Quantifying the cumulative effects of stream restoration and environmental site design on nitrate loads in nested urban watersheds using a high-frequency sensor network

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Abstract

We analyzed high-frequency nitrate and stream discharge data from heavily instrumented, nested watersheds in suburban Baltimore to address the Chesapeake Bay Trust (CBT) Restoration Research question: *What are the cumulative effects of watershed restoration activities within a watershed?* Restoration for the purpose of stream stabilization was installed in 2017-2018 over 536 m of Dead Run in Baltimore County, MD under auspices of the Baltimore County Department of Environmental Protection and Sustainability. The CBT project supported subsequent installation of nitrate sensors and pressure transducers at the inlets to, and outlet from, the restored stream reaches. Nitrate concentration and stream discharge data were collected beginning in August 2018 and used to calculate 30-minute nitrate mass fluxes at the stream stations. Mass fluxes were summed to determine mass balance across the restoration reach and daily, quarterly, and annual intervals. For the calendar year 2020, mass balance calculations showed no net removal of nitrate across the restored reach. However, for the same period, seasonal mass balances showed a slight reduction in nitrate load across the restored reach during the growing season. Mass balance calculations also identified a steady tributary hotspot of high nitrate concentration as one input to the restored reach. The restoration was nested within three downstream stations where four years of pre- and three years of post-restoration data were available. Evaluation of mean daily nitrate concentration as a function of mean daily discharge at these downstream stations suggests that there may have been some enhanced nitrate reduction at intermediate discharge values for the years following restoration, but available data do not allow us to attribute these changes to any one cause.

1. Introduction

This project sought to address elements of Question 1 of the Chesapeake Bay Trust 2018 RFP on watershed restoration assessment: ***What are the cumulative effects of watershed restoration activities within a watershed?*** We analyzed high-frequency nitrate and flow data from heavily instrumented watersheds in suburban Baltimore to address this question.

The specific objectives of the project were as follows:

(1) Assess the effectiveness of a treatment train (a wetland pond coupled with stream restoration) on removal of nitrate loads, where the water quality detention basin is designed to treat storm flows and the stream restoration is expected to be most effective (remove a higher percentage of nitrate) at base flow and small storms.

(2) Quantify nitrate loads for the same time period at each of the measurement locations upstream of the restoration site and within the restoration site to calculate a mass balance across the restoration site.

(3) Quantify nitrate loads in relation to flow at the watershed outlet downstream of the restoration for conditions before and after installation of the restoration project and wetland pond.

2. Site Description

The experimental design focused on nested urbanized catchments within Dead Run watershed, in suburban Baltimore, MD (Figure 1b, Table 1). Dead Run drains to the Gwynns Falls, which empties into Baltimore Harbor and Chesapeake Bay (Figure 1a). Water quality impairment of Dead Run has been assessed by Baltimore County's Phase II Watershed Implementation Plan (WIP) (Baltimore County DEPS, 2012), and is designated as high priority for reduction of nutrients and sediment to the Middle Gwynns Falls by Baltimore County's Small Watershed Action Plan (SWAP) (Parsons Brinckerhoff, 2013a,b).

In fall of 2017, a stream restoration along the upper reaches of the DR5 drainage network was installed by Baltimore County, primarily for the purpose of stream stabilization, but with expected ancillary nutrient and sediment removal benefits (WSP/ Parsons Brinckerhoff, 2015). The length of stream restored was 536 m (1760 ft). Using nutrient credit values for stream restoration in Berg et al. (2013, Table 3), the restoration was projected to reduce the total nitrogen load to the stream by 60 kg/yr (132 lb/yr). In addition, in late fall of 2017 and continuing into spring of 2018, a water quality pond was installed adjacent to the stream restoration that is designed to reduce nitrogen loading by ~100 kg/yr (228 lb/yr) (WSP/ Parsons Brinckerhoff, 2016). The pond is designed to treat the first one inch of runoff from storm flows exiting the Gilston Park Road culvert. The extent of the stream restoration and location of the water quality pond are delineated by red lines in Figure 2b.

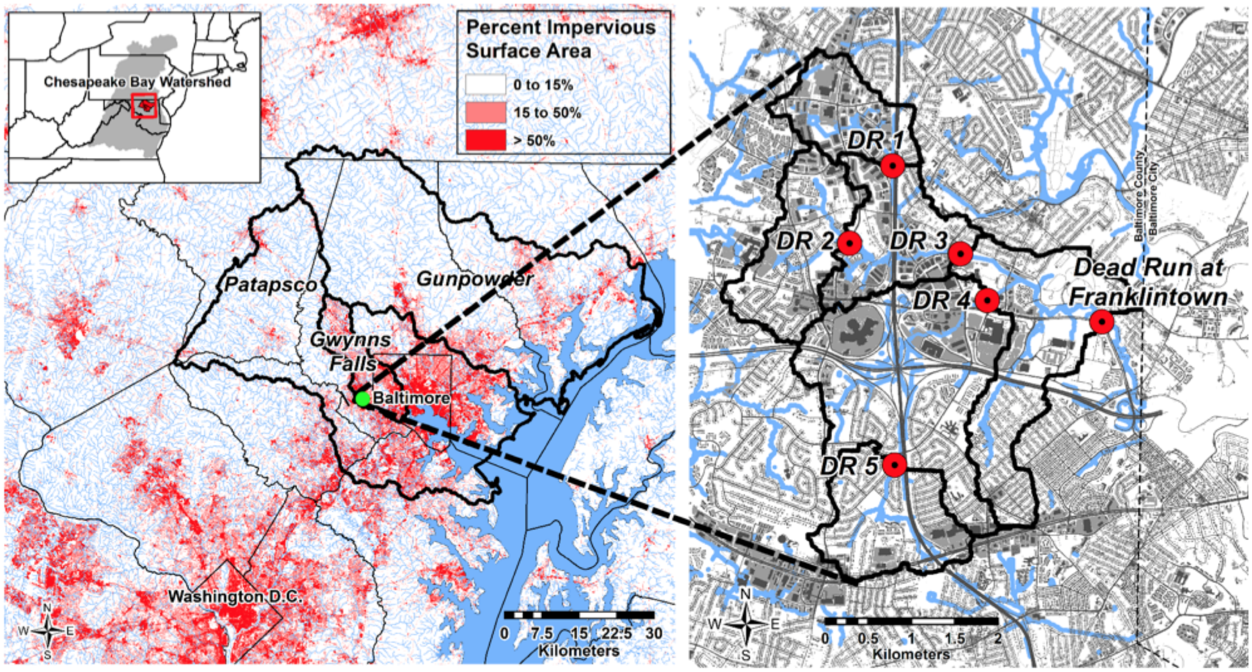


Figure 1. (a) The Gunpowder-Patapsco (~3500 sq km) drainage to the Chesapeake Bay; (b) Dead Run urbanized watershed in suburban Baltimore, ~14.2 sq km. Red dots in (b) indicate USGS stream gages at which water quality sensors are co-located. DR1, DR2, and DR5 are headwater streams; DR1 and DR2 drain to DR3; DR5 drains to DR4; DR3 and DR4 drain to DRKR (Dead Run Franklintown). Watershed attributes are summarized in Table 1.

Table 1. Dead Run watershed attributes

Watershed	Area (sq km)	% Impervious	Nested within
DR1	1.19	63	DR3
DR2	1.92	49	DR3
DR5	1.59	45	DR4
DR3	5.09	55	DRKR
DR4	5.84	47	DRKR
DRKR	14.2	47	--

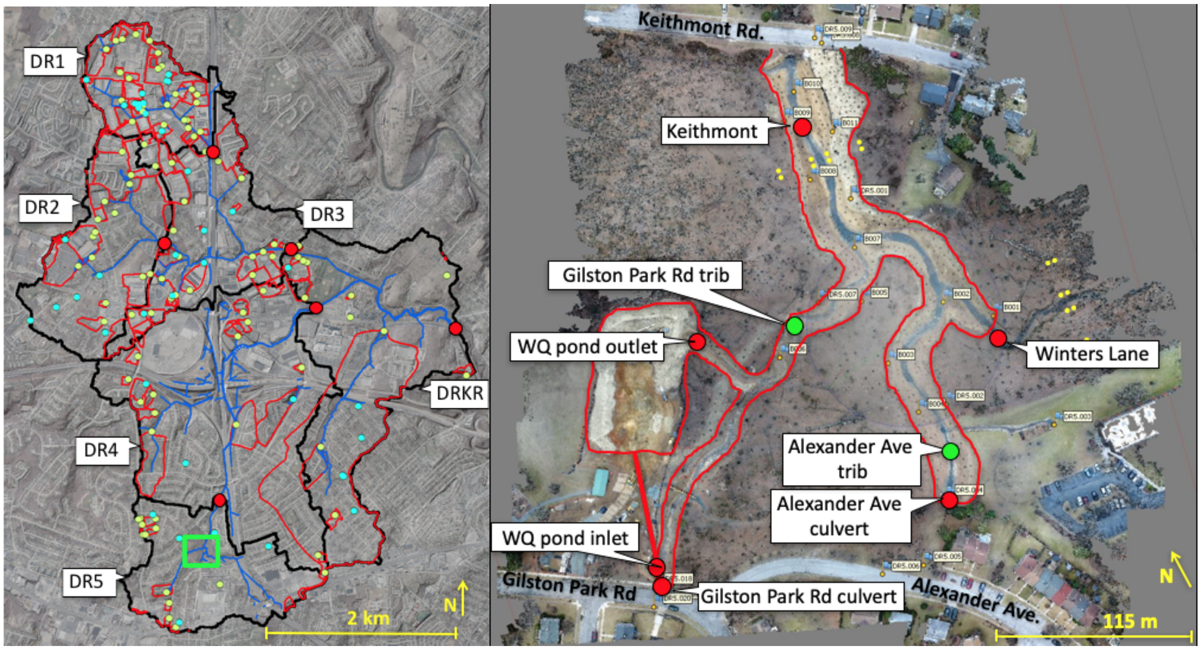


Figure 2. (a) Stormwater management facilities in Dead Run as of May 2017. Pale yellow-green dots indicate facilities installed prior to 2017; turquoise dots indicate facilities installed in 2017. Watershed boundaries are indicated by black lines; stream gages are indicated by red dots. Green rectangle indicates location of stream restoration, as shown in (b). (b) Extent of stream restoration and water quality pond (outlined in red) installed in 2017-2018 in an upland portion of the DR5 tributary of Dead Run; locations of new water quality stations (SUNA nitrate sensors and flow measurements) (red dots) for this project. Additional staff gages were installed at the locations indicated by green dots.

Table 2. Restoration site drainage areas

Drainage point	Drainage area (sq km)
Gilston Park Road Culvert	0.197
Alexander Avenue Culvert	0.416
Winters Lane	0.503
Keithmont	1.23

3. Methods

3.1 Nitrate and discharge measurement

In order to conduct a mass balance of nitrate loads from surface water inflows and outflows to this restoration area, SUNAs (Submersible Ultraviolet Nitrate Analyzers, Satlantic/Seabird) and stream gages/flow measurement devices were deployed at the locations shown in Figure 2b. Inflow nitrate loads to the restored reach were calculated at Gilston Park Road, Alexander Avenue and Winters Lane. The outflow nitrate load was calculated at Keithmont. Nitrate outflow loads were also computed downstream at the three water quality stations DR5, DR4, and DRKR (Figure 1b). Drainage areas to each of the stream monitoring points are provided in Table 2.

Existing USGS stream gages for stations DR1 - DRKR (Figure 1b) were maintained (and data published on the USGS National Water Information System) by the US Geological Survey MD-DE-DC Water Science Center. New gages were constructed at two stream stations (Keithmont, Winters Lane, Figure 2b) consisting of a Hobo U-20 water level logger (http://www.onsetcomp.com/) and a staff gage, that were maintained by UMBC. Rating curves were developed by conducting stream gaging (discharge measurement) across a range of wadeable flows. Flow measurement devices (one Blue Siren ultrasonic depth sensor and one Blue Siren acoustic doppler "micro" velocity sensor) were installed in each of the four pipes: the Alexander Avenue stormwater outfall, the Gilston Park Road stormwater outfall, the water quality pond inlet and at the water quality pond outlet. Discharge was calculated at these stations using depth and velocity data together with pipe geometry.

The inlet nitrate concentration to the pond was represented by the concentration measured in the Gilston Park Rd pipe outfall, since the pond flow is split off at the pipe outfall location and is well mixed before the split. SUNAs were manually cleaned every 1-2 weeks to remove post-storm sediment deposits in these shallow streams.

SUNA data and pipe depth / velocity data were recorded by Campbell Scientific CR1000 data loggers housed in utility boxes installed above the stream channel banks and pipe outfalls, at elevations above flooding potential. Stations were powered by 30-W solar panels charging 12V, 42-amp hr batteries. Data were telemetered to UMBC via Sierra Wireless RV50 modems using AT&T as a provider. Hobo water level loggers were downloaded manually on a monthly basis. One Hobo was deployed in air to use as a barometric correction to the measured water pressure. Stage data was recorded at a 5-minute interval at the stream stations; stage and velocity were recorded at a 1-minute interval at the pipe stations. SUNA data were recorded at a 30-minute interval.

4. Results

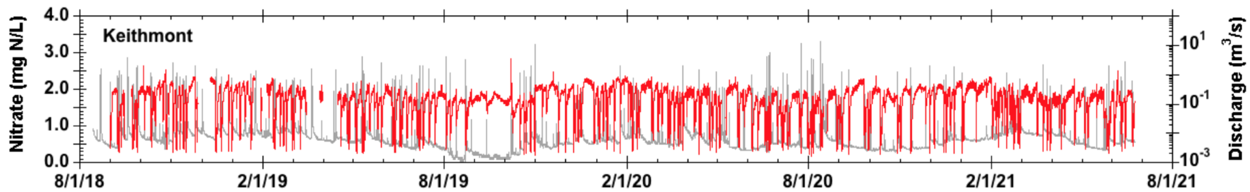
4.1 Restoration mass balance

Time series of nitrate concentration were plotted directly from instrument measurements; an example from the Keithmont station is shown in Figure 3(a); other stations are shown in Appendix A. (Data have been edited to remove erroneous values recorded when the sensor is covered with sediment). Nitrate mass flux (daily load) (Figure 3(b)) was calculated by multiplying concentration by discharge for every 30-minute time stamp, and then assuming that this represents the average flux across a 30-minute period, and summing the 30-minute loads to obtain daily load. For purposes of this report, area-weighted discharge values from DR5 were used for mass flux calculations to assure mass balance across sites. Nitrate mass yields ($kg/d/km^2$; Appendix A) are derived by dividing the daily load by watershed area. Mean daily nitrate concentration (Appendix A) was calculated as the arithmetic mean of the 30-minute instantaneous values for each day.

Seasonal box plots for mean daily nitrate yields spanning 2018-2021 are shown for each of the restoration sites (Appendix B). Cumulative distribution functions of mean daily nitrate concentration, mean daily nitrate flux (load), and mean daily nitrate yields across the restoration sites, spanning 2018-2021, are shown in Figure 4.

Column plots are used to illustrate the comparative discharge and loads across sites for 2020-2021, where data are available for the three inlets (Gilston Park Road, Alexander Avenue, and Winters Lane) and the outlet (Keithmont) as well as DR5 for this 1-year period (Figures 5, 6). Discharge increases with drainage area (Figure 5), as expected. Annual loads (Figure 6(a)) also increase with watershed drainage area; when scaled by area (Figure 6(b)), the yields highlight again the nature of the Alexander Avenue hotspot. When the loads of the inputs (GPR, AA, WL) are summed to compare to the output (KM), the two appear to be about in balance (Figure 6(c)). Figure 7 illustrates the seasonal variability of this relationship throughout the year.

(a)



(b)

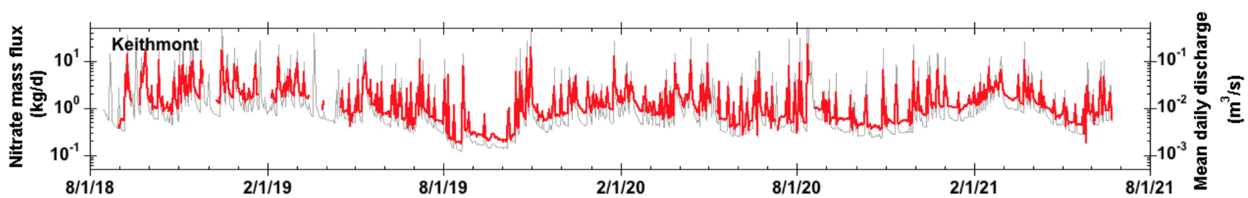


Figure 3. For the Keithmont station (a) 30 minute nitrate time series (red) superimposed on 30-minute stream discharge time series (gray); (b) nitrate mass flux (daily load) and mean daily discharge calculated from the instantaneous data. Nitrate daily mass yields (kg/d/km^2) are calculated by dividing daily load by watershed area (Appendix A).

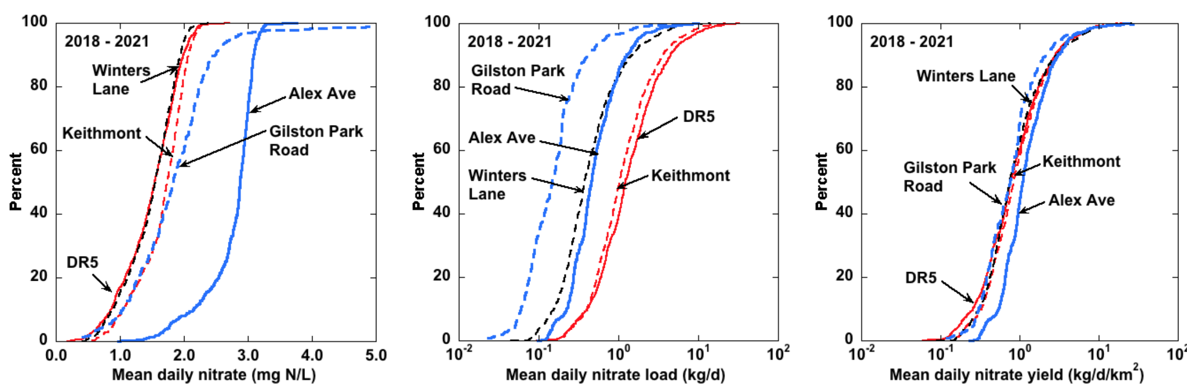


Figure 4. CDFs of (a) mean daily nitrate concentration, (b) mean daily nitrate load, and (c) mean daily nitrate yield of the time series data (Appendix A) for data from Winters Lane, Keithmont, and DR5 stations spanning 2018-2021. Data from Alexander Avenue span 2019-2021; data from Gilston Park Road spanning 2020-2021.

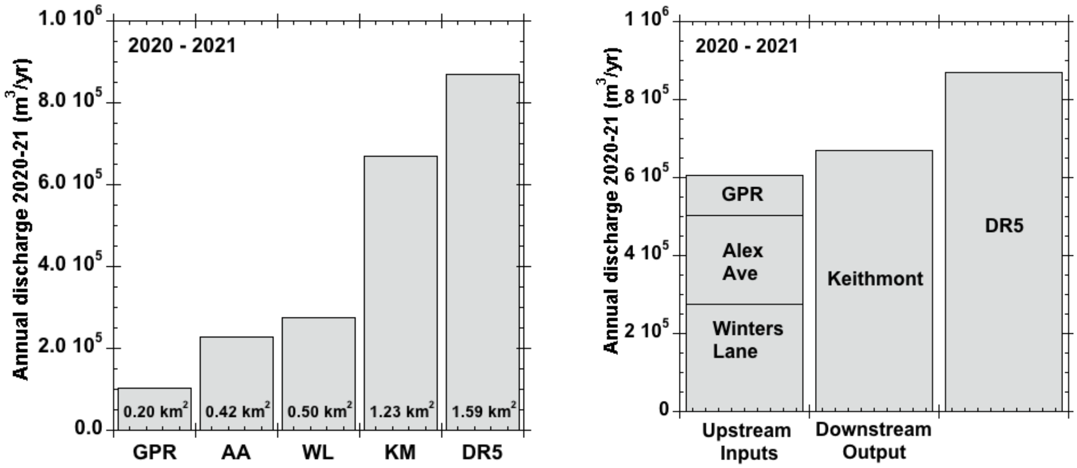


Figure 5. (a) Annual streamflow discharge across the restoration sites and at DR5 for 2020-21, with drainage areas indicated. Panel (b) illustrates the sum of the discharge values shown in (a) (Gilston Park Road, Alexander Avenue, Winters Lane) compared to the output load (Keithmont) and the downstream station (DR5) for this one-year period.

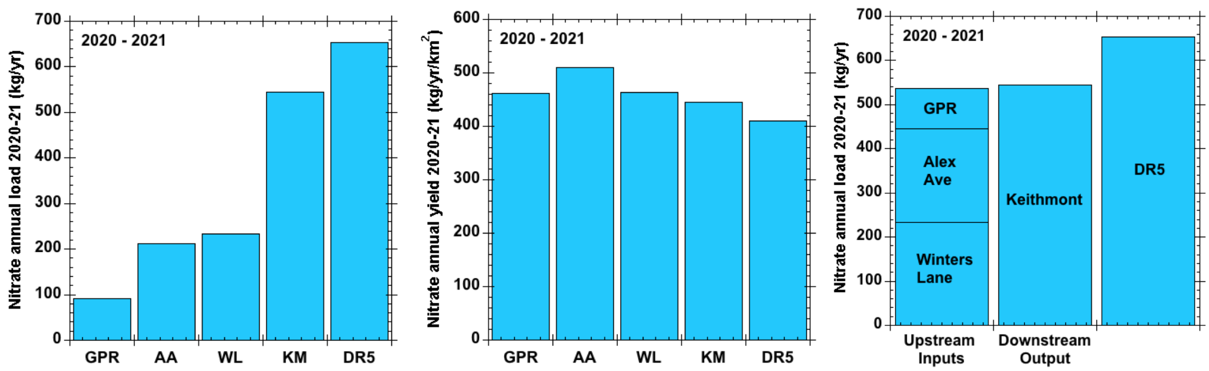


Figure 6. (a) Annual nitrate loads and (b) annual nitrate yields across the restoration sites and at DR5 for 2020-21. Panel (c) illustrates the sum of the input loads shown in (a) (Gilston Park Road, Alexander Avenue, Winters Lane) compared to the output load (Keithmont) and the downstream station (DR5) for this one-year period.

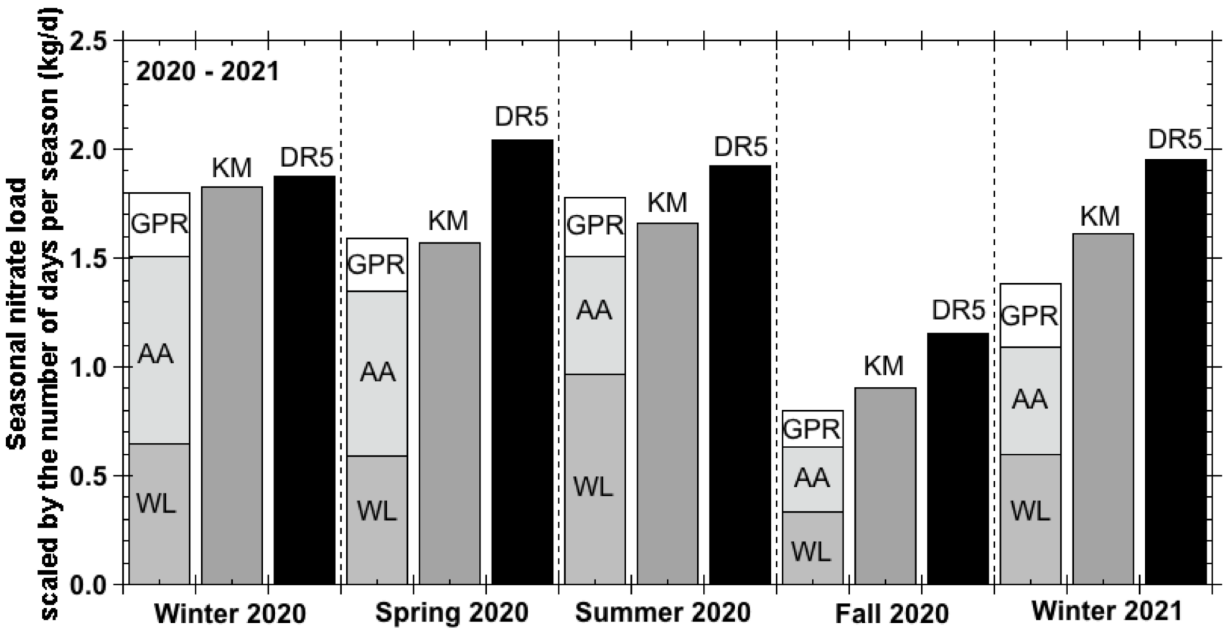
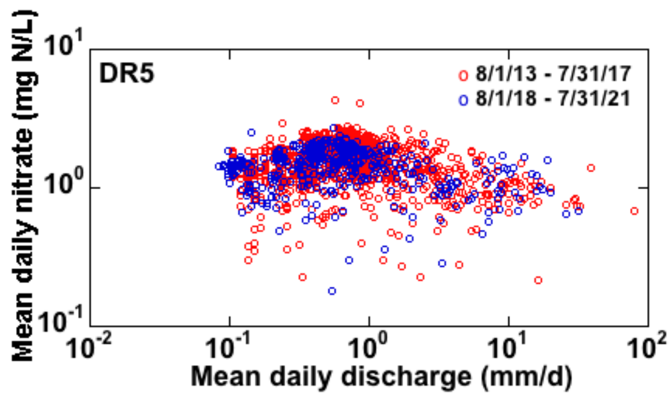


Figure 7. Nitrate loads shown in Figure 6(a) divided into seasons and scaled by the number of days in the season.

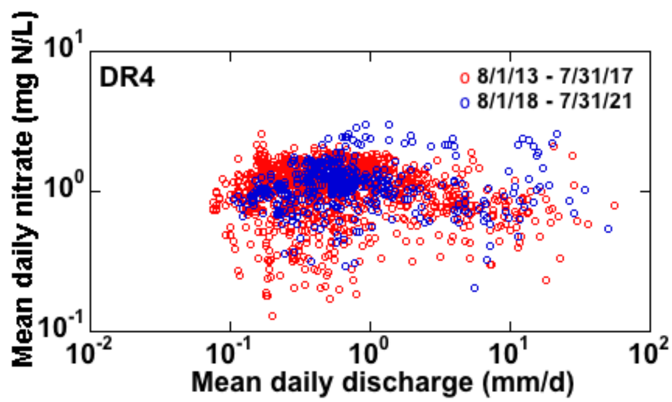
4.2 Pre- vs post restoration observations at nested stations downstream of the restoration site

Nitrate and discharge data were collected at DR5, DR4, and DRKR, the nested stations downstream of the restoration site, beginning in December 2012. This data set thus provides four years of observations at these stations prior to restoration (August 1, 2013 - July 31, 2017), and three years of observations following restoration (August 1, 2018 - July 31, 2021). Data were omitted for August 1, 2017 through July 31, 2018 in order to avoid using data collected during the construction period and the first few months after completion of the stream restoration and water-quality pond. Mean daily nitrate concentration as a function of mean daily discharge for the pre- and post-restoration periods for common dates across sites are shown as point clouds in Figure 8; CDFs of the same mean daily nitrate and discharge data are shown in Appendix C. Table 3 summarizes the statistics of this data set.

(a)



(b)



(c)

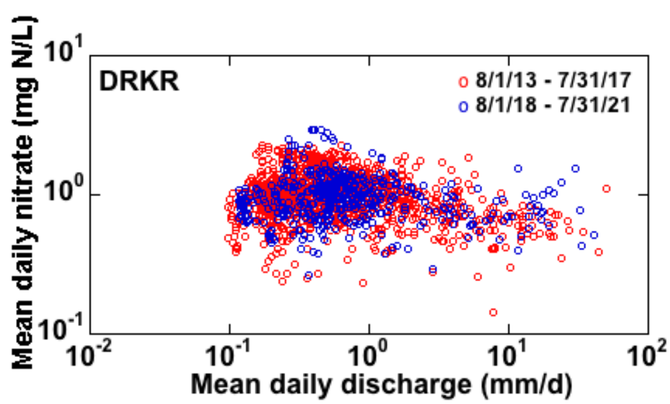


Figure 8. Mean daily nitrate concentration as a function of mean daily discharge across nested watersheds DR5, DR4, DRKR (Figure 1) downstream of the restoration site, before and after restoration, for common dates where data are available. Statistics are summarized in Table 3.

Table 3. Statistics of mean daily nitrate and discharge across common dates for DR5, DR4, and DRKR, before and after restoration at Keithmont.

DR5	N	Mean daily discharge (mm/d)			Mean daily nitrate (mg N/L)		
Analysis period		Mean	Median	Range	Mean	Median	Range
2013-2017 (before restoration)	1125	1.6	0.69	0.10 – 80.	1.6	1.6	0.21 – 4.5
2018-2021 (after restoration)	466	1.5	0.52	0.09 – 32.	1.5	1.5	0.18 – 2.7

DR4	N	Mean daily discharge (mm/d)			Mean daily nitrate (mg N/L)		
Analysis period		Mean	Median	Range	Mean	Median	Range
2013-2017 (before restoration)	1125	1.6	0.48	0.075 – 104	1.1	1.1	0.10 – 2.6
2018-2021 (after restoration)	466	1.9	0.56	0.010 – 50.	1.2	1.1	0.20 – 3.0

DRKR	N	Mean daily discharge (mm/d)			Mean daily nitrate (mg N/L)		
Analysis period		Mean	Median	Range	Mean	Median	Range
2013-2017 (before restoration)	1125	1.6	0.47	0.096 – 120	1.0	0.98	0.14 – 2.3
2018-2021 (after restoration)	466	1.8	0.54	0.12 – 41	1.0	0.95	0.26 – 2.9

5. Discussion

5.1 High-frequency data

High-frequency nitrate and discharge observations (Figure 3; Appendix A) illustrate process details as a function of time. The diel signal of nitrate at base flow resulting from in-stream processing is clearly documented. Dilution from base-flow nitrate concentrations during storm flow is also apparent, with recovery to base flow nitrate values as storm flow recedes. In very few instances is there evidence of the “first flush” effect of nitrate increasing with discharge at the beginning of a storm. The fine temporal scale of paired nitrate-discharge measurements allows for mass flux and mass balance calculations across stations and over any period of interest.

Seasonal variability of nitrate concentrations, loads, and yields quantified across nested watersheds using box plots (Appendix B) illustrate the well-known phenomenon that median nitrate yields are typically highest in winter and lowest in summer/fall. This pattern is consistent across sites. The interannual variability of seasonal yields for each site is also illustrated by these plots.

CDFs of mean daily nitrate concentration (Figure 4(a)) illustrate that Alexander Avenue is a hot spot compared to the other stations, although its loads are similar to Winters Lane (Figure 4(b)). Scaling by area (FIgure 4(c)) further highlights that Alexander Avenue is a nitrate hotspot compared to the other stations. This steady-state hot spot of nitrate input from the Alexander Avenue tributary to the restoration reach was not documented prior to this study. This hot spot might be most effectively treated by approaches that are lower cost than stream restoration, if, for example, the data reflect sanitary sewers leaking into the buried stream channel. Documenting the location and nature of major sources may be helpful in decision-making rather than applying a general approach that treats all sources as equivalent. We recognize that nitrate reduction was not the major objective of the restoration project, but in cases where this is a major goal it may make more sense to focus on finding and treating a hot spot at its source rather than treating an extensive reach of the stream network to mitigate the hot spot.

5.2 Nitrate reduction at the reach scale

For the restored stream reach instrumented, results to date for 2020-21 suggest that there is no net discernable nitrate removal between upstream inputs and downstream output at Keithmont for this one-year observation period (Figure 6c). Dividing the one year of data into seasons shows a different result (Figure 7). First, the trend of variability of loads across seasons due to variability of discharge is apparent. For example, fall of 2020 was characterized by lower discharge and therefore lower loads for all 5 stations compared the other seasons in this year. Second, in terms of the comparison of the inputs (WL, AA, GPR) to the output at KM across seasons, there is a barely discernible load decrease at Keithmont during spring and summer 2020. Conversely, there is a small increase in winter and fall 2020 and more marked increase in winter 2021 at the KM outlet compared to the inlet loads at WL, AA, GPR. These observations make sense in the context of in-stream metabolism. In this restored reach with no canopy over the channel, and therefore little light limitation during the growing season, in-stream metabolism can be limited by temperature and dissolved oxygen. Therefore slight reductions of in-stream nitrate could be attributed to enhanced uptake by periphyton and benthic algae in spring and summer seasons. In fall and winter it could be the case that seasonal light limitation (shorter day lengths), cooler temperatures, and possibly increased respiration limit instream primary production and therefore nitrate assimilation. This seasonal variability is not evident when the data are lumped together on an annual basis.

We point out that the stream restoration section of the study area was not designed for N removal. We estimated potential credits using lbs N per linear ft in the Chesapeake Bay stream restoration manual. Credits for the water quality pond were added to the estimate of credits for the restoration. The projected credits of ~160 kg/yr for total nitrogen would translate into about 110 kg/yr of nitrate-nitrogen, assuming that nitrate is about 70% of total nitrogen from independent grab-sample measurements of TN and nitrate-nitrogen (Appendix D). Results suggest that this target removal of 110 kg/yr of nitrate was not met for the time period during which data were collected for this study.

5.3 Nitrate reduction at the watershed scale

Point cloud plots of mean daily nitrate as a function of mean daily discharge (Figure 8a) at DR5, the station 500 m downstream of Keithmont, for four years prior to restoration and three years after restoration suggest that there may be some downstream reduction of nitrate concentration at DR5 for intermediate flows (0.3 - 1.2 mm/d) for post- vs pre- restoration. This range of flows brackets base flows to smaller storm flows. At higher flows, the percent of total discharge interacting with the restored reach is much smaller and concentrations in these urban watersheds are typically dilute. At lowest base flows, there is smaller surface area for instream assimilation of nitrate into periphyton and algae. During these lowest of flows, there is also less hyporheic surface area available for denitrification. Therefore, examination of nitrate concentration during intermediate flows should be optimal for assessing impacts of the stream restoration. Concentrations can be ecologically important but we note that concentration differences at intermediate flows will not substantially impact mass balances.

However, the plots for the same periods of time farther downstream at DR4 (Figure 8b) and DRKR (Figure 8c) show similar behavior and therefore it is not clear that the patterns observed at DR5 can be attributed to the restoration at Keithmont. On one hand, to a first approximation, the DR4 and DRKR patterns reflect that of DR5. Given the drainage area to DR5 is ~ 1/14 of the the area draining to DRKR, it could mean there are other changes at the full watershed scale across all stations, perhaps driven by hydroclimate, potable water leaks, or repair of sewer leaks. On the other hand, patterns at DR4 and DRKR are less distinct compared to DR5, where there are almost no high-concentration data points in the intermediate flow range for the post-restoration period that fall above the pre-restoration period. At DR4 and DRKR, the upper envelope of the post-restoration c-Q plot- have significant overlap with the upper envelope of the pre restoration c-Q plots at these sites, potentially suggesting there is a real difference between these plots and the DR5 c-Q plot.

6. Conclusions

We have demonstrated in this study that high frequency sensors are a powerful tool for evaluating the effects of stream restoration on nitrate concentrations by allowing use of a mass balance approach across spatial scales ranging from reach to watershed, and across time scales ranging from minutes to years. Even with short periods of data missing due to power failures and sediment burial of the sensors, the sample size of data points available to work with across the study was quite large compared to typical grab-sample studies. We point out that this study evaluated mass balances for nitrate-nitrogen only; detachment and transport of particulate nitrogen during high flows could affect total nitrogen mass balances.

For the site evaluated that underwent restoration in 2017-2018, the Keithmont area in Westview Park in Dead Run watershed, Baltimore County, Maryland, pre-restoration data across the restoration reach were not collected. Post-restoration data across the restoration reach, collection of which began with this project in August 2018 (a few months after restoration was completed), showed that reduction in nitrate load across the restoration reach was negligible on an annual basis, whereas evaluation on a seasonal basis illustrated more nuanced results where a small amount of reduction in nitrate load was shown during the growing season.

Although data were not available pre-restoration for the restored reach, 4 years of pre-restoration and 3 years of post-restoration data were available at a station 500 m downstream of the restoration area. These data could suggest possible reductions in nitrate concentration at intermediate discharge values.

Acknowledgements
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References

Baltimore County Dept. of Environmental Protection and Sustainability. 2012. Phase II Watershed Implementation Plan. http://resources.baltimorecountymd.gov/Documents/Environment/Watersheds/bcwip2july2012.pdf

Berg, H. et al. 2013. Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects. US EPA Chesapeake Bay Program. http://chesapeakestormwater.net/wp-content/uploads/downloads/2014/02/Stream_Panel_Report_Final_02062014_LONG_Version.pdf

Parsons Brinckerhoff. 2013a. Middle Gwynns Falls Small Watershed Action Plan, Volume 1. http://resources.baltimorecountymd.gov/Documents/Environment/Watersheds/2013/swapmgfareacvol131113.pdf

Parsons Brinckerhoff. 2013b. Middle Gwynns Falls Small Watershed Action Plan, Volume 2. http://resources.baltimorecountymd.gov/Documents/Environment/Watersheds/2013/swapmgfareacvol2131105.pdf

WSP/ Parsons Brinckerhoff. 2015. Dead Run stream restoration at Westview Park, Final design report. December 2015.

WSP/ Parsons Brinckerhoff. 2016. Dead Run water quality BMP at Westview Park, Stormwater management report. August 2016.

Appendix A
Nitrate and discharge time series data

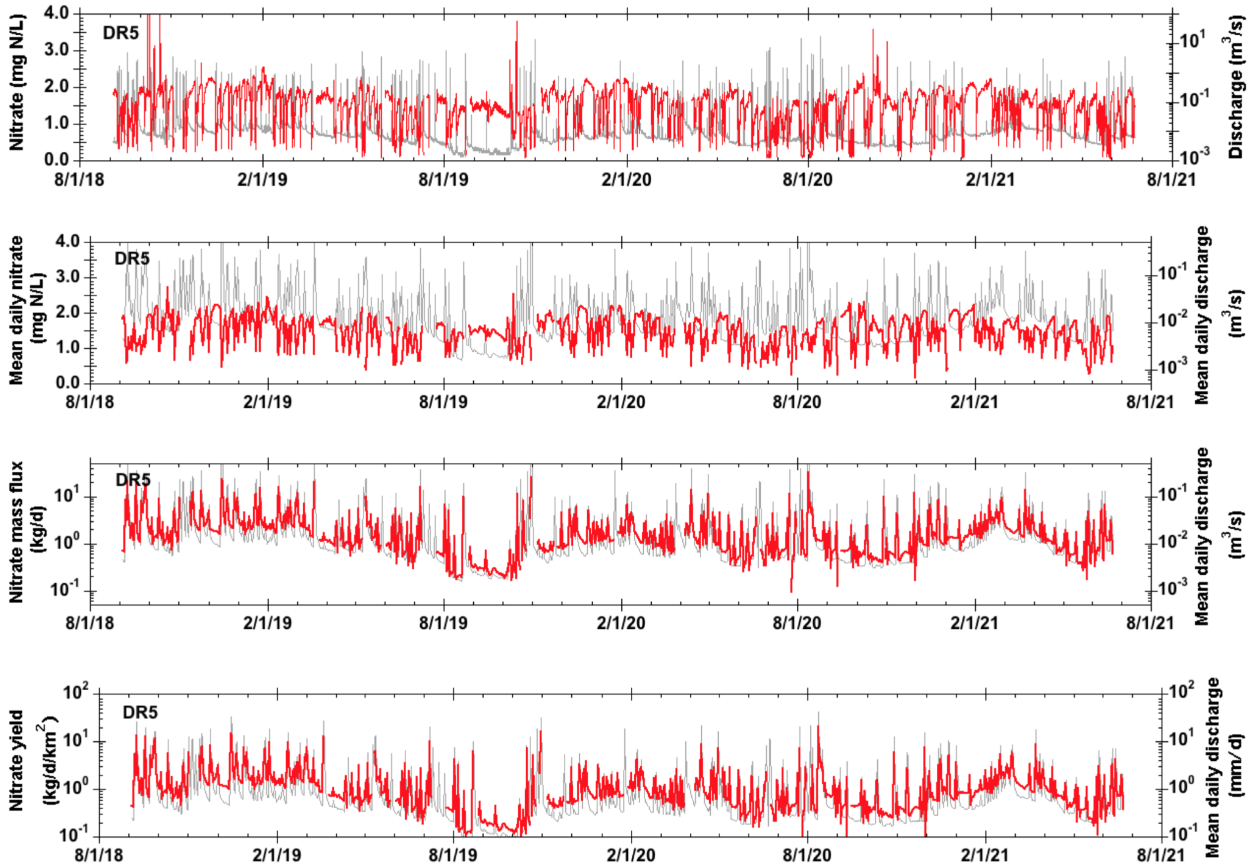

Figure A-1. Nitrate concentrations and loads at DR5. Nitrate is indicated in red and discharge is indicated in gray. Scaled discharge (mm/d) is derived by dividing mean daily discharge by watershed area.

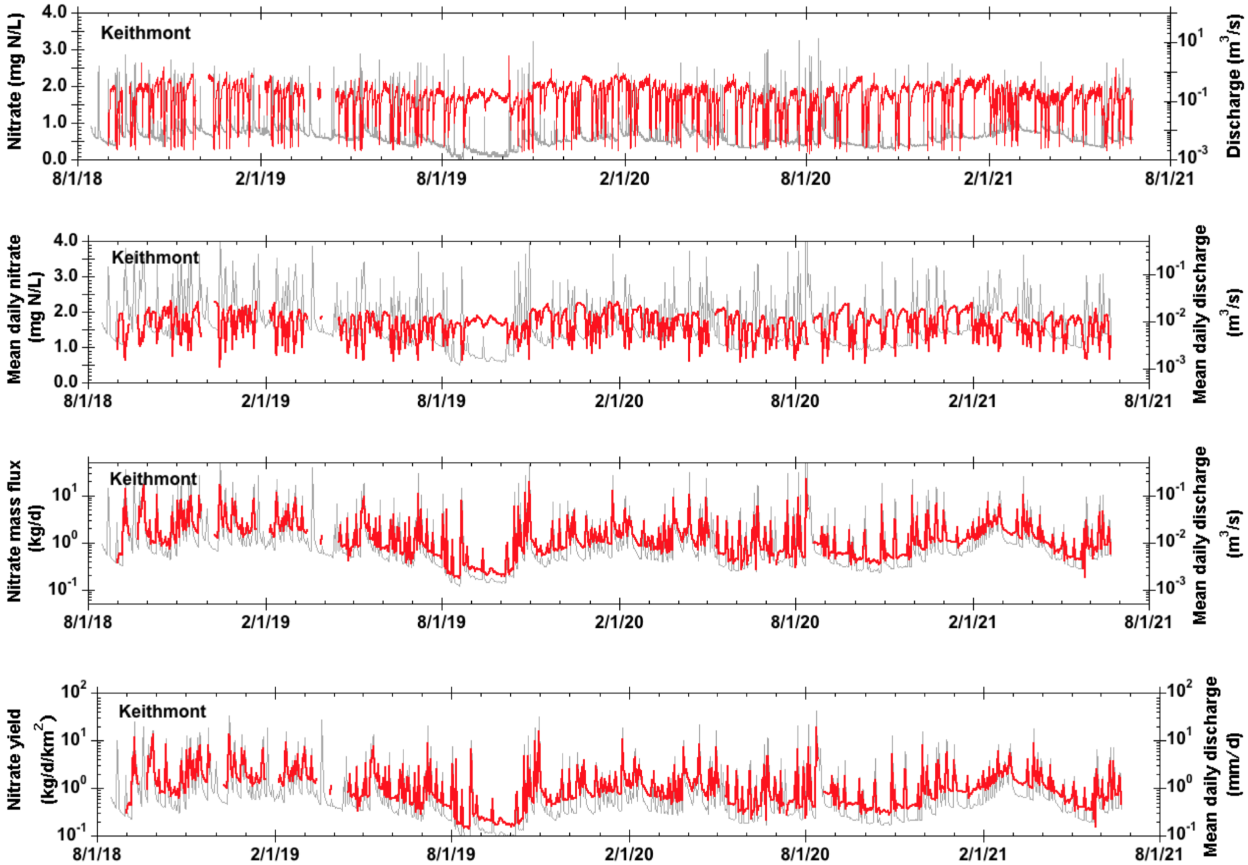

Figure A-2. Nitrate concentrations and loads at Keithmont. Nitrate is indicated in red and discharge is indicated in gray. Scaled discharge (mm/d) is derived by dividing mean daily discharge by watershed area.

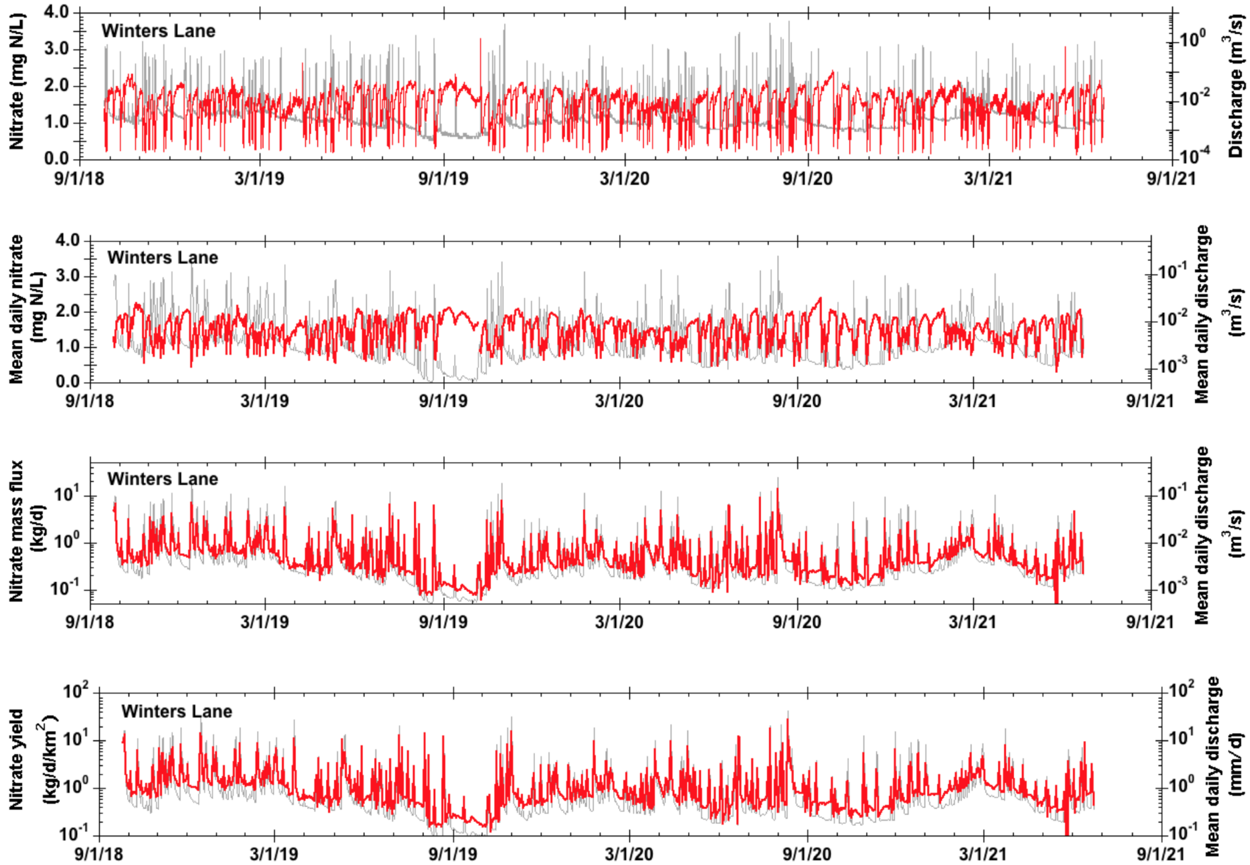

Figure A-3. Nitrate concentrations and loads at WInters Lane Nitrate is indicated in red and discharge is indicated in gray. Scaled discharge (mm/d) is derived by dividing mean daily discharge by watershed area.

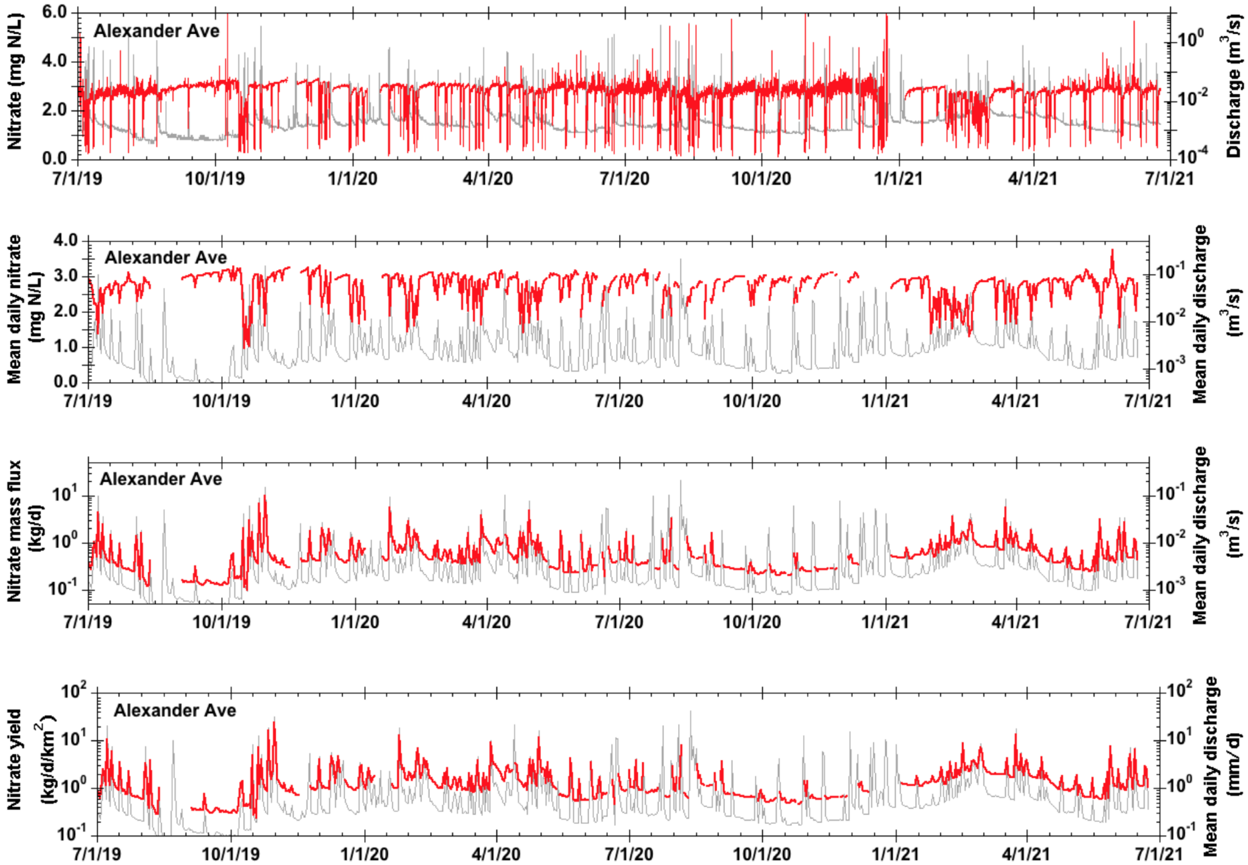

Figure A-4. Nitrate concentrations and loads at Alexander Avenue. Nitrate is indicated in red and discharge is indicated in gray. Scaled discharge (mm/d) is derived by dividing mean daily discharge by watershed area.

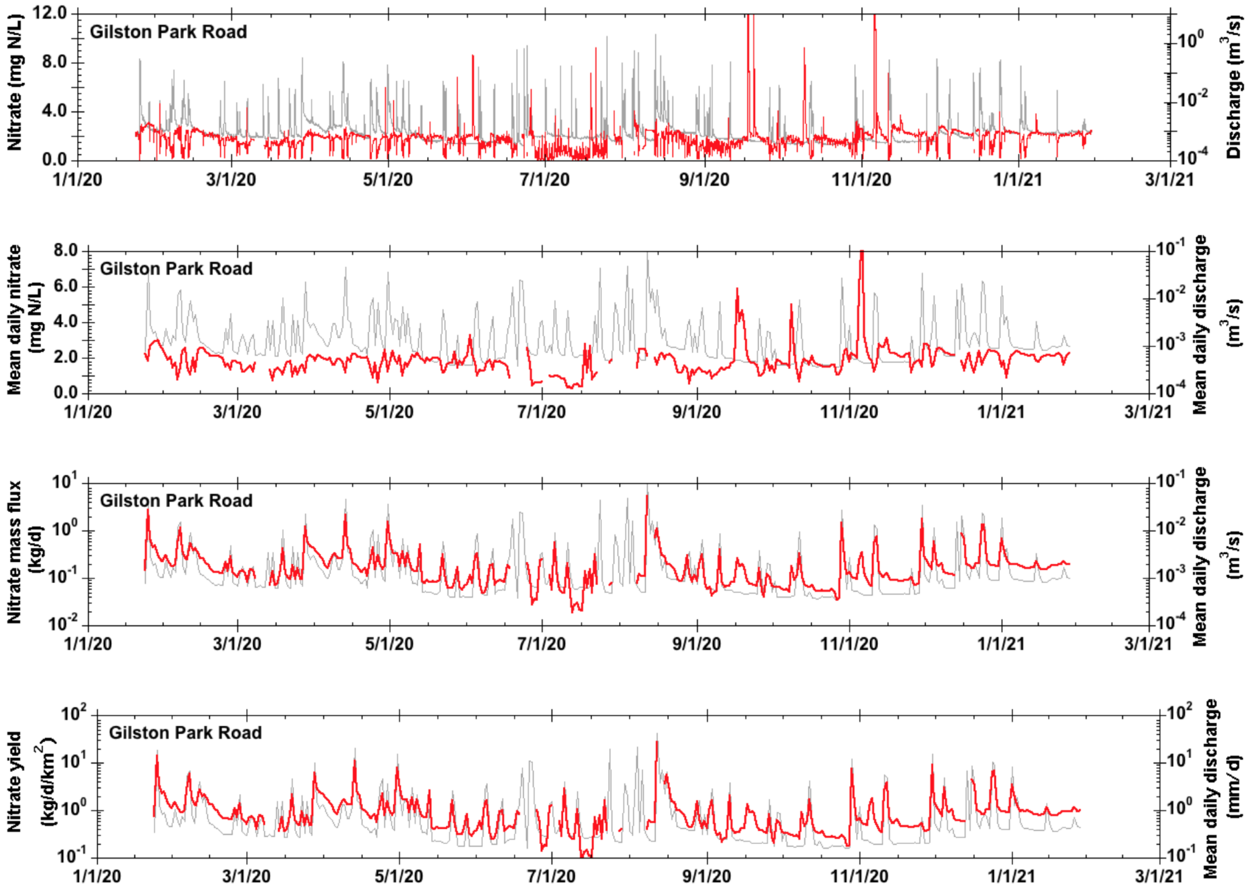

Figure A-5. Nitrate concentrations and loads at Gilston Park Road. Nitrate is indicated in red and discharge is indicated in gray. Scaled discharge (mm/d) is derived by dividing mean daily discharge by watershed area.

Appendix B
Nitrate yield seasonal box plots

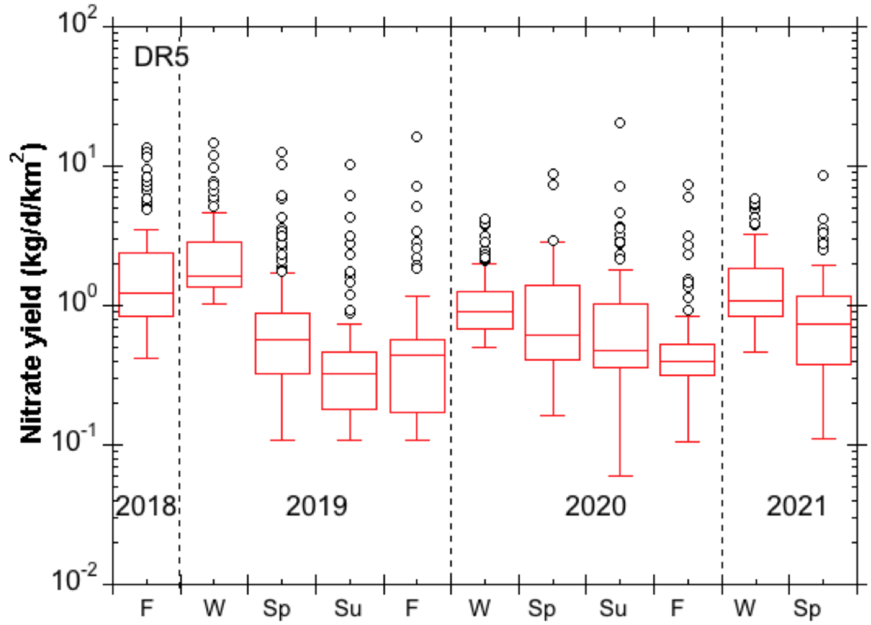

Figure B-1. Seasonal box plots of mean daily nitrate yield at DR5.

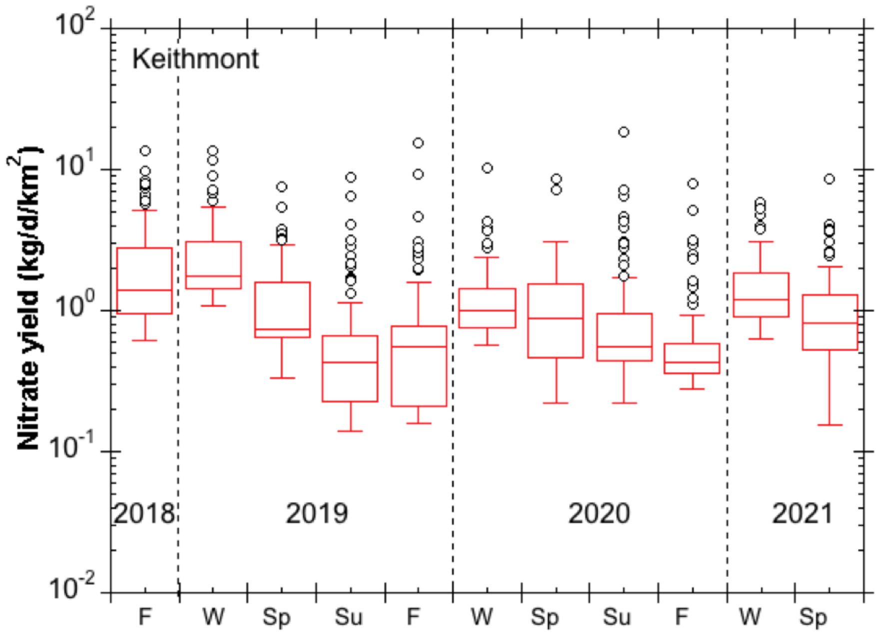

Figure B-2. Seasonal box plots of mean daily nitrate yield at Keithmont.

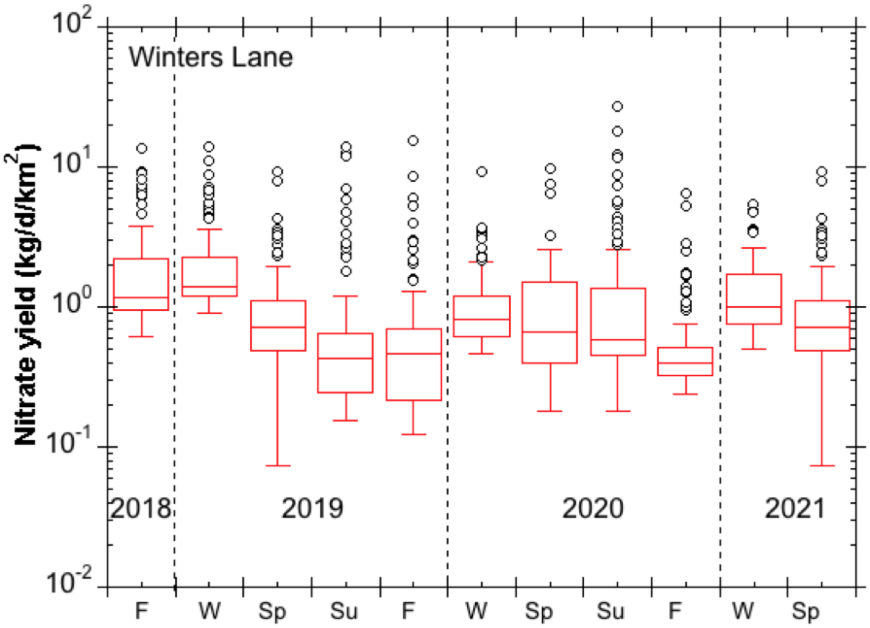

Figure B-3. Seasonal box plots of mean daily nitrate yield at Winters Lane.

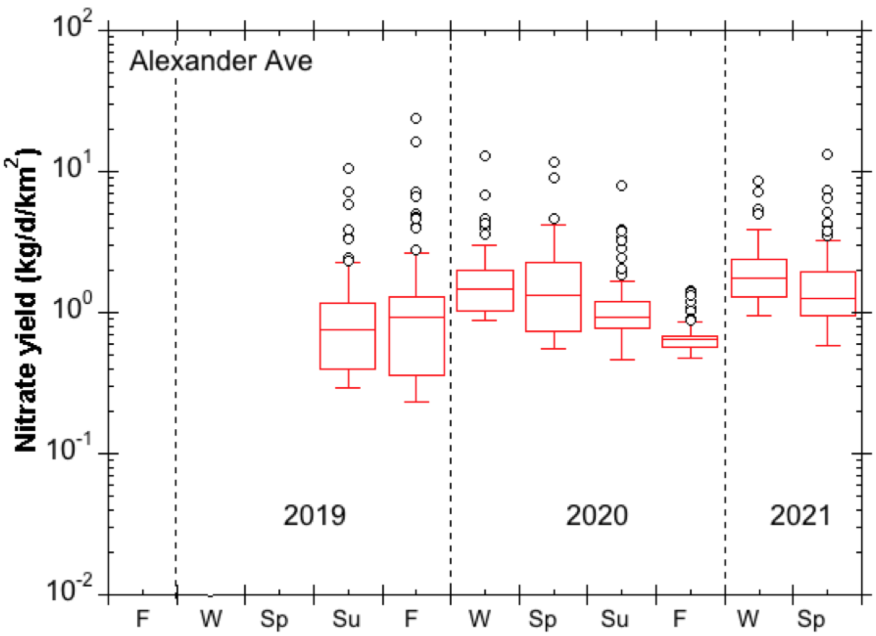

Figure B-4. Seasonal box plots of mean daily nitrate yield at Alexander Avenue.

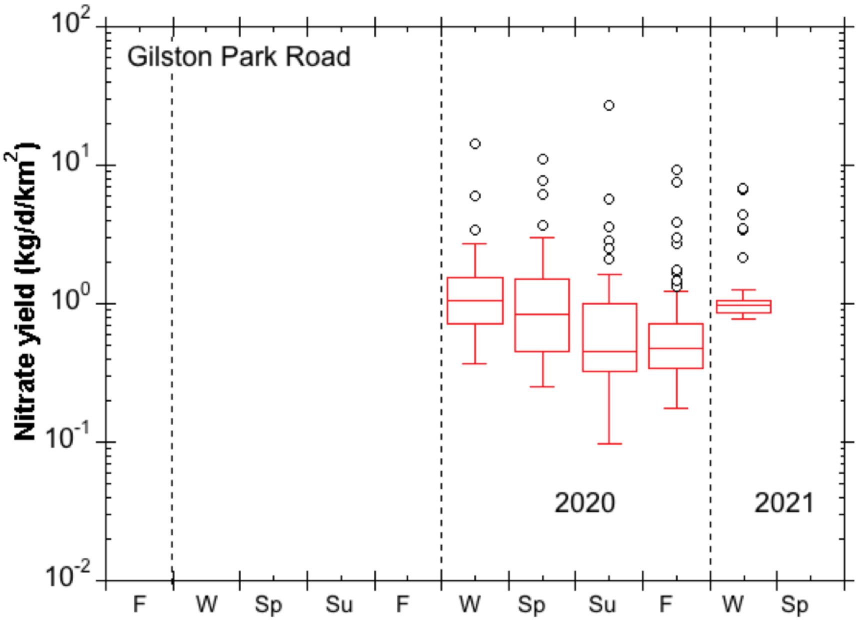

Figure B-5. Seasonal box plots of mean daily nitrate yield at Gilston Park Road.

Appendix C

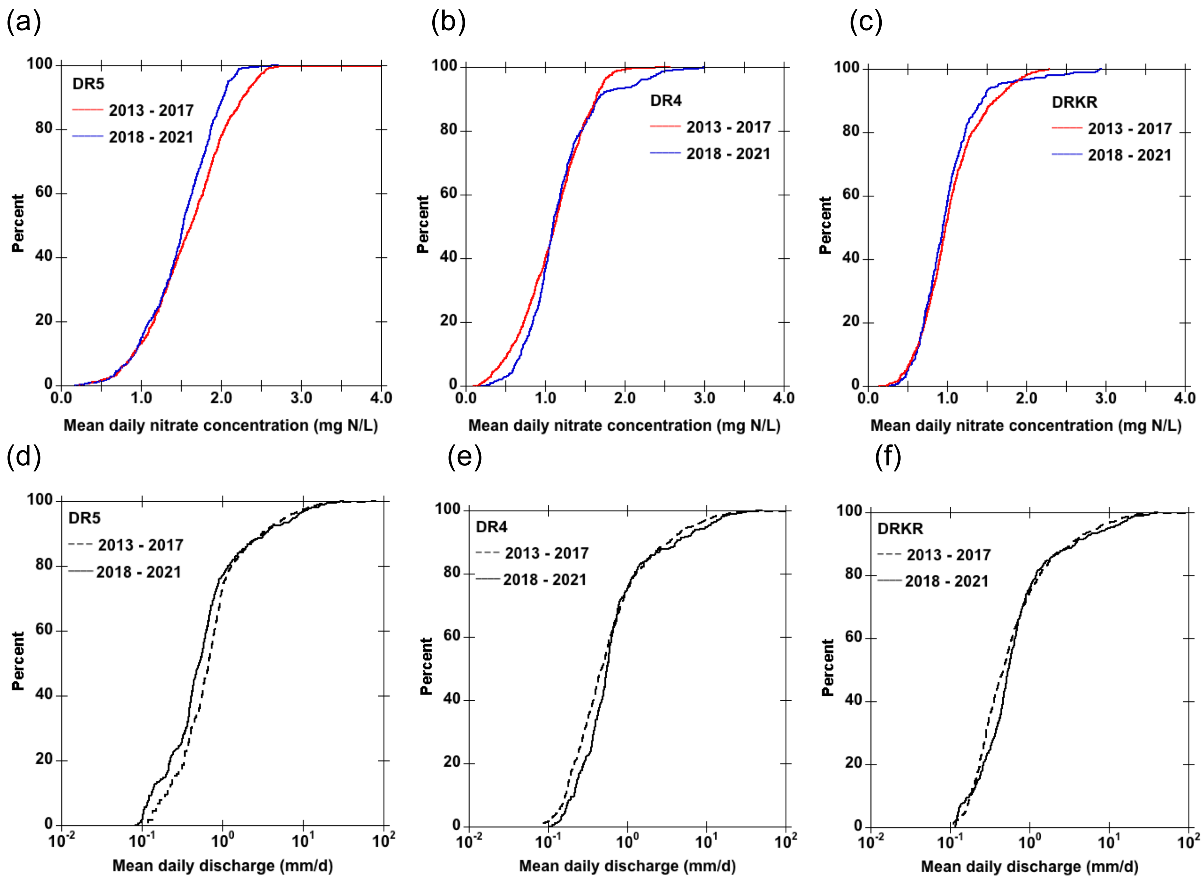

Figure C-1. CDFs of mean daily nitrate concentration and mean daily discharge for the three nested stations downstream of the restoration site, before (2013-2017) and after (2019-2021) restoration for common dates where data are available.

Appendix D

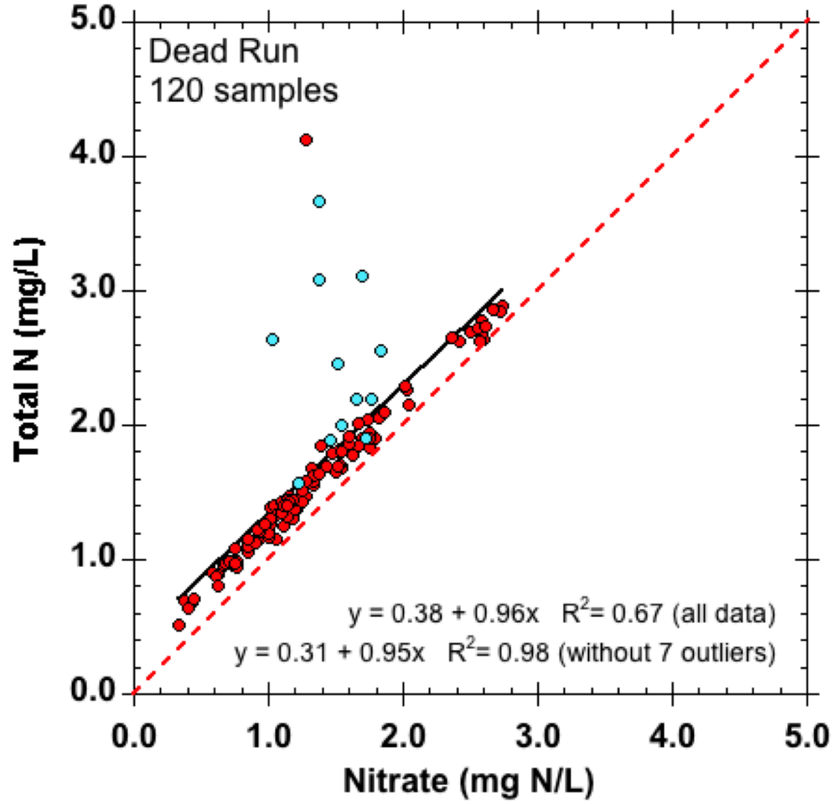

Figure D-1. Nitrate-nitrogen and total nitrogen determined from 120 split grab samples at 10 stations across Dead Run. Nitrate-nitrogen was determined using a Dionex Ion Chromatography system at UMBC; total nitrogen was determined using offline digestion by the Cary Institute of Ecosystem Studies in Millbrook, NY.