Stream hydrology and water quality impacts of contrasting urban stormwater mitigation strategies: centralized versus distributed

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U.S. Department of the Interior
U.S. Geological Survey

Outline

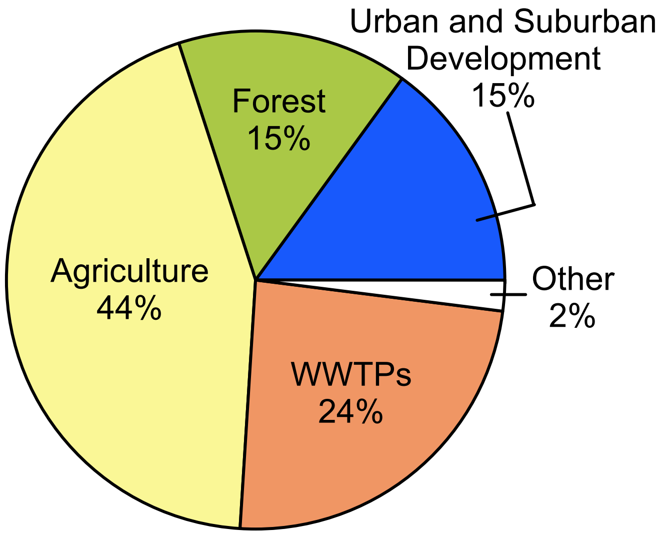
- Background
- Study Design & Methods
- Stream Hydrology
- Nutrients & Sediment
- Conclusions & Future Work

Background

- Problem: Chesapeake Bay eutrophication and hypoxia

- Urban and Suburban contributions to the Bay[1]:
  - 15% of total phosphorus
  - 8% of total nitrogen
  - 16% of sediment

- Variety of sources requires a mix of solutions to achieve Chesapeake Bay TMDL goals
  - 24% P reduction
  - 25% N reduction
  - 20% Sediment reduction



Phosphorus loading to the Cheseapeake Bay[1]

[1]Based on data from US EPA, *Chesapeake Bay TMDL for Nitrogen, Phosphorus and Sediment,* 2010; WWTPs phosphorus loading includes municipal, industrial, and on-site WWTPs

Background

- Other impacts of urban stormwater runoff:
  - Hydrology
    - Impervious cover increases peak discharge → increased flooding[1]
    - Altered groundwater levels and stream baseflow due to urbanization[2]
  - Geomorphology
    - Channel erosion due to high water velocities[1]
  - Chemistry
    - Transport of toxic urban pollutants (e.g. metals and organics)[3]
  - Biology
    - Decreased aquatic invertebrate and fish diversity and density[1]

USGS

[1] *Urban Ecology: An International Perspective on the Interaction Between Humans and Nature* (2008), pp. 207-231
[2] *Journal of Hydrology* (2013), 485, pp. 201-211
[3] *Water Environment Research* (1995), 67, pp. 260-275

Background

- Landmarks in Stormwater Management
  - 1972: Clean Water Act
  - 1987: NPDES Stormwater Program
  - 1999: NPDES Phase II
- Low Impact Development (LID):
  "LID is a site design strategy with a goal of…replicating…a functionally equivalent hydrologic landscape." EPA Report EPA-841-B-00-005

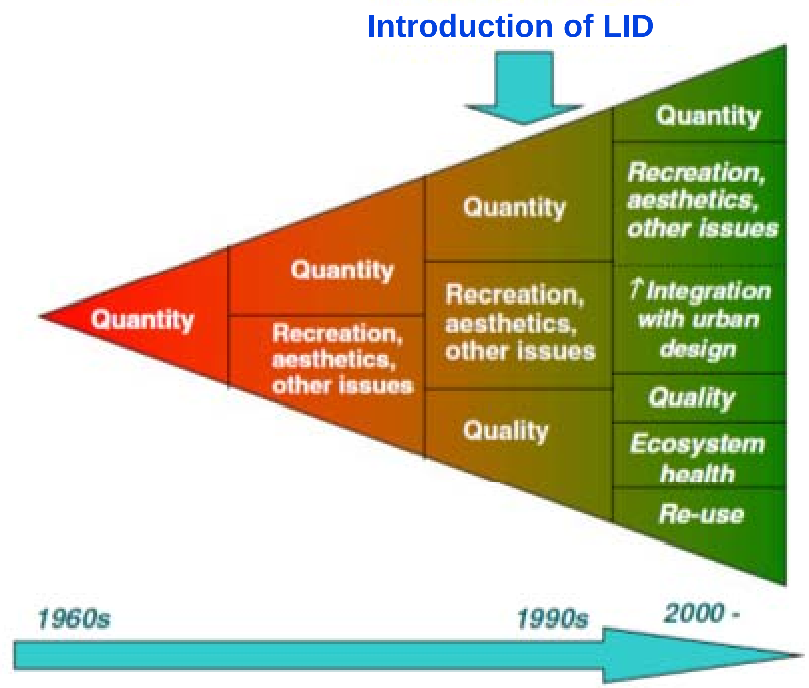


Figure used with author permission; Adapted from *Environmental Management* (2008), 42, pp. 344-359

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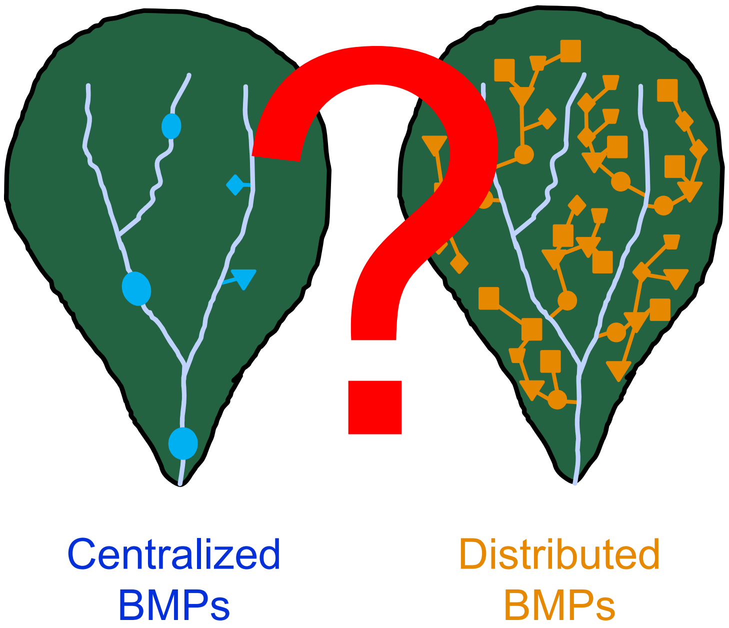
Background

- Stormwater Best Management Practices (BMPs) are used to address urban stormwater runoff:
  - Detention/retention ponds
  - Infiltration trenches/grassed swales
  - Filters/bioretention cells
  - Public education/involvement

- BMPs have traditionally been constructed in a centralized manner to address urban stormwater runoff

- Recently, distributed BMPs have been used to achieve low impact development by providing treatment operations in series and on the landscape



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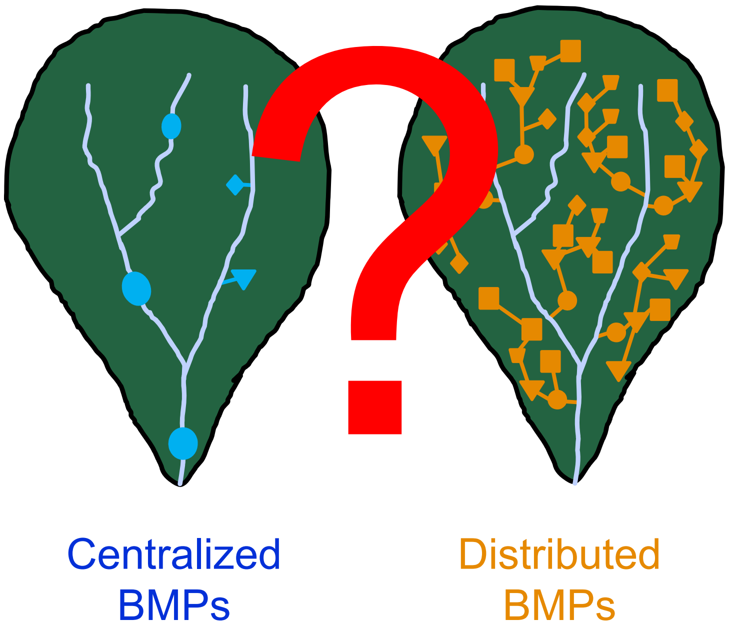
Figures modified from Loperfido and Hogan (2012), USGS Fact Sheet 2012-3079

Research Objectives

- Assess how urban stormwater management strategies utilizing either centralized or distributed BMPs affect:
  - Water quantity: Magnitude and pattern of water export
  - Water quality: Magnitude and form of exported phosphorus, nitrogen, and sediment



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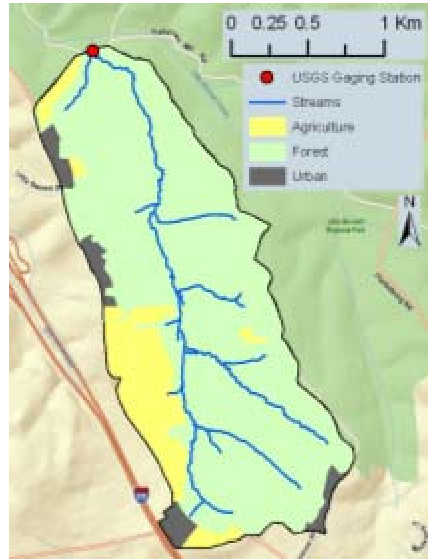
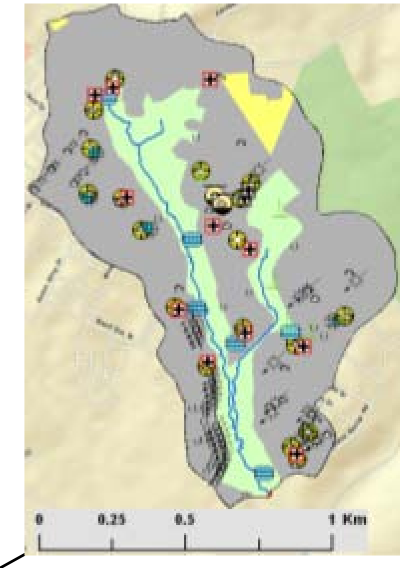
Study Design

- Paired watershed approach to monitor catchment outlets
  - 1 Forest
  - 2 Urban Centralized BMPs (VA & MD)
  - 1 Urban Distributed BMPs

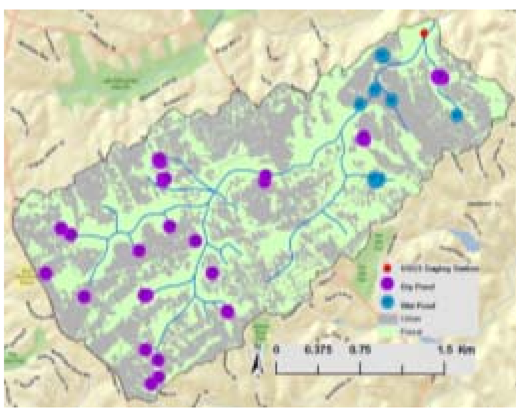
Forest-MD



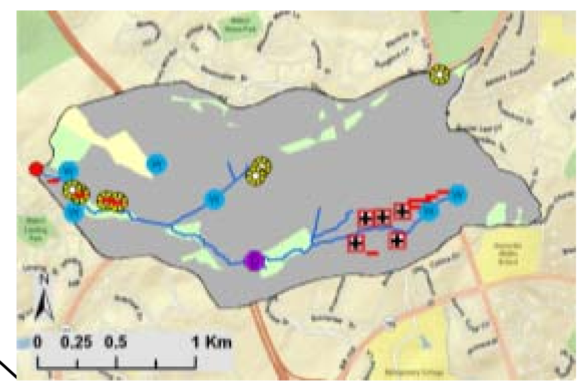
Distributed BMPs-MD



Centralized BMPs-VA



Centralized BMPs-MD



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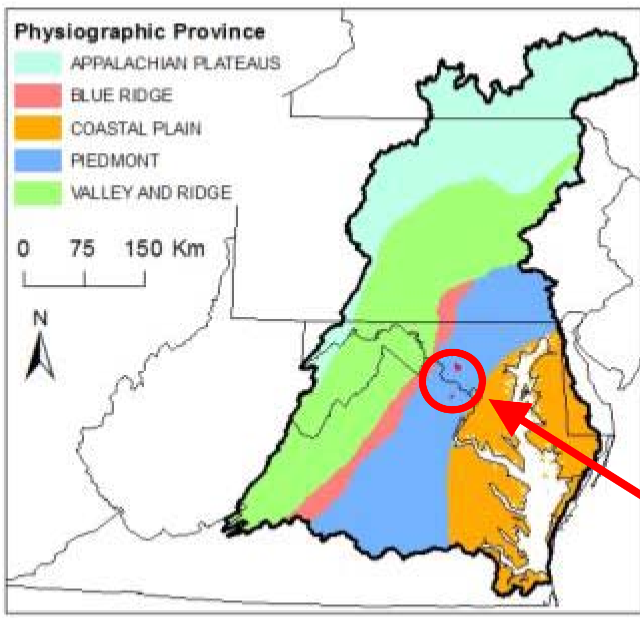
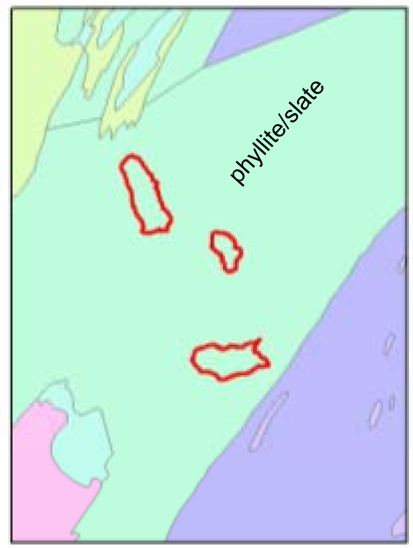
Study Area Geology

- All catchments in Piedmont physiographic province
- MD catchments bedrock: phyllite/slate
- VA catchment bedrock: several different types

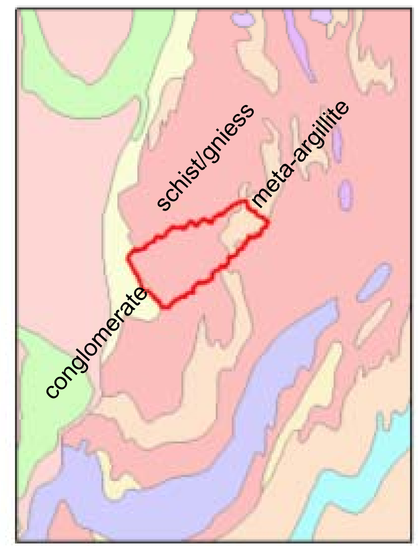


Study catchments

MD Catchments



VA Catchment

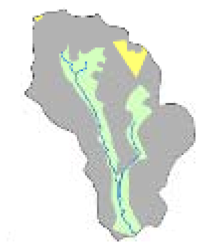


Land Cover

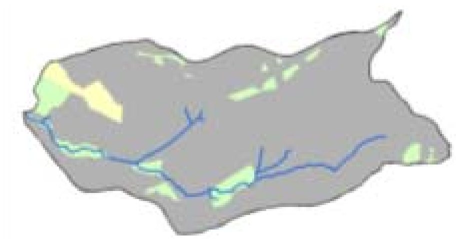
Watershed	Drainage Area (km^2)	% Urban	% Agriculture	% Forest
Forest-MD	3.0	4%	14%	82%
Distributed BMPs-MD	1.1	77%	3%	20%
Centralized BMPs-MD	3.5	89%	3%	8%
Centralized BMPs-VA	7.0	43%	0%	57%

- Differences between urban Centralized BMPs-VA compared to Centralized BMPs-MD/Distributed BMPs-MD
  - Lower housing density
  - Wider riparian zones and floodplains

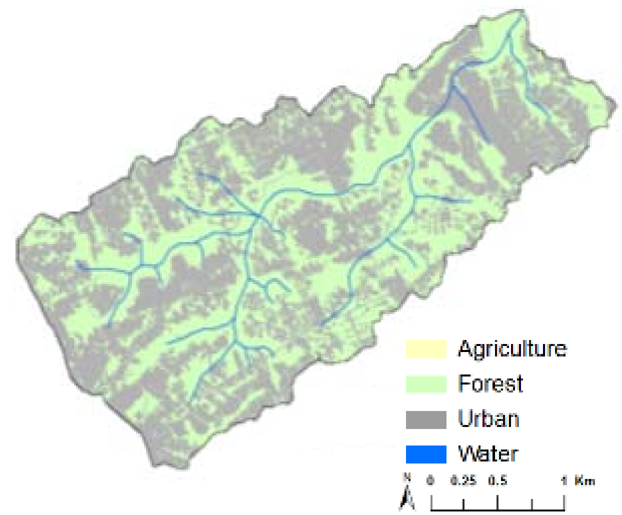
Distributed BMPs-MD



Centralized BMPs-MD

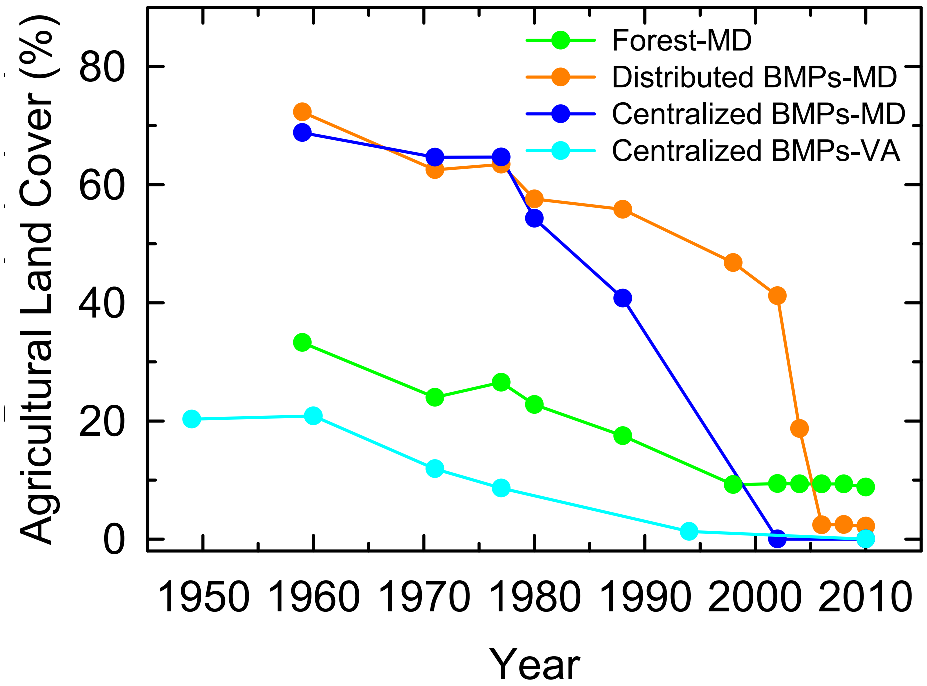


Centralized BMPs-VA



Historical Agricultural Activity

- Centralized BMPs-MD and Distributed BMPs-MD watersheds have recently been converted from agricultural to urban land use.
  - → more recent inputs of agricultural fertilizer



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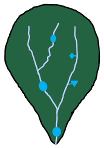
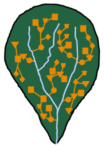
Centralized versus Distributed BMPs



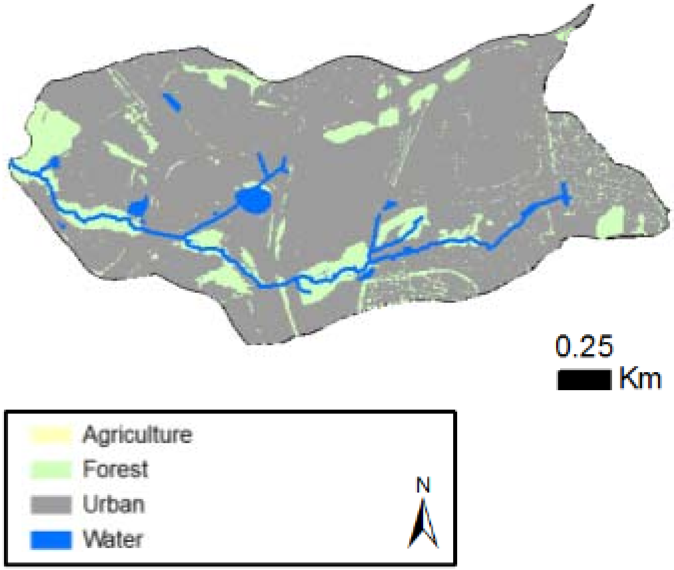
Centralized BMPs

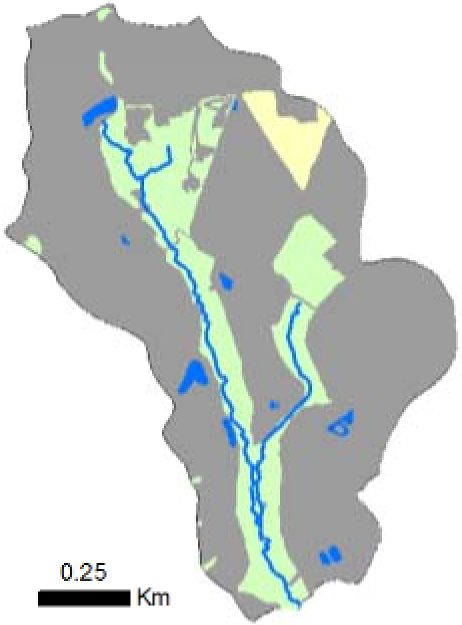
- located instream or directly adjacent to stream
- treat larger areas



Distributed BMPs

- located on the landscape
- typically connected in series
- protected riparian zone





Figures modified from Loperfido et al. (in review), submitted to *Journal of Hydrology*, July 7, 2013

Distributed BMP Treatment Trains

Stormwater BMPs Inventory

Table A1. Stormwater BMPs present in the study catchments.

Stormwater BMP Types present in Study Catchments	Number of BMPs in Study Catchments	Primary Design Goal
Dist-MD		
Drywell Recharge Facilities	35	Infiltration
Recharge Chambers	2	Infiltration
Storm Drain Recharge Facilities	18	Infiltration
Dry Swales	13	Infiltration/Stormwater Conveyance
Bioretention Facilities	5	Infiltration/Hydraulic Detention/Water Quality
Volume Storage Facilities	6	Hydraulic Detention
Dry Pond	6	Hydraulic Detention
Oil/Grit Separator	18	Water Quality
Underground Storm Filters	5	Water Quality
Sand Filter	13	Water Quality
Flow Splitter	40	First Flush Separator
Cent-MD		
Volume Storage Facilities	1	Hydraulic Detention
Dry Pond - Quantity Control Only	4	Hydraulic Detention
Dry Pond - Quantity and Quality Control	1	Hydraulic Detention/Water Quality
Wet Pond	6	Hydraulic Detention/Water Quality
Water Quality Infiltration Trench	9	Water Quality
Water Quality Bioretention Cell	6	Water Quality
Oil/Grit Separator	7	Water Quality
Oil/Grit Separator with Sand Filter	1	Water Quality
Sand Filter	8	Water Quality
Flow Splitter	11	First Flush Separation
Cent-VA		
Dry Pond	20	Hydraulic Detention
Wet Pond	5	Hydraulic Detention/Water Quality

Field Methods

Sample/Measurement	Instrument	Interval (min)
Whole water stream samples	Isco 6712 Automatic Sampler (24 bottles)	typically 60
Turbidity/Temp	DTS-12 Turbidity Sensor/CR200X datalogger	5
Specific Conductance/Temp	INW CT2X Conductivity Sensor	5
Precipitation amount	J&S Instruments Rain Gauge	5

Field Methods

- Water quality monitoring: nutrients, sediment, and general water quality parameters
  - Sampling conducted throughout the hydrograph to understand water quality improvements provided by distributed BMPs and centralized BMPs

Data logger

Isco sampler

Turbidity, temperature, conductivity sensors

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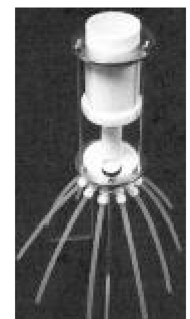
Laboratory Methods

Parameter	Method	Instrument
Nitrogen (TN, NH_3, NO_2^-+NO_3^-)	EPA (2011)	Segmented flow autoanalyzer
Phosphorus (TP, SRP, TDP)	EPA (2011)	Segmented flow autoanalyzer
Turbidity	EPA (2011)	Hach 2100Q
Suspended Sediment Concentration (SSC)	ASTM D 3977	Dekaport Teflon sample splitter for high concentrations
Specific conductance, pH	EPA (2011)	Beckman Coulter PHi 460 meter

Astoria Pacific, http://www.astoria-pacific.com/

Hach, http://www.hach.com/2100q



Rickly Hydrological Company
http://www.rickly.com/sai/
dekaport.htm

U.S. EPA (2011) "Approved General Purpose Methods.", <http://water.epa.gov/scitech/methods/cwa/methods_index.cfm>
ASTM (1999). *Annual Book of ASTM Standard: Water and Environmental Technology*, American Society For Testing And Materials, West Conshohocken, PA

Data Sources

Parameter	Source	Notes
Stream Discharge	MD-DE-DC WSC & VA WSC	– Daily and Instantaneous data from 3/1/2011– 9/30/2011
Daily Precipitation	NWS NCDC	– Inverse distance weighting[1] used to estimate precipitation in study catchments using data from 3 stations

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[1]Brutsaert, W., 2005. Hydrology – An Introduction, Cambridge University Press, Cambridge, UK.

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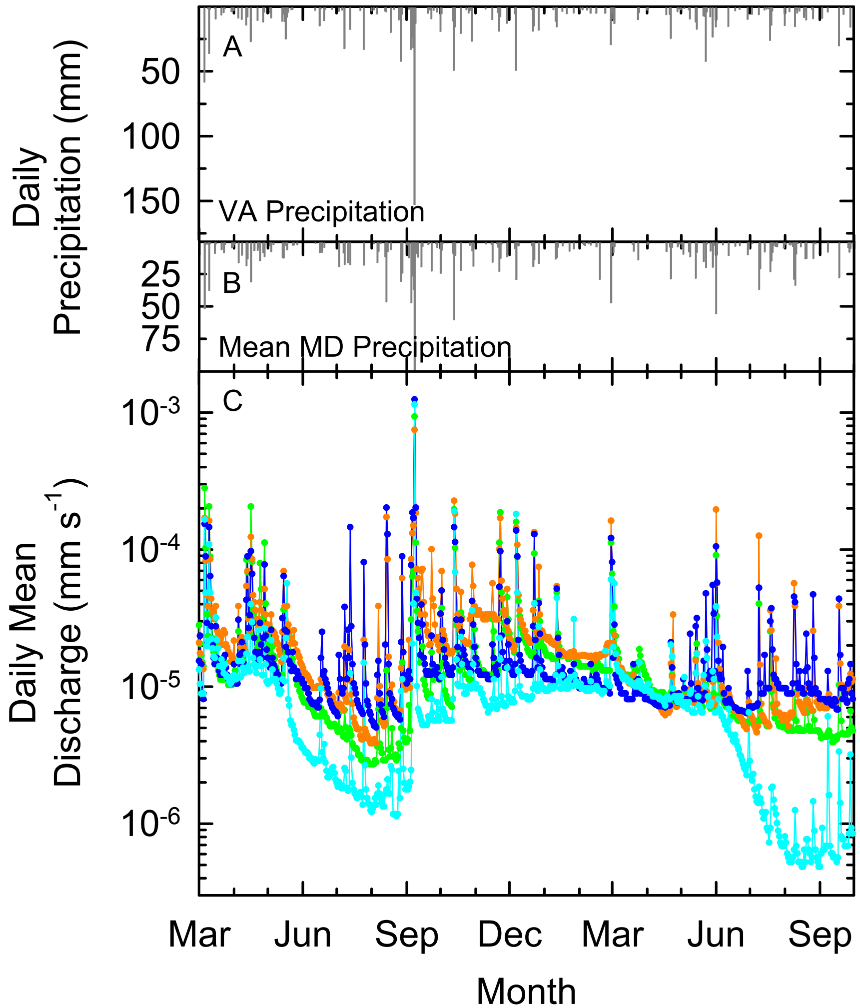
Discharge/Precipitation Records

- 19 month study period: 3/1/2011 – 9/30/2012
- Stream Discharge
  - Seasonal trend with higher baseflow in spring and declining baseflow through summer
- Precipitation
  - Approximately 76mm or 8% less precipitation in VA over the study period



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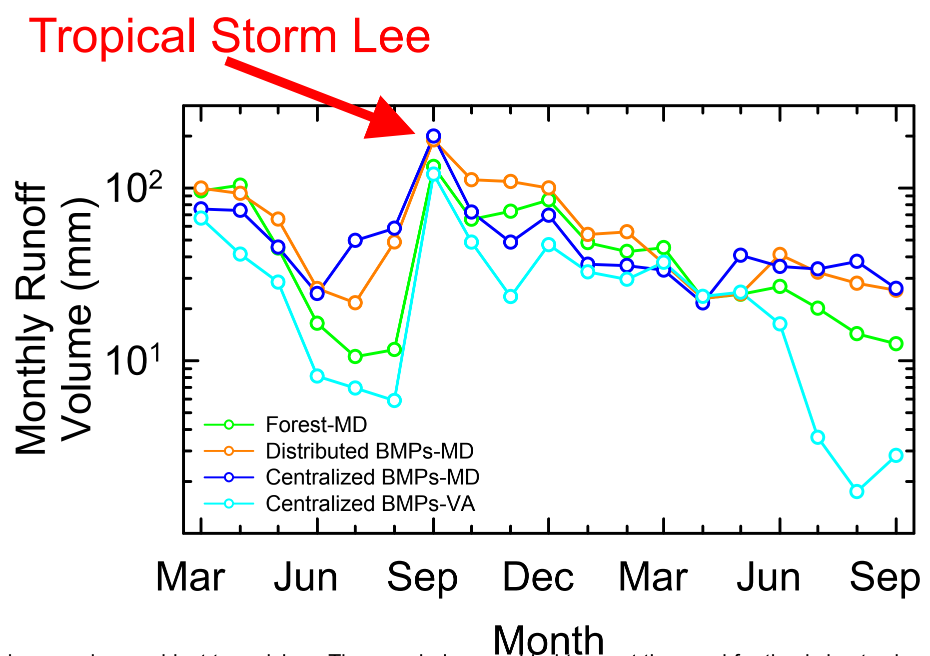
Runoff Volume

- Total Runoff Volume: Distributed BMPs-MD > Centralized BMPs-MD > Forest-MD > Centralized BMPs-VA
- Normalizing for precipitation, total runoff volume trends remain
- Effect of Tropical Storm Lee is apparent

Catchment	Total Runoff Volume ($x10^2$ mm)*
Forest-MD	9.0
Distributed BMPs-MD	12
Centralized BMPs-MD	10
Centralized BMPs-VA	5.7



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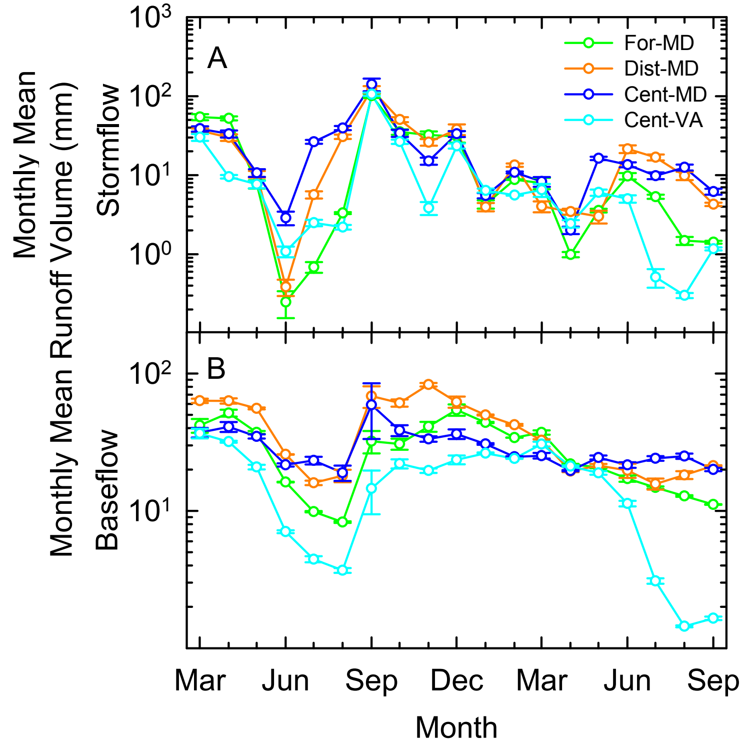
Stormflow/Baseflow

- A. Stormflow
  - Lower total stormflow in Forest-MD and Centralized BMPs-VA
  - Lower[1] monthly stormflow in Centralized BMPs-VA and Forest-MD from May-October
- B. Baseflow
  - Total and monthly[1] baseflow highest in Distributed BMPs-MD
  - Total and monthly[1] baseflow lowest in Centralized BMPs-VA
  - Forest-MD versus Centralized BMPs-MD: lower[1] in summer, greater[1] in winter
  - Monthly percent runoff volume as baseflow greater in Distributed BMPs-MD versus Centralized BMPs-MD
- Similar stormflow and baseflow trends when normalizing for precipitation

Catchment	Total Runoff Volume ($x10^2$ mm)		
	Stormflow	Baseflow	Total
Forest-MD			9.0
Distributed BMPs-MD			12
Centralized BMPs-MD			10
Centralized BMPs-VA			5.7



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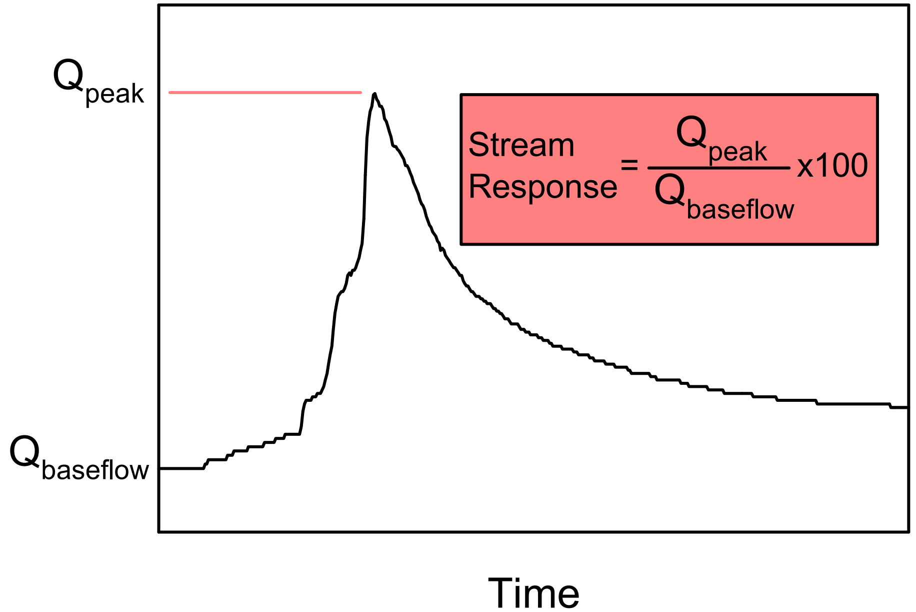
*Error bars indicate standard deviation of monthly mean estimates from three baseflow separation methods
[1]p-value <0.05, determined via Wilcoxon paired sample test in R

Stream Response To Precipitation

- Breakpoint in linear regression model was significant[1] for Distributed BMPs-MD, Forest-MD, Centralized BMPs-VA, but not Centralized BMPs-MD.
  - Left slope not significantly different than zero suggests a precipitation 'threshold' prior to stream response

- Patterns observed in stream response data were similar to those with maximum discharge data



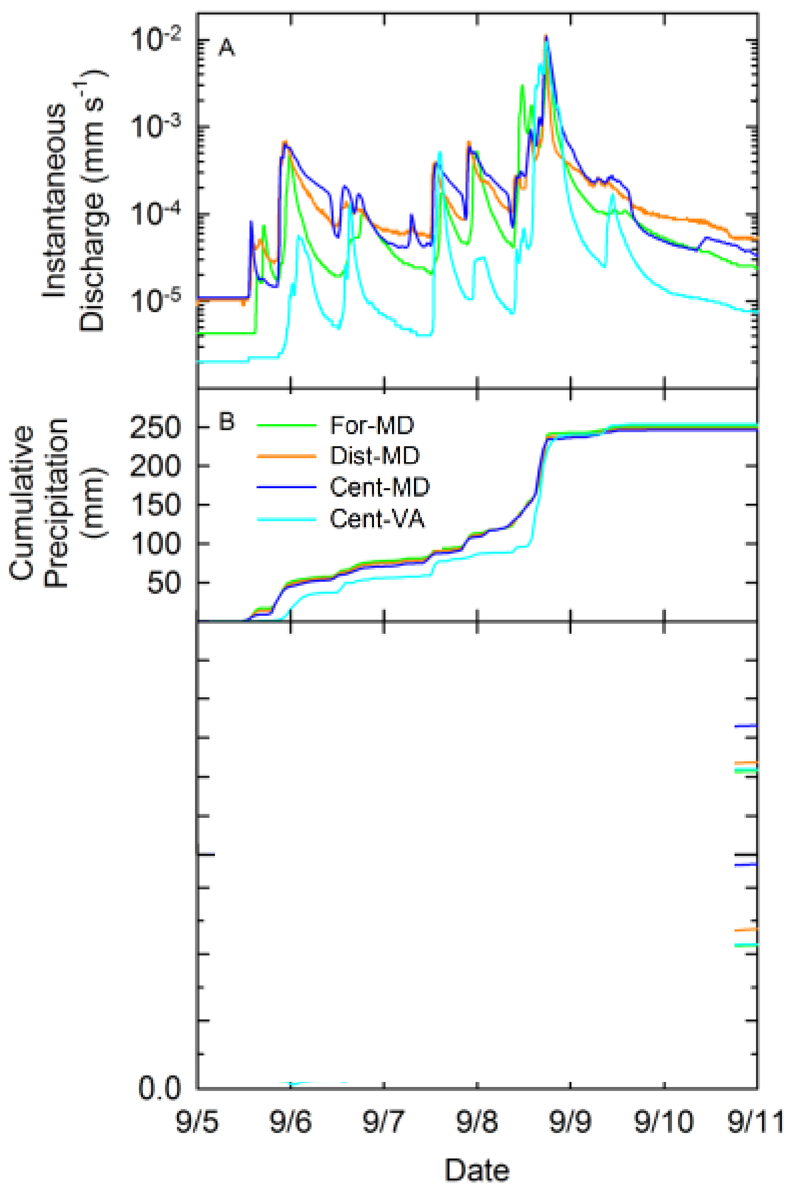
Log$_{10}$ Total Storm Event Precipitation (mm)

[1]p-value <0.05, determined via piecewise linear regression modeling performed using the 'segmented' package in R (segmented package reference: Muggeo, V.M.R., 2008. segmented: an R Package to Fit Regression Models with Broken-Line Relationships. R News, 8/1, 20-25).

Tropical Storm Lee

- Precipitation totaled nearly 10” over a 6-day span in September, 2011
- Total runoff highest in Centralized BMPs-MD
- Broader discharge peaks observed in Centralized BMPs-MD, increased baseflow in Distributed BMPs-MD

Catchment	Cumulative Runoff Volume (mm)
Forest-MD	107
Distributed BMPs-MD	118
Centralized BMPs-MD	165
Centralized BMPs-VA	109



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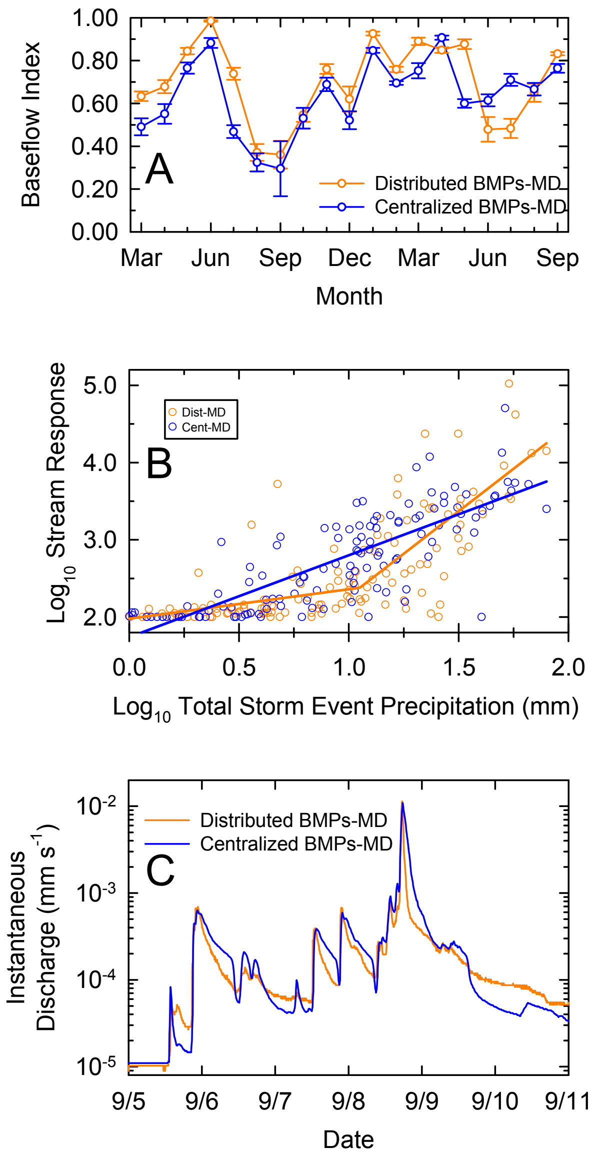
Factors Affecting Runoff Volume: Stormwater BMPs

- Water quantity improvements provided by Distributed BMPs-MD as compared to Centralized BMPs-MD
  - A. Higher percentage of runoff as baseflow
  - B. Precipitation threshold for stream response, lower stormflow runoff
  - C. Reduced water export as peak discharge during an extreme precipitation event
  - Overall more 'consistent' discharge



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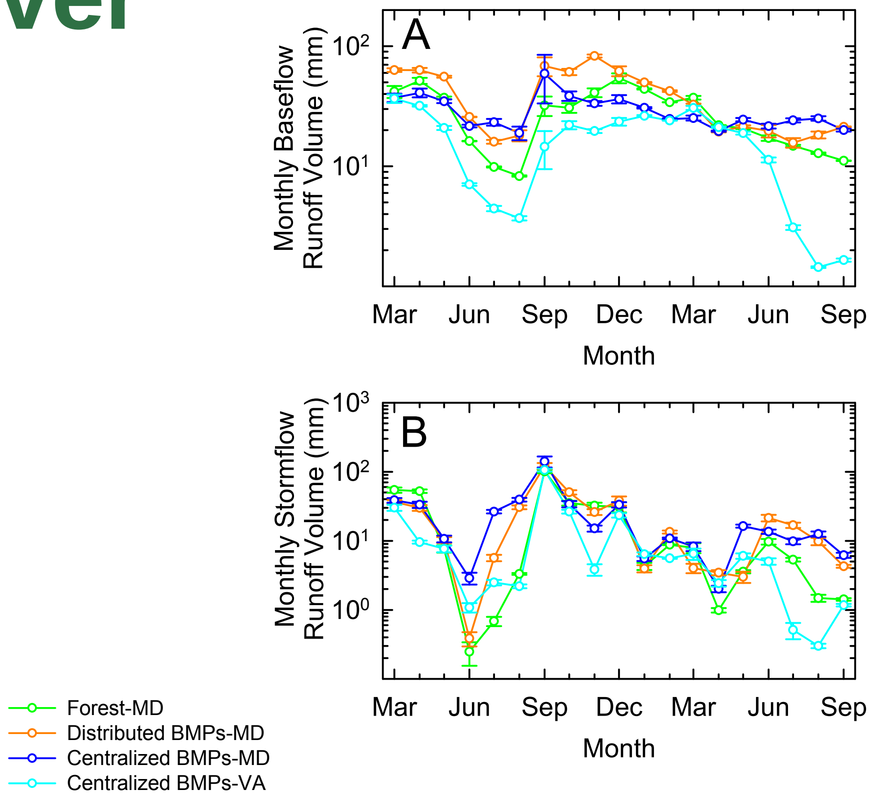
Factors Affecting Runoff Volume: Forest Land Cover

- Water quantity control provided by Forest-MD and Centralized BMPs-VA as compared to dense urban MD catchments
  - A. Transpiration: seasonal decreases in baseflow suggest increase in transpiration
  - B. Interception: decreased stormflow in May-Oct suggests canopy interception
  - C. Impervious Cover: greater runoff volume associated with increased impervious cover



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Catchments (*n*)	Runoff Volume ($x10^2$ mm)		
	Total	Baseflow	Stormflow
Increased Forest Land Cover (2)	7.4	4.3	3.1
Increased Impervious Cover (2)	11	6.6	4.5

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Discharge Analysis Summary

- Distributed BMPs led to a shift in the timing of water export to a pattern more similar to that of the Forest catchment
    - Increased water export as baseflow
    - Reduction in the stream response to smaller typical precipitation events
    - Lower runoff volume for extreme precipitation event

- Land cover was a major factor in dictating water export
    - Increased stormflow and baseflow in dense-urban catchments

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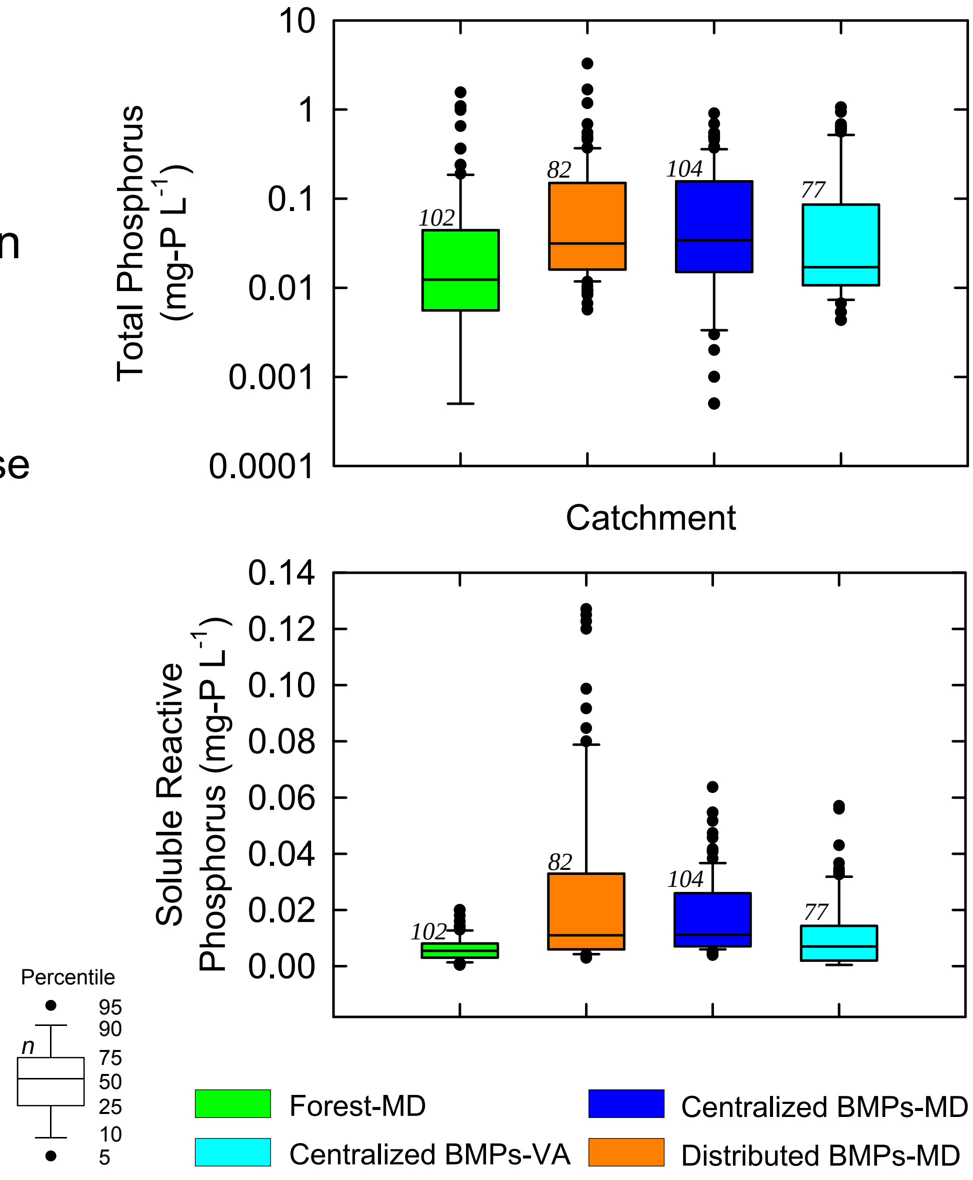
Phosphorus

- TP concentrations generally lowest in Forest-MD, higher in urbanized areas
- Total phosphorus phases:
  - Stormflow – particulate phase
  - Baseflow – dissolved phase



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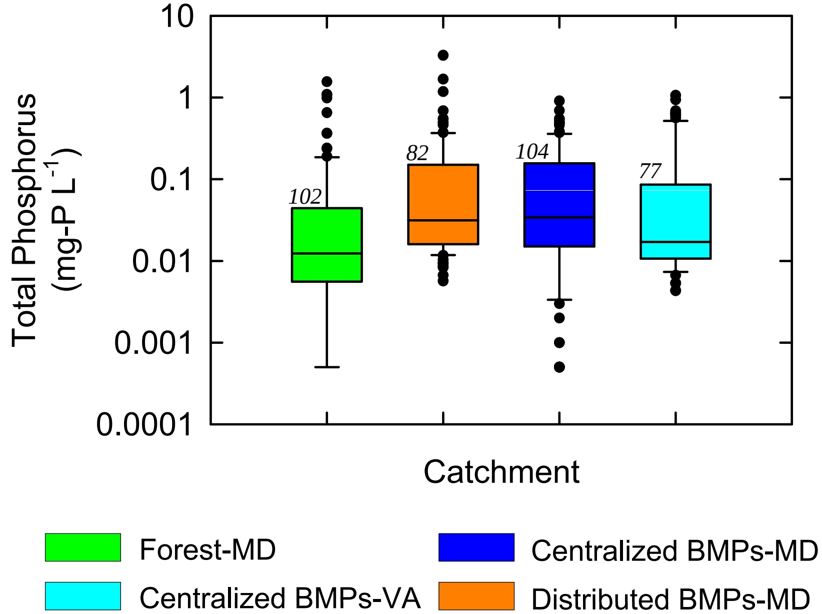
Phosphorus and Distributed BMPs

- Why high phosphorus concentrations in Distributed BMPs-MD?
- Where is phosphorus coming from in Distributed BMPs-MD?



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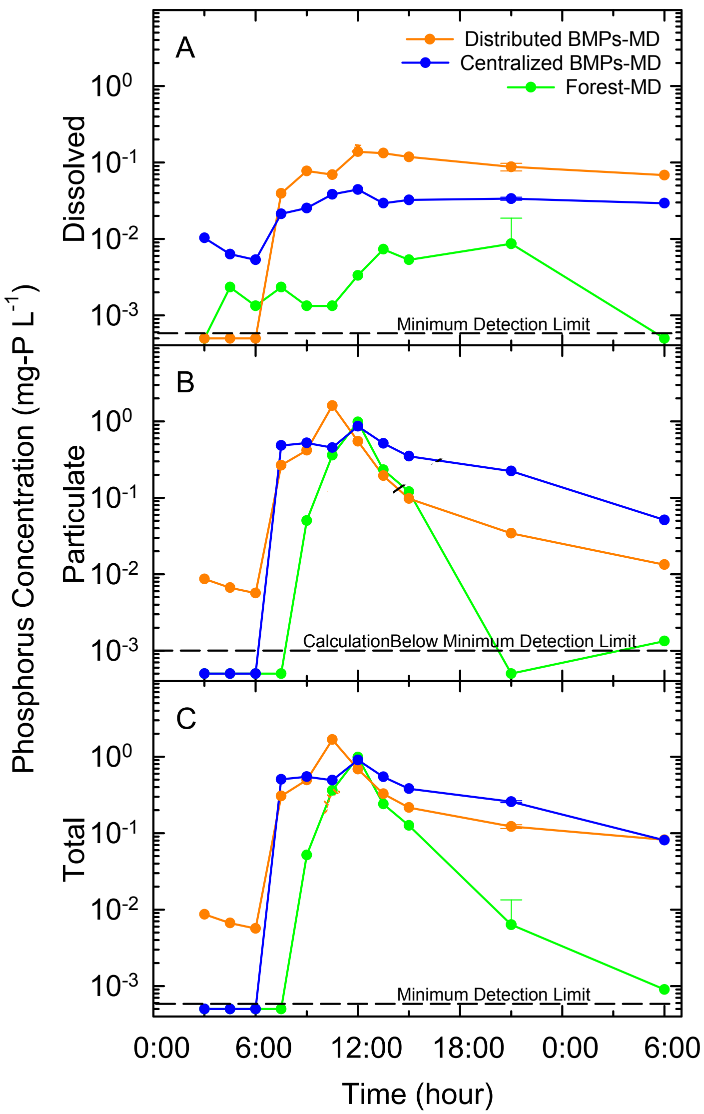
Factors affecting P – BMPs & Sediment

- Samples from 54 mm (2.1 in) storm event on 10/2/2012
- Forest-MD generally lowest P concentrations
- Catchment outlet Distributed BMPs-MD versus Centralized BMPs-MD:
  - Distributed BMPs-MD: higher dissolved P
  - Similar particulate, total P
- Distributed BMPs effluent versus catchment outlet:
  - Higher dissolved P from BMPs
  - Higher particulate and total P from catchment – overall good urban runoff treatment



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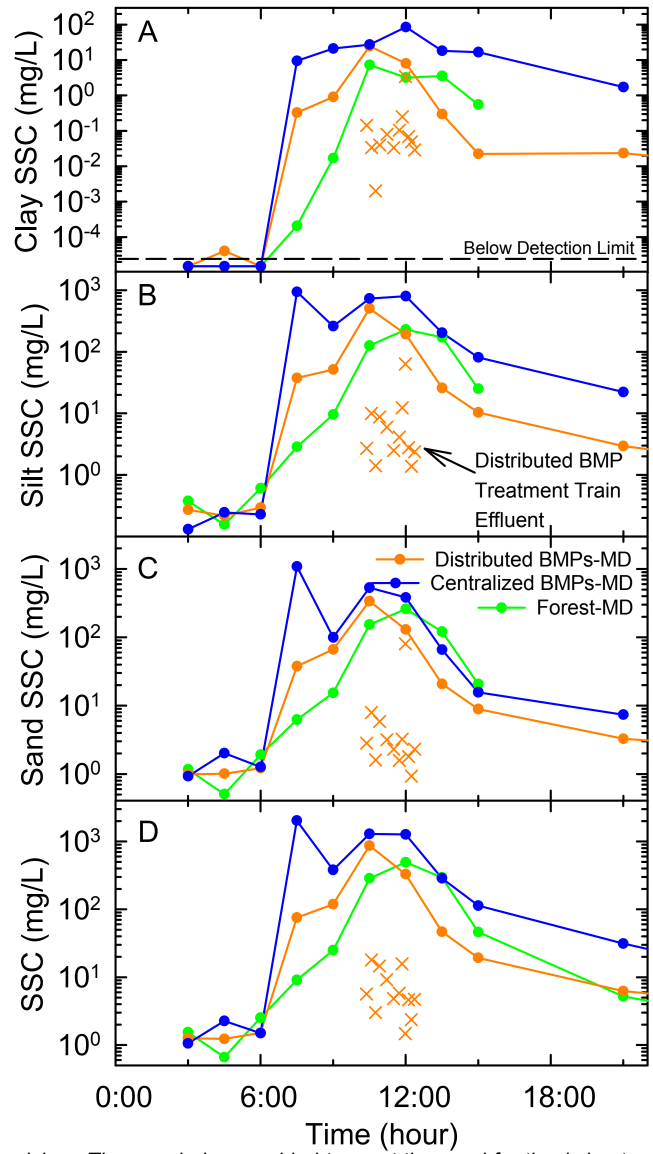
Factors affecting P – BMPs & Sediment

- Samples from 54 mm (2.1 in) storm event on 10/2/2012
- Generally highest sediment concentrations in Centralized BMPs-MD
- Distributed BMPs effluent versus catchment outlet:
  - Sediment from urban areas <<< catchment



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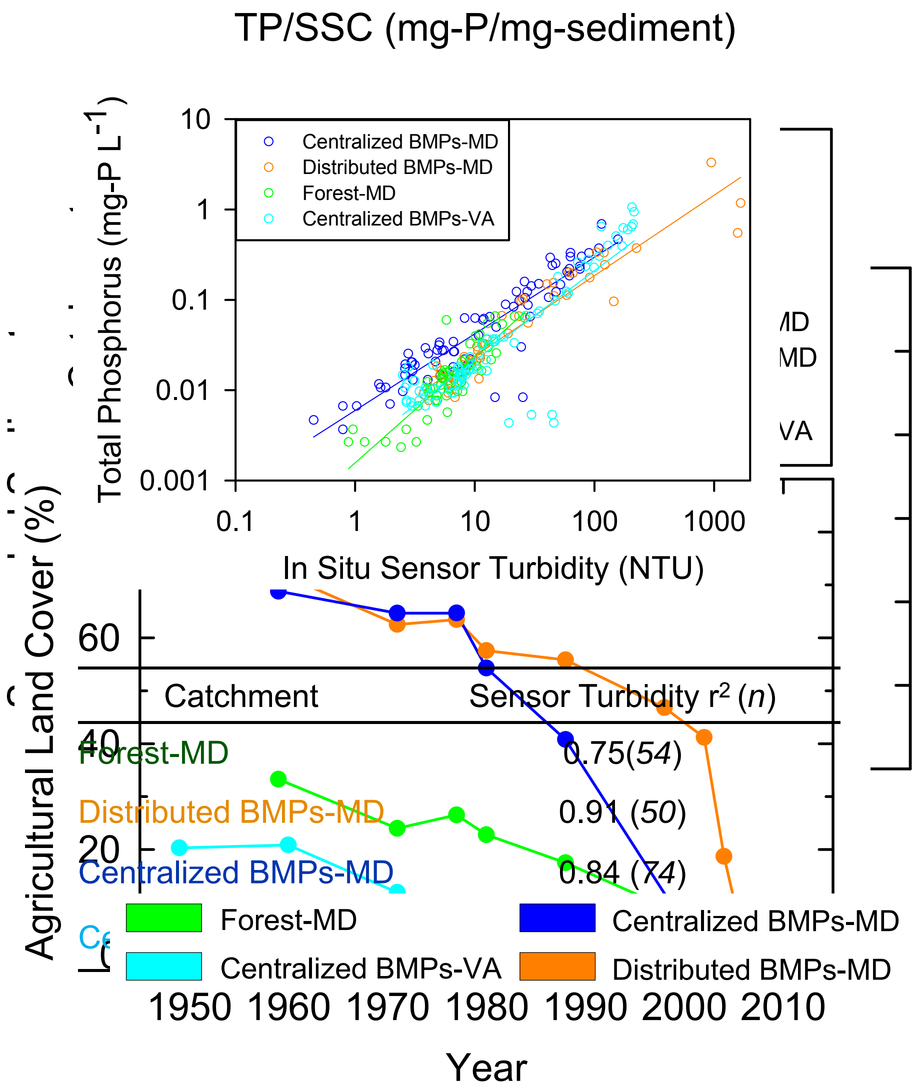
Factors affecting TP – historical LU

- TP is transported via suspended sediment
- Sediment concentrations similar/slightly lower in Distributed BMPs-MD as compared to Centralized BMPs-MD
- Sediment appears to be enriched with phosphorus in recently converted Distributed BMPs-MD catchment
- Although lower sediment at catchment outlet, p-enrichment of sediment from non-urban areas means less sediment provides the same amount of total phosphorus



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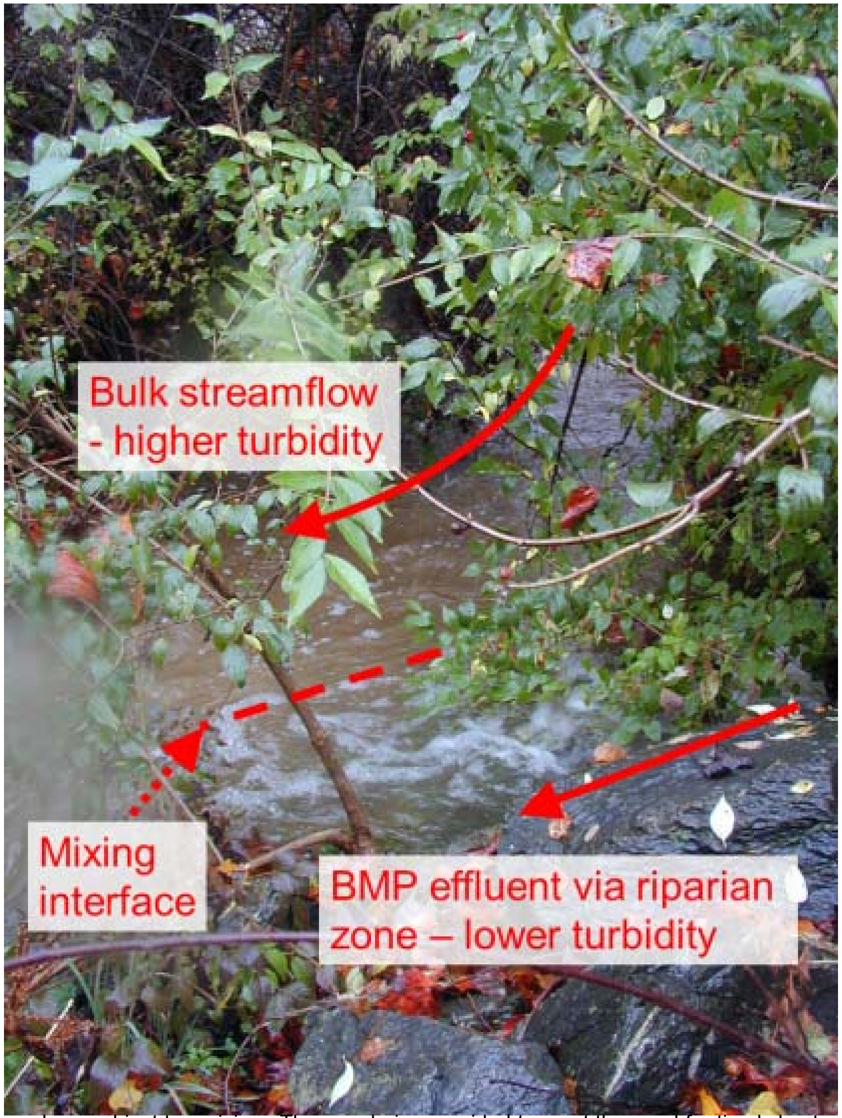
Phosphorus and Distributed BMPs

- Why high phosphorus concentrations in Distributed BMPs-MD?
- Where is phosphorus coming from in Distributed BMPs-MD?



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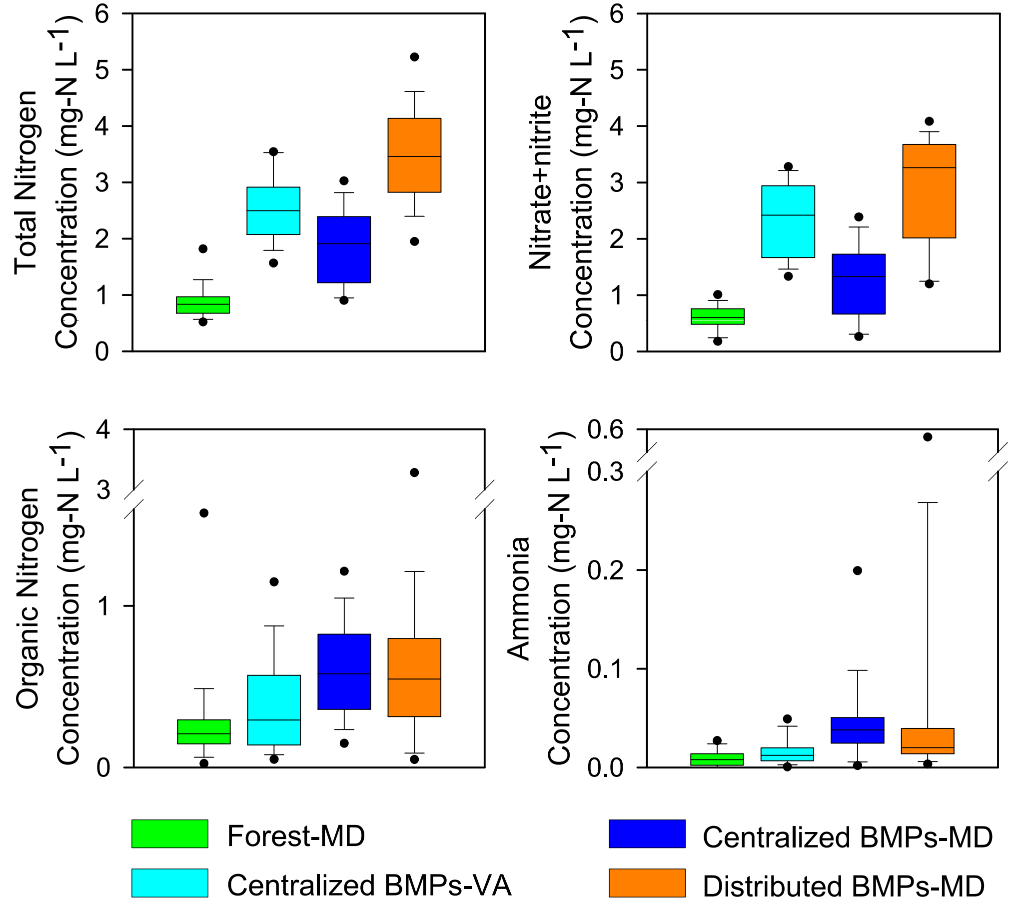
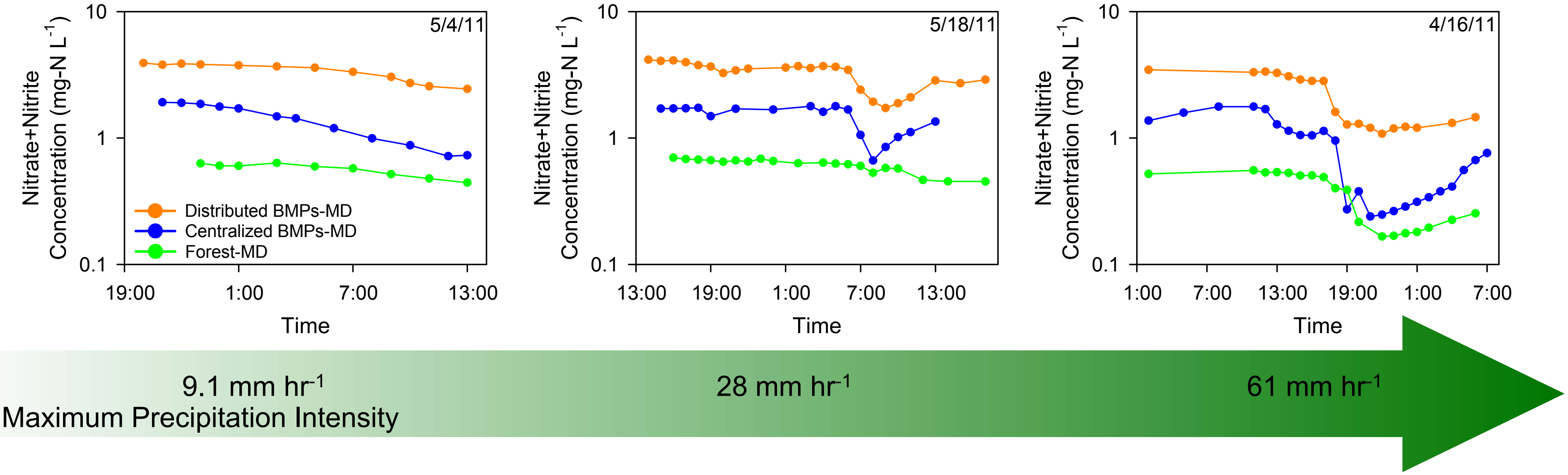
Nitrogen

- TN largely composed of nitrate+nitrite at all sites
- Lowest concentrations Forest-MD and higher concentrations in urban areas
- Distributed BMPs-MD: Highest concentrations



Nitrate+Nitrite

- Highest concentration in Distributed BMPs-MD watershed likely linked to historical land use
- Highest dilution occurs in Centralized BMPs-MD
- Forest-MD: little dilution in smaller storms, significant dilution in large storm



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Nutrient & Sediment Summary

- Phosphorus
  - Phosphorus export is largely associated with sediment in all watersheds
  - Distributed BMPs provided good treatment of particulate phosphorus in urban stormwater runoff
- Nitrogen
  - Total Nitrogen largely composed of nitrate+nitrite which responds to water quantity control from the stormwater BMPs
- Historical land use is a key factor
  - Elevated phosphorus and nitrogen measurements in recently converted Distributed BMPs catchment (both dissolved and particulate phases appear to be effected)

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Preliminary Stormwater Management Implications

- Discharge in Distributed BMPs-MD more consistent, is this good/bad?
  - Reduction in peak discharge (duration and runoff volume) could result in more favorable ecological conditions or more stable stream banks
  - Reduced discharge during extreme events could reduce flooding and nutrient export that may be associated with future shifts in climate
  - What are the impacts of higher baseflow and more water export?

- Nutrients
  - Distributed BMPs could reduce the export of toxic urban pollutants associated with sediment
  - Historical land use should be considered when selecting watersheds for urban development due to legacy nutrients from fertilizer application on agricultural lands
    - High baseflow nitrate concentrations and phosphorus enriched sediment

Integration of Distributed Stormwater Management with Urban Design

- Distributed stormwater management enabled:
  - Multi-purpose use of land
  - Aesthetic value
  - Preservation of stream riparian zone provides aesthetics and wildlife habitat

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