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Nitrogen in Runoff from Residential Roads in a Coastal Area

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Abstract Non-point sources of nitrogen (N) contribute to pollution of many coastal waters. Road runoff of N has been estimated for busy highways, but residential roads could also be important non-point sources. Here we estimate N in runoff from two small residential roads (average annual daily traffic [AADT] <1,000) and a state highway (AADT=8,800) in a coastal watershed of Massachusetts, USA. The antecedent dry-day traffic was correlated with total dissolved nitrogen (TDN) concentrations at the beginning of each rain event for the highway, but not for the residential roads. The TDN concentrations declined exponentially with cumulative precipitation during storms. Estimated annual road runoff is about 10 kg TDN-N ha^{-1} of road surface for all three roads, which is about twice the bulk precipitation input. Because much of this road runoff enters sensitive coast water bodies directly, these inputs could be important for local water quality concerns.

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1 Introduction

Non-point sources of nitrogen (N) are thought to be the important contributors to pollution of many coastal waters (EPA 2001; Howarth et al. 2000, 2005; NRC 1993, 2000; Pew Oceans Commission 2003). Two-thirds of the nation's estuaries are moderately or severely degraded from N pollution, and the coastal zone of the northeastern USA has some of the most acute problems from N pollution in the country (Bricker et al. 1999; NRC 2000). Excess N inputs to coastal ecosystems cause eutrophication (Howarth and Marino 2006; Nixon 1995), which results in alterations in aquatic community structure, degradation of habitat quality, and increased incidences and duration of harmful algal blooms (Howarth et al. 2000; NRC 2000; Rabalais 2002). The inputs of N to the coastal waters of the USA are projected to continue to increase over future decades (Howarth et al. 2002a, 2005), in part due to rapid population growth in the coastal zone (Paerl 1997). Non-point sources of N pollution present a major challenge, not only because the sources are diffuse, but also because not all sources have been identified and well quantified. Important non-point sources can include septic tank discharge through groundwater, runoff of fertilizer from lawns and agricultural fields, animal feedlot operations, atmospheric deposition, and road runoff (NRC 2000; Howarth et al. 2002b; Valiela and Bowen 2002).

Nitrogen in vehicle exhaust, emitted as nitric oxide, nitrogen dioxide, nitrous acid, and ammonia, is a source of N both to the air and to road surfaces, which in turn can enter aquatic systems as atmospheric deposition and as road runoff during precipitation events. Increasing density of impervious surfaces within watersheds has been shown to be related to increased concentrations of streamwater N (Kaushal et al. 2008; Wollheim et al. 2005) and salinity (Kaushal et al. 2005), and has been related to declines in stream biodiversity (Paul and Meyer 2001). Here we examine N in runoff from small and moderate-sized residential roads as a potential source of N to a coastal water body.

Barnstable County is a coastal community in Massachusetts, locally known as "Cape Cod," which has seen very large increases in population, development, and vehicular traffic during the last 50 years. Population has increased 400% from 47,000 in 1950 to 230,000 in 2004. Consequently, during that same period, the number of miles driven on Cape Cod has also increased dramatically. For instance, the number of bridge crossings (cars coming onto Cape Cod) increased from 35,500 cars per day in 1969 to 98,000 cars per day in 2004 (Cape Cod Commission 2005). The estimated daily average of total vehicle miles traveled on Cape Cod in 2000 is five to six million miles (Cape Cod Commission 2007). The consequences of the increased local traffic volume on the rates of N deposition and road runoff in coastal land and water bodies are poorly known. Although the total traffic volume and road densities are high on Cape Cod, much of the traffic is distributed on two-lane roads that have annual average daily traffic (AADT) <30,000 vehicles. Nevertheless, many of these roads pass close to sensitive coastal areas, where road runoff of N could affect water quality of coastal lagoons. Much of the road runoff is directed to ditches that often flow directly into coastal ponds or waterways or that pass through sandy soils on glacial till, resulting in largely unmodified inputs of road surface deposition.

Most of the data in the literature on N in road runoff are from highways with high traffic volumes. Published studies on highways with AADT >100,000 have shown that the accumulation of N on roadways reaches an asymptote after several days without precipitation (Han et al. 2006; Kim et al. 2006). In a study of rural and urban roads in California ranging in AADT from 2,100 to 328,000, Kayhanian et al. (2007) found that both AADT and antecedent dry days (ADD) were positively correlated with nutrient runoff concentrations, including N, but no quantitative relationships were offered. Gilbert and Clausen (2006) demonstrated that N concentrations in runoff from residential driveways were within the range reported in other studies for busy highways, suggesting that N in road runoff could be significant in areas with low traffic volumes. The objectives of this study are (1) to estimate runoff of N from roads near a coastal region of Cape Cod that usually experience from 300 to 10,000 vehicles per day and (2) to estimate the amount of N in road runoff annually for three such representative roads in the Oyster Pond watershed of Falmouth, Massachusetts.

2 Site and Methodology

2.1 Site Description

This study was conducted in the Town of Falmouth, Massachusetts, which has a population of about 33,000 year-round residents. Located about 120 km from Boston, Falmouth, a residential community, is the home of several scientific research organizations, and is a popular tourist destination. Like other townships on Cape Cod, Falmouth experiences a large increase of summer residents and tourists. Woods Hole Road is a state highway that connects the small business center of Falmouth with the village of Woods Hole and the terminal for ferry service to the island of Martha's Vineyard.

The sample sites for this study, on Woods Hole Road, Oyster Pond Road, and Quonset Road, are located in the watershed of Oyster Pond, which is a brackish coastal lagoon (Fig. 1). Soils along Woods Hole Road and Oyster Pond Road are predominately of the Barnstable–Plymouth complex, which are excessively drained to well-drained, rolling, and very bouldery. The Barnstable series are classified as coarse-loamy over sandy or sandy-skeletal, mixed, active Typic Dystrochrepts. The Plymouth series is excessively drained sand, classified as

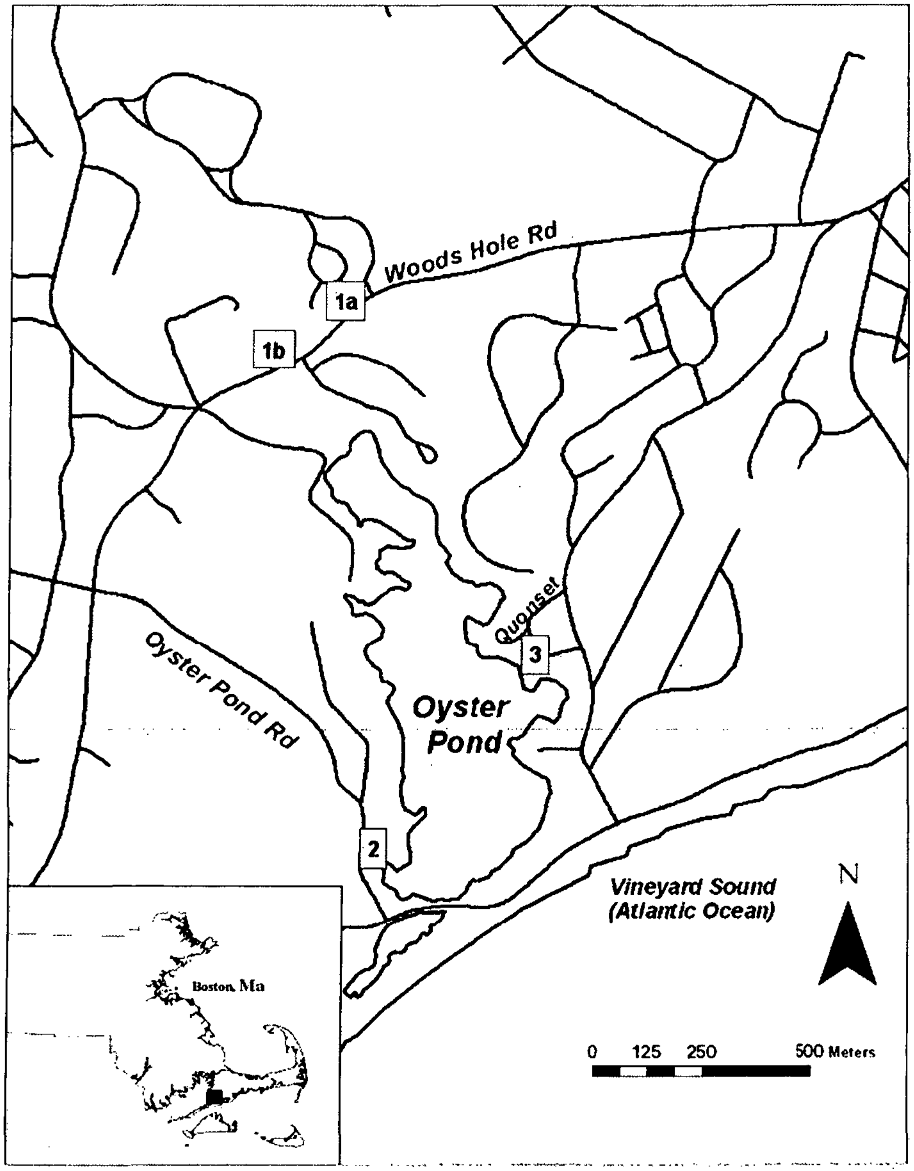

Fig. 1 Map of local roads and road runoff sampling locations around Oyster Pond, Falmouth, MA, USA: *1a* Woods Hole Road sampling point A, *1b* Woods Hole Road sampling point B, *2* Oyster Pond Road, *3* Quonset Road. The *inset* map shows the location on Cape Cod (*black square*) relative to Boston and eastern Massachusetts

mesic, coated Typic Quartzipsamments. Soils near Quonset Road are Sudbury series, moderate to poorly drained, classified as sandy mixed, mesic Aquic Dystrochrepts.

Three sections of road within the Oyster Pond watershed were selected: (1a and 1b) Woods Hole Road (41°32′54.62″ N, 70°38′34.40″ W), with approximately 8,800 AADT; (2) Oyster Pond Road (41°32′28.84″ N, 70°38′30.30″ W), a residential road with estimated AADT of 650; and (3) Quonset Road (41°32′31.87″ N, 70°38′09.81″ W), which is another residential road similar to number 2 and with estimated AADT of 320. During one precipitation event on September 15, 2006, we were able to collect samples nearly simultaneously at two locations on Woods Hole Road, about 100 m apart, which provides some indication of replicability for this road. The two residential roads are treated here as replicates for traffic classes with low (<1,000) AADT. The Town of Falmouth has collected vehicle count data on Woods Hole Road during snow-free periods, and these data were used to derive a daily vehicle count during our study period. No seasonally variable traffic counts were available specifically for the two small residential roads, but monthly traffic counts were available for similar roads that were identified by the Town of

Falmouth as being in the same traffic count classes, which we used to estimate the seasonal patterns of daily traffic count on Oyster Pond and Quonset roads. Vehicle traffic on residential roads and highways on Cape Cod peaks during the summer tourist season and declines in winter. The AADTs of these roads are among the lowest values of studies reported in the literature (Table 1).

2.2 Sample Collection

Road runoff was collected by placing rubber gasket material flush with the asphalt pavement at the diversion ditch on the side of the road and diverting the flow into a wide mouth plastic bottle on the downslope side of the road. Care was taken to collect the sample directly from the pavement and to avoid commingling with runoff in contact with unpaved surfaces. On three separate rainfall events, road runoff samples were collected as soon after the rain began as possible and at approximately hourly intervals, or more frequently as the rainfall intensity required. For four additional storm events, only the initial collections were made. The time was recorded when each sample was taken so that sample time could be matched with the precipitation intensity record logged by a tipping bucket rainfall collector located in an open field at the Woods Hole Research Center campus on Woods Hole Road. The tipping bucket recorded each 0.25 mm precipitation.

During rainfall events we observed and measured the length and width of road segment that drained into each ditch. These areas were 239, 972, and 536 m^2 for Woods Hole, Oyster Pond, and Quonset roads, respectively.

2.3 Analysis of Nitrogen

Within a few hours after collection, samples were passed through a glass microfiber filter, (Ahlstrom, 0.70 μm) and frozen until analysis. Samples were analyzed for N using a Lachat QuickChem Flow Injection Analyzer. Total dissolved nitrogen (TDN) was determined by an inline persulfate digestion method (QuikChem method 10-107-04-3-). Nitrate/nitrite concentrations were determined by cadmium reduction and colorimetry (QuikChem method 10-107-04-1-L). Ammonia was determined by colorimetry (Quickchem method 10-107-06-2-A).

2.4 Statistical Analyses

For each road, we explored relationships between the initial TDN concentrations and antecedent dry days, the average daily traffic (ADT), and the product of these two (antecedent dry day traffic (ADDT)= ADD×ADT; Fig. 2). To characterize the rate of decline of N concentrations (flushing) during precipitation events, the N concentrations for each road and each time point were normalized by the initial

Table 1 Comparison of reported event mean nitrogen concentrations (EMC) of road runoff in a variety of land uses

Study	Surrounding land use	AADT	EMC(mg N L^{-1})
Han et al.2006[a]	Urban	260,000	12.6
Caltrans state wide data 1997–2003[a,b]	Urban	>30,000	3.70
Re-analysis of Caltran using only rural roads 2002–2003 only[a]	Rural	<10,000	1.50
Wu et al.1998[a]	Rural/residential	17,300	2.07
Flint and Davis2007[a]	Urban	Unknown	4.54
This study[c]	Highway/residential	8,800	1.07
	Woods Hole Road	655	1.19
	Oyster Pond Road	325	1.30
	Quonset Road		

[a] EMC values are the sum of Total Kjeldahl Digestion (TKN), NO_2^- and NO_3^- from the respective manuscripts

[b] California Department of Transportation, Caltrans Environmental Program: Stormwater Monitoring Data http://www.dot.ca.gov/hq/env/stormwater/ongoing/monitoring/

[c] EMC values are TDN, which includes NH_4^+, NO_2^-, and NO_3^-

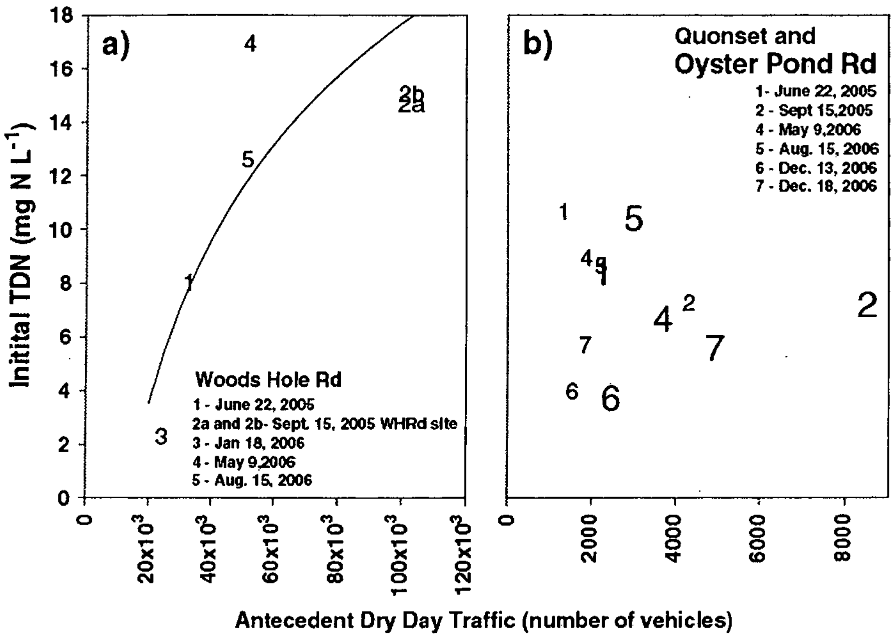

Fig. 2 **a** Initial total dissolved nitrogen (TDN) concentrations in road runoff for Woods Hole Road as a function of antecedent dry day traffic (ADDT) estimates for five rainfall events. Each data point is plotted with a number, which also serves as a code for the sampling date, as indicated. The two sampling stations on Woods Hole Road for Sept 15, 2005 (a and b) were averaged prior to the regression analysis. The regression equation for the fit in panel a is: $[\mathrm{TDN}] = 8.82^{*} \ln(\mathrm{ADDT}) - 83.84$ $R^2 = 0.58$, $p = 0.08$. **b** Initial total dissolved nitrogen (TDN) concentrations in road runoff for Quonset (*small number symbols*) and Oyster Pond Road (*large number symbols*) for the dates indicated by the symbol numbers

concentration for that road and that storm event. These normalized concentrations were plotted against cumulative precipitation of each storm event. An exponential function was fit to these data for Woods Hole Road and a separate exponential function was fitted for the combined small residential roads. The *Y* intercept was forced through unity, and the asymptote was forced through the average observed fraction of normalized TDN concentration at the end of each storm event. Hence, the only fitted parameter was the exponent that determined the shape of the curve (Fig. 3).

2.5 Calculation of Annual Rates of Road Runoff of TDN

The antecedent dry day traffic for each precipitation event from April 2006 to March 2007 was calculated based on the precipitation record and the monthly estimates of average daily traffic for each road. The correlations between ADDT and initial TDN concentrations were used to estimate the initial TDN concentration for each precipitation event during this period for Woods Hole Road. For the residential roads, a seasonal mean was used to estimate initial TDN concentrations for each storm event, because there was no correlation with ADDT for these roads. A precipitation event was defined as starting at the initial measurement of rainfall and ending when there were >24 h of no rainfall. No road runoff was produced with precipitation events of 0.25 mm or less, and therefore these events were not included.

Once the initial TDN concentration on each road was estimated for each precipitation event, the exponential functions derived to fit the declining concentrations during flushing (Fig. 3) were used to estimate the time course of TDN concentrations for each event and road class. The first 0.25 mm usually generated no runoff and was not included in this sum. We assume that the remainder runs off the road, because each of these three roads have features that promote rapid runoff and little puddle formation and evaporation. As a state

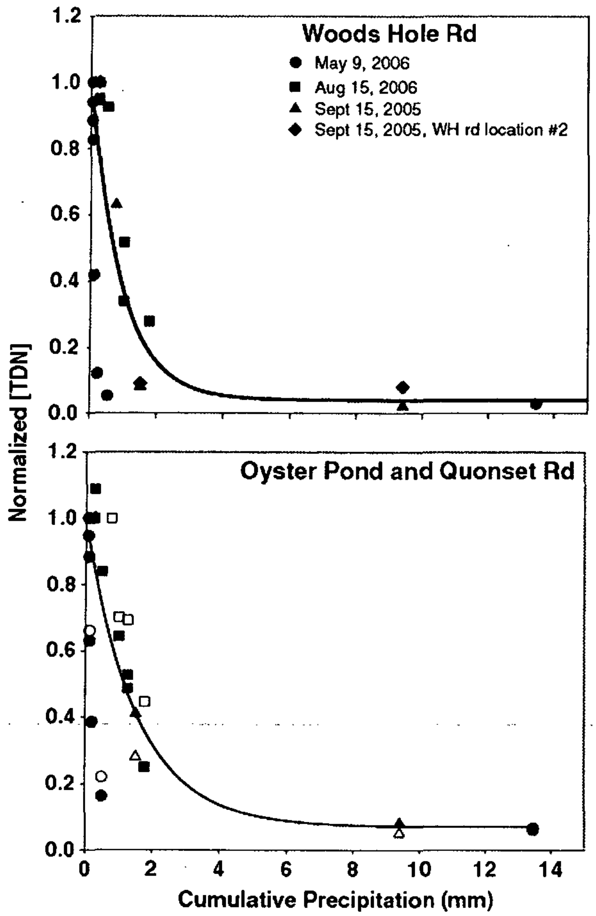

Fig. 3 Normalized total dissolved nitrogen (TDN) concentrations as a function of cumulative precipitation during three storm events on Woods Hole Road (*top panel*) and Oyster Pond and Quonset Roads (*lower panel—symbols* in the lower panel represent the same dates as indicated in the upper panel; *open symbols* are for Quonset Road and *closed symbols* are for Oyster Pond Road). The equations for the regressions are: Upper panel : $Y = 0.04 + 0.96^* \exp(-1.06^* X)$, $R^2 = 0.59$, $p = 0.0005$; Lower panel : $Y = 0.07 + 0.93^* \exp(-0.66^* X)$, $R^2 = 0.58$, $p < 0.0001$

highway, Woods Hole Road is designed with sloping sides to direct runoff into storm sewers. Oyster Pond Road is on a hill. The segment of Quonset Road that we studied was also designed to drain into a storm sewer that then drained directly into Oyster Pond.

Based on the estimates of concentration for each 0.25 mm increment of precipitation, the TDN load in each 0.25 mm of runoff increment was calculated, and these products were summed for volume of precipitation recorded for each event by a tipping bucket rainfall collector. The calculation for a single storm event is represented by the following equation:

$$\mathrm{TDN}_{\mathrm{total}} = \sum_{i=0.25}^{i=P\mathrm{tot}} 0.25 \times \mathrm{TDN}_{\mathrm{initial}} \times \left[\alpha + \left(\beta \times e^{(\gamma \times Pi)}\right]\right. \quad (1)$$

where $\mathrm{TDN}_{\mathrm{initial}}$ is the initial TDN concentration at the beginning of each storm event, determined from ADDT estimates for Woods Hole Road and from seasonal means for the small residential roads (Fig. 2), P_{tot} is the total precipitation in the event, α, β, and γ are parameters describing the shape of the exponential decay of TDN during the storm (Fig. 3), and P_i is the cumulative precipitation during the event for each increment of 0.25 mm. For Woods Hole Road, α, β, and γ were 0.04, 0.96, and −1.06, respectively; for the residential roads they were 0.07, 0.93, and −0.66, respectively (see Fig. 3 caption).

3 Results and Discussion

3.1 Nitrogen Concentrations

Initial concentrations of TDN in road runoff at the beginning of precipitation events ranged from to 2 to 17 mg N L^{-1} on Woods Hole Road and 0.4 to 10 mg N L^{-1} on the small residential roads, which generally exceeded the average bulk precipitation concentration of 0.5 mg N L^{-1}. Ammonium ranged from 7–74% of TDN, averaging 34% of TDN. Nitrate ranged from 0.2–64% of TDN, averaging 25%. The event mean concentrations were similar to other values reported in the literature for residential and rural roads (Table 1).

For Woods Hole Road, the initial TDN concentrations were correlated with antecedent dry-day traffic (ADDT; Fig. 2a). Using ADDT as the independent variable provided a better fit for Woods Hole Road than only the number of antecedent dry days. In contrast to the state highway, there was no relationship between initial TDN and ADDT for both Oyster Pond and Quonset residential roads (Fig. 2b). However, there was a seasonal trend (Fig. 2b), with higher concentrations of TDN measured in runoff from these roads during the summer (mean 8.5 mgN L^{-1}, SD 1.5, n=8) compared to the winter (mean 4.7, SD 1.1, n=4).

These results indicate that significant N is present in road runoff even on small residential roads (ADDT <1,000). A similar result has been reported for residential driveways (Gilbert and Clausen 2006) and parking lots (Hope et al. 2004), which are also significant sources of N in runoff. Because automobile catalytic converters operate less effectively during the first 1–2 min after ignition (Wallington et al. 2006), vehicles may deposit more N on residential roads as they depart from residences compared to when they are later cruising on larger roads that are generally used by traffic originating from longer distances. Quantities of N emitted from exhaust vary, depending on several factors related to the type of engine, catalytic converter, fuel, and operating conditions (Cape et al. 2004; Durbin et al. 2002). Bird droppings, insect frass, and intercepted dry deposition from overhanging trees may be additional sources of N inputs to residential roads and driveways. Pet excrement and runoff from fertilized lawns could also contribute N to some residential roads. Although some of the sources of N may be non-vehicular, the residential road nevertheless can serve as a conduit for transporting the N to nearby water bodies.

The TDN concentration declined exponentially as a function of cumulative precipitation during each storm event (Fig. 3). This type of flushing has been commonly observed in the literature (Egodawatta et al. 2007; Han et al. 2006). The exponential decline in TDN concentrations was somewhat less steep in the residential roads compared to the state highway (Fig. 3), which could reflect delayed runoff from adjacent lawns. The final TDN concentrations at the end of precipitation events averaged 4–7% of the initial concentrations and were nearly identical to TDN in bulk precipitation, which averaged 0.5 mg N L^{-1}.

3.2 Uncertainty Analysis of N Load in Storm Runoff

To estimate uncertainty in estimates of the N load during a single storm, we applied a Monte Carlo analysis to the data from the storm of September 15, 2005, first analyzing uncertainty in the initial TDN concentration estimates, and then analyzing uncertainty in the fitted β values for the exponential decay of TDN concentrations during the storm (Eq. 1). A normally distributed population of 1,000 estimates of initial TDN was generated for each road, using the summer mean (8.5 mg N L^{-1}) and standard deviation (1.5 mg N L^{-1}) for the small roads and the predicted TDN for Woods Hole Road (18.0 mg N L^{-1}, based on ADDT for that storm and the regression in Fig. 2a) and the mean square error of that regression model (3.8 mg N L^{-1}). The N load for that storm was calculated according to Eq. 1 for each of the 1,000 estimates of initial TDN concentrations. The mean± standard deviation of these distributions of N load estimates were 17.0±2.9 mg N m^{-2} for the small roads and 21.8±4.8 mg N m^{-2} for the Woods Hole Road. The N loads estimated using measured initial TDN on September 15 rather seasonal means and regression estimates were 14.1 and 19.3 mg N L^{-1} for the small roads and Woods Hole Road, respectively.

A similar Monte Carlo analysis was conducted for the fitted β parameter of Eq. 1, which accounts for the shape of the flushing function (Fig. 3). A boot strapping procedure with replacement was run in R software on the regressions shown in Fig. 3 to estimate the standard deviation of the fitted β value. A normally distributed population of 1,000 estimates of β was calculated for each road, and the N load for the September 15 storm was estimated using the initial TDN estimates for each road and the population of β values. The mean±standard deviation of these distributions of estimates were 19.0± 1.2 mg N m^{-2} for the small roads and 22.2± 2.0 mg N m^{-2} for the Woods Hole Road. Hence, the shapes of these flushing functions contribute less uncertainty to the estimated N load than do the estimates of the initial TDN concentrations.

3.3 Annual Estimates

We used the relationships developed from our measurements during seven storm events to estimate N in road runoff for all storm events for a 12-month period. First, a value for initial TDN concentrations ($TDN_{initial}$ in Eq. 1) was calculated for each storm event and each road. For Woods Hole Road, $TDN_{initial}$ values were determined from ADDT estimates for Woods Hole Road based on the regression in Fig. 2a. For the two small residential roads, summer (mean 8.5 mg N L^{-1}, SD 1.5, n=8), and winter (mean 4.7, SD 1.1, n=4) seasonal means of $TDN_{initial}$ concentration were used. Second, because the road runoff concentrations are initially high and then drop off quickly during the storm, the total amount of TDN in road runoff during a storm event must be calculated by estimating the concentration change with cumulative runoff volume throughout the storm (Fig. 3, Eq. 1). We applied Eq. 1, using the functions for the nonlinear regressions shown in Fig. 3, to estimate the time course of decreasing concentration of TDN during each precipitation event. The sum for each storm event is plotted in Fig. 4, and the sums for all events for the 12-month period are also indicated there.

The largest estimated TDN load for an event occurred during a large rainfall (16 cm) in June 2006, following 5 days with no significant precipitation (Fig. 4). Large cumulative sums of TDN for big precipitation events partly reflect the accumulation of N in the rainfall, whereas large cumulative sums of TDN after several antecedent dry days reflect the accumulation of N derived from traffic and other sources.

The importance of the N from the road surface relative to the N in the rainfall can be identified by comparing the annual estimate of road runoff to annual estimate of N in bulk precipitation. We estimate that annual road runoff was about 10 kg TDN-N ha^{-1} of road surface, for both road classes of this study (Fig. 4). For comparison, TDN in bulk precipitation collectors was 4.8 (SE±0.2) kg N ha^{-1} $year^{-1}$ at nearby Waquoit Bay in the Town of Falmouth (Bettez 2009). Some atmospheric dry

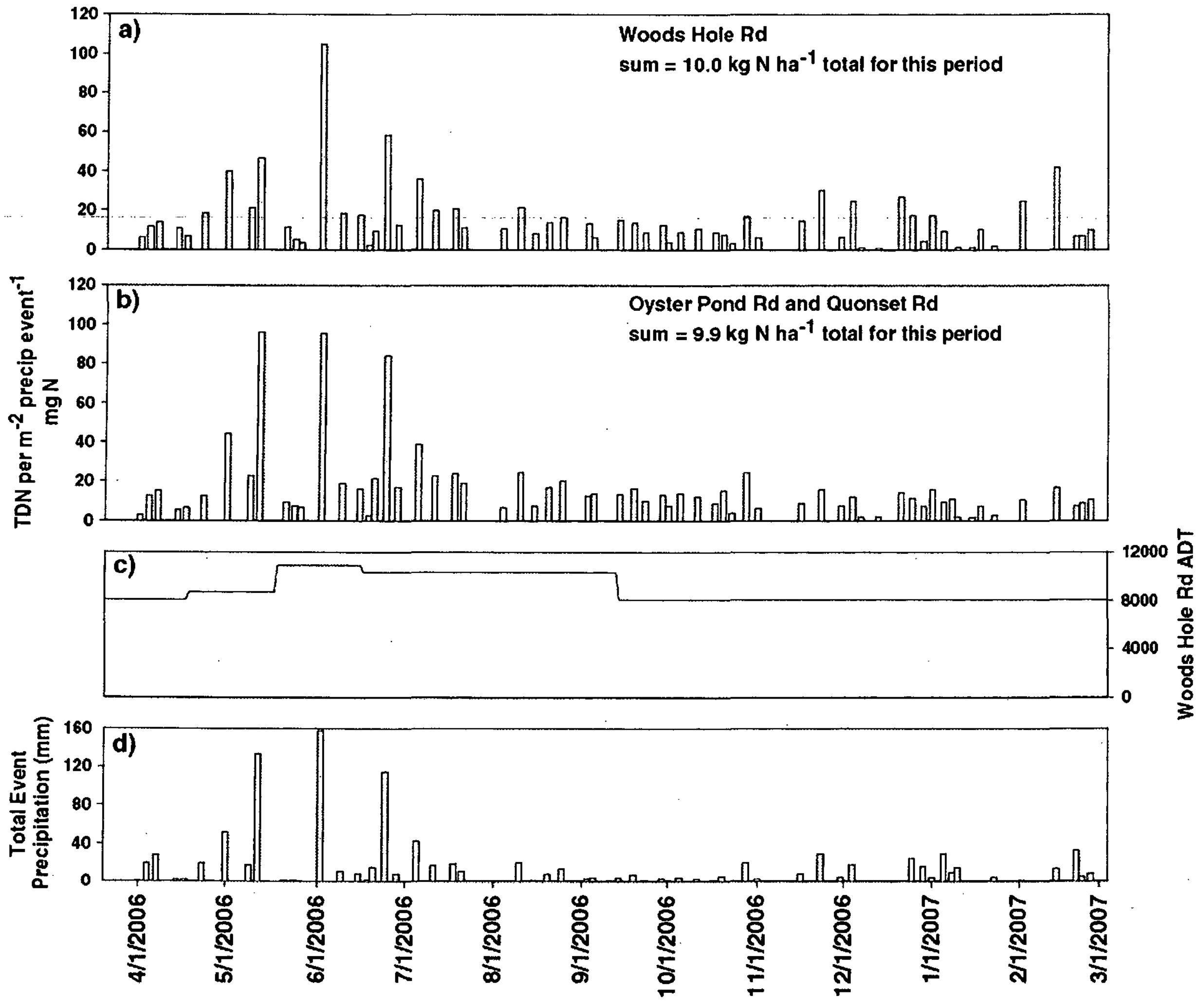

Fig. 4 Calculated total dissolved nitrogen (TDN) in road runoff for each precipitation event for **a** Woods Hole Road, **b** Oyster Pond Road and Quonset Road combined, **c** the monthly pattern of traffic on Woods Hole Road (*ADT* average daily traffic) and **d** daily precipitation during the study periods

deposition onto road surfaces is possible, but roads generally are poor interceptors of dry deposition compared to foliage, which has more exposed leafy surface area per unit of ground area. A further complication is that N in throughfall collected beneath trees within 10 m of roads (8.7 kg N $ha^{-1}year^{-1}$; SE=0.4) has been shown to be greater than deposition in forest stands 150 m from a road (6.8 kg N ha^{-1} $year^{-1}$; SE±0.5), indicating that local vehicular traffic not only contributes to N on road surfaces, but also to dry deposition onto nearby foliage (Bettez 2009). Estimates of dry deposition range from 4.0 to 2.0 kg N $ha^{-1}year^{-1}$ along transects perpendicular to roads (Bettez 2009). As discussed above, we cannot distinguish among N from automobile exhaust deposited directly onto the road surface, deposition and throughfall from overhanging trees and shrubs, and runoff from driveways and lawns as the sources of the N being transported by road runoff. In any case, the difference between N in road runoff and in bulk precipitation provides an estimate the sum of N inputs to roads. The annual road runoff estimates are about double the annual bulk precipitation N deposition estimates, indicating an important role for the road as a potential conduit for elevated concentrations of N to adjacent water bodies.

Paved surfaces (roads and parking lots) cover 12–13% of Cape Cod and only 5% of the Oyster Pond watershed (T. Stone and K Savage, unpublished data, The Woods Hole Research Center), so it might seem at first that increased transport of N over this relatively small area of paved surfaces would be trivial in the watershed N balance. However, much of the N that is deposited onto the unpaved landscape is retained rather than being exported. For a nearby forest on Cape Cod, Lajtha et al. (1995) estimate that ~50% of deposition is retained and 50% exported. For most forests on less sandy soils, an even smaller percentage of deposition is exported downstream (Howarth et al. 2002b). A model often used to predict N loading to coastal waters on Cape Cod assumes that approximately 90% of N deposition is retained by both forests and suburban lawns (Valiela and Bowen 2002). In contrast, the runoff from Quonset Road flows directly into a drain, which is then diverted directly into Oyster Pond via a storm sewer, and runoff from Oyster Pond Road has been observed to overflow a small berm at the bottom of a hill and then flow through an unpaved gully into Oyster Pond. We have also observed runoff from Woods Hole Road reaching Oyster Pond during large storm events by flooding the property between the road and the pond with storm sewer overflow. This state highway is well designed to drain into storm sewers and gutters, but the fate of that runoff is then often inadequately managed. In short, management of stormflow from lawns, driveways, and roads is inconsistent, often ineffective, and sometimes nonexistent. Although some road runoff probably infiltrates the sandy soils, much of the N in road runoff may be shunted directly to the water body before it can be absorbed by soils and vegetation along the way, thereby potentially having a larger impact on water quality than the N that is deposited in a distributed fashion throughout the watershed as rainfall and as dry deposition.

Assuming that total deposition onto the watershed averages ~5 kg N $ha^{-1}year^{-1}$, and that 50% (Lajtha et al. 1995) to 90% (Valiela and Bowen 2002) of that is retained by vegetation and soils where it falls on the unpaved surfaces, then the average export from unpaved surfaces would be about 0.5–2.5 kg N $ha^{-1}year^{-1}$. Assuming that 50–100% of the 10 kg N $ha^{-1}year^{-1}$ of road surface runoff is exported—50% is the lower limit based on export estimates in sandy soils by Lajtha et al. (1995) and 100% is obviously the upper limit—then average export from paved surfaces would be 5–10 kg N $ha^{-1}year^{-1}$. Given that 95% of the watershed is unpaved and 5% paved, then the area-weighted average export must be in the range of 0.7–2.8 kg N $ha^{-1}year^{-1}$, and the road runoff contribution of this total export would be 0.25–0.5 kg N $ha^{-1}year^{-1}$, or about 10–70% of the total N exported from the watershed. Watersheds with higher road densities could have larger contributions from road runoff. For comparison, Valiela and Bowen (2002) estimated delivery of N from land to the estuary in the nearby Waquoit Bay watershed at average rates of 1.4, 0.7, and 2.2 kg N $ha^{-1}year^{-1}$ from atmospheric deposition onto land surfaces, fertilizers, and wastewater respectively. Of course, there are many uncertainties in our road runoff estimate, but the calculations demonstrate that the magnitude of N in runoff from small residential roads and from a state highway with relatively modest traffic flow is sufficiently large to potentially be an important contributor of N to nearby coastal water bodies.

Diversion of road runoff to retention basins has been shown to reduce the load of N in stormwater

(Zhu et al. 2004; Scholz and Yazdi 2009). Here we show that stormwater management could also be important for retention of N in road runoff from both small and large roads that might otherwise lead to direct releases of N to coastal water bodies.

4 Conclusions

This study demonstrates that even small residential roads (annual average daily traffic <1,000) can accumulate significant N between precipitation events. For both the residential roads and a state highway (AADT=8,800), annual runoff was about 10 kg TDN-N ha^{-1} of road surface, which was about double bulk precipitation input. Because much of the road runoff near sensitive coast water bodies enters those waters directly, these inputs could be important for local water quality concerns. Hence, mitigation efforts to manage runoff may be warranted for both small and large roads near sensitive water bodies.

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