# A paired-watershed study to assess the aggregated effectiveness of green stormwater infrastructure in suburban residential development

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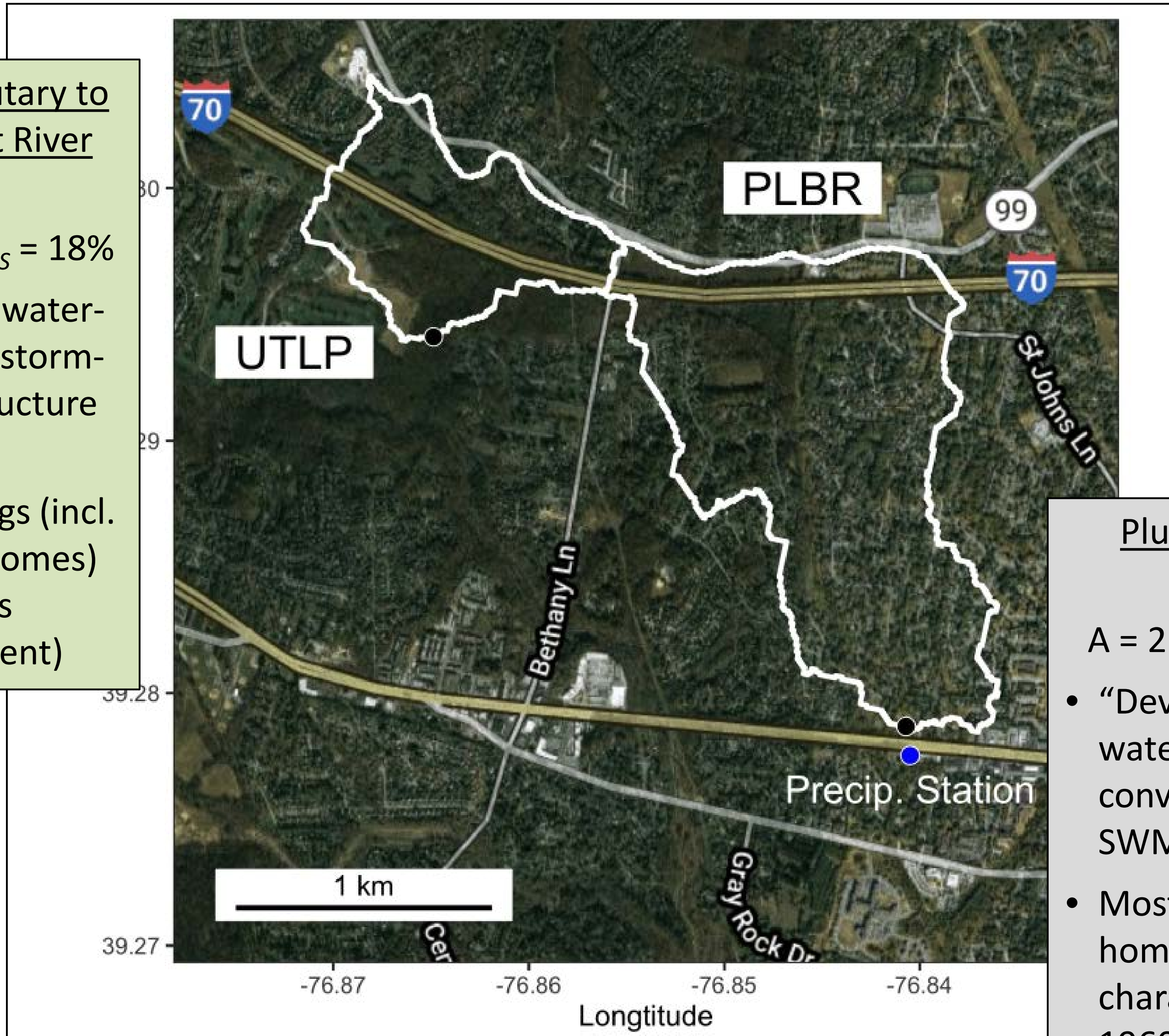
CBTRUST Chesapeake Bay Trust
University of Maryland Center for Environmental Science
Maryland Department of Natural Resources

# Paired watershed study (2019 – present)

<u>Unnamed Tributary to Little Patuxent River</u>
(UTLP)

A = 0.80 km$^2$; $I_S$ = 18%

- “Developing” water-shed”: green storm-water infrastructure (GSI)
- Larger buildings (incl. multi-family homes) on smaller lots (1990’s – present)




<u>Plumtree Branch</u>
(PLBR)

A = 2.15 km$^2$; $I_S$ = 28%

- “Developed” watershed: mostly conventional (“gray”) SWM
- Mostly smaller homes on larger lots characteristic of 1960’s - 1980’s development

# Outline

- Review hypotheses/objectives/methods/project status
- Update on UTLP development/BMP implementation
- Water quantity results
  - Annual runoff comparison (UTLP anomaly)
  - Hydrograph separation
- Water quality results
  - Baseflow chemistry
  - Stormflow EMC's
  - Pollutant load comparisons
- Summary

# Paired watershed study (2019 – present)

Objective: determine the spatially-aggregated effectiveness of green stormwater infrastructure (GSI) at the watershed scale (relative to a comparable "control" watershed with conventional stormwater management)

- *lower stormflow runoff*
- *higher baseflow runoff*
- *lower runoff peaks*
- *lower storm runoff ratios*
- *less overland flow*
- *more attenuated unit-graphs*
- *lower EMC's of N and P*

AquaTroll 500

UTLP stormwater monitoring station

Common monitoring equipment:

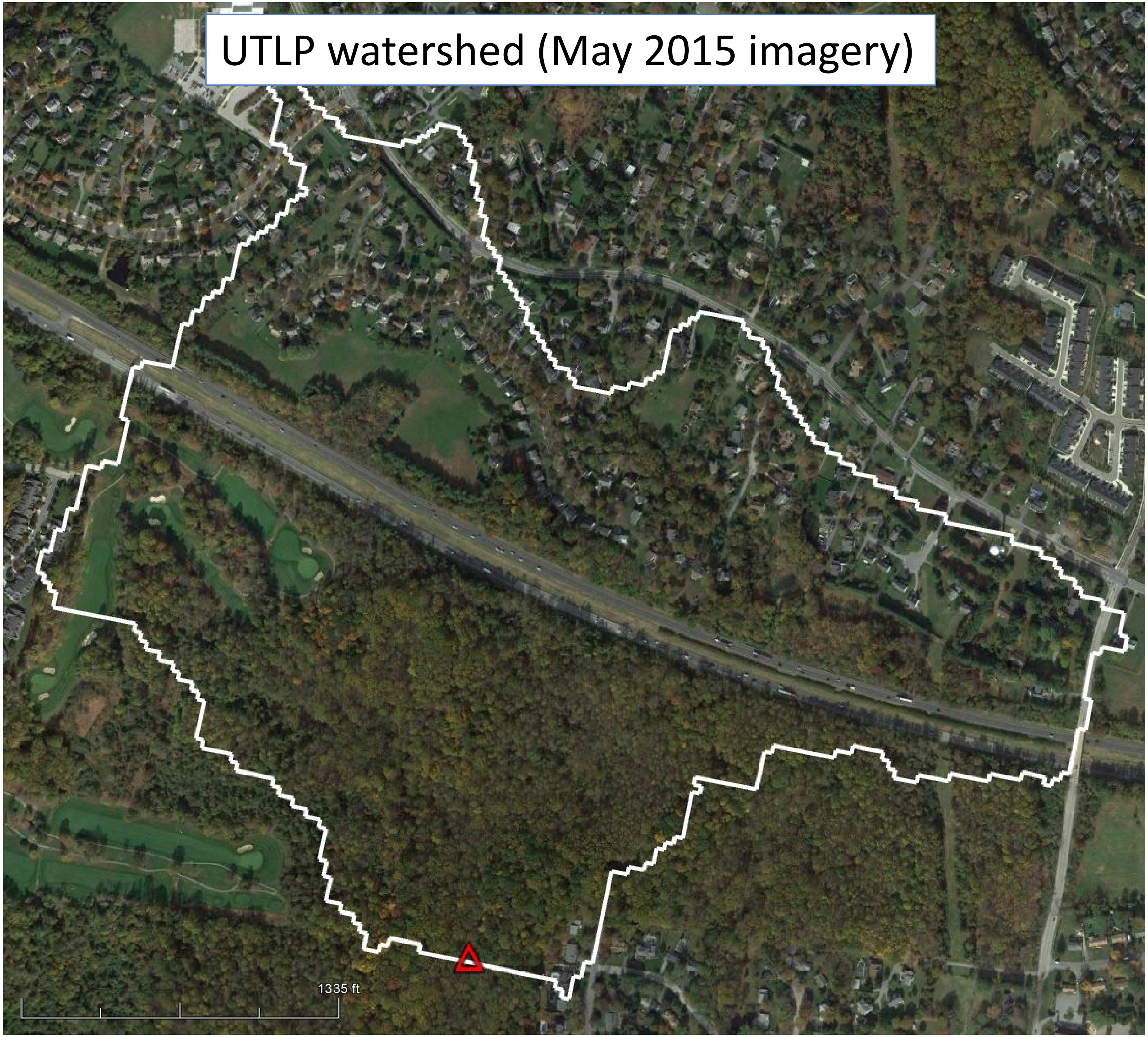
- Stilling well/instrument shelter housing digital water level recorder
- In Situ AquaTroll 500 and "tube" for transmitting data to HydroVu website
- Programmable sequential stormwater sampler
- Two unheated tipping bucket rain gauges (located nearby)

PLBR stormwater monitoring station

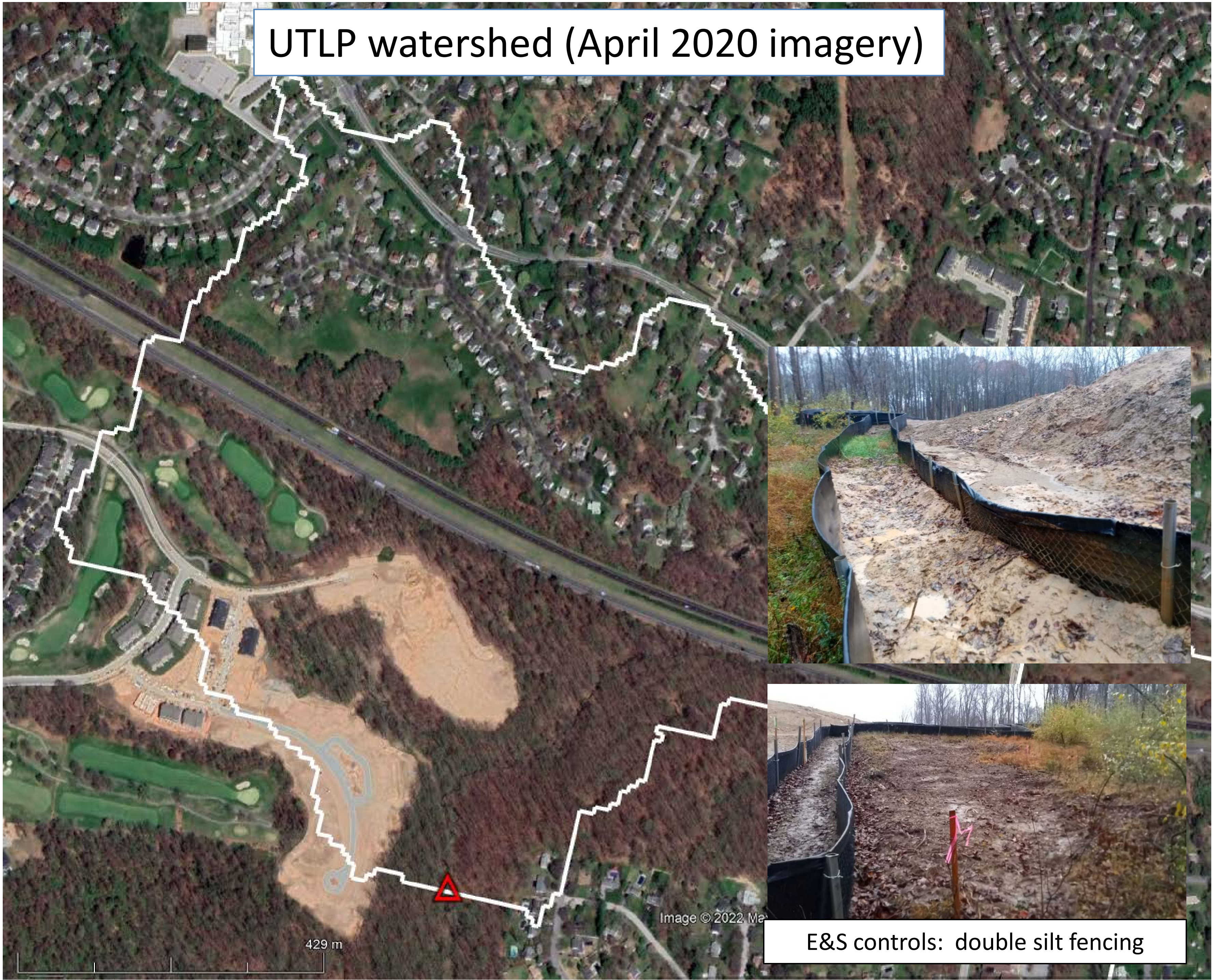
# Project Data Highlights (2019-present)

- Hydrologic/water quality monitoring (~3 years)
  - Rating curves; complete 5-min gage height/discharge records; hourly rainfall data (2 stations)
  - Sterling VA NEXRAD Level III data used to estimate (gage-adjusted) areal rainfall and identify “outlier” events
  - Monthly baseflow concentrations (both sites)
  - 83 major stormflow-producing events characterized: 76 common events (26 with intensive water quality sampling)
    - Max. one-hour rainfall mostly < 1-year R.I.
    - June 20, 2020: one-hour rainfall of ~2.3” at UTLP only (5-year R.I.)
    - June 22, 2020: one-hour rainfall of ~2.5” at both sites (20-year R.I.)
  - 5-min *in situ* conductivity, turbidity, temperature, water level data
  - ~1,150 surface water samples analyzed for TSS, TN, TP, nutrients, anions, etc. (both sites; “pre” and “during” phases of GSI implementation at UTLP)

# UTLP watershed (May 2015 imagery)



# UTLP watershed (April 2020 imagery)




E&S controls: double silt fencing

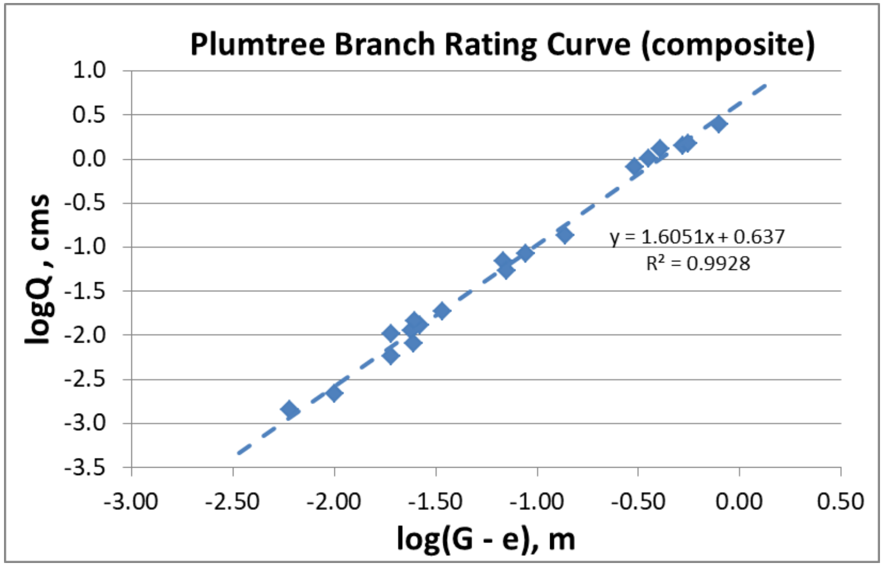
# UTLP watershed (April 2022 imagery)

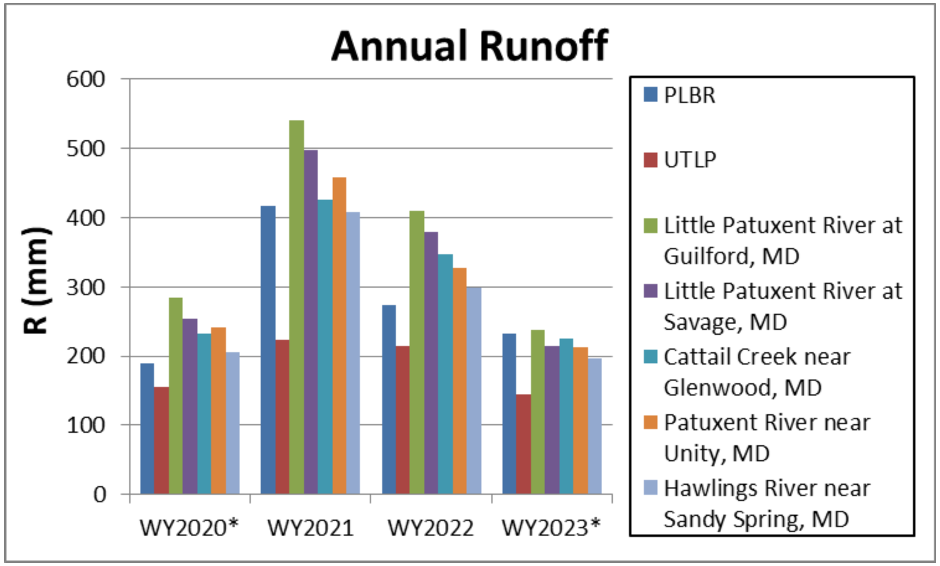
# Stormwater Management in UTLP Watershed

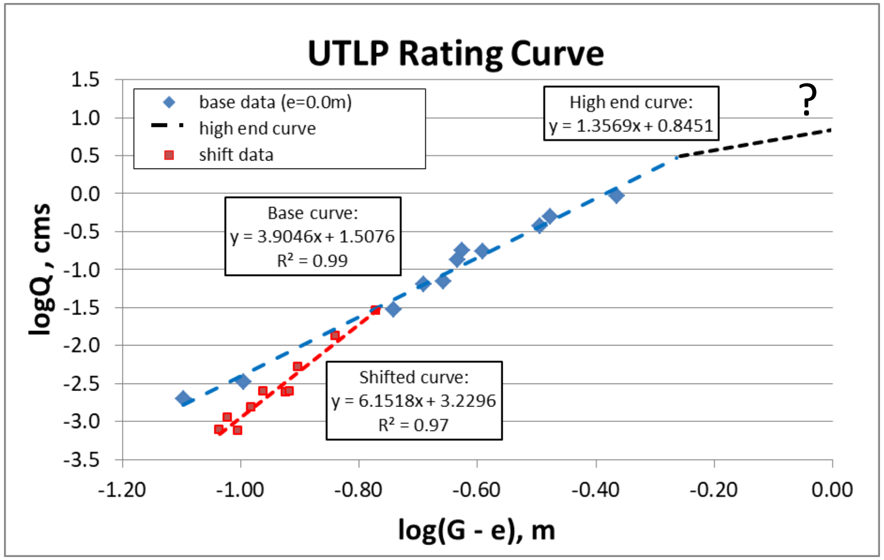
| Plan No. or BMP Name | SWM Code (no.) | SWM Type | Drainage Area (ft$^2$) | ISA (ft$^2$) | Notes |
|---|---|---|---|---|---|
| N/A | N/A (10) | 2A Grass Swales (abandoned) | 663,600 | 434,958 | I-70 legacy ISA (areas est.); SWM from MDOT-SHA NPDES SWMFAC |
| F-88-232_POND | N/A (1) | Wet Pond | 1,533,748 | 744,466 | MDE StormwaterPrint; ISA est. |
| F-87-188_POND | N/A (1) | Dry Pond | 217,800 | 105,718 | MDE StormwaterPrint; ISA est. |
| F-93-073_POND | N/A (1) | Wet Pond | 530,125 | 257,317 | MDE StormwaterPrint; ISA est. |
| F-07-158 | F-6 (2) | Bioretention | 28,750 | 28,750 | Resort Road extension #1 (areas est.) |
| F-16-004 | F-6 (1) | Bioretention | 43,560 | 43,560 | Resort Road extension #2 (areas est.) |
| F-17-095 | M-6 (2) | Microbioretention | 40,904 | 22,156 | Areas from development plan |
| F-17-095 | F-6 (1) | Bioretention | 60,657 | 32,753 | Areas from development plan |
| F-17-096 | F-6 (5) | Bioretention | 249,205 | 136,610 | Areas from development plan |
| F-17-096 | M-6 (1) | Microbioretention | 16,200 | 5,139 | Areas from development plan |
| F-17-096 | M-5 (44) | Dry wells | 35,640 | 35,640 | Areas est. from development plan (44 x 810) |
| F-18-027 | M-6 (1) | Microbioretention | 22,684 | 12,906 | Areas from development plan |
| F-18-027 | M-5 (14) | Dry wells | 11,550 | 11,550 | Areas from development plan |
| SDP-20-036 | M-6 (7) | Microbioretention | 131,983 | 123,042 | Areas from development plan (under construction) |
| Totals (acres), 2015 | | | 67.6 | 35.4 | |
| Totals (acres), 2023 | | | 82.3 | 45.8 | |
| Watershed area (acres) | | | 198.4 | | |
| **ISA (%), 2015** | | | | **17.8** | |
| **ISA (%), 2023** | | | | **23.1** | ~30% increase in ISA (2015 – 2023) |

- New residential development: estimated 30% increase in ISA (17.8 to 23.1%)
- GSI implementation: 9 bioretentions; 11 micro-bioretentions; 56 dry wells

# Rating Curves/Annual Runoff



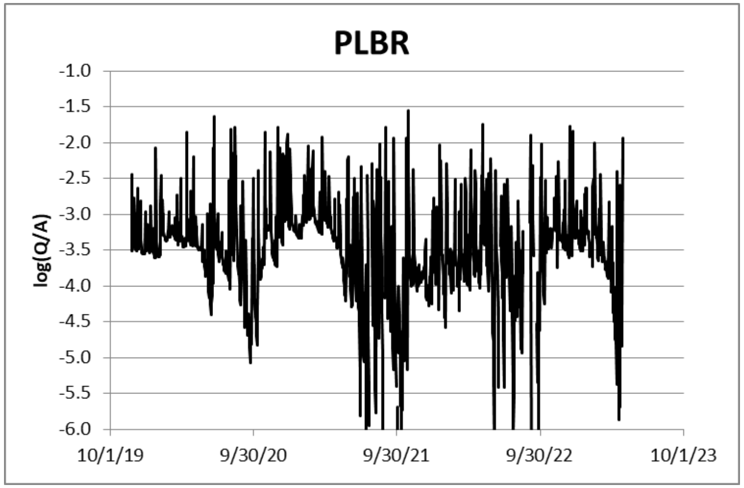



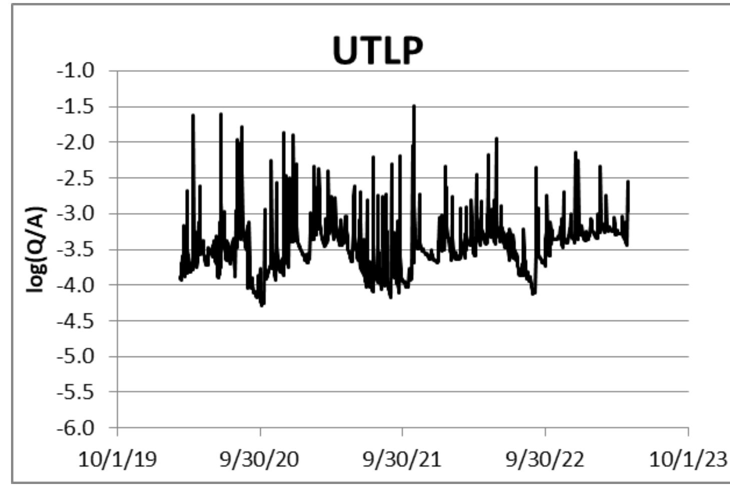



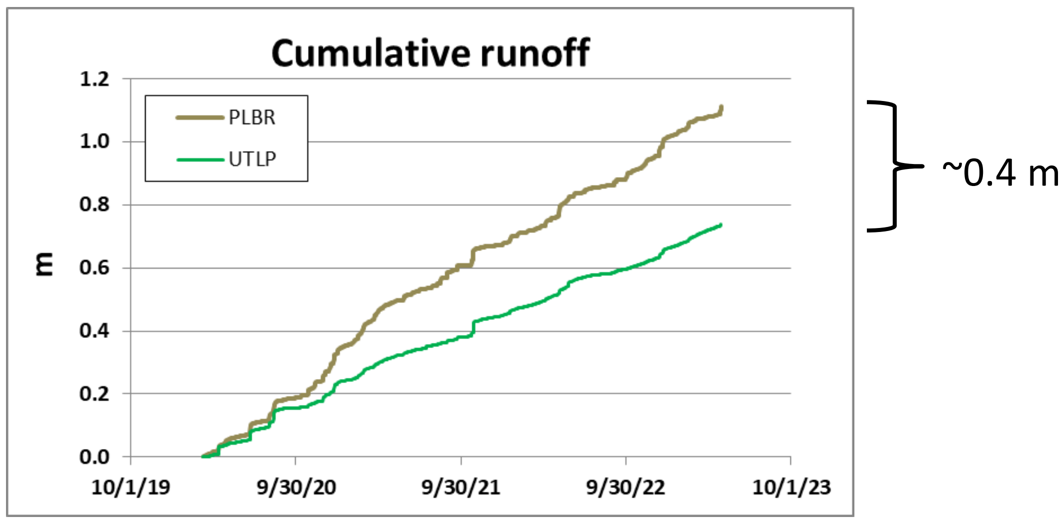

*partial water year data (3/10/20 – 9/30/20; 10/1/22 – 5/30/23)

- Very flashy streams gaged over 3 orders of magnitude
- Highest discharge measurements exceeded <0.05% of the time!
- PLBR annual runoff agrees well with data from nearby USGS watersheds
- UTLP runoff is lower (esp. in WY’21)

# Annual runoff anomaly

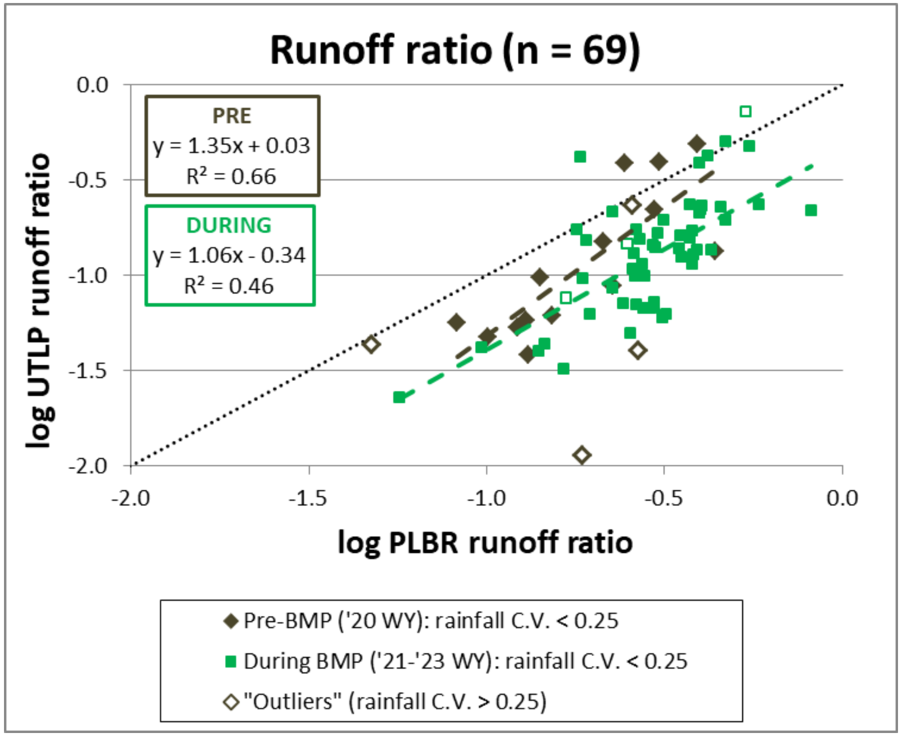


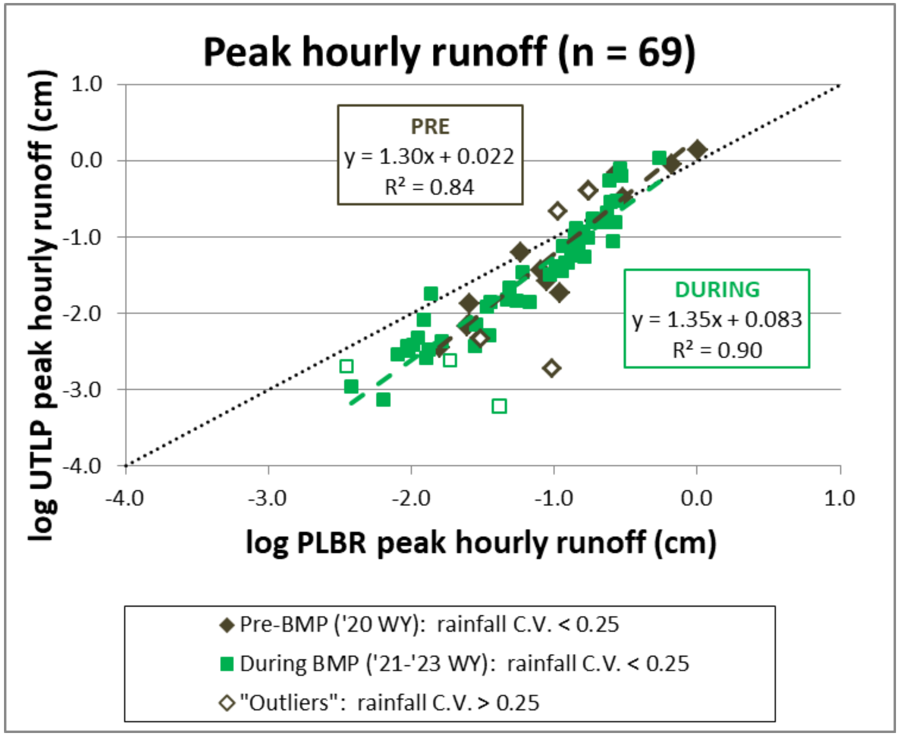




- Similar annual hydrographs: area-normalized mean daily discharge (log scale)
- Greater range at PLBR mostly due to lower summer baseflow
- Large UTLP runoff anomaly of ~ -40 cm (-33%) over 3+ years

# Paired Storm Event Analyses




One way ANCOVA: $P < 0.05$

One way ANCOVA: NS

- Paired data analysis (ANCOVA) (removed 7 “outlier” events)
- Statistically significant difference in adjusted mean event runoff ratio at UTLP ($P < 0.05$) in WY21 – WY23 compared to WY20 (pre-BMP period)
- No difference in adjusted mean peak hourly runoff, however

# Two-component hydrograph separation: natural tracer mass balance*

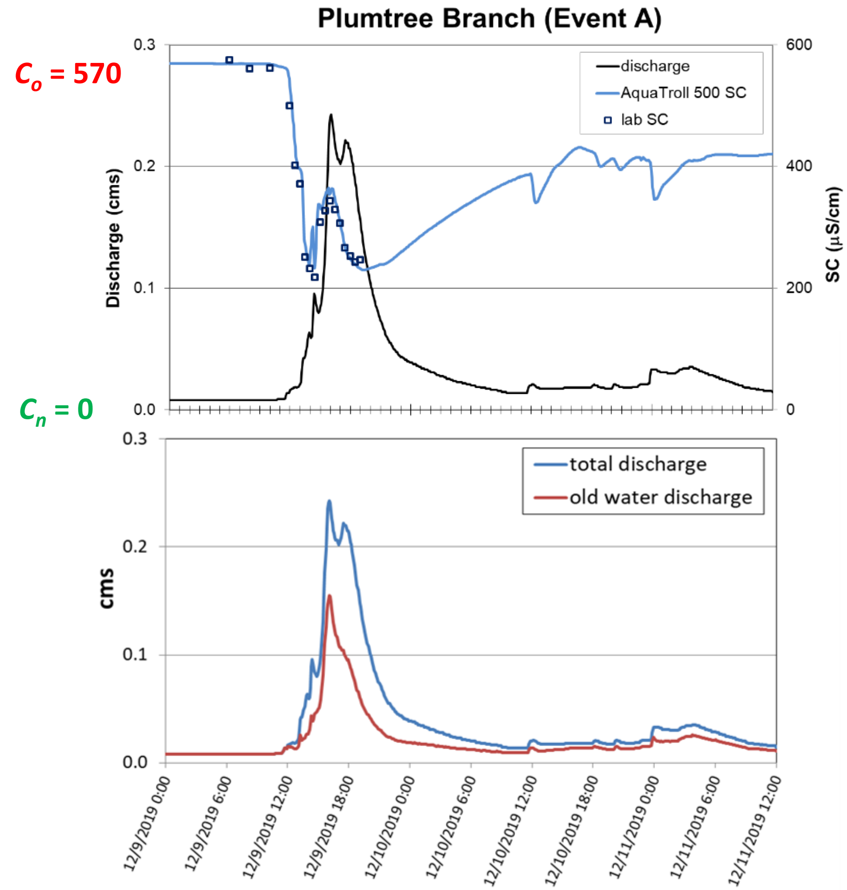
Mathematics is straightforward: solve two equations (two unknowns) simultaneously

- Water balance equation: $Q_T(t) = \boldsymbol{Q_n(t)} + \boldsymbol{Q_o(t)}$ [1]
- Tracer (SC) mass balance equation: $Q_T(t)C_T(t) =$
  $\boldsymbol{Q_n(t)}C_n + \boldsymbol{Q_o(t)}C_o$ [2]
- Substituting [1] into [2] and rearranging:

$$\boldsymbol{Q_n(t)} = Q_T(t)\left[\frac{C_o - C_T(t)}{C_o - C_n}\right] \quad [3]$$

- Substituting [3] into [1]: $\boldsymbol{Q_o(t)} = Q_T(t) - \boldsymbol{Q_n(t)}$ [4]

  where the *Q*'s are time-varying discharges and the *C*'s are concentrations ($C_n$ and $C_o$ are constants, but $C_T$ is time-varying). Equations [1] and [3] can be solved for each time (*t*) for which data on $Q_T(t)$ and $C_T(t)$ are available.

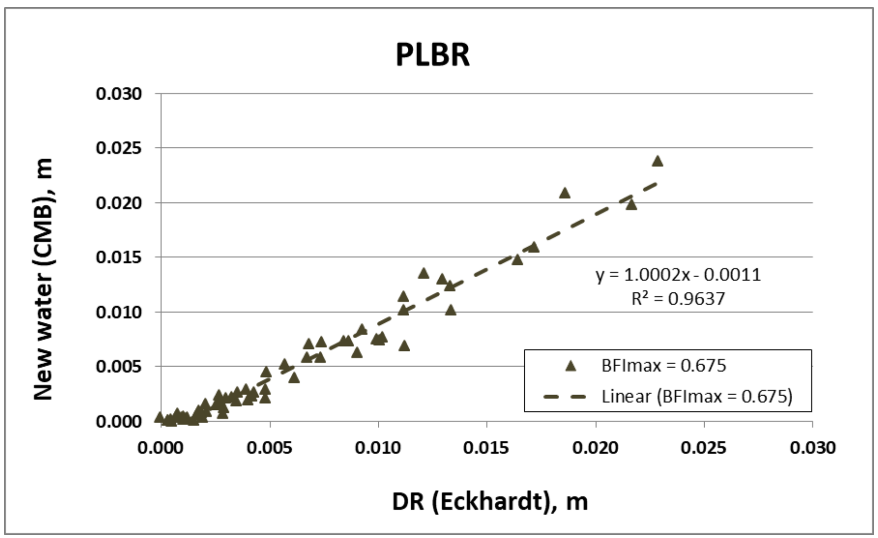


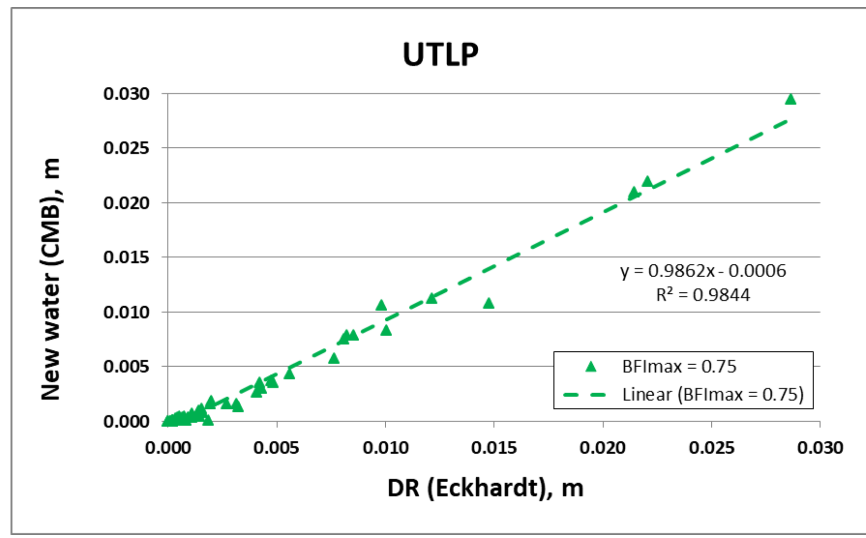

- In this example: $\frac{\int Q_o(t)dt}{A} = 0.23cm$; $\frac{\int Q_n(t)dt}{A} = 0.16cm$; $[Q_n(t)/Q_T(t)]_{max} = 60\%$
- Method was generally applicable to both watersheds (except for winter storms with road-salting)

*e.g., Sklash *et al.* (1976); Pellerin *et al.* (2008)

# Hydrograph Separation: recursive digital filtering (RDF, Eckhardt 2005)

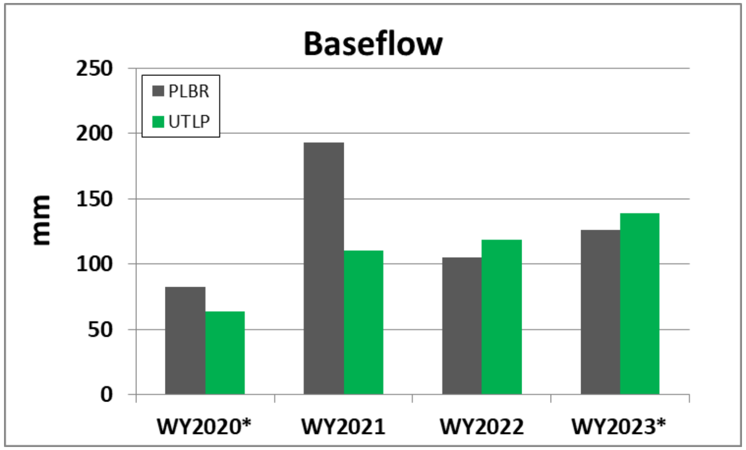
- Two-parameter RDF to separate hydrograph into two components: direct runoff (*DR*) and baseflow (*BF*)
- Linear reservoir assumption: *BF* decays exponentially (recession constant, ***a*** ($0 < a < 1$) can be estimated independently from field data)
- Second parameter ($BFI_{max}$, the maximum value of the "baseflow index") is unknown
- Assume that $Q_o = BF$ and $Q_n = DR$; estimate $BFI_{max}$ using SC mass balance results for monitored storm events

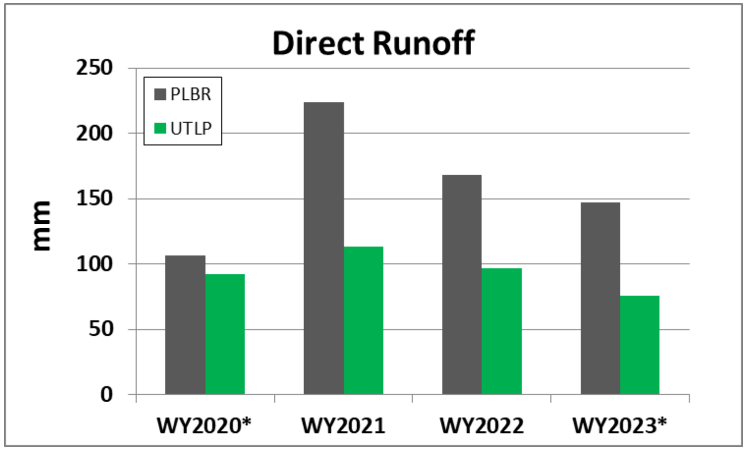


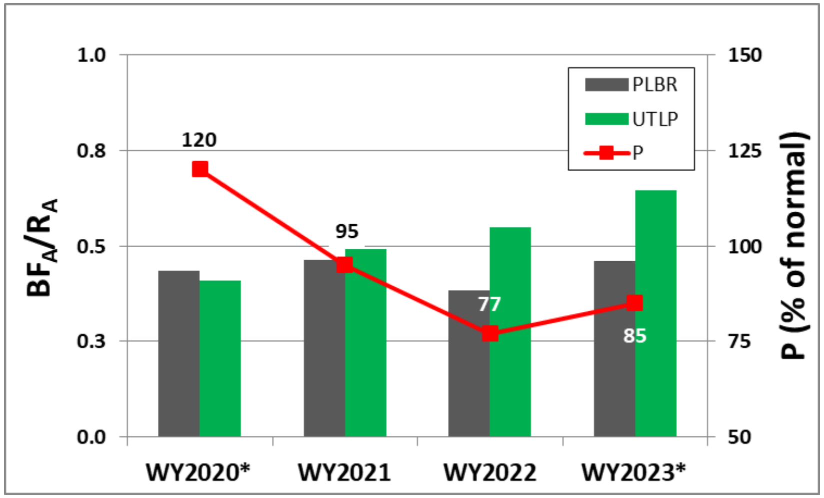




- Obtained ~1:1 linear relationships between new water runoff and direct runoff
- $BFI_{max}$ values = 0.675 (PLBR) and 0.750 (UTLP)

# Annual flow components based on calibrated RDF



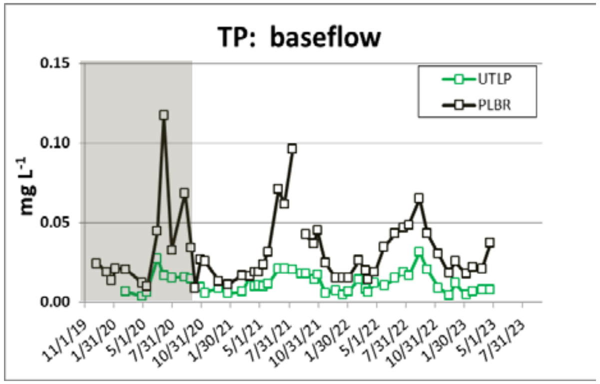



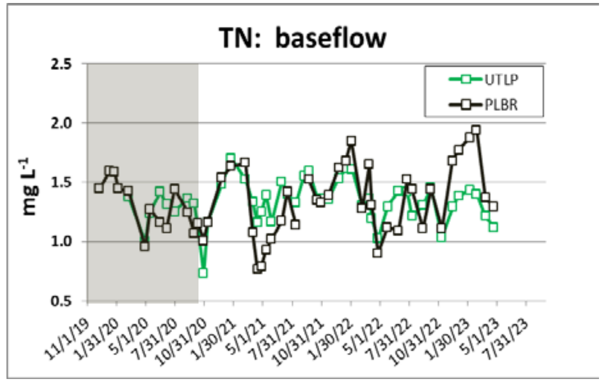



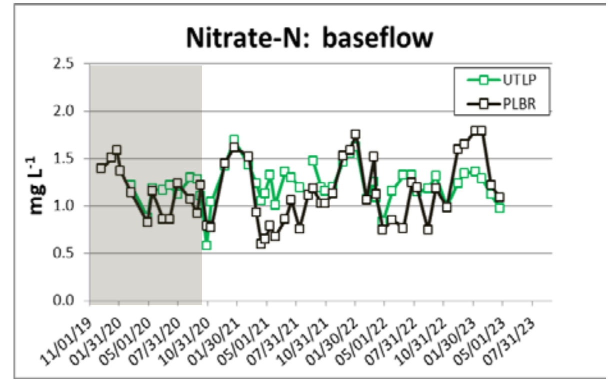

- The baseflow index ($BFI = BF_A/R_A$) has steadily increased at UTLP during GSI implementation, while *BFI* at PLBR has remained relatively constant
- Temporal pattern at UTLP seems largely independent of hydroclimatic variability

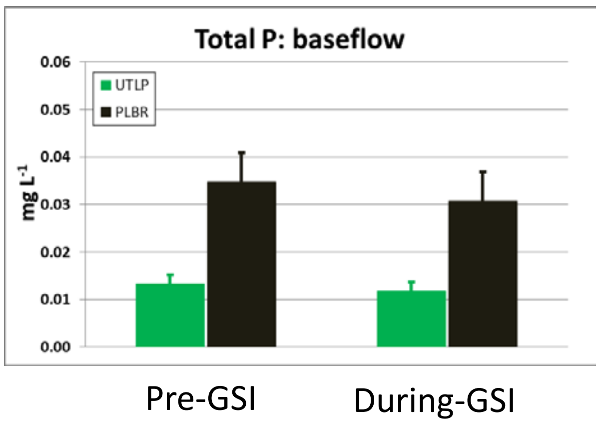
*partial water year data (3/10/20 – 9/30/20; 10/1/22 – 4/30/23)

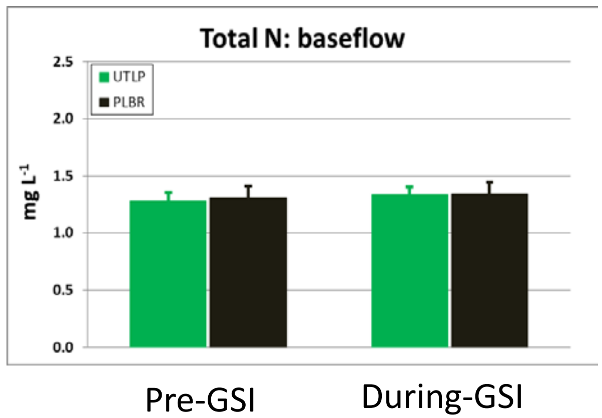
# Baseflow water quality

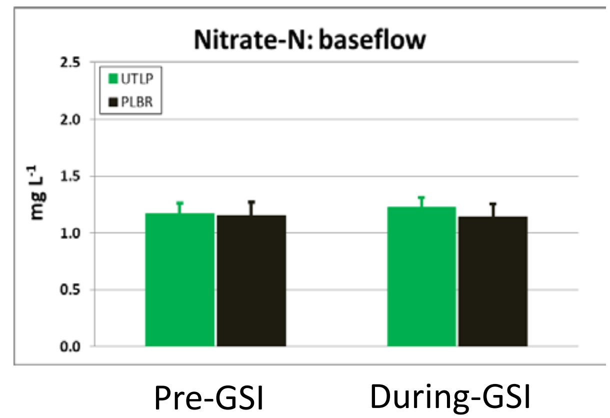


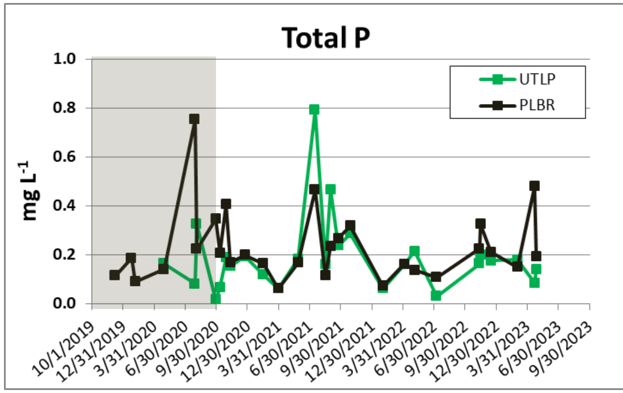



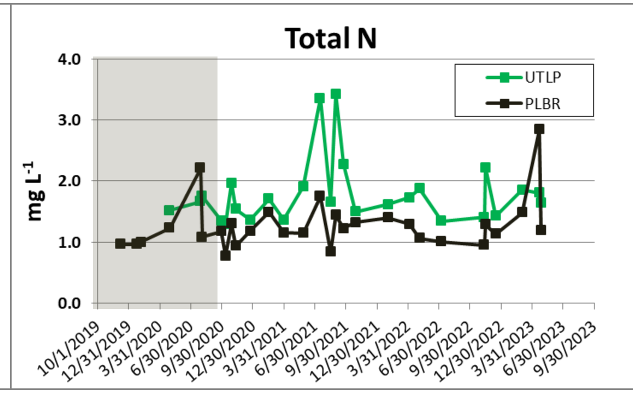



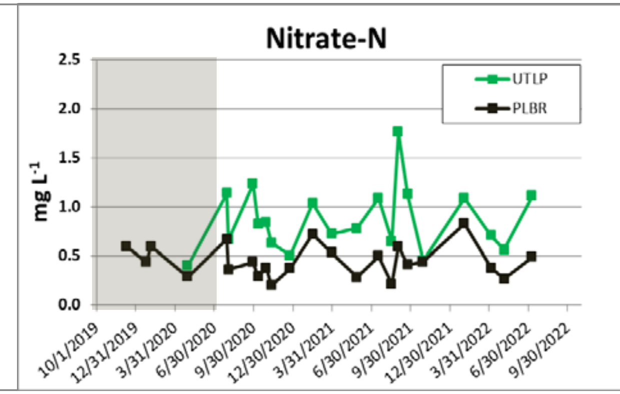



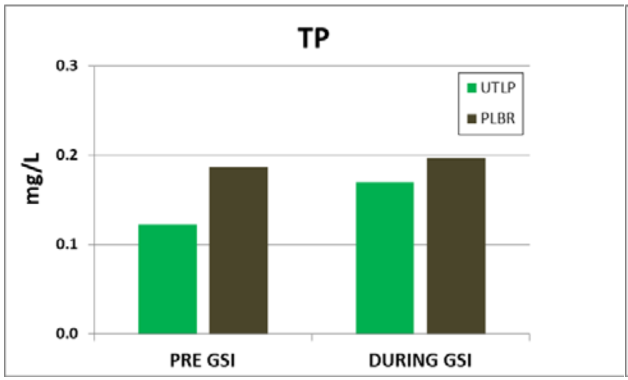

- Repeating intra-annual variations are apparent: TN and TP out of phase
- Mean baseflow TP (and orthophosphate-P) concentrations lower at UTLP ($P < 0.001$), but stable over time (differences unlikely related to GSI implementation)
- No differences in mean baseflow TN or nitrate-N concentrations

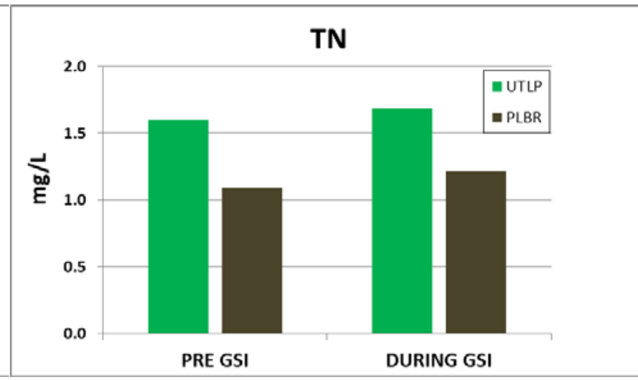
# Stormflow EMC's

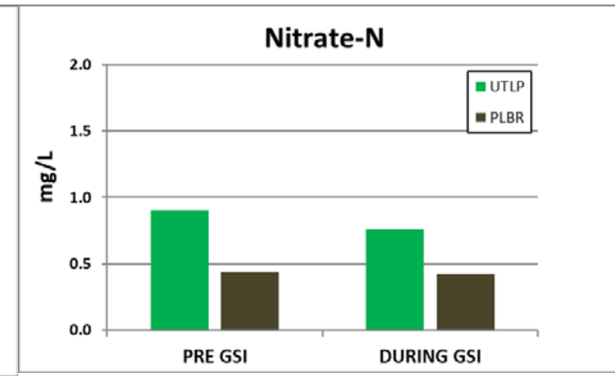



- EMC data are considerably "noisier" than baseflow concentrations
- Insufficient number of common events for pre-BMP period (n = 4) to use ANCOVA
- Statistically significant differences ($P < 0.05$; n = 26) in median TP, TN, and nitrate-N EMC's between watersheds (paired analysis)
- No statistically significant differences in median EMC's between pre-GSI and during-GSI periods for either watershed

# Pollutant Load Modeling

- LOADEST: widely-applied 7-parameter empirical loading model (Cohn *et al.*, 2003; Runkel *et al.*, 2004; 2013)

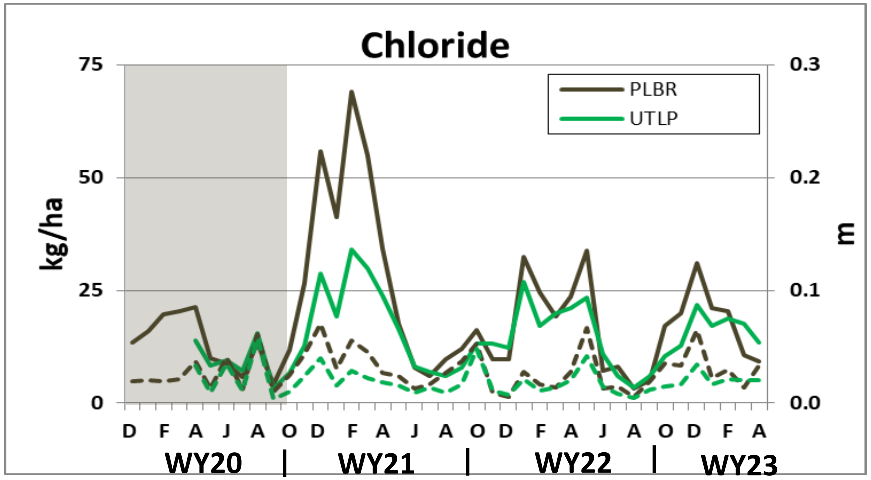
$$lnL = a_0 + a_1 lnQ + a_2 lnQ^2 + a_3 \sin(2\pi dtime) + a_4(cos2\pi dtime) + a_5(dtime) + a_6 dtime^2$$

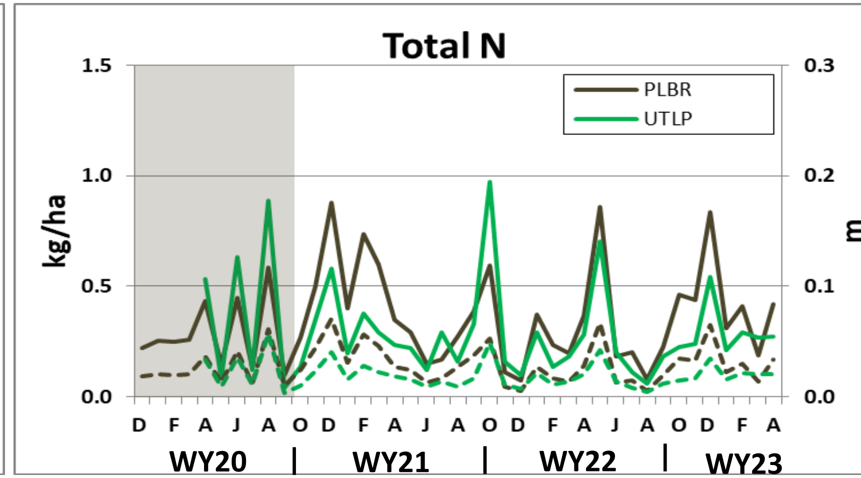
where $L$ = load, $Q$ = stream discharge, and *dtime* is a decimal representation of time

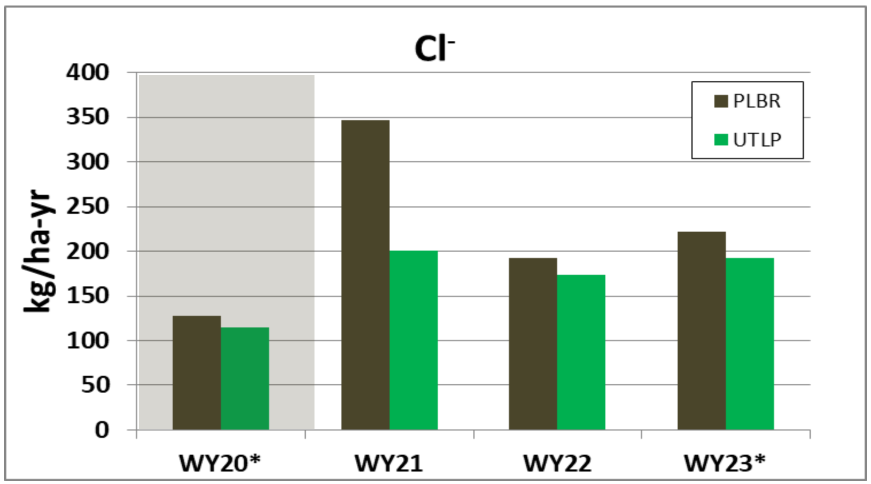
- Instantaneous hourly *C-Q* data used to calibrate LOADEST for both watersheds
- Estimation for entire period of record (with aggregation to monthly and annual periods)

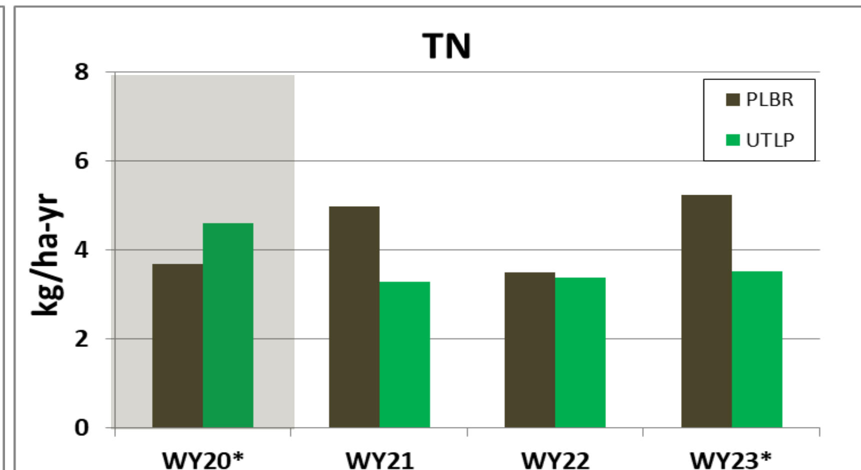
| Pollutant | PLBR | | | UTLP | | |
|---|---|---|---|---|---|---|
| | $R^2$ | $B_p$ (%) | E | $R^2$ | $B_p$ (%) | E |
| **$Cl^-$** | *0.93* | *-3.6* | *0.52* | *0.89* | *-8.5* | *0.47* |
| **SC** | *0.97* | *0.0* | *0.72* | *0.95* | *-3.5* | *0.83* |
| **$NO_3$-N** | *0.95* | *-4.0* | *0.72* | *0.94* | *-7.1* | *0.78* |
| **TN** | *0.99* | *-4.3* | *0.91* | *0.98* | *0.5* | *0.81* |
| **TP** | *0.97* | *20.1* | *0.32* | *0.94* | *83.2* | *-1.36* |
| **Ortho-P** | *0.97* | *8.7* | *0.91* | *0.90* | *70.1* | *-1.84* |
| **TSS** | *0.95* | *40.9* | *-0.60* | *0.93* | *-197.8* | *-8.87* |

# Pollutant Load Modeling



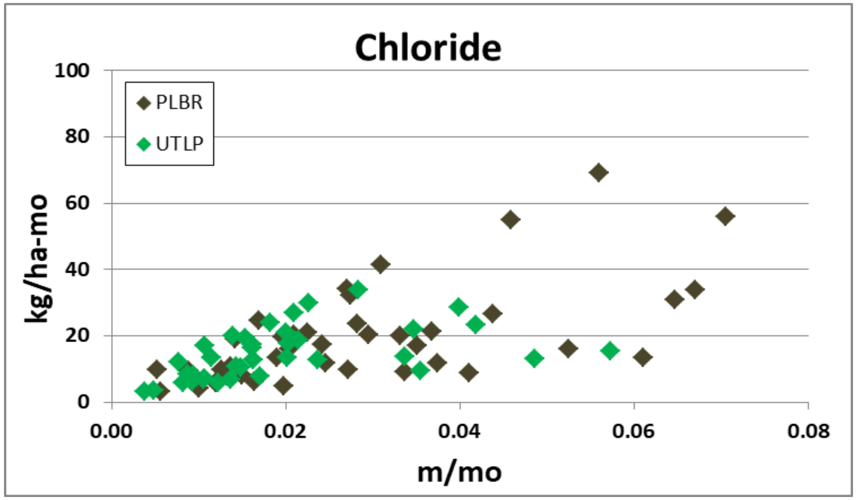



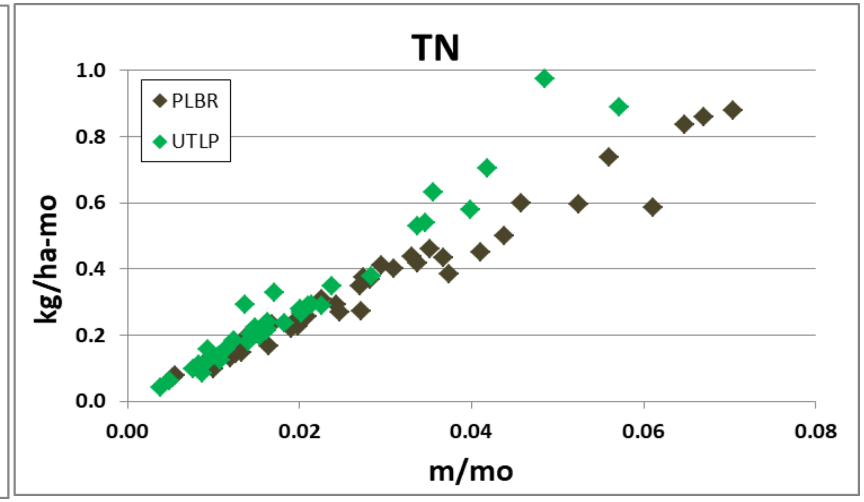



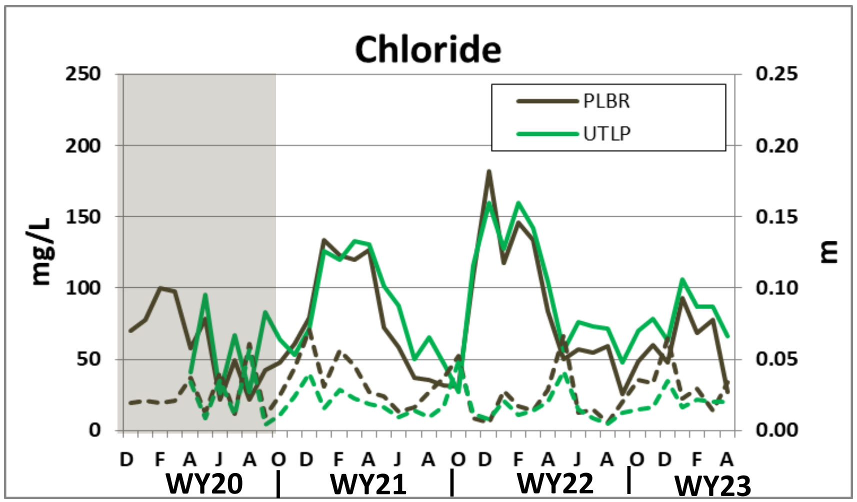

- Seasonal variations in $Cl^-$ loads explained by timing/amount of road salt application
- Differences in annual $Cl^-$ loads between watersheds explained by UTLP runoff anomaly
- Monthly TN loads appear "random", but strongly correlated with runoff; TN load peaks can occur in any season

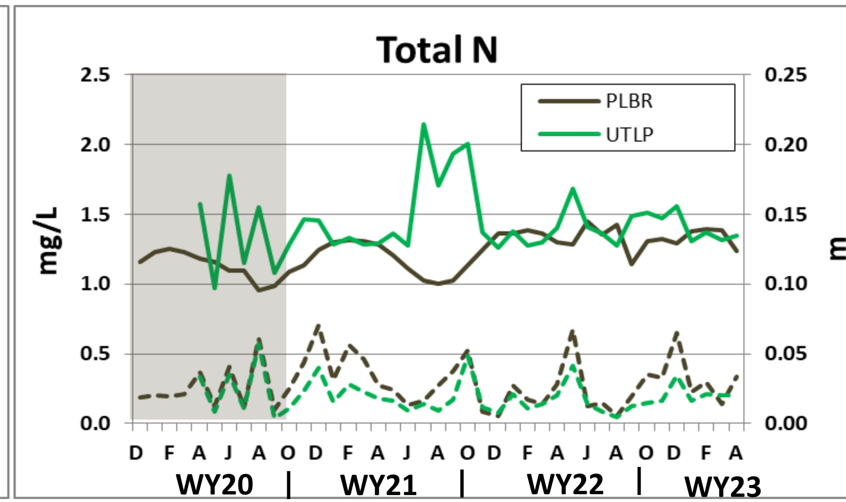
*partial water year data (3/10/20 – 9/30/20; 10/1/22 – 4/30/23)

# Pollutant Load Modeling




- As expected, TN loads very strongly correlated with runoff; chloride less well correlated
- Monthly flow-weighted concentrations: $Cl^-$ shows strong intra-annual pattern at both watersheds; intra-annual pattern for TN only evident at PLBR
- Does the TN graph suggest a response to GSI implementation at UTLP?

# Summary of Key Results

- Integration of conventional and newer field/analytical methods allowed detection of some important watershed-scale hydrologic changes at UTLP likely related to GSI implementation:
  - *Reduction in storm event runoff ratios*
  - *Increasing baseflow index (and commensurate decrease in direct runoff)*
- We have not detected any significant changes in:
  - *Peak storm event runoff*
  - *Baseflow chemistry*
  - *Event mean pollutant concentrations (TN, TP, etc.)*
- Full interpretation of pollutant loads is still in progress
- Data from natural hydrologic systems are often very noisy: role of PLBR as control watershed
- Development/GSI implementation in UTLP is on-going; lack of “post BMP” data is a major limitation

# Acknowledgments

- Chesapeake Bay Trust/MD-DNR: sponsorship
- Howard County (Mark Richmond *et al*.): ROE permits; site development plans
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  - Briana Rice
  - Jim Garlitz
  - Ev Demott
  - Joel Bostic
  - Trevor Frissell
- Neal Eshleman
- Elizabeth Eshleman

# A PAIRED-WATERSHED STUDY:
## TRANSLATION OF KEITH ESHLEMAN'S PRESENTATION BY KIMBERLY L. GROVE, P.E. BALTIMORE CITY DPW

CBT Pooled Monitoring Forum
June 21, 2023

# MONITORING TIMEFRAME

Pre GSI = ESC

During GSI

GSI (ESD) practices are designed to treat the first 1 inch of rain storm and "mimic" natural hydrology for a 1-year, 24-hour storm.

# NORMALIZE TO COMPARE

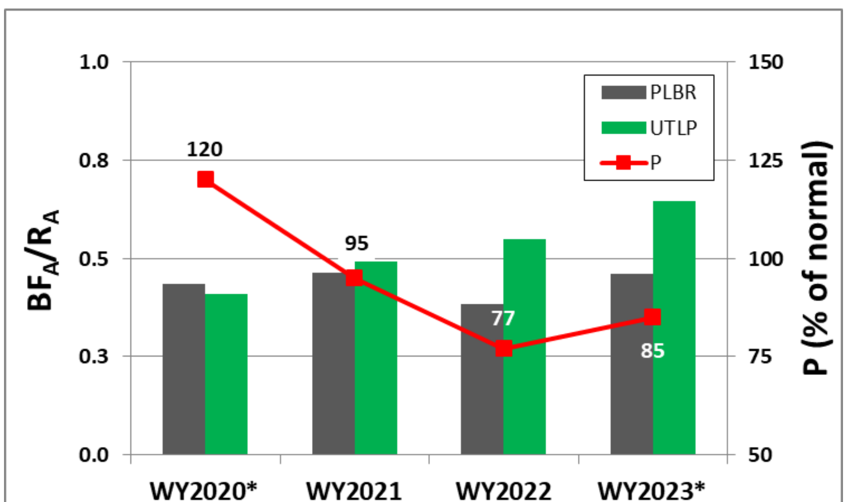
Annual runoff

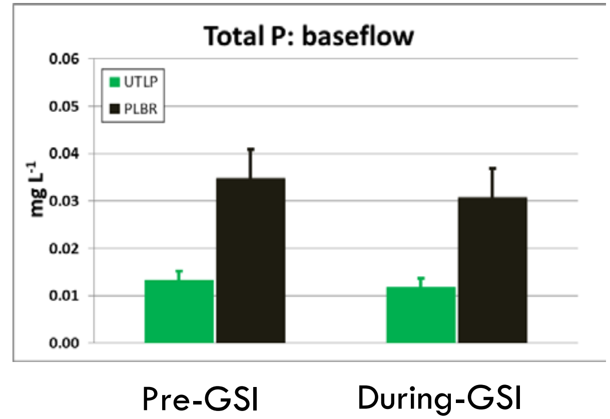
Storm events without “outliers”

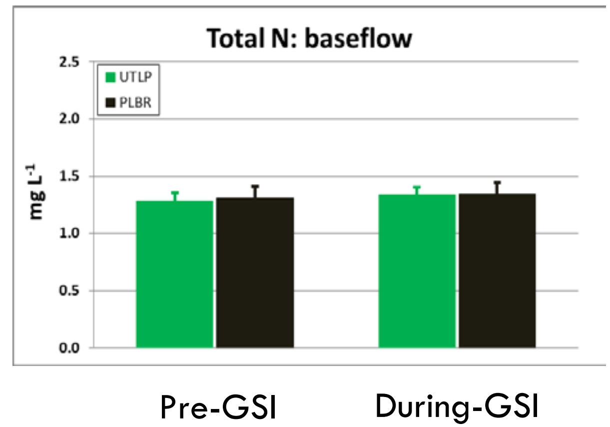
Base flow vs. runoff

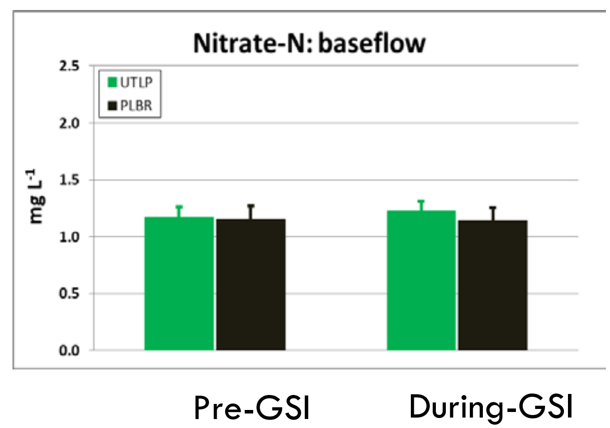
Base flow water chemistry

Storm flow event mean concentrations



# MAJOR TAKE-AWAYS

Comparison of developments, not to reference forest, to study the evolution of stormwater management.

Usability of data is dependent on statistical analysis.

TN and TP are different.

Any "control" is better than none, but effectiveness would require a deeper dive into the basis of design.

GSI performance is improving over time.

Pollution loading is complex: GSI appears to help with the base flow but stream and riparian buffer conditions may still be a factor for wet weather loading.