# Daily Resolution 2001-2017 Time Series of Total Nitrogen Load to Narragansett Bay (RI/MA USA) from Bay-Wide Treatment Facility and Watershed Sources

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**ABSTRACT**

Time series for the load of total nitrogen (TN) to Narragansett Bay, from 18 wastewater treatment facility (WWTF) and land-based runoff sources bay-wide, have been estimated at daily resolution for 2001-2017. The motivation for daily resolution is to enable including nitrogen load as a candidate influence (with others such as river flow, temperature, tidal conditions, etc; e.g., Codiga et al 2009) in statistical analyses investigating drivers of hypoxic events at the short timescales of days to weeks on which events are known to vary. Time series were estimated back to 2001 because such analyses rely on Narragansett Bay Fixed Site Monitoring Network time series oxygen observations, which began that year. The WWTF and riverine sources treated are generally the same as those in the annual-budget analyses in the State of Narragansett Bay and Its Watershed (NBEP 2017). The 18 sources include 11 WWTFs (nine in Rhode Island and two in Massachusetts) discharging directly to the bay; 6 rivers where they enter the bay, which include load from WWTFs located upstream on them; and runoff direct to the bay from ungauged riparian areas. The observations were obtained from the Rhode Island Department of Environmental Management, the Narragansett Bay Commission, the Fall River treatment facility, and the US Geological Survey. Load was computed as the product of concentration and flow. For concentration, linear interpolation was necessary as the nominal frequency of observations ranged from weekly or biweekly, for most of the largest sources, to monthly. However, temporal variations in load are dominated by flow variability, which spans multiple orders of magnitude while concentration variations are less pronounced, and daily flow measurements were available for many of the largest sources. During periods when TN was not directly measured, it was computed as the sum of other measured concentrations (e.g., total Kjeldahl nitrogen plus nitrate plus nitrite), or using a correlation between TN and other constituents during periods when both were measured, or as the long-term mean seasonal cycle of TN computed from sampled years. As a check on the reasonableness of the results, the annual-mean loads from the new time series, computed by averaging the daily values, were compared to results of earlier budgets reported in NBEP (2017) for three periods: 2000-2004 (Nixon et al 2008), 2007-2010 (Krumholz 2012), and 2013-2015 (NBEP 2017). The differences are notable, as expected given the divergent methods, but the agreement is acceptable for the intended use of the new daily time series; for ascertaining long-term changes in loading, the NBEP results are more appropriate. It is recognized that the estimated daily TN loads are approximate, particularly for the several earliest years when fewer concentration measurements were made. A number of suggestions for how to improve the methods are given. The new time series were used to investigate hypoxia in a companion report (Codiga 2020) and are expected to be of use for various other studies. They are available for download in spreadsheet (.xlsx) and Matlab (.mat) file formats, with documented supporting code, at https://figshare.com/s/7d51f2540df6638a4552.

## 1. INTRODUCTION

Nutrient loads to Narragansett Bay (NB) play a role in its degradation by eutrophication and have been the subject of extensive research interest in recent decades. Bay-wide load can be attributed to contributions from wastewater treatment facilities (WWTFs) discharging directly to the bay, from riverine inputs which include load from WWTFs located on rivers upstream, and from direct runoff not included in gauged river flows. An analysis of loads by the Narragansett Bay Estuary Program (NBEP), published as Chapter 8 in the State of Narragansett Bay and Its Watershed report, compiled an updated budget and reviewed prior findings to improve our understanding of the impact that treatment plant upgrades has had on reducing loads (NBEP, 2017). Here, results of an effort to augment that previous work by generating time series for estimated loads of total nitrogen (TN) at daily resolution are described.

Excluding possibly the upstream reaches of rivers flowing to the bay, nitrogen is the limiting nutrient for phytoplankton in NB. For this reason, only nitrogen is treated here (not nitrogen and phosphorous, which were both examined by NBEP 2017). Also following NBEP, and in part due to limitations in available measurements, only the load for TN is treated (without also estimating loads of other individual constituents such and nitrate or ammonium).

Measurements of nutrient concentrations at WWTFs and in rivers have generally been made at monthly or biweekly temporal resolution, or at most weekly in the case of a few of the larger sources. Consequently, past analyses have almost all been limited to annualized budgets, or inclusion of variations on monthly timescales at the shortest. However, one of the main impacts of eutrophication is hypoxia, and hypoxic events vary on timescales of days to weeks (e.g. Codiga et al., 2009). An important reason to estimate loads at daily resolution is to facilitate investigations of the relationship between hypoxia and variations in nutrient load on those shorter timescales, which has not been possible to date.

Load is the product of flow and concentration. The variability of flow on timescales of days to weeks is more pronounced than that of concentration. At these high frequencies flow varies by at least a few orders of magnitude while concentration variations, though less well understood, generally appear not to exceed roughly one order of magnitude. Consequently, variability in loads is dominated by variability in flow. Because measurements of flow are available at daily resolution for many of the larger sources, it is possible to generate meaningful estimates of daily loads despite that the sampling frequency for concentration is not more than weekly.

## 2. METHODS

The supporting Matlab code and associated data files for all calculations are provided online at [https://figshare.com/s/7d51f2540df6638a4552](https://figshare.com/s/7d51f2540df6638a4552) and documented in the section "All Tasks: Data and Code Files Documentation" of the companion report (Codiga, 2020) under Task 2.

Measurements were obtained from the Rhode Island Department of Environmental Management (RIDEM), the Narragansett Bay Commission (NBC), and the Fall River treatment facility.

The total load to the bay is taken to consist of loads from 18 sources (Table 1): eleven WWTFs with direct discharge to the bay, six rivers (which include the load of any WWTFs that discharge to them upstream from the site, generally near where they enter the bay, where their load is computed), and runoff from ungauged riparian area direct to the bay (Figure 1). This approach follows NBEP (2017), except for two differences: the South Kingstown and Scarboro treatment facility loads are not included here, as they discharge at locations outside the bay to the south of the Lower East Passage; and the Somerset WWTF, though not treated as discharging directly the NB in the SNBIW analysis, is included here as it discharges to the Taunton River downstream from the site where its riverine input is estimated.

Figures 2 to 19 correspond to the 18 sources in the order they appear in Table 1. Each figure has three frames: the TN load, the TN concentration, and the flow. For all sources, the TN load and TN concentration are estimated at daily resolution for the entire period from 2001 through 2017. For all sources except one, measured or estimated flow is also included at daily resolution for the entire period.

For all records, outliers were removed as needed, and for most records (except flow, in cases where it was provided at daily resolution for the entire period) linear interpolation was used to fill the record to daily resolution. Periods of up to a month after the last measurement were filled by its value, and periods of up to a month prior to the earliest measurement were filled by its value. As described in more detail on a case by case basis below, for some cases missing values were filled by regression against a surrogate variable (other measured quantity or sum of other measured quantities), using other time periods during which the needed variable and the surrogate were both measured, when the regression relationship was found to be reasonably strong; for some cases, missing periods were filled using the mean seasonal cycle computed from other years when measurements were available. Load values were provided as part of some datasets, along with concentration and flow, but these were not used; load was computed as the product of flow and concentration.

For ease of comparison with their results, the same units are used as in NBEP (2017): 1000 lb $y^{-1}$ for TN load, mg $L^{-1}$ for TN concentration, and millions of gallons per day (MGD) for flow.

**Eleven WWTF sources.** Methods for each source are described, with the sources listed in order of descending long-term mean load (same order as in Table 1).

For the Fields Point WWTF (Figure 4), measured flow and nutrient concentrations were obtained from NBC at nominally weekly temporal resolution from early 2004 through 2017. The load during nearly all of this time period was computed as the product of measured TN concentration and flow. Some of the dates did not have TN measurements but had total Kjeldhal nitrogren (TKN), nitrate (NO3), and nitrate (NO2) so their sum was used for TN; for a small number of dates without TN measurements the only other constituents measured were NO3 and ammonium (NH4) so TN was estimated from the regression of TN against summed NO3 and NH4. For the period prior to early 2004, nominally monthly concentration observations were obtained from RIDEM. For early 2001 through 2004 measured TN concentration was available and prior to that the TN concentration was estimated by a regression against the sum of NO2, NO3, and NH4. No flow measurements were available prior to 2004 so the load during this period was computed using a regression of load against concentration during the later years.

For the Fall River WWTF (Figure 6), measurements were obtained directly from the facility. Concentrations were available at least weekly or biweekly during summer and monthly during winter, with daily flow measurements. TN concentration was computed as summed TKN, NO3, and NO2.

For the Bucklin Point WWTF (Figure 8), measured flow and nutrient concentrations were obtained from NBC at nominally weekly temporal resolution from early 2004 through 2017. The load during nearly all of this time period was computed as the product of measured TN concentration and flow. Some dates did not have TN measurements but had data for TKN and combined nitrate/nitrite (NO32) so their sum was used for TN; for a small number of dates without TN measurements the only other constituent measured was NH4 so TN was estimated from the regression of TN against NH4. For the period prior to early 2004, nominally monthly concentration observations were obtained from RIDEM. For early 2001 through 2004 measured TN concentration was available and prior to that the TN concentration was estimated by a regression against the sum of NO2, NO3, and NH4.

Measurements for all the remaining WWTFs were obtained from RIDEM.

For the Newport WWTF (Figure 10), during the May to October period, nominally monthly TN measurements were available since 2008, and earlier years were filled by the monthly means of available years. For November to April no concentration measurements were available and the mean of all May to October measurements was used. This is somewhat justified based on examination of measurements from nearby facilities (Quonset, Bristol) where year-round data were available for most years and the difference between long-term means from May to October and November to April was smaller than the typical range of variability within each year.

For the Bristol WWTF (Figure 11), since 2005 nominally monthly concentration measurements were available year-round. For earlier years, only TKN and NO3 were available, so TN was estimated by regression against their sum.

For the East Providence WWTF (Figure 12), nominally monthly TN concentrations were available year-round starting in early 2002. Prior to that only NO2, NO3, and NH4 were measured, so TN was estimated by regression against their sum, using years prior to 2008 when substantial facility upgrades took effect.

For the Somerset WWTF (Figure 14), the TN concentrations were estimated as the sum of measured TKN and NO32, which was available nominally monthly starting in 2004; for earlier dates the mean seasonal cycle of the later years was used. Before mid-2004 both the mean and maximum flow each month was available and the mean was used. After mid-2004 only the maximum flow each month was available, which was used after subtracting 1.125 MGD, the mean difference between the maximum and the mean when both were available during 2001 to mid-2004.

For the Warren WWTF (Figure 16), nominally monthly TN concentrations were available year-round starting in early 2002. Prior to that only TKN was measured, so TN was estimated by regression against TKN.

For the Quonset WWTF (Figure 17), nominally monthly TN concentrations were available year-round all years.

For the East Greenwich WWTF (Figure 18), nominally monthly TN concentrations were available year-round all years.

For the Jamestown WWTF (Figure 19), during May to October, nominally monthly TN observations were available since 2005 and prior to that the sum of TKN, NO3, and NO2 was used. During November to April no measurements were available and the mean of all May to October measurements was used. This is somewhat justified based on examination of measurements from nearby facilities (Quonset, Bristol) where year-round data were available for most years and the difference between long-term means from May to October and November to April was smaller than the typical range of variability within each year.

**Six river sources.** In order of descending long-term mean TN load results for river sources, the sampling locations are in the Taunton River (Figure 2), the Blackstone River (Figure 3), the Pawtuxet River (Figure 5), the Ten Mile River (Figure 9), the Woonasquatucket River (Figure 13), and the Moshassuck River (Figure 15).

The six rivers treated, the sources for the nutrient concentration and volume flow observations (from the US Geological Survey), and the ratios of gauged area to total drainage area are the same as in Tables 1 and 2 of NBEP (2017). Concentration data are from NBC (downloaded at http://snapshot.narrabay.com/app/WaterQualityInitiatives/NutrientMonitoring). They consist of total dissolved nitrogen (TDN) from mid-2005 to 2017 and TN from mid-2011 to 2017, sampled nominally each 2-4 weeks. Volume flow data are daily observations from the US Geological Survey, scaled up by the ratio of gauged area to total drainage area.

The estimated daily TN concentration timeseries was generated using a different method during each of three time periods: mid-2011 through 2017, mid-2005 through mid-2011, and 2001 through mid-2005. For mid-2011 through 2017 the direct measurements of TN were used.

For mid-2005 through mid-2011, TN was not directly measured so the TN concentration was estimated for dates when TDN was measured, by applying a linear additive constant (0.161, 0.105, 0.076, 0.188, 0.015, 0.004 mg $L^{-1}$ for the Taunton, Blackstone, Pawtuxet, Ten Mile, Woonasquatucket, and Moshassuck, respectively) to each direct TDN measurement. The constant was computed for each river using the mean of the differences between TN and TDN when both were measured during mid-2011 through 2017. Initially a multiplicative factor was sought using regression of TN against TDN, but the resulting relationships were weak; an additive constant was determined to be more justified than a multiplicative factor.

For the 2001 through mid-2005 period the daily TN concentrations were estimated as the repeated mean seasonal cycle of TN during the mid-2005 to 2011 period. This period was used because it ends approximately when facility upgrades at WWTFs that discharge to the rivers were phased in, substantially altering the seasonal cycle in most rivers. The mean seasonal cycle was estimated by averaging mid-2005 to 2011 TN values in six 2-month intervals (Dec-Jan, Feb-Mar, …), assigning the results to the middle date of the intervals (Jan 1, Mar 1, …), and linearly interpolating to daily resolution. Two-month intervals were chosen in order to give sufficiently smooth results while also capturing the main features of the seasonal cycles, which exhibit maxima during different times of year in different rivers. An attempt was made to compute the TN load for the 2001 to mid-2005 period using measured daily flow and a correlation between daily flow and daily TN load during the mid-2005 to mid-2011 period but, based on the weak resulting correlation, computing concentration using the mean seasonal cycle was determined to be more justified.

**Ungauged runoff source.** Following NBEP (2017) and Nixon et al (2008), the load from ungauged riparian areas was estimated (Figure 7) based on the results of Fulweiler and Nixon (2005) for the Pawcatuck watershed. Fulweiler and Nixon measured a yield (TN load per unit watershed area) of Y = 21 kmol N $km^{-2}$ $y^{-1}$ from this watershed of area A = 725 $km^2$ during 2001-02. Average flow during that time period was Q = 0.83 x $10^6$ $m^3$ $d^{-1}$, so the equivalent mean TN concentration of the runoff was $C_r$ = Y * A / Q = 703 ug $L^{-1}$. This concentration is taken to apply for runoff from ungauged riparian areas.

The ungauged riparian areas are $A_r$ = 240.7 mi$^2$ and the watershed areas accounted for by the 6 rivers are collectively $A_6$ = 1464.2 mi$^2$ (Table 2 of Chapter 8 in NBEP, 2017), including the ungauged areas in each of their watersheds for which they are scaled up (see above). The daily unmeasured flow from the ungauged riparian areas is estimated as $Q_r = Q_6 * A_r/A_6$ where $Q_6$ is the summed daily flow of the 6 measured rivers, each scaled up for ungauged area in its watershed, as described above. The daily TN load from ungauged riparian areas for 2001-2017 is computed as $Q_r * C_r$.

This method diverges from that of Nixon et al (2008) and NBEP (2017). Their results are from computing the TN load as the product of the ungauged riparian area and the 2001-02 measured yield of 21 kmol N km$^{-2}$ y$^{-1}$. For a result applicable to long-term mean conditions, for which flow is higher than that during the 2001-02 measurements, as noted by Fulweiler and Nixon (2005) the appropriate yield to use is 34 kmol N km$^{-2}$ y$^{-1}$.

## 3. RESULTS

Inspection of the daily resolution time series (Figures 2 – 19, for the 18 sources shown in Figure 1 and listed in Table 1, respectively) reveals many characteristics of the of flow, TN concentration, and TN load.

As expected, river flows show pronounced variability at weather-band timescales, a seasonal cycle peaking during the spring with a late summer minimum, and strong inter-annual variability. Flow at WWTFs has many similarities to river flows but generally with relatively muted weather-band and inter-annual variability. Variations in flow typically span up to several orders of magnitude.

A prominent short-term peak in flow, for both rivers and WWTFs, visible in these records is the early spring 2010 event which caused major flooding. The WWTFs impacted by flooding were Warwick, West Warwick, and Cranston (as well as Westerly, which is not included in this analysis). The load from these three WWTFs in the present budget is the Pawtuxet River, on which they are all located upstream. Concentration sampling on the Pawtuxet may have been disrupted for a short period due to the flooding, but was not substantially less frequent than normal. There were minimal or no disruptions to river flow measurements. Disruptions to monitoring at the WWTFs do not affect the present calculations. It is possible that flow, and therefore nitrogen load, was underestimated during the flooding due to limitations in flow measurement methods when the river is flooded. However there are no additional measurements of flow or concentration to further investigate, so improvements to the estimates made here are not possible. Although results during the event are likely somewhat more uncertain than during other periods, there is no reason to suspect they are strongly inaccurate or unrepresentative of conditions during the flooding.

The nature of variability in TN concentrations is generally distinct from source to source, with varying degrees of seasonality, and inter-annual variability is typically not particularly pronounced. The secular shift in concentrations to lower levels, associated with treatment plant upgrades, is visible in many records over a period of up to a few years (occurring during approximately 2010 to 2013 for many sources). This shift is clearest for WWTFs, while for river sources it is also apparent, due to the load reductions at WWTFs located upstream on the rivers, though more muted. Variations in TN concentration typically span up to about one order of magnitude.

The TN loads, as the product of flow and concentration, reflect the combined attributes of flow and concentration just described. Because flow variability is generally more pronounced than concentration variability, load variability tends to be dominated by flow variability. After the secular decrease in concentration, load from many sources fell, also becoming more distinctly seasonal with further-reduced minimum values during the May to October period when regulatory compliance is required.

The relative magnitudes of the TN loads due to the 18 sources are somewhat easier to judge when the timeseries are all superposed on the same plot (Figures 20a and 20b; these show the same data, but with linear and logarithmic y-axes, respectively). The purpose of these figures is not to enable identification of specific features of individual curves from each other, which is recognized to be difficult due to the large number of sources and years included, but rather to provide a general sense of the relative magnitudes of the sources and how they vary through the 17-year period. When the loads are averaged over the entire time period the resulting rank of the sources is the order in which they appear in the legends for Figures 20a and 20b (the same order as in Table 1).

Finally, Figure 21 shows the total summed TN load of all 18 sources, with the contributions of each source annotated by color, making clear the timing and magnitude of how the secular decreases have affected bay-wide load. Figure 21 also highlights the nature of the seasonality of the summed total load of all sources, and how it has become sharper in recent years since the WWTF load reductions occurred, due to much lower loads in the May-October period when compliance with regulatory limits is required.

**Comparison to past annual budgets.** As noted above, the primary reason for computing the new time series, at daily-resolution, is so TN load can be included along with other conditions (river flow, tidal stage, etc) in multi-parameter investigations of the driving agents affecting hypoxia events on timescales of days-weeks. The new time series were not intended to be used for detailed assessments of changes in nutrient loading before and after treatment facility upgrades, such as were undertaken by NBEP (2017). For that purpose, it is more appropriate to use the results of NBEP than the new time series.

Nonetheless, for the purpose of gauging the reasonableness of the new results they are now compared to the past annual budgets for the three periods 2000-04, 2007-10, and 2013-2015 (as reported in NBEP, 2017). In Table 2 those prior results are compared to the averages of subsets of the new time series.

For the 2000-2004 period the percent differences of individual sources are typically -30% to -5% (ranging from -56% to +11%) with mean magnitude 17%, and the percent difference of the summed loads is -21%. Note that the 2001-2004 period in the new time series is rather uncertain due to poor availability of measurements, as detailed in the above descriptions. For the 2007-2010 period the percent differences of individual sources are typically -5% to +20% (ranging from -57% to +86%) with mean magnitude 22%, and the percent difference of the summed loads is +9%. For the 2013-2015 period the percent differences of individual sources are typically -5% to +20% (ranging from -15% to +50%) with mean magnitude 12%, and the percent difference of the summed loads is +10%.

Many aspects of the methods for the new estimates differ from those used by the past budgets and contribute to the differences in results. The new estimates are simple arithmetic averages of the estimated daily values, whereas past budgets relied on Beale's estimator (Beale, 1962) to compute annual averages from infrequently sampled concentrations using more frequent flow measurements. As described in the methods section above, the new estimates applied linear interpolation to TN concentrations, and during some periods used TN concentrations estimated by correlation with other constituents, or used the mean seasonal cycle based on available years; whereas past budgets assigned load to months that were not sampled using months that were sampled (NBEP 2017). In the context of these considerations, recognizing that the methods are fundamentally different and will lead to substantially different results, the new estimates agree acceptably well with the past budgets.

## 4. DISCUSSION

The ranking of the sources in Table 1 is mostly very similar to results of NBEP (2017), but there are some aspects it highlights differently. In contrast to the present breakouts, NBEP (2017) focused on comparisons among all WWTFs, including those upstream on the rivers, which here are not examined individually but included as part of the river sources. The present results highlight that the three most important loads are the Taunton River with its upstream WWTFs, the Blackstone River with its upstream WWTFs, and the Fields Point WWTF. The prominence of the Taunton River and its upstream WWTFs may not have been made so clear by earlier studies. Another result that is perhaps less expected is that the load from ungauged riparian areas direct to the bay is comparable to the next-largest sources: Pawtuxet River and its upstream WWTFs, Fall River and its upstream WWTFs, and Bucklin Point WWTF.

There are many ways to improve the methods. Some, which seem the most germane, are listed next. Should an extension of this analysis be taken up, these could form a logical starting point.

First, daily flow measurements have been made at many of the WWTFs but (as explained above) for many of the facilities the files obtained and used here have nominally monthly, biweekly, or weekly resolution. Each WWTF should be contacted to obtain their daily data. RI DEM offered to coordinate this, but it was beyond the scope of the current effort. In some cases the daily data may only be available in paper format and the process of digitizing them may be necessary.

Second, for any periods of time when daily flow data is not available from a WWTF, estimates of the daily flow need to be constructed. Regression of the available flow data against nearby rivers and/or nearby treatment plants should be explored.

Finally, better methods for filling the TN concentration time series to daily resolution, by relying on the daily flow, need to be investigated. The linear interpolation of TN concentration measurements, used here to fill to daily resolution, is recognized to lead to loads that are biased high due to the concave-upward nature of temporal variability in flow. Beale's estimator is commonly used in load calculations to yield less biased results and mitigate this, but it is not possible to use Beale's to generate daily-resolution time series, so some other approach must be used. There are a number of different methods, both well established (such regression-based approaches like LOADEST, Runkel et al. 2004) and more experimental (e.g. Lee et al. 2016). Making improvements to the linear interpolation used here represents an important effort, but is not expected to be straightforward for regression-based methods, due to the secular changes that have occurred in the load levels and their seasonality (as shown above).

## 5. CONCLUSION

Daily resolution time series for TN load to Narragansett Bay from 18 sources bay-wide have been estimated. The flow, concentration, and load data shown in Figures 2-19 are available to researchers for download in self-documented spreadsheet (.xlsx) and Matlab (.mat) file formats at [https://figshare.com/s/7d51f2540df6638a4552](https://figshare.com/s/7d51f2540df6638a4552), along with all supporting code. They have been used for investigations of hypoxia in a companion report (Codiga, 2020).

Some portions of the daily-resolution time series are highly uncertain, for the various reasons noted above, given the limitations of available observations. This is particularly true for the time period earlier than about 2005. However, by using simple diagnostic plots of the time series for flow, concentration, and load such as those provided here, researchers should be able to straightforwardly identify the time periods when uncertainties are the largest, and avoid or omit them from their analyses as needed.

Therefore the time series could be valuable, for a given investigation, even if only the portions with relatively smaller uncertainties are found to be useful. In addition, if a researcher needs weekly or monthly temporal resolution but not daily, they may find that suitably averaging these new time series yields useful results more conveniently than would otherwise be possible.

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**Table 1.** The eighteen sources treated in this analysis, listed in descending order based on their mean TN load from the estimated 2001-2017 timeseries. WWTF sources (11) blue, riverine sources (6) green, ungauged runoff purple.

| Source | Figure below |
|---|---|
| Taunton River and upstream WWTFs | 2 |
| Blackstone River and upstream WWTFs | 3 |
| Fields Point WWTF | 4 |
| Pawtuxet River and upstream WWTFs | 5 |
| Fall River WWTF | 6 |
| Ungauged direct runoff to bay | 7 |
| Bucklin Point WWTF | 8 |
| Ten Mile River and upstream WWTFs | 9 |
| Newport WWTF | 10 |
| Bristol WWTF | 11 |
| East Providence WWTF | 12 |
| Woonasquatucket River and upstream WWTF | 13 |
| Somerset WWTF | 14 |
| Moshassuck River | 15 |
| Warren WWTF | 16 |
| Quonset WWTF | 17 |
| East Greenwich WWTF | 18 |
| Jamestown WWTF | 19 |

**Table 2.** Comparison of averaged daily time series results ("Daily") to prior budgets ("NBEP") in NBEP (2017) for 2000-2004 (Nixon et al 2008), 2007-2010 (Krumholz 2012), and 2013-2015 (NBEP 2017). NBEP and Daily columns are TN loads in 1000 lb $y^{-1}$. Third column ("PctDiff") for each period is percent difference of Daily result compared to the NBEP result. Percent differences have average magnitude (absolute value; not shown in table) of 17%, 22%, and 12%, respectively, for the three periods.

| **Time period:** | 2000-2004 | | | 2007-2010 | | | 2013-2015 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Source**[1] | NBEP | Daily[2] | PctDiff | NBEP | Daily | PctDiff | NBEP | Daily | PctDiff |
| Taunton River and upstream WWTFs | 4220 | 2657 | -37% | 2772[3] | 3053 | +10% | 1925 | 2235 | +16% |
| Blackstone River and upstream WWTFs | 3038 | 2544 | -16% | 2610 | 3206 | +23% | 1536 | 1832 | +19% |
| Fields Point WWTF | 1993 | 1884 | -5% | 1956 | 1821 | -7% | 727 | 747 | +3% |
| Pawtuxet River and upstream WWTFs | 1826 | 1120 | -39% | 1133 | 1483 | +31% | 756 | 992 | +31% |
| Fall River WWTF | 1056 | 972 | -8% | 1023 | 1145 | +12% | 1010 | 995 | -1% |
| Ungauged direct runoff | 748[4] | 597 | -20% | 748[3,4] | 747 | 0% | 652[4] | 556 | -15% |
| Bucklin Point WWTF | 1149 | 1168 | +2% | 582 | 496 | -15% | 339 | 346 | +2% |
| Ten Mile River and upstream WWTFs | 434 | 398 | -8% | 443 | 501 | +13% | 313 | 338 | +8% |
| Newport WWTF | 400 | 317 | -21% | 323 | 309 | -4% | 156 | 234 | +50% |
| Bristol WWTF | 209 | 191 | -9% | 193 | 241 | +25% | 286 | 263 | -8% |
| East Providence WWTF | 302 | 291 | -4% | 232 | 234 | +1% | 124 | 124 | 0% |
| Woonasquatucket River and upstream WWTF | 265 | 155 | -42% | 176 | 179 | +2% | 110 | 121 | +10% |
| Somerset WWTF | 129 | 123 | -5% | 255 | 110 | -57% | 140 | 137 | -2% |
| Moshassuck River | 147 | 65 | -56% | 83 | 84 | +1% | 50 | 55 | +10% |
| Warren WWTF | 69 | 76 | +10% | 57 | 80 | +40% | 58 | 59 | +2% |
| Quonset WWTF | 29 | 29 | 0% | 22 | 41 | +86% | 36 | 36 | 0% |
| East Greenwich WWTF | 37 | 34 | -8% | 27 | 27 | 0% | 35 | 35 | 0% |
| Jamestown WWTF | 9 | 8 | -11% | 5 | 8 | +60% | 6 | 8 | +33% |
| **All sources summed**[5] | 16060 | 12629 | -21% | 12640 | 13765 | +9% | 8259 | 9113 | +10% |

1. Daily higher than NBEP likely due to linear interpolation (Daily) vs unbiased Beale's (NBEP).
2. Daily results from 2001-2004 were averaged, as the daily resolution time series do not include 2000.
3.,4. Two adjustments were made. First, to make the comparison appropriate to watershed areas assigned to the sources used here, the 2007-2010 load reported by NBEP for the Taunton River and WWTFs was increased by 1161 lb $y^{-1}$ and the NBEP load for ungauged direct runoff was decreased by 1161 lb $y^{-1}$, such that the load from ungauged runoff was unchanged (at 462 lb $y^{-1}$, see NBEP 2017) from 2000-2004 to 2007-2010 as is consistent with NBEP (2017). Second, using the results after the first adjustment was made, all values for ungauged runoff given by NBEP were scaled up by 34/21 (see Fulweiler and Nixon 2005) so they reflect load of long-term mean conditions instead of 2001-02 conditions, as explained in the methods section above.
5. Here the Somerset WWTF is included in the totals, unlike for the totals in NBEP (2017).

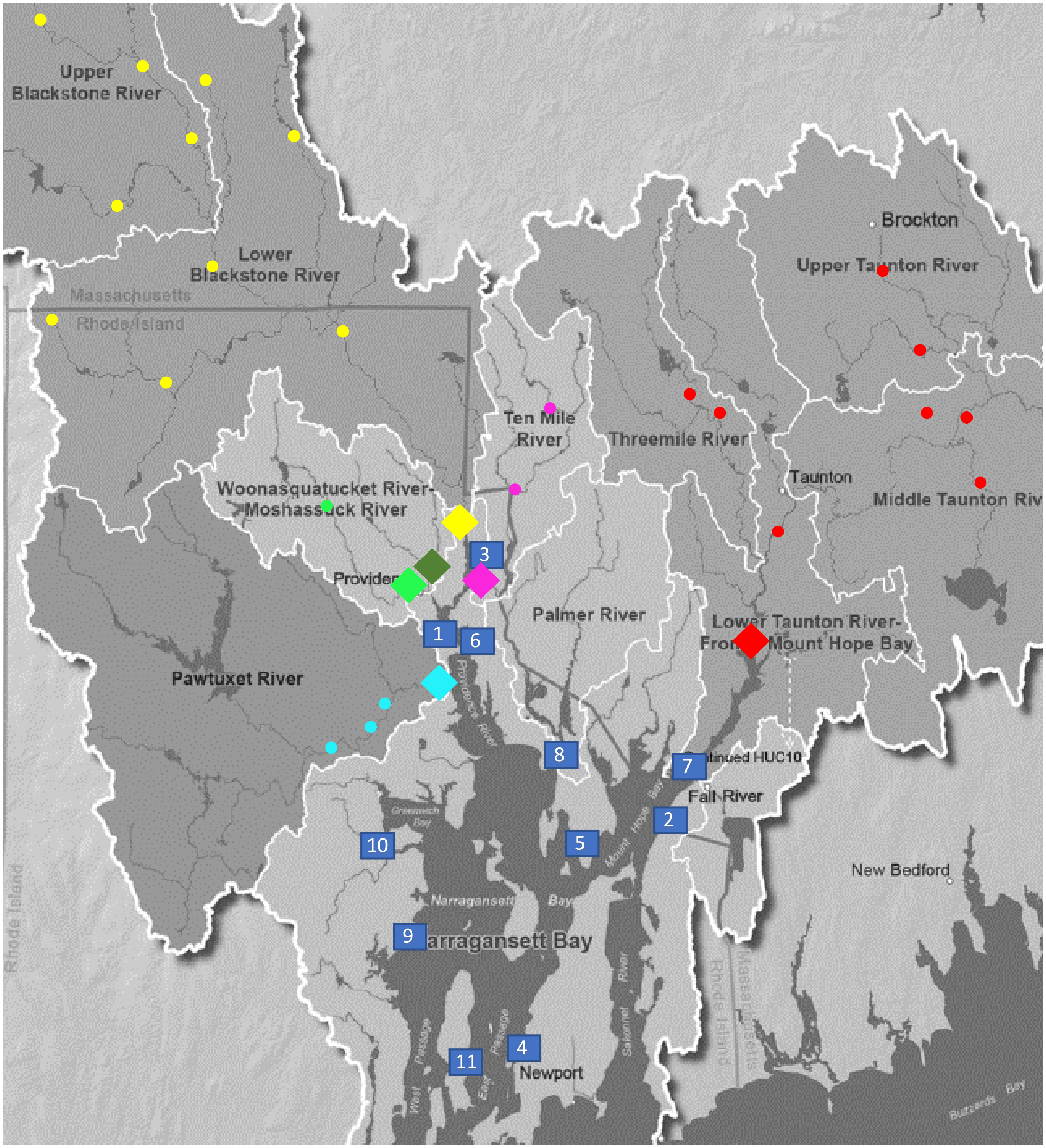


**Figure 1.** Seventeen sources (rectangles and diamonds), superposed in color on black/gray background of Figure A-2 from Appendix of NBEP 2017; the 18th source is ungauged runoff direct to the bay from riparian areas (gray land adjacent the bay excluding riversheds of the Ten Mile, Woonasquatucket, and Moshassuck Rivers). Blue rectangles are treatment facilities discharging directly to the bay: Fields Point (1), Fall River (2), Bucklin Point (3), Newport (4), Bristol (5), East Providence (6), Somerset (7), Warren (8), Quonset (9), East Greenwich (10), and Jamestown (11). Diamonds are six river mouth sampling locations: Taunton (red), Blackstone (yellow), Pawtuxet (cyan), Ten Mile (magenta), Woonasquatucket (light green), and Moshassuck (dark green) Rivers. Color-coded circles show treatment facilities, located upstream on rivers, whose loads are accounted for in the river loads (corresponding diamonds).

**Figure 2.** Taunton River and upstream WWTFs.

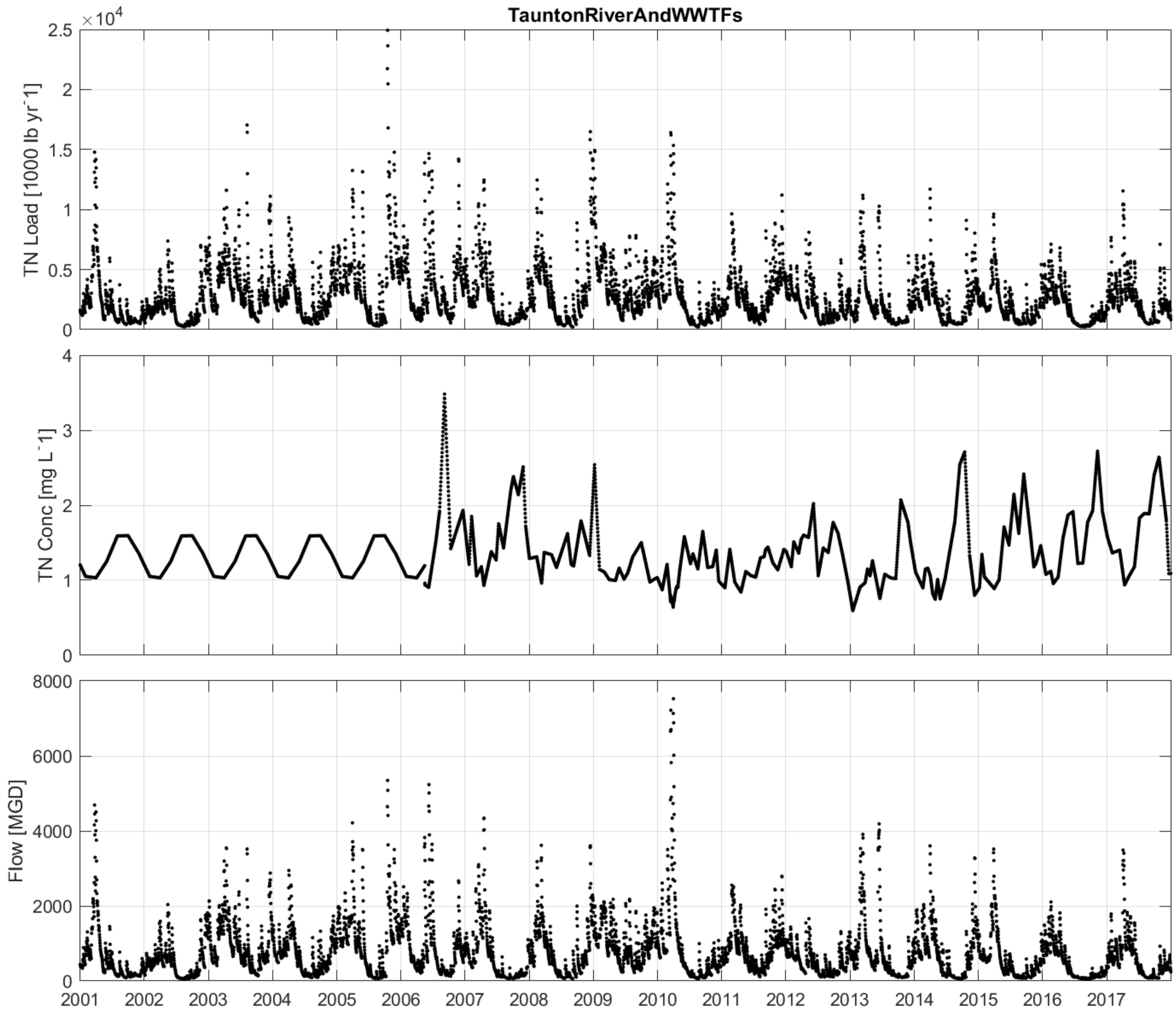

**Figure 3.** Blackstone River and upstream WWTFs.

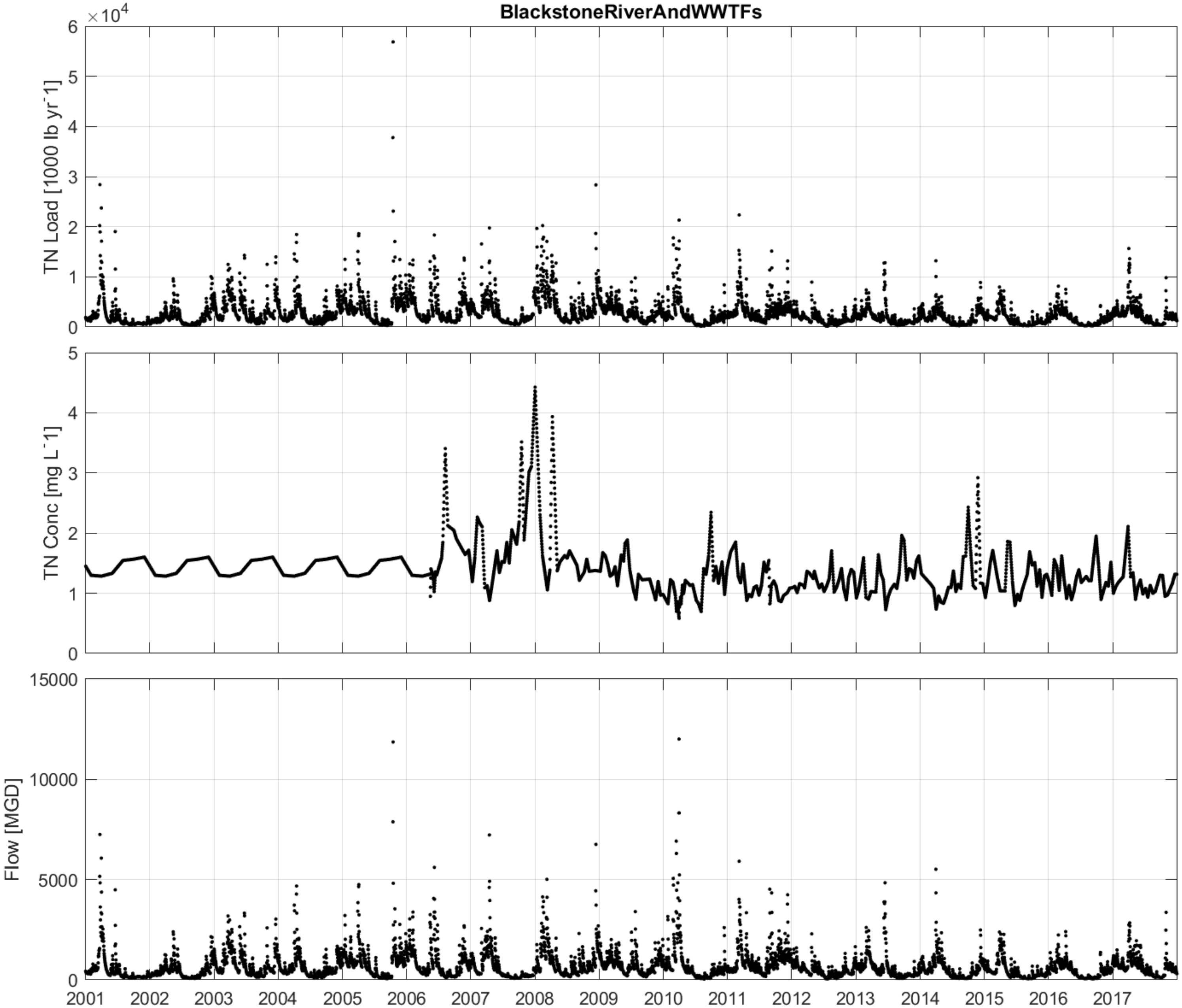

**Figure 4.** Fields Point WWTF.

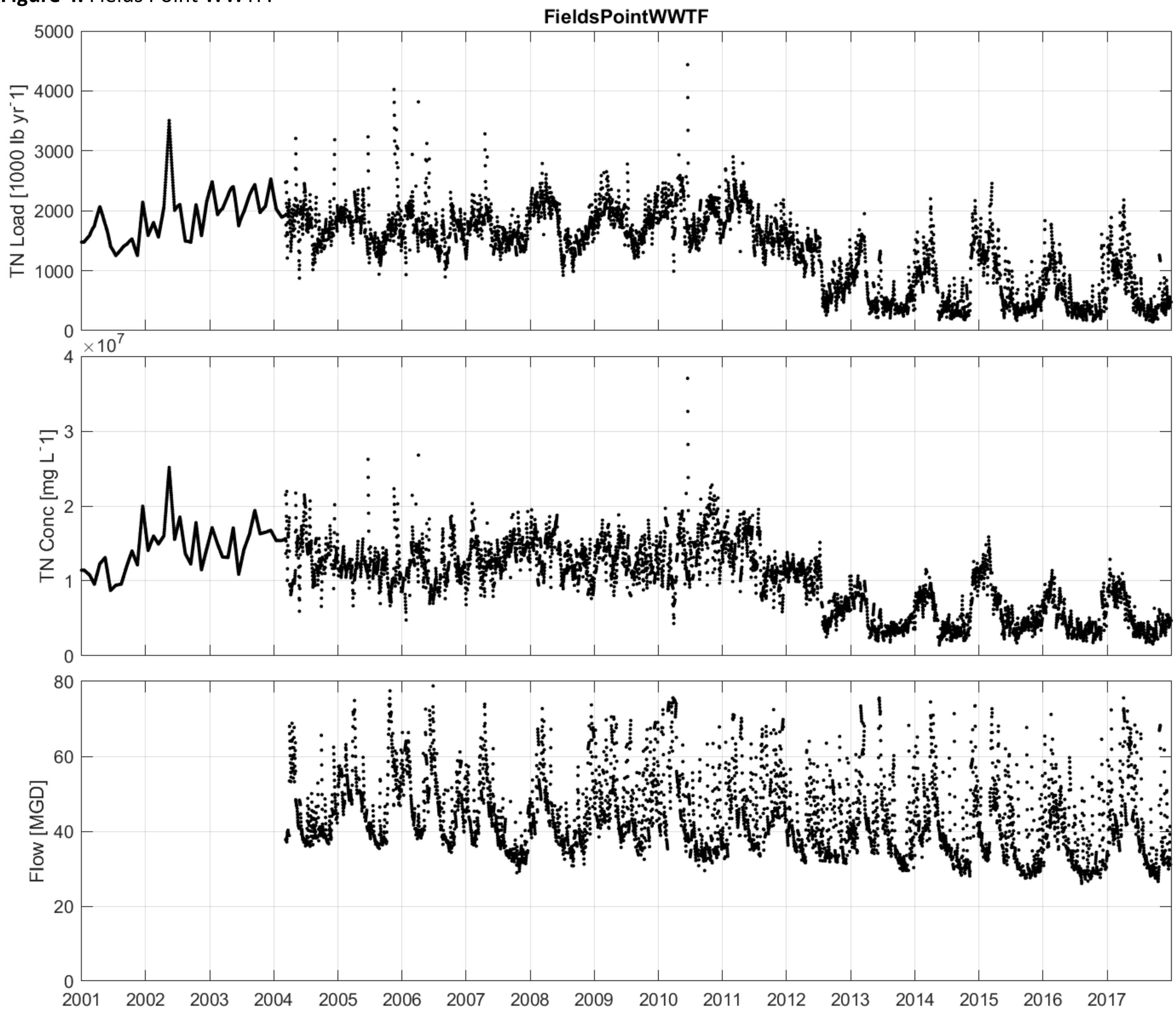

**Figure 5.** Pawtuxet River and upstream WWTFs.

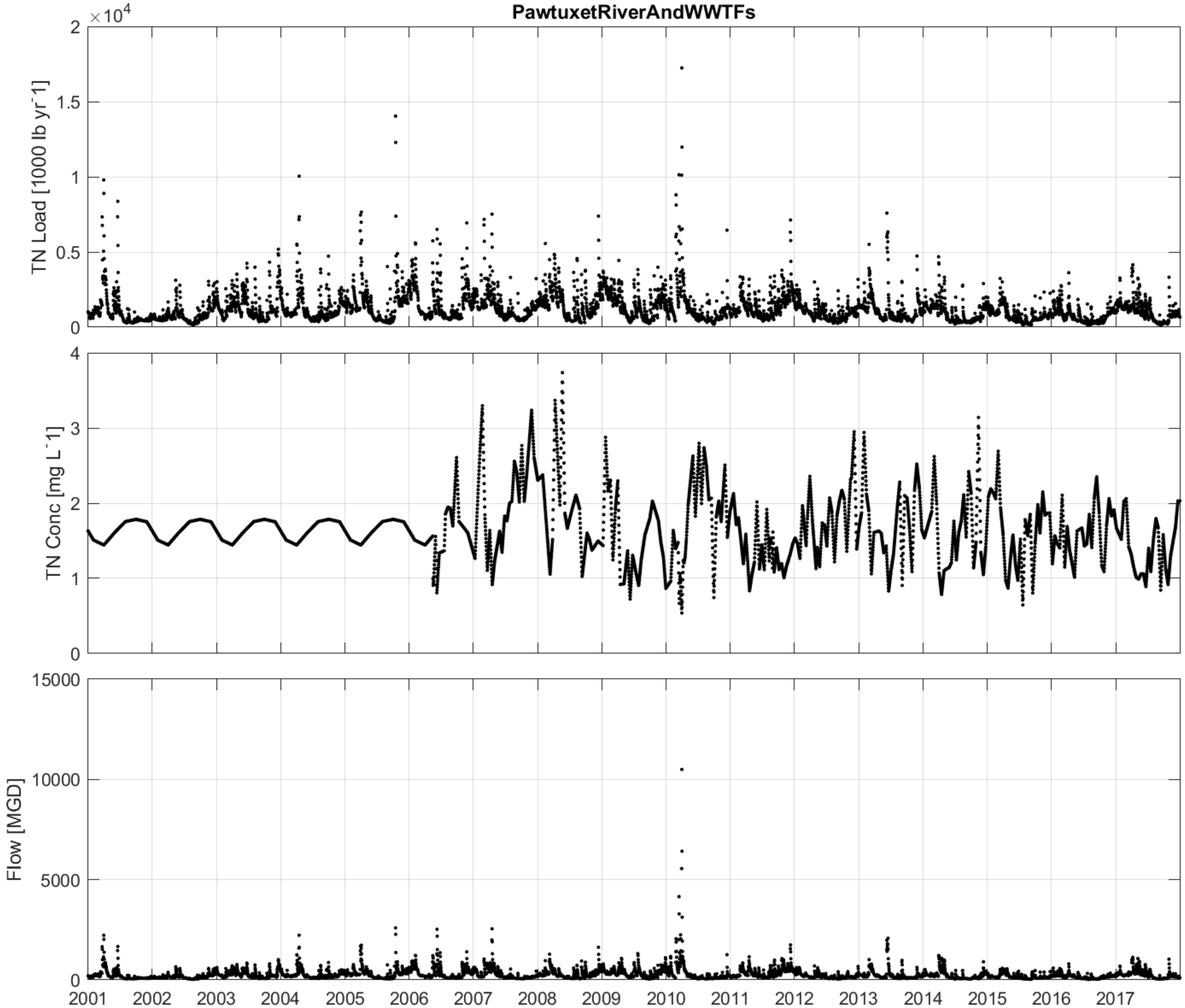

**Figure 6.** Fall River WWTF.

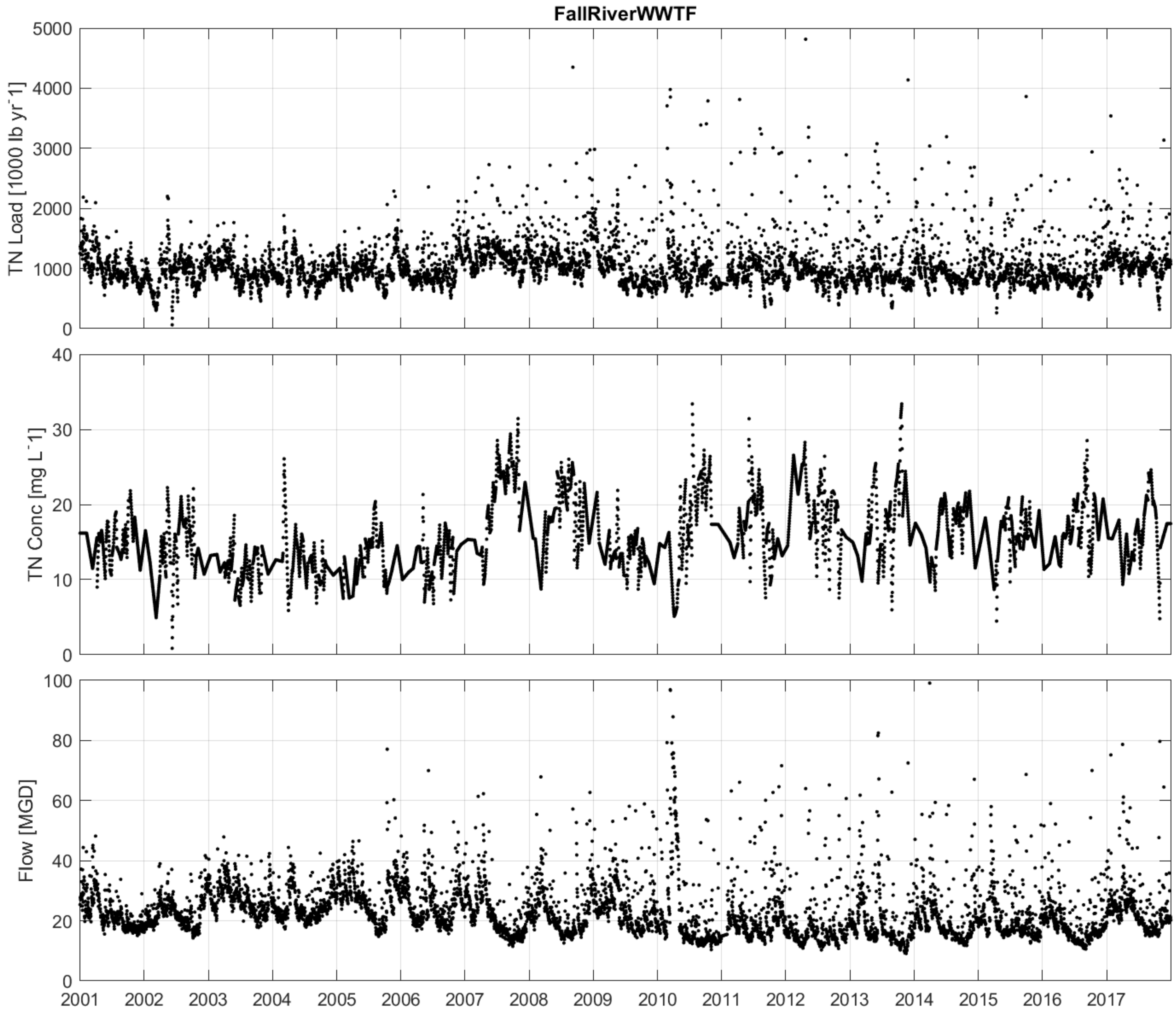

**Figure 7.** Ungauged runoff from riparian areas.

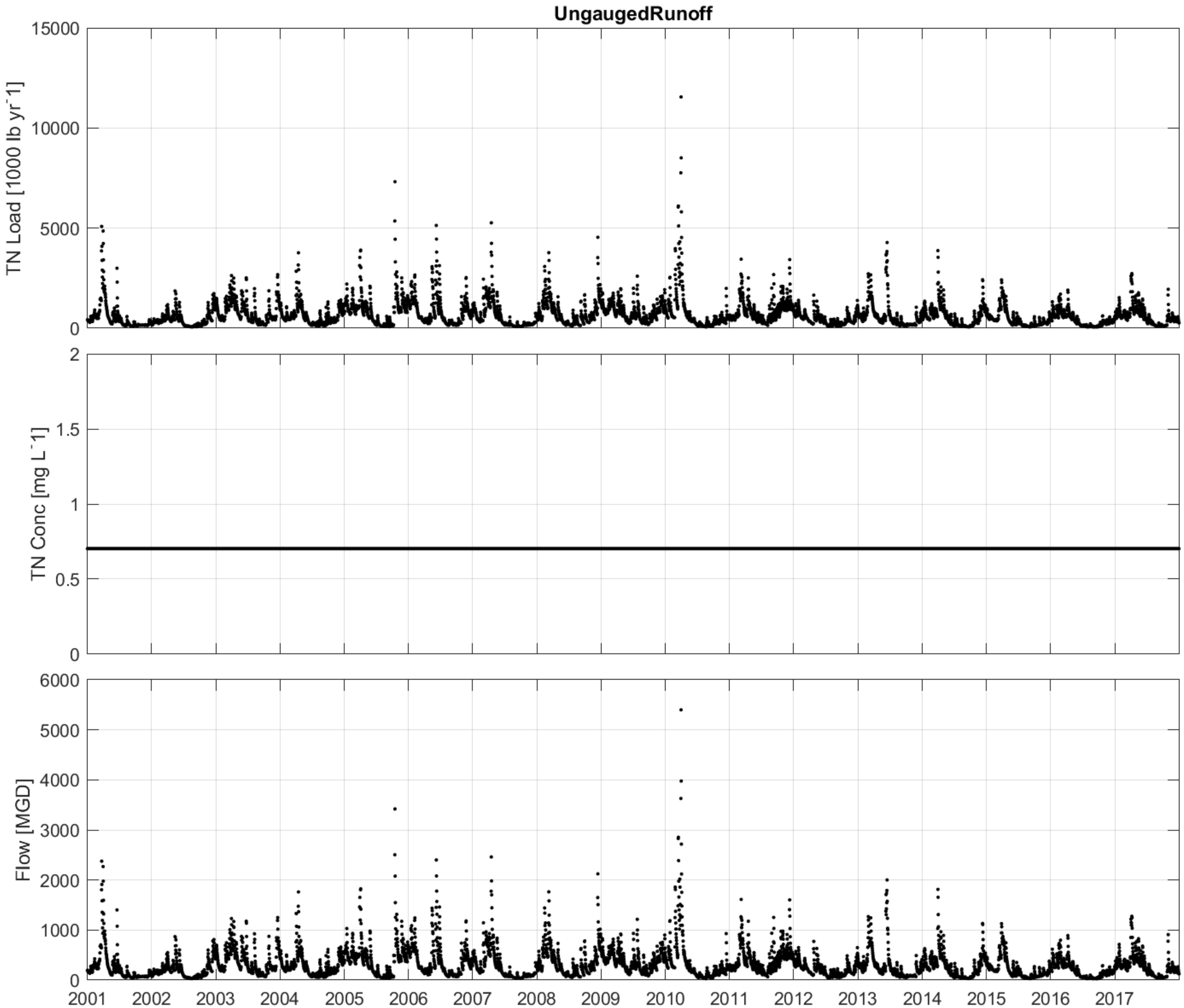

**Figure 8.** Bucklin Point WWTF.

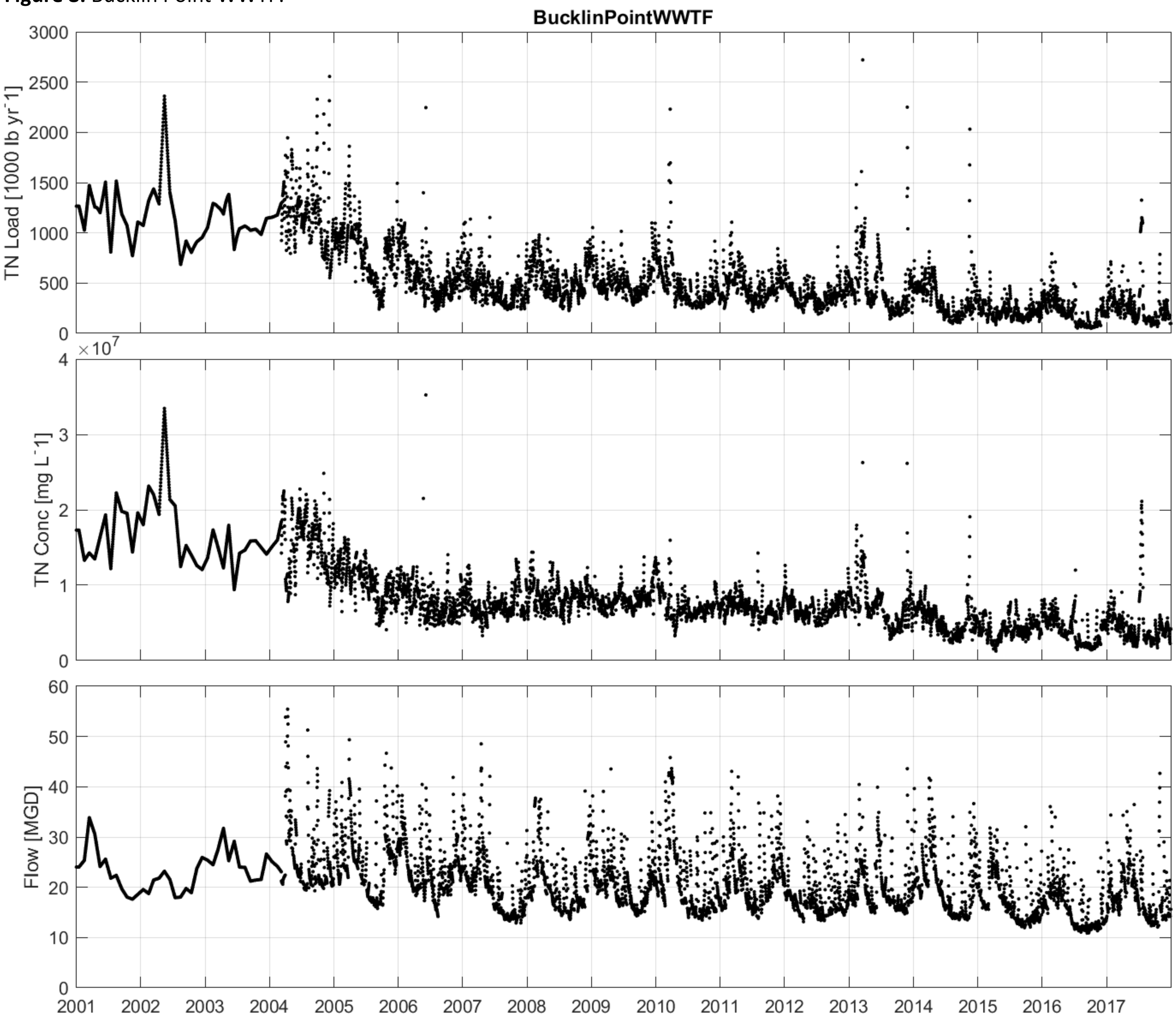

**Figure 9.** Ten Mile River and upstream WWTFs.

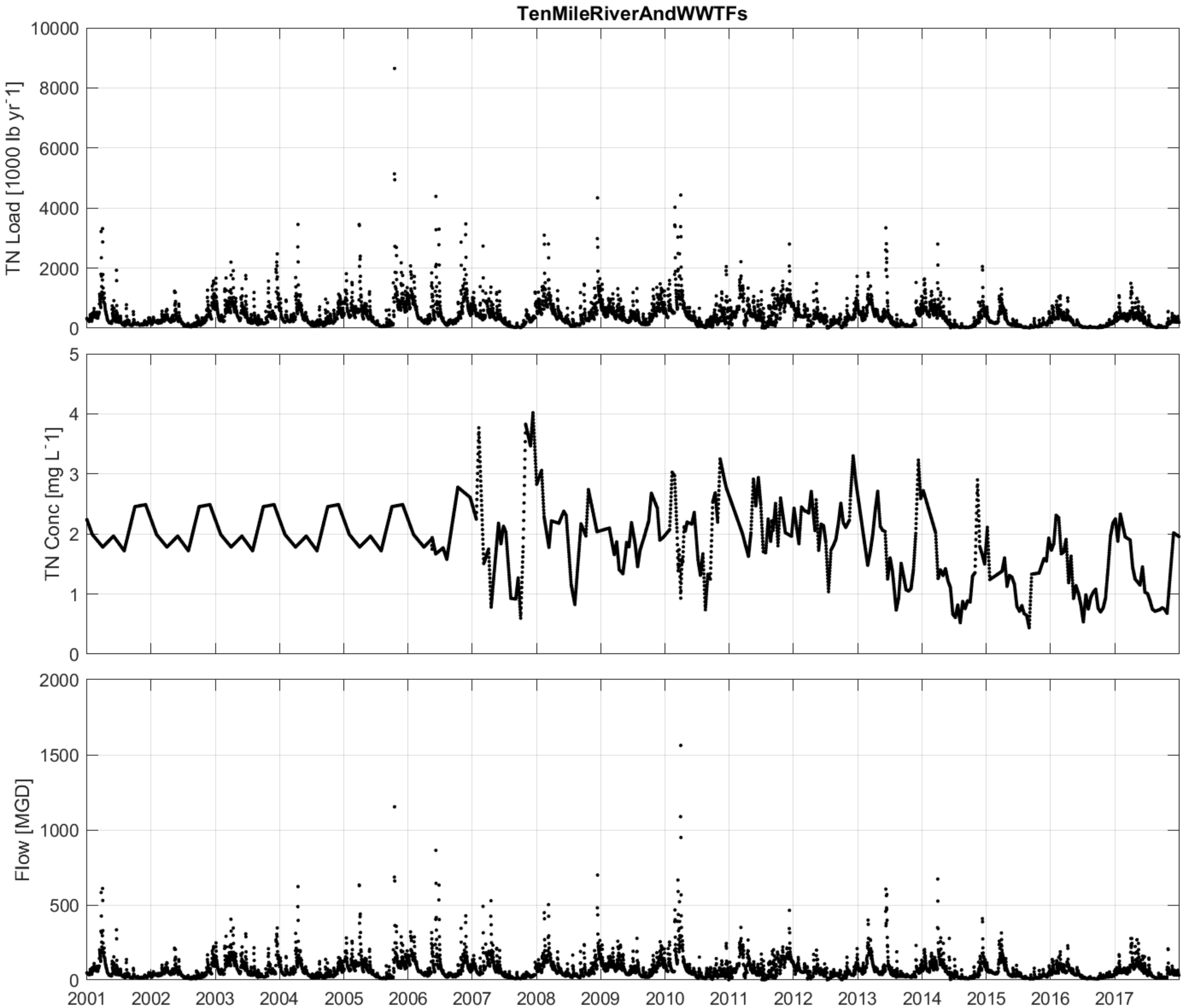

**Figure 10.** Newport WWTF.

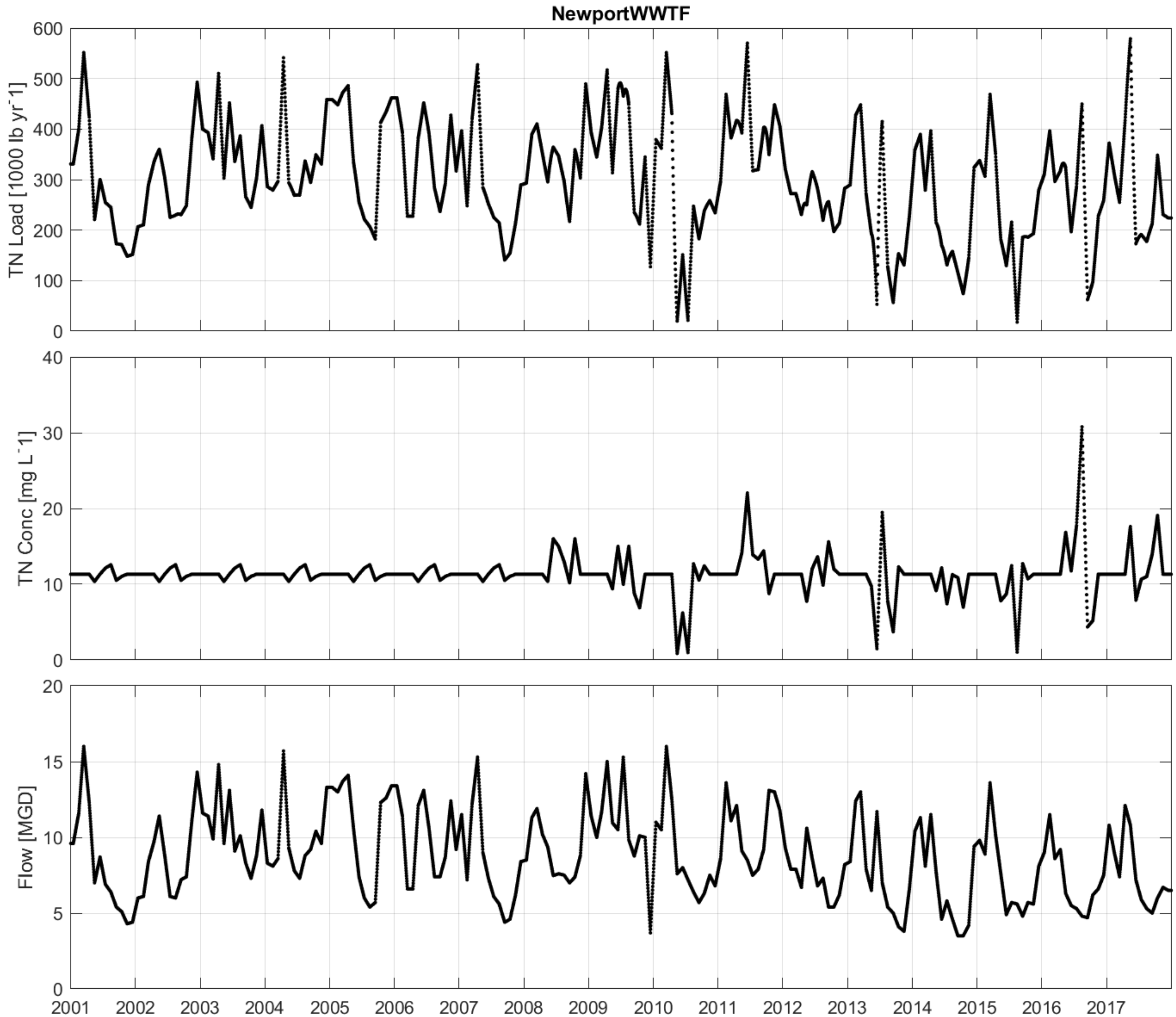

**Figure 11.** Bristol WWTF.

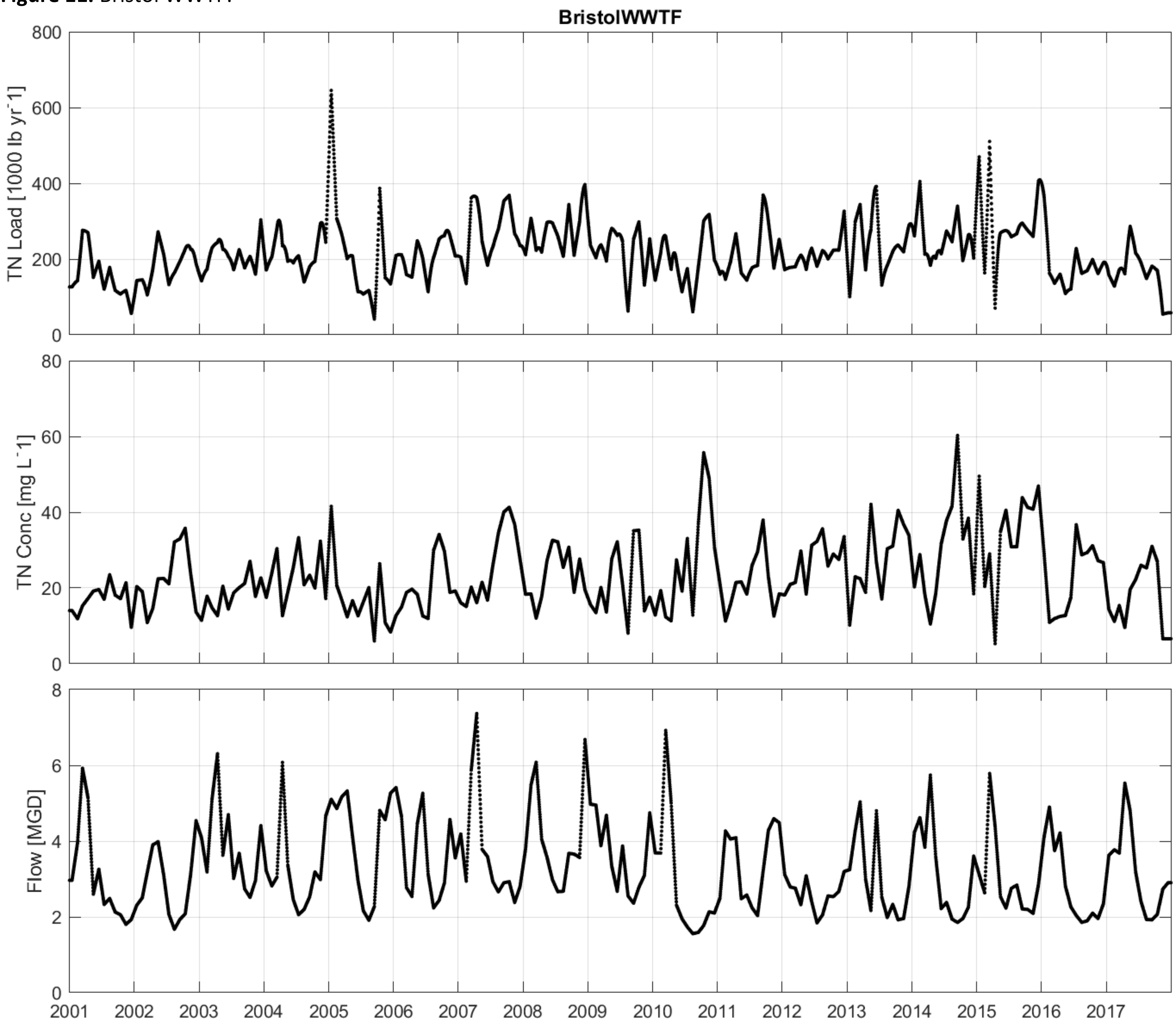

**Figure 12.** East Providence WWTF.

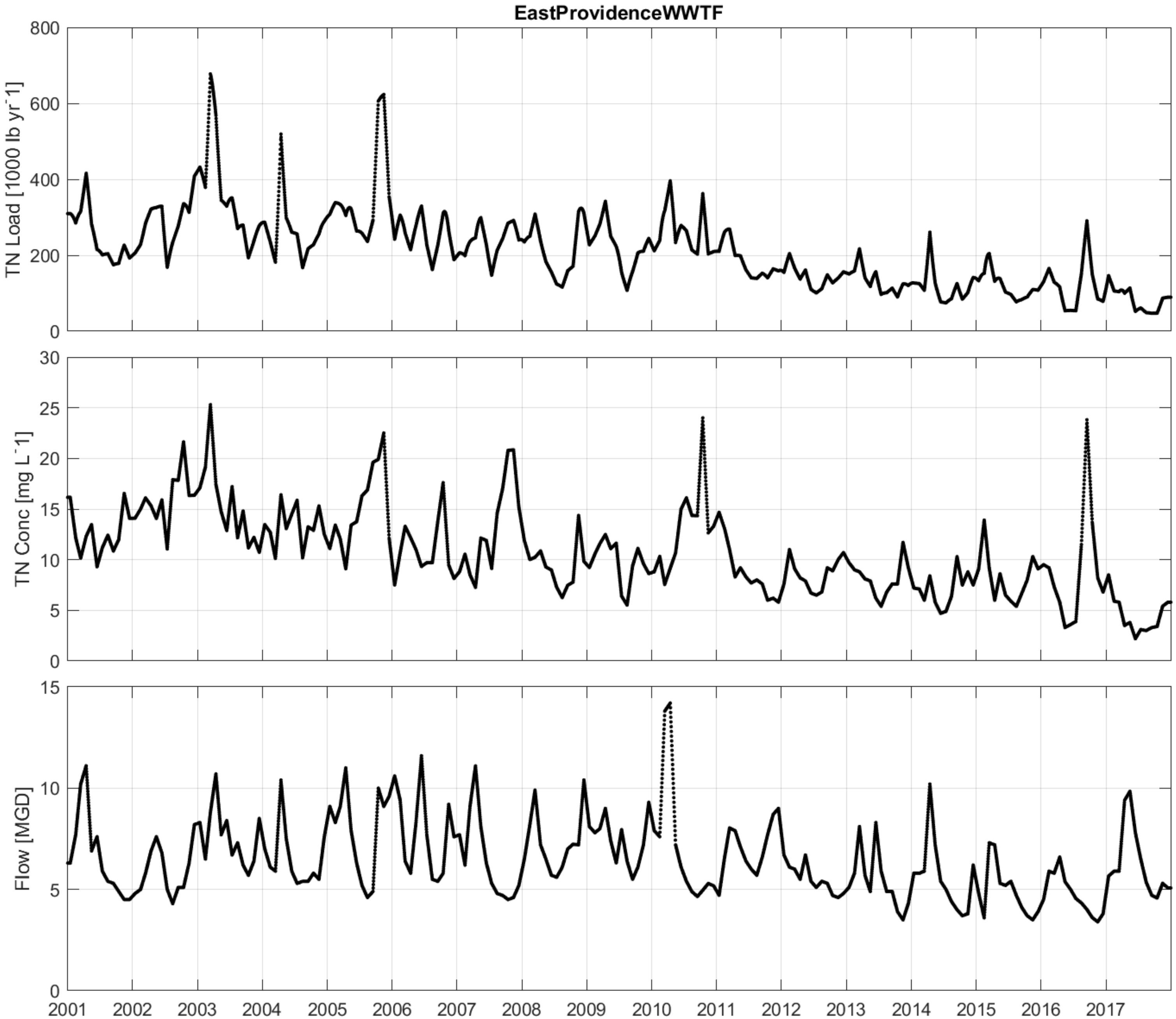

**Figure 13.** Woonasquatucket River and upstream WWTF.

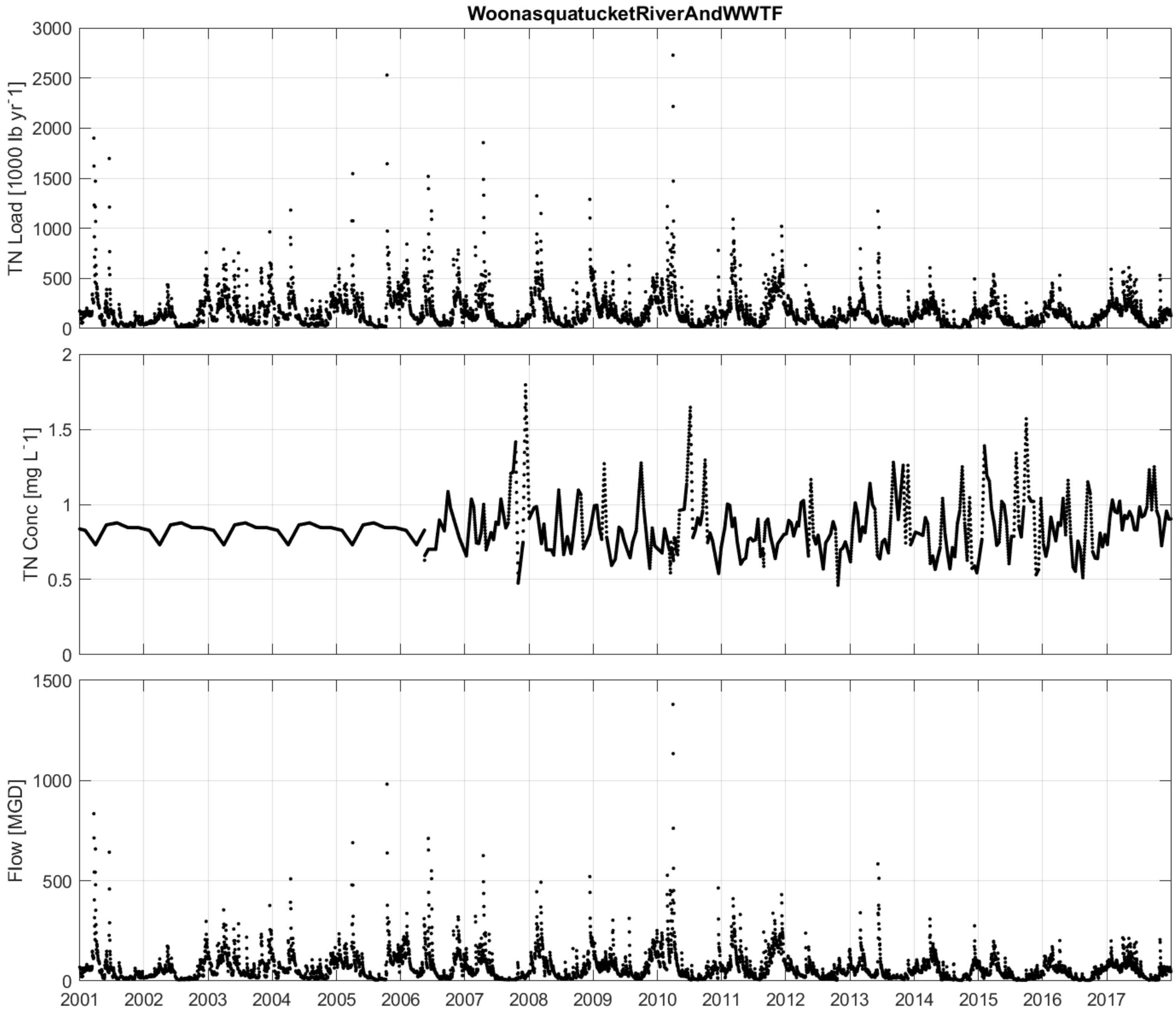

**Figure 14.** Somerset WWTF.

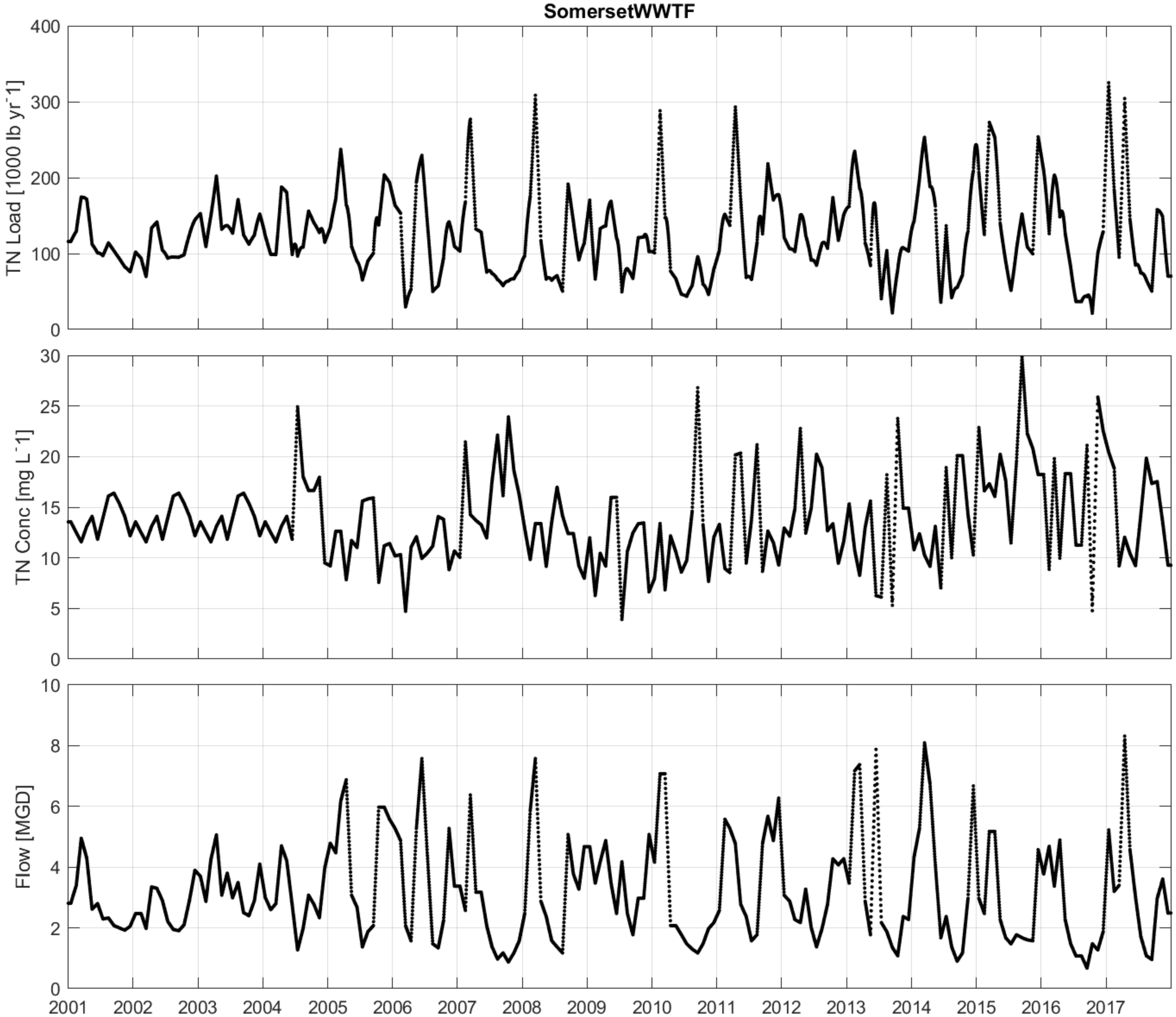

**Figure 15.** Moshassuck River.

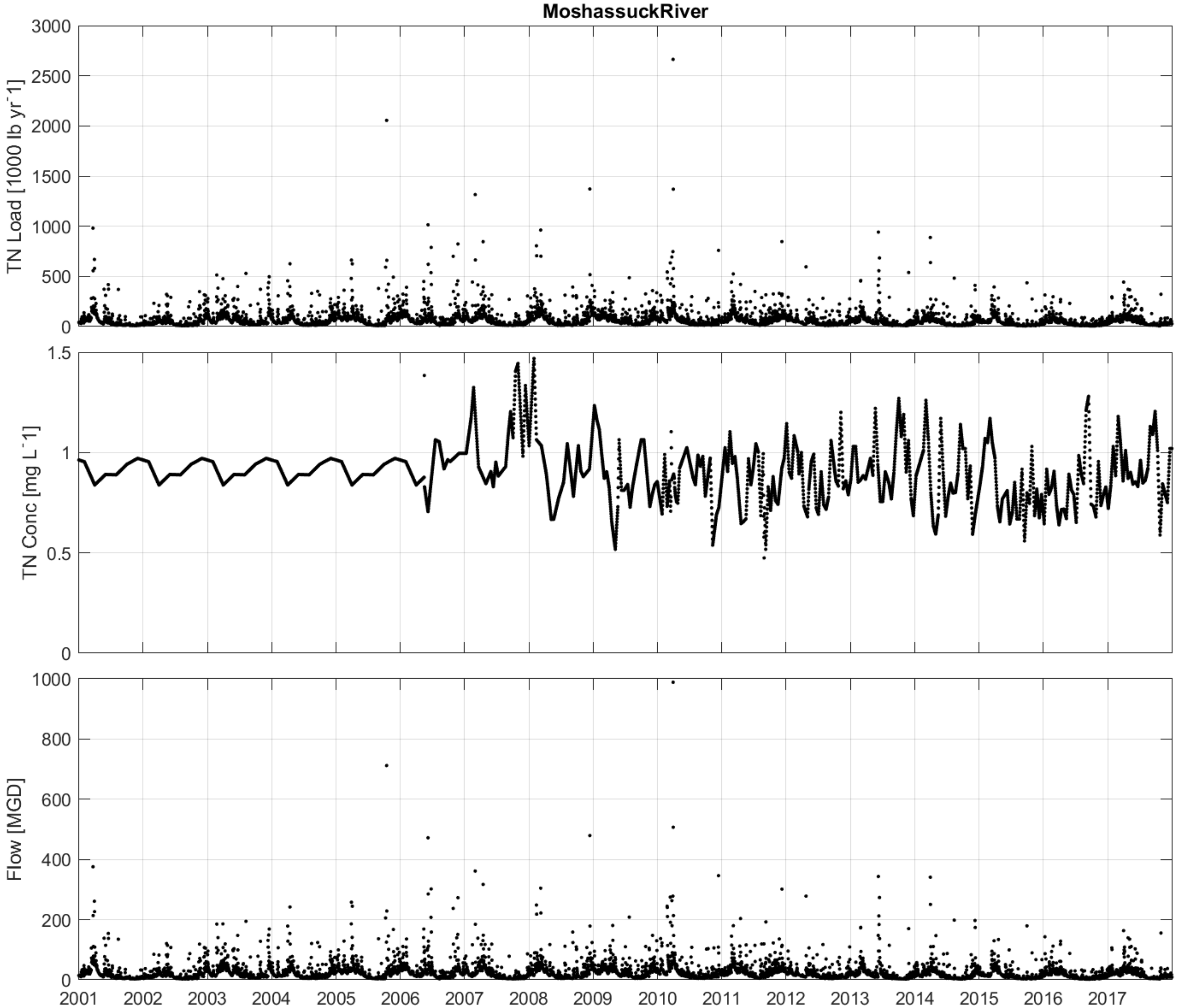

**Figure 16.** Warren WWTF.

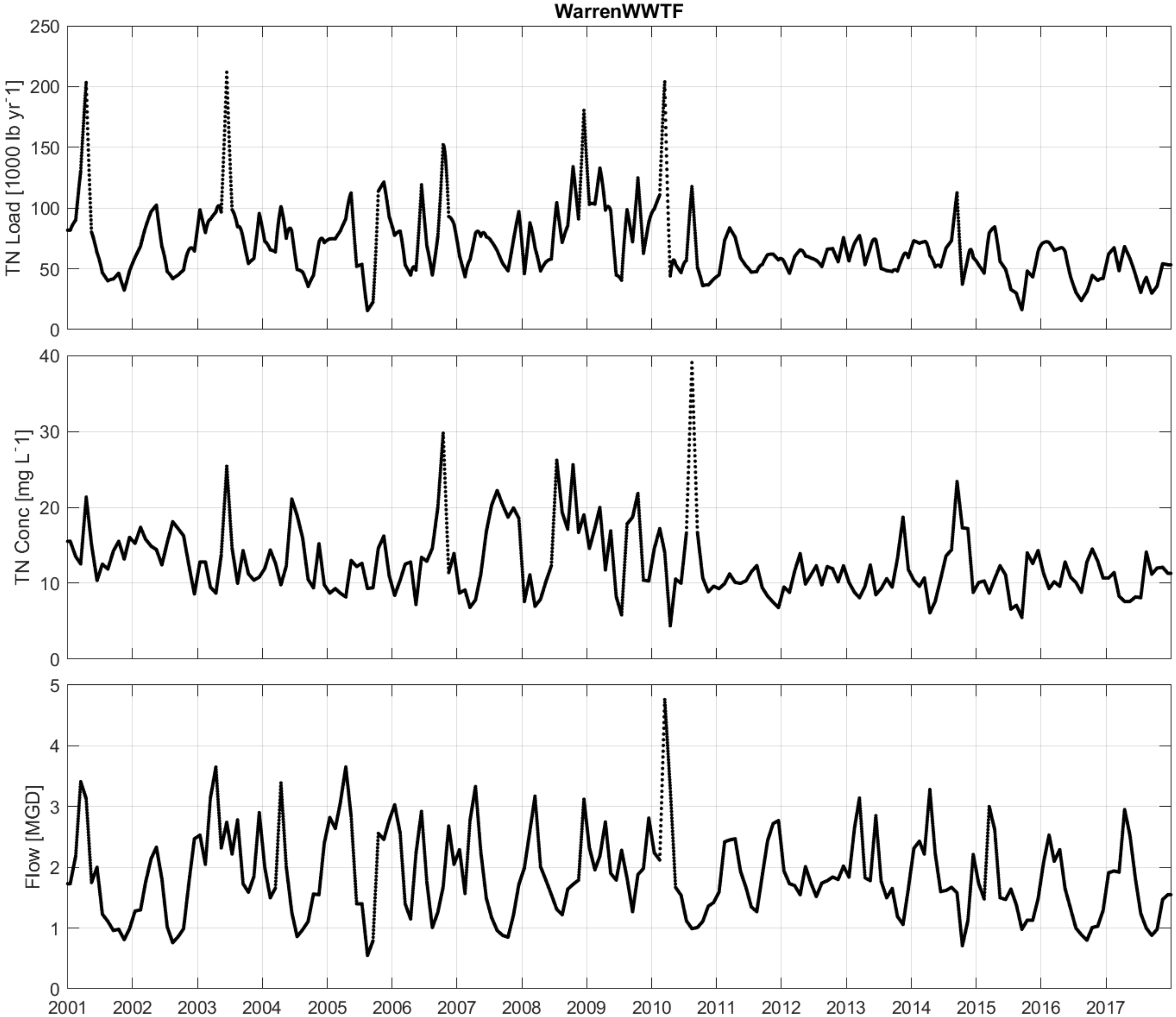

**Figure 17.** Quonset WWTF.

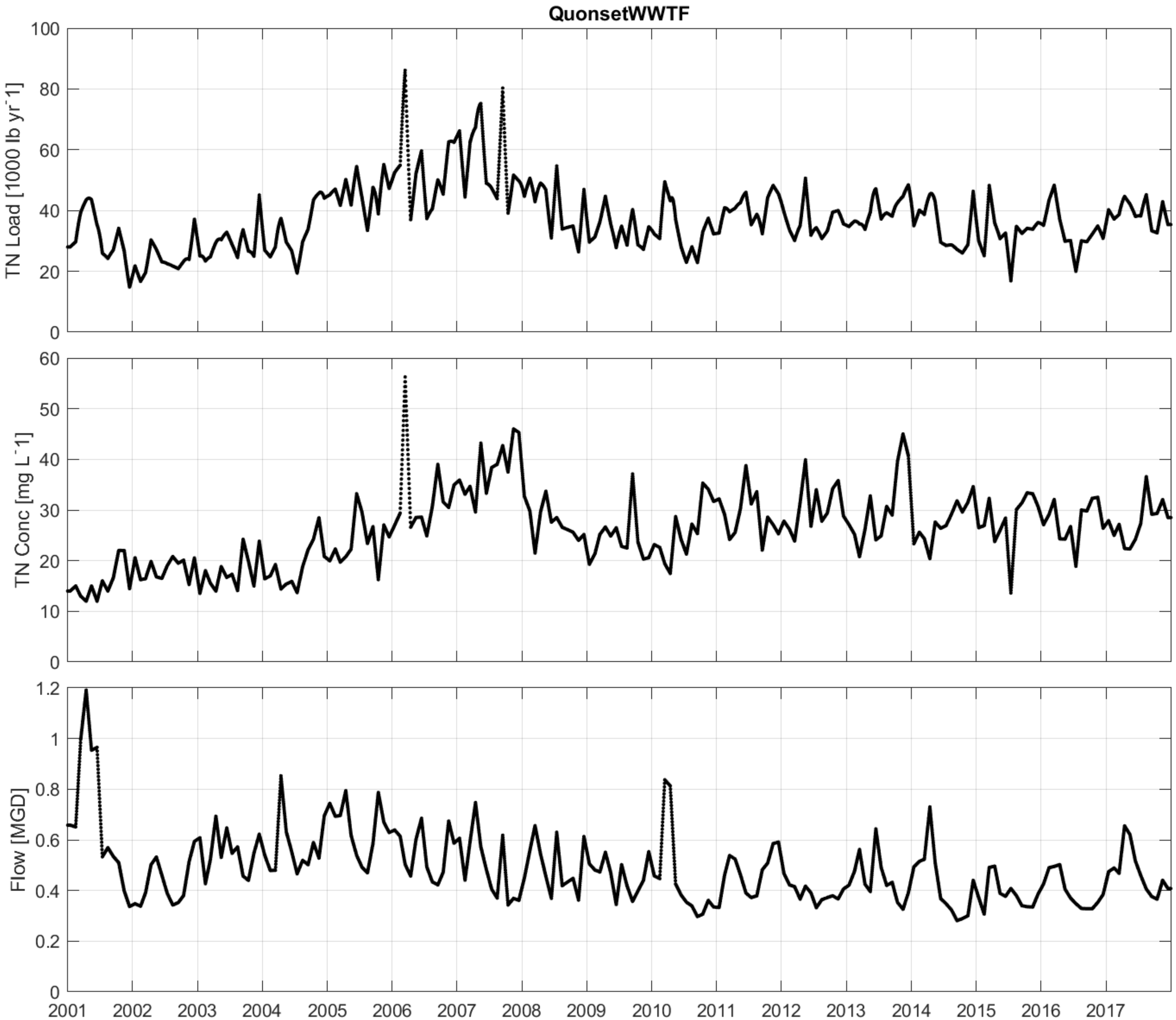

**Figure 18.** East Greenwich WWTF.

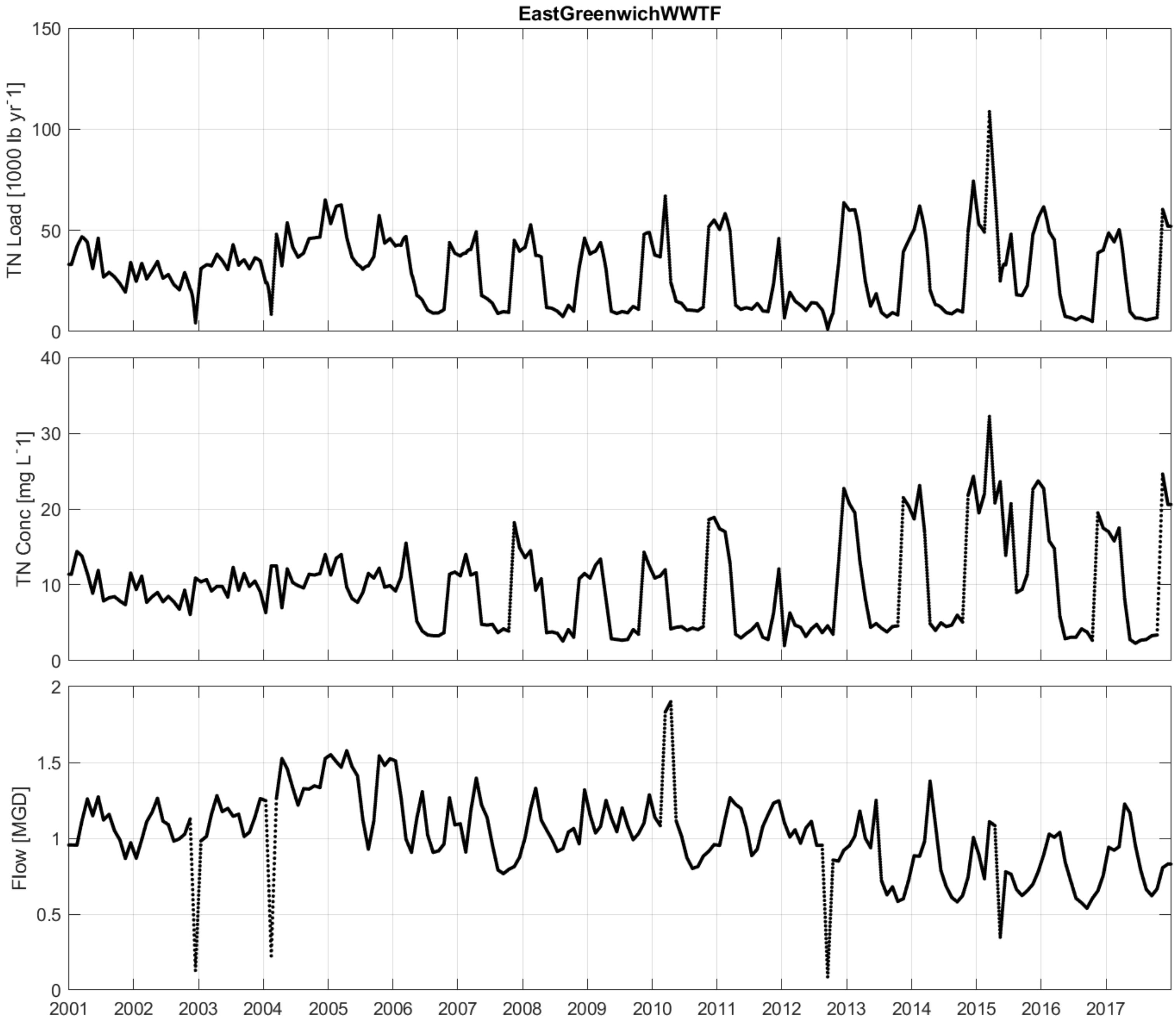

**Figure 19.** Jamestown WWTF.

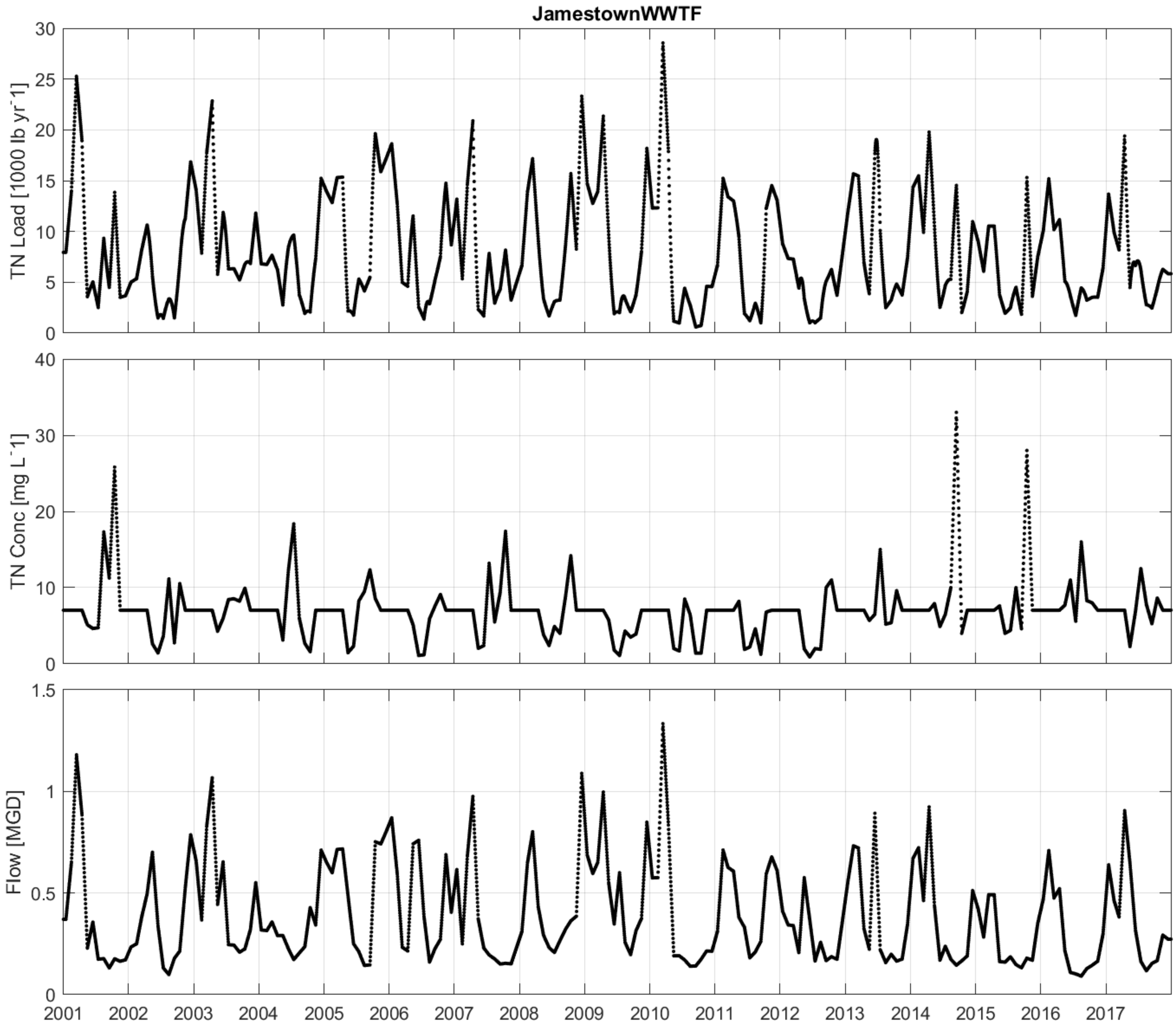

**Figure 20a.** TN load time series of the 18 sources superposed on the same figure. Linear y-axis scale.

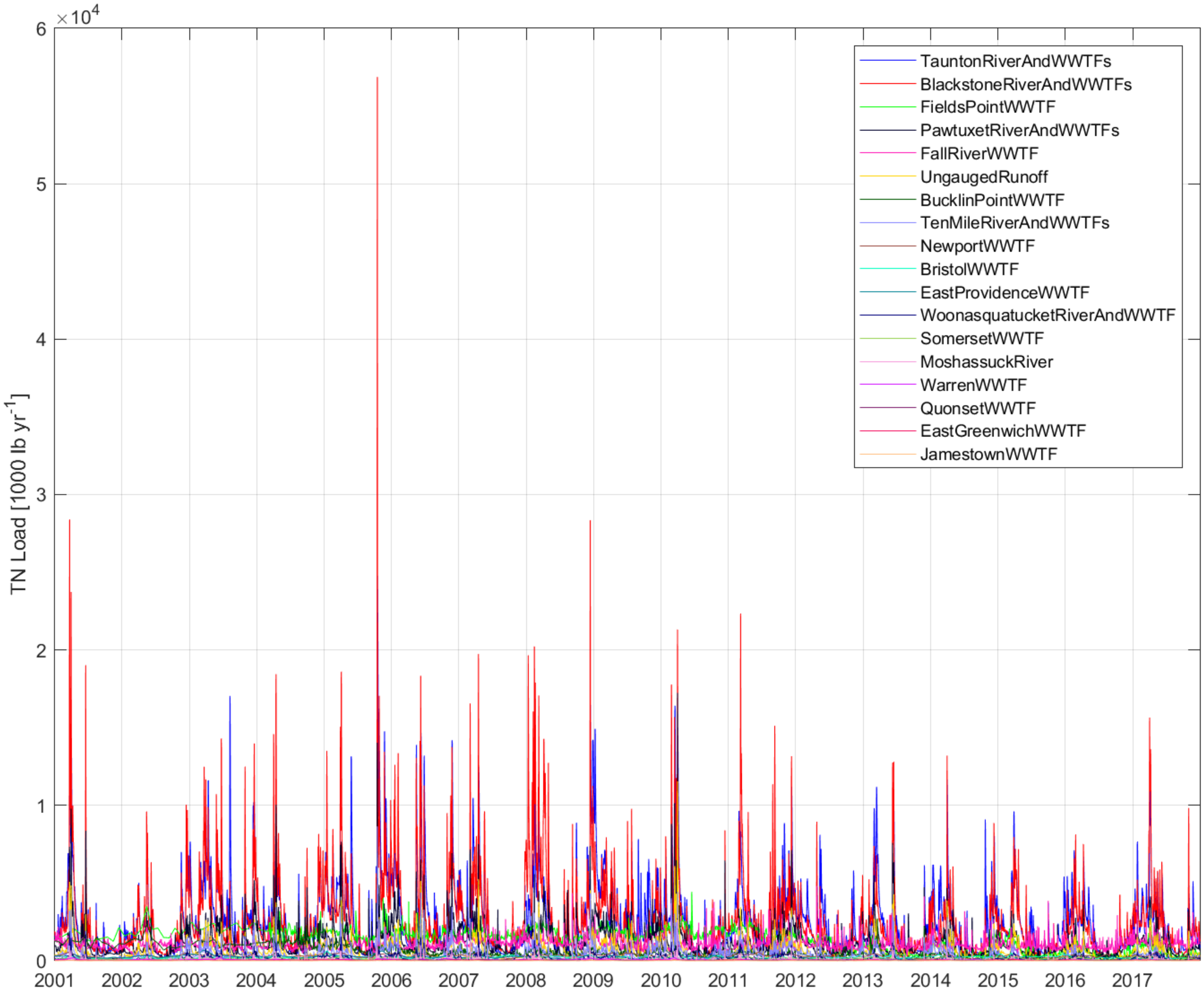

**Figure 20b.** TN load time series of the 18 sources superposed on the same figure. Logarithmic y-axis scale.

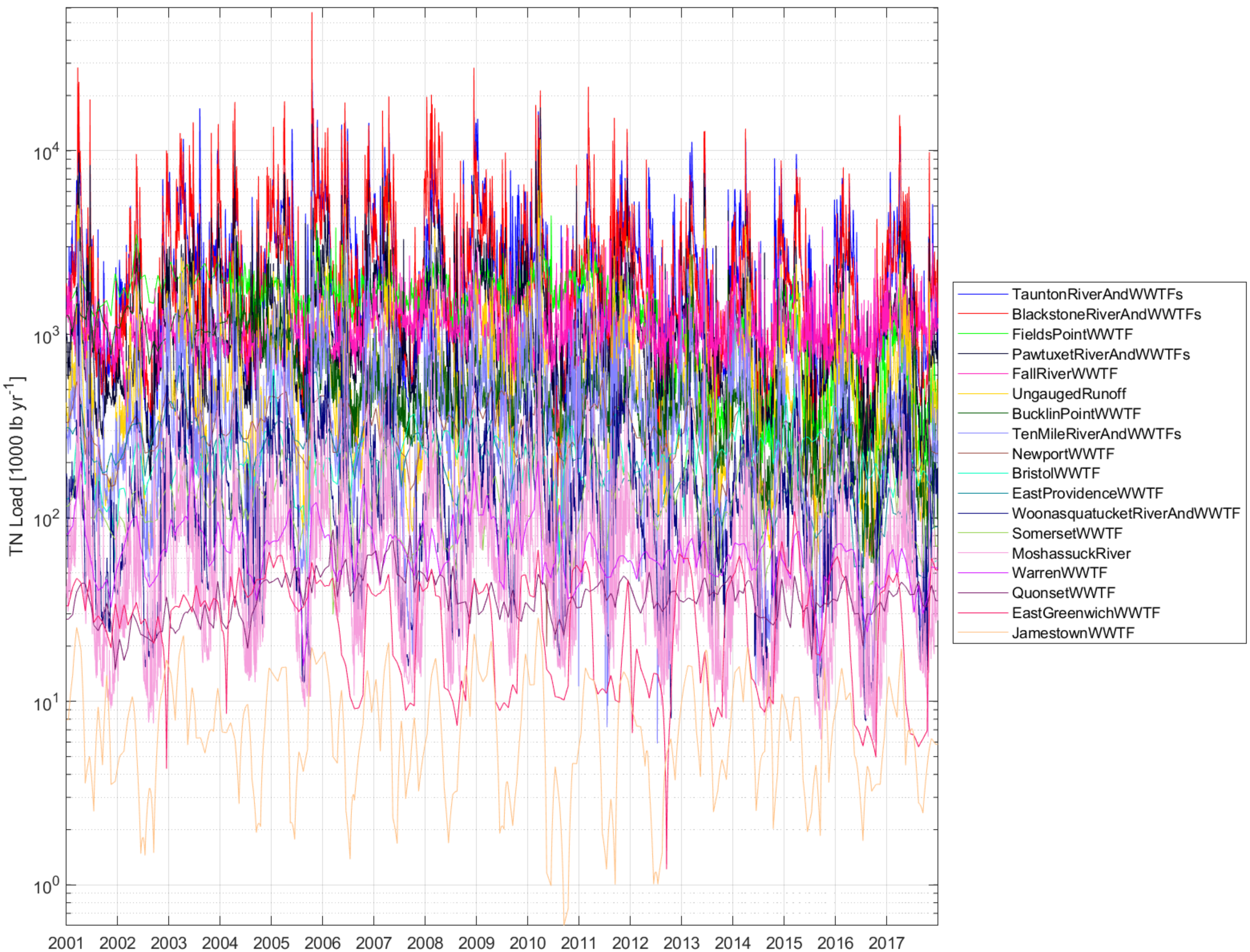

**Figure 21.** Total TN load (summed loads from 18 sources) to Narragansett Bay.