Governing Rules of Water Movement

- Like all physical processes, the flow of water always occurs across some form of **energy gradient** from high to low…
  - e.g., a topographic (slope) gradient from high to low elevation
  - Or a **concentration gradient, pressure gradient**, etc.
- All other things being equal, in a fluvial landscape that **has some relief**, water movement near the surface is going to follow the **topographic gradient downhill**
- Thus, by **modeling terrain** using a continuous surface, we can learn some useful things about the **movement of water** through a landscape

Watershed (a.k.a. Drainage Basin, Catchment)

- A geomorphically distinct **landscape unit** defined by topographic boundaries, or drainage 'divides' that acts as a spatially discrete hydrological system

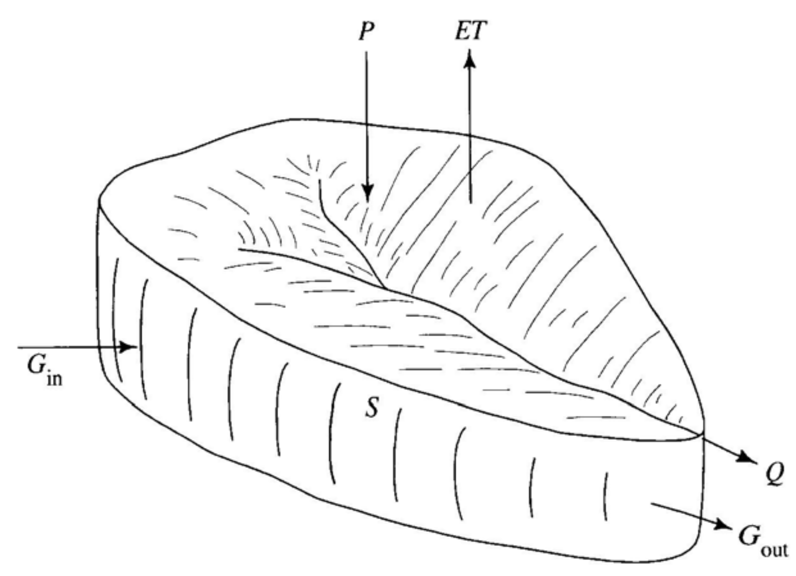


FIGURE 2-3
Schematic diagram of a watershed, showing the components of the regional water balance: P = precipitation, ET = evapotranspiration, Q = stream outflow, G_{in} = ground-water inflow, G_{out} = ground-water outflow.

Water Budget Equations

- This leaves us with the following **equation**:

$$\frac{dV}{dt} = 0 = p - so - et \quad \text{or} \quad p = so + et$$

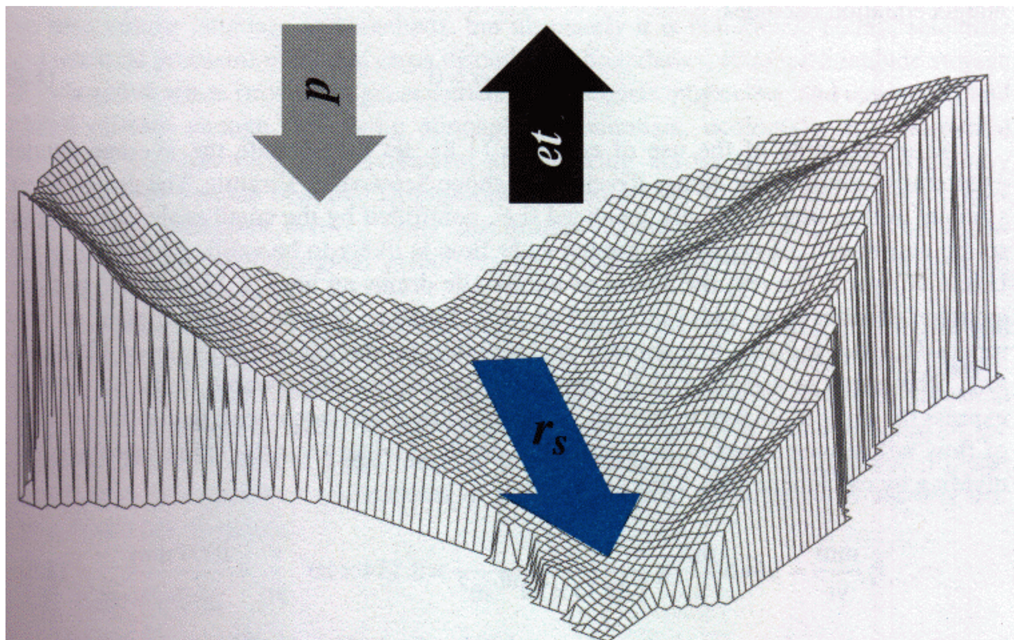


Figure 1.5 The catchment. The boundary of the catchment is referred to as a divide. If the catchment has been properly delineated, there should be no surface-water inflows or outflows across the divide, except at the outlet. In this case, the major inflow is precipitation (*p*), and the major outflows are evapotranspiration (*et*) and surface-water outflow through the catchment outlet (r_s). The topography of the land surface controls where divides are drawn. In the figure, two mountain peaks, and their adjacent ridges, constitute the divide.

Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A.

TOPMODEL Background –
Adapted from Ch.9 of *Elements of Physical Hydrology*

- Let's begin with the idea that the **topography** of the landscape exerts an **enormous influence** on the **movement of water** in the **subsurface** and likewise should control the movement of **surface water**.
- Therefore, we can base a model of catchment dynamics on the idea that **topography** is the **most important** landscape feature **controlling water flow**.
- Next, let's extend the idea of catchment "reservoirs" to **elements** of the landscape. If we could break the catchment up into **blocks of a given size**, we might be able to **route water through each block** as we move down a **hillslope**.

TOPMODEL Background –
Adapted from Ch.9 of *Elements of Physical Hydrology*

- Each block would **differ in its position** along the hillslope and in the slope of the land surface (and probably the water table) through the block.
- If the water table is **relatively flat** within a given block, the hydraulic gradient is small and we might **expect an increase in water storage** through time within that block.
- The **increase in storage** is **even greater** if the block is at the **base of a convergent hillslope**, such that a **great deal of upslope flow** into the block occurs (Figure 9.6).

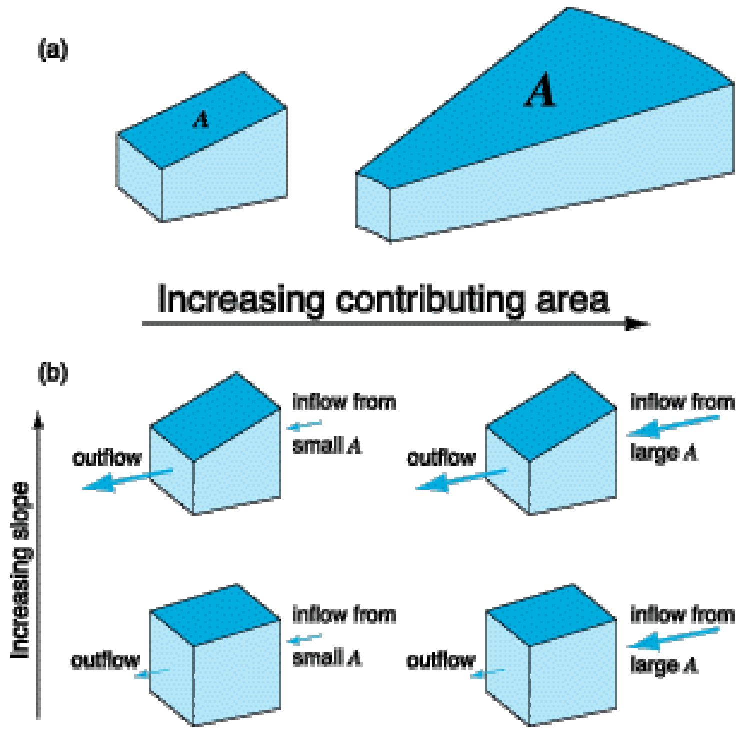


Figure 9.6 Local slope and contributing area control the water balance for a catchment "block." The inflow rate is proportional to the contributing area *A*, which depends on how long the hillslope is as well as whether it is convergent, divergent, or planar (a). The local slope controls the outflow from the blocks (b). If inflow is smaller than outflow (upper left in b), the water table declines. Conversely, if inflow is greater than outflow (lower right in b), the water table will rise and surface saturation may occur. (Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A.)

TOPMODEL Background –

Adapted from Ch.9 of *Elements of Physical Hydrology*

- One catchment model that is based on the idea that **topography exerts a dominant control on flow routing** through upland catchments is called **TOPMODEL** (Beven and Kirkby, 1979).
- TOPMODEL uses the **equation for conservation of mass** ("inflow rate minus outflow rate equals rate of change of storage") for **several "reservoirs" in a catchment**.
- By **linking together** the water balance equations for all of the hypothetical reservoirs in the catchment, a routing computation can be completed.

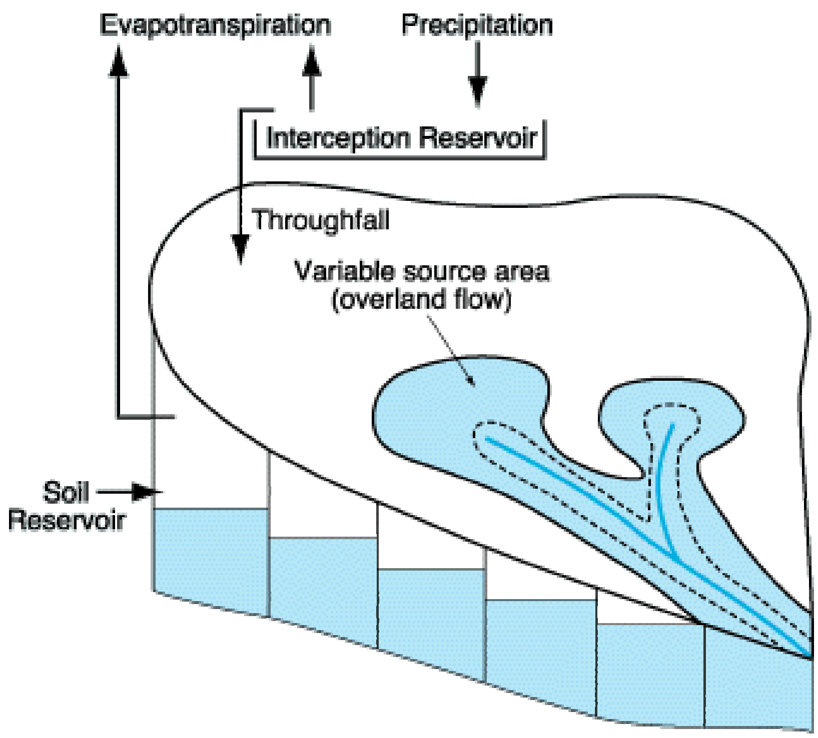


Figure 9.7 Schematic diagram of the TOPMODEL concept. (Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A.)

TOPMODEL Background –

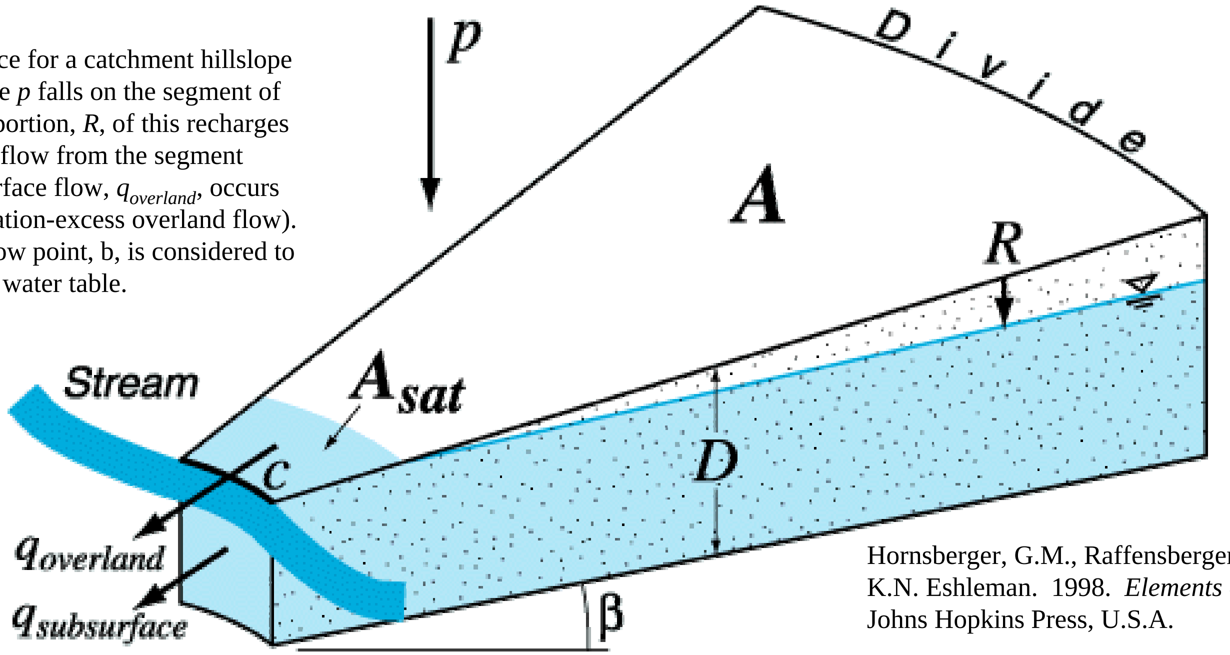
Adapted from Ch.9 of *Elements of Physical Hydrology*

- **TOPMODEL** performs the bookkeeping for the water balance computations in the **framework of topographically defined elements** and uses Darcy's law to calculate flow rates through the soil.
- Consider **a segment of a catchment** defined by a cut along an elevation contour line at the bottom, and "sides" running perpendicular to contours up to the catchment divide. Recall our assumption that flow is driven by topography; hence, the flow of subsurface water is conditioned strongly by the local topography. **The degree of convergence of "flow lines"** (lines perpendicular to the contours) determines **how much upslope area drains to a unit length of contour at any given point**.

TOPMODEL Background –
Adapted from Ch.9 of *Elements of Physical Hydrology*

- The local slope, the thickness of the soil, and the hydraulic conductivity of the soil determine the **"ability" of the soil to move water farther down the slope** once it has arrived at the given point. Source areas for surface runoff occur where **subsurface water accumulates**-points to which large upslope areas drain (such as convergent hillslopes or "hollows") and where **the capacity to drain the water downslope is limited** (where slopes flatten at the base of hollows). Conservation of mass can be applied to the segment depicted in Figure 9.8 to determine the fluxes.

Figure 9.8 The water balance for a catchment hillslope segment. Throughfall at rate *p* falls on the segment of area *A* and thickness *D*. A portion, *R*, of this recharges the subsurface. Subsurface flow from the segment occurs at rate $q_{subsurface}$. Surface flow, $q_{overland}$, occurs from saturated areas (saturation-excess overland flow). The local slope at the outflow point, b, is considered to be equal to the slope of the water table.



Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A.

TOPMODEL Background –
Adapted from Ch.9 of *Elements of Physical Hydrology*

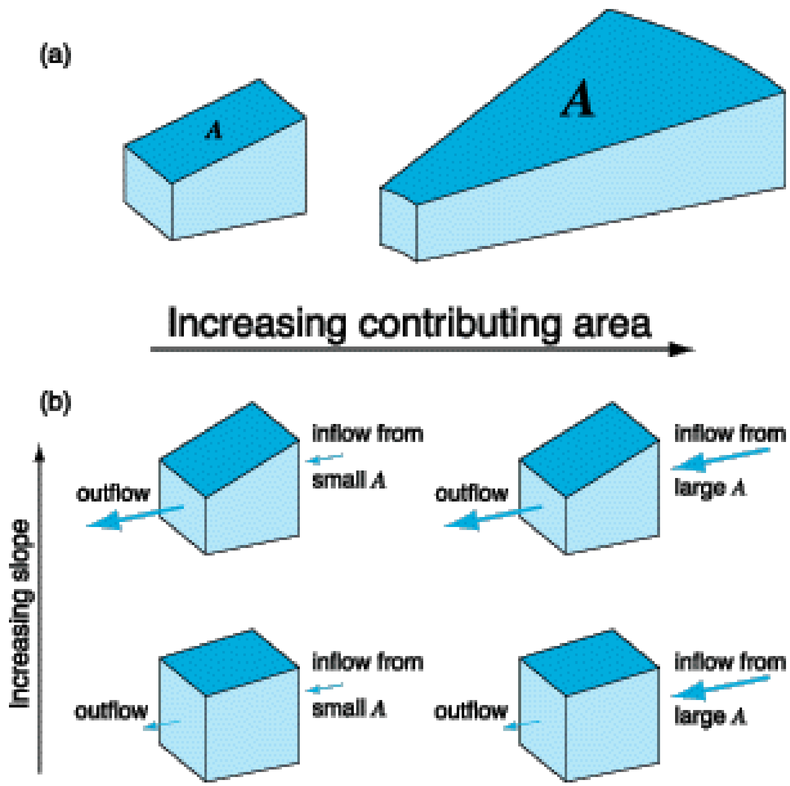
- For our purposes here, we are **not going to develop the TOPMODEL equations** (you can always refer to Beven and Kirkby, 1979 for the full details)
- However, we are interested in **the means** by which TOPMODEL **characterizes the important characteristics of a hillslope** that influence the likelihood of areas of saturation developing as a function of the upslope "contributing area" and the slope of the block:

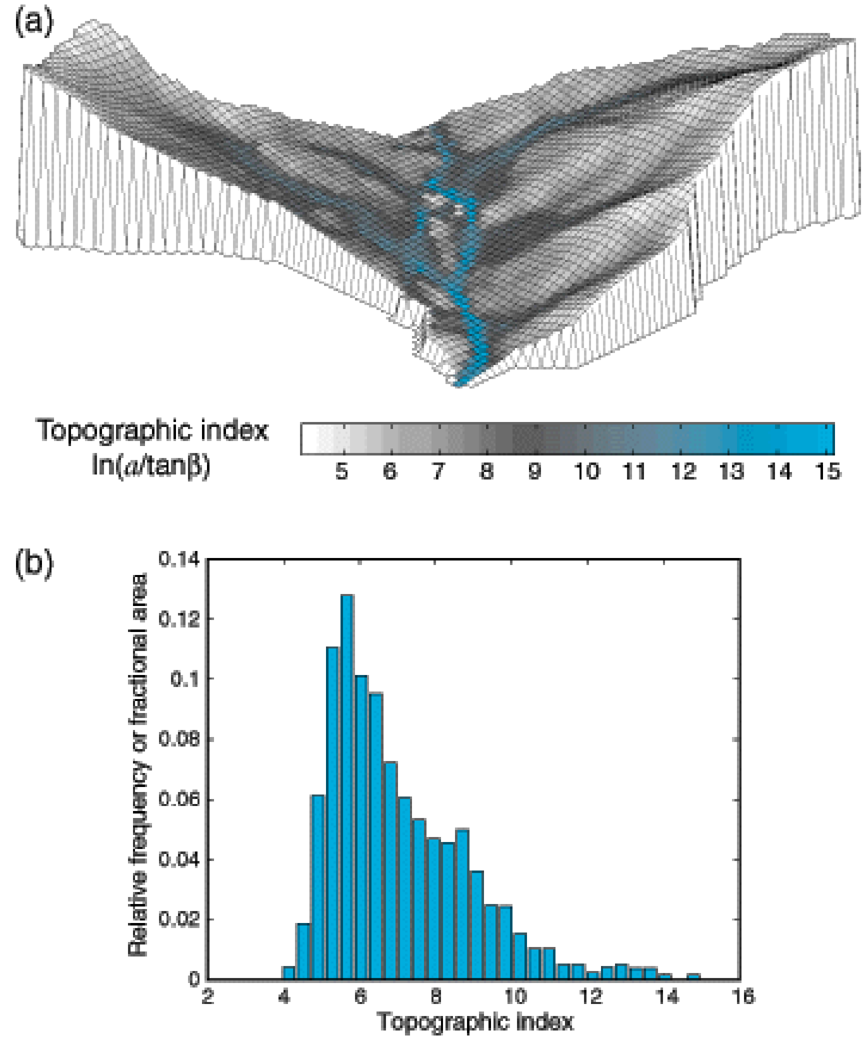
$$\text{TMI} = \ln(a/\tan\beta)$$

where ***a*** is the **upslope contributing area per unit contour length** (A/c) and **tanβ** is **the local slope**, quantitatively captures the effect of topography. The upslope contributing area is determined by **finding flow paths** through the catchment, based only on the catchment topography. The contributing area is related to the **accumulation of the flow paths** above each point

Topographic Moisture Index

$$TMI = \ln(a/\tan\beta)$$





Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A., p. 210 & p. 216.

Slope and Aspect

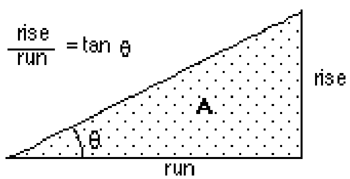
- These are **measurements of terrain attributes**, usually calculated from a digital elevation model
- **Slope and aspect** are calculated for each cell in the grid, by comparing a cell's elevation to that of its neighbors
  - Usually **eight neighbors** are used and the result is expressed as an angle, but the exact method varies
  - It is important to know exactly what method is used when calculating slope, and exactly how slope is defined, because **different methods** can give **different results**

Slope and Aspect

- We can **calculate** these topographic attributes directly from the grid-elevation values using a second-order finite difference scheme applied over a 3x3 neighborhood

From ArcView 3.2 Help

Degree of slope = θ



Degree of slope = 30
Percent of slope = 58

Slope

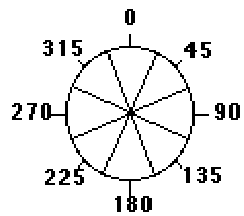
The actual algorithm that is used to calculate slope is:

```
rise_run = SQRT(SQR(dz/dx)+SQR(dz/dy))
degree_slope = ATAN(rise_run) * 57.29578
```

where the deltas are calculated using a 3x3 roving window,

```
a b c
d e f
g h I
```

```
(dz/dx) = ((a + 2d + g) - (c + 2f + i)) / (8 * x_mesh_spacing)
(dz/dy) = ((a + 2b + c) - (g + 2h + i)) / (8 * y_mesh_spacing)
```



Aspect

1	1	1	1	1	1
1	3	3	2	1	
1	1	3	2	2	2
1	2	2	2	2	2
1	1	1	2	2	2
1	1	1	1	1	2

INGRID1

=

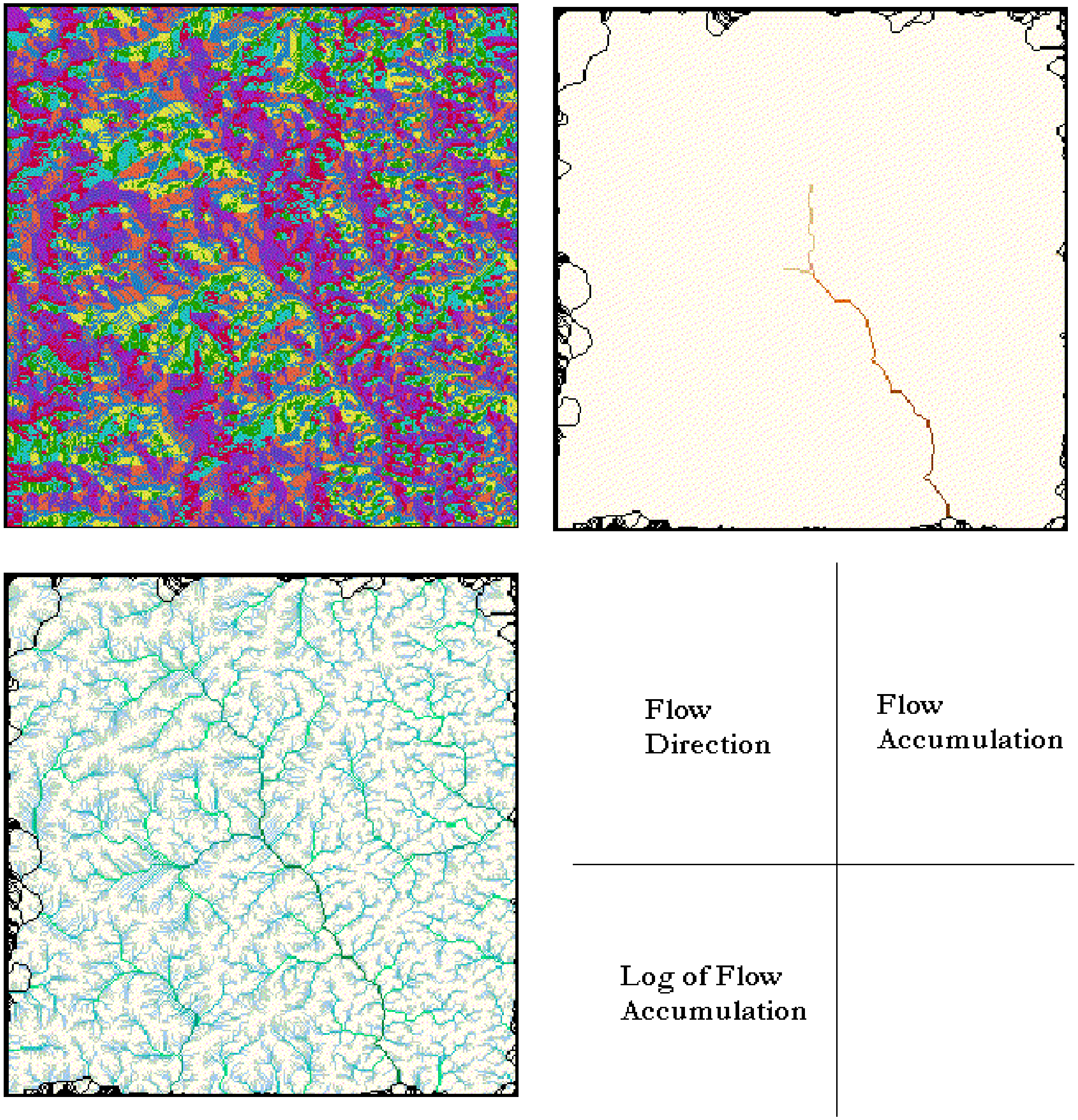
315.0	341.6	8.1	26.6	45.0	-1.0
270.0	288.4	11.3	45.0	26.6	
251.6	246.8	198.4	90.0	0.0	315.0
270.0	243.4	206.6	180.0	-1.0	-1.0
225.0	198.4	206.6	206.6	198.4	225.0
-1.0	-1.0	225.0	198.4	206.6	270.0

OUTGRID

Value = NODATA

White Cells
Value = 0

Flow Direction and Accumulation



- Slope and aspect are needed to produce **flow direction**, which assigns each cell a **direction of steepest descent**
- **Flow accumulation** uses flow direction to find the **number of cells** that **drain to each cell**
- Taking the **log** of accumulation makes the **pattern** much easier to see

Flow Direction

- Flow Direction evaluates the **direction of steepest decent** for each cell in the grid by **comparing a cell with its eight neighbors** in the following fashion:
  - drop = change in z value / distance * 100
  - Note that diagonal neighbors are 1.414214 times as far away as 4-connected orthogonal neighbors
- ArcGIS **encodes** the resulting direction of steepest decent in the grid using **the following scheme**:

32	64	128
16	X	1
8	4	2

- For example:

From ArcView 3.2 Help

78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

elevGrid

=

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

flowGrid

Flow Accumulation

- Flow accumulation find the **number of cells that drain to any cell** in the grid, taking the flow direction grid as input:
  - Output cells with a **high flow accumulation** are areas of concentrated flow and may be used to **identify stream channels**.
  - Output cells with a **flow accumulation of 0** are local topographic highs and may be used to **identify ridges**.
- For example:

From ArcView 3.2 Help

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

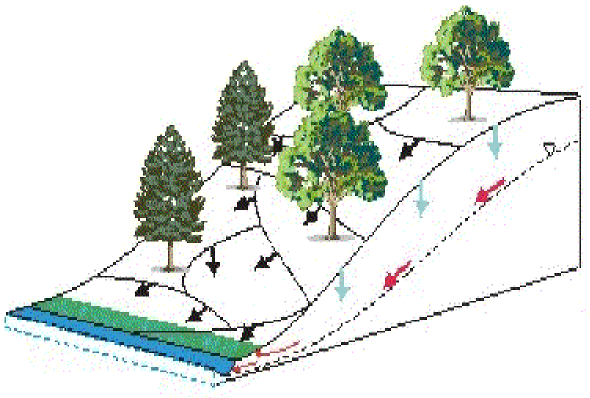
flowGrid

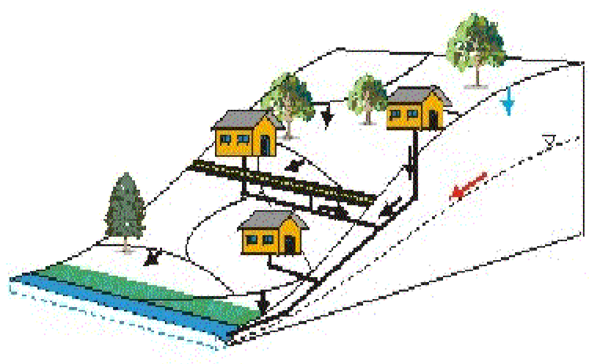
=

0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	2

accumGrid

Fine Scale Topographic Effects on Near Surface Soil Moisture Patterns





- The urbanizing landscape’s greater **heterogeneity** impacts land cover and modifies **flowpaths**:
- **Soil moisture** is a key, observable hydrologic store that can be used to characterize the spatial distribution of changes in patterns and processes

Differences in Soil Moisture Pattern Dynamics

Does the presence of **urbanizing infrastructure** on the landscape modify the **soil moisture** regime?

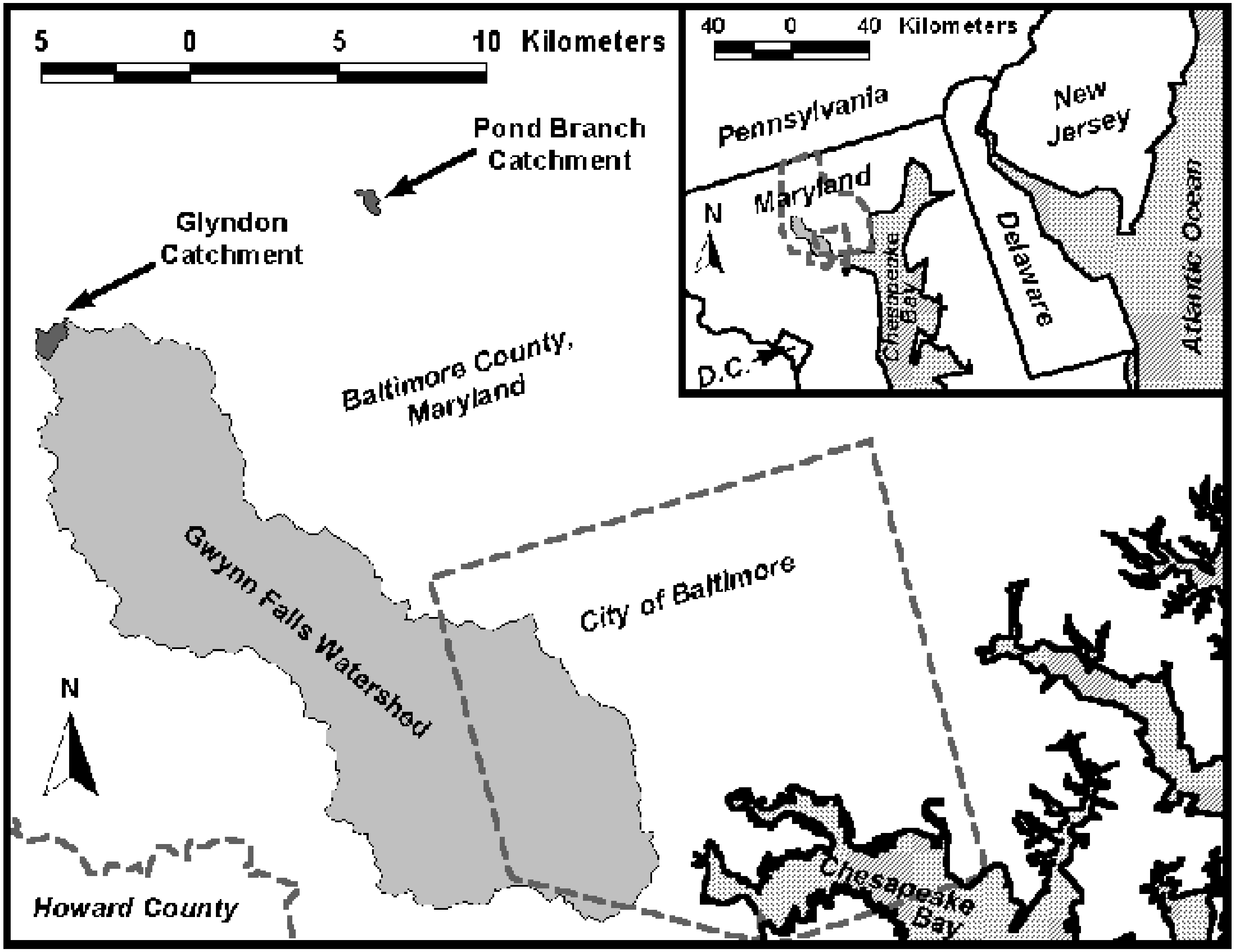
↳

- To what extent is **topography** a controlling influence on soil moisture pattern dynamics in urbanizing catchments?

- To what extent is **TMI** an effective descriptor of relative wetness at different locations at the same time?

- Will the **relationship** between TMI and sampled soil moisture be different in urbanizing and control catchments?

Study Catchments in Suburban Maryland

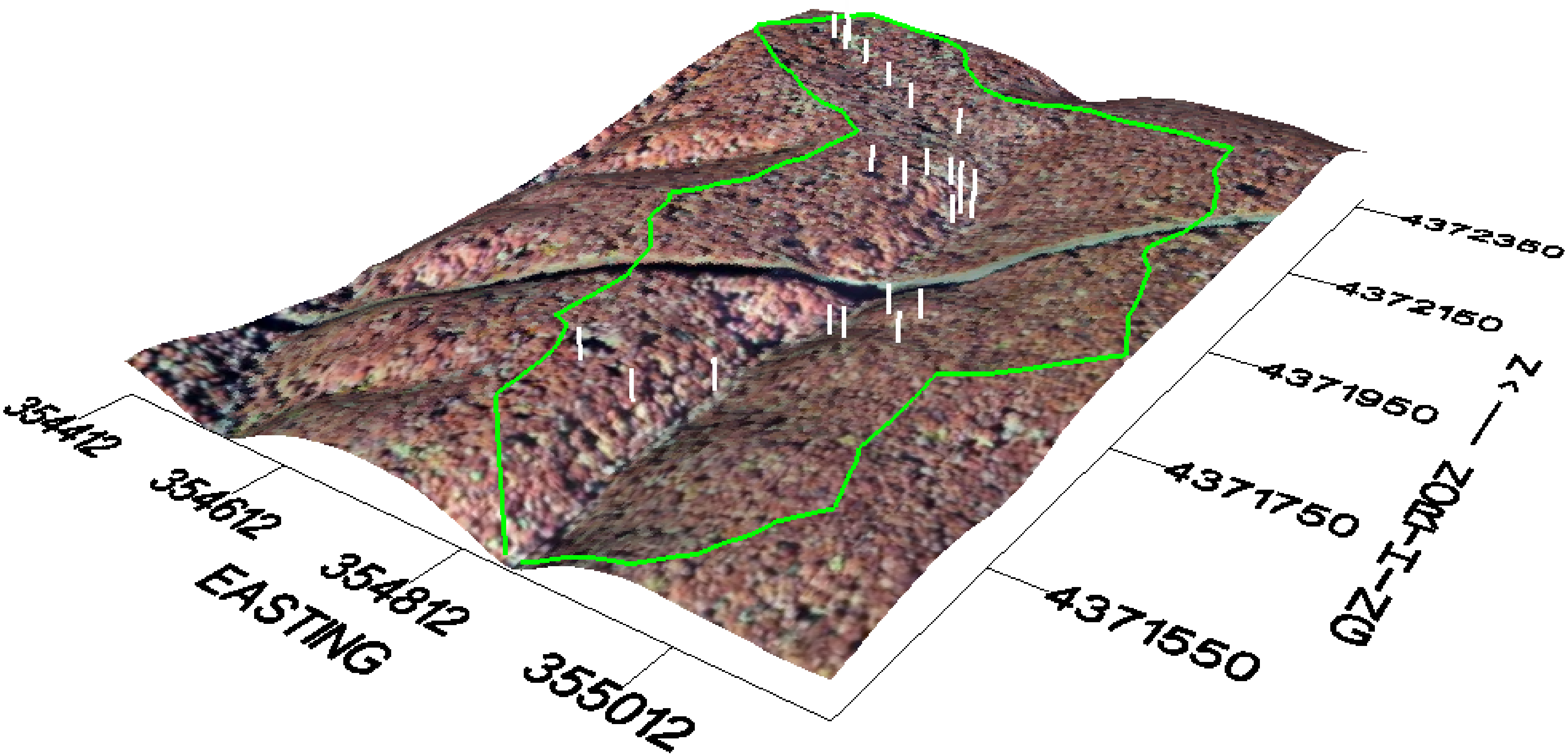


Study Catchments

Catchment	Land Use	Area (ha)	Sampling Dates
Pond Branch (control)	Forested	37.55	2/12/02, 2/21/02, 2/28/02, 3/7/02, 3/15/02, 3/29/02, 4/4/02, 4/11/02, 4/18/02, 4/24/02, 5/3/02, 5/8/02, 5/14/02, 5/20/02, 5/30/02, 6/7/02, 6/12/02, 6/19/02, 6/26/02, 7/11/02, 7/24/02, 8/15/02, 8/22/02
Glyndon (urbanizing)	Low and medium density residential	81.05	2/1/02, 2/8/02, 2/15/02, 2/22/02, 3/1/02, 3/8/02, 3/29/02, 4/4/02, 4/11/02, 4/17/02, 4/25/02, 5/9/02, 5/16/02, 5/21/02, 5/29/02, 6/6/02, 6/12/02, 6/19/02, 6/28/02, 7/11/02, 7/19/02, 8/1/02, 8/15/02, 8/22/02

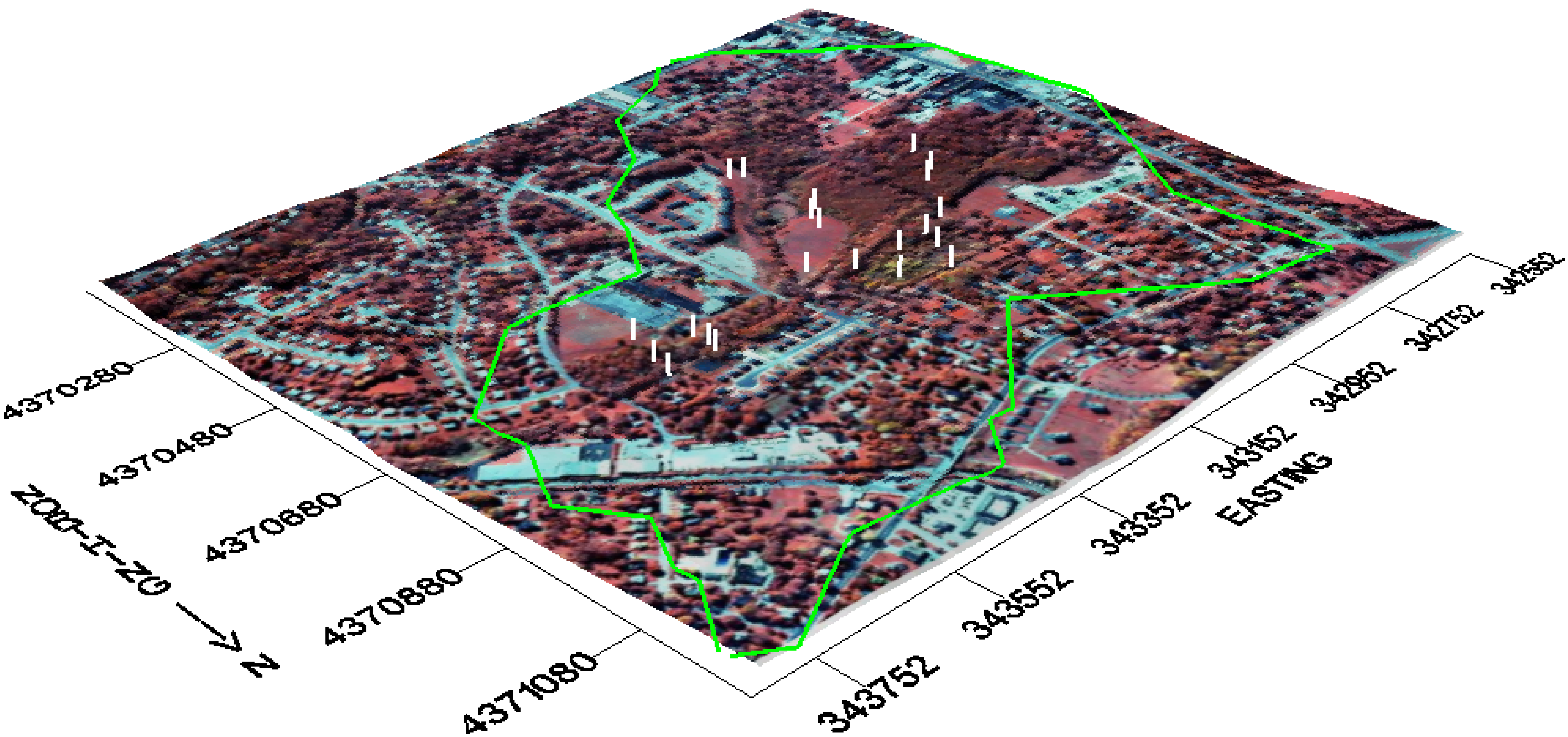
Pond Branch Catchment – Control

Color Infrared Digital Orthophotography



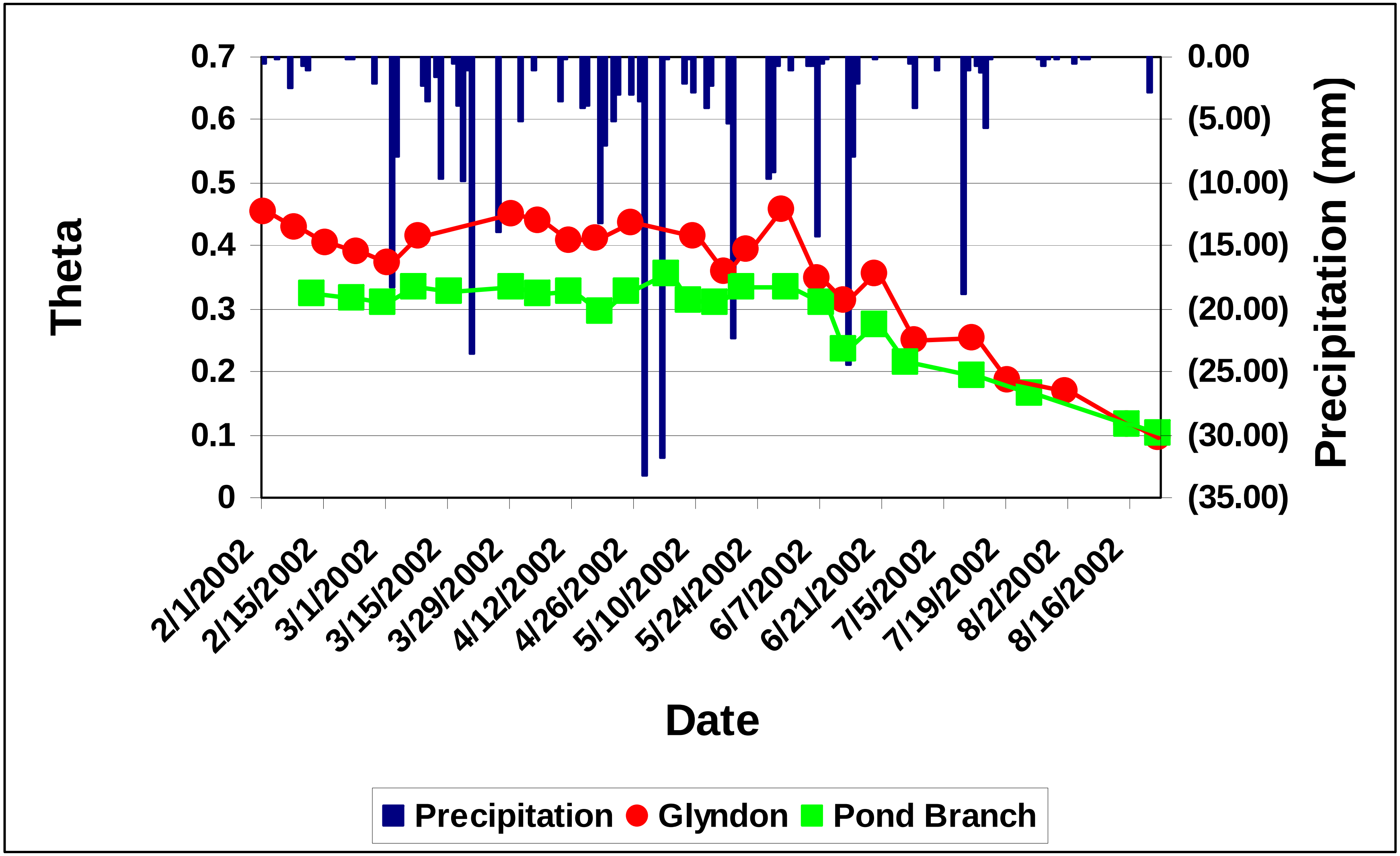
Stream Gauge at Pond Branch

Glyndon Catchment – Urbanizing
Color Infrared Digital Orthophotography

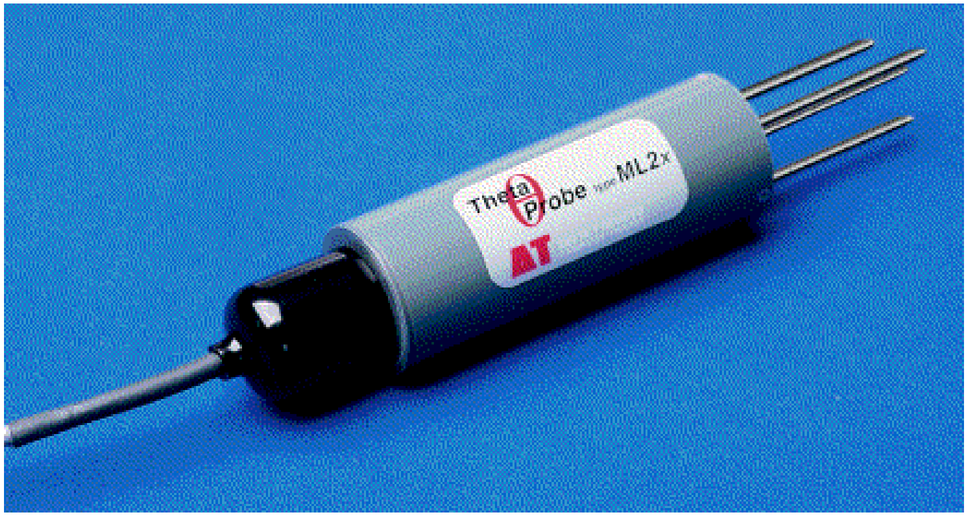


Incised Right Fork at Glyndon

Precipitation and Soil Moisture Records

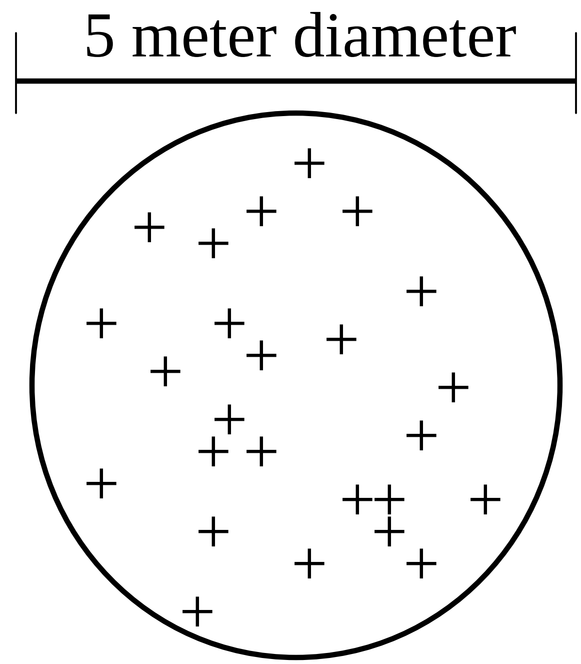


Soil Moisture Sampling Method



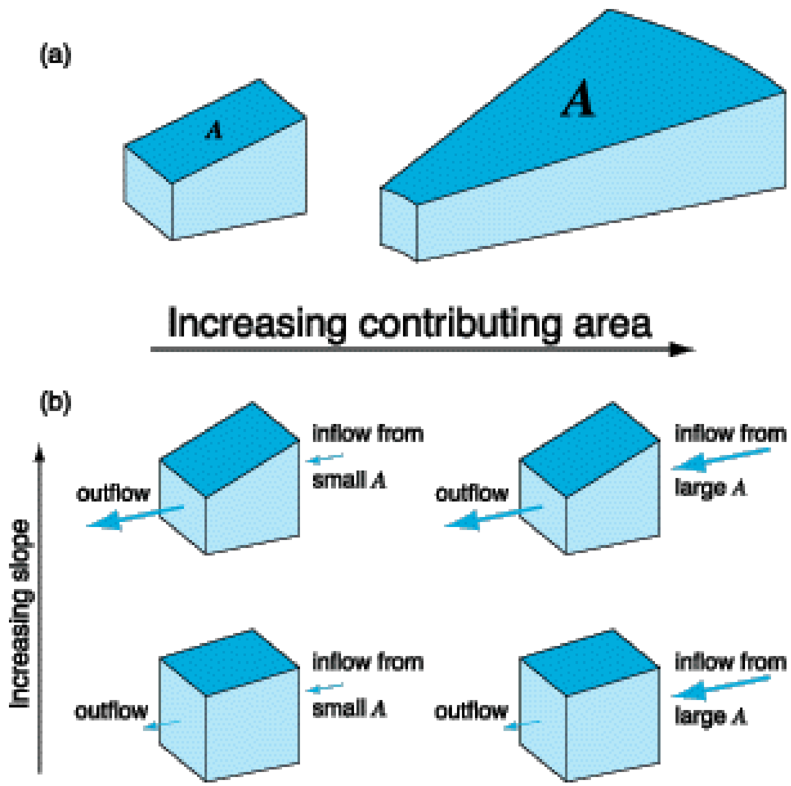
ThetaProbe Soil Moisture Sensor - measures the impedance of the sensing rod array, a f(x) of the soil's moisture content

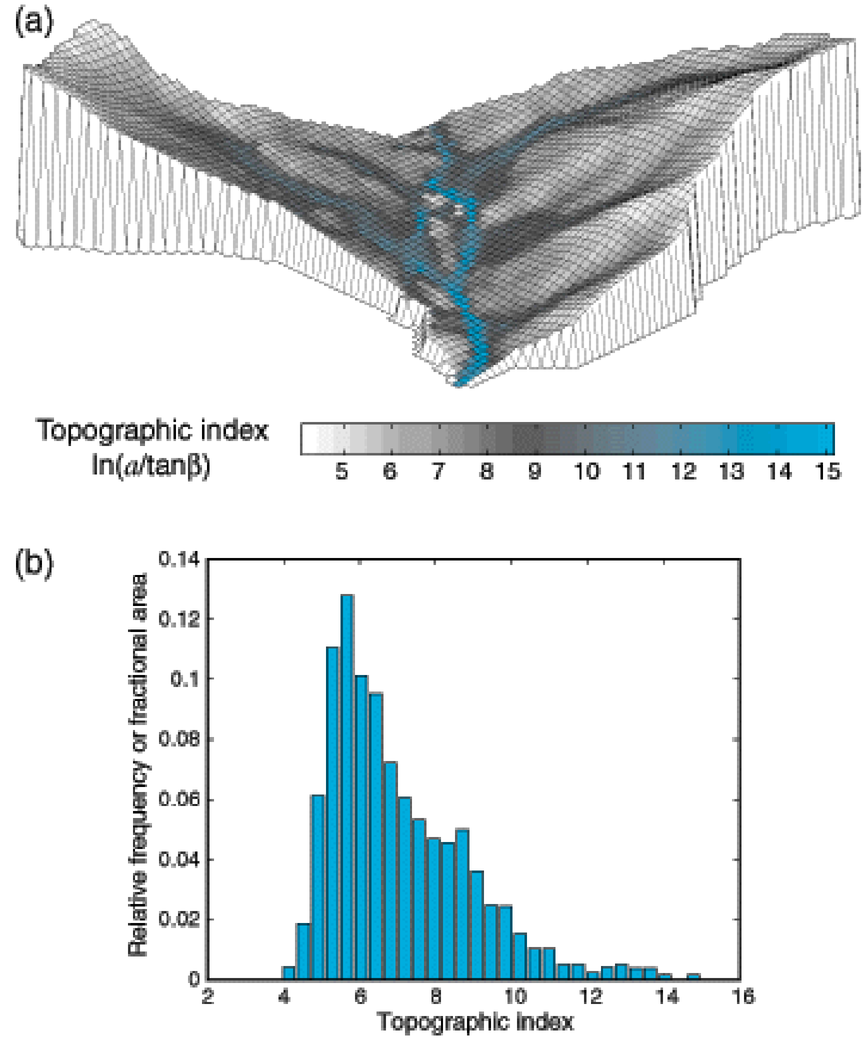
25 samples taken using a random walk within a 5 meter circle



Topographic Moisture Index

$$\mathrm{TMI} = \ln(a/\tan\beta)$$

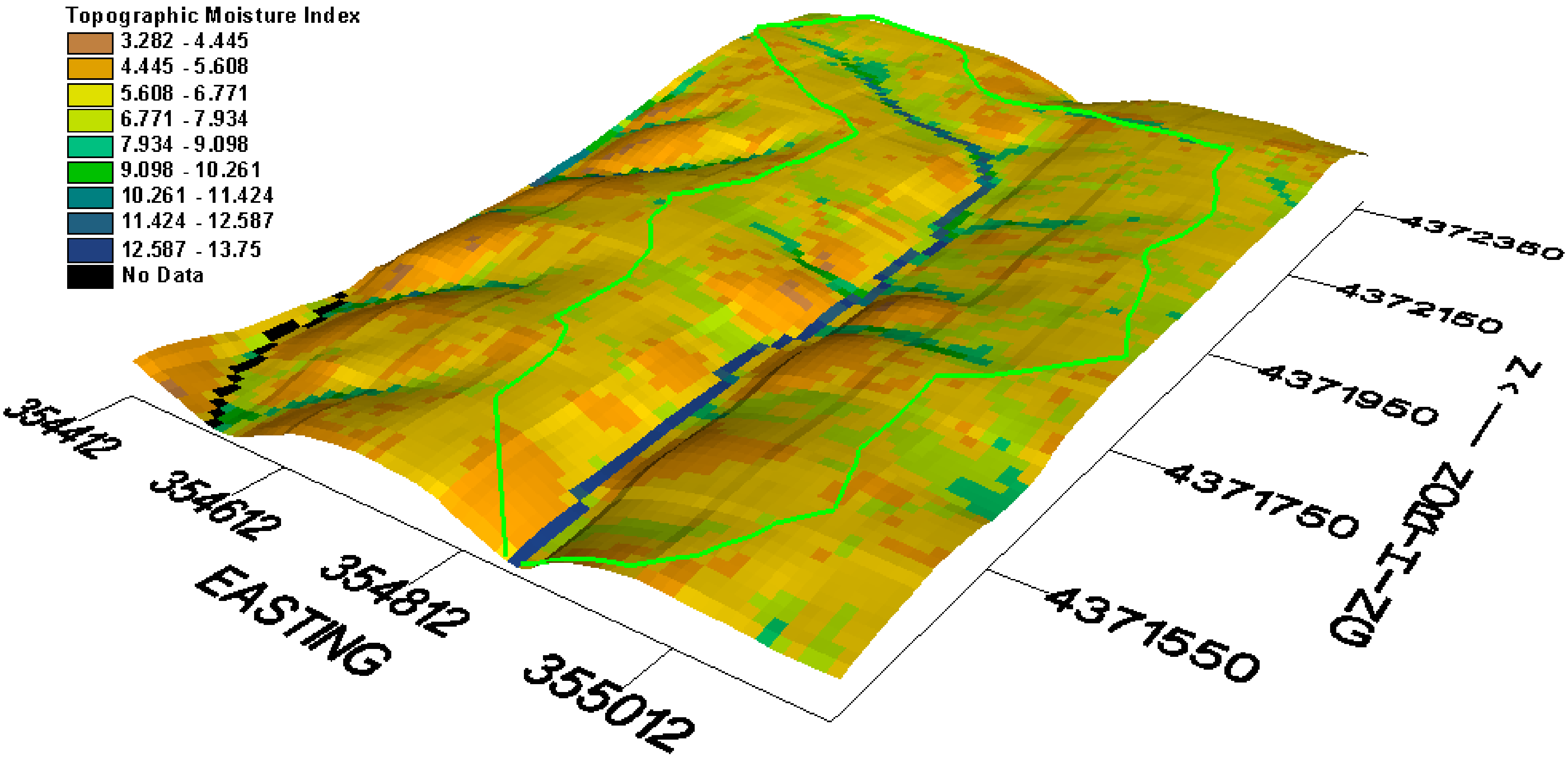




Hornsberger, G.M., Raffensberger, J.P., Wiberg, P.L. and K.N. Eshleman. 1998. *Elements of Physical Hydrology*, Johns Hopkins Press, U.S.A., p. 210 & p. 216.

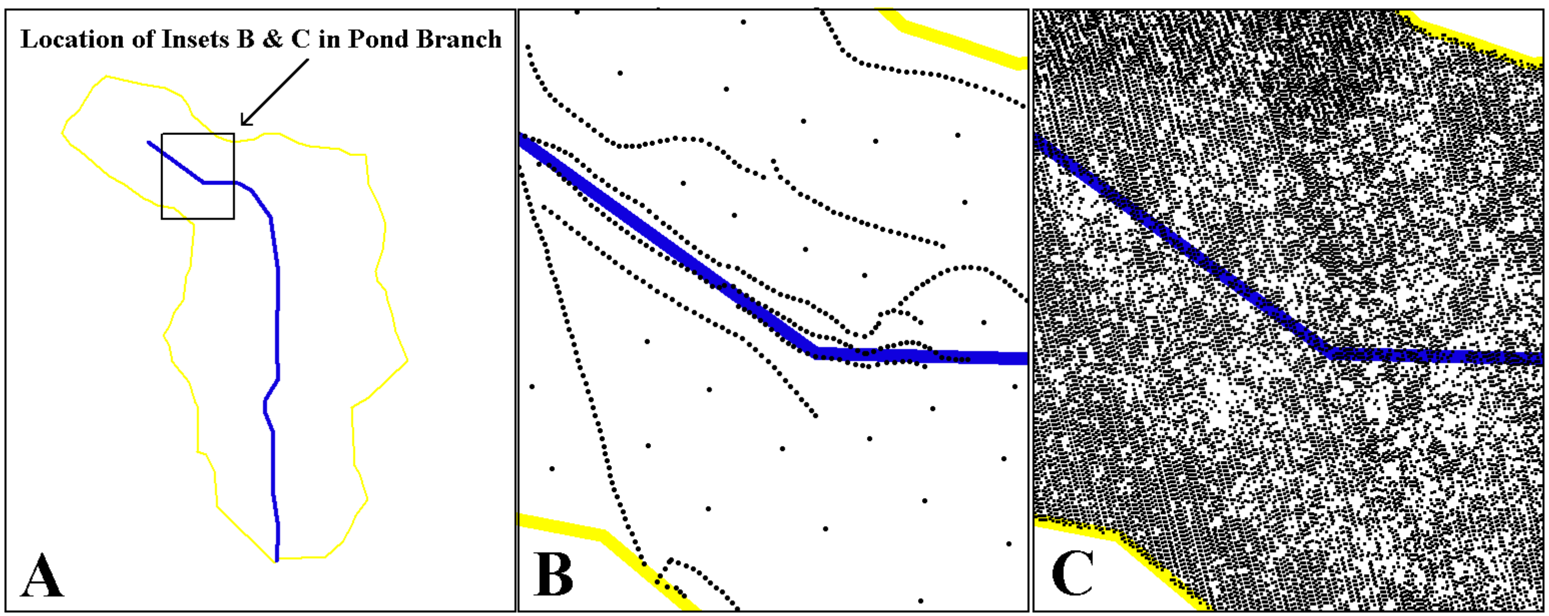
Pond Branch Catchment – Control

Topographic Index Example



Sources of Digital Elevation Data

Catchment	Area (ha)	Data Source	Number of Points	Points per m2
Pond Branch (control)	37.55	Photogrammetric	6569	0.017
		LIDAR	273228	0.727
Glyndon (urbanizing)	81.05	Photogrammetric	39687	0.049
		LIDAR	437759	0.540

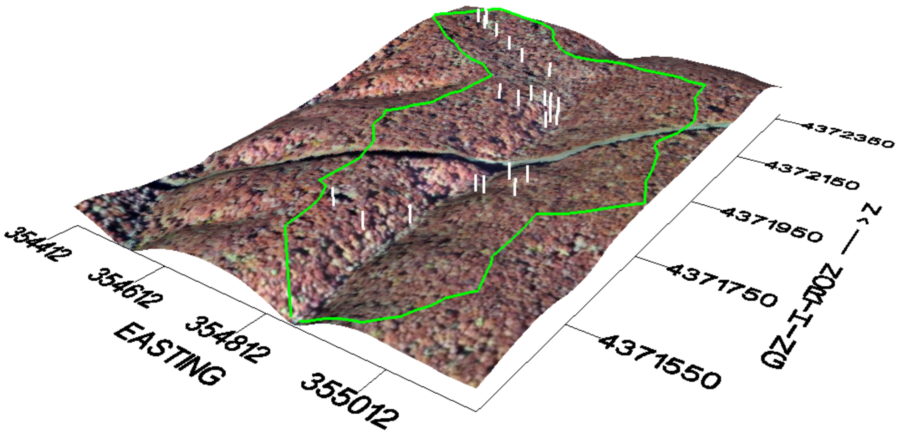


Digital Elevation Models Resolutions

- **Interpolate** DEMS from photogrammetric and LIDAR spot elevations at a **range** of **resolutions**:
- **0.5 m** to **5 m** DEMs in **0.5 m increments** (e.g. 0.5m, 1m, 1.5m, 2m, 2.5m, 3m, 3.5m, 4m etc.)
- **5 m** to **30 m** DEMs in **1.25 m increments** (e.g. 5m, 6.25m, 7.5m, 8.75m, 10m, 11.25m etc.)

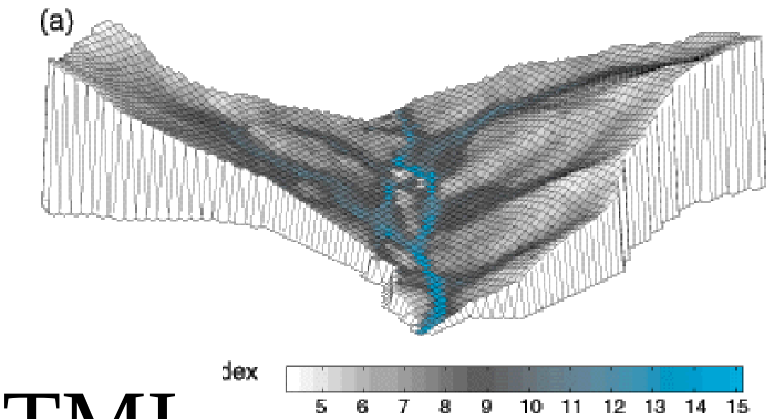
- For DEMs with cells **smaller** the field **sampling size**, use **kernel averaging** to adjust the scale (e.g. 0.5m DEM using 3x3, 5x5, 7x7, 9x9, 11x11 etc.)

Comparing Soil Moisture and TMI

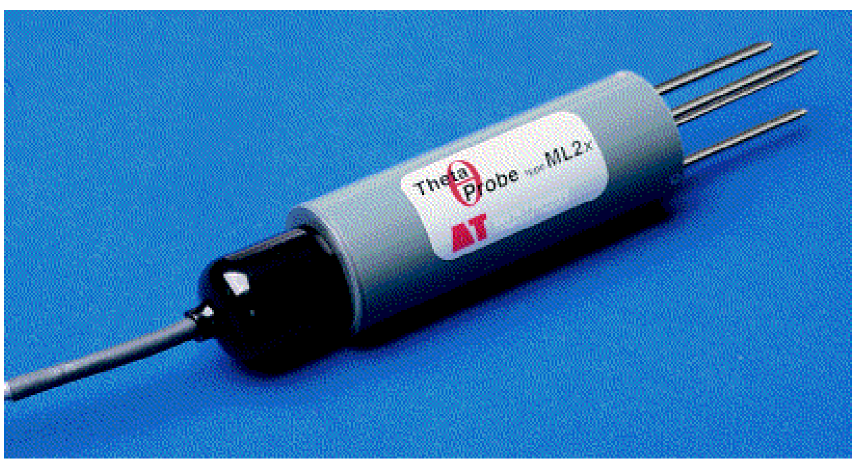


Sites

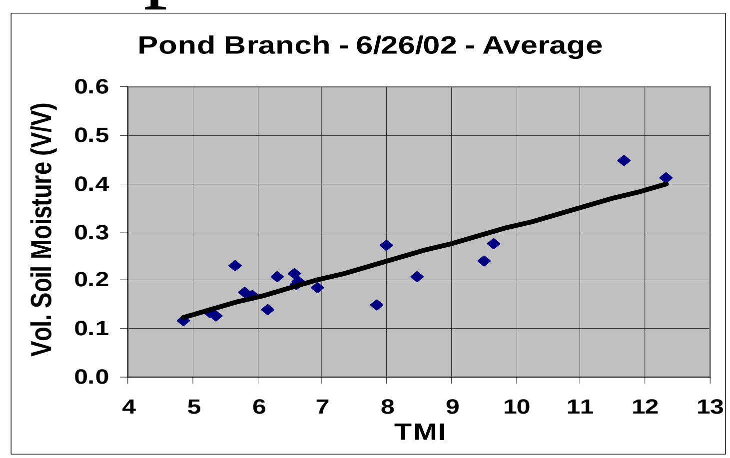
TMI



Theta



Compare



A Subset of Results

- From the **sampling period**, I have selected **three representative days** for wet, average and dry conditions:

Wet – May 29/30

Avg. – June 26/28

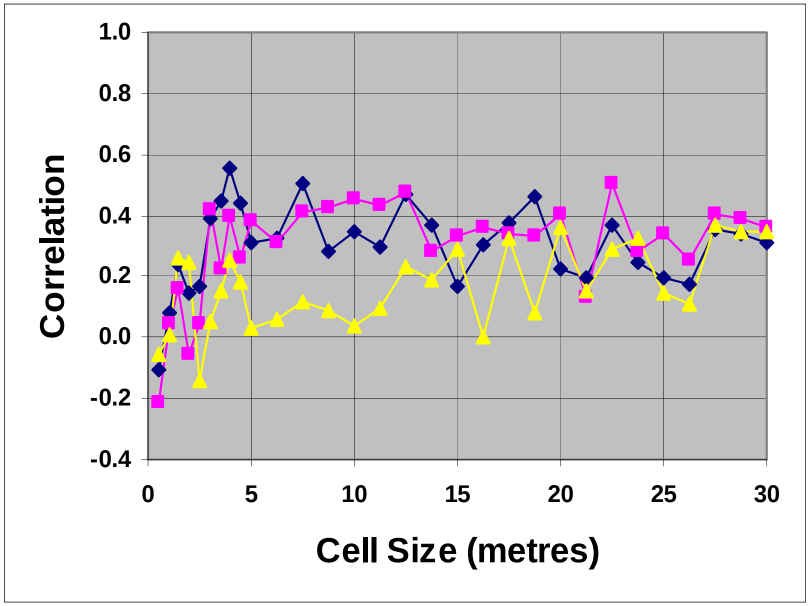
Dry – August 22

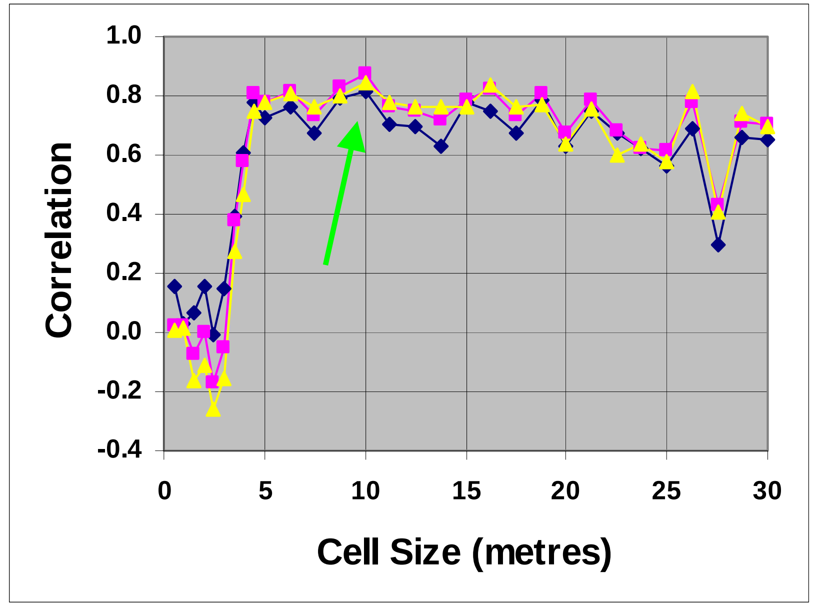
- **LIDAR** and **Photogrammetric DEMs**
- **Cell Sizes** and a range of **Kernel Sizes** for **0.5 m** DEMs

Cell Size

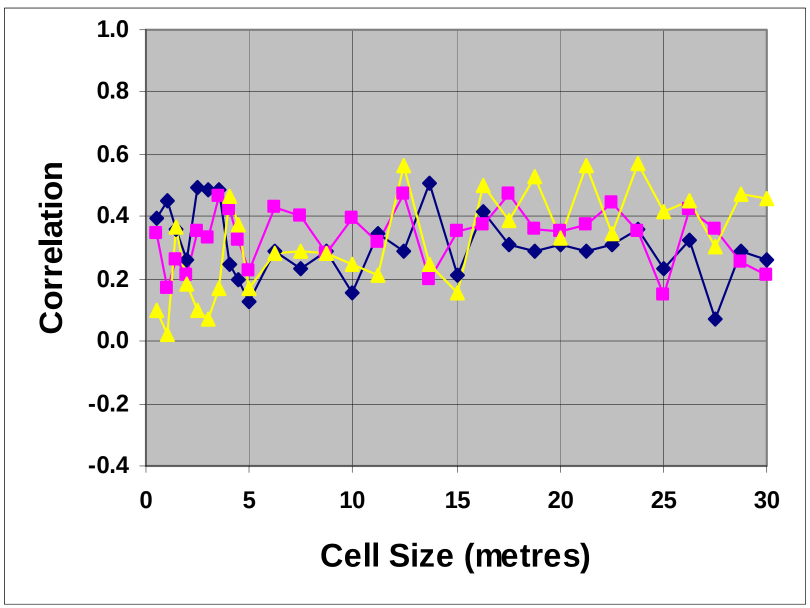
Glyndon | Pond Branch

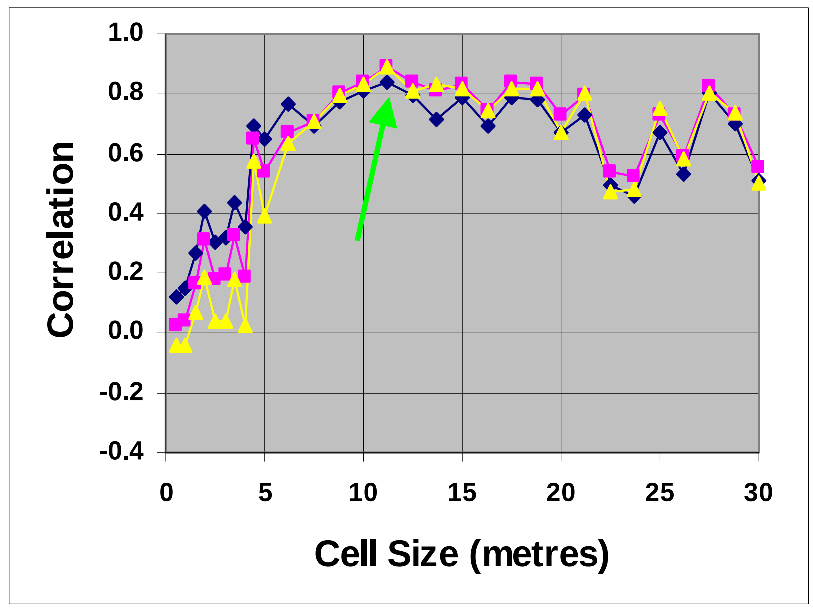
LIDAR





Photogram.

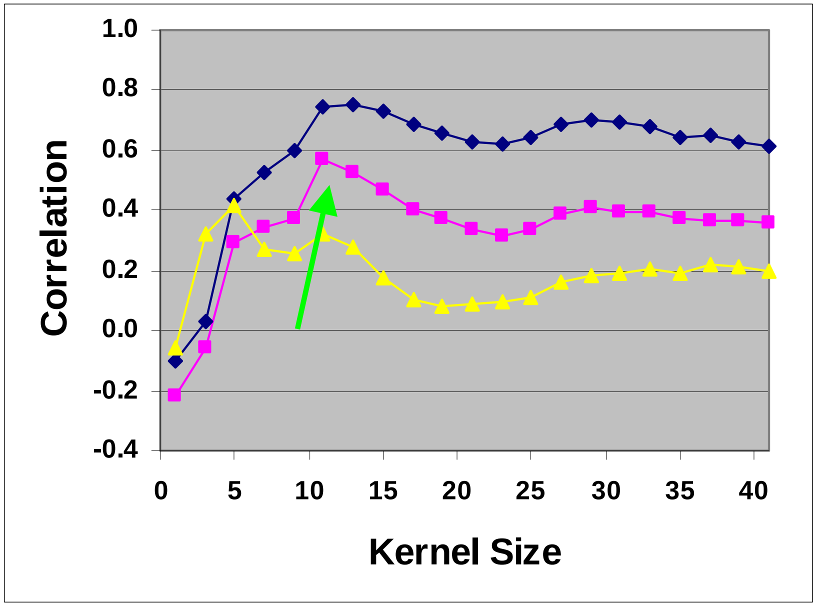


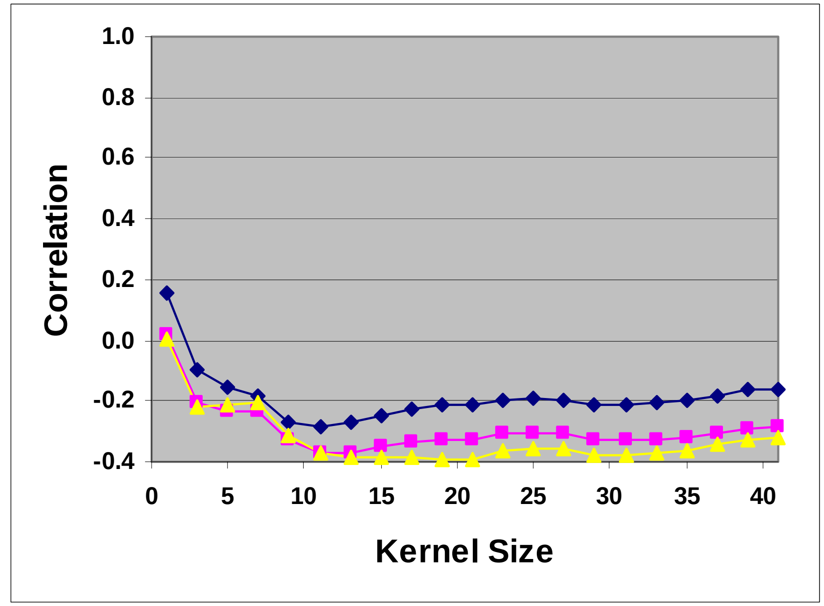


Kernel Size

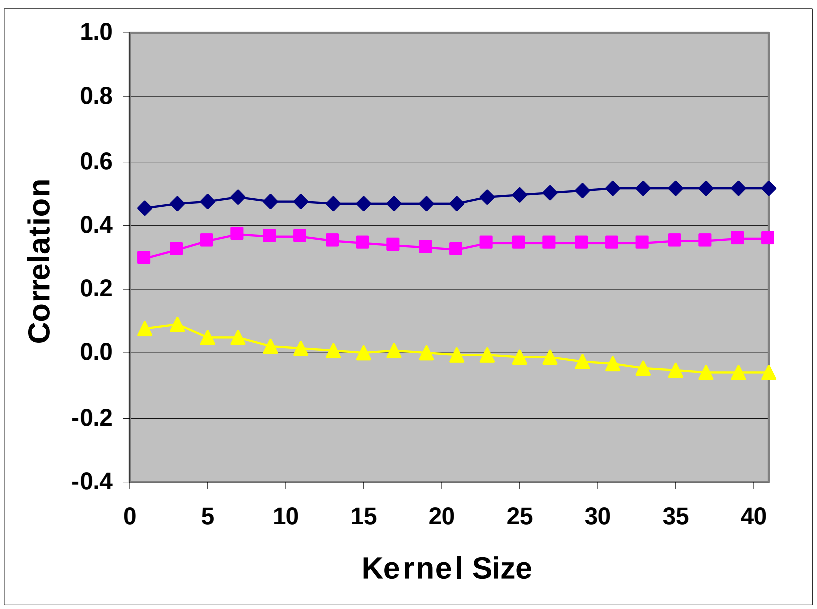
Glyndon — Pond Branch

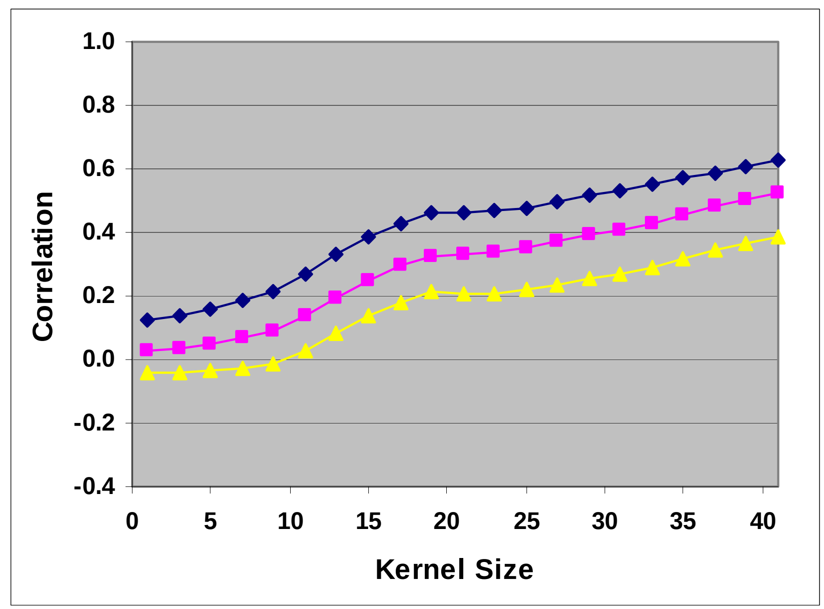
LIDAR



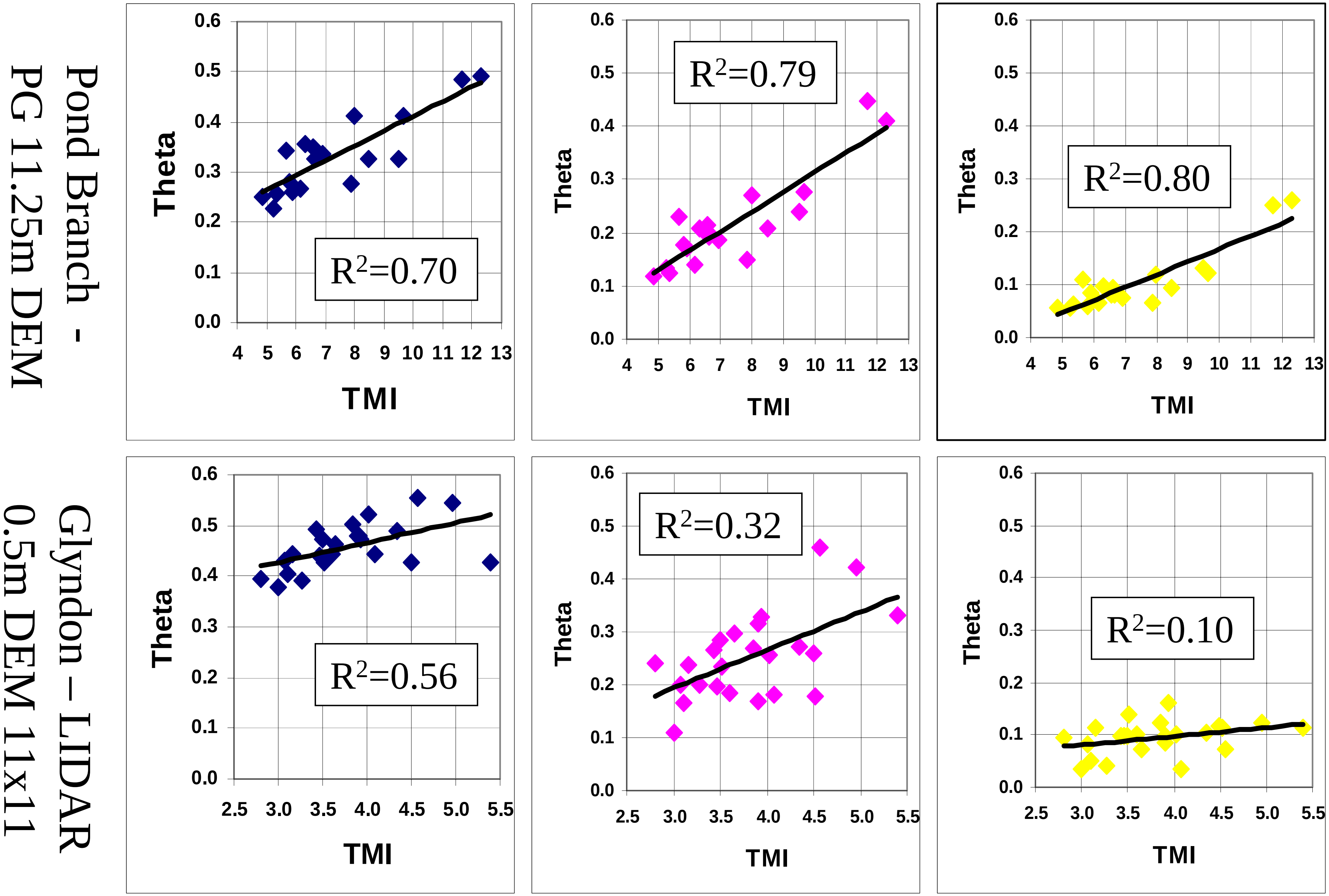


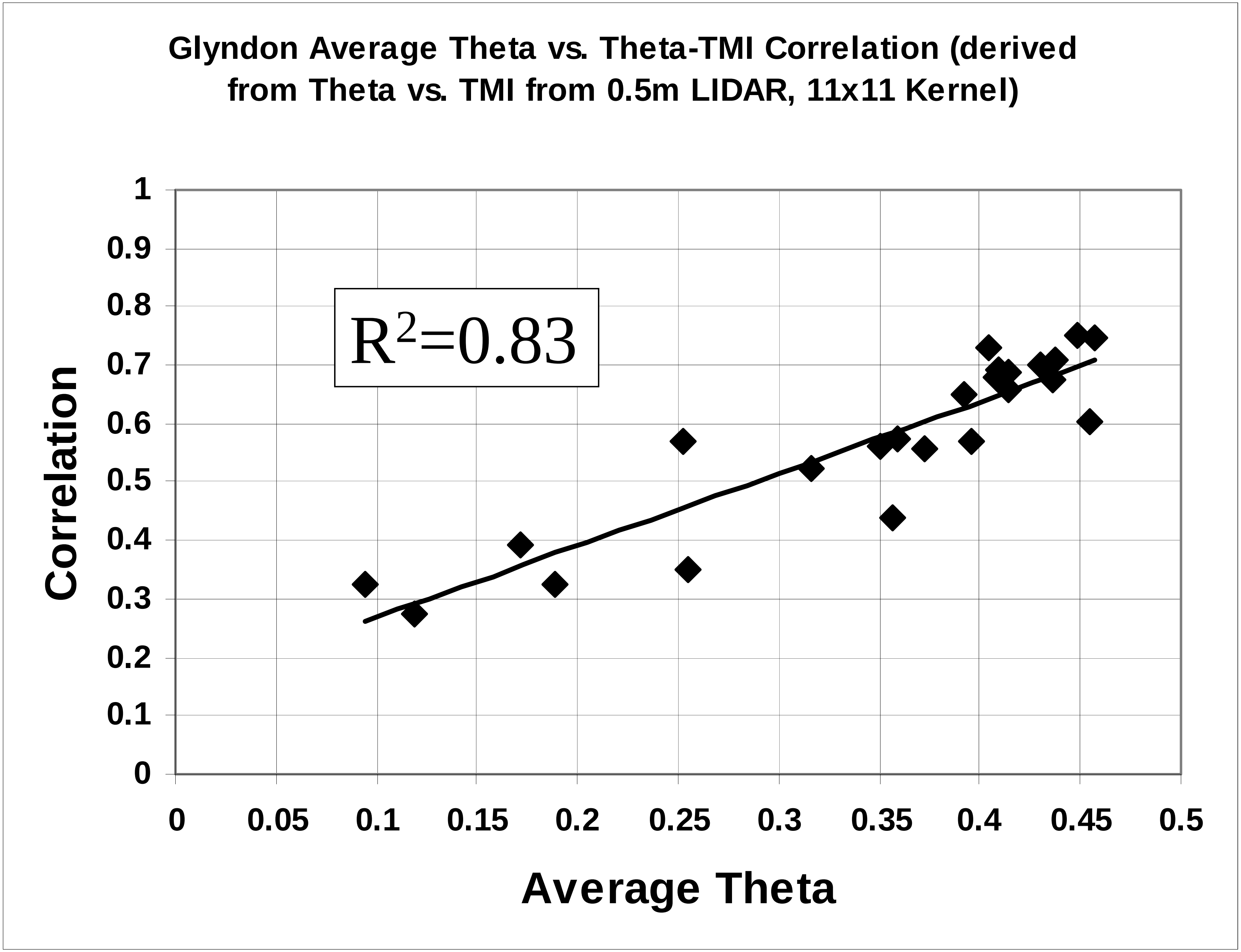
Photogram.

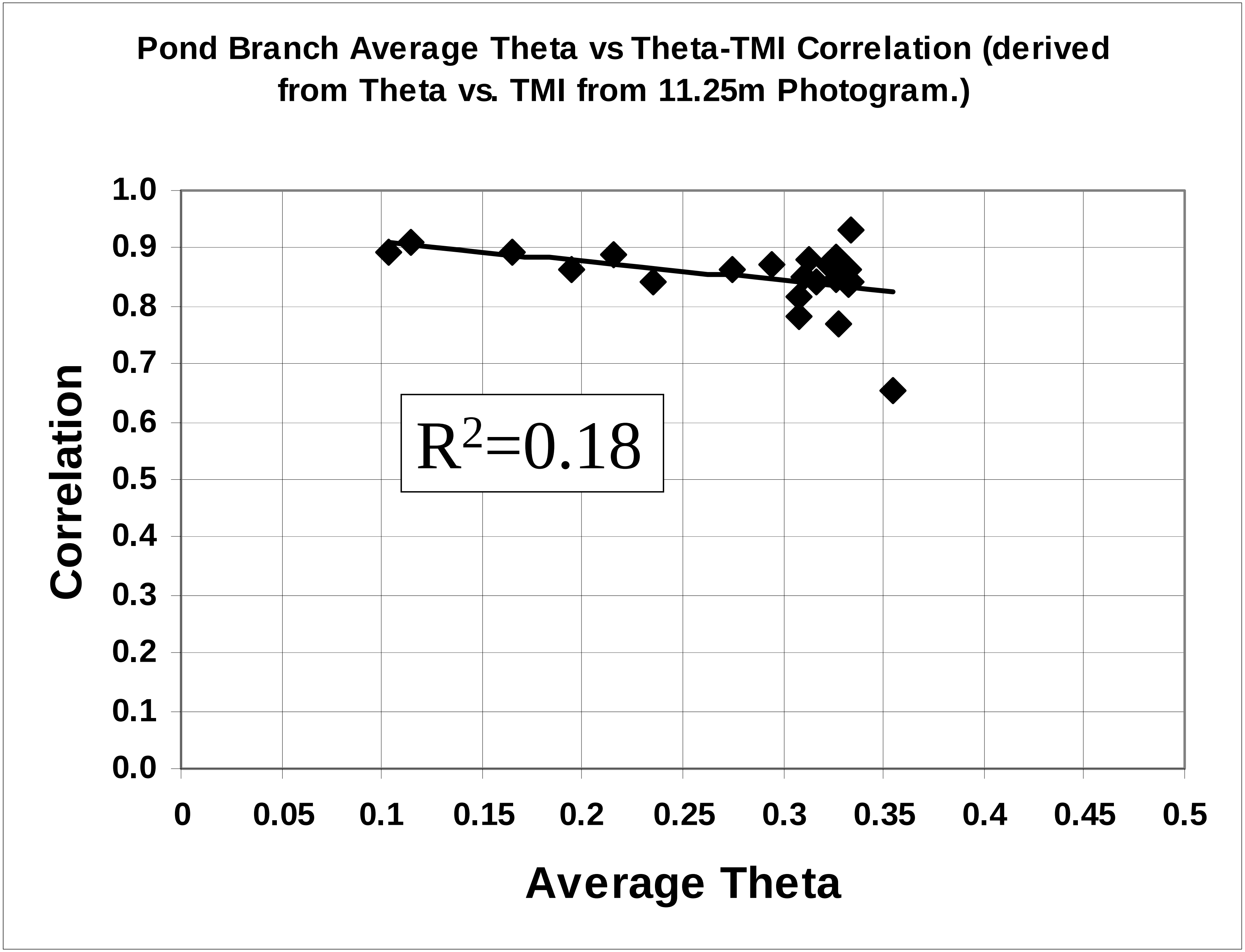




Wet – May 29/30 | Avg. – June 26/28 | Dry – August 22




Glyndon Average Theta vs. Theta-TMI Correlation (derived from Theta vs. TMI from 0.5m LIDAR, 11x11 Kernel)
R2=0.83
Correlation
Average Theta
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5


Pond Branch Average Theta vs Theta-TMI Correlation (derived from Theta vs. TMI from 11.25m Photogram.)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Correlation
R2=0.18
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Average Theta