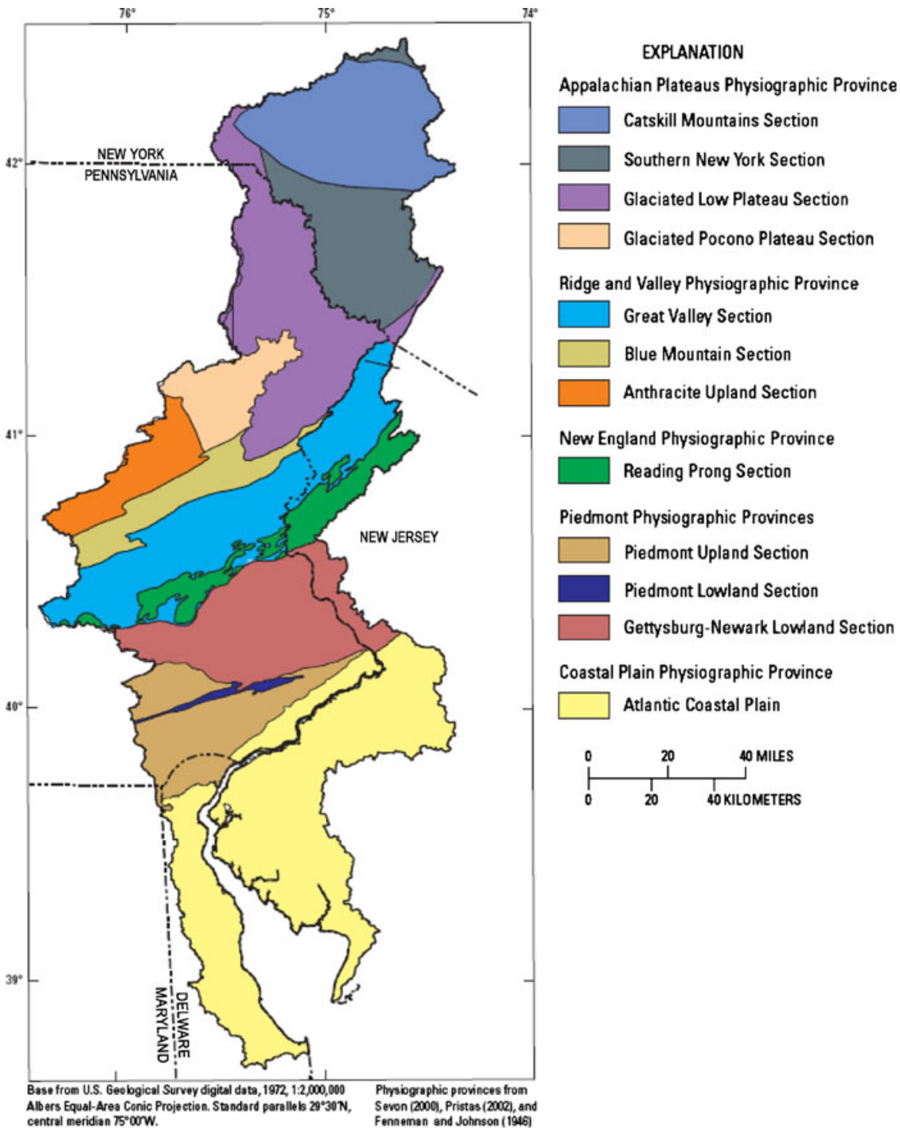
Fig. 1 Water quality monitoring stations along the Delaware River and tributaries (Kauffman et al. 2008)

Delaware Basin is projected to exceed 8,000,000, up from 7,000,000 people recorded by the 1980 Census. Over the last 30 years, population growth averaged 33,000 people per year.

The Delaware Estuary is internationally significant as the refueling habitat for shorebirds such as the red knot that feed on horseshoe crab eggs on their spring migration from the tip of South America enroute to the Arctic Circle. While American shad, striped bass, and blue crab populations are recovering in the Delaware Estuary, American oyster and Atlantic sturgeon populations are dwindling and many miles of waters of the Estuary have fish consumption advisories due to high levels of legacy PCBs and mercury in fish tissue (DRBC 2008a; PDE 2008).

The Delaware Estuary is the largest freshwater port in the world and generates \$19 billion in annual economic activity. The Delaware is home to the third largest petrochemical port with five of the largest East Coast refineries. It is the largest North American port for steel, paper, and meat imports and the largest importer of cocoa and fruit on the East Coast. Over 65% of South

Fig. 2 Physiographic provinces in the Delaware Basin (USGS 2004)



American fruits imported into the United States arrive through Delaware Estuary ports. Wilmington, Delaware is the largest US banana port with one million tons imported annually.

Literature review

1940–1960

In 1940, INCODEL called the Delaware Estuary below Trenton at Philadelphia "one of the most grossly polluted areas in the United States" (INCODEL 1940). In the river between Chester and Burlington, "more than 400 million gallons of untreated domestic sewage and industrial wastes are discharged daily." Shad and herring were unable to migrate through the zero oxygen barrier along the Delaware Estuary at Philadelphia to upriver spawning grounds.

Water pollution was so bad during World War II that a newly painted hospital ship turned into the colors of a rainbow as it sailed out to the Delaware River (Albert 1988). Nothing would grow on the hulls at the Philadelphia Navy yard in the polluted river. Navy pilots were instructed to ignore the sulfur stench from the river as they were flying a mile overhead. During the 1940s, up to 350 mgd (1,330 MLD) of raw sewage poured into the Delaware River from Philadelphia alone. Pollution from war industries resulted in a 1946 report by the US Fish and Wildlife Service that recorded an all time-worse anoxia condition from shore to shore. Berthed at the Philadelphia Navy Yard after World War II, the Admiralty gave British officers on the HMS Nelson extra allowances to replace gold braid tarnished by corrosive river gases.

During summers of the 1950s, DO levels were 1 mg/l or less over a 20-mile (32 km) section of estuary from the Ben Franklin Bridge in Philadelphia to Marcus Hook near Delaware. In 1950, the urban reach of the Delaware River was noted as one of most polluted stretches of river in the world. In 1952, ichthyologist Edward Raney (1952) cited the Delaware as an "outstanding example of destruction of (striped) bass habitat by industrial and domestic pollution." In September 1958, dissolved oxygen along the Delaware Estuary (Fig. 3) declined from 95% saturated at Trenton to 15% saturated at Philadelphia and 50% saturated at Wilmington (Smith et al. 1959).

The first water quality improvements in the Delaware Estuary appeared after construction of primary sewage treatment plants by Philadelphia, Camden, and Wilmington between 1951 and 1954. INCODEL water pollution abatement projects boosted the towns with sewage treatment from 63 municipalities in 1935 to 236 by 1959.

1960–1990

During the 1960s drought, Fig. 4 indicates dissolved oxygen in the Delaware Estuary between Wilmington and Philadelphia reached near zero from May through October due to high ammonia levels from untreated wastewater (Thomann 1972). A $1.2 million Delaware Estuary Comprehensive Study by the US Public Health Service found nearly 100 cities and industries were discharging waste into the Delaware Estuary. Seeking to restore basin water quality, the DRBC adopted a waste load allocation program in 1967 and with the four states started a basin-wide point source pollution abatement program. In 1968, the DRBC issued waste load allocations to 90 Delaware Estuary dischargers requiring wastewater treatment upgrades to secondary standards that resulted in an 89% decrease in chemical biochemical oxygen demand (CBOD) loading (Fig. 5) from municipal and industrial sources to the Delaware Estuary from 1,136,000 lbs/day (516,000 kg/day) in 1958 to 128,000 lbs/day 58,000 kg/day) by 1995 (USEPA 2000a).

By 1970, the Delaware was still polluted as American shad landings were down to 0.5 million pounds (0.23 million kilograms), 20 times lower than the late 19th century (Fig. 6) when over 10 million pounds (4.5 million kilograms) of shad were caught annually (DEP 1996). The suspected causes of the shad fishery crash were overfishing and zero oxygen levels due to pollution in the

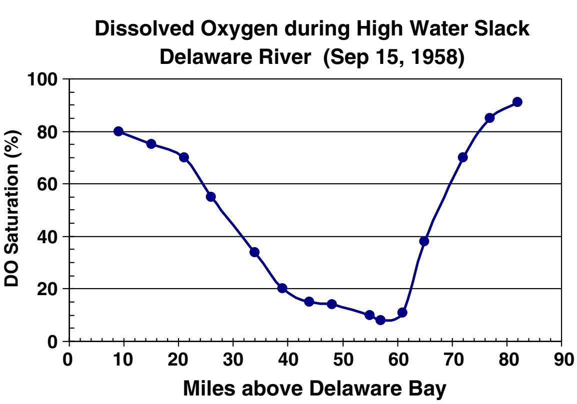


Fig. 3 Dissolved oxygen along the tidal Delaware River. Mile 55 = Philadelphia and mile 25 = Wilmington

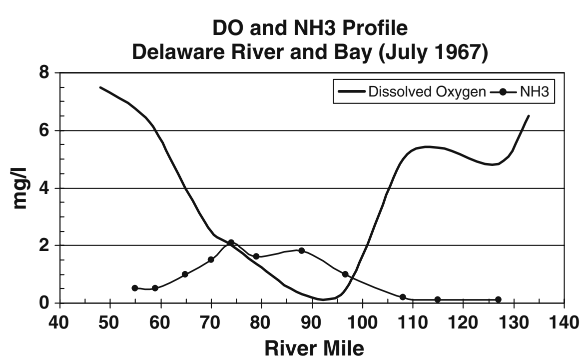


Fig. 4 Dissolved oxygen and ammonia nitrogen profile along the Delaware River and Bay, July 1967. River mile 100 = Philadelphia and river mile 133 = Trenton, New Jersey

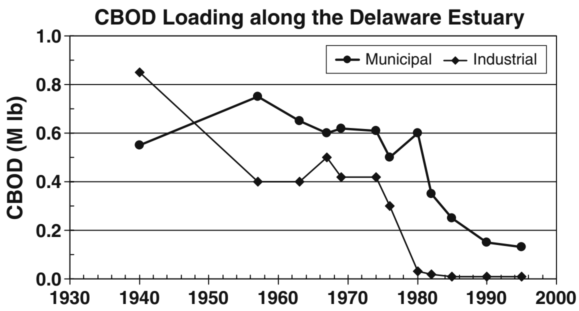


Fig. 5 CBOD loading along the Delaware Estuary, 1940 to 1995 (USEPA 2000a)

Delaware River at Philadelphia that served as a block to the shad migrating upstream (Chittendon 1974). By 1971, "gross pollution of tidal freshwater had extirpated the striped bass from its historical chief spawning and nursery areas in the Delaware River" (Chittendon 1971).

In 1972, water quality was good along the Delaware River from the Catskill headwaters to Trenton, extremely poor in the Delaware Estuary near Philadelphia, and recovered to good to excellent near the entrance of the Delaware Bay (Thomann 1972). In 1973, only a year after passage of the Federal Clean Water Act, a USEPA study concluded that the Delaware Estuary would never achieve designated fishable standards (USEPA 2000a). New York became the first state in the Delaware Basin to ban phosphate detergent in 1973 followed by Pennsylvania in 1990. By 1994, manufacturers stopped producing phosphate detergent (Litke 1999).

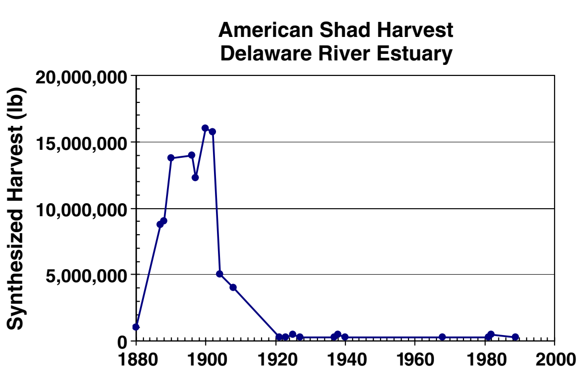


Fig. 6 Synthesized American shad harvest in the Delaware Estuary (Delaware Estuary Program 1996)

In 1974, water quality in the tidal Delaware Estuary above Wilmington was improving but still poor as Chittenden asserted that due to water quality concerns and the threat of a Tocks Island dam impoundment, "extirpation of the remnant (shad) runs is a distinct possibility" (Chittendon 1974). In 1975, DO levels along the Delaware Estuary were 1.7 mg/l at Philadelphia, 1.2 mg/l at Chester, and 3.1 mg/l at Wilmington, all less than the 4 mg/l fishable water quality standard (DRBC 1975).

1990–2009

By 1981, dissolved oxygen levels in the Delaware Estuary near Philadelphia were rising but still short of the fishable standard of 4 mg/l. Wastewater treatment plants at Philadelphia, Camden, and Trenton had not yet met standards set by the USEPA National Pollution Discharge Elimination System (NPDES) and DRBC waste load allocation program (DRBC 1981).

By the end of the 1980's, over $1.5 billion was spent on wastewater treatment plants along the Delaware Estuary and tributaries between Wilmington, Philadelphia and Trenton. Improvements to wastewater treatment prompted by the 1968 DRBC waste load allocations and 1972 Federal Clean Water Act improved water quality in the Delaware Estuary at Philadelphia where average annual DO levels increased from 3 mg/l in 1968, to 3.5 mg/l in 1981, to 8 mg/l by 1987.

By 1988, the Delaware Estuary was reported to have better water quality than at any time in a century due to pollution abatement programs conducted over 50 years (Albert 1991). The Delaware Estuary cleanup was called "one of the premier water quality success stories in the United States." Between 1974 and 1987, Trenton, Philadelphia, Camden, and Wilmington constructed secondary wastewater treatment plants which treated over 700 mgd (2,660 MLD) of sewage before discharge into the Delaware Estuary. With increasing dissolved oxygen levels during the 1990s, the states detected evidence of spawning fish again downstream from Trenton as striped bass and American shad returned to the Delaware River in large numbers.

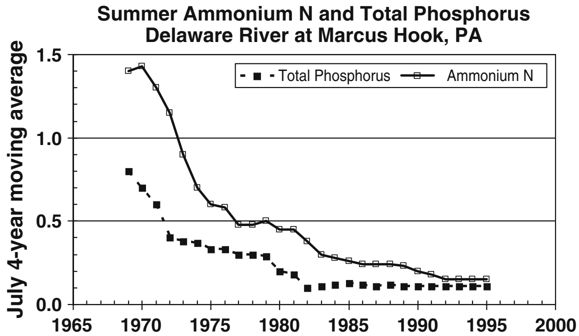


Fig. 7 Ammonium N and total phosphorus in the tidal Delaware River at Marcus Hook, PA (USEPA 2000a from Santoro)

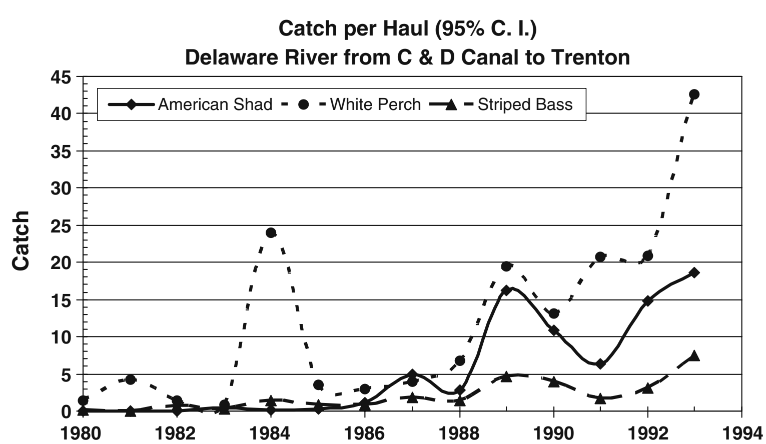
In 1993, University of Delaware scientists concluded: "During the last 30 years, there has been a fourfold decrease in total phosphorus (TP) concentrations in the tidal river of the Delaware Estuary." Total phosphorus reached peak levels in the Delaware Bay in the high turbidity zone near the Chesapeake and Delaware Canal and decreased to minimum concentrations at the mouth of the bay (Lebo and Sharp 1993).

In 1994, the DRBC reported 96% of the Delaware Estuary had good, 3% had fair, and 1% had poor water quality. Mean annual DO in the Delaware River at Philadelphia improved from 1 mg/l in 1958 to 5 mg/l by 1995. Total nitrogen in the Delaware Bay near the C & D Canal was 4 mg/l during 1968–1970 and decreased to 2.5 mg/l by 1988–1990. Total phosphorus along the Delaware River at Philadelphia decreased from 0.45 mg/l during 1968–1970 to 0.15 mg/l during 1988–1990. At Marcus Hook, total phosphorus declined from 0.8 mg/l in 1966 to 0.1 mg/l by 1995 and ammonium N declined from 1.4 to 0.2 mg/l during the same period (Fig. 7). Increased landings of American shad, striped bass, and white perch between 1980 and 1993 correlated with the improved water quality in the Delaware Estuary (USEPA 2000a).

By 1995, 99 major municipal and industrial dischargers were permitted along the Delaware Estuary, most in compliance with DRBC water quality standards. By 1996, over 90% of the Delaware Estuary met fishable and swimmable goals of the Clean Water Act (USEPA 2000a).

By 1996, water quality in the Delaware Estuary improved dramatically as areas near Philadelphia that formed a pollution block to migratory fish passage now rarely experienced dissolved oxygen concentrations less than 3 mg/l. From 1980–1993, the number of captured fish species increased and the increase was greatest in areas of the Delaware Estuary downstream from Philadelphia where water quality had improved the most. Juvenile striped bass and American shad abundance, migratory species susceptible to water quality problems, both increased 1000-fold over the past decade (Fig. 8). The increase in fish abundance in the tidal Delaware related closely to improving water quality conditions (Weisberg et al. 1996). In 1996, the Delaware Estuary Program reported "dramatic improvements in water quality since the 1960s" as the Delaware River was cited as "a prime example of the environmental benefits of

Fig. 8 Catch per haul of fish species in the Delaware River, 1980–1993 (Weisberg et al. 1996)



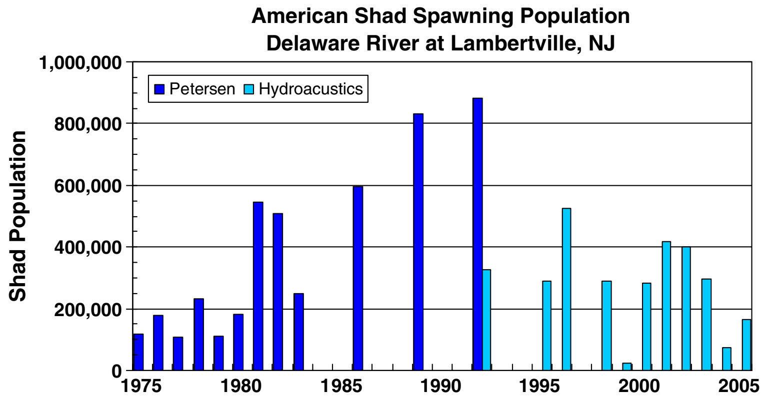


Fig. 9 American shad spawning population in the Delaware River at Lambertville, New Jersey

secondary sewage treatment" (Sutton et al. 1996). From 1977 to 1991, phosphorus, nitrogen, and DO levels improved during a period which saw major upgrades to sewage treatment plants along the Delaware Estuary.

During 1990 to 1999, the Philadelphia Water Department reported water quality at the Baxter intake along the tidal Delaware River improved for dissolved oxygen, fecal coliform bacteria, phosphorus, ammonia, total organic carbon, and total suspended solids. Total phosphorus and nitrates improved along tributaries such as the Lehigh River and Neshaminy Creek. Ammonia decreased along the Schuylkill River at Philadelphia from 1970 to 2000 (Interlandi and Crockett 2003).

In 1998, the Atlantic States Marine Fisheries Commission declared that Delaware River striped bass stocks were restored. In 2002, over 29,000 American shad were caught and counted in the Delaware Estuary. Figure 9 indicates over 200,000 migrating shad were detected annually between 2001 and 2005 along the Delaware River at Lambertville, New Jersey (NJDEP 2006a, b). In 2005, Delaware recreational anglers landed 20,000 striped bass totaling a combined weight of 250,000 lbs (114,000 kg) in the Delaware Estuary (Kahn et al. 2006).

The Wildlands Conservancy (2003) called the Lehigh River, the largest Delaware's largest tributary, "cleaner than it had been in the last 150 years." In 2003, the DRBC reported that mean annual dissolved oxygen along the Delaware Estuary at Philadelphia was almost 6 mg/l, up from 2.5 mg/l in 1980 and 2.0 mg/l in 1967 (Fig. 10). Concentrations of PCBs in fish from four out of six rivers in the Delaware Basin declined from the 1970s and 1980s to the late 1990s. PCB concentrations in fish tissue have declined over the last 25 years in the Delaware River at Trenton, Upper Delaware River, Brandywine Creek, and Upper Schuylkill River (USGS 2004).

Along Christina Basin tributaries in Delaware from 1970 to 1990, bacteria, phosphorus, and sediment levels improved (DNREC 1996). During the same period, dissolved oxygen, and nitrate nitrogen levels deteriorated. A USGS analysis along the Brandywine Creek in Pennsylvania indicated annual median bacteria levels declined from 1973 to 1999, but bacteria levels were found to increase with increased streamflow (Town 2001).

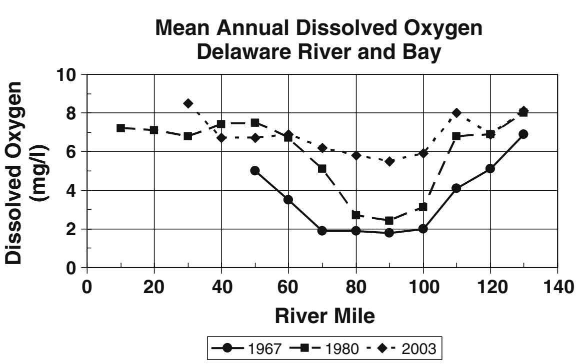


Fig. 10 Mean annual dissolved oxygen levels along the Delaware River and Bay (DRBC) Wilmington, Philadelphia, and Trenton are situated at river miles 70, 100, and 130, respectively

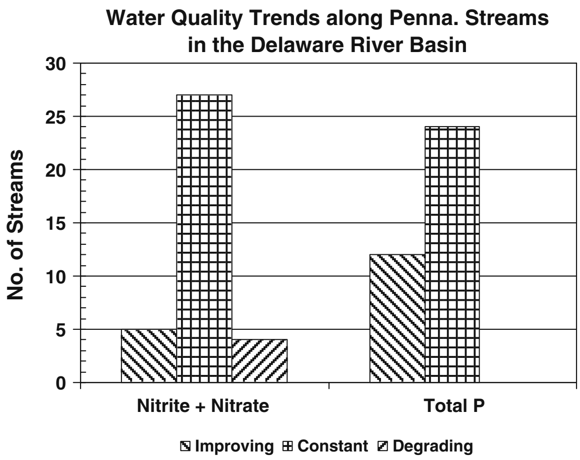


Fig. 11 Water quality trends along Pennsylvania streams in the Delaware Basin (PADEP 2005)

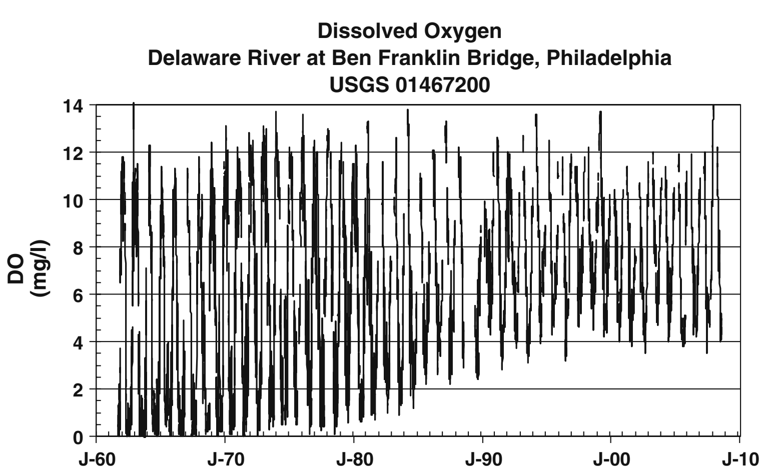
The USGS used the Mann–Kendall test to assess nitrate nitrogen and phosphorus trends along streams in Chester County, Pennsylvania from 1981 to 1997 (Reif 2002). Nitrate levels increased at 16 of 43 sites, decreased at three sites, and no significant trends were observed at 24 sites. Phosphorus levels decreased at 13 of 43 sites, increased at one site, and had no significant trend at 29 sites.

The New Jersey Department of Environmental Protection (2004) conducted a trend analysis along 36 New Jersey streams from 1985 to 2004 using the Seasonal Kendall Test with $p \leq 0.05$. Dissolved oxygen levels improved at 18% and remained stable at 80% of the stations. Total nitrogen improved at 63%, remained stable at 32%, and declined at 5% of the sites. Total phosphorus improved at 45% and remained stable at 55% of the stations.

The Pennsylvania DEP (2005) evaluated water quality trends between 1995 and 2005 using the nonparametric Seasonal Kendall test for trend where $p \leq 0.05$ (Fig. 11). Along Pennsylvania streams in the Delaware Basin, five nitrogen stations had improving trends, 27 had no change, and four stations had degrading trends. For total phosphorus, 12 stations had improving trends, 24 stations had no change, and no stations had degrading trends.

In 2008, the Philadelphia Water Department reported that Delaware Estuary water quality significantly improved over the past 20 years (Crockett 2002). Nitrate levels increased over the past two decades while dissolved oxygen and phosphorus significantly improved due to agricultural runoff reductions and improved wastewater treatment. The PWD reported: "the Delaware River is a much healthier river now than it was over the past century. The periods of the river smelling of raw sewage, covered in sheens of oil or foaming with detergent bubbles are now gone, resulting in improvements in fish, wildlife, and water quality over the past 20 years." The PWD attributed Delaware River quality improvements to decline of the coal industry and manufacturing (steel, paper, textiles), construction of sewage treatment plants, regulations banning phosphorus in detergents, and toxic chemical regulations.

Fig. 12 Mean daily dissolved oxygen along the Delaware River at Ben Franklin Bridge, Philadelphia



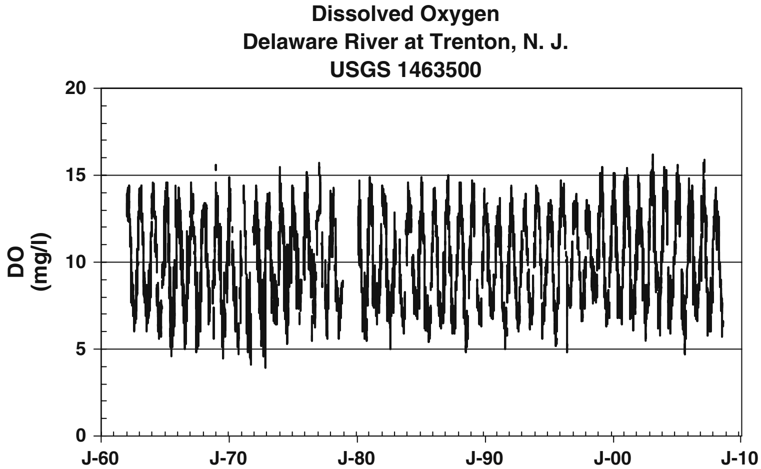


Fig. 13 Mean daily dissolved oxygen along the Delaware River at Trenton, NJ

Seminal research by University of Delaware oceanography professor Jonathan Sharp (2010) based on a century of dissolved oxygen data documents that the Delaware Estuary has experienced one of the most dramatic improvements of water quality of any river worldwide.

Surface water quality data from the USGS indicate dissolved oxygen levels have measurably increased along the Delaware Estuary and major tributaries. Since 1960, mean daily DO has improved markedly along the tidal Delaware River at the Ben Franklin Bridge in Philadelphia (Fig. 12). Along the Delaware River at Trenton, DO levels have been good since 1960 and rarely dipped below 5 mg/l (Fig. 13). Along the Lehigh River at Easton, DO levels have rarely declined below 5 mg/l since 2000 whereas readings below 5 mg/l occurred frequently during the late 1960s and 1970s (Fig. 14). Along the Schuylkill River at Linwood, Pa, DO readings since 2000 have not declined below 4 mg/l compared to the late 1980s when DO frequently reached as low as 1 to 3 mg/l (Fig. 15).

Total phosphorus levels have decreased substantially along the Delaware River at Trenton and along three of the Delaware Estuaries largest tributaries at Lehigh River at Glendon, Schuylkill River at Philadelphia, and Brandywine River above Wilmington (Fig. 16). Except at Trenton, total P levels are still high with most individual readings above USEPA 0.1 mg/l water quality criteria.

Total suspended sediment levels have improved along the Schuylkill and Lehigh Rivers, the two largest tributaries to the Delaware Es-

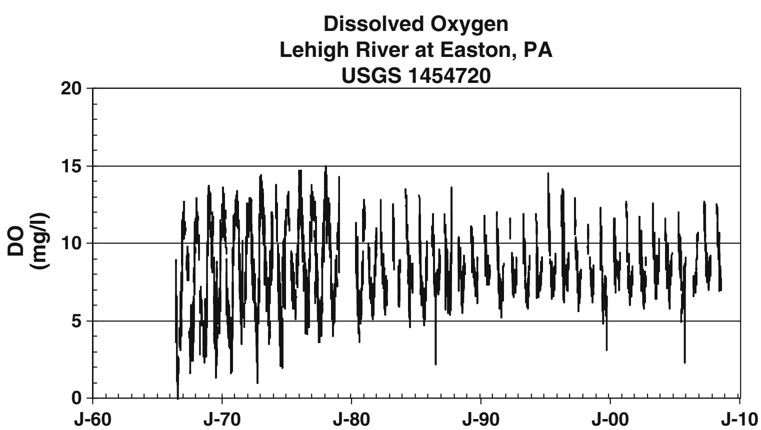


Fig. 14 Mean daily dissolved oxygen along the Lehigh River at Easton, PA

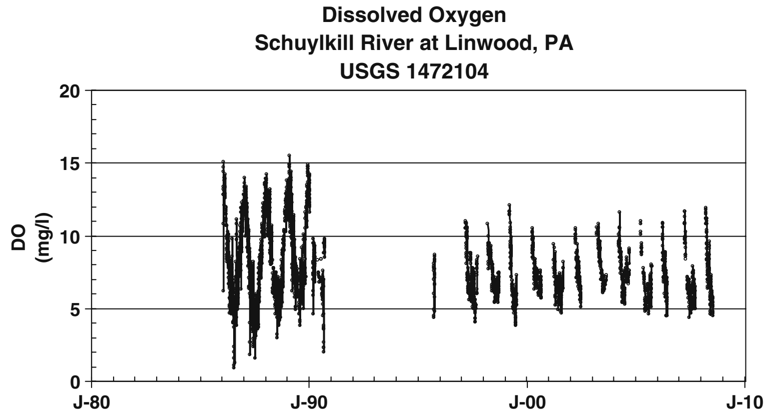


Fig. 15 Mean daily dissolved oxygen along the Schuylkill River at Linwood, PA

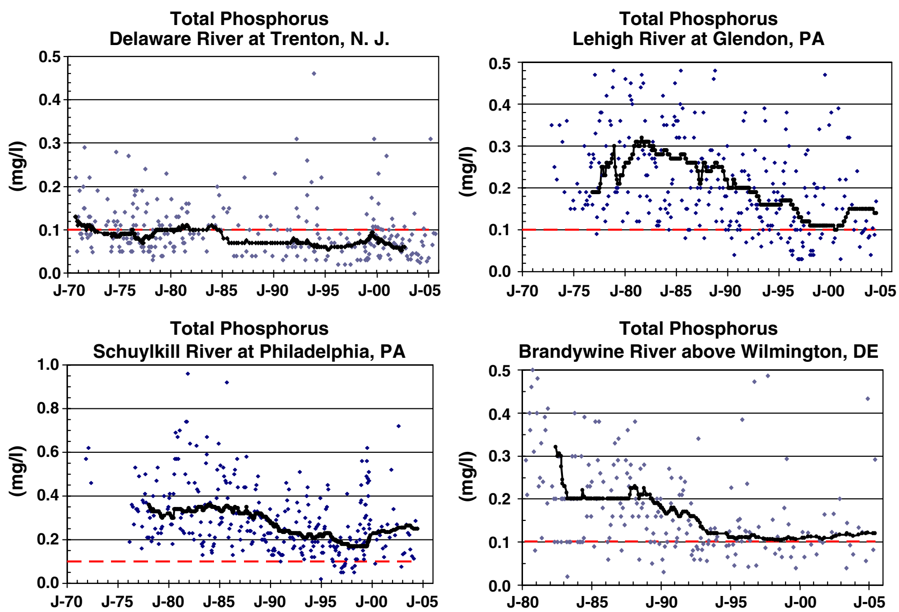


Fig. 16 Total phosphorus along the largest tributaries of the Delaware Estuary. The *smoothed line* is a 50-point rolling median (PADEP, NJDEP, DNREC)

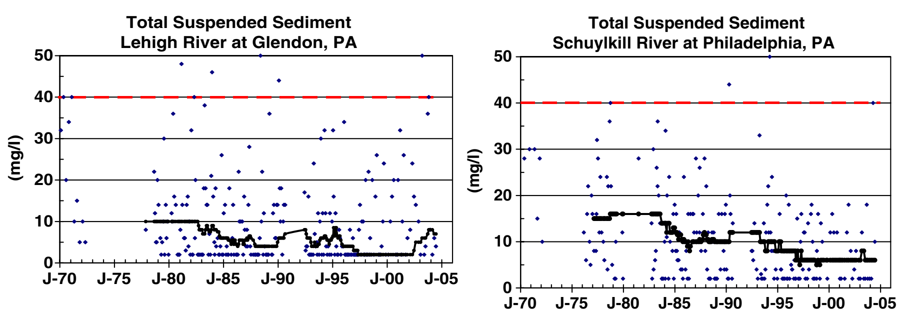


Fig. 17 Total suspended sediment along the Lehigh and Schuylkill Rivers. The *smoothed line* is a 50-point rolling median. (PADEP)

tuary (Fig. 17). Most individual total suspended sediment (TSS) samples are below a 40 mg/l TSS standard used by New Jersey for warm water streams.

Methods

We compiled an original list of 40 stream water quality monitoring stations within the Delaware Basin from networks maintained by the four states, USEPA, USGS, and DRBC. Criteria for the original list of 40 stations include sites (1) along the main stem of the river and bay and at downstream reaches of the largest tributaries, (2) within all physiographic provinces, (3) dispersed north to south throughout the basin above and below tidewater, (4) that drain watersheds with a mix of different land uses and population densities, and (5) with data for the priority parameters of DO, TP, total nitrogen (TN), and TSS.

From the initial list of 40 stations, 15 monitoring stations along the Delaware River and major tributaries were selected with sufficient data for water quality trend analysis (Table 1). Favorable monitoring stations include data that span the period of analysis (1980 to 2005) with no more than 2 years of missing data at the beginning and end of the time period and at least one half of the data present in the first and last thirds of the record (Lanfear and Alexander 1990). Four (4) monitoring stations are located along the Delaware River and Estuary, four stations are along major tributaries to the non-tidal Delaware, and seven stations are along tributaries that flow to the Delaware Estuary. Monitoring stations are spread throughout each of the Delaware Basin Physiographic provinces: Appalachian Plateau (two stations), Ridge and Valley (four), Piedmont Plateau (three), and Coastal Plain (six).

Suitable water quality monitoring stations contain at least 4 sampling points per year from 1980 through 2005 for DO, TP, TN, and TSS. The USEPA and DRBC have identified these priority parameters to establish Total Maximum Daily Loads (TMDLs) in accordance with the Federal

Table 1 Water quality monitoring stations along the Delaware River, Estuary, and tributaries

	Water quality station (data source)	D.A. (square miles)	PP	WQ use
Main stem				
RM304	Delaware R. at Callicoon, NY (PADEP WQN0185)	1,820	AP	Zone 1B
RM253	Delaware R. at Port Jervis, NY (USGS Gage 1434000)	3,070	AP	Zone 1B
RM134	Delaware R. at Trenton, NJ (USGS Gage 1463500)	6,780	PT	Zone 1E
RM100.	Delaware R. at Ben Franklin Br. (USGS 1467200 DRBC 892071L)	7,993	CP	Zone 3
Tributary				
LW1	Lackawaxen R. at Lackawaxen, Pa. (PADEP WQN 147)	589	AP	HQ
UC1	Brodhead Cr. at Del. Water Gap, Pa. (PADEP WQN 137)	259	AP	TSF
UC2	Paulins Kill at Blairstown, NJ (USGS Gage 1443500)	126	RV	FW-TM
LV3	Lehigh R. at Glendon, Pa. (PADEP WQN 123)	1,359	RV	WWF
UE1	Neshaminy Cr. at Langhorne, Pa. (PADEP WQN 121)	210	PT	WWF
UE2	N. Branch. Rancocas Cr. at Pemberton, NJ (USGS Gage 1467000)	118	CP	FW-NT
SV3	Schuylkill R. at Philadelphia, Pa. (PADEP WQN 110)	1,893	PT	CWF
LE1	Brandywine R. above Wilmington, Del. (DNREC:104051)	314	PT	ERES
LE3	Salem R. at Woodstown, NJ (USGS Gage 1482500)	15	CP	FW2
DB2	Maurice R. at Norma, NJ (USGS Gage 411500)	112	CP	FW2
DB1	St. Jones R. at Dover, Del. (DNREC 205041)	32	CP	FW

DRBC: Interstate water quality zones. DEL: FW, ERES. PA: CWF, WWF, TSF, HQ. NJ: FW, NT, TM, NY: Class C Fresh Surface Waters

FW freshwater, *ERES* exceptional recreational and ecological significance, *CWF* coldwater fish, *WWF* warmwater fish, *TSF* trout stocking, *HQ* high quality. *NT* non-trout, *TM* trout maintenance, *PP* Physiographic province, *AP* Appalachian Plateau, *RV* Ridge and Valley, *NE* New England, *PT* Piedmont Plateau, *CP* Coastal Plain

Clean Water Act. Sufficient DO is necessary to sustain aquatic life and is the basis for fishable water quality standards. Phosphorus is needed for plant metabolism, however, in high amounts it is a limiting factor in algae blooms, eutrophication, and fish kills. Elevated nitrogen causes eutrophication and algae blooms and depleted oxygen levels and high turbidity. High TSS concentrations smother fish habitat, block sunlight causing water plants to die, decrease DO levels, and increase water temperature.

Water quality data were plotted on time series scatterplots with concentration on the vertical axis and time on the horizontal axis. Scatterplots illustrate basic statistical parameters such as the sample, maximum and minimum, range, and variance. Two-dimensional scatterplots of the sample illustrate the relationship between water quality concentration and time period and show the original characteristics of the data (Helsel and Hirsch 2002). Because the human eye has difficulty in judging the center of the scatterplot pattern, boxplots are used to illustrate the median (50th percentile) as a measure of central tendency and the 25th and 75th percentile to illustrate the range and skewness of the water quality data. The median, instead of the mean, is preferred for water quality analysis because the median is resistant to and minimally affected by outliers.

Water quality trends were detected using the flow-weighted, nonparametric Seasonal Kendall test for statistical significance as outlined in Hirsch et al. (1982) and Helsel and Hirsch (2002). Trend analyses determine if water quality is improved, constant, or degraded according to the slope of the line and if probability $p \leq 0.10$. This nonparametric test was chosen because data collection was semi-uniform for each sampling site over the period of record. The USGS Kendall.exe computer program was used to perform the Seasonal Kendall test for quality trend (Helsel et al. 2005). The program lists the correlation coefficient Kendall's tau, slope and intercept of the Kendall's trend line, and the p value for significance of trend. Data for each station were divided into four seasons of 3 months per season.

Monotonic trends were determined over 25 years from 1980 through 2005. The direction of trend was detected by the slope of the Seasonal Kendall test line. A positive (+) slope indicated an improving trend for DO and degrading trend for other parameters. A negative (−) slope indicated a degrading trend for DO and improving trend for other parameters. Since the monotonic Seasonal Kendall analysis is limited in detecting reversals in trends over the time period, the analysis was supplemented with visual examination of time series scatterplots and boxplots depicting the 2 percentile (bottom of the box), 50th percentile median (line though the middle of the box), and 75th percentile (top of the box), at 5-year periods. Visual analyses using scatterplots and boxplots can detect trends where water quality change is not monotonic, for instance, where water quality may degrade over the first years of record, reverses, and improves over the latter years (the banana curve).

We plotted standards and criteria (Table 2) on the scatterplots to compare water quality between the stations (NJDEP 2006a, b, NYSDEC 1999; PADEP 2007; DNREC 2004, 2007; USEPA 2000b; DRBC 2006). Dissolved oxygen standards range from 4.0 mg/l for warm water fish to 7.0 mg/l for cold water fish. Total phosphorus criteria range from 0.02 mg/l for New York cold water streams to 0.03 mg/l set by USEPA and 0.05 mg/l

Table 2 Water quality criteria in the Delaware Basin

Parameter	NJ	NY	PA	DEL	USEPA
DO (mg/l)	4.0 non trout	4.0 non trout	4.0 warm water	4.0 fresh water	
	5.0 trout maintenance	6.0 trout	5.0 cold water	5.0 cold water	
	7.0 trout production	7.0 trout spawn	7.0 HQ cold		
TP (mg/l)	0.1	0.02		<0.05 low	0.03
TN (mg/l)				<1.0 low	0.71
TSS (mg/l)	25 trout				
	40 non-trout				

NJDEP 2006a, b; NYSDEC 1999; PADEP 2007; DNREC 2004, 2007; USEPA 2000b

Table 3 Water quality criteria along the Delaware River and Estuary (DRBC 2006)

WQ zone	RM	Description	DO (mg/l)	P (mg/l)	Nitrate (mg/l)	TSS (mg/l)
1A	330.7–289.9	Hancock–Narrowsburg, NY	5.0 minimum 7.0 trout 9.0 existing	0.029	0.293	4.0
1B, 1C	289.9–217.0	Narrowsburg–Tocks Island	4.0 minimum 9.0 existing	0.029	0.293	4.0
1D, 1E	217.0–133.4	Tocks Island–Trenton, NJ	4.0 min 9.2 existing	0.027	0.246	3.4
2	133.4–108.4	Trenton, NJ–Philadelphia	5.0 (24 hr)			
3, 4	108.4–78.8	Philadelphia–PA/DE line	3.5 (24 hr)			
5	78.8–48.2	PA/DE line–Liston Point	3.5 (RM 78.8) 4.5 (RM 70.0) 6.0 (RM 59.5)			
6	48.2–0.9	Liston Pt.–Atlantic Ocean	5.0			

set by Delaware. In Pennsylvania, we assigned a default target of 0.1 mg/l for TP. Delaware defines total N target values below 1.0 mg/l for setting TMDLs and USEPA defines ambient criteria of 0.71 mg/l. We used a default TN value of 1.0 mg/l for other states. New Jersey is the sole state that set TSS standards of 25 mg/l for cold water trout streams and 40 mg/l for non-trout streams. We used New Jersey TSS standards as default criteria for other Delaware Basin states.

Table 3 summarizes water quality standards along the Delaware River and Estuary. In the fresh water Delaware River above Trenton, the DRBC (2008b) sets antidegradation standards to preserve existing good water quality. In the tidal Delaware Estuary, since the DRBC has not assigned standards for these parameters, we assigned default criteria of 1.0 mg/l for TN, 0.1 mg/l for TP, and as the tidal estuary is a warm water reach, 40 mg/l for TSS.

To compare the health of the Delaware River, Estuary, and tributaries, we defined a water quality ladder as good, fair, or poor by comparing 2001–2005 medians to criteria summarized in Table 4. Good water quality indicates the 5-year median for 2001–2005 exceeded water quality criteria by 50% or more. Fair water quality indicates the median is just above the criteria. Poor water quality indicates the 2001–2005 median is below criteria and does not meet the water quality standards.

Using the University of Delaware geographic information system (GIS), we classified land use in each drainage area into five categories: developed (urban/suburban), cultivated (agriculture), forests, and water/wetlands, and other (Table 5). The National Oceanographic and Atmospheric Administration Coastal Service Center provided 2001 land use for each station drainage area.

Lastly, we compared water quality to watershed influences such as stream flow, drainage basin, seasonality, land use, and pollution point sources. Correlations between stream flow and water quality, and watershed land use were determined

Table 4 Water-quality ladder

Water quality	Description	DO (mg/l)	P (mg/l)	N (mg/l)	TSS (mg/l)
Good	Comfortably exceeds water quality standards	8.0	<0.02	<0.5	<25
Fair	Just above water quality standards	5.0–8.0	0.02–0.1	0.5–1.0	25–40
Poor	Below stream water quality standards	<5.0	>0.1	>1.0	>40

Table 5 Land use upstream from water quality monitoring stations in the Delaware Basin

Monitoring station	Developed (%)	Forest (%)	Cultivated (%)	Wetland (%)	Other (%)	Area square miles (km^2)
RM304 Delaware R. at Callicoon, NY	3	81	14	2	0	1,820 (4,718)
RM253 Delaware R. at Port Jervis, NY	5	84	8	3	0	3,070 (7,957)
RM134 Delaware R. at Trenton, NJ	9	71	17	2	1	6,780 (17,574)
RM100 Delaware R. Philadelphia, Pa.	15	63	19	3	0	7,993 (20,718)
LW1 Lackawaxen River, Pa.	7	73	15	4	0	589 (1,527)
UC1 Brodhead Cr. Del. Water Gap, Pa.	15	69	14	2	0	259 (671)
UC2 Paulins Kill at Blairstown, NJ	11	60	25	3	0	126 (327)
LV3 Lehigh River at Glendon, Pa	30	26	43	1	0	1,359 (3,523)
UE1 Neshaminy Cr. at Langhorne, Pa	53	20	22	4	1	210 (544)
UE2 N. Br. Rancocas at Pemberton, NJ	28	39	26	4	3	118 (306)
SV3 Schuylkill R. at Philadelphia, Pa	25	34	40	1	1	1,893 (4,907)
LE1 Brandywine R.Wilmington, Del.	24	28	45	1	2	314 (814)
LE3 Salem River at Woodstown, NJ	7	29	49	12	2	15 (39)
DB2 Maurice River at Normal, NJ	9	46	28	16	2	112 (290)
DB1 St. Jones River, Dover, Del.	7	23	55	14	1	32 (83)

NOAA CSC Land Use/Land Cover (2001)

Table 6 Dissolved oxygen, total phosphorus, total nitrogen, and total suspended sediment water quality trends along the Delaware River, Estuary, and tributaries

Station	DO (mg/l)	TP (mg/l)	TN (mg/l)	TSS (mg/l)
Delaware River mainstem stations				
RM304 Callicoon, NY	11.0 ●	0.01 ▲*	0.3 ●	2 ●
RM253 Port Jervis, NY	10.7 ●	0.02 ▲*	0.2	6 ●
RM134 Trenton, NJ	11.2 ●	0.07 ▲*		
RM100 Ben Franklin Bridge, Philadelphia, PA	7.3 ▲*	0.11 ●	1.1 ●	13 ●
Delaware River tributaries				
LW1 Lackawaxen R. at Lackawaxen, PA	12.6 ▲	0.02	0.2 ●	6 ●
UC1 Brodhead Cr at Del. Water Gap, PA	12.0 ▲*	0.05 ▲*	0.5 ▼*	2 ●
UC2 Paulins Kill at Blairstown, NJ	10.0 ●	0.02 ▲*	1.0 ●	7 ●
LV3 Lehigh River at Glendon, PA	11.2 ▲*	0.11 ▲*	2.1 ▼*	9 ▼
UE1 Neshaminy Cr. at Langhorne, PA	10.7 ●	0.18 ▲*	2.3	6 ●
UE2 N. Br. Rancocas at Pemberton, NJ	7.1 ●	▲*		
SV3 Schuylkill R. at Philadelphia, PA	10.8 ▲*	0.23 ▲*	3.2 ●	2 ▲*
LE1 Brandywine R. above Wilmington, Del.	9.9 ●	0.12 ▲*	2.5 ▲*	9 ●
LE3 Salem River at Woodstown, NJ	9.5 ▲	0.15 ▲	3.7	17 ●
DB2 Maurice River at Normal, NJ	8.2 ▼*	0.01 ●	2.0	3 ●
DB1 St. Jones River at Barkers Ldg., Del.	5.0 ▼	0.23 ●		
Water quality trend:				
Improved ▲	6/15 (40%)	11/14 (79%)	1/8 (12%)	1/12 (8%)
Constant ●	7/15 (47%)	3/14 (21%)	5/8 (63%)	10/12 (84%)
Degraded ▼	2/15 (10%)	0/14 (0%)	2/8 (25%)	1/12 (8%)

Five-year median 2001–2005 level (mg/l): 8.0 = Good 6.0 = Fair 4.0 = Poor

*$p < 0.10$—statistically significant trends

Table 7 Results of flow-weighted seasonal Kendall test of Delaware Basin water-quality monitoring stations

	DO			TP			N			TSS		
	p value	Slope[a]	Start[b]	*p* value	Slope[a]	Start[b]	*p* value	Slope[a]	Start[b]	*p* value	Slope[a]	Start[b]
Delaware River mainstem stations												
RM304 Callicoon, NY	0.63	−0.014	1988	**0.00**	−0.001	1988				0.87	0.000	1988
RM253 Port Jervis, NY	0.88	−0.004	1981	**0.00**	0.000	1981				0.23	0.000	1987
RM134 Trenton, NJ	0.40	0.021	1981	**0.02**	−0.002	1981						
RM100 Ben Franklin Bridge, Phila, Pa.	**0.00**	0.081	1981									
Delaware River tributaries												
LW1 Lackawaxen R. at Lackawaxen, PA	0.12	0.050	1983	**0.00**	−0.001	1981	0.42	−0.002	1981	0.84	0.000	1988
UC1 Brodhead Cr at Del. Water Gap, PA	**0.01**	0.120	1982	**0.03**	−0.003	1981	**0.01**	0.006	1981	0.78	0.000	1988
UC2 Paulins Kill at Blairstown, NJ	0.61	−0.012	1981	**0.00**	−0.002	1981						
LV3 Lehigh River at Glendon, PA	**0.01**	0.057	1981	**0.00**	−0.006	1981	**0.01**	0.020	1981	0.67	0.000	1981
UE1 Neshaminy Cr. at Langhorne, PA	0.22	0.059	1981	**0.00**	−0.020	1981				0.84	0.000	1988
UE2 N. Br. Rancocas at Pemberton, NJ	0.14	0.041	1981	**0.00**	−0.012	1981						
SV3 Schuylkill R. at Philadelphia, PA	**0.00**	0.076	1984	**0.01**	−0.008	1981	0.93	0.000	1981	**0.01**	−0.282	1981
LE1 Brandywine R. abv. Wilmington, Del.	0.27	0.020	1981	**0.00**	−0.006	1981	**0.01**	0.031	1981			
LE3 Salem River at Woodstown, NJ	0.48	0.030	1981	0.12	−0.002	1983						
DB2 Maurice River at Normal, NJ	**0.01**	−0.062	1981	0.47	0.000	1981						
DB1 St. Jones R. at Barkers Landing, Del.	0.84	−0.007	1981	0.34	0.002	1981						

Bold *p* values are below the 0.10 level;

[a]Slope of the linear trend estimation in mg/l/year

[b]First year in the monitoring period

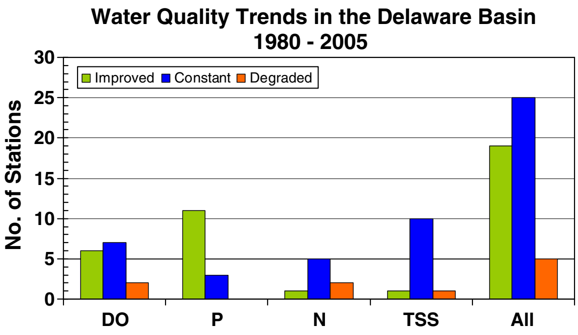


Fig. 18 Water quality trends in the Delaware Basin from 1980 to 2005

using simple linear regression and estimates of the coefficient of determination (r^2). Influences of seasonality on stream water quality were esti mated by comparison of boxplots. Point source pollutant load influences were evaluated based on the locations of wastewater treatment plants in each watershed.

Results

Table 6 summarizes results expressed as trends and 5-year median (2001–2005) for water quality monitoring stations along the Delaware River, Estuary, and tributaries. Table 7 summarizes results of the flow-weighted Seasonal Kendall statistical analysis. Figure 18 illustrates spatial water quality trends on maps of the Delaware Basin.

Between 1980 and 2005, water quality overall improved at 39%, remained constant at 51%, and degraded at 10% of the stations (Table 8 and Fig. 19). Over 25 years, dissolved oxygen improved at 40%, remained constant at 47%, and degraded at 13% of the stations. Total phosphorus improved at 79% and remained constant at 21% of the stations. Nitrogen improved at 12%, remained constant at 63%, and degraded at 25% of the stations. Total suspended sediment improved at 8%, remained constant at 84%, degraded at 8% of the stations. Since 1980, the number of improving water quality stations (19) outnumbered degrading stations (five) by a margin of nearly 4 to 1. Figures 20, 21, 22, 23, 24, 25, 26, 27 illustrate scatterplots and boxplots for dissolved oxygen, nitrogen, phosphorus, and total suspended sediment at the 15 monitoring stations.

Spatially, median (2001–2005) concentrations of DO, TP, TN, and TSS indicate water quality in the non-tidal Delaware River is good upstream from the Delaware Water Gap, good to fair above Trenton, and declines downstream in the Estuary at Philadelphia to fair for DO and TSS and poor for N and P. Water quality is good along the forested tributaries from Easton, Pa. north to the Catskill mountain headwaters above Port Jervis, New York. Water quality declines to fair to poor for TP and TN along tributaries that flow to the Delaware Estuary between Trenton and the Bay as watersheds are more populated near the Philadelphia/Camden/Wilmington metropolitan area and more agrarian further south along the Coastal Plain tributaries to the Delaware Bay.

Dissolved oxygen

Between 1980 and 2005, dissolved oxygen levels improved at six of 15 stations, remained constant at seven stations, and declined at two stations in the Delaware Basin. Improved DO levels were recorded in the Delaware Estuary at Philadelphia and along forested, mountainous tributaries in the headwaters such as the Lackawaxen, Brodhead, Lehigh, and Schuylkill. The Salem River in the Coastal Plain of southern New Jersey also recorded improved dissolved oxygen. DO remained constant at good to excellent levels along the Delaware River at Callicoon and Port Jervis in the Catskill mountains, along the Delaware

Table 8 Summary of water quality trends in the Delaware Basin from 1980 to 2005

No. of stations where water quality trend	DO	TP	TN	TSS	Total
Improved	6	11	1	1	19 (39%)
Constant	7	3	5	10	25 (51%)
Degraded	2	0	2	1	5 (10%)
Subtotal	15	14	8	12	49 (100%)

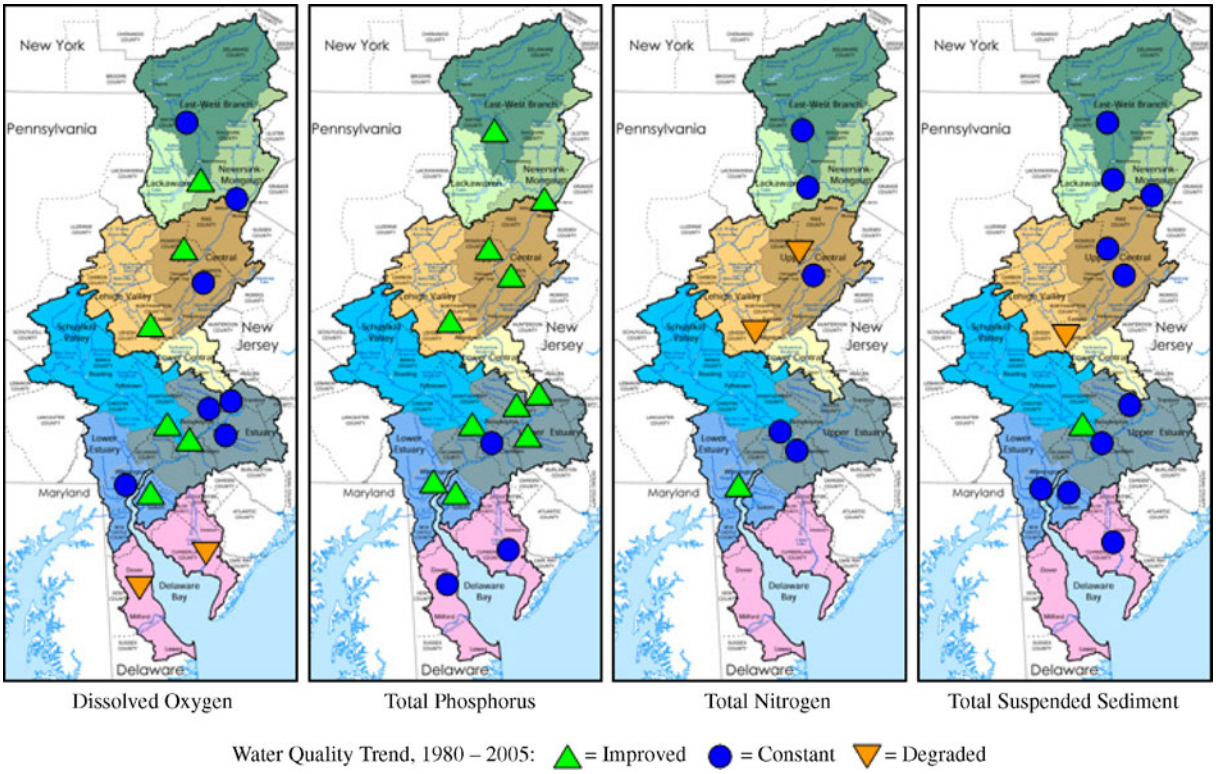


Fig. 19 Water quality trends along the Delaware River and tributaries from 1980 through 2005

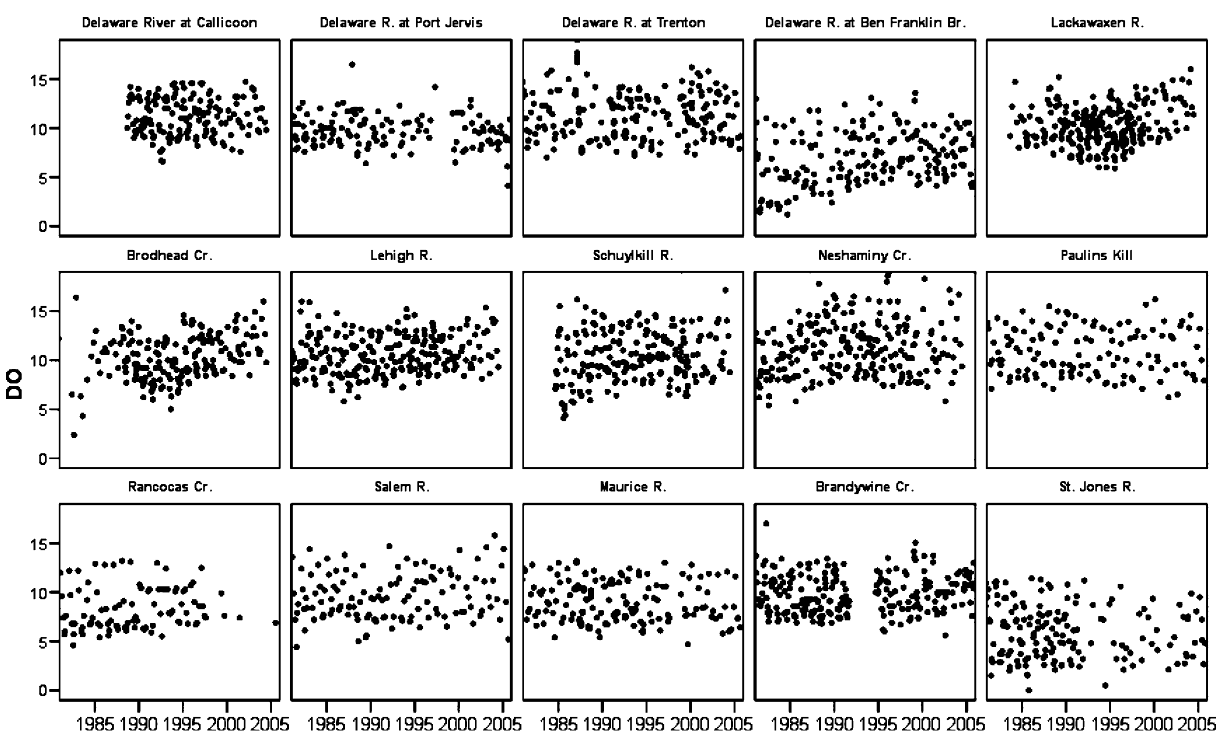


Fig. 20 Dissolved oxygen scatterplots for the Delaware Basin

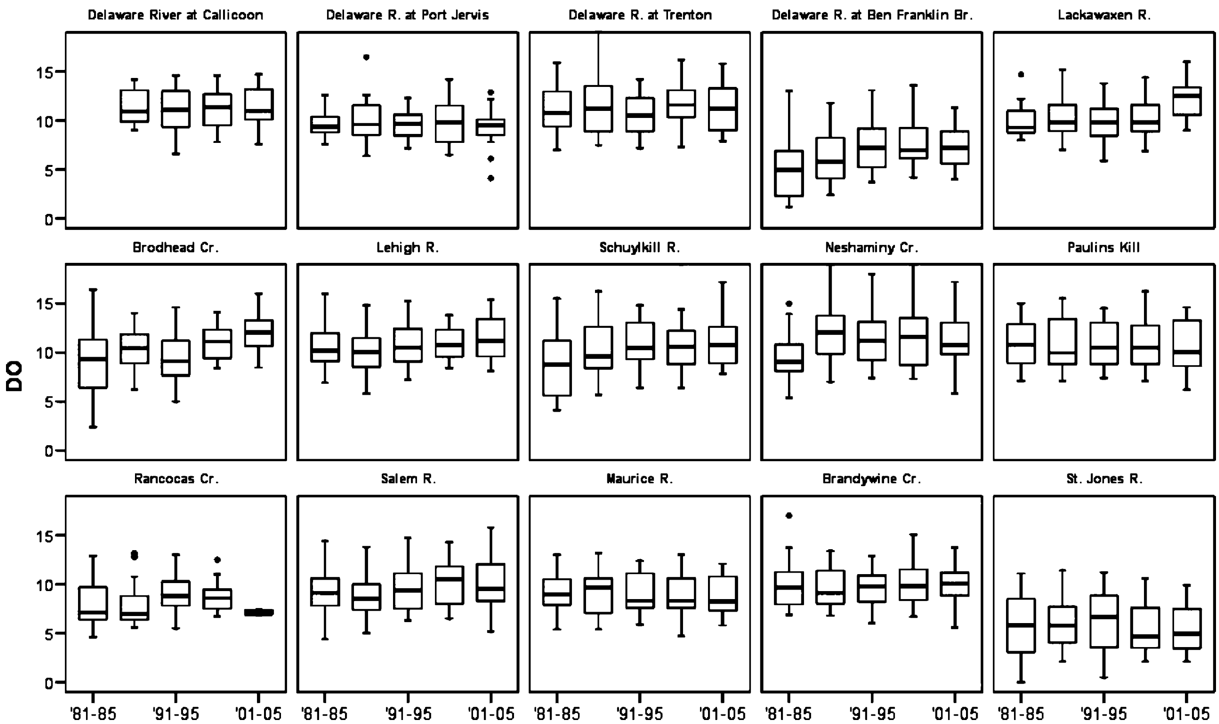


Fig. 21 Dissolved oxygen boxplots in the Delaware Basin

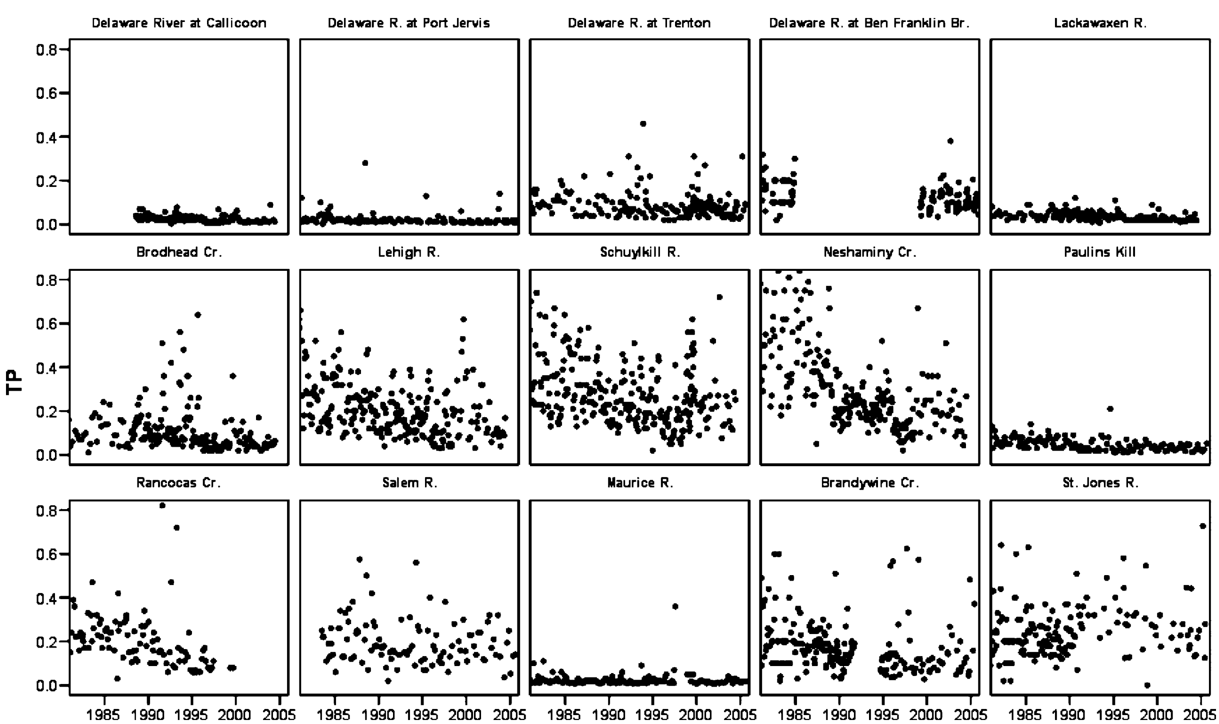


Fig. 22 Total phosphorus scatterplots in the Delaware Basin

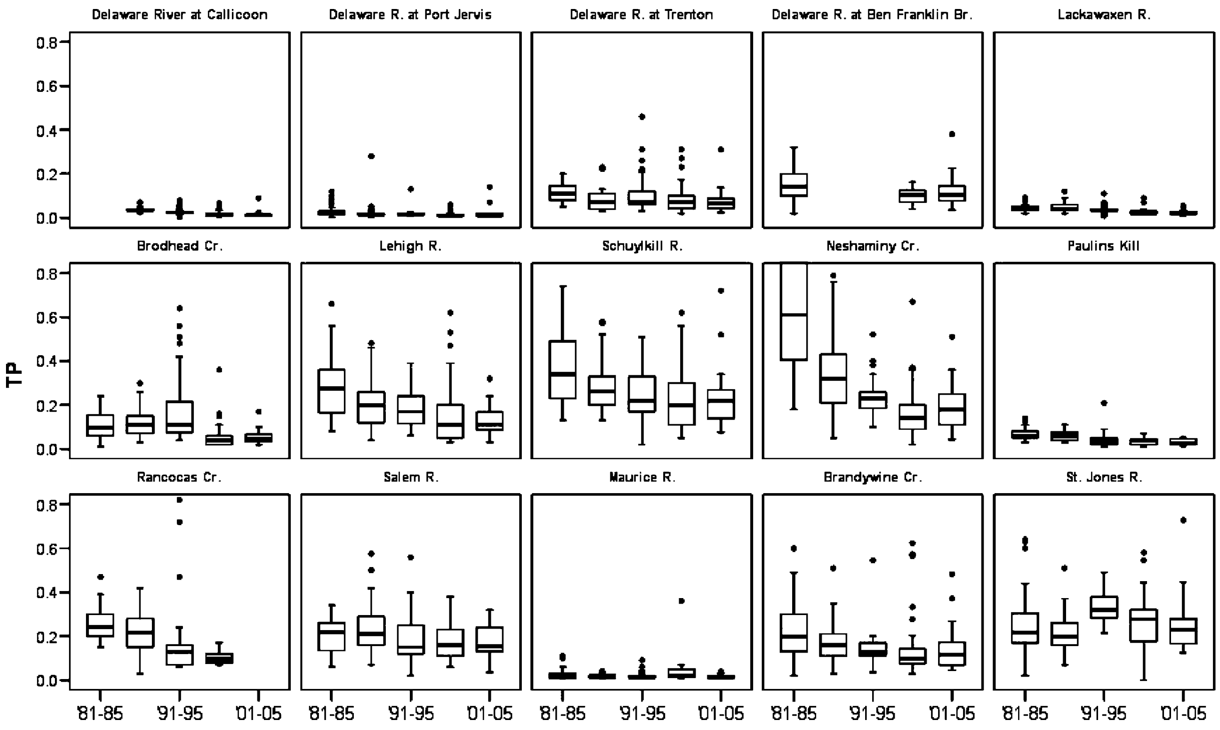


Fig. 23 Total phosphorus boxplots in the Delaware Basin

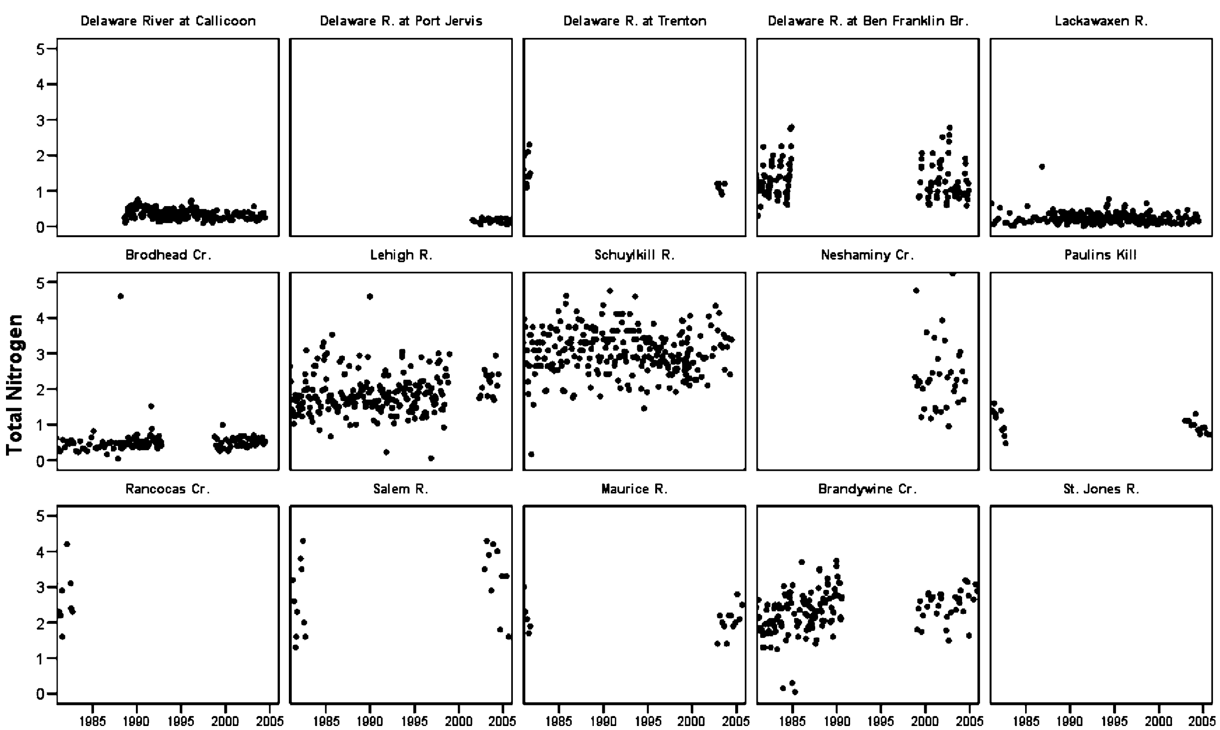


Fig. 24 Total nitrogen scatterplots in the Delaware Basin

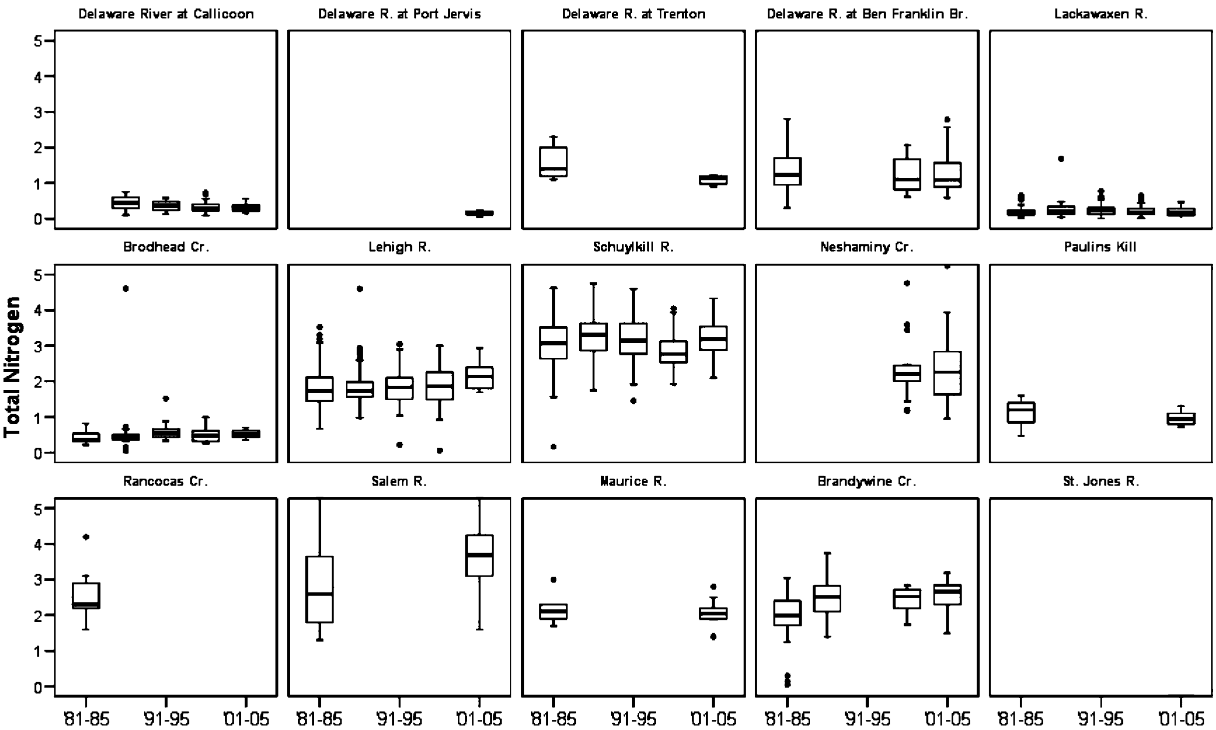


Fig. 25 Total nitrogen boxplots in the Delaware Basin

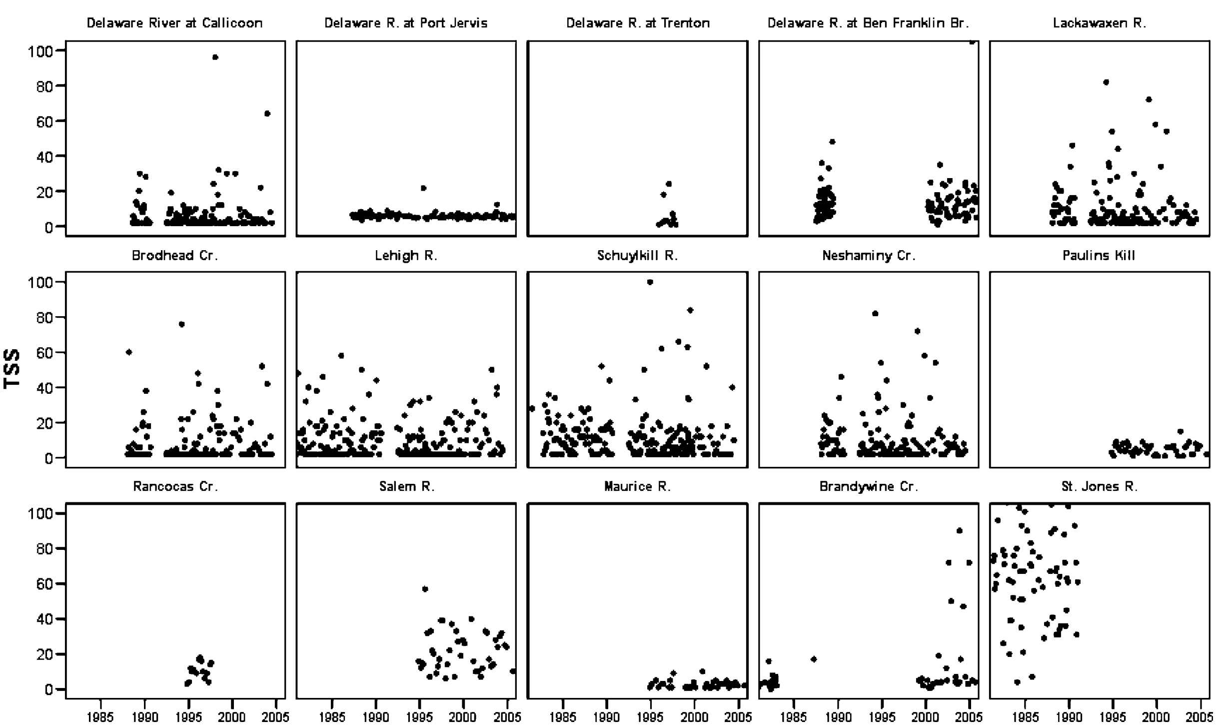


Fig. 26 Total suspended sediment scatterplots in the Delaware Basin

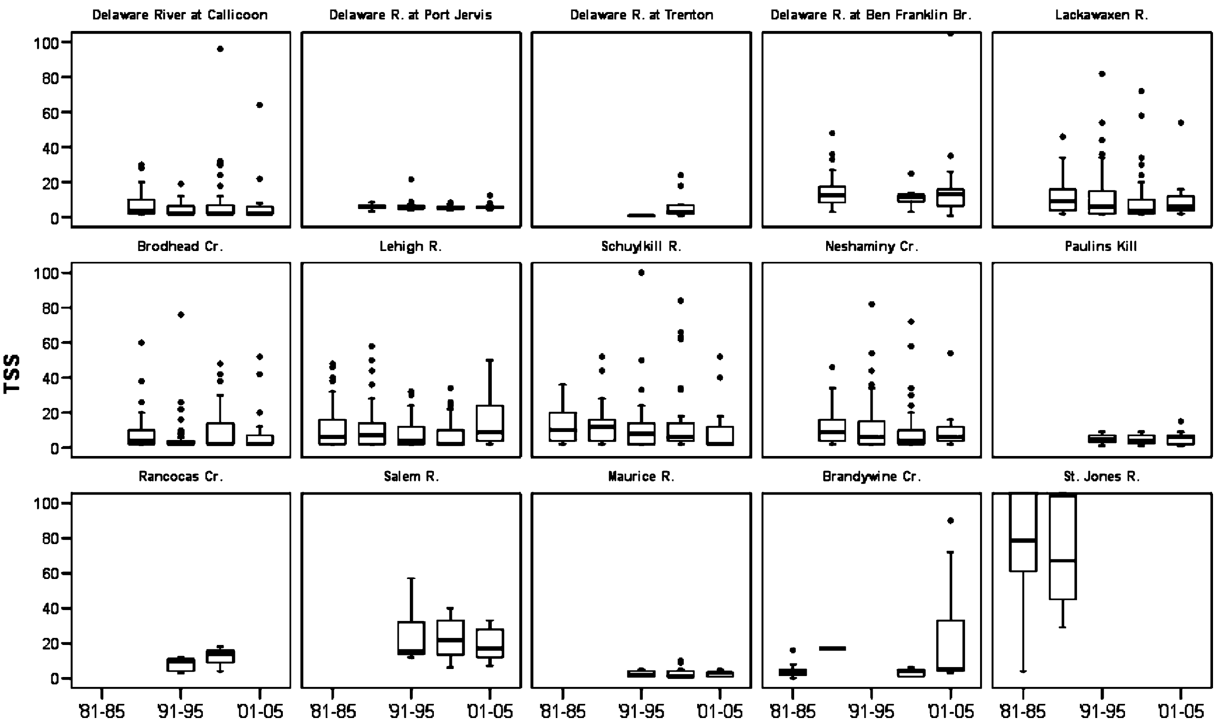
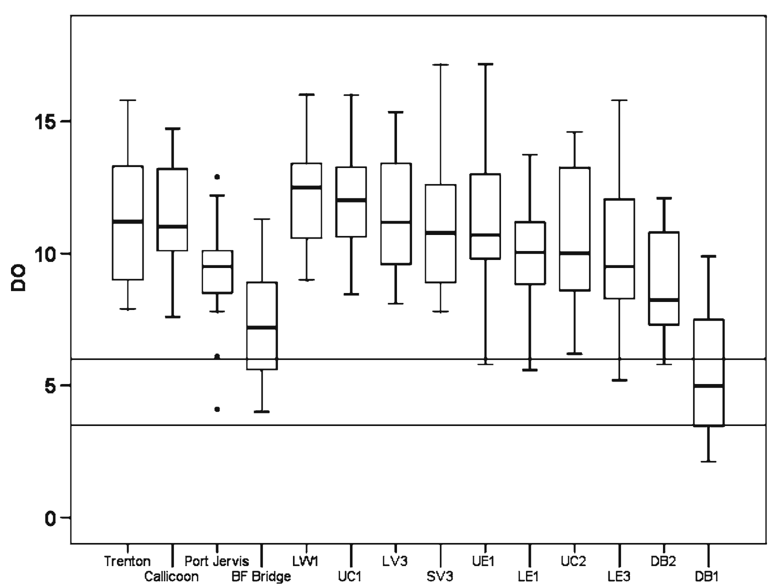


Fig. 27 Total suspended sediment boxplots in the Delaware Basin

River at Trenton, and the Brandywine Creek at Wilmington. Only two stations recording degraded DO over 25 years along the Maurice River, NJ and St. Jones River, Del. where both watersheds drain high amounts (over 25%) of agricultural land. Median (2001–2005) dissolved oxygen levels were good (exceeded 8 mg/l) at all stations except for fair (5 to 8 mg/l) along the Delaware River at Philadelphia, Rancocas Creek, and St. Jones River (Fig. 28). None of the 15 stations

Fig. 28 Dissolved oxygen levels (2001–2005) in the Delaware Basin



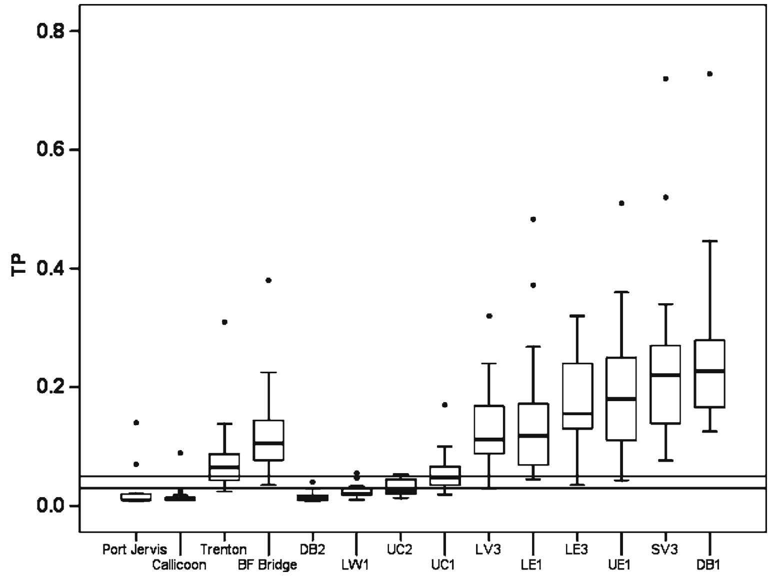


Fig. 29 Total phosphorus (2001–2005) levels in the Delaware Basin

recorded poor median DO levels at less than water quality standards (<5 mg/l).

Phosphorus

Total phosphorus improved substantially at 11 of 14 stations and remained constant at three other stations over 25 years between 1980 and 2005. Median phosphorus levels are fair (0.02–0.1 mg/l to good <0.02 mg/l) along the forested, mountainous Delaware River above Trenton and Port Jervis and the mountain tributaries such as the Lackawaxen River and Paulins Kill that enter the Delaware above the Delaware Water Gap. Median phosphorus levels, although vastly improved over 25 years, remain poor (>0.1 mg/l) along the Delaware Estuary at Philadelphia and along more populated and agricultural tributaries that flow to the Delaware below Easton, Pa. such as the Lehigh, Schuylkill, Neshaminy, Salem River, Brandywine, and St. Jones (Fig. 29).

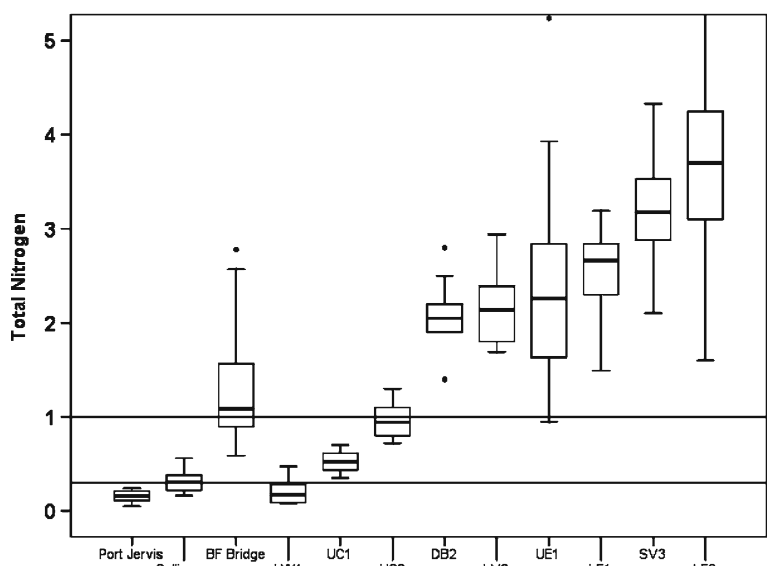


Fig. 30 Total Nitrogen (2001–2005) Levels in the Delaware Basin

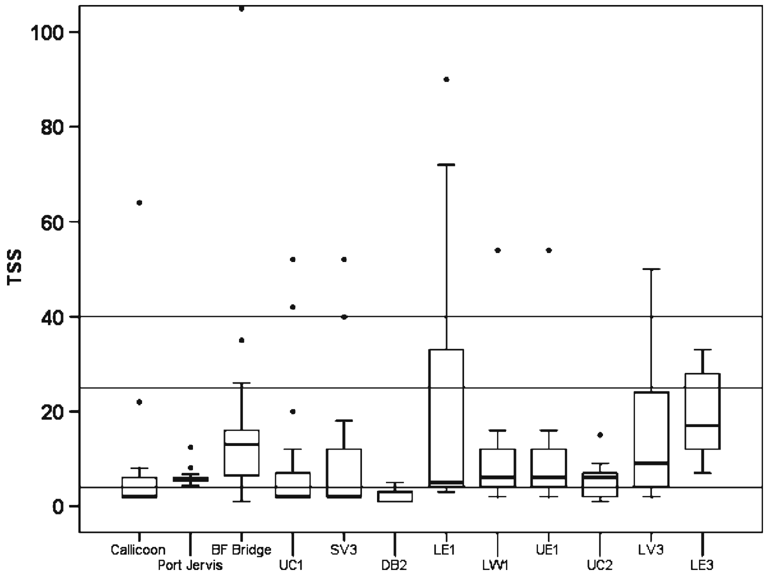


Fig. 31 Total suspended sediment (2001–2005) levels in the Delaware Basin

Total nitrogen

Median total nitrogen levels (2001–2005) improved at one station (Brandywine Creek), remained constant at five stations, and degraded at two stations (Brodhead Creek and Lehigh River) between 1980 and 2005. Nitrogen levels are good (<0.5 mg/l) in the mountain headwaters of the Delaware River above Port Jervis and forested tributaries of the Lackawaxen River and Brodhead Creek, and fair (0.5–1.0 mg/l along the Paulins Kill). Nitrogen levels remain poor (>1.0 mg/l) and exceeded water quality standards in the Delaware Estuary at Philadelphia and along agricultural and urban tributaries such as the Lehigh, Schuylkill, Neshaminy Creek, Salem River, Maurice River, and Brandywine Creek (Fig. 30).

Total suspended sediment

Between 1980 and 2005, total suspended sediment levels improved at one station (Schuylkill),

Table 9 Coefficient of determination (r^2) by linear regression between stream flow and water quality in the Delaware Basin

Land Use	DO	TP	TN	TSS
Main stem stations				
RM304 Callicoon, NY		0.093	0.081	0.077
RM253 Port Jervis, NY	0.095	0.053		0.036
RM134 Trenton, NJ	0.003	0.016		
RM100 Ben Franklin Bridge, Phila, PA				
Tributaries				
LW1 Lackawaxen R. at Lackawaxen, PA				
UC1 Brodhead Cr at Del. Water Gap, PA				
LV3 Lehigh River at Glendon, PA	0.062	0.277	0.269	0.025
SV3 Schuylkill R. at Philadelphia, PA	0.013	0.028	0.078	0.183
UE1 Neshaminy Cr. at Langhorne, PA				
UC2 Paulins Kill at Blairstown, NJ				
UE2 N. Br. Rancocas at Pemberton, NJ				
LE3 Salem River at Woodstown, NJ				
DB2 Maurice River at Normal, NJ				
LE1 Brandywine R. above Wilmington, Del.	0.127	0.004	0.016	0.148
DB1 St. Jones River at Barkers Ldg., Del.				

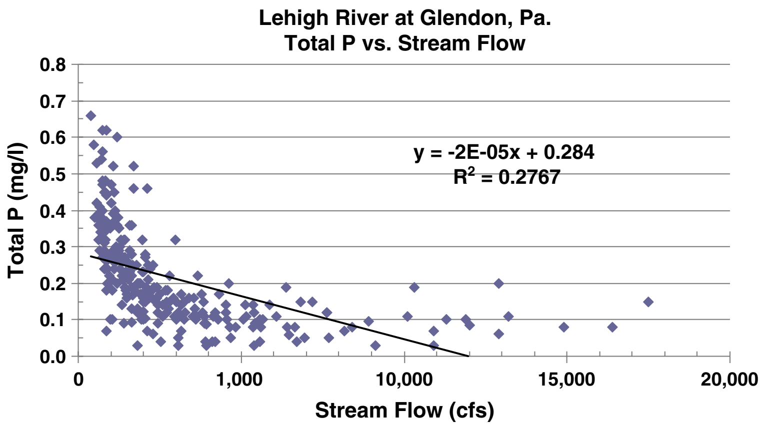


Fig. 32 Total phosphorus versus stream flow linear regression along the Lehigh River at Glendon, PA

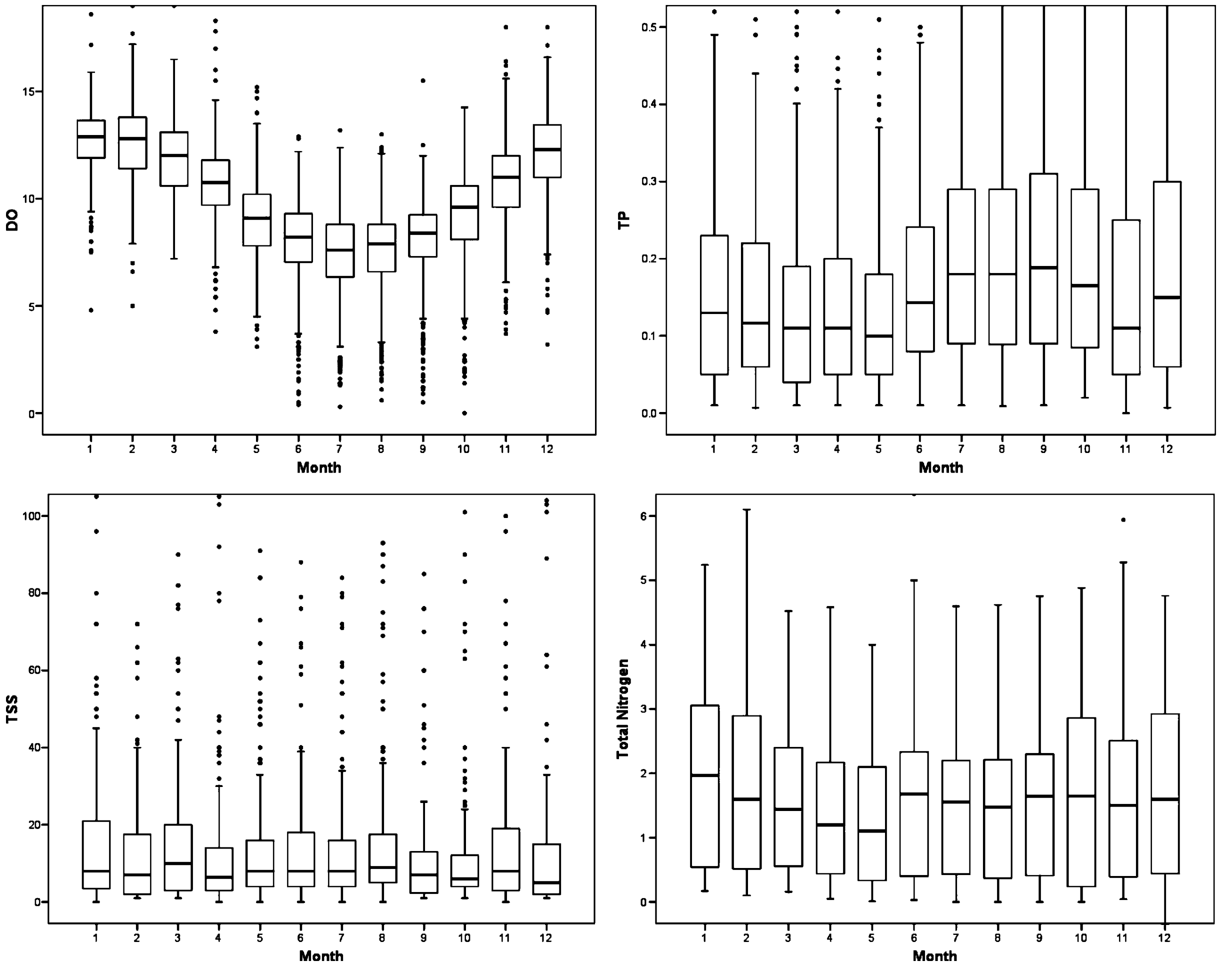


Fig. 33 Seasonal comparison of water quality boxplots (2001–2005) in the Delaware Basin

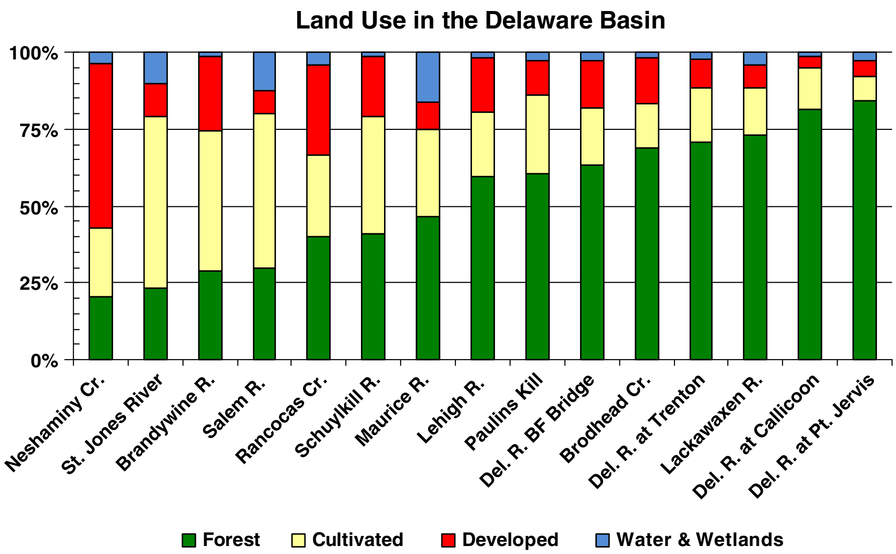


Fig. 34 Land use in watersheds upstream from monitoring stations in the Delaware Basin

remained constant at 10 stations, and degraded at one station (Lehigh River). Median and 75th percentile (2001–2005) TSS levels were good and significantly below 25 and 40 mg/l (NJ cold water and warm water TSS standards) at all 12 stations along the Delaware River, Estuary, and tributaries (Fig. 31).

Discussion

Stream flow

Stream flow can influence water quality as nitrogen and total suspended sediment may increase in concentration with rising stream flow due to buildup and wash-off of pollutants from watersheds during storms. Phosphorus concentrations may increase at first during storms and then decrease with rising stream flow due to dilution effects. The flow-weighted Seasonal Kendall Test screens out the impacts of stream flow on water quality trends.

Except for a few tributaries, simple linear regression analyses along stations with long-term USGS stream gage data indicate little correlation between stream flow and water quality (Table 9). The coefficient of determination (r^2) for the streams measured between 0.003 and 0.279, evidence of poor to moderate correlation between stream flow and water quality. Only the Lehigh River ($r^2 = 0.277$ for TP and 0.279 for TN) and Brandywine Creek ($r^2 = 0.127$ for DO and 0.148 for TSS) had coefficients of determination that exceeded 0.10, evidence of marginal correlation between stream flow and water quality. Figure 32 illustrates a typical linear regression plot of total phosphorus versus stream flow along the Lehigh River with $r^2 = 0.277$, the highest r^2 of the studied streams. Along the Lehigh River, phosphorus concentrations declined with rising stream flow due to dilution.

Seasonality

Many surface water quality parameters show strong seasonal patterns. For instance, higher dis-

Table 10 Coefficient of determination (r^2) by linear regression between land use and water quality in the Delaware Basin

Land use	DO	TP	TN	TSS
Cultivated	0.31	0.53	0.79	0.21
Forest	0.26	0.63	0.76	0.11
Developed	0.01	0.24	0.14	0.01

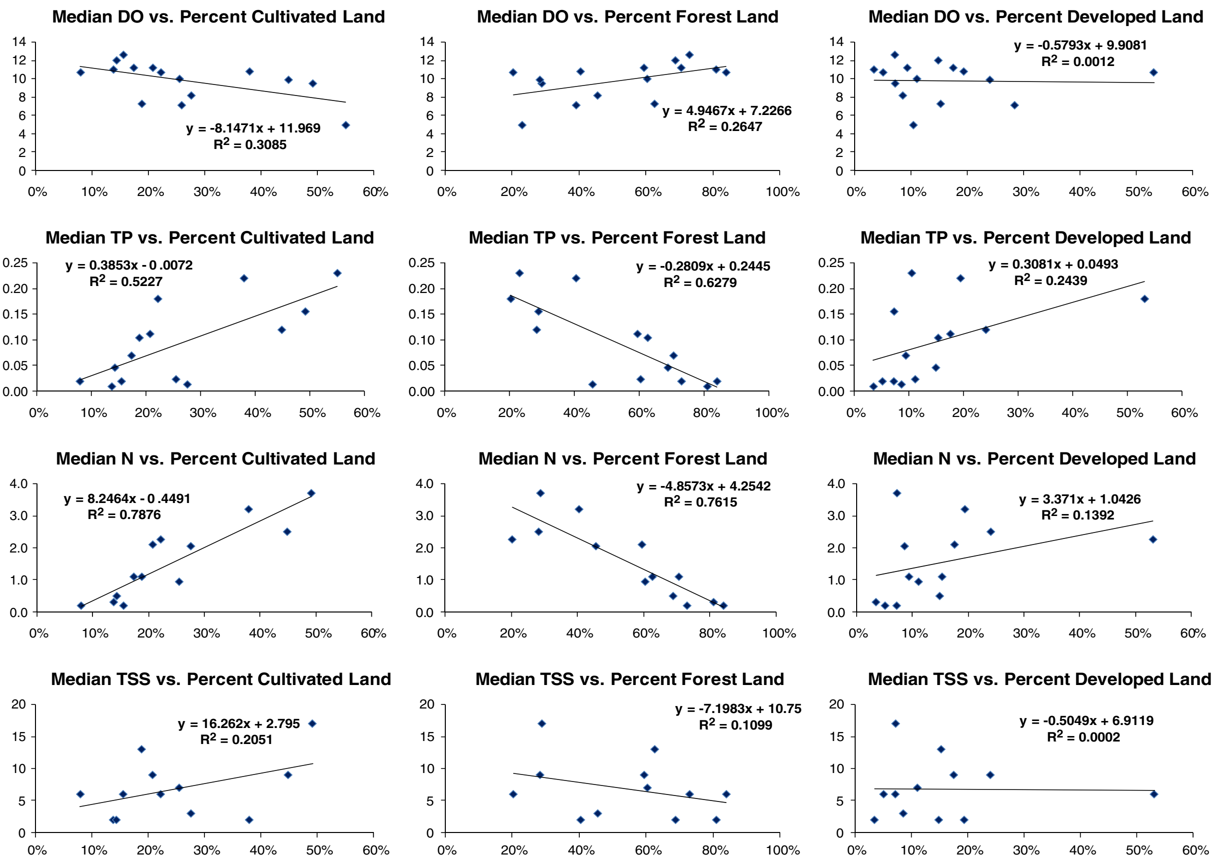


Fig. 35 Linear regression plots of water quality versus land use in the Delaware Basin

solved oxygen concentrations are observed in cool water during the winter than in warm water during the summer. The Seasonal Kendall test screens for seasonality by grouping data into the four seasons of the year, thus reducing the effect that seasonal differences in concentration may have on water quality trends. We also evaluated seasonal water quality changes by comparing month by month boxplots (Fig. 33). Dissolved oxygen in Delaware Basin waters varies with the seasons ranging from highest levels during the colder months of November through March to the lowest levels during the warm summer months of June through September. The 25th percentile of DO readings along Delaware Basin waters exceeded 6 mg/l in every month of the year. Nutrients usually rise during spring and early summer due to fertilizer runoff from farms and lawns. Phosphorus levels rose from June though October due to lawn and agricultural fertilizer use during the growing season and then declined by November. Nitrogen levels declined during the spring until May and then increased and remained constant and high over the summer. TSS levels were constant year-round with no discernible change with the seasons.

Land use

Stream water quality often varies depending on watershed land use. Land use in the Delaware Basin varies from more than 20% developed in the urbanized watersheds that extend from Easton, Pa. south through Philadelphia and Wilmington to less than 10% developed in the forested, mountain headwaters above the Delaware Water Gap and in the agricultural Coastal Plain tributaries that flow to the Delaware Estuary in South Jersey and southern Delaware. Delaware Basin

Table 11 Major NPDES municipal wastewater discharge permits in the Delaware Basin

NPDES ID	Facility	Location
PA0027103	Delaware Co. Regional Water Authority	Chester, PA
PA0026859	Coatesville WWTP	Coatesville, PA
PA0026531	Downingtown Regional WPCC	Downingtown, PA
PA0027031	Goose Creek STP	West Chester, PA
PA0024058	Kennett Square Borough WWTP	Kennett Square, PA
PA0026018	West Chester Taylor Run STP	West Chester, PA
PA0028584	West Goshen STP	West Chester, PA
PA0026867	Abington Twp. STP	Abington, PA
PA0026794	Conshohocken Borough Auth.	Conshohocken, PA
PA0051985	Horsham Twp. STP	Horsham, PA
PA0026182	Lansdale Borough STP	Lansdale, PA
PA0027421	Norristown Borough WWTP	Norristown, PA
PA0029441	Upper Dublin Twp. MS4 UA	Fort Washington, PA
PA0039004	Upper Gwynedd Towamencin STP	Lansdale, PA
PA0023256	Upper Gwynedd Twp. WWTP	West Point, PA
PA0020532	Upper Montgomery Joint Sewer Auth.	Pennsburg, PA
PA0025976	Upper Moreland Hatboro Joint Sewer Auth.	Willow Grove, PA
PA0026298	Whitemarsh STP	Lafayette Hill, PA
PA0026689	Northeast WPCP	Philadelphia, PA
PA0026662	Philadelphia Southeast POTW	Philadelphia, PA
PA0026671	Southwest Water Pollution Control	Philadelphia, PA
PA0026549	Reading WWTP	Reading, PA
PA0026549	Borough of Doylestown WWTP	Doylestown, PA
PA0021181	Bristol Borough Water and Sewer	Bristol, PA
PA0026468	Morrisville Mun. Auth. Water System	Morrisville, PA
PA0020460	Quakertown Wastewater Treament	Quakertown, PA
PA0026042	Bethlehem City STP	Bethlehem, PA
PA0027235	Easton Area Joint Sewer Auth. WWTP	Easton, PA
PA0026000	Allentown City WWTP	Allentown, PA
PA0020168	East Stroudsburg Water Filtration Plant	Stroudsburg, PA
PA0029289	Stroudsburg STP	Stroudsburg, PA
NY0030074	Liberty WWTF	Liberty, NY
NY0022454	Monticello STP	Monticello, NY
NY0020265	Delhi WWTP	Delhi, NY
NY0029271	Sidney WWTP	Sidney, NY
NJ0020184	Newton Town DPW	Newton, NJ
NJ0024716	Phillipsburg Town STP	Phillipsburg, NJ
NJ0020915	Lambertville City Sewer Auth.	Lambertville, NJ
NJ0024759	Ewing Lawrence Sewer Auth WWTP	Lawrenceville, NJ
NJ0026301	Hamilton Twp. DPW Water Pollution	Hamilton Twp., NJ
NJ0020923	Trenton City DPW Sewer Auth.	Trenton, NJ
NJ0027481	Beverly City Sewer Auth. STP	Beverly, NJ
NJ0024678	Bordentown Sewerage Auth.	Bordentown, NJ
NJ0024660	Burlington City STP	Burlington, NJ
NJ0021709	Burlington Twp. DPW	Burlington, NJ
NJ0024007	Cinnaminson Twp. Sewerage Auth.	Cinnaminson, NJ
NJ0023701	Florence Twp. DPW Sewer Auth.	Florence, NJ
NJ0069167	Maple Shade Twp. Util, Authority POTW	Maple Shade, NJ
NJ0026832	Medford Twp. Sewer Auth. STP	Medford, NJ
NJ0024996	Moorestown Twp. Utilities Auth WWTP	Moorestown, NJ
NJ0024015	Mount Holly Twp. MUA	Mount Holly, NJ
NJ0024821	Pemberton Twp. MUA STP	Pemberton, NJ
NJ0022519	Riverside Twp. DPW	Riverside, NJ

Table 11 (continued)

NPDES ID	Facility	Location
NJ0023361	Willingboro Twp. MUA	Willingboro, NJ
NJ0026182	Camden County MUA	Camden, NJ
NJ0024686	Gloucester Co. Util. Auth. STP	Thorofare, NJ
NJ0021601	Carneys Point Twp. Sewer Auth WWTP	Carneys Point, NJ
NJ0024023	Penns Grove Sewerage Auth.	Penns Grove, NJ
NJ0021598	Pennsville Twp. Sewer Auth.	Pennsville, NJ
NJ0024856	Salem WWTP Facility	Salem, NJ
NJ0024651	Cumberland Co. Utility Auth. WWTP	Bridgeton, NJ
NJ0029467	Millville City Sewer Auth.	Millville, NJ
DE0021512	Lewes City POTW	Lewes, DE
DE0020338	Kent Co. Levy Court WWTR	Federica, DE
DE0020320	Wilmington Wastewater Plant	Wilmington, DE

streams that recorded poor phosphorus and nitrogen water quality are significantly impacted by human activity as the sum of developed plus cultivated land exceeds 50% in the Lehigh, Schuylkill, Neshaminy, Salem, Brandywine, and St. Jones watersheds (Fig. 34).

Streams with the best water quality tend to have the most watershed forest cover. Watersheds with over 50% forest cover along the Delaware above Trenton, Port Jervis, and Callicoon and tributaries such as the Lackawaxen, Brodhead, Paulins Kill have good to excellent water quality for DO, TP, TN, and TSS. The Lackawaxen River with a watershed covered with 73% forest recorded the highest median DO (12.6 mg/l) of any station. The Delaware River at Callicoon with a watershed covered with 81% forest recorded very low median P (0.01 mg/l), N (0.3 mg/l), and TSS (2 mg/l) levels.

Linear regression analyses utilizing coefficients of determination (r^2) indicate reasonably good correlation between cultivated and forest land uses and water quality at Delaware Basin stations (Table 10 and Fig. 35). An r^2 greater than 0.3 would be considered moderate and above 0.5 good correlation. Water quality declines with increased cultivated land in the watershed as r^2 values for DO (0.31), TP (0.53), and TN (0.79) indicate moderate to good inverse correlation. Water quality improves with increased forest land as r^2 values for DO (0.26), TP (0.63), and TN (0.76) indicates moderate to good direct corre-

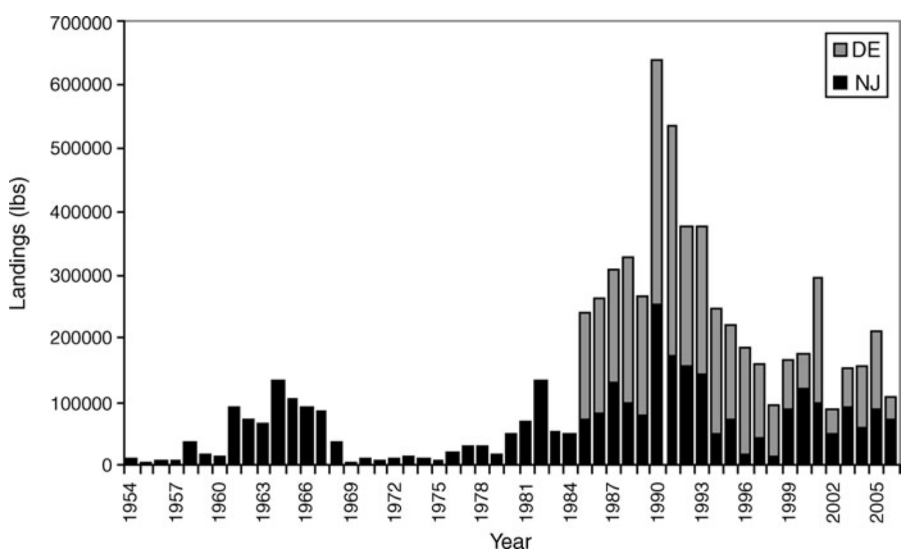


Fig. 36 Commercial landings of American shad in the Delaware River Basin (ASMFC 2008)

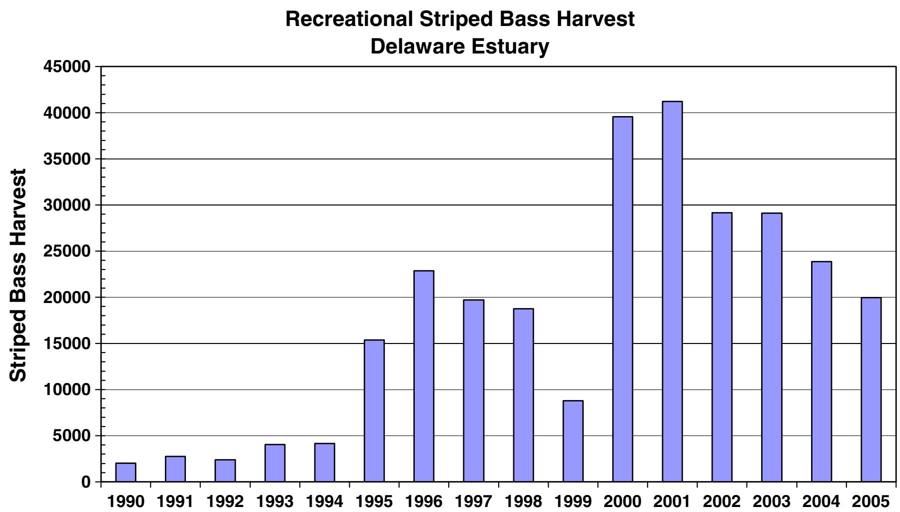


Fig. 37 Recreational striped bass harvest in the Delaware Estuary (Kahn et al. 2006)

lation. Linear regression plots of cultivated and forest land versus TSS recorded r^2 values of 0.21 or less, evidence of less than moderate correlation. Linear regression between developed land and water quality indicate little correlation as r^2 ranges from 0.01 for DO and TSS to 0.24 for TP. Watersheds with over 5% wetlands include the Coastal Plain streams of St. Jones, Salem River, and Maurice River that flow directly to the Delaware Bay. Little correlation was found between water quality and wetland cover.

Point source pollutants

The Delaware River Basin Commission (2008a, b) regulates point source wastewater dischargers in accordance with the following designated uses: (1) agricultural, industrial, and public water supplies, (2) wildlife, fish and aquatic life, (3) recreation, (4) navigation, and (5) regulated waste assimilation. The DRBC water pollution control program manages wastewater discharges based on waste load allocations in water quality management zones that have been in effect since 1968. Since then, the DRBC has issued waste load permits to over 140 municipal wastewater discharges along the Delaware River, Estuary, and tributaries including the major dischargers listed in Table 11. Since 1980, improved water quality trends along the Delaware River, Estuary, and tributaries can be attributed to construction of new and rehabilitated sewage treatment plants.

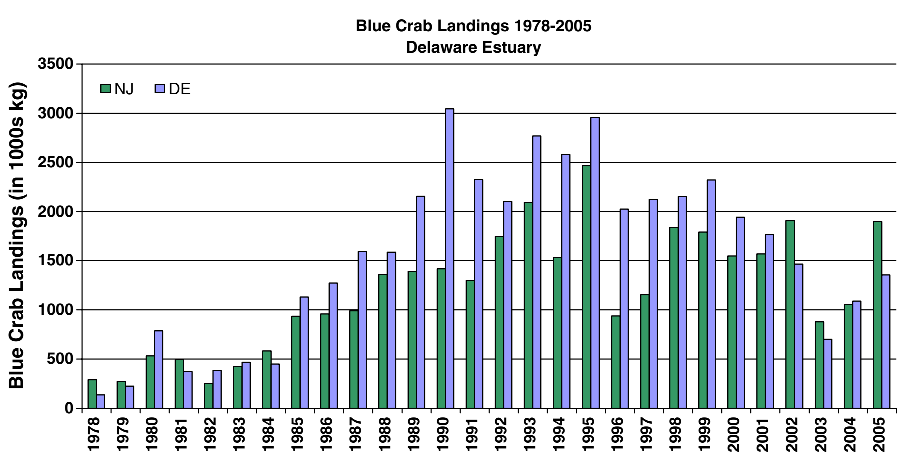


Fig. 38 Blue crab landings in the Delaware Estuary (NJDEP; DNREC)

The ban on phosphate detergent during the 1980s and phosphorus removal at wastewater plants resulted in significant phosphorus reductions in the waterways. Many of the wastewater treatment plants have been fitted with denitrification; however, greater attention is needed to reverse degrading nitrogen trends observed recently along Delaware Basin streams.

Habitat

Water quality recovery is coincident with the return of striped bass, American shad, blue crab, and bald eagle populations to the Delaware Estuary. With cleaner water, the American shad and striped bass have returned to the Delaware Estuary in numbers not recorded in decades as depicted in Figs. 36 and 37 (ASMFC 2008; Kahn et al. 2006). Blue crabs, a $7 million shellfishery, are increasingly abundant in the Delaware Estuary (Fig. 38). The bald eagle, a species that relies on clean water and a fish-laden diet, returned to the Delaware Basin in impressive numbers as the four states reported that 96 bald eagle nests were observed in 2004, more than double the total of 44 in 2001 (Fig. 39). Cleaner water, the Federal DDT ban in 1980, Federal endangered species protection, and preservation of habitat along Delaware Bay have contributed to the growth in bald eagle numbers. In 2007, a bald eagle nest was sighted in South Philadelphia at the mouth of the Schuylkill River, one of the most urban places in the watershed.

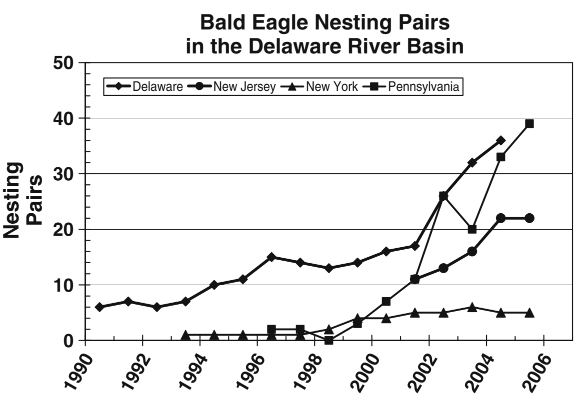


Fig. 39 Bald eagle nesting pairs in the Delaware River Basin (DNREC; PA Fish and Game; NYSDEC; NJDEP)

Even with improvements, troublesome water quality trends remain (Kauffman et al. 2008). Common pesticides atrazine and metolachlor have been detected in at least 80 of 100 streams in the basin. Fish-consumption advisories remain along 4,000 miles of streams in the Delaware Basin. Eastern oyster catches have dropped to 100,000 bushels per year in the Delaware Bay, down from 500,000 bushels during the 1980s. About 15% of the habitat of the brook trout—the state fish of New Jersey, New York, and Pennsylvania—has been extirpated, and its habitat remains in just 50% of the basin. The Atlantic sturgeon is teetering on extinction in the river as only two fish per haul were caught in the Delaware in 2004, none in 2005. The Delaware Basin has lost 18 square miles of agriculture, 4 square miles of wetlands, 48 square miles of forests, and gained 70 square miles of urban/suburban land between 1996 and 2001. These are all declines worth reversing.

Summary

Between 1980 and 2005, water quality improved at 39%, remained constant at 51%, and degraded at 10% of 15 monitoring stations examined along the Delaware River and tributaries. Since 1980, the number of improving water quality stations (19) outnumbered degrading stations (five) by a margin of nearly 4 to 1. Water quality is good in the freshwater Delaware River and tributaries upstream from Trenton and, although improved, remains fair to poor where nitrogen and phosphorus levels exceed standards in the tidal estuary at Philadelphia and in the two largest tributaries, the Lehigh and Schuylkill Rivers. Good water quality correlates with high amounts of forest area (>50%) and poor water quality correlates with high amounts of cultivated land in Delaware Basin watersheds. Redoubled efforts in watershed reforestation, agricultural conservation, and urban stormwater management will be needed to reduce TP and TN levels to meet water quality standards in the lower half of the Delaware Basin.

Even though the Delaware River Basin population has grown by a million people from 1980 to 2010, water quality has improved due to water pollution control actions that extend back to Congressional consent to the Delaware Estuary Act in 1996 and Clean Water Act amendments in 1972 and 1977, JFK's signature on the DRBC Compact in 1961, and the original Delaware River watershed agency, INCODEL, when America was in the grips of the Great Depression. In 1968, the DRBC was cited as one of the early actors responsible for restored water quality in the Delaware Estuary as Stewart Udall, JFK's Secretary of the Interior stated: "Only the Delaware among the nation's river basins is moving into high gear in its program to combat water pollution." In 1996, William D. Ruckelshaus, the Nixon's first Administrator of the USEPA remarked: "Looking back, the DRBC was the vanguard in the Johnny-come-lately march to manage water resources on a watershed basis." Recent environmental history indicates the Delaware River, Estuary, and tributaries may continue to recover under the cooperative watershed approach employed by the Federal government through the Clean Water Act and four states through the comity of the Delaware River Basin Commission and the Partnership for the Delaware Estuary.

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