Water Air Soil Pollut (2010) 208:345–375
DOI 10.1007/s11270-009-0172-z

Water Quality Trends (1970 to 2005) Along Delaware Streams in the Delaware and Chesapeake Bay Watersheds, USA

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Received: 18 February 2009 / Accepted: 23 July 2009 / Published online: 20 August 2009

Abstract Water quality trends from 1970 to 2005 were defined along 30 Delaware streams in the Delaware and Chesapeake Bay watersheds in the USA. Water quality improved or was constant at 69% of stations since 1990 and at 80% of stations since 1970/1980. Dissolved oxygen (DO) improved or was constant at 73% of streams since 1990 and 32% of streams since 1970/1980. Total suspended sediment improved or was constant at 75% of streams since 1990 and 100% of streams since 1970/1980. *Enterococcus* bacteria improved or remained constant at 80% of streams since 1990 and 93% of streams since 1970/1980. Total Kjeldahl nitrogen improved or was constant at 48% of streams since 1990 and 100% of streams since 1970/1980. Total phosphorus improved or was constant at 66% of streams since 1990 and 85% of streams since 1970/1980. During 2001–2005, median levels were good or fair at 100% of the stations for DO, 78% for sediment, 50% for bacteria, 59% for nitrogen, and 56% for phosphorus. Good water quality correlates with high amounts of forest area (>25%) in Delaware watersheds. Since the Federal Clean Water Act Amendments of the 1970s, improving Delaware water quality stations (50) outnumbered degrading stations (23) by a 2:1 margin. Since 1990, degrading water quality stations (46) exceeded improving stations (38) mostly due to deteriorating nitrogen levels in half of Delaware streams, a reversal from early gains achieved since the 1970s. Over the last three and a half decades, watershed strategies have improved or preserved water quality along Delaware streams; however, greater emphasis is needed to curb recently resurging increases in nitrogen levels.

Keywords Water quality · Water pollution · Watershed · Clean Water Act

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1 Introduction

The year 1970 was a watershed or turning point in the environmental movement as Americans observed the first Earth Day and Richard Milhous Nixon signed a bill creating the U.S. Environmental Protection Agency (USEPA) to protect the nation's water, air, and land resources (Cech 2003). Congress later passed the Federal Water Pollution Control Act Amendments of 1972 and 1977, known as the Clean Water Act (CWA). The CWA set limits on pollutant discharges, funded sewage treatment plants, and set goals for fishable and swimmable waters. The 1987 Water Quality Act amended the CWA to control nonpoint source pollutants from urban runoff. In the early 1990s, the USEPA began working with the states to adopt a watershed approach to control pollutants. By 2000, the USEPA issued regulations requiring states to list impaired waters and implement watershed-based Total Maximum Daily Loads (TMDL) to restrict pollutant loads entering streams (USEPA 2007).

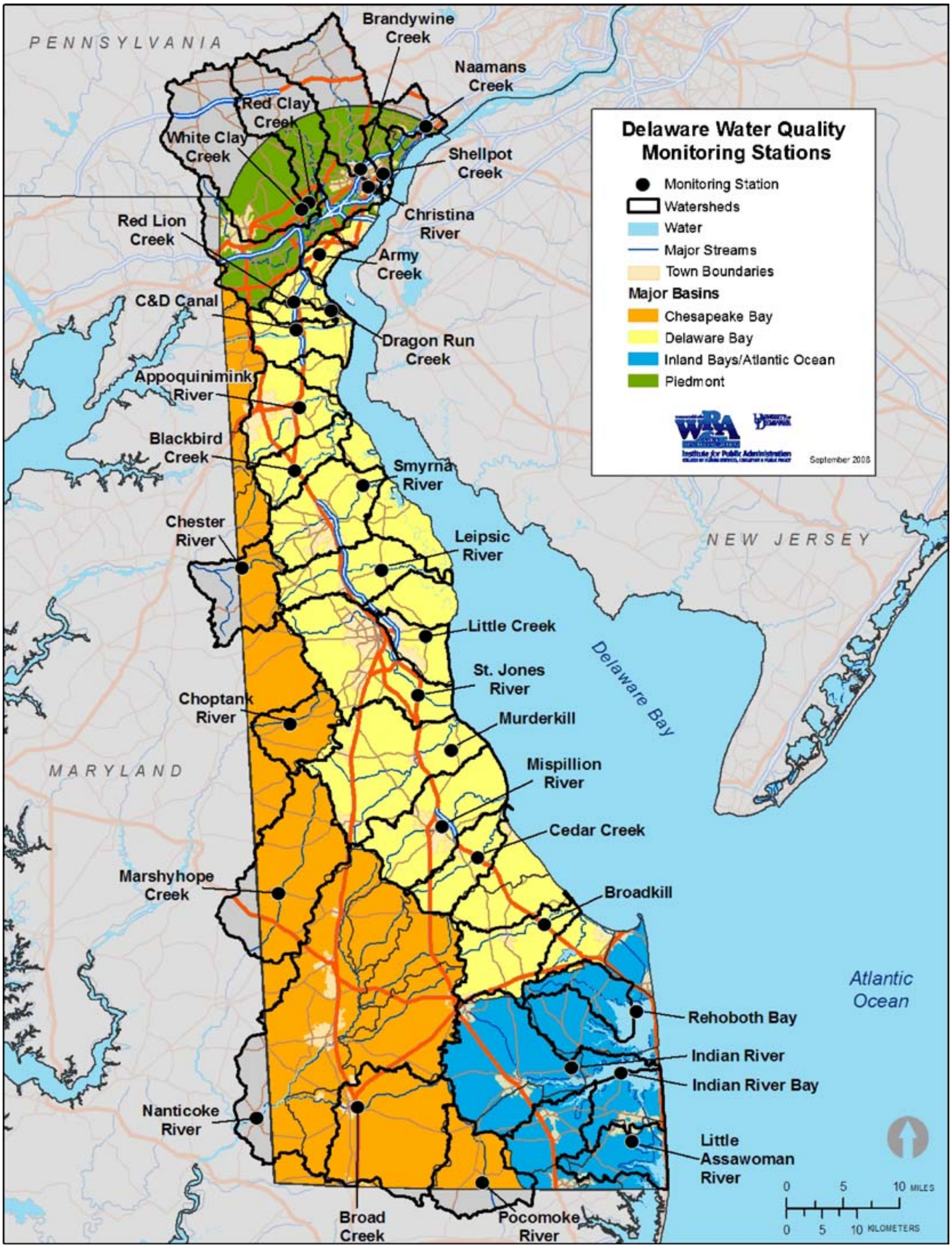


Fig. 1 Stream water quality-monitoring stations in Delaware

Concurrent with Federal actions, states such as Delaware created environmental programs to clean up water pollution. The Delaware General Assembly created the Department of Natural Resources and Environmental Control (DNREC) in 1969. The DNREC (2006) first adopted water pollution control regulations in 1974 last amended in 2006. The DNREC (2004) established amended surface water quality standards in 2004.

Water quality trend analyses are useful to detect for deterioration, evaluate the effectiveness of corrective actions, and determine if watershed programs have been successful in meeting standards set by state and federal governments (Berryman et al.

Table 1 Land use and impervious cover in Delaware watersheds upstream from stream-monitoring stations

Watershed (DNREC station no.)	Drainage area (km^2)	Impervious (%)	Developed (%)	Cultivated (%)	Forest (%)	Wetland (%)
Piedmont basin						
Naamans Creek at Naamans Road (101021)	26	39	86	1	12	1
Shellpot Creek at Route 13 (102011)	36	44	85	1	11	3
Brandywine Creek at Footbridge (104011)	835	14	30	35	33	1
White Clay Creek at Stanton (105011)	274	18	38	32	28	2
Red Clay Creek at Stanton (103011)	138	17	40	31	28	1
Christina River at Route 13 (106011)	200	40	61	13	19	6
Delaware Estuary basin						
Army Creek at Route 13 (114021)	26	38	62	15	10	12
Red Lion Creek at Route 7 (107011)	28	24	44	33	13	13
Dragon Run at Route 9 (111011)	26	23	43	33	13	11
C & D Canal at St. Georges Bridge (108021)	113	11	19	42	13	25
Appoquinimink River at Odessa (109051)	118	12	20	53	9	18
Blackbird Creek at Route 13 (110021)	79	7	13	37	20	29
Smyrna River at Route 9 (201041)	164	10	15	55	10	20
Leipsic River at Route 9 (202031)	269	5	6	41	7	46
Little Creek at Route 9 (204031)	59	18	22	41	4	33
St. Jones River at Barkers Landing (205041)	230	16	29	43	10	18
Murderkill River near Mouth (206141)	274	8	13	56	12	19
Mispillion River at Route 1 (208021)	195	9	14	47	15	24
Cedar Creek at Route 1	90	9	10	45	15	30
Broadkill River at Road 246 (303011)	274	8	13	44	22	21
Inland Bays basin						
Rehoboth Bay at Buoy 3 (306071)	184	9	17	29	23	30
Indian River Inlet (306321)	220	9	13	43	29	14
Indian River Bay Buoy 20 (306121)	220	9	15	33	14	37
Little Assawoman Bay at Road 363 (310101)	95	10	18	36	11	34
Chesapeake Bay basin						
Chester River at Sewell Bridge Road (112021)	102	5	9	44	12	34
Choptank River at Road 208 (207021)	248	6	9	51	12	27
Marshyhope Creek (302011)	246	4	4	58	13	25
Broad Creek at Records Pond (307011)	307	6	10	60	25	5
Nanticoke River at Md. Route 313 (304011)	369	8	12	59	13	15
Pocomoke River at Road 419 (313011)	90	3	3	49	11	37

Sources: University of Delaware—Water Resources Agency and State of Delaware, 2007

1988). Long-term water quality trends since 1970 can measure progress in restoring streams to meet fishable and swimmable goals set by the 1972 and 1977 Federal CWA amendments. Short-term trends since 1990 can measure progress toward meeting TMDL in accordance with Section 303(d) of the 1987 Water Quality Act.

2 Objectives

Our research objectives are to evaluate water quality trends along 30 Delaware streams and determine whether watershed management programs have restored or preserved water quality. We examined stream-monitoring data in Delaware to determine whether water quality trends have improved, remained constant, or degraded between 1970 and 2005. Water quality trends were detected using the nonparametric seasonal Kendall test for statistical significance supplemented by visual examination of time series scatter plots and box plots illustrating the 25th, 50th (median), and 75th percentiles of the sample. We compared water quality changes with watershed influences such as stream flow, seasonality, drainage basin, land use, and point source pollutants.

3 Study Area

The State of Delaware lies midway between New York City and Washington, DC along the Atlantic Seaboard of the United States. Approximately 60% of Delaware's watershed area drains east to the Delaware

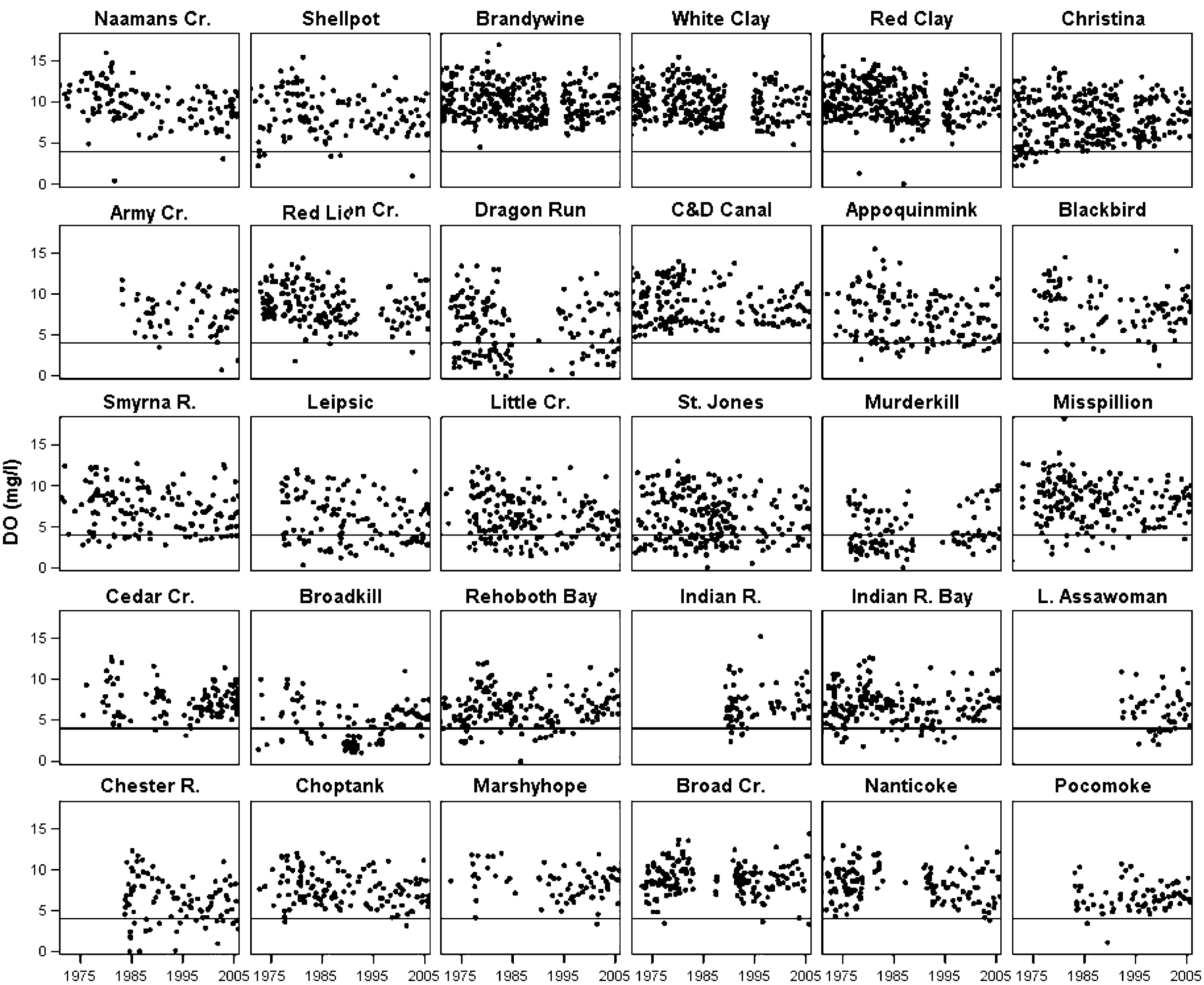


Fig. 2 DO scatter plots along Delaware streams

Bay and Atlantic Ocean and 40% of the state's watershed area drains west to the Chesapeake Bay. Approximately 6% of the state is covered by the hilly, rocky Piedmont Plateau province in populous northern Delaware and 94% of the state is situated in the flat, sandy Coastal Plain province in the rural and agricultural south below the Chesapeake and Delaware Canal. The state is drained by four whole basins: the Piedmont, Delaware Estuary, Inland Bays/Atlantic Ocean, and Chesapeake Bay.

4 Literature Review

The literature reports on water quality trends in mid-Atlantic watersheds over the last three decades. Most water quality trend studies utilized the nonparametric seasonal Kendall test for statistical significance if probability $(p)\leq 0.05$ or 0.10. Most of the reports concluded that more stations showed improvements for phosphorus than nitrogen and that, overall, nitrogen levels seem to be degrading over time. Published reports summarize water quality trend analyses in watersheds upstream, downstream, and adjacent to Delaware. Except for a 1996 assessment of water quality data in the Christina Basin, little is published on water quality trends along Delaware streams.

The United States Geological Survey (USGS) evaluated water quality trends at over 300 waterways in the United States from 1974 to 1981 using the nonparametric seasonal Kendall test for median slope change and statistical significance if $p\leq 0.1$ (Smith et al. 1987).

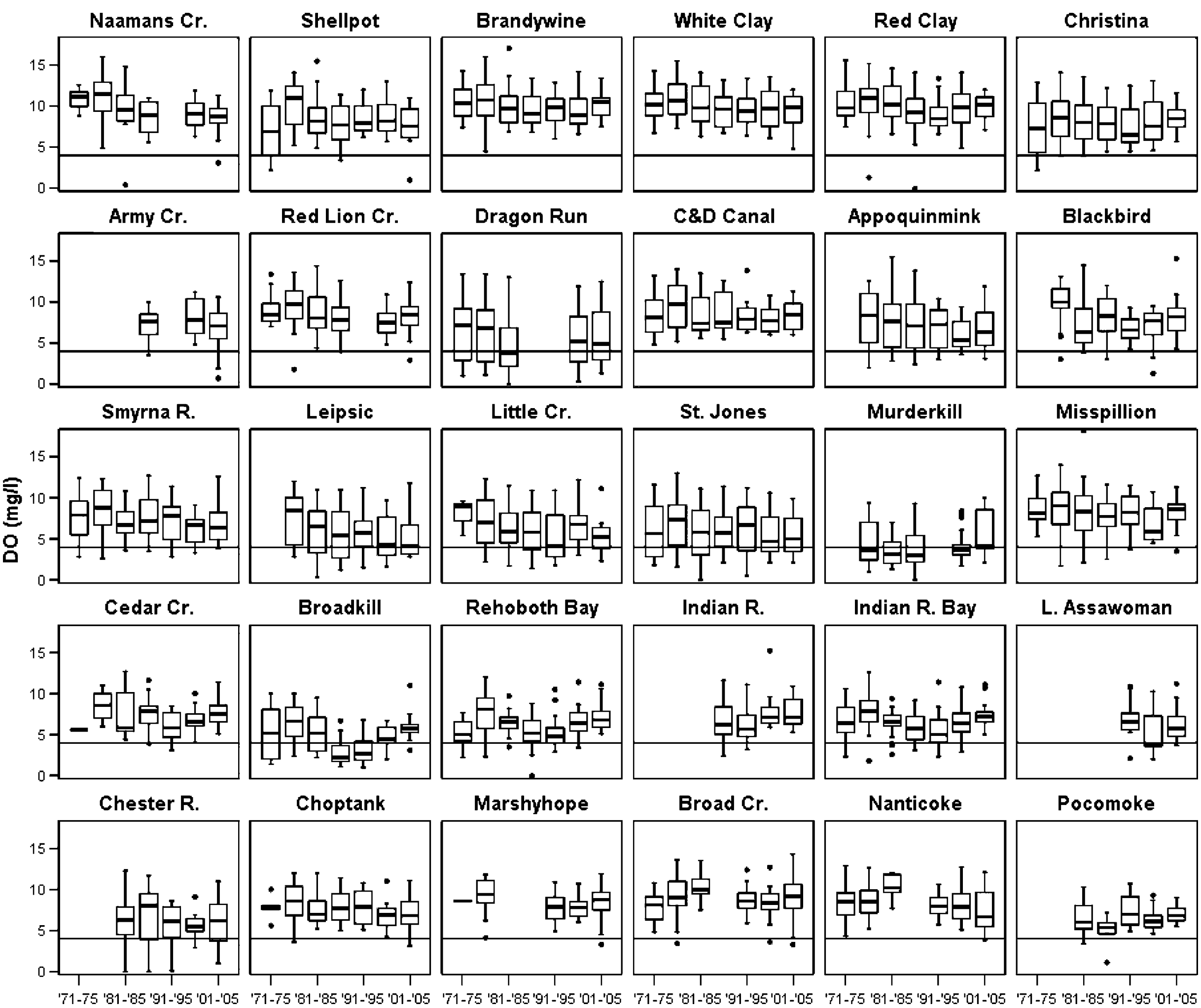


Fig. 3 DO box plots along Delaware streams

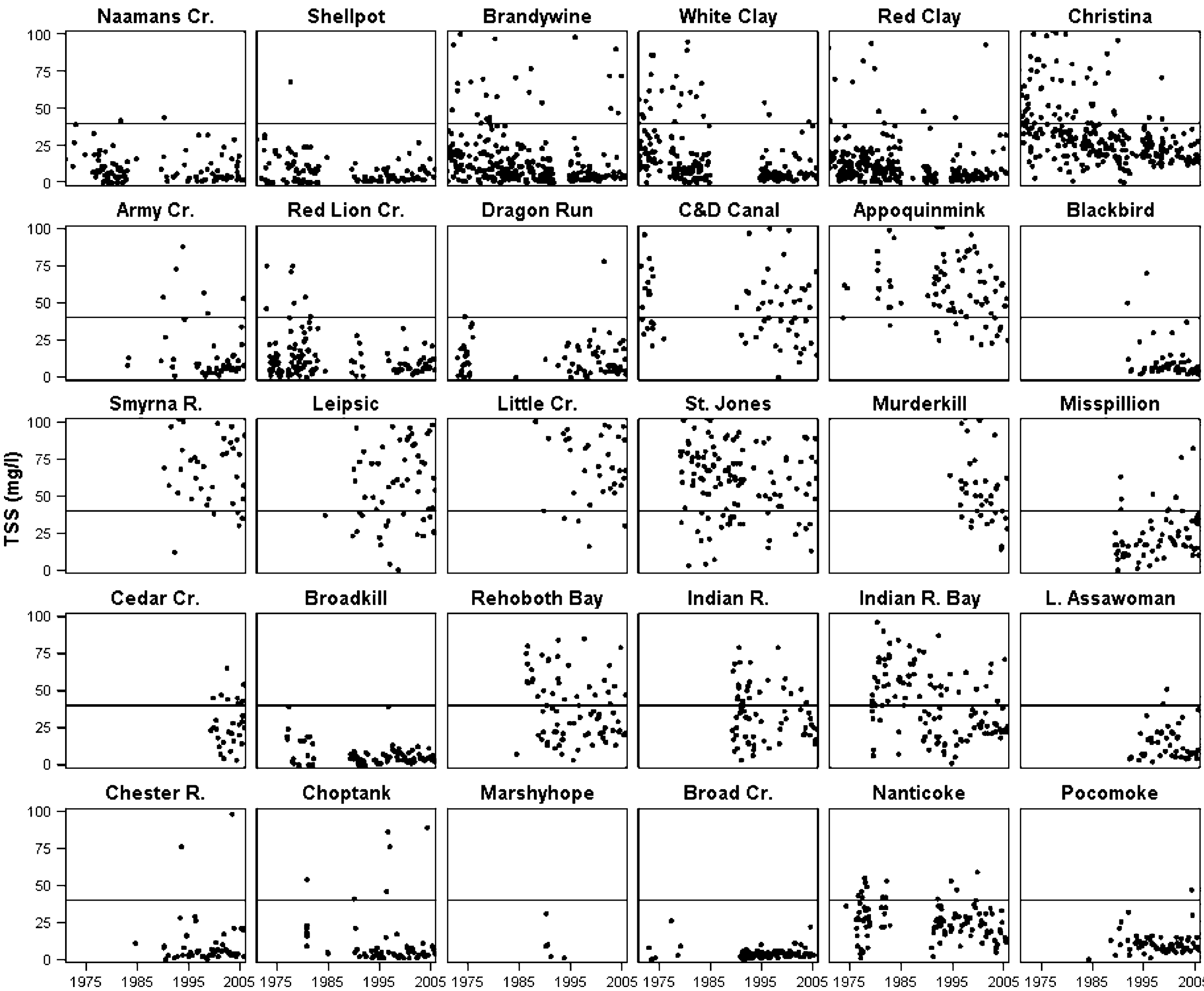


Fig. 4 TSS scatter plots along Delaware streams

Nitrate nitrogen increased at 30% and decreased at 7% of the stations. Total phosphorus (TP) increased at 11% and decreased at 13% of the stations. Total suspended sediment (TSS) increased at 15% and decreased at 14% of the stations. Dissolved oxygen (DO) improved at 17% and degraded at 11% of the stations. Along Christina Basin streams in Delaware from 1970 to 1990, comparison of annual median levels indicate that bacteria, phosphorus, and sediment levels improved, but during the same period, DO and nitrate nitrogen levels deteriorated (DNREC 1996).

Hainly and Loper (1997) assessed water quality trends in the Lower Susquehanna River Basin in Pennsylvania and Maryland from 1975 to 1990 using graphical techniques such as box plots, scatter plot smoothing (LOWESS) curves, and the Kruskal–Wallis test. Nitrate concentrations in streams increased slightly from 1980 to 1985 and decreased slightly from 1985 to 1989. Concentrations of nutrients and suspended sediment were elevated in agricultural drainage areas.

Stream water quality trends were evaluated using the seasonal Kendall tau rank correlation test at 191 stations in Virginia from the 1960s to 1997 (Zipper et al. 1998). TP improvements outnumbered deterioration by a 3:1 ratio. Deteriorating nitrate nitrogen and total Kjeldahl nitrogen (TKN) water quality outnumbered improving stations.

A USGS analysis along the Brandywine Creek in Pennsylvania indicated that annual median bacteria levels declined from 1973 to 1999 (Town 2001). Bacteria increased with increased stream flow. The

Kruskal–Wallis test at 95% confidence level showed no statistically significant differences between fecal coliform concentrations in agricultural, forested, and residential sub-basins. Bacteria concentrations in the Brandywine Creek were lower in the spring and fall than during the summer.

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.

Water quality sampling at 33 sites in the Chesapeake Basin showed nitrogen, phosphorus, and sediment decreased at 55%, 75%, and 48% of the sites from 1985 to 2003, respectively (Langland et al. 2004).

The Maryland Department of Natural Resources (2004) reported on water quality trends along the upper Eastern Shore of the Chesapeake Bay from 1985 to 2003. Long-term trends were significant provided $p \leq 0.1$ according to the seasonal Kendall procedure using the monthly median. Total nitrogen concentrations improved at one station and remained unchanged at seven stations. TP concentrations improved at two stations and remained unchanged at six stations. Total suspended solids improved at three stations and remained unchanged at five stations.

The New Jersey Department of Environmental Protection (2004) conducted a trend analysis along

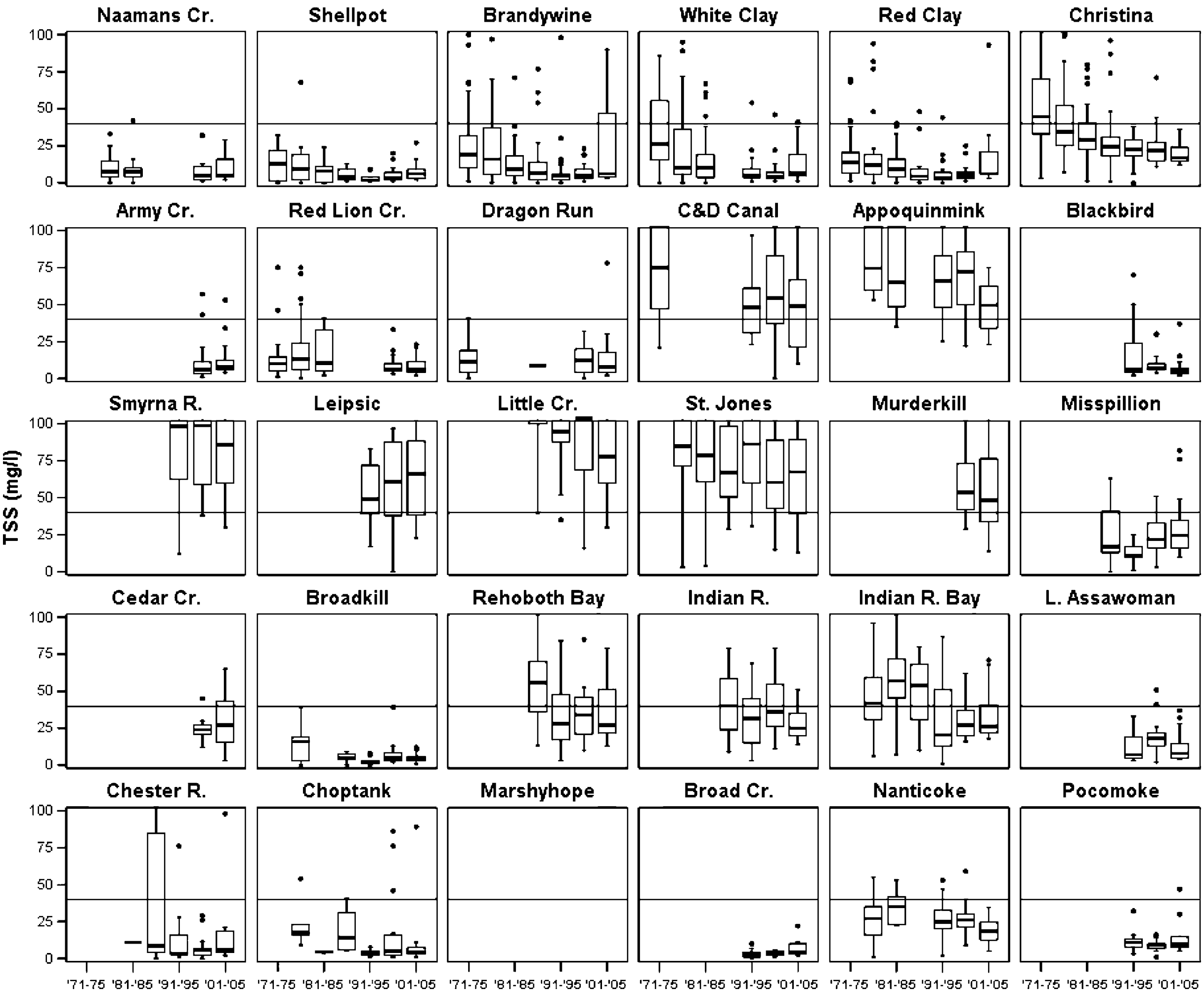


Fig. 5 TSS box plots along Delaware streams

36 New Jersey streams from 1985 to 2004 using the seasonal Kendall test with $p \leq 0.05$. DO 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. TP improved at 45% and remained stable at 55% of the stations.

The Pennsylvania Department of Environmental Protection (2005) evaluated water quality trends between 1995 and 2005 using the nonparametric seasonal Kendall test for trend ($p \leq 0.05$). Along Pennsylvania streams in the Delaware River Basin, five nitrogen stations had improving trends, 27 had no change, and four stations had degrading trends. For TP, 12 stations had improving trends, 24 stations had no change, and no stations had degrading trends.

Water quality trend analyses using the seasonal Kendall test indicated that inorganic nitrogen and phosphorus concentrations decreased in the Patuxent River estuary in Maryland from 1985 to 2003 following upgrades to sewage treatment plants (Testa et al. 2008).

5 Methods

The Delaware DNREC, Watershed Assessment Branch provided water quality-monitoring data along 30 Delaware streams (Fig. 1). Favorable monitoring stations included data that span the period of analysis (1970 to 2005), with no more than 2 years of missing data at the beginning/end of the time period, and at least one half

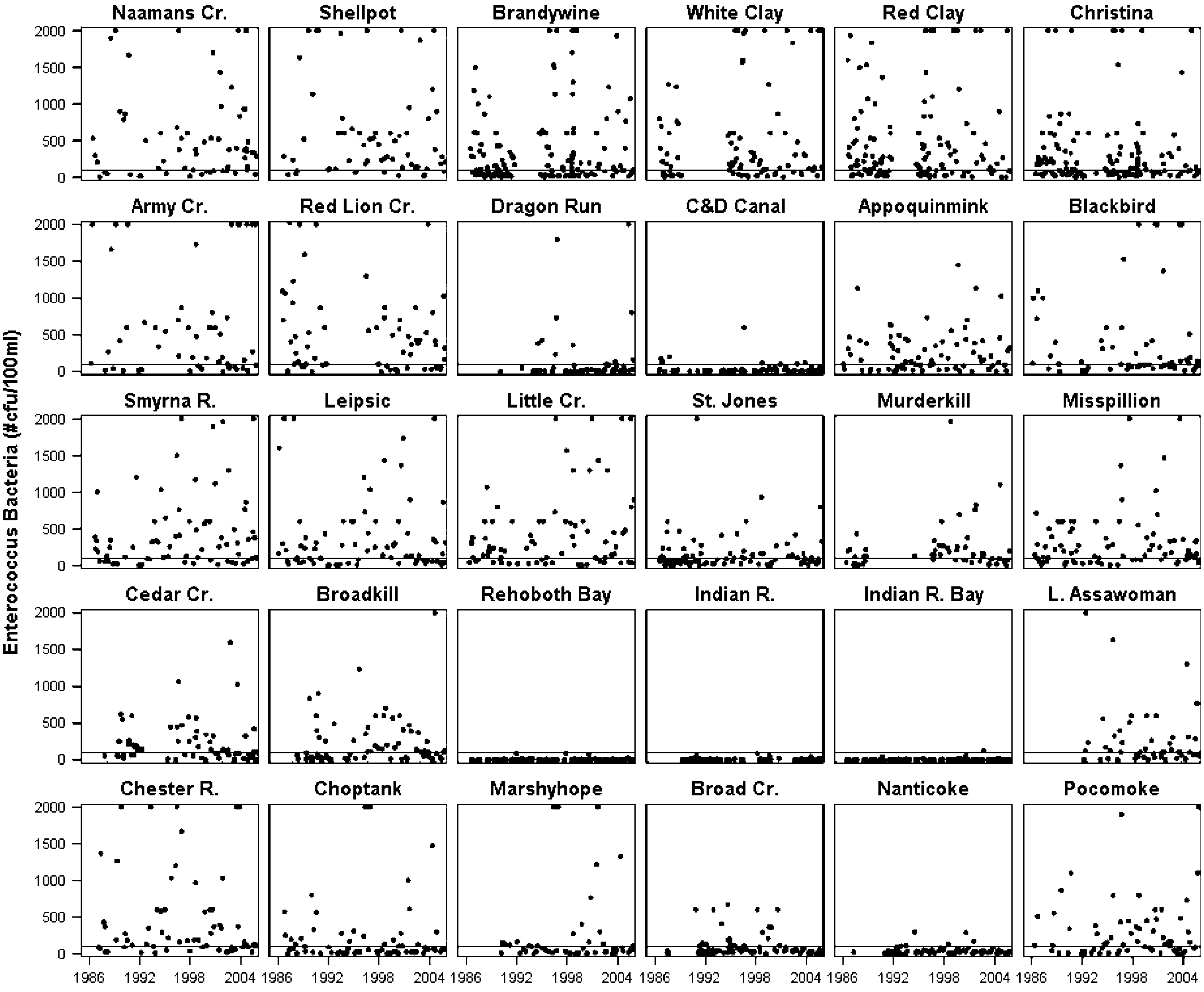


Fig. 6 EB scatter plots along Delaware streams

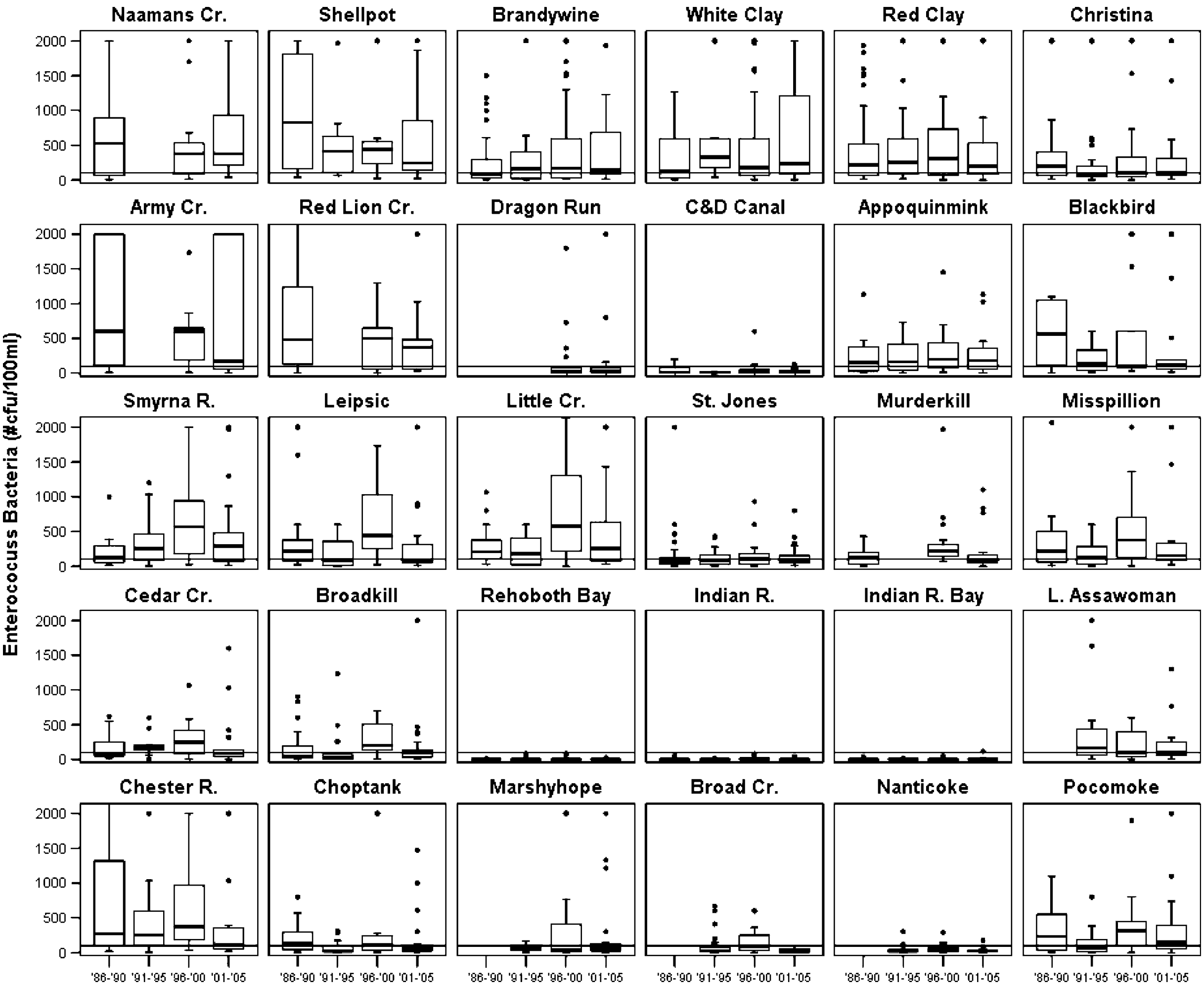


Fig. 7 EB box plots along Delaware streams

of the data present in the first and last thirds of the record (Lanfear and Alexander 1990). Stream-monitoring stations were mostly upstream from the head of tide yet far enough downstream to characterize water quality from most of the watershed. Twenty-four streams flow east to the Delaware Estuary/Atlantic Ocean and six streams flow west to the Chesapeake Bay. Monitoring stations are located in each of Delaware's four drainage basins: Piedmont (six stations), Delaware Estuary (14 stations), Inland Bays (four stations), and Chesapeake Bay (six stations). Six streams drain watersheds in the northern hilly, rocky Piedmont physiographic province and 24 are in the flat, sandy Coastal Plain province to the south.

Watershed land uses for each station were compiled using geographical information system (GIS) data obtained from the State of Delaware 2007 GIS orthophoto quarter quadrangle coverage and then grouped into four categories: developed (urban/suburban), cultivated (farms/agriculture), forests, and water/wetlands (Table 1). Watershed impervious cover was estimated using GIS by multiplying the area of each land use by an impervious cover factor, summing the products, and dividing by total watershed area. Impervious cover factors were obtained and summarized by directly measuring the area of roof and pavement for each land use category including: developed urban/suburban (30% to 70%), cultivated farms and agriculture (5%), forests (0%), and water/wetlands (0%).

Candidate water quality-monitoring stations contain at least four sampling points per year from 1970 to 2005 for DO, TSS, *Enterococcus* bacteria (EB), TKN, and TP. The USEPA and DNREC have identified these as priority parameters to establish TMDL along Delaware streams. DO levels higher than 4 mg/L are necessary to sustain aquatic life and are the basis for the Delaware fishable water quality standard. High TSS concentrations smother fish habitat, block sunlight causing water plants to die, decrease DO levels, and increase water temperature. High bacteria levels originate from sewage or animal waste and cause health problems if ingested during swimming or contact with polluted waters. Elevated nitrogen causes eutrophication and algae blooms and depleted oxygen levels and high turbidity. Phosphorus is needed for plant metabolism; however, in high amounts, it is a limiting factor in algae blooms, eutrophication, and fish kills.

Water quality data were plotted on time series scatter plots and box plots with concentration on the vertical axis and time on the horizontal axis (Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11). Scatter plots portray basic statistical parameters such as the sample, maximum and minimum, range, and variance. Two-dimensional scatter plots 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 scatter plot pattern, box plots 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 preferable when water quality concentrations are analyzed because the median is resistant to and minimally affected by outliers.

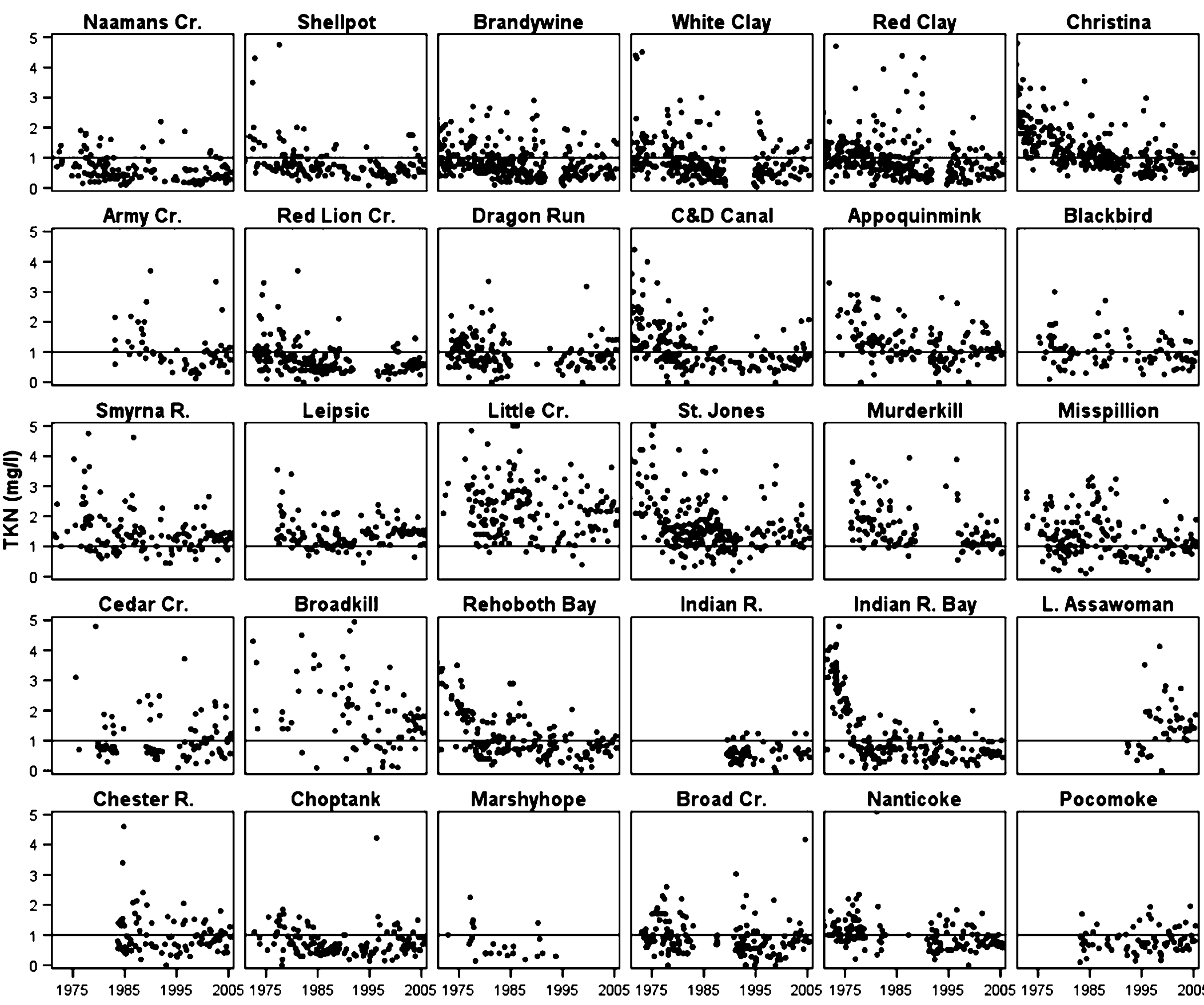


Fig. 8 TKN scatter plots along Delaware streams

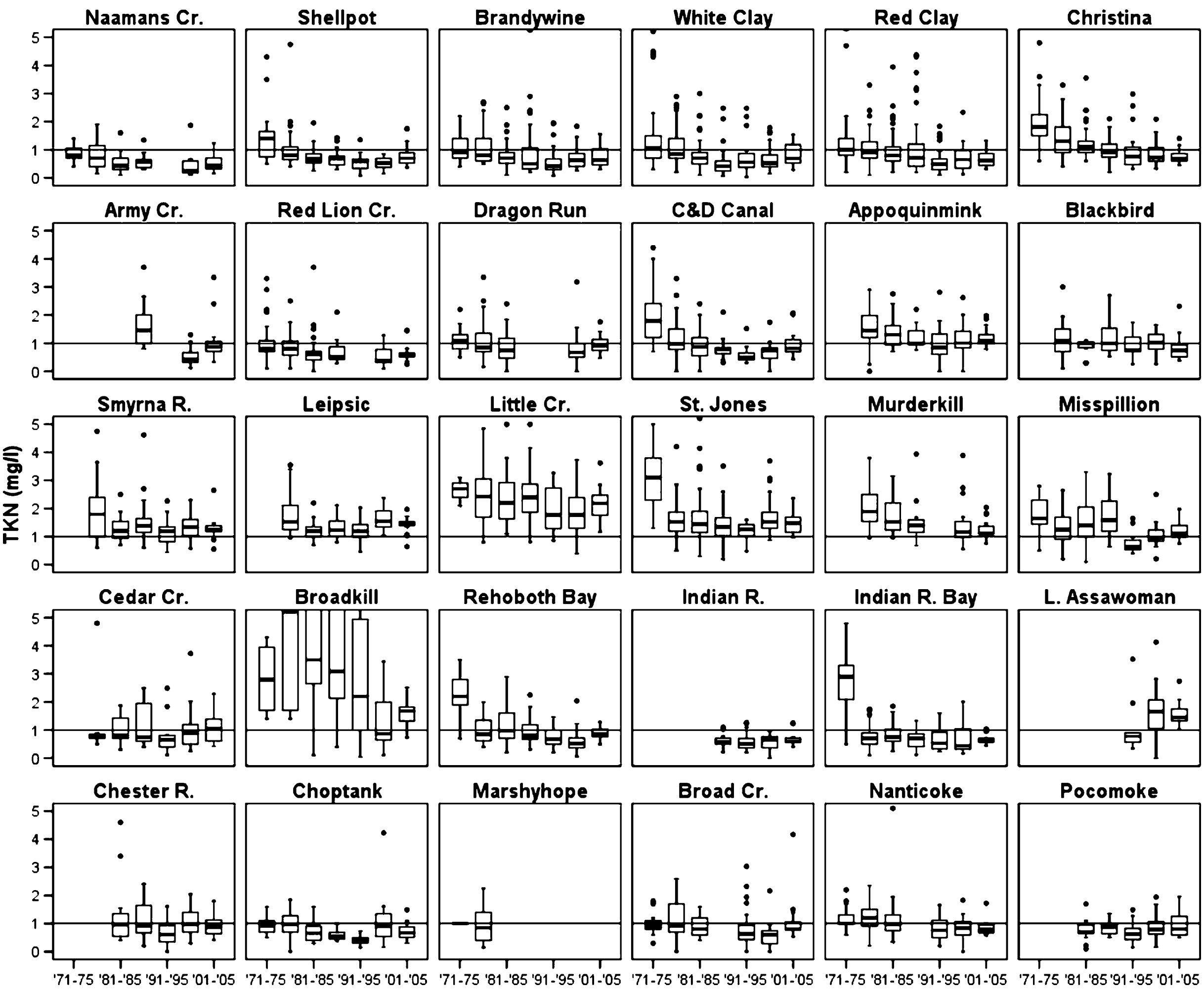


Fig. 9 TKN box plots along Delaware streams

Water quality trends along Delaware streams were detected using the nonparametric seasonal Kendall test for statistical significance if $p \leq 0.1$ 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 direction of slope of the line and if $p \leq 0.10$. 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, the 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 seasonal periods of 3 months per period. Monotonic trends were determined over the long term from 1970/1980 through 2005 and short term from 1990 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. Tables 2 and 3 summarize the seasonal Kendall test results for water quality trends.

The seasonal Kendall monotonic test for trend is appropriate as water quality data is usually skewed and not normally distributed and the test can adjust for seasonality and analyze missing data sets (Cude 2001). The seasonal Kendall test divides data into quarterly seasons and determines the direction and statistical significance (p) of trends by using a slope estimator

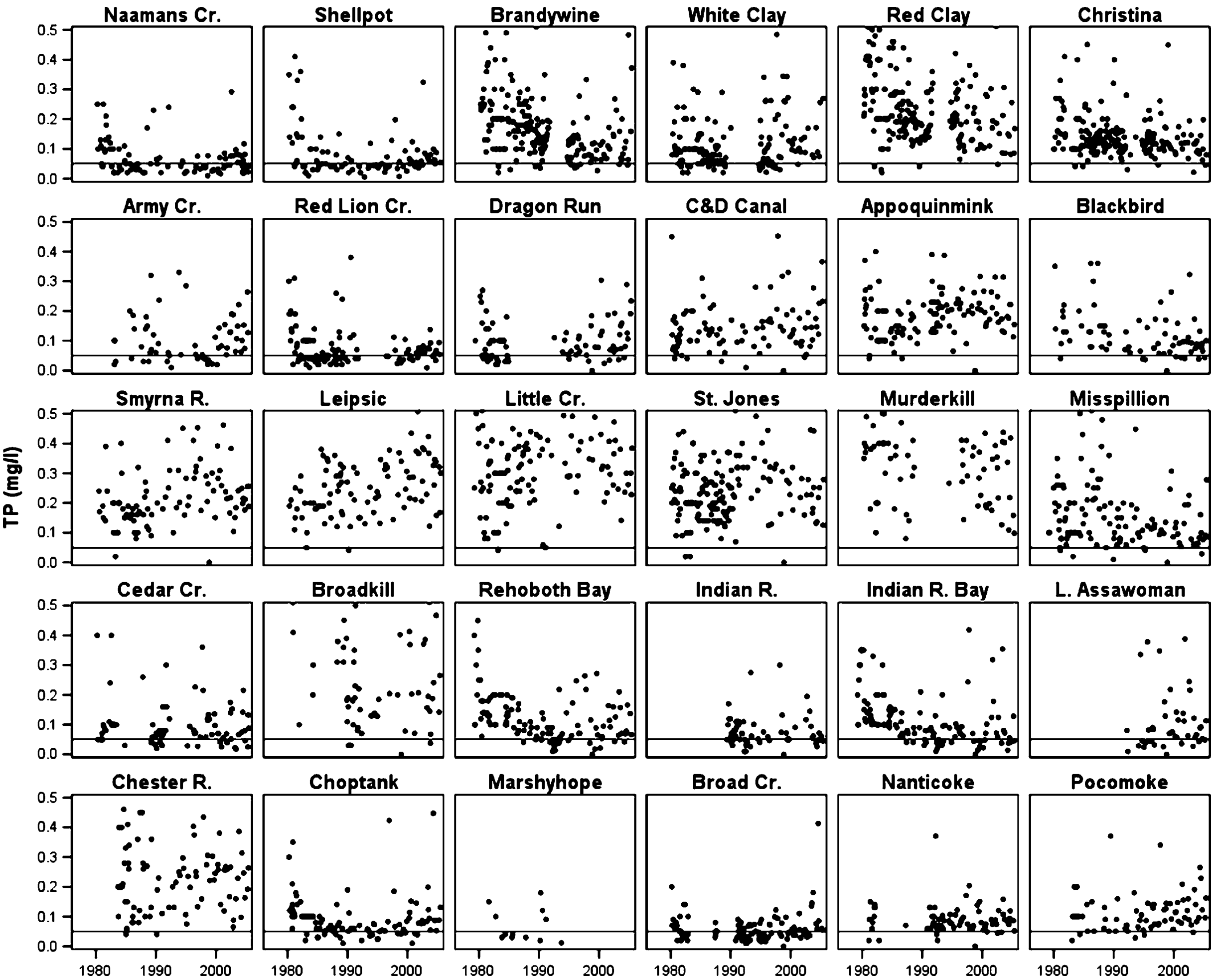


Fig. 10 TP scatter plots along Delaware streams

defined by the median of paired observations in the seasons. The seasonal Kendall test reduces the effect that seasonal differences in concentration may have on water quality trends (Hirsch et al. 1982). Water quality data for suspended sediment, nutrients, and bacteria are asymmetrically distributed; therefore, nonparametric tests for trend such as the seasonal Kendall test are preferred (Schertz et al. 1991). Hirsch et al. (1982) presented the nonparametric seasonal Kendall test as suitable to define monotonic water quality trends. However, this technique is not a substitute for visual examination of the time series plots. If seasonality and skewness is present, visual examination of data may be different from trends derived by a statistical procedure such as the seasonal Kendall test. Other statistical tests for trends over time such as linear regression are not as appropriate because water quality data is not evenly or normally distributed. 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 scatter plots and box plots depicting the 25th 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 scatter plots and box plots 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). Figure 12 depicts a scatter plot and box plot that depicts reversals in water quality trend since 1970 and improved DO from 1990 to 2005 for Rehoboth Bay.

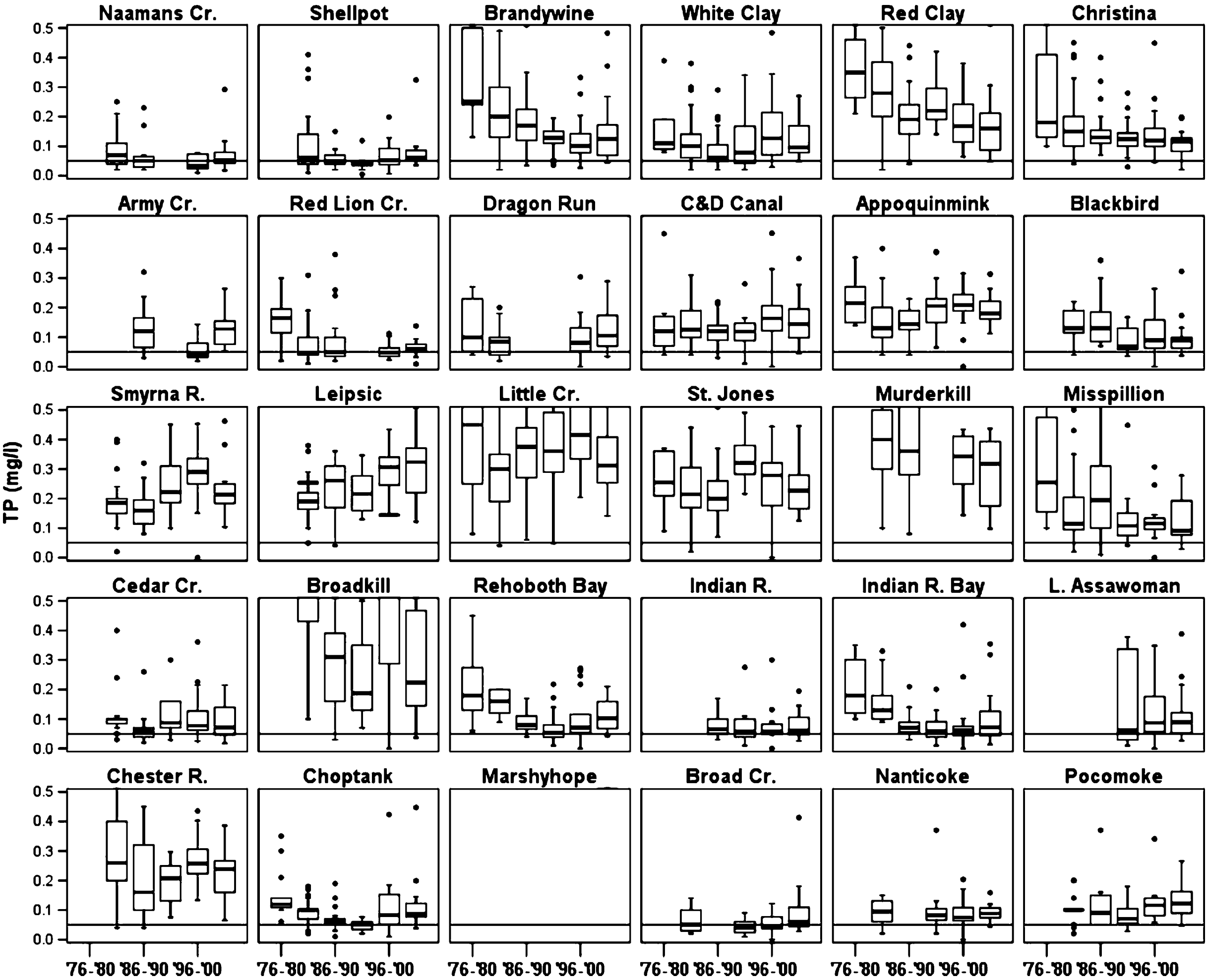


Fig. 11 TP box plots along Delaware streams

We compared median water quality data for 2001 to 2005 to Delaware criteria to categorize stream health as good, fair, or poor. The Delaware DO standard is 4 mg/L for warm water streams and 5 mg/L for cold water put and take trout streams (Table 4). Delaware does not have a TSS standard. Therefore, neighboring New Jersey TSS standards of 25 mg/L for cold water and 40 mg/L for warm water streams are included for comparison (New Jersey Department of Environmental Protection 2006). The Delaware EB standard is 100 colonies per 100 ml. Delaware does not have a TKN standard; therefore, the total nitrogen criteria of 1.0 mg/L was included for comparison. TKN levels in streams are usually half of total N levels. DNREC defines TP concentrations below 0.1 mg/L as low and this TP criterion was included for comparison (DNREC 2008).

While analytical methods have changed over the sampling period of 1970 through 2005, method detection limits (MDL) were consistent over the sampling period in accordance with the laboratory procedures and criteria listed in Table 4. Therefore, it is unlikely that individual sample concentrations observed near the MDL would impact the median and trend analyses.

We defined water quality along Delaware streams as good, fair, or poor by comparing the 2001 to 2005 median to the criteria summarized in Table 5. Good water quality indicates that the 5-year median for 2001–2005 exceeds water quality criteria by 50% or more. Fair water quality indicates that

Table 2 Short-term (1990 to 2005) seasonal Kendall test results for water quality-monitoring stations in Delaware

No.	Stream	DO				TSS				EB				TKN				TP			
		p	Slope	Year	*n*	*p*	Slope	Year	*n*	*p*	Slope	Year	*n*	*p*	Slope	Year	*n*	*p*	Slope	Year	*n*
1	Naamans Cr	0.963	−0.028	1991	51	0.956	0.000	1991	44	0.089	25.2	1991	51	0.683	0.014	1991	48	0.332	0.001	1991	47
2	Shellpot Creek	0.404	−0.073	1991	49	0.005	0.329	1991	46	0.710	4.7	1991	51	0.121	0.027	1991	46	0.015	0.003	1991	46
3	Brandywine Cr	0.093	0.086	1991	91	0.108	0.275	1991	89	0.347	8.3	1991	90	0.225	0.018	1991	75	0.858	−0.001	1991	75
4	White Clay Cr	0.321	0.035	1994	67	0.142	0.800	1994	65	0.928	2.1	1994	65	0.114	0.034	1994	62	0.382	0.004	1994	59
5	Red Clay Cr	0.142	0.112	1991	80	0.052	0.400	1991	75	0.690	8.4	1991	78	0.530	0.010	1991	75	0.147	−0.005	1991	76
6	Christina River	0.025	0.146	1991	99	0.893	0.000	1991	98	0.225	3.8	1991	100	0.775	−0.008	1991	83	0.098	−0.002	1991	83
7	Army Creek	0.491	−0.088	1991	42	0.571	−0.400	1991	48	0.061	37.0	1991	42	0.319	0.026	1991	39	0.148	0.007	1991	39
8	Red Lion Creek	0.368	0.081	1991	42	0.318	0.500	1996	126	1.000	−0.5	1991	40	0.054	0.008	1991	38	0.276	0.003	1991	38
9	Dragon Run Cr	0.452	−0.126	1992	48	0.632	−0.167	1994	71	0.607	0.8	1992	48	0.034	0.031	1992	44	0.145	0.004	1992	44
10	C&D Canal	0.375	0.049	1991	50	0.405	1.250	1991	93	0.073	1.6	1991	50	0.004	0.032	1991	47	0.052	0.005	1991	47
11	Appoquinimink	0.685	−0.031	1991	69	0.105	−1.500	1991	93	0.651	2.5	1991	69	0.168	0.019	1991	66	1.000	0.000	1991	67
12	Blackbird Creek	0.032	0.171	1991	48	0.219	−0.188	1991	49	0.568	5.2	1991	48	0.902	0.001	1991	44	0.514	0.001	1991	44
13	Smyrna River	0.343	−0.035	1991	57	0.973	−0.031	1991	62	0.324	10.5	1991	58	0.243	0.017	1991	53	0.969	−0.001	1991	52
14	Leipsic River	0.010	0.102	1991	55	1.000	−0.004	1991	61	0.581	4.0	1991	56	0.092	0.023	1991	52	0.010	0.010	1991	52
15	Little Creek	0.809	−0.021	1991	55	0.618	−0.938	1991	66	0.790	5.0	1991	56	0.738	0.021	1991	52	0.738	−0.002	1991	52
16	St. Jones River	0.641	−0.041	1991	52	0.085	−2.583	1991	54	0.851	−0.4	1991	53	0.457	0.015	1991	51	0.007	−0.010	1991	52
17	Murderkill River	0.014	0.215	1994	41	n/a	n/a	n/a	n/a	0.046	−23.5	1994	41	0.412	−0.069	1994	38	0.145	−0.018	1994	38
18	Mispillion River	0.974	−0.001	1991	55	0.027	1.183	1991	67	0.441	4.4	1991	54	0.020	0.045	1991	52	0.819	−0.001	1991	51
19	Cedar Creek	0.007	0.225	1991	76	0.604	0.450	1999	30	0.268	−6.6	1991	53	0.047	0.048	1991	48	0.428	−0.002	1991	48
20	Broadkill River	0.001	0.291	1991	58	0.388	0.111	1991	90	0.365	1.3	1991	57	0.491	−0.048	1991	54	0.916	−0.002	1991	55
21	Rehoboth Bay	0.007	0.187	1991	55	0.450	0.611	1991	82	0.390	0.0	1991	58	0.348	0.018	1991	55	0.104	0.003	1991	53
22	Indian River	0.044	0.143	1991	45	0.500	−0.631	1991	66	0.531	0.0	1991	47	0.464	0.011	1991	45	0.828	0.001	1991	44
23	Indian R. Bay	0.002	0.208	1991	56	0.724	0.278	1991	59	0.607	0.0	1991	58	0.258	0.011	1991	56	0.818	0.001	1991	54
24	L. Assawoman	0.658	0.025	1992	48	0.425	−0.375	1994	49	0.967	−0.6	1992	49	0.095	0.061	1992	45	0.687	−0.001	1992	45
25	Chester River	0.957	0.002	1991	51	0.535	0.293	1991	54	0.821	−2.4	1991	51	0.190	0.027	1991	49	0.234	0.006	1991	49
26	Choptank River	0.637	−0.025	1991	50	0.141	0.250	1991	64	0.465	2.6	1991	51	0.078	0.030	1991	48	0.054	0.004	1991	48
27	Marshyhope Cr	0.367	0.075	1991	49	–	–	–	–	0.540	−1.9	1991	49	–	–	–	–	–	–	–	–
28	Broad Creek	0.309	0.050	1991	83	0.006	0.268	1991	90	0.720	−0.8	1991	81	0.061	0.031	1991	82	0.080	0.002	1991	79
29	Nanticoke R.	0.734	−0.030	1991	65	0.350	−0.438	1991	111	0.781	0.3	1991	66	0.733	0.003	1991	64	1.000	0.000	1991	62
30	Pocomoke	0.847	−0.015	1991	52	0.696	0.058	1991	58	0.106	9.5	1991	54	0.352	0.023	1991	51	0.008	0.006	1991	51

Slope of seasonal Kendall trend line in milligrams per liter per year or number of colony-forming units per 100 ml per year

p probability≤0.1=statistically significant, *Year* first year record, *n* number of samples

Table 3 Long-term (1970/1980 to 2005) seasonal Kendall test results for water quality-monitoring stations in Delaware

No.	Stream	DO				TSS				EB				TKN				TP			
		p	Slope	Year	*n*	*p*	Slope	Year	*n*	*p*	Slope	Year	*n*	*p*	Slope	Year	*n*	*p*	Slope	Year	*n*
1	Naamans Cr	0.000	−0.082	1971	135					0.576	5.56	1986	64	0.012	−0.011	1971	131	0.945	0.000	1980	91
2	Shellpot Creek	0.112	−0.044	1971	135	0.281	−0.100	1970	109	0.948	0.45	1986	63	0.003	−0.012	1971	130	0.925	0.000	1980	89
3	Brandywine Cr	0.091	−0.024	1971	325	0.000	−0.370	1970	302	0.189	6.50	1986	146	0.001	−0.015	1971	304	0.001	−0.006	1980	198
4	White Clay Cr	0.057	−0.027	1971	269	0.006	−0.360	1971	210	0.260	14.68	1986	91	0.002	−0.015	1971	253	0.110	0.002	1980	153
5	Red Clay Cr	0.021	−0.025	1971	361	0.014	−0.216	1971	283	0.463	5.00	1986	127	0.000	−0.013	1971	341	0.007	−0.005	1980	200
6	Christina River	0.087	0.030	1971	312	0.000	−0.724	1971	292	1.000	0.13	1986	148	0.000	−0.035	1971	293	0.001	−0.002	1980	193
7	Army Creek	–	–	–	–	–	–	–	–	0.532	−19.12	1986	55	–	–	–	–	0.812	0.001	1983	60
8	Red Lion Creek	0.063	−0.045	1971	181	–	–	–	–	0.048	−20.14	1986	65	0.001	−0.010	1971	171	0.632	0.000	1980	110
9	Dragon Run Cr	0.488	−0.021	1972	155	–	–	–	–	–	–	–	–	0.499	−0.002	1972	147	0.112	0.002	1979	81
10	C&D Canal	0.463	−0.009	1971	189	–	–	–	–	0.152	0.44	1986	61	0.000	−0.030	1971	185	0.219	0.002	1980	91
11	Appoquinimink	0.089	−0.033	1971	159	–	–	–	–	0.482	2.08	1986	82	0.000	−0.020	1971	144	0.016	0.003	1980	126
12	Blackbird Creek	0.145	−0.044	1971	101	–	–	–	–	0.396	−12.90	1986	60	0.079	−0.012	1971	97	0.004	−0.003	1980	72
13	Smyrna River	0.057	−0.039	1971	141	–	–	–	–	0.024	14.81	1986	73	0.073	−0.010	1971	130	0.026	0.003	1980	98
14	Leipsic River	0.417	0.014	1971	126	–	–	–	–	0.868	0.63	1986	78	0.464	0.005	1971	117	0.009	0.005	1979	99
15	Little Creek	0.016	−0.055	1971	179	–	–	–	–	0.462	4.04	1986	82	0.051	−0.022	1971	172	0.205	0.003	1979	141
16	St. Jones River	0.327	−0.020	1971	236	0.030	−1.366	1979	172	0.262	0.08	1989	100	0.000	−0.026	1971	230	0.244	0.002	1980	171
17	Murderkill River	0.044	0.046	1976	115	–	–	–	–	0.709	−2.14	1986	54	0.001	−0.023	1976	111	0.067	−0.005	1980	83
18	Mispillion River	0.324	−0.024	1971	181	–	–	–	–	0.357	4.42	1986	83	0.028	−0.019	1971	173	0.124	−0.002	1979	133
19	Cedar Creek	0.743	0.012	1975	118	–	–	–	–	0.942	−0.50	1987	66	0.849	0.001	1975	84	0.976	0.000	1980	81
20	Broadkill River	0.285	0.035	1971	109	–	–	–	–	0.260	1.54	1988	76	0.001	−0.119	1971	103	0.137	−0.011	1980	86
21	Rehoboth Bay	0.797	0.004	1971	170	–	–	–	–	0.896	0.00	1986	76	0.001	−0.025	1971	168	0.035	−0.002	1979	119
22	Indian River	–	–	–	–	–	–	–	–	0.262	0.08	1989	66	–	–	–	–	–	–	–	–
23	Indian R. Bay	0.724	0.009	1971	200	–	–	–	–	0.534	0.00	1986	77	0.001	−0.025	1971	203	0.005	−0.003	1979	122
24	L. Assawoman	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
25	Chester River	–	–	–	–	–	–	–	–	0.545	−4.77	1986	66	–	–	–	–	0.275	0.003	1983	90
26	Choptank River	0.007	−0.046	1971	135	–	–	–	–	0.718	0.93	1986	66	0.050	−0.010	1971	123	0.732	0.000	1980	105
27	Marshyhope Cr	0.159	−0.046	1971	71	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
28	Broad Creek	0.764	0.002	1971	172	–	–	–	–	0.787	0.47	1987	88	0.105	−0.006	1971	162	0.345	0.001	1980	105
29	Nanticoke R.	0.109	−0.031	1971	149	–	–	–	–	0.393	0.50	1987	68	–	–	–	–	0.715	0.000	1981	74
30	Pocomoke	–	–	–	–	–	–	–	–	0.817	1.19	1986	64	–	–	–	–	0.010	0.002	1983	74

Slope of seasonal Kendall trend line in milligrams per liter per year or number of colony-forming units per 100 ml per year

p probability$\leq$0.1=statistically significant, *Year* first year record, *n* number of samples

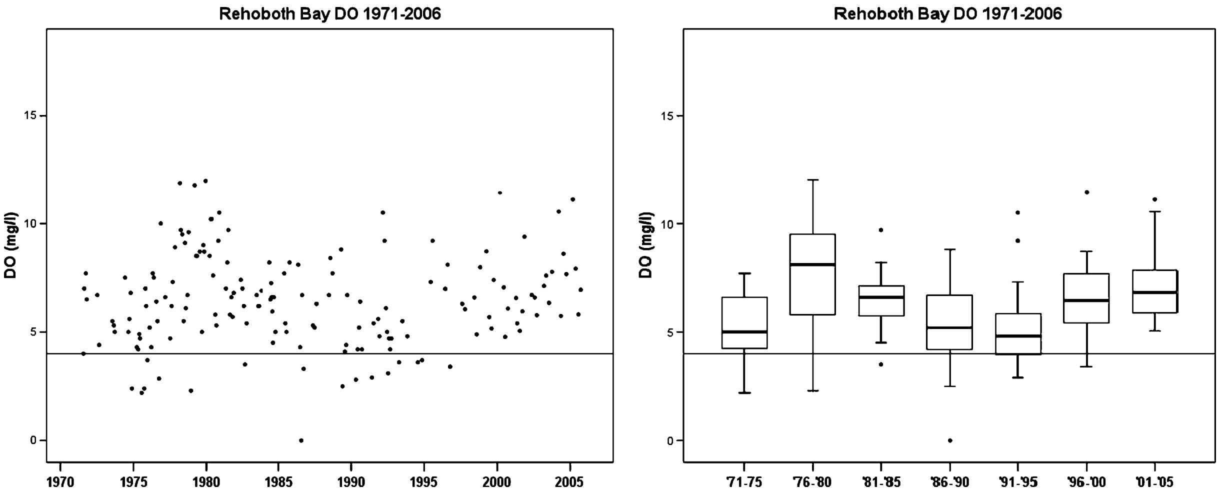


Fig. 12 DO scatter plot and box plot for the Rehoboth Bay

the median is just above the criteria. Poor water quality indicates that the 2001–2005 median is below the criteria and does not meet the water quality standards.

We compared water quality trends with watershed influences such as land use, stream flow, drainage basin, seasonality, and pollution point sources. Correlations between water quality and land use and stream flow were determined using simple linear regression and estimates of the coefficient of determination (r^2). Influences of drainage basin and seasonality on stream water quality were estimated by comparison of box plots. Point source pollutant load influences were evaluated based on the locations of wastewater treatment plants in each watershed.

6 Results

Water quality along Delaware streams improved or was constant at 69% of the stations over the short term since 1990 and 80% of the stations over the long term since 1970/1980 (Tables 6 and 7, Figs. 13 and 14). Since 1970/1980, water quality improved at 44%, remained constant at 36%, and degraded at 20% of the stations as improving stations outweighed degrading stations by a 2:1 margin. Since 1990, water quality improved at 27%, remained constant at 42%, and degraded at 31% of the stations as degrading stations slightly outweighed the improving stations.

6.1 Short-Term Trends Since 1990

Since 1990, DO improved at 53% of streams, was constant at 20%, and degraded at 27% of streams. TSS improved at 32% of streams, was constant at 43%, and degraded at 25% of streams. EB improved at 10% of streams, was constant at 70%, and degraded at 20% of streams. TKN improved at 7%, was constant at 41%, and degraded at 52% of streams. TP improved at 28%, was constant at 38%, and degraded at 34% of streams.

Table 4 Surface water quality criteria and MDL in Delaware

Parameter	Criteria (mg/L)	MDL (mg/L)	Method
DO	4.0 warm water, 5.0 cold water	0.02	EPA 360.1
TSS	25 nontrout, 40 trout (NJ default)	1	EPA 160.2
EB	100 colonies/100 ml	33 cfu/ 100 ml	SM 9230C
Total Nitrogen	1.0	0.05 (TKN)	EPA 351.2
TP	0.1	0.005	EPA 365.4

Table 5 Water quality ladder for Delaware streams

Water quality	Description	DO (mg/L)	TSS (mg/L)	EB (no./100 ml)	TKN (mg/L)	TP (mg/L)
Good	Comfortably exceeds water quality standards	>6.0	<25	<50	<0.5	<0.05
Fair	Just above water quality standards	4.0–6.0	25–40	50–100	0.5–1.0	0.05–0.10
Poor	Below stream water quality standards	<4.0	>40	>100	>1.0	>0.10

In the Piedmont basin in northern Delaware near Wilmington, water quality improved or remained constant at 21 of 30 stations over the last 15 years with nine stations recording degrading trends (Fig. 15). Four Piedmont stations recorded deteriorating trends for sediment and three stations had degrading TKN trends. In the Delaware Estuary basin, 47 of 69 stations recorded improving or constant trends. Much of the degrading trends were recorded for TKN. Streams recording two or more parameters with worsening trends include urban watersheds with more than 40% developed land such as Army Creek (DO, bacteria, TKN, and TP) and Dragon Run Creek (DO, TKN, and TP) and rural yet suburbanizing watersheds with over 30% cultivated land such as Leipsic River (TSS, TKN, and TP) and Mispillion (TSS and TKN). In the Inland Bays, water quality improved or remained constant at 16 of 20 or 80% of the stations. Degrading levels of TKN and TP were observed in the Rehoboth Bay. Little Assowoman Bay had degrading trends for DO and TKN. In the Chesapeake Bay basin, three stations had improving trends and 11 stations recorded degrading trends. Most of the degrading trends were observed for TKN and TP.

6.2 Long-Term Trends Since 1970/1980

Since 1970/1980, DO improved at 16% of streams, was constant at 16%, and degraded at 68% of streams. TSS improved at 100% of the 11 monitored streams. Bacteria improved at 19% of streams, remained constant at 69%, and degraded at 7% of streams. TKN improved at 88% and was constant at 12% of streams. TP improved at 33%, was constant at 52%, and degraded at 15% of streams.

In the Piedmont Basin since 1970/1980, 24 of 29 or 83% of the streams recorded improving or constant trends in water quality (Fig. 16). Five Piedmont streams recorded degrading water quality trends for DO, yet all six streams recorded improved TKN. In the Delaware Bay Basin, 42 of 66 or 64% of the stations recorded improving or constant water quality trends. Nine stations recorded degrading trends for DO over the last

Table 6 Water quality trends along Delaware streams

Water quality trend	DO	TSS	EB	TKN	TP	Total
Short term since 1990						
Improving	16	9	3	2	8	38 (27%)
Constant	6	12	21	12	11	62 (42%)
Degrading	8	7	6	15	10	46 (31%)
	30	28	30	29	29	146
Long term since 1970/1980						
Improving	4	11	5	21	9	50 (44%)
Constant	4	0	20	3	14	41 (36%)
Degrading	17	0	2	0	4	23 (20%)
	25	11	27	24	27	114

Table 7 Long-term and short-term water quality trends along Delaware streams

Stream	Long term water quality trends since 1970/1980					Short term water quality trends since 1990				
	DO (mg/L)	TSS (mg/L)	Bacteria (#/100ml)	TKN (mg/L)	Total P (mg/L)	DO (mg/L)	TSS (mg/L)	Bacteria (#/100ml)	TKN (mg/L)	Total P (mg/L)
Naamans Cr	8.7 ▼*	5 –	380 ●	0.44 ▲*	0.05 ●	8.7 ●	5 ●	380 ▼*	0.44 ●	0.05 ●
Shellpot Creek	7.5 ▼	6 ▲	245 ▲	0.70 ▲*	0.06 ●	7.5 ●	6 ▼*	245 ●	0.70 ▼	0.06 ▼*
Brandywine Cr	10.5 ▼*	6 ▲*	143 ●	0.64 ▲*	0.13 ▲*	10.5 ▲*	6 ▼	143 ●	0.64 ▼	0.13 ▲
White Clay Cr	9.9 ▼*	6 ▲*	232 ●	0.69 ▲*	0.11 ●	9.9 ▲	6 ▼	232 ●	0.69 ▼	0.11 ●
Red Clay Cr	10.1 ▼*	6 ▲*	195 ●	0.62 ▲*	0.16 ▲*	10.1 ▲	6 ▼*	195 ●	0.62 ●	0.16 ▲
Christina River	8.5 ▲*	17 ▲*	100 ●	0.69 ▲*	0.12 ▲*	8.5 ▲*	17 ▲	100 ●	0.69 ▲	0.12 ▲*
Army Creek	7.1 –	8 –	172 ▲	0.88 –	0.13 ●	7.1 ▼	8 ●	172 ▼*	0.88 ▼	0.13 ▼
Red Lion Creek	8.4 ▼*	6 ▲	370 ▲*	0.58 ▲*	0.06 ●	8.4 ▲	6 ●	370 ●	0.58 ▼*	0.06 ●
Dragon Run Cr	4.9 ▼	8 –	33 –	0.91 ●	0.11 ●	4.9 ▼	8 ▲	33 ●	0.91 ▼*	0.11 ▼
C&D Canal	8.4 ●	49 –	12 ●	0.81 ▲*	0.15 ●	8.4 ▲	49 ●	12 ▼*	0.81 ▼*	0.15 ▼*
Appoquinimink	6.3 ▼*	49 ▲	180 ●	1.10 ▲*	0.18 ▼*	6.3 ▼	49 ▲*	180 ●	1.10 ●	0.18 ●
Blackbird Creek	8.2 ▼	5 –	117 ▲	0.75 ▲*	0.09 ▲*	8.2 ▲*	5 ▲	117 ●	0.75 ●	0.09 ●
Smyrna River	6.4 ▼	86 –	290 ▼*	1.24 ▲*	0.21 ▼*	6.4 ▼	86 ●	290 ▲*	1.24 ●	0.21 ●
Leipsic River	4.1 ▼	66 –	80 ●	1.43 ●	0.32 ▼*	4.1 ▲*	66 ▼	80 ●	1.43 ▼*	0.32 ▼*
Little Creek	5.2 ▼*	78 –	200 ▼	2.19 ▲*	0.31 ●	5.2 ●	78 ▲	200 ▼	2.19 ●	0.31 ●
St. Jones River	5.0 ▼	67 ▲*	92 ●	1.48 ▲*	0.23 ●	5.0 ▼	67 ▲*	92 ●	1.48 ●	0.23 ▲*
Murderkill River	4.2 ▲*	48 –	90 ●	1.13 ▲*	0.32 ▲*	4.2 ▲*	48 –	90 ▲*	1.13 ●	0.32 ▲
Mispillion River	8.6 ▼	24 –	155 ●	1.15 ▲*	0.09 ▲	8.6 ●	24 ▼*	155 ●	1.15 ▼*	0.09 ▲
Cedar Creek	7.5 ●	25 –	87 ●	1.06 ●	0.07 ●	7.5 ▲*	25 ●	87 ▲	1.06 ▼*	0.07 ▲
Broadkill River	6.6 ▲	4 –	105 ●	1.70 ▲*	0.20 ▲	6.6 ▲*	4 ●	105 ▼	1.70 ▲	0.20 ▲
Rehoboth Bay	6.8 ▲	27 –	0 ●	0.84 ▲*	0.10 ▲*	6.8 ▲*	27 ●	0 ●	0.84 ▼	0.10 ▼
Indian River	7.1 –	25 –	0 ●	0.59 –	0.06 –	7.1 ▲*	25 ▲	0 ●	0.59 ●	0.06 ●
Indian R. Bay	7.3 ●	26 ▲	0 ●	0.64 ▲*	0.07 ▲*	7.3 ▲*	26 ▲	0 ●	0.64 ●	0.07 ●
L. Assawoman	5.7 –	8 –	100 –	1.45 –	0.09 –	5.7 ▼	8 ●	100 ●	1.45 ▼*	0.09 ●
Chester River	6.2 –	6 –	122 ●	0.88 –	0.24 ●	6.2 ●	6 ●	122 ●	0.88 ▼	0.24 ▼
Choptank River	6.8 ▼*	4 ▲	65 ●	0.67 ▲*	0.09 ●	6.8 ▼	4 ●	65 ●	0.67 ▼*	0.09 ▼*
Marshyhope Cr	8.7 ▼	– –	53 –	– –	– –	8.7 ▲	– –	53 ●	– –	– –
Broad Creek	9.1 ●	4 –	33 ●	0.81 ▲*	0.06 ●	9.1 ▲	4 ▼*	33 ●	0.81 ▼*	0.06 ▼*
Nanticoke R.	6.6 ▼	18 ▲	29 ●	0.78 ▲	0.09 ●	6.6 ▼	18 ▲	29 ●	0.78 ●	0.09 ●
Pocomoke	6.7 –	9 –	147 ▲	0.80 –	0.12 ▼*	6.7 ●	9 ●	147 ▼	0.80 ●	0.12 ▼*
▲ Improving	4/25 (16%)	11/11(100%)	5/27 (19%)	21/24 (88%)	9/27 (33%)	16/30 (53%)	9/28 (32%)	3/30 (10%)	2/29 (7%)	8/29 (28%)
● Constant	4/25 (16%)	0/11 (0%)	20/27 (74%)	3/24 (12%)	14/27 (52%)	6/30 (20%)	12/28 (43%)	21/30 (70%)	12/29 (41%)	11/29 (38%)
▼ Degrading	17/25 (68%)	0/11 (0%)	2/27 (7%)	0/24 (0%)	4/27 (15%)	8/30 (27%)	7/28 (25%)	6/30 (20%)	15/29 (52%)	10/29 (34%)

Note: (*) denotes a statistically significant Seasonal Kendall trend at the p < 0.10 level. 2001 – 2005 median water quality: 8.1 green = good blue = fair red = poor

2001–2005 median water quality=8.1

green good, *blue* fair, *red* poor

*$p<0.10$, statistically significant seasonal Kendall trend

30 years particularly in the urban watersheds of Red Lion Creek and Dragon Run and in the agricultural Coastal Plain watersheds from the Appoquinimink in southern New Castle County down to the St. Jones River in Kent County. In the Inland Bays, all stations recorded improved or constant water quality since 1970/1980. In the Chesapeake Bay basin since 1970/1980, only four of 19 stations (18%) recorded degrading water quality along the Choptank (DO), Marshyhope, (DO), Nanticoke (DO), and Pocomoke (bacteria).

6.3 Median Water Quality, 2001–2005

During 2001–2005, median levels were good or fair at 100% of the stations for DO, 78% for sediment, 50% for bacteria, 59% for nitrogen, and 56% for phosphorus.

DO levels as recorded by the 5-year median from 2001 to 2005 are good and exceed 6 mg/L in 24 of 30 (80%) of the streams and levels are fair and exceed the Delaware fresh water standard of 4 mg/L in six (20%) of the streams (Fig. 17). None of the streams recorded poor median DO levels below the 4-mg/L standard. A handful of streams have recorded individual DO samples below the 4-mg/L standard between 2001 and 2005 notably along the Dragon Run, Appoquinimink, Leipsic River, Little Creek, St. Jones, Murderkill, and Mispillion.

Median TSS levels from 2001 to 2005 are good (<40 mg/L) along most streams except along Coastal Plain streams in the Delaware Estuary basin where levels are poor and exceed 40 mg/L (Fig. 18). Eight streams from the C & D Canal south to the Murderkill drain cultivated land exceeding 40% of the watershed with poor median sediment levels between 45 and 90 mg/L, appreciably higher than other Delaware streams.

Median bacteria levels from 2001 to 2005 are poor and exceed the Delaware standard of 100 colonies per

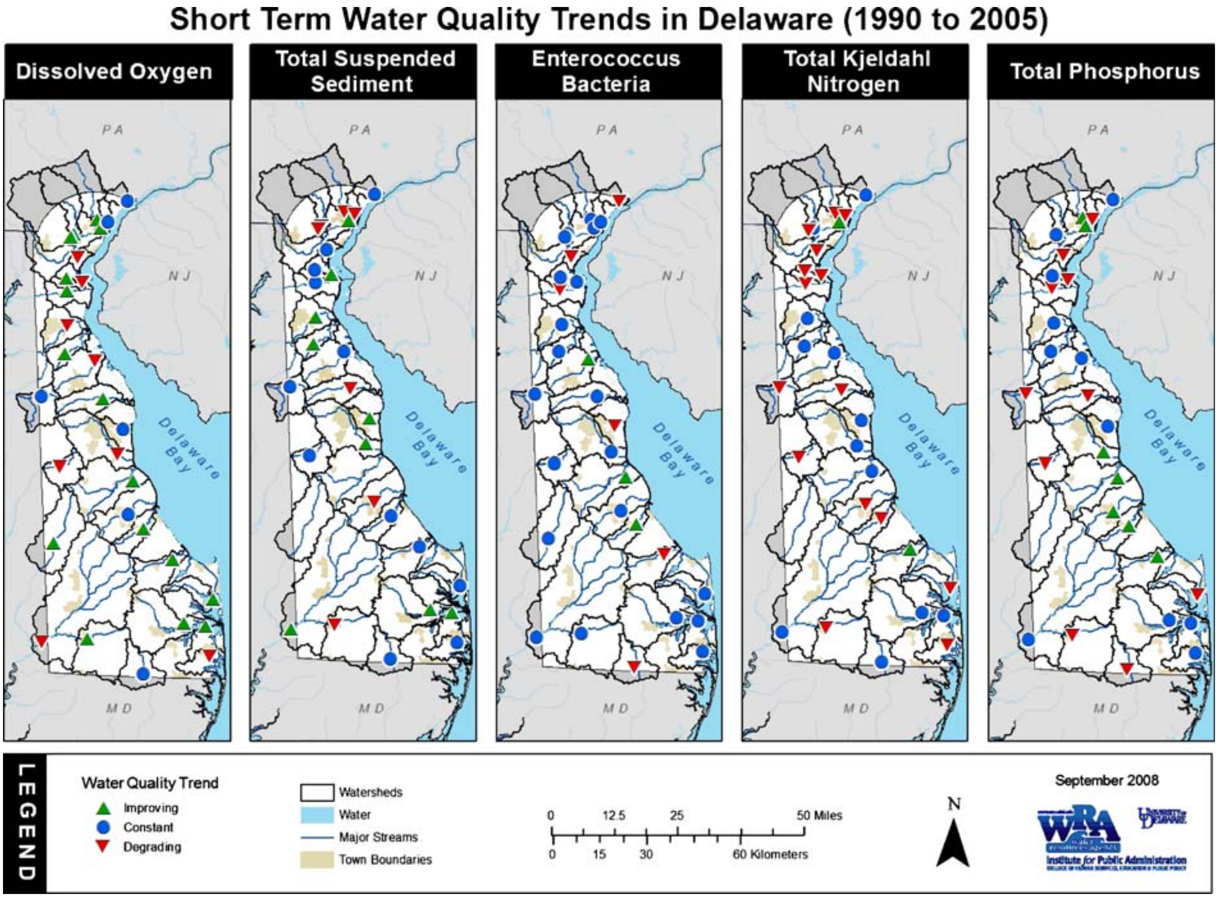


Fig. 13 Short-term water quality trends along Delaware streams from 1990 to 2005

100 ml in 50% or 15 of 30 streams (Fig. 19). Bacteria levels are good in the Inland Bays and along several Chesapeake Bay tributaries such as the Broad Creek and Nanticoke where bacteria levels are less than 35 colonies per 100 ml. Median bacteria levels are particularly poor ranging from 140 to 380 colonies per 100 ml in five of the six Piedmont streams in urbanized northern Delaware.

Median TKN levels are good or fair and less than 1.0 mg/L in 59% of the Delaware streams and poor in 41% of the streams (Fig. 20). Delaware Estuary watersheds in the agricultural yet suburbanizing Coastal Plain from the Appoquinimink River south to the Broadkill (except for the forested and wetland-covered Blackbird watershed) have poor median TKN levels exceeding 1 mg/L.

Median TP levels are poor and exceed 0.1 mg/L in over half of the watersheds in Delaware (Fig. 21). TP levels are poor and exceed 0.1 mg/L in the urbanized Piedmont (except for the Naamans and Shellpot), agricultural Delaware Estuary basin, and along the Chester and Pocomoke Rivers in the Chesapeake Bay basin. In the Inland Bays and Chesapeake basins, TP is mostly fair ranging from 0.05 to 0.1 mg/L. None of the Delaware streams have good median TP levels (less than 0.5 mg/L).

7 Discussion

Water quality as measured by DO, TSS, EB, TKN, and TP along Delaware streams improved or remained constant at 69% of the monitoring stations over the short term between 1990 and 2005 and at 80% of the stations over the long term from 1970/1980 to 2005. The following sections

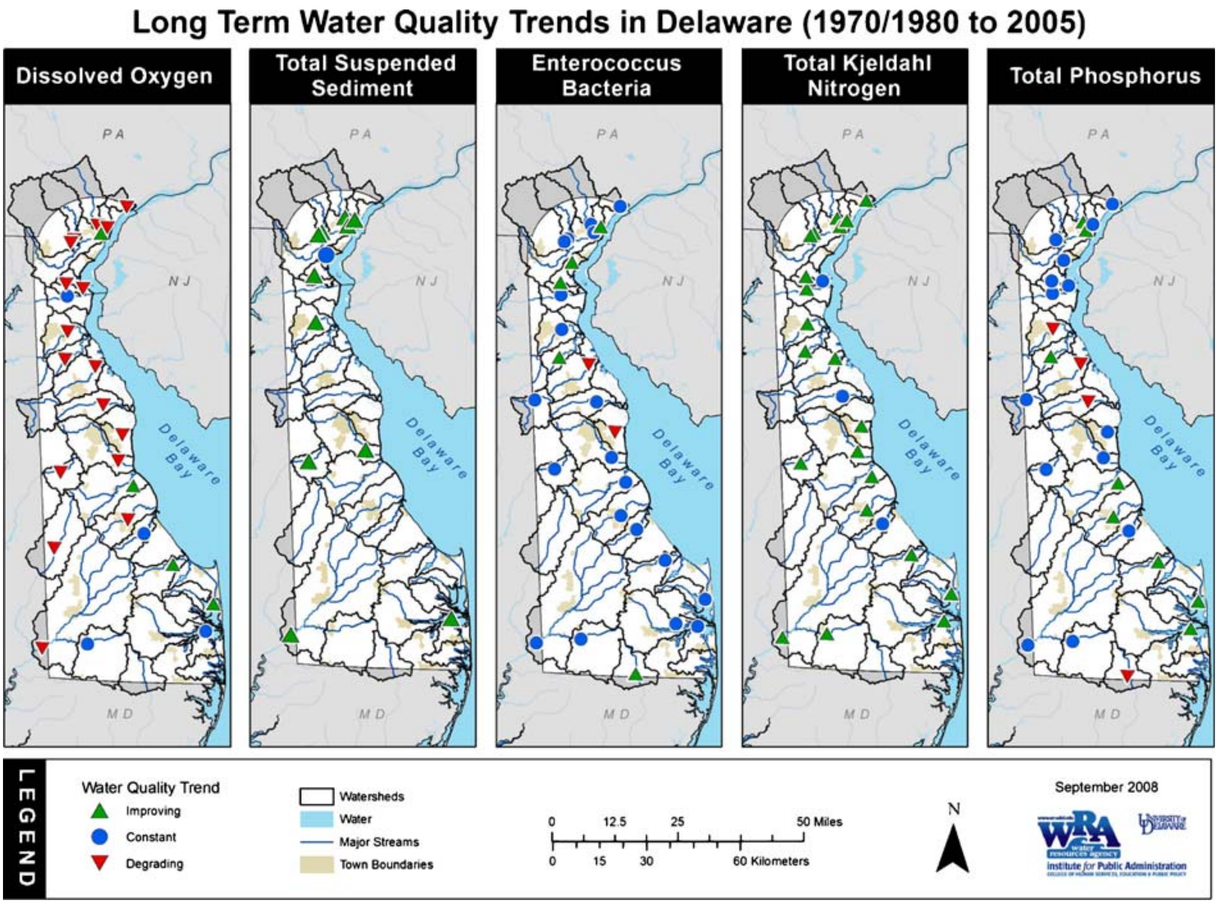


Fig. 14 Long-term water quality trends along Delaware streams from 1970/1980 to 2005

discuss the influences of watershed factors such as stream flow, seasonality, drainage basin, land use, and point source pollutants on changing water quality.

7.1 Precipitation and Stream Flow

Stream flow can influence stream water quality. Bacteria and TSS may increase in concentration

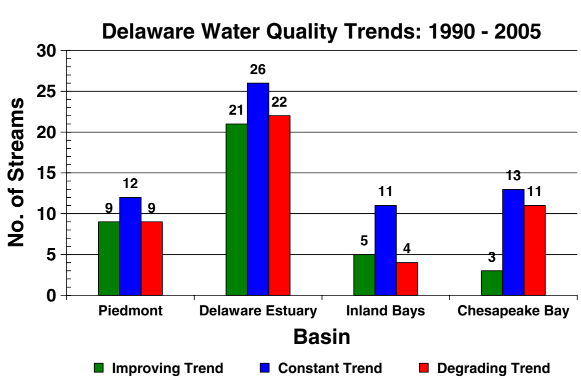


Fig. 15 Short-term water quality trends along Delaware streams from 1990 to 2005

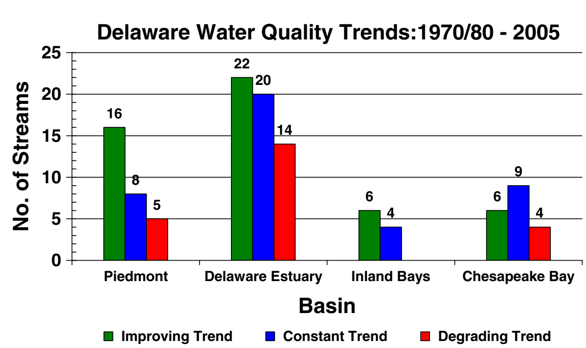


Fig. 16 Long-term water quality trends along Delaware streams from 1970/1980 to 2005

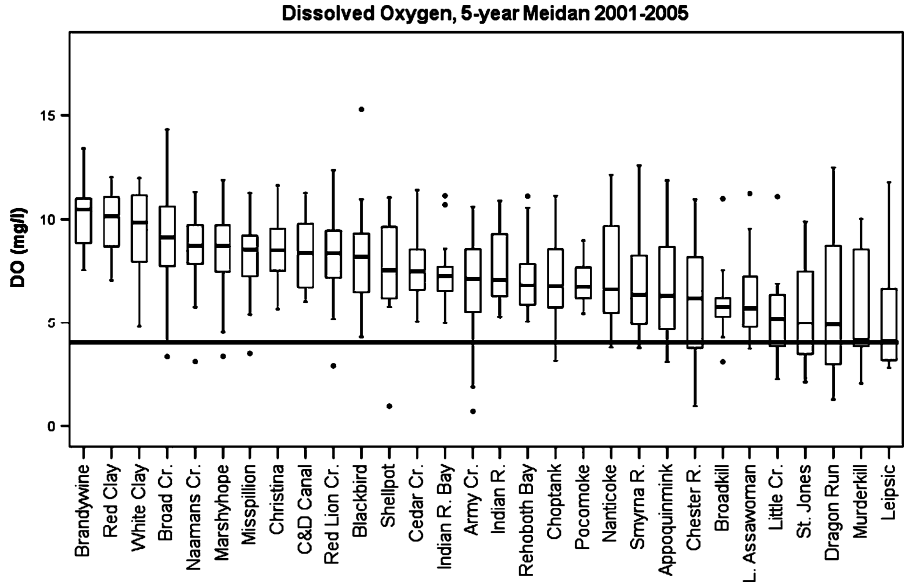


Fig. 17 DO levels along Delaware streams (2001–2005). The Delaware DO standard is delineated at 4 mg/L

with rising stream flow due to build up and wash off of pollutants from watersheds during storms. Phosphorus concentrations may increase at first during storms and then decrease with increased stream flow due to dilution effects. Seven of the 30 monitored streams have USGS stream gage stations with long-term periods of record; therefore, stream flow as an influence on water quality change was evaluated for just these stations.

Simple linear regression analyses indicate little correlation between stream flow and water quality. The coefficient of determination (r^2) for the seven streams measured between 0.005 and 0.0013, evidence of poor correlation between stream flow and water quality (Table 8). An r^2 greater than 0.30 would be considered evidence of moderate correlation. Figure 22 illustrates a linear regression plot of TKN versus stream flow along the Shellpot Creek with r^2=0.13, the highest r^2 of the studied streams, but indication of little correlation.

Annual precipitation and mean annual stream flow have decreased slightly over the water quality

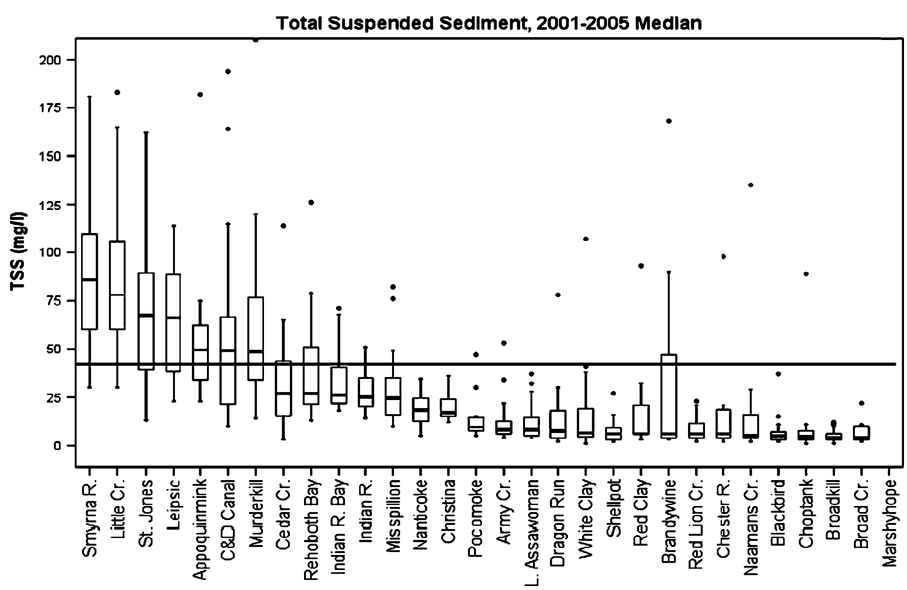


Fig. 18 TSS levels along Delaware streams (2001–2005). The default New Jersey nontrout TSS standard is delineated at 40 mg/L

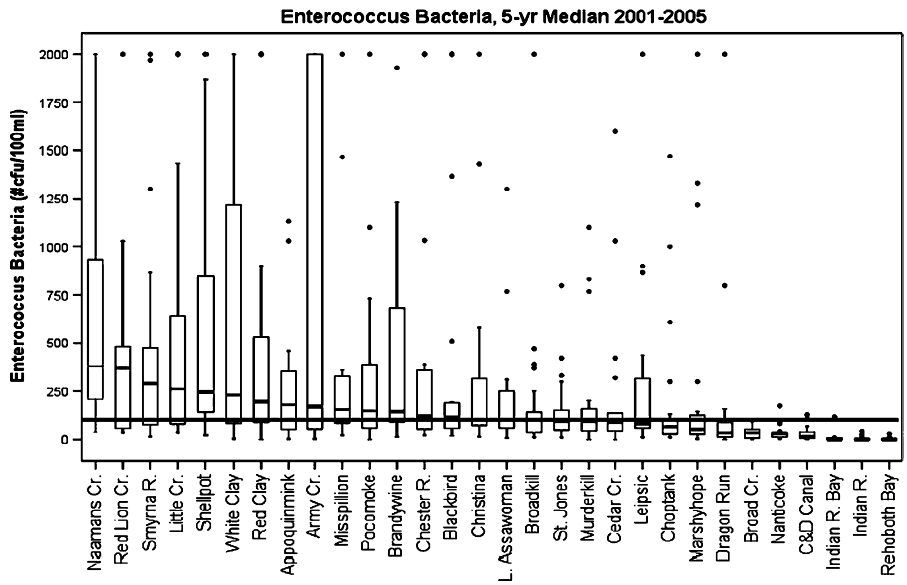


Fig. 19 EB levels along Delaware streams (2001–2005). The Delaware standard is delineated as 100 colonies per 100 ml

sampling period from 1970 through 2005 (Fig. 23). While annual precipitation at the Wilmington Airport in Delaware ranged from 27 to 58 in., the 5-year moving average decreased from 43 to 45 in. during the late 1970s and early 1980s to 40 in. by 2001 through 2005. Congruently, mean annual stream flow along the Brandywine Creek at Wilmington as measured by the 5-year moving average declined from near 25 in. during the late 1970s to around 20 in. by 2001 through 2005. Significant droughts occurred in Delaware during 1995, 1999, and 2002 which may have reduced loads of the nonpoint source pollutants such as sediment, bacteria, and nitrogen in those years. However, during the same period, significant floods capable of generating high pollutant loads occurred during Hurricane Floyd in September 1999 and Tropical Storms Henri in September 2003 and Jeanne in September 2004. Water quality change during the sampling period may have been impacted by the slight decrease in annual precipitation over the three and a half decades but any change was probably offset by the swings

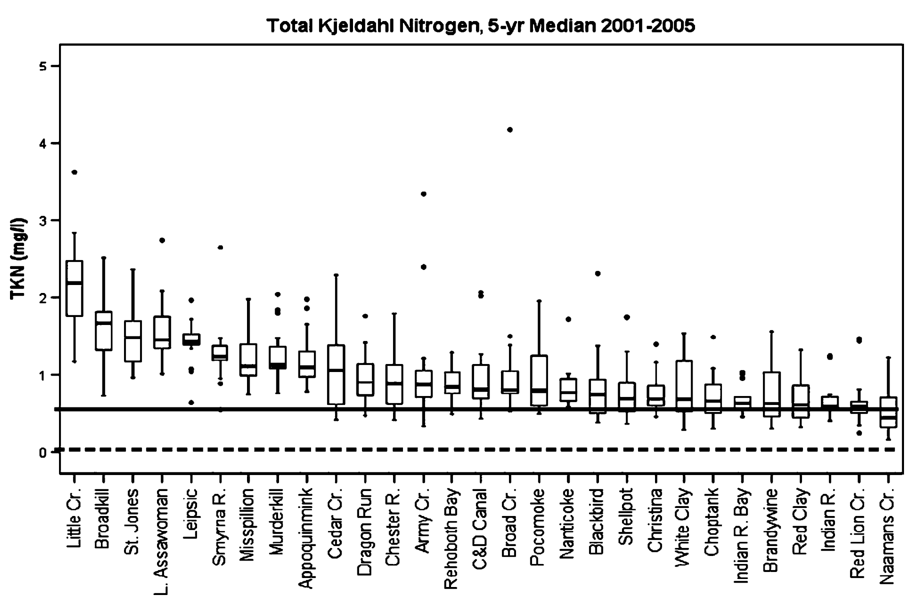


Fig. 20 TKN levels along Delaware streams (2001–2005). The Delaware total nitrogen criteria is 1 mg/L. TKN levels are usually recorded at half of TN levels; therefore, 0.5 mg/L is reported as criteria for TKN

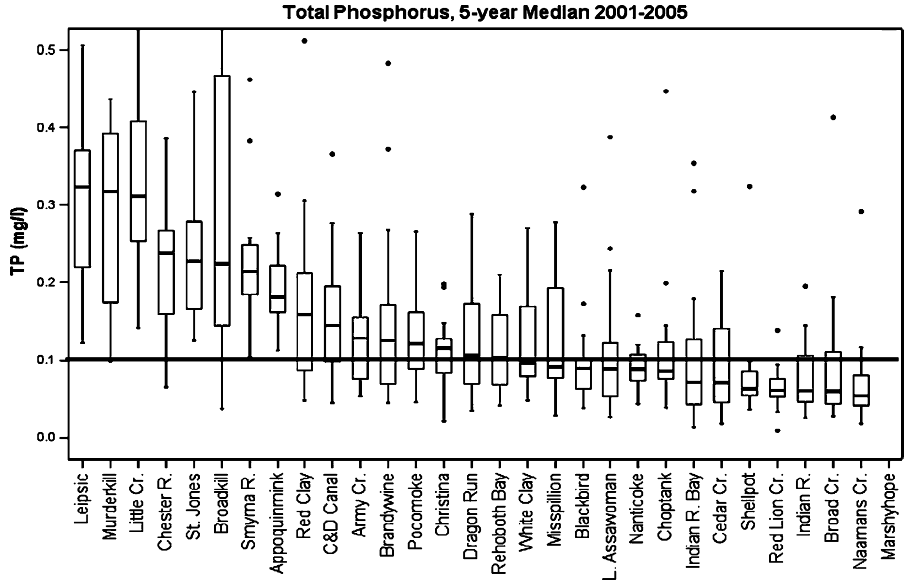


Fig. 21 TP levels along Delaware streams (2001–2005). The Delaware criteria is delineated as 0.10 mg/L

between drought and flood during the last 10 years of the record.

7.2 Seasonality

Many surface water quality parameters show strong seasonal patterns. For instance, higher DO concentrations are observed in cooler water during the winter than warmer 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 box plots (Fig. 24). DO 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 in Delaware streams exceed the 4-mg/L water quality standard in every month of the year. TSS levels began rising in April, peak from July through August, and start declining by October in synchronicity with the construction season and agricultural plowing cycle. Bacteria levels peak with increased biological activity during the warm months of July through September. Nutrients usually rise during spring and early summer due to fertilizer runoff from farms and lawns. TKN levels along Delaware streams did not

Table 8 Coefficients of determination (r^2) for stream flow versus water quality linear regression plots along Delaware streams

Stream	TKN (r^2)	TP (r^2)
Shellpot Creek	0.1299	0.0020
Brandywine Creek	0.0026	0.0207
Red Clay Creek	0.0086	0.0248
White Clay Creek	0.0044	0.0006
St. Jones River	0.0039	0.0046
Marshyhope Creek	0.0642	0.1037
Pocomoke Creek	0.0070	0.0314

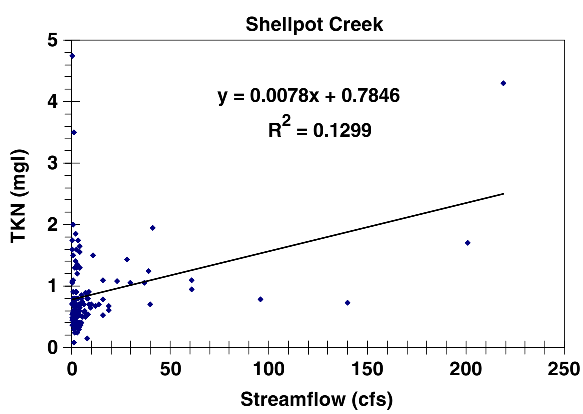


Fig. 22 Linear regression plot indicating poor correlation of stream flow versus TKN along Shellpot Creek, Delaware

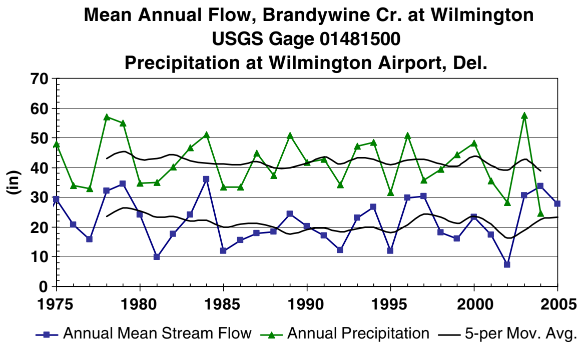


Fig. 23 Mean annual flow along the Brandywine Creek at Wilmington and annual precipitation at Wilmington Airport, Delaware

vary over the course of the year. Nitrogen levels along Delaware streams did not rise during spring and summer. Phosphorus levels rose from June through September and then declined during the fall.

7.3 Drainage Basin

Stream water quality in Delaware varies depending on the drainage basin (Fig. 25). Median DO levels are higher in the urbanized hilly, rocky Piedmont basin compared to lower DO levels in the agricultural, flat sandy Coastal Plain basins draining to the Delaware Estuary, Inland Bays, and Chesapeake Bay. The Delaware Estuary basin recorded the highest median levels of TSS, TKN, and TP probably due to runoff from high percentages of agricultural land and rural septic systems in the watersheds. Piedmont basin streams had the highest bacteria levels most likely due to runoff from development and runoff from horse, cattle, and poultry farms upstream in the Delaware and Pennsylvania portions of the basin.

7.4 Land Use

Stream water quality varies depending on watershed land use. Land use varies from more than 50% developed (urban/suburban) in four watersheds in the urbanized Piedmont basin near Wilmington to less than 20% developed along the rural coastal streams in the Delaware Bay, Inland Bays, and Chesapeake Bay basins (Fig. 26). Delaware streams are impacted by human activity as the sum of developed plus cultivated land exceeds 45% in each of the 30 monitored watersheds (Fig. 27). Watersheds such as the Chester, Pocomoke, Leipsic, Blackbird, Rehoboth Bay, and Indian River Bay retain nearly 50% natural cover as forest plus wetlands and water. Impervious cover ranges from 14% to 40% in the Piedmont basin watersheds in urban northern Delaware to less than 10% in lightly developed Delaware Bay, Chesapeake Bay, and Inland Bay watersheds such as the Broadkill, Pocomoke, Marshyhope, and Nanticoke in rural southern Delaware.

Streams recording degrading water quality since 1990 for at least three of five parameters include urbanizing watersheds such as the Shellpot Creek, Army Creek, and Dragon Run with developed land exceeding 60% of the watershed and rural C & D Canal, Liepsic, Choptank, and Broad Creek watersheds where agricultural land covers over 30% of the watershed.

Streams with the best water quality tend to have the highest watershed forest cover. The Brandywine Creek has the highest median DO of 10.5 mg/L and a watershed covered with 33% forest. Broad Creek and Broadkill have the lowest sediment levels at 4 mg/L and watersheds with 22% forested land. The Rehoboth Bay and Indian River Bay have the lowest median bacteria counts close to zero with watershed forest land at 23% and 29%, respectively.

The coefficient of determination (r^2=0.42) from linear regression analyses indicates that good water quality correlates with large areas of forest in Delaware watersheds (Fig. 28). An r^2>0.3 would be considered moderate correlation. Visual examination of box plots for streams ranked in order of increasing percentage of forest also indicates that DO increases with more forest cover (Fig. 29). Sediment, nitrogen, and phosphorus levels decline (improve) with increasing forest cover in Delaware watersheds although the r^2 values are less significant, ranging from 0.12 to 0.23. The linear regression plots indicate that good water quality appears when the percentage of forest area exceeds 20% to 30% in Delaware watersheds. Linear regression plots of developed, cultivated, and wetland area versus median water quality for DO, TSS, bacteria, TKN, and TP indicate little correlation as r^2 values are all less than 0.1.

7.5 Point Source Pollutants

Since 1990, Delaware DNREC has addressed point source pollutants in Delaware watersheds by issuing

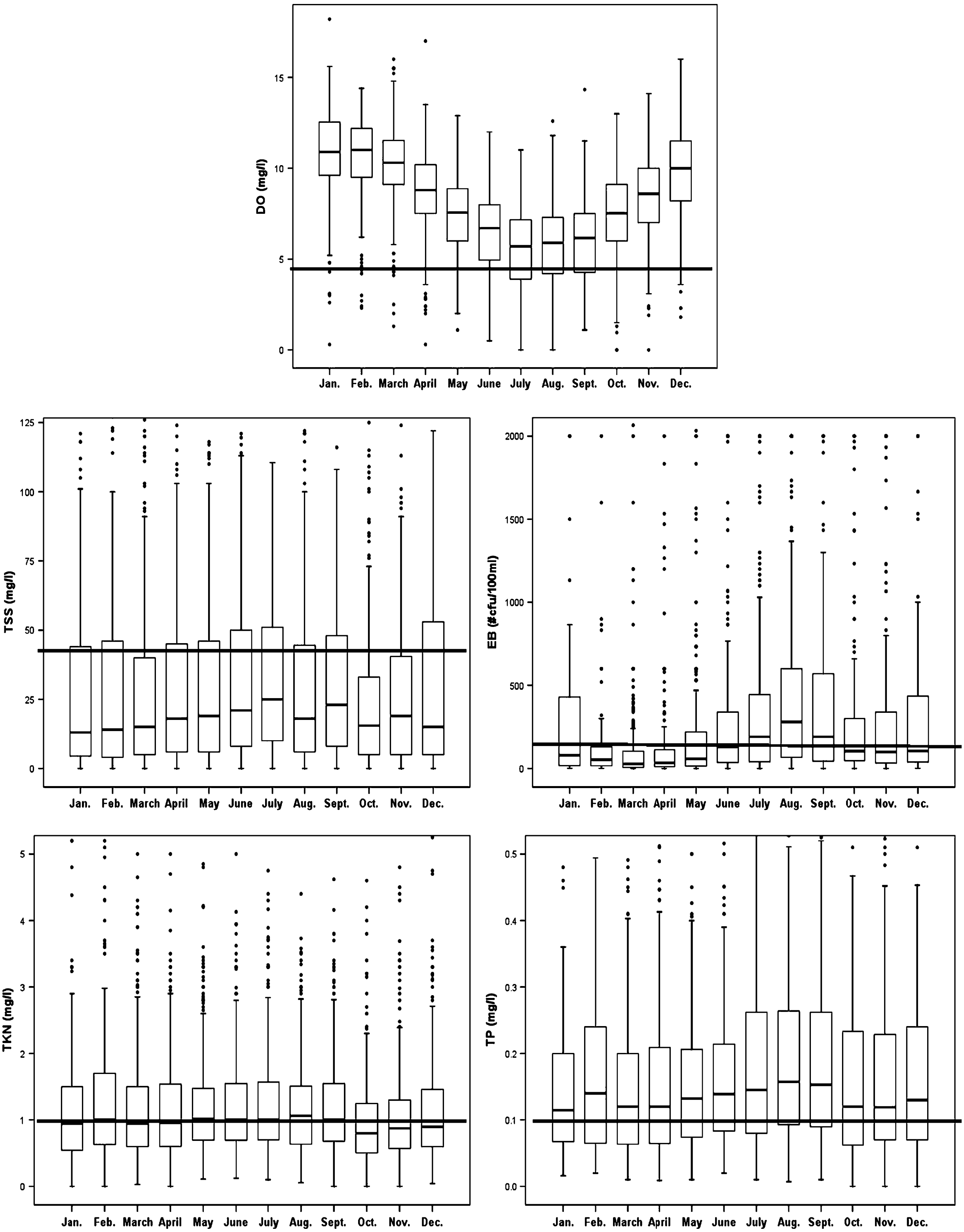
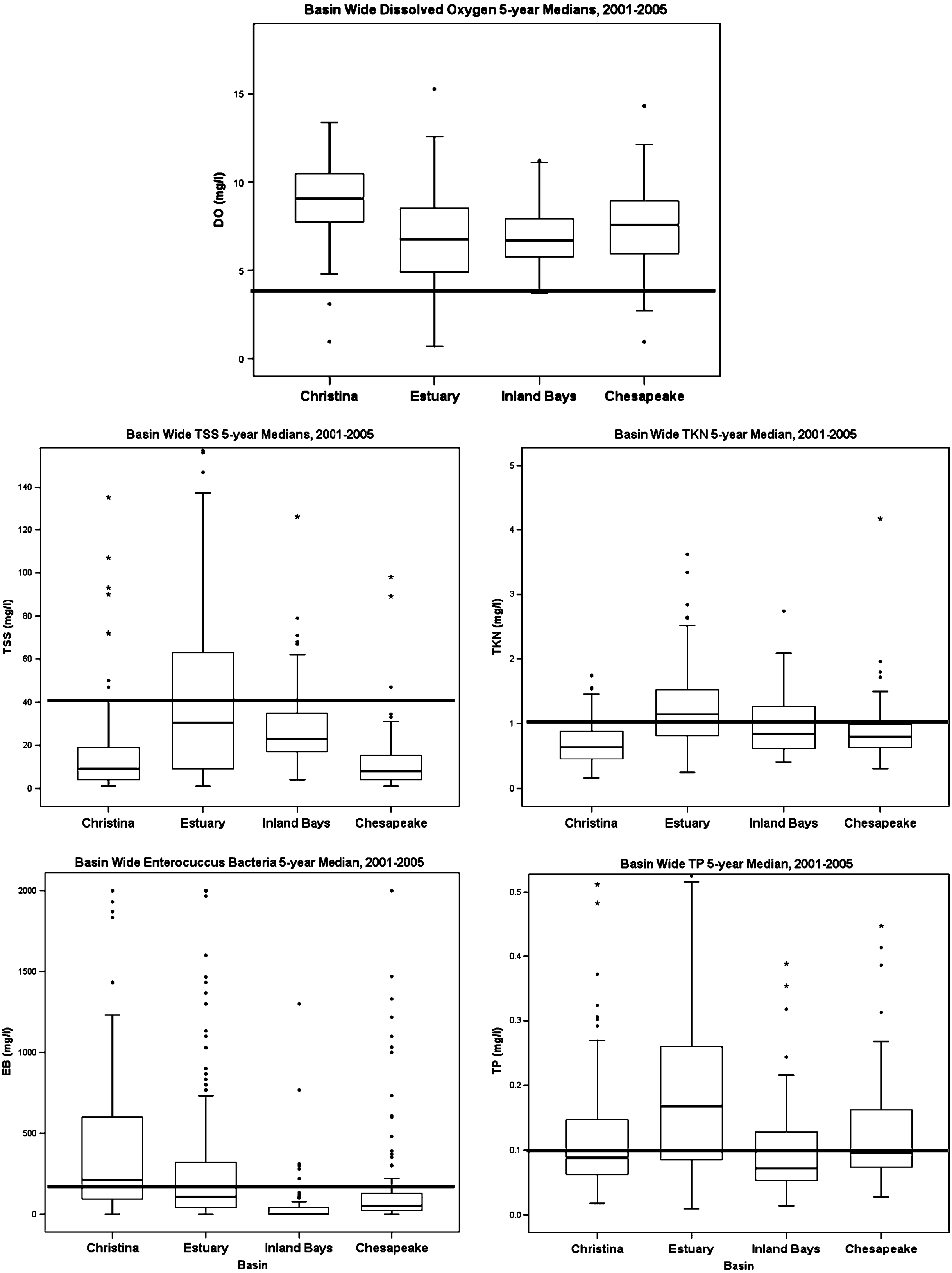


Fig. 24 Seasonal comparison of water quality box plots (2001–2005) along Delaware streams


Basin Wide Dissolved Oxygen 5-year Medians, 2001-2005
DO (mg/l)
0
5
10
15
Christina
Estuary
Inland Bays
Chesapeake
Basin Wide TSS 5-year Medians, 2001-2005
TSS (mg/l)
0
20
40
60
80
100
120
140
Christina
Estuary
Inland Bays
Chesapeake
Basin Wide TKN 5-year Median, 2001-2005
TKN (mg/l)
0
1
2
3
4
5
Christina
Estuary
Inland Bays
Chesapeake
Basin Wide Enterocuccus Bacteria 5-year Median, 2001-2005
EB (mg/l)
0
500
1000
1500
2000
Christina
Estuary
Inland Bays
Chesapeake
Basin
Basin Wide TP 5-year Median, 2001-2005
TP (mg/l)
0.0
0.1
0.2
0.3
0.4
0.5
Christina
Estuary
Inland Bays
Chesapeake
Basin

◀ **Fig. 25** Comparison of water quality box plots (2001–2005) by drainage basin along Delaware streams

National Pollutant Discharge Elimination System (NPDES) permits to 21 sewage treatment plants (Table 9). Since 1990, water quality trends have mostly improved in the Murderkill and Nanticoke Rivers due to construction of new sewage treatment plants owned by Kent County and the City of Seaford, Delaware. The Delaware DNREC established a policy to prohibit new water treatment plants that discharge to streams and is systematically eliminating surface water discharges through the TMDL process. The Inland Bays TMDL requires the elimination of Rehoboth and Indian River Bay wastewater treatment plants, actions that will spur even more water quality recovery in the bays. The ban on phosphate detergent during the 1980s and phosphorus removal at wastewater plants resulted in significant TP reductions in Delaware streams. In 1998, Delaware began implementing TMDL per Section 303(d) of the CWA and by the end of 2006 set TMDL standards for 28 watersheds. The TMDL are being implemented by Delaware Tributary Action Teams who have developed voluntary and regulatory Pollution Control Strategies such as agricultural nutrient management, soil erosion and sediment control, reforestation, septic system relief, and stream restoration programs. Regulatory TMDL measures for the Delaware Inland Bays were promulgated in October 2008. These watershed restoration strategies have resulted in improved or preserved water quality along 80% of stations over the last decade. However, greater attention is needed to reverse degrading nitrogen trends observed recently along half of Delaware streams.

8 Conclusions

Water quality improved or was constant along 30 Delaware streams at 69% of the stations since 1990 and 80% of the stations since 1970/1980. DO improved or was constant at 73% of the streams since 1990 and 32% of the streams since 1970/1980. TSS improved or was constant at 75% of the streams since 1990 and 100% of the streams since 1970/1980. EB improved or was constant at 80% of the streams since 1990 and 93% of the streams since 1970/1980. TKN improved or was constant at 48% of the streams since 1990 and 100% of the streams since 1970/1980. TP improved or was constant at 66% of the streams since 1990 and 85% of the streams since 1970/1980.

During 2001–2005, median water quality levels were good or fair at 100% of the stations for DO, 78% for TSS, 50% for bacteria, 59% for TKN, and 56% of the stations for TP. DO, nitrogen, sediment, and phosphorus levels improve with increased forest cover in Delaware watersheds. Good water quality correlates with high amounts of forest area (>20% to 30%) in Delaware watersheds

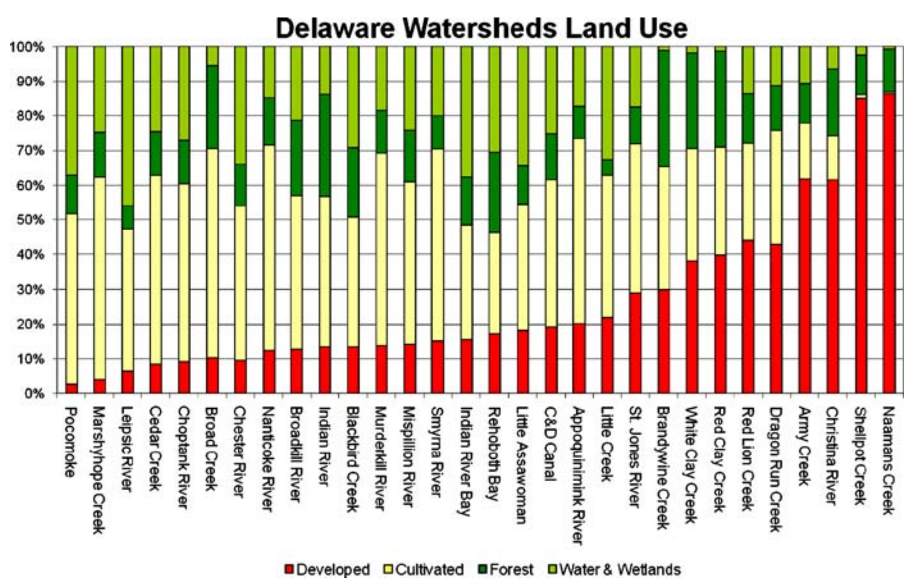


Fig. 26 Land use area in Delaware watersheds

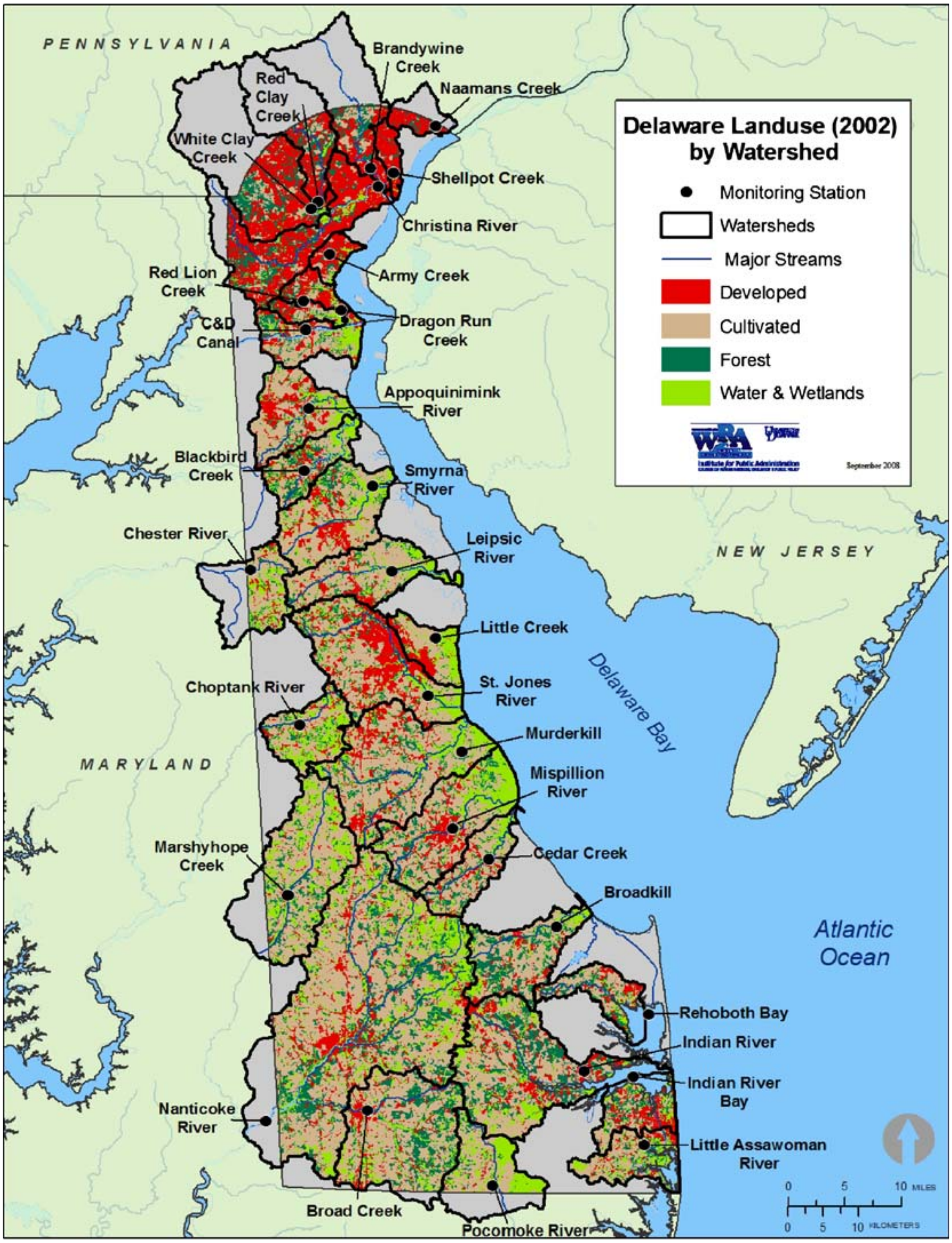


Fig. 27 Land use in Delaware watersheds

Approximately three quarters of monitored streams in Delaware recorded improved or constant water quality trends over the last three decades during an era that coincided with federal and state water quality regulations that required NPDES wastewater discharge permits and TMDL along Delaware watersheds. Since the 1970s, when governments passed laws creating the USEPA, Delaware DNREC, and the Federal CWA, improving water quality stations (50) outnumbered degrading stations (23) along Delaware

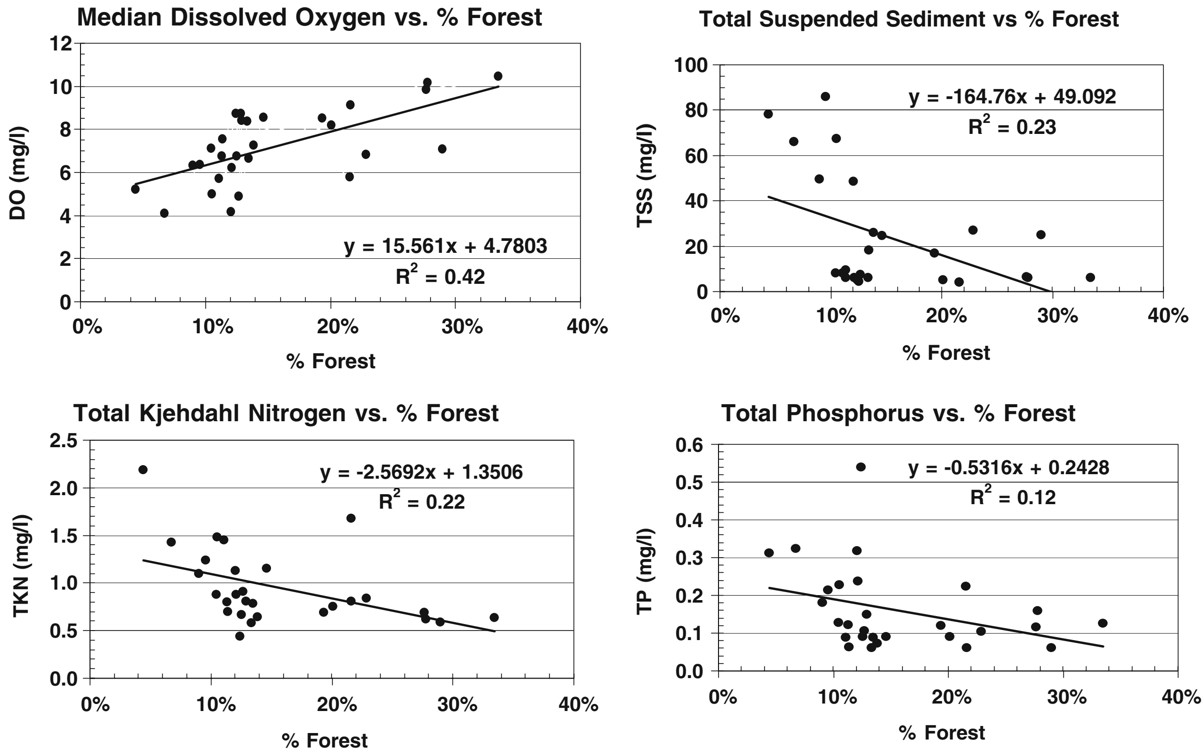


Fig. 28 Linear regression plots of water quality versus forest cover in Delaware watersheds

Fig. 29 Median (2001–2005) DO along Delaware streams ranked in order of increased watershed forest cover

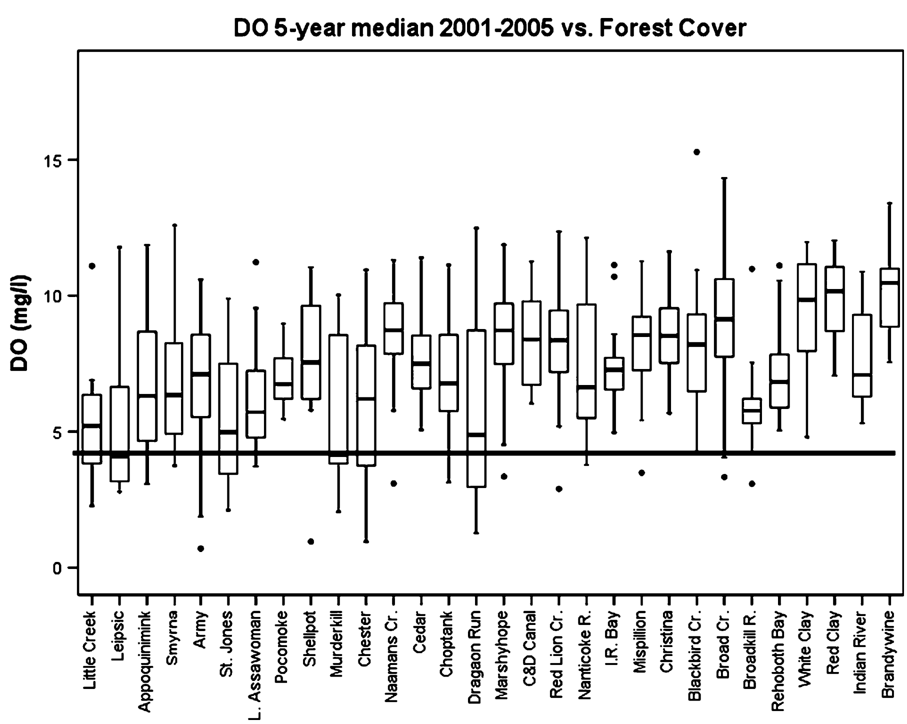


Table 9 NPDES sewage treatment plants and TMDL in Delaware watersheds

Watershed	NPDES sewage treatment plant	TMDL
Piedmont basin		
Naamans Creek		2005
Shellpot Creek		2005
Brandywine Creek	Greenville Country Club, Winterthur	2001
White Clay Creek		2001
Red Clay Creek		2001
Christina River		2001
Delaware Estuary basin		
Army Creek		2006
Red Lion Creek		2006
Dragon Run Creek		2006
C & D Canal	Lums Pond State Park	
Appoquinimink River	Middletown-Odessa	2003
Blackbird Creek		2006
Smyrna River	Hanover Foods	2006
Leipsic River		2006
Little Creek		
St. Jones River		2006
Murderkill	Harrington, Kent County, Southwood, Canterbury Crossing	2006
Mispillion River		2006
Cedar Creek		2006
Broadkill River	Milton STP	2006
Inland Bays Basin		
Rehoboth Bay	Lewes STP, Colonial Estates MHP	2005
Indian River		2005
Indian River Bay	Bayshore, Georgetown, Millsboro	2005
Little Assawoman	Selbyville, South Coastal Regional	2005
Chesapeake Bay basin		
Chester River		2005
Choptank River		2005
Marshyhope Creek		2005
Broad Creek	Laurel STP	1998
Nanticoke River	Mobile Gardens Trailer Park, Bridgeville, Seaford	1998
Pocomoke Creek		2005

streams by a 2:1 margin. The Delaware DNREC has enforced a policy to regulate and reduce surface water dischargers and, presently, only 21 municipal wastewater treatment plants have NPDES permits to discharge to Delaware streams. Since 1998, Delaware has issued TMDL for 28 watersheds with the objectives to meet CWA stream water quality standards. Each year, the Delaware DNREC issues over $1 million in Section 319 of the Federal CWA grant funds for nonpoint source pollutant restoration projects

Since 1990, the number of stations with degrading water quality (46) exceeded the stations with improving quality (38), indicating a reversal from the early gains achieved after the 1970s CWA amendments. The number of degrading water quality stations have increased over the last 15 years primarily due to increased nitrogen levels along half of the monitored Delaware streams. Increased nitrogen loads to Delaware streams may be flowing from agricultural sources and/or urban/suburban sources. However, the Delaware Census of Agriculture indicates that farmland in Delaware has decreased by 15% over roughly the same period from 2,385 km^2 in 2002 to 2,063 km^2 by 2007. The Delaware Nutrient Management Commission was formed in 1999 to control nitrogen and phosphorus loads and, in 2007 alone, installed nutrient management plans on 606 km^2 of farmland. Increased nitrogen may be flowing from urban/suburban sources as the U.S. Census indicates that the population of Delaware has increased by 27% from 658,274 in 1990 to 838,519 by 2005. Greater emphasis is needed to curb recently resurging nitrogen increases along Delaware streams through denitrification techniques such as planting forests (Brush 2009), urban stormwater retrofitting, and agricultural nutrient management efforts.

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