VILLANOVA UNIVERSITY
COLLEGE OF ENGINEERING

CENTER FOR RESILIENT WATER SYSTEMS

Evapotranspiration Performance of Vegetated Stormwater Control Measures (SCMs)

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Advised By:

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Stroud Presentation:

July 15th, 2021

Presentation Agenda

I. Site Description & Data Collection

II. Predictive Equations for Potential ET

III. Mass Balance Approach for Measured ET

IV. Maintenance and Monitoring of SCMs

V. Future Work

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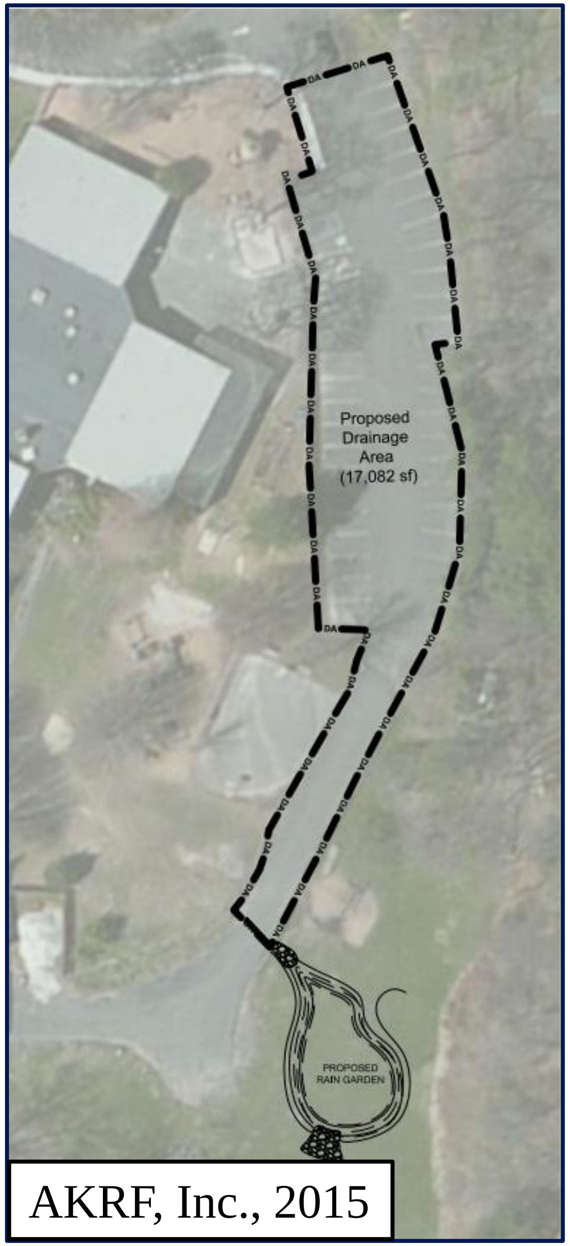
I.) Site Description & Data Collection

Abington Friends School Rain Garden

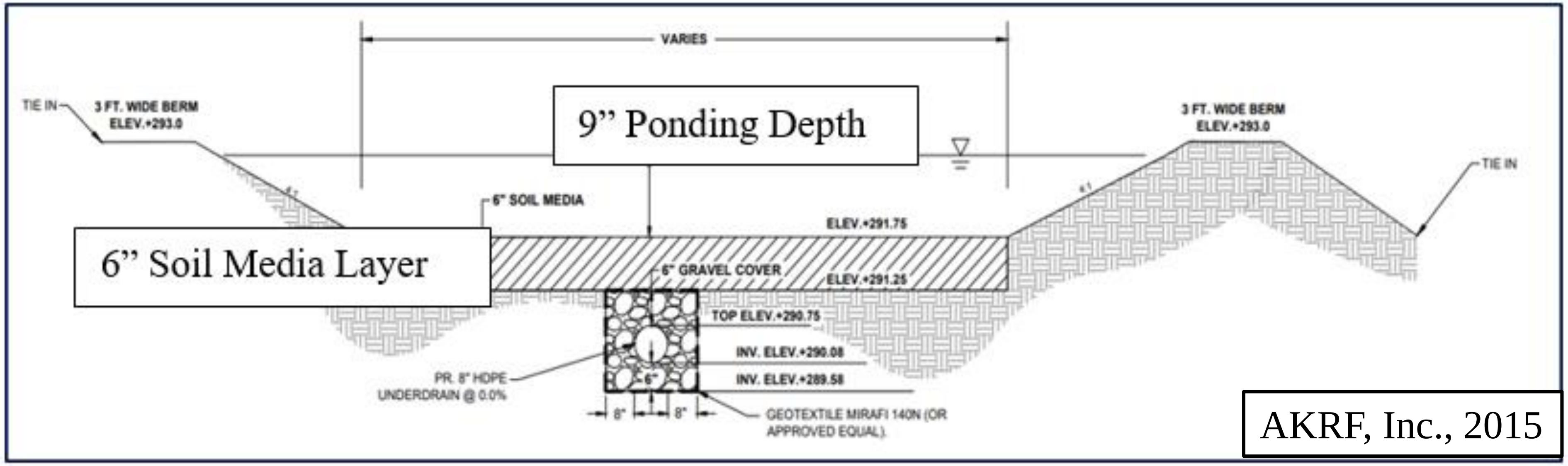
August 4, 2020 – Tropical Storm Isaias



AKRF, Inc., 2015

Abington Friends School Rain Garden

Soil Type	Grain Size Range	Percent Distribution
Sand	0.05 to 2.0 mm	50-85% maximum
Silt	0.002 to 0.05 mm	40% maximum
Clay	< 0.002 mm	10% maximum
Gravel	2.0 to 12.7 mm	15% maximum



AKRF, Inc., 2015

Rain Garden Vegetation

PLANT LIST

Native Grasses (plugs)

#	Size	Botanical Name	Common Name	Mature Height
75	Plugs	Acorus americanus	Sweetflag	3'
75	Plugs	Carex comosa	Long-hair sedge	2'
75	Plugs	Carex lurida	Shallow sedge	3'
75	Plugs	Carex scoparia	Broom sedge	2'
75	Plugs	Chasmanthium latifolium	Sea Oats	3'
50	Plugs	Eragrostis spectabilis	Purple love grass	2'

Native Perennials (plugs)

#	Size	Botanical Name	Common Name	Mature Height
50	Plugs	Asclepias tuberosa	Butterfly weed	1-3'
50	Plugs	Baptisia australis	False blue indigo	3-5'
50	Plugs	Echinacea purpurea	Purple coneflower	2-4'
50	Plugs	Liatris spicata	Blazing star	3'
50	Plugs	Lobelia cardinalis	Cardinal flower	3'
50	Plugs	Lobelia siphilitica	Blue Lobelia	3'
50	Plugs	Mondarda fistulosa	Wild bergamot	2-4'
50	Plugs	Rudbeckia fuligida	Orange Coneflower	2'
50	Plugs	Symphyotrichum novi-belgii	New York Aster	3'

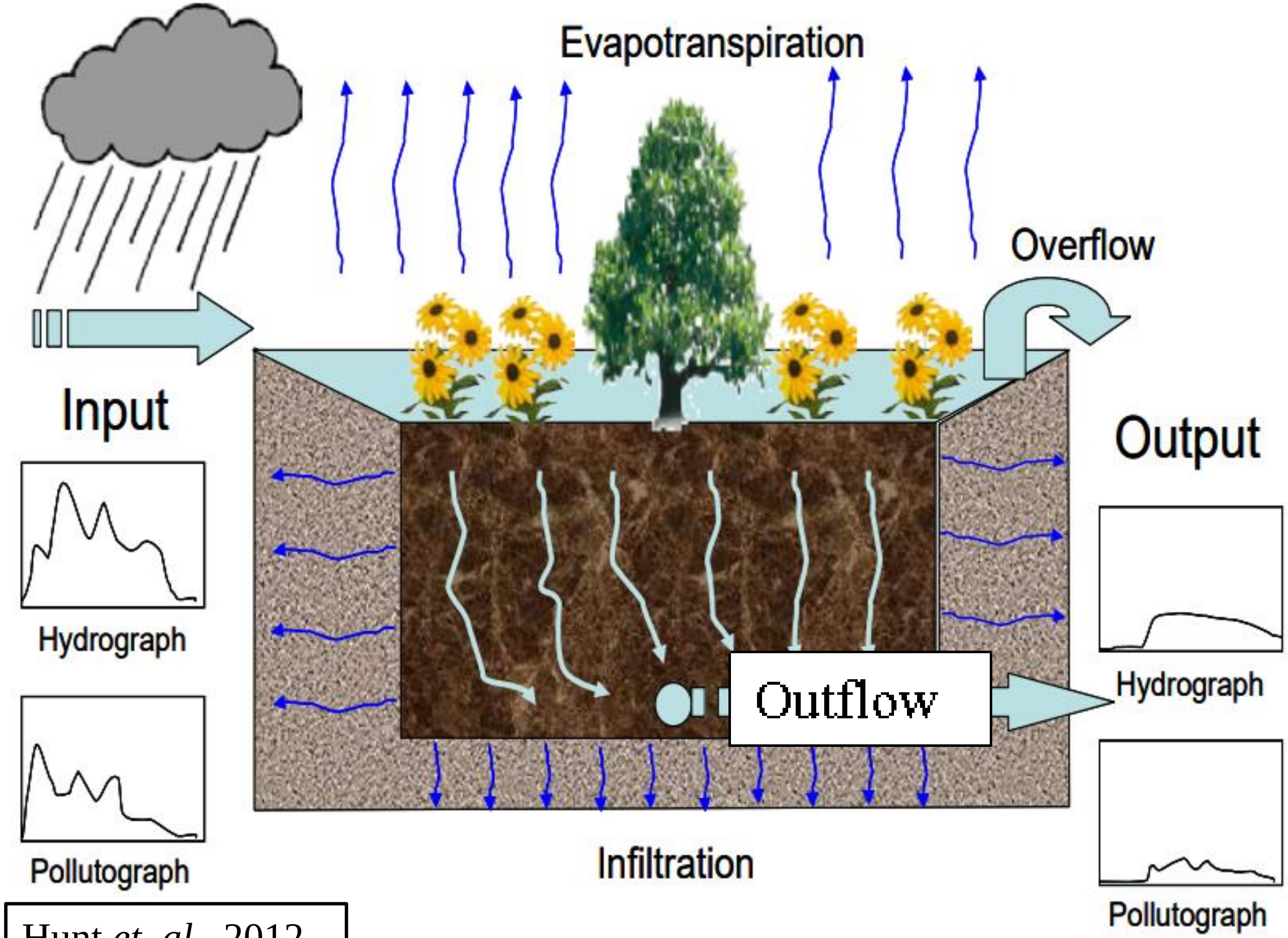
Native Shrubs

#	Size	Botanical Name	Common Name	Mature Height	Symbol
4		Cephalanthus occidentalis	Buttonbush	3-9'	Co
4		Clethra alnifolia	Sweet pepperbush	3-8'	Ca
2		Lindera benzoin	Spicebush	10-16'	Lb
		Physocarpus opulifolius	Ninebark	5-8'	Po
3		Rhus copallinium	Winged sumac	11-18'	Rc
3		Viburnum dentatum	Arrowood viburnum	6-10'	Vd

Native Trees Understory/Canopy

#	Size	Botanical Name	Common Name	Mature Height	Symbol
1		Amelanchier canadensis	Serviceberry	15-30'	AC
1		Celtis occidentalis	Hackberry	30-50'	CO
1		Cercis canadensis	Redbud	20-30'	CC
1		Cornus florida	Flowering Dogwood	15-30'	CF

Abington Friends School Hydrologic Budget



Hunt *et. al.*, 2012

AFS Site Instrumentation

Location	Sensor	Variable
Weather Station	Tipping Bucket	Precipitation [in.]
	Met One Station	Wind Speed [Mile/hr]
		Wind Direction [Degrees]
		Air Temperature [F]
		Relative Humidity [%]
		Barometric Pressure [mmHg]
	Pyranometer	Radiation [W/m^2]
Rain Garden	Bubbler	Water Level [m]
		Pressure [psi]
		Temperature [Celsius]
	Stevens Hydraprobe (x5)	Soil Moisture (vol/vol)
	Pressure Transducer	Water Level [m]

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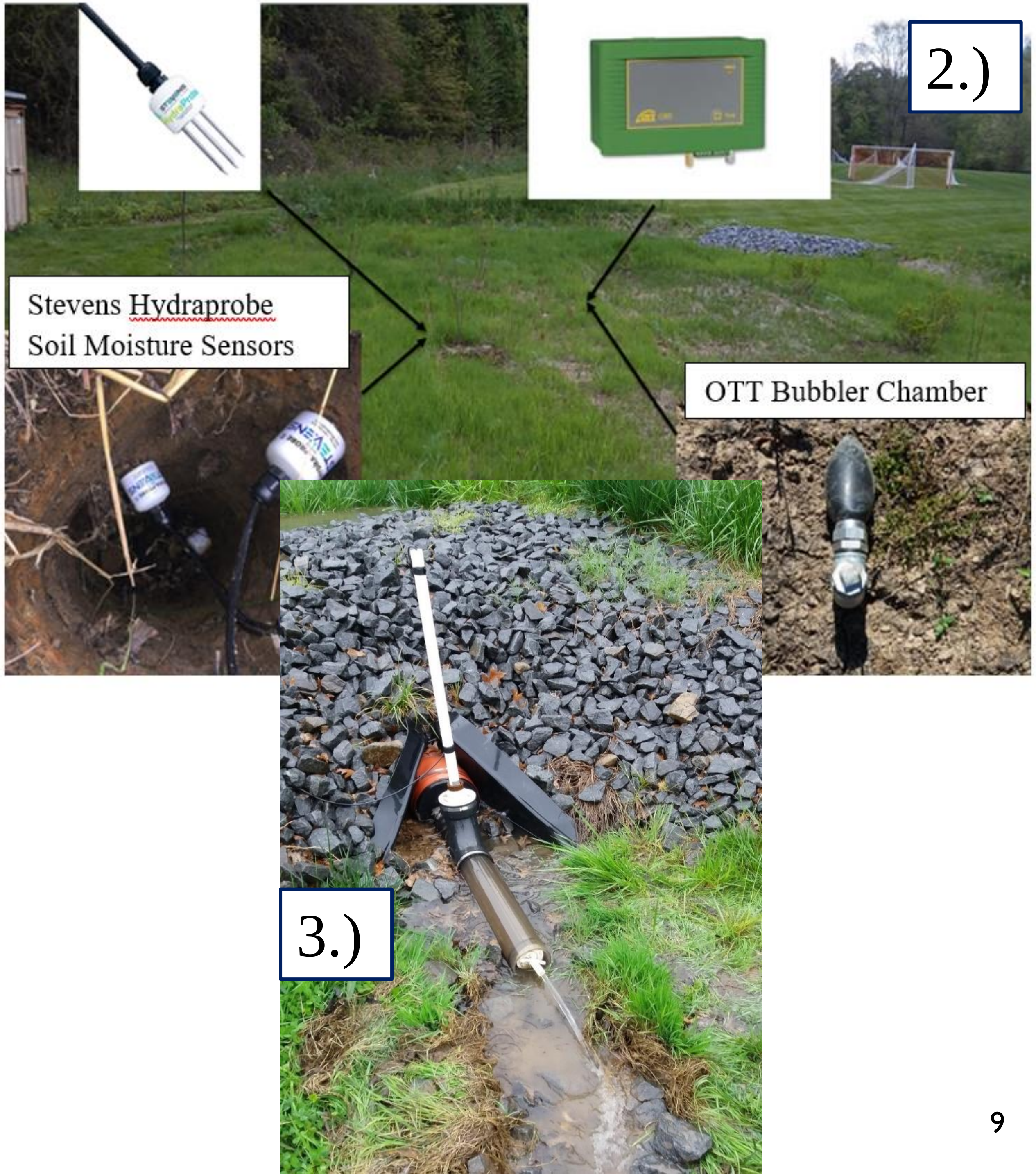
1.)
Stevens


2.)
Stevens Hydraprobe
Soil Moisture Sensors
OTT Bubbler Chamber
3.)

Why Evapotranspiration?

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II.) Predictive Equations for Potential ET

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Predictive ET Equations

- ASCE Penman-Monteith Equation:

$$ET_{Std} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2(e_s^o - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

- Hargreaves:

$$Hargreaves\ Ref.ET = c_H * 0.408\ R_a * (T + 17.8) * \sqrt{T_{max} - T_{min}}$$

- Soil Moisture Extraction Function (SMEF):

$$SMEF = \frac{SM_{10cm}}{FC - WP}$$

$$ET_{Adj.} = SMEF * K_c * ET_o$$

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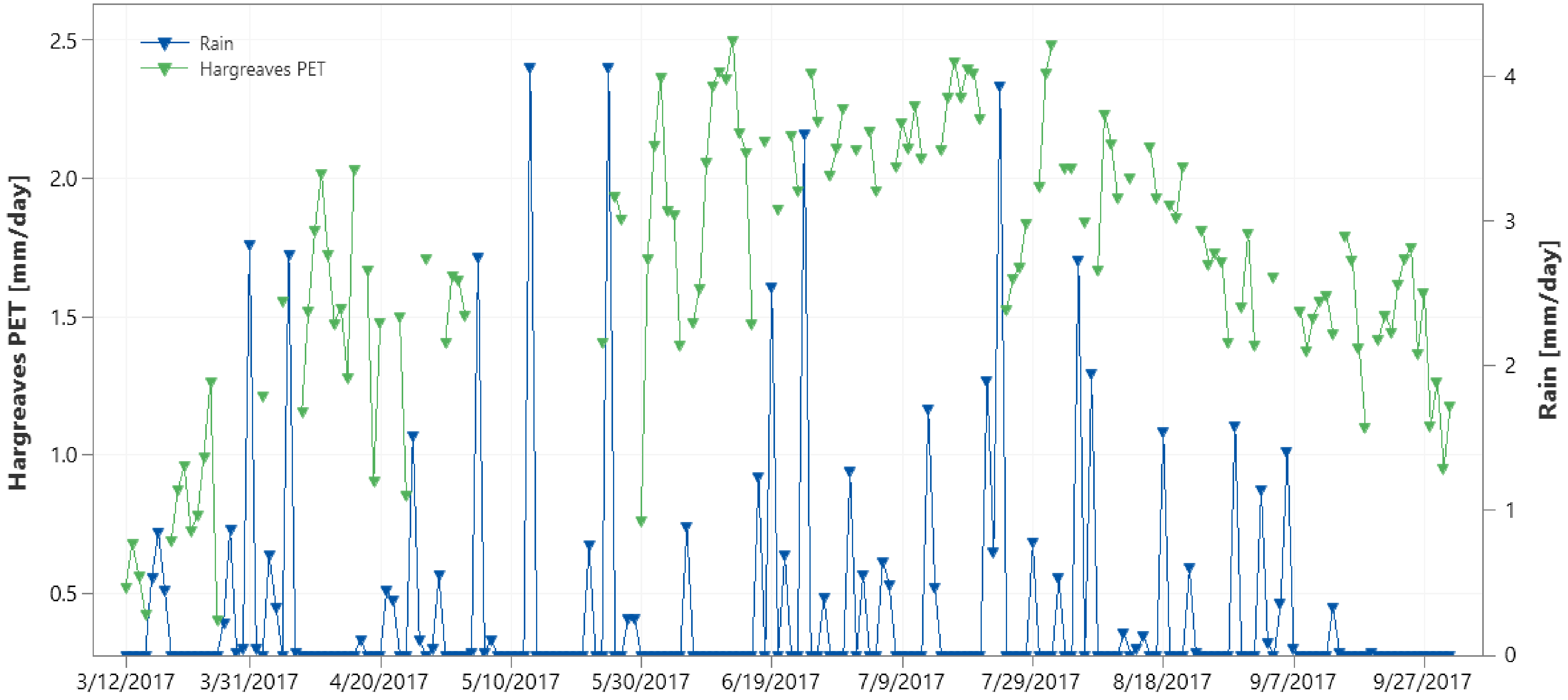
Potential ET: Hargreaves



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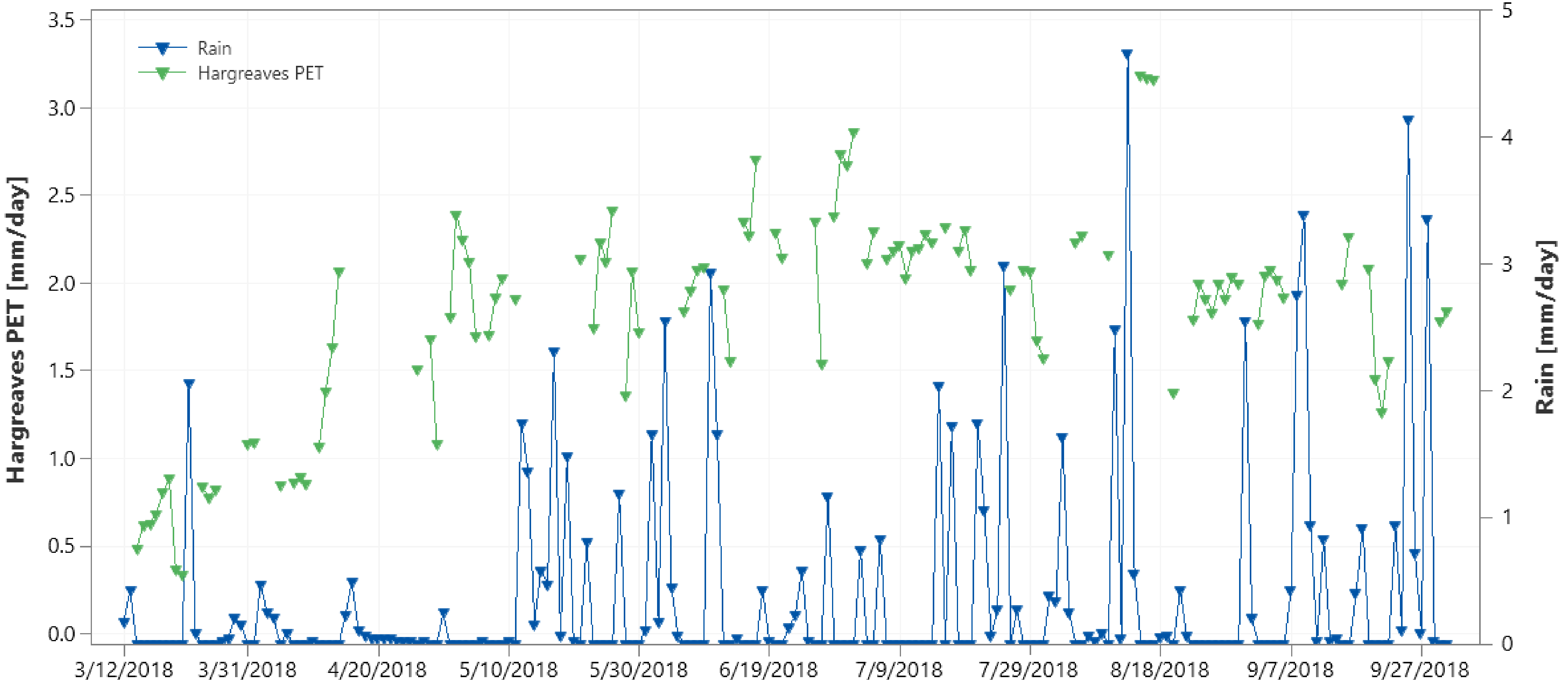
Potential ET: Hargreaves



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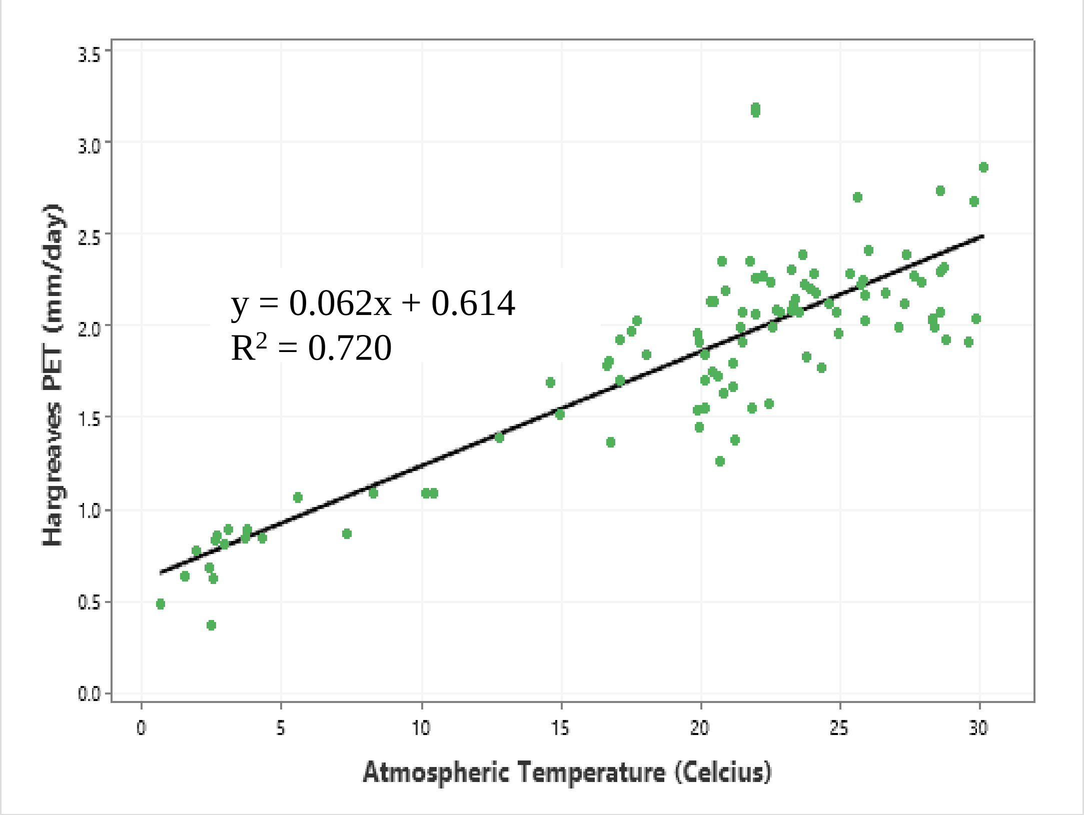
Potential ET: Hargreaves



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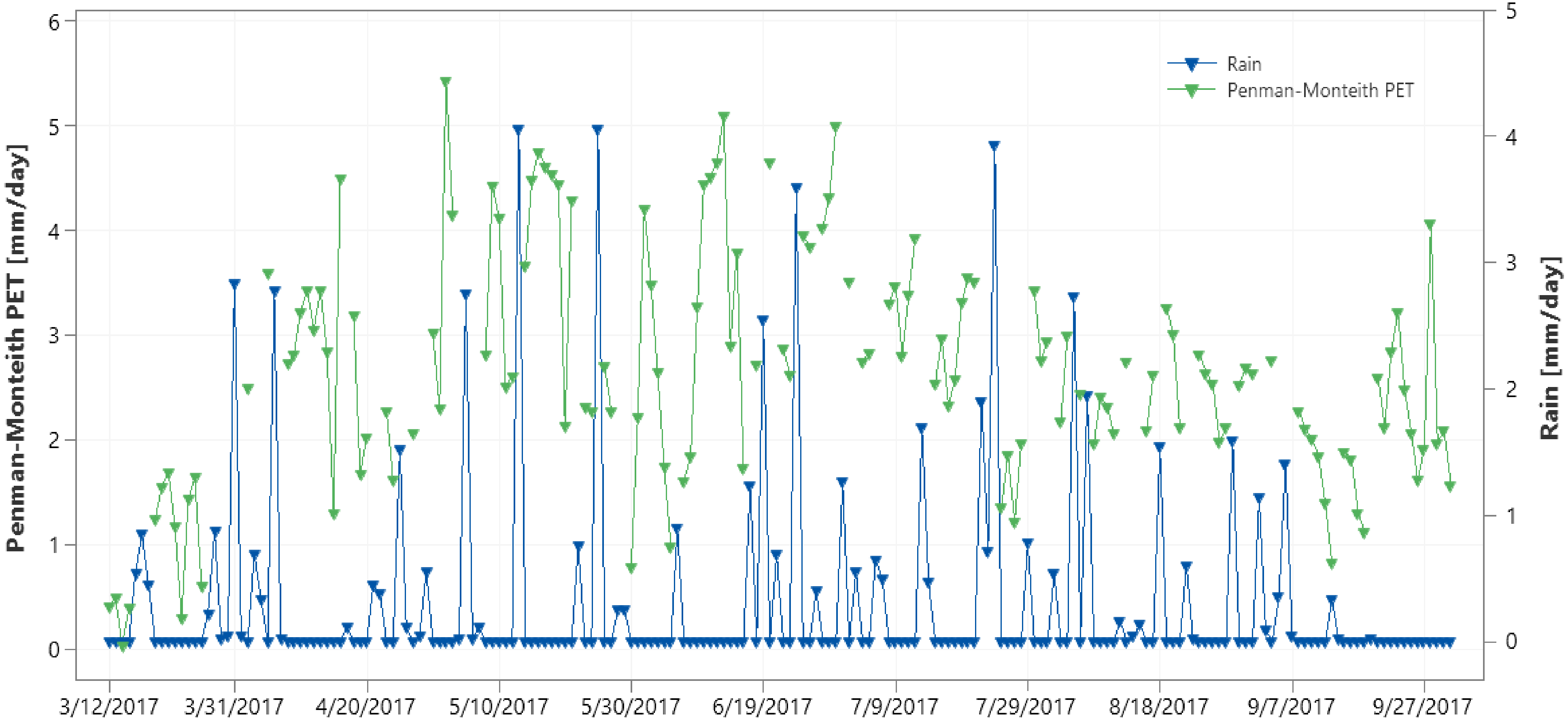
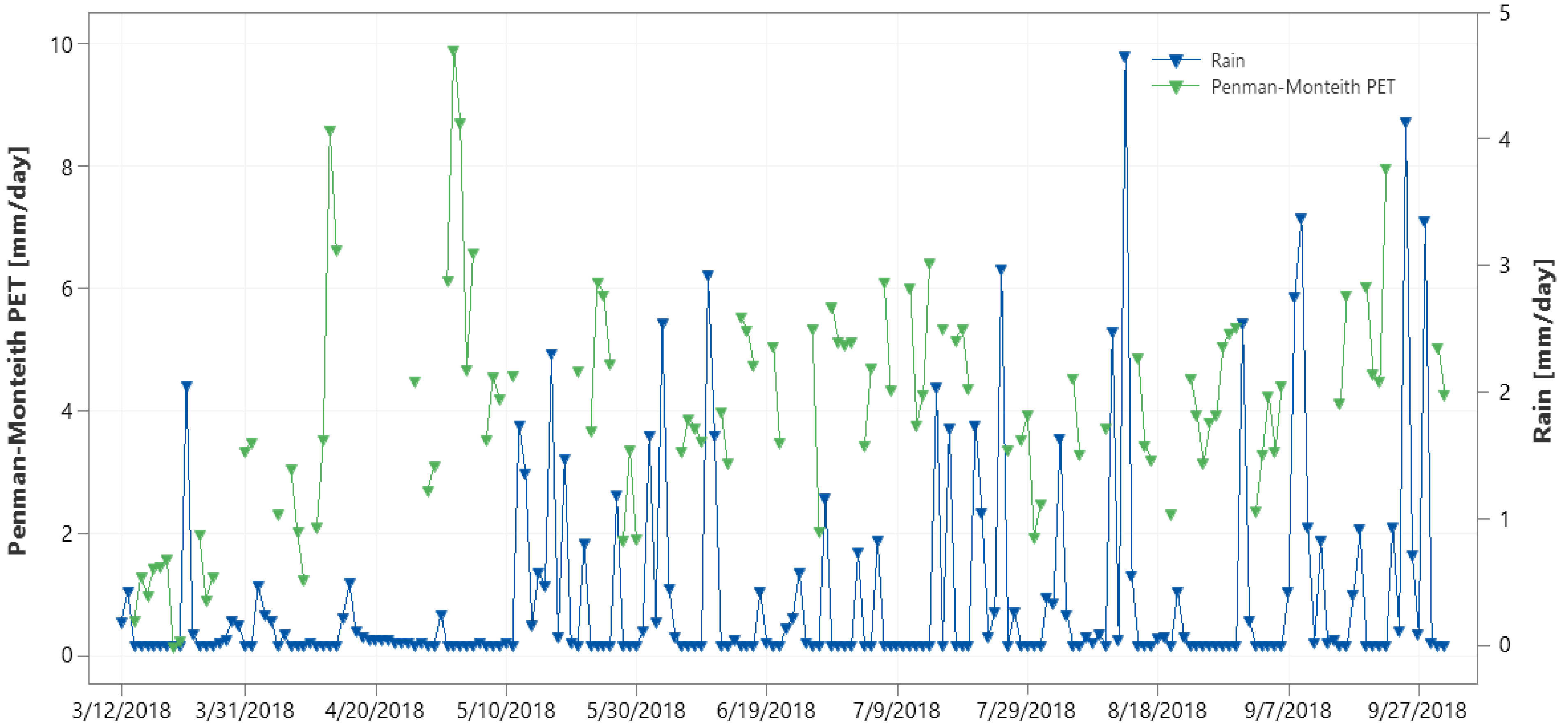
Potential ET: Penman-Monteith



Potential ET: Penman-Monteith



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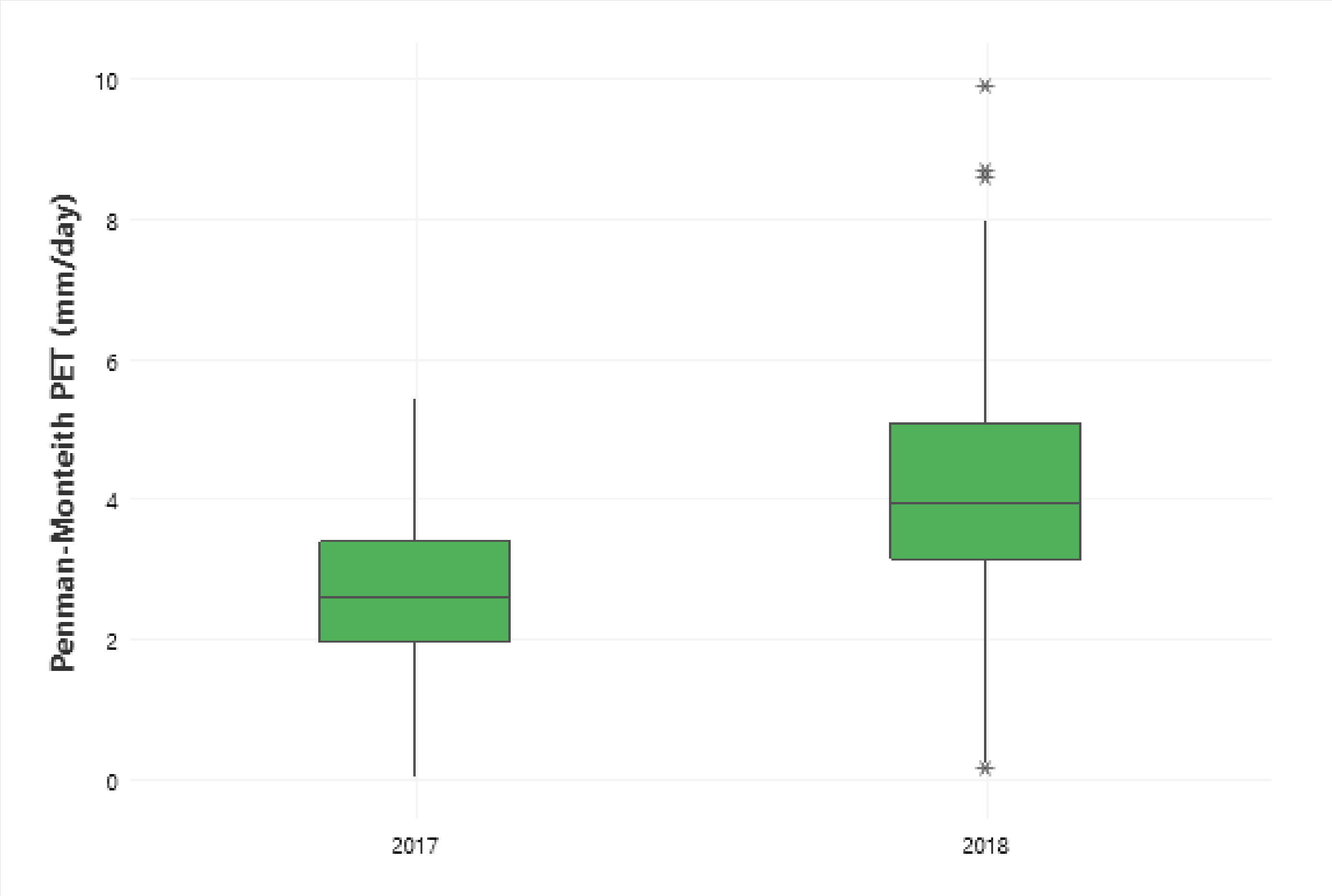
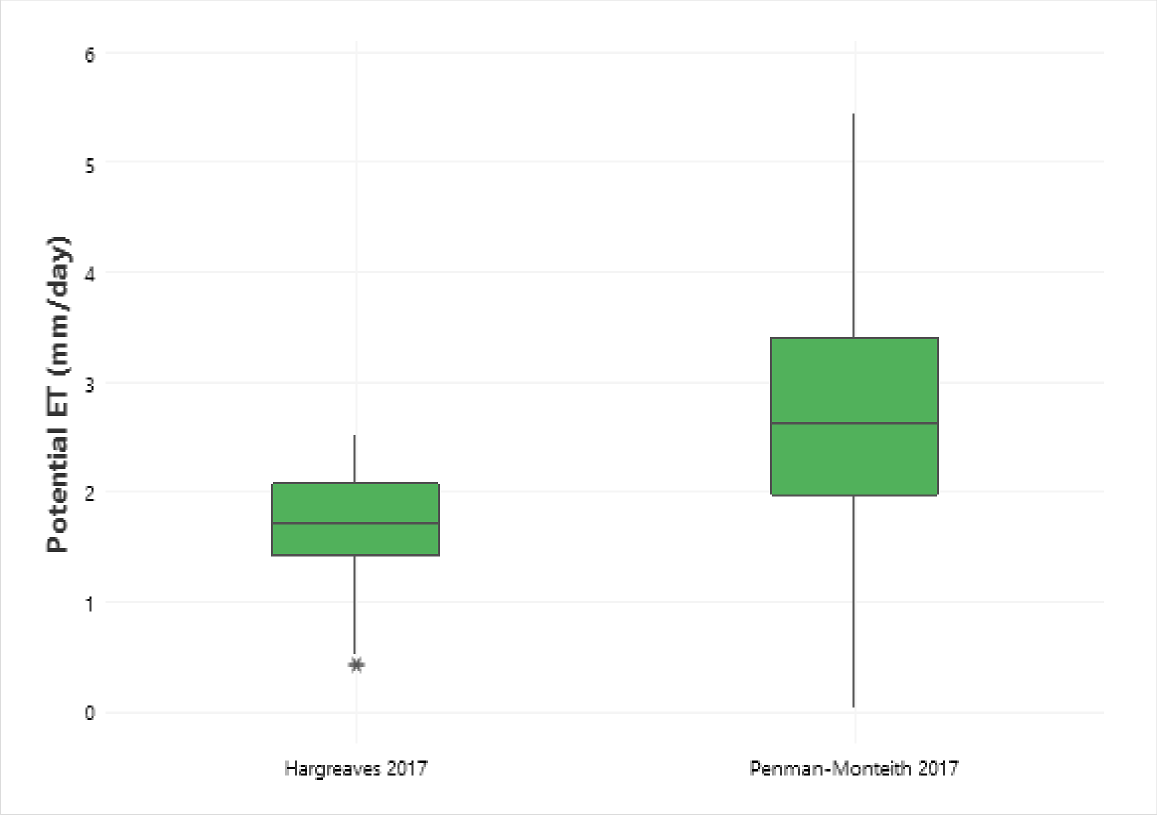
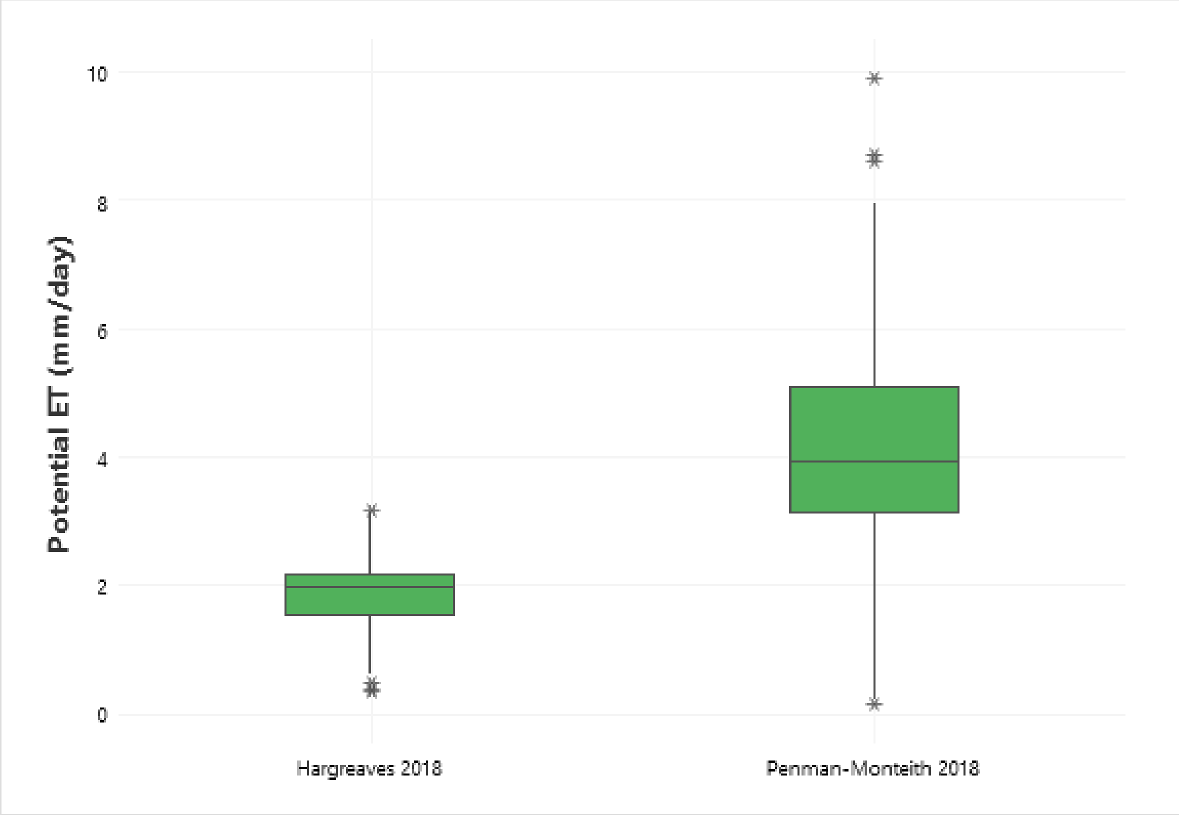
Potential ET: Penman-Monteith



Comparing Potential ET Methods





Comparing Potential ET Methods

Hargreaves 95% Confidence Intervals						
	Mean		Median		Standard Deviation	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
2017	1.607	1.777	1.628	1.853	0.432	0.553
2018	1.713	1.946	1.843	2.070	0.532	0.699

Penman-Monteith 95% Confidence Intervals						
	Mean		Median		Standard Deviation	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
2017	2.478	2.845	2.334	2.761	0.991	1.252
2018	3.666	4.364	3.534	4.480	1.571	2.069

III.) Mass Balance Approach for Measured ET

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Mass Balance

- In an open system, hydrologic cycle quantification can be considered as a mass balance equation where:

$$Inputs = Outputs$$

$$Precipitation + Inflow = Outflow + \frac{dS}{dt}$$

- Defining a change in storage:

$$\frac{dS}{dt} = ET + Percolation$$

- After a 24-hour period, percolation is assumed to no longer be active, so:

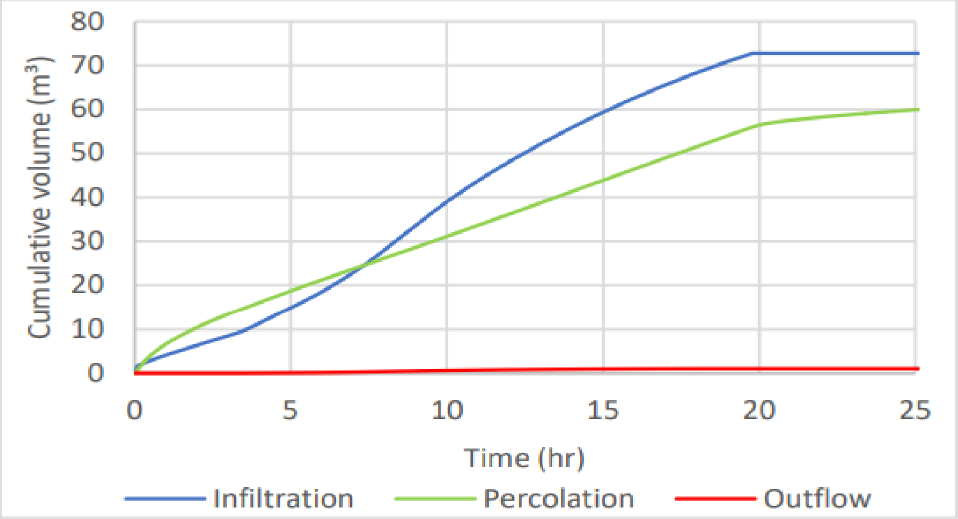
$$\frac{dS}{dt} = ET$$

- Taking change in storage as a change in soil moisture:

$$\frac{dS}{dt} = \frac{dSM_{10cm}}{dt} + \frac{dSM_{35cm}}{dt} + \frac{dSM_{65cm}}{dt}$$

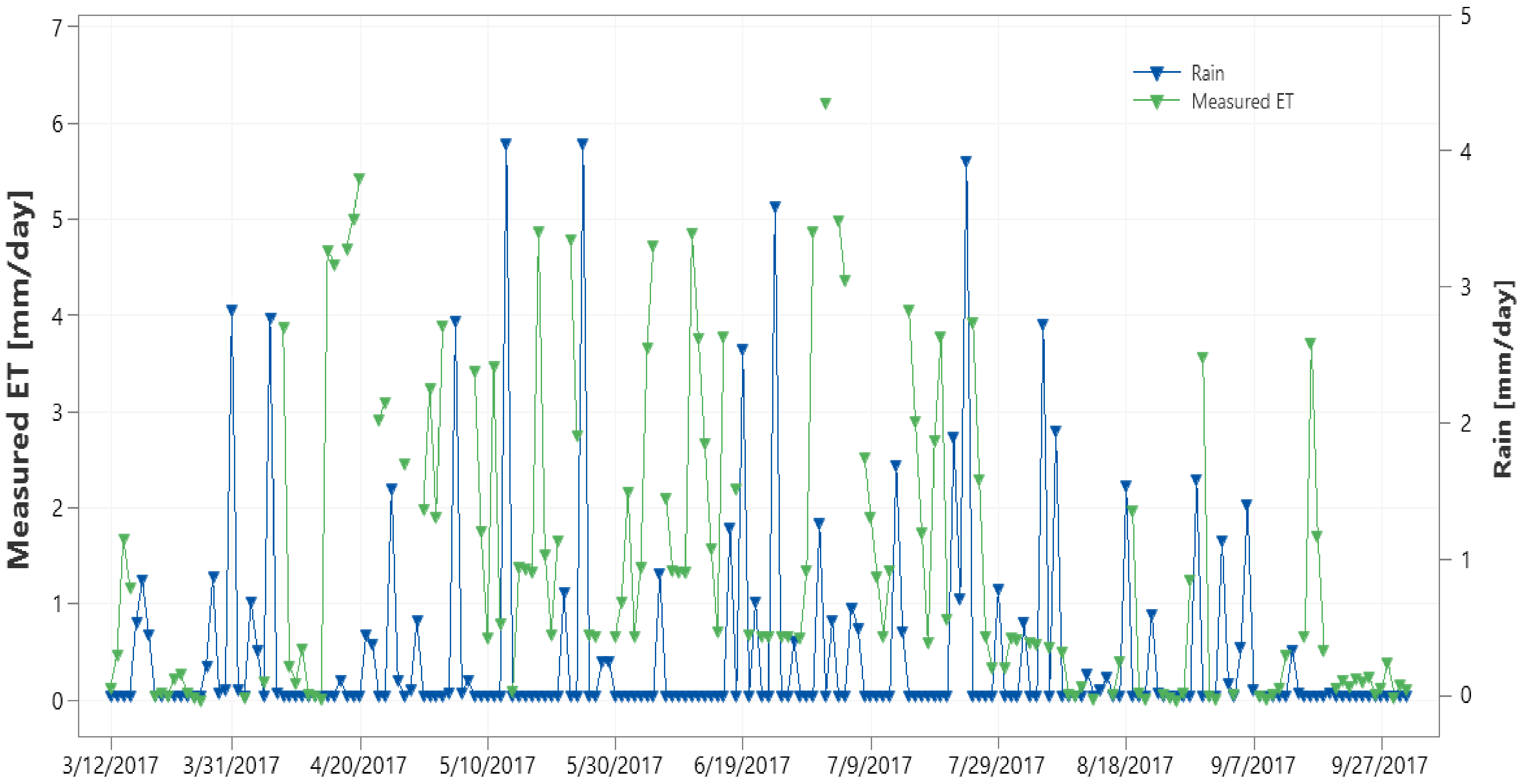
- Evapotranspiration can then be defined as such:

$$ET = \frac{dSM_{10cm}}{dt} + \frac{dSM_{35cm}}{dt} + \frac{dSM_{65cm}}{dt}$$



Mohammed, 2020

Mass Balance



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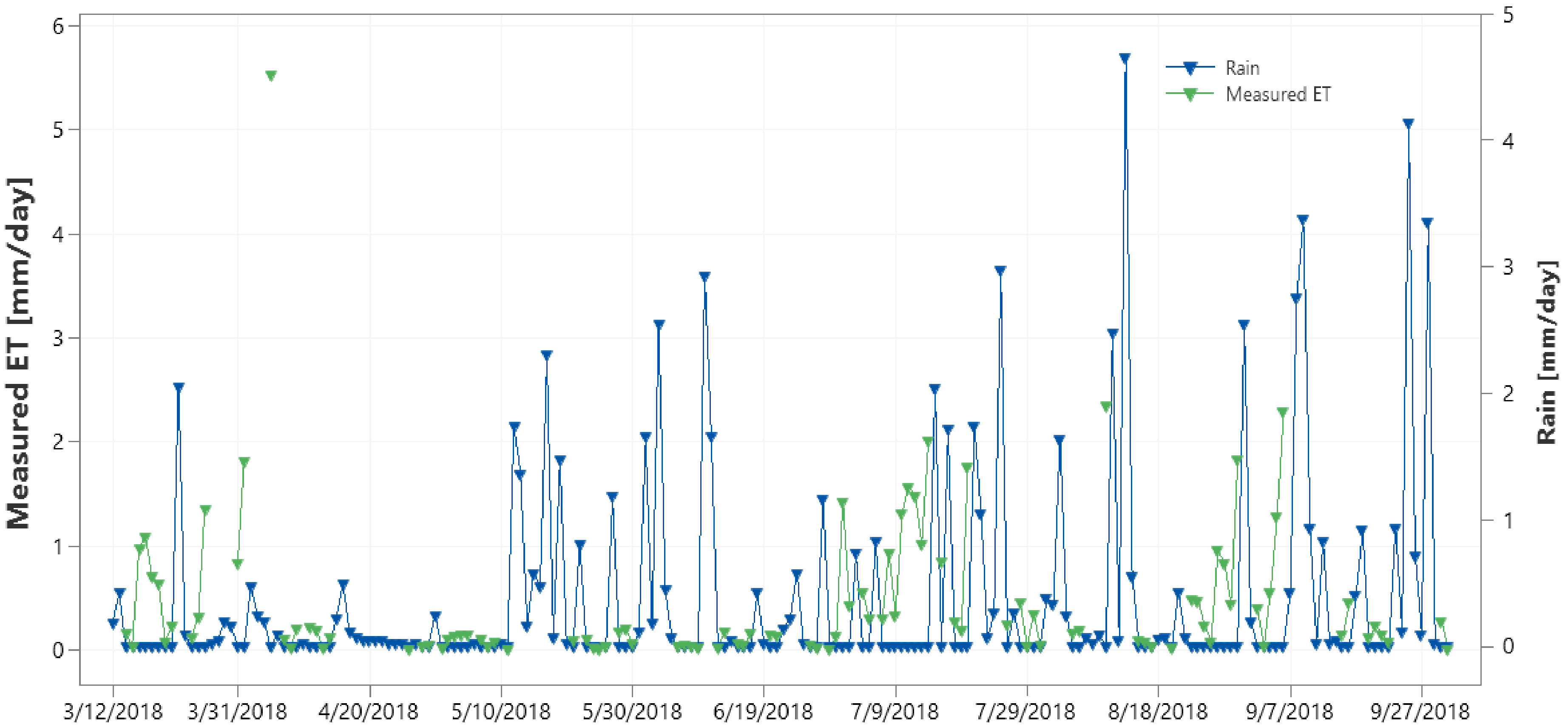
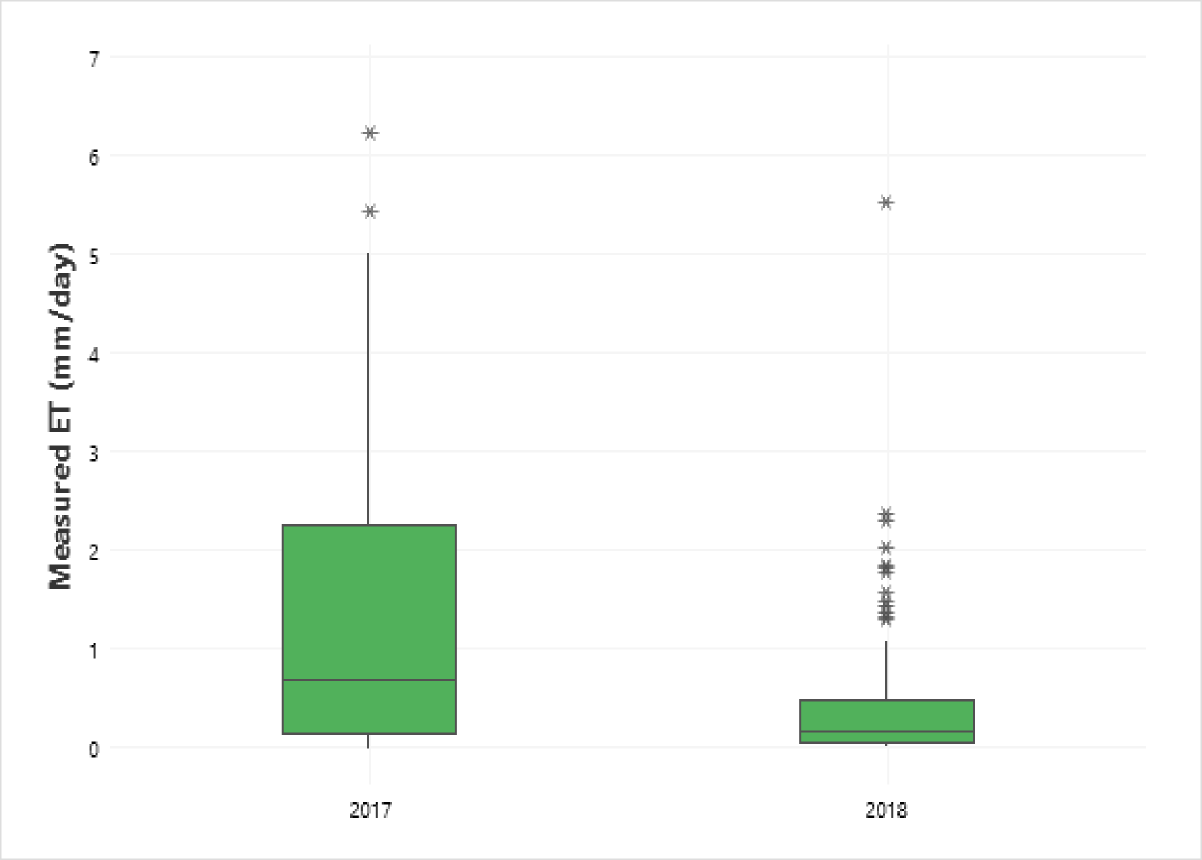
Mass Balance



Mass Balance



Change in Soil Moisture 95% Confidence Intervals						
	Mean		Median		Standard Deviation	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
2017	1.190	1.718	0.623	1.281	1.422	1.799
2018	0.313	0.600	0.121	0.238	0.653	0.857

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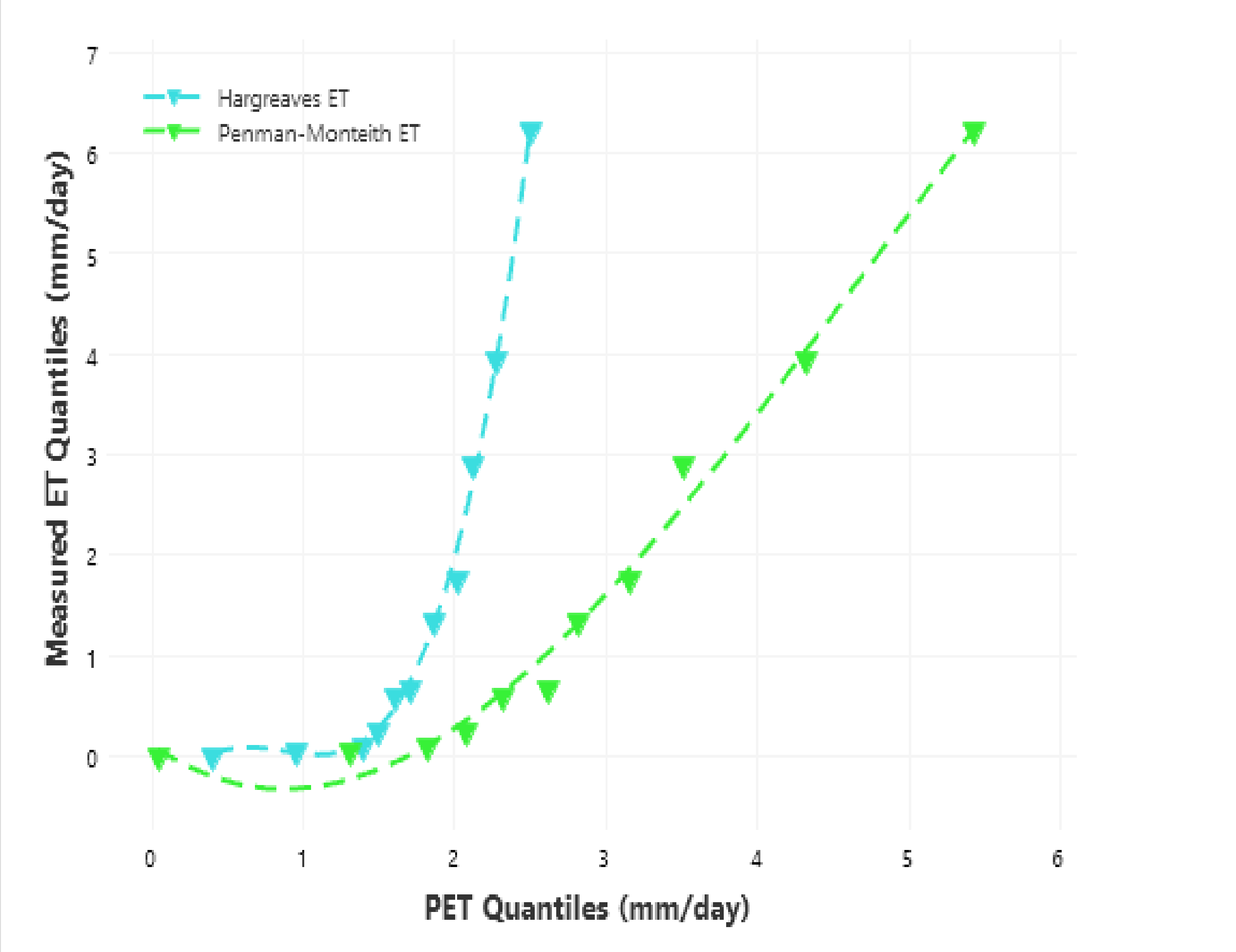
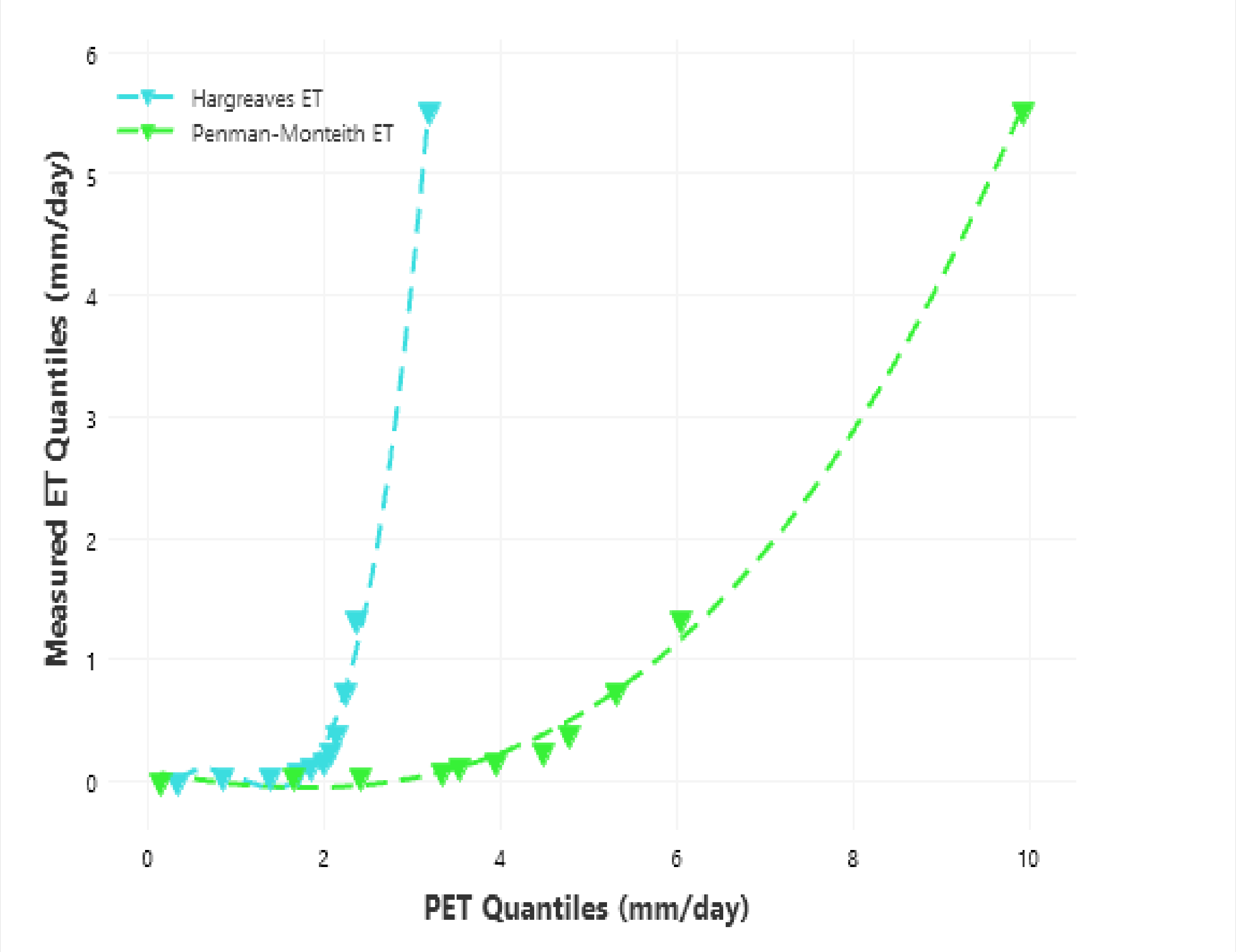
2017 Quantile Analysis



2018 Quantile Analysis



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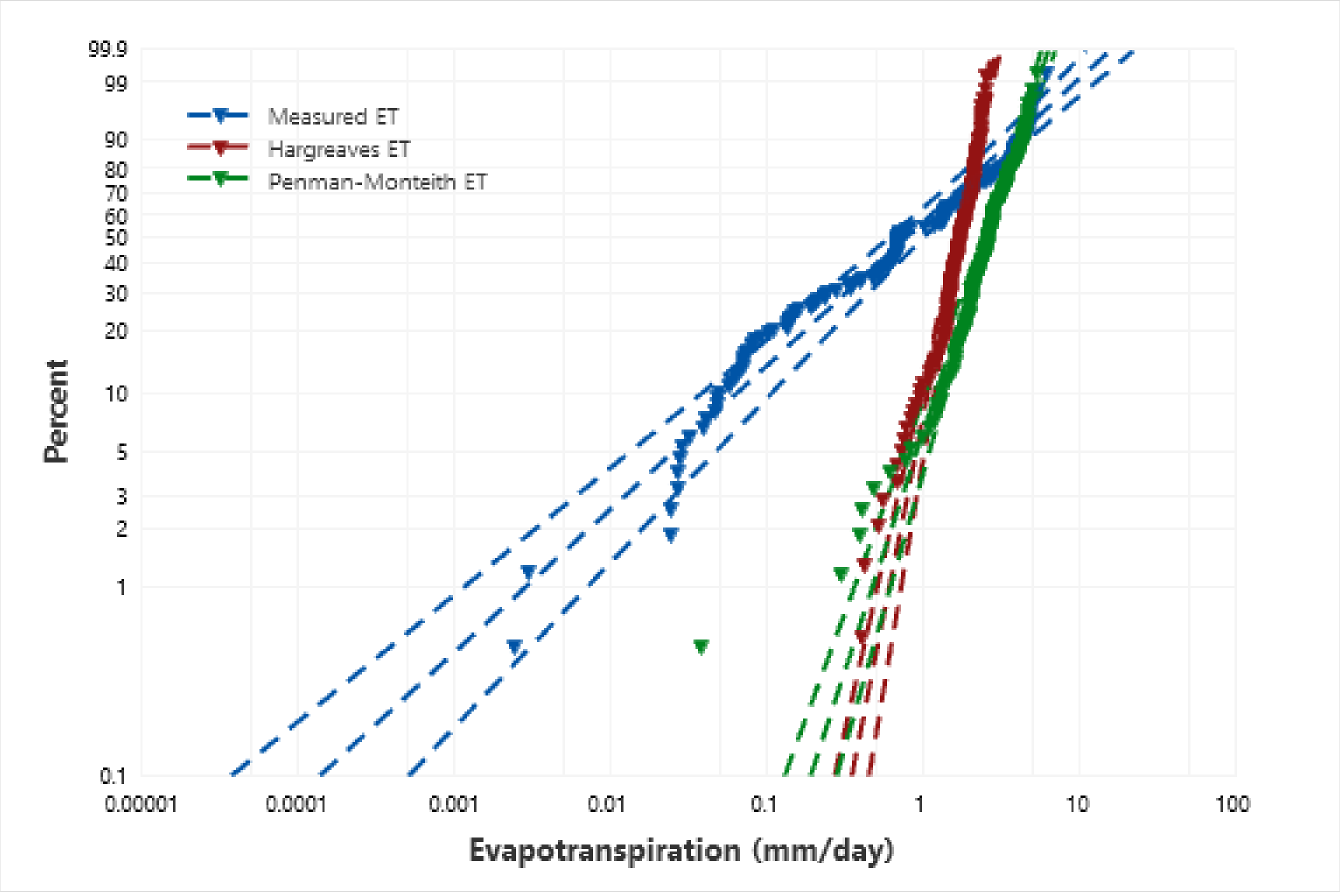
Abington Friends School 2017 ET Performance						
	Minimum	Maximum	Quartile 1	Quartile 3	Median	Mean
Measured ET	0.002	6.230	0.146	2.257	0.680	1.454
Penman-Monteith	0.038	5.441	1.971	3.401	2.620	2.662
Hargreaves	0.402	2.506	1.425	2.074	1.712	1.692
Rainfall	0.022	4.064	0.112	1.411	0.537	0.950
Abington Friends School 2018 ET Performance						
	Minimum	Maximum	Quartile 1	Quartile 3	Median	Mean
Measured ET	0.007	5.540	0.055	0.483	0.159	0.457
Penman-Monteith	0.133	9.931	3.145	5.100	3.946	4.015
Hargreaves	0.336	3.186	1.548	2.197	1.995	1.830
Rainfall	0.022	4.660	0.067	0.940	0.246	0.736

2017 ET Weibull Analysis



β-Value for Weibull Distributions				
	Measured ET	Hargreaves ET	Penman-Monteith ET	Rainfall
2017	0.76	4.16	2.53	0.79
2018	0.73	3.49	2.33	0.68

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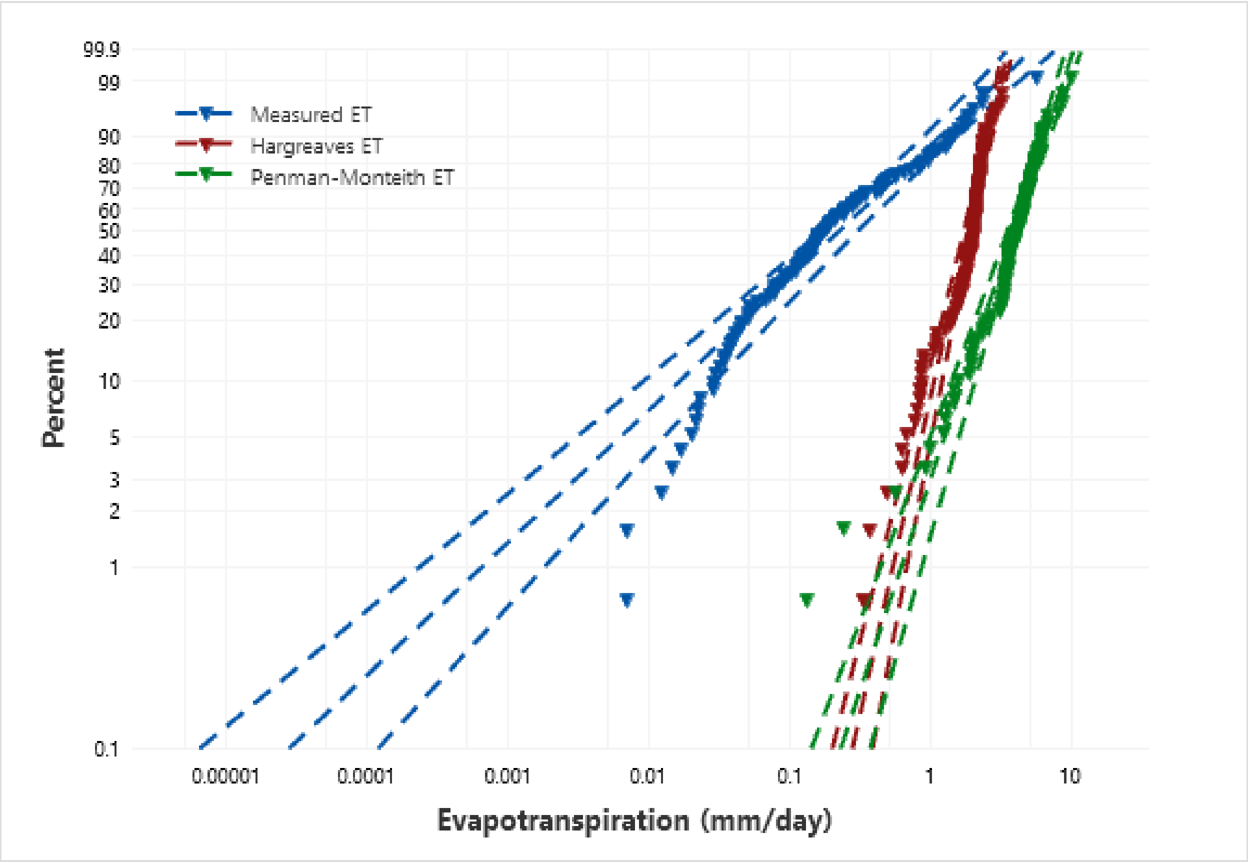
2018 ET Weibull Analysis



β-Value for Weibull Distributions				
	Measured ET	Hargreaves ET	Penman-Monteith ET	Rainfall
2017	0.76	4.16	2.53	0.79
2018	0.73	3.49	2.33	0.68

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IV.) Monitoring and Maintenance

Field Work:

- Come prepared
  - Tools, devices, batteries, wires, and so on
  - “Expect the unexpected”
- Document everything
- Dress appropriately
  - Long pants, durable shoes
  - Layers in the winter
  - Sunscreen
- Always have water!!
- Communication protocol, as well

SCM Maintenance:

- From instrumentation point of view:
  - Wire replacement
  - Battery changing
  - Programming issues
  - Sensor interruptions
- Visual inspections:
  - Check for debris at inflow & outflow points
  - Check vegetation health
  - Ponding/infiltration performance
  - Structure stability and seals

Data Collection

- Advantages of a continuous time scale
  - Before, during, and after storm event for stormwater control
  - Peaks in water quality and water quantity parameters
- Outlier identification & removal
  - Context is key for data
  - Neighboring sites or other devices (i.e. handheld insitu measurements)
  - Manufacturer’s detection limits
- Data representation
  - Temporal and spatial scales
  - Understand how parameters behave
  - Make it attractive and easy to understand

V.) Future Work

EnviroDIY at Naylor’s Run

- “Treatment train” operation for Naylor’s Run
  - Captures runoff from impervious surfaces within neighborhood
  - Rain garden in the first part, bioswale in the second
- Instrumentation in the system and downstream of SCM operation
  - Water quality and water quantity metrics
  - EnviroDIY logger deployment downstream
- Turbidity trends, aligning with total suspended and dissolved solid data
- Water quality in stream vs. out of stream

Research at Naylor's Run

- Water Quality:
  - SCM Constituents vs. Stream Constituents
  - Rain Garden Concentrations vs. Bioswale Concentrations
  - Storm Events vs. Baseflow Conditions
- Water Quantity:
  - ET performance of rain garden
  - Hydrologic budget of the system
  - Inflow vs. Outflow vs. Streamflow
  - Storm Events vs. Baseflow Conditions

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  - Rebecca Martin
  - Sergio Carvajal-Sanchez
  - James Press
  - Shiva Khosravi

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The Delaware River Watershed Initiative

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Questions, Recommendations, or Feedback?

Email: mburns35@Villanova.edu

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