Lawrence E. Band, Pitma Patterson, Ramakrishna Nemani and Steven W. Running

# Forest ecosystem processes at the watershed scale: incorporating hill slope hydrology

**Uttam Babu Shrestha**
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# Outline

## Introduction

- RHESSys (Regional hydro ecological Simulation System
- FOREST-BGC (Forest ecosystem Process Model)
- TOPMODEL (Hydrological Model)

## Model implementation on field site
## Simulation results
## Discussion and Conclusion

# Introduction

The spatial patterns of forest ecological and hydrological fluxes and storages in hilly terrain are largely dependent on topography

**Broad Objective:**

To investigate the distributed feedbacks between ecological and hydrological fluxes and storage processes at the watershed.

**Specific Objectives:**

•To calculate forest evapotranspiration (**ET**), canopy net photosynthesis **(PSN**).

•To compute carbon and water budgets.

•To observe the impact of lateral water redistribution processes (subsurface water flow) and the resulting patterns of available soil water on **ET** and **PSN**.

•To compare the results of TOPMODEL and Bucket Model.

# Introduction

**Forest Ecosystem Processes Model (FOREST-BGC)**     **Hydrological Model TOPMODEL**

RS/GIS FRAMEWORK

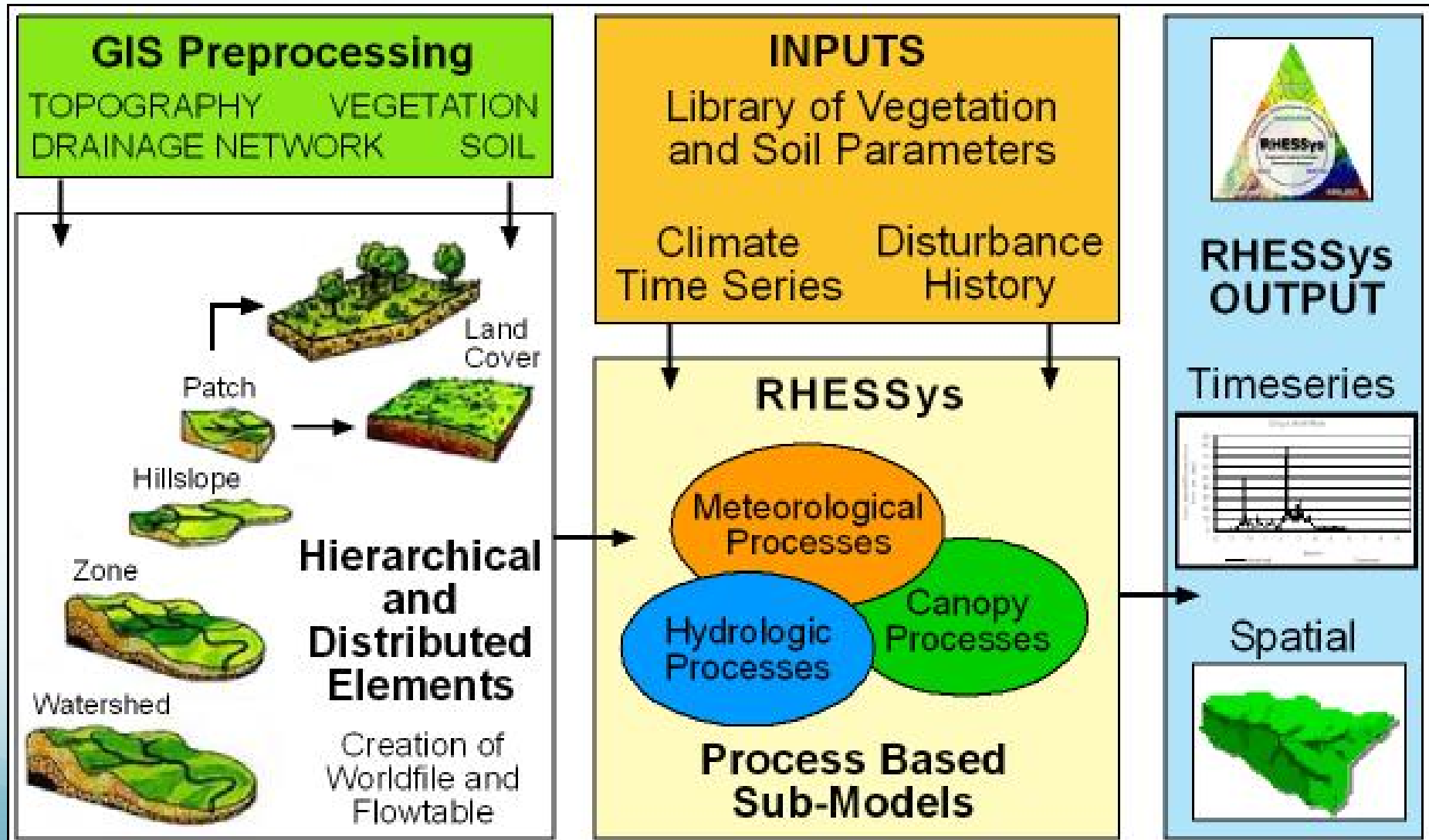**Regional Hydro Ecological Simulation System**



**Automate the parameterization and simulate ecological and hydrological fluxes in watershed by combining information drawn from digital terrain data, remote sensing, and digitized soil maps**

# What is RHESSys ?

- GIS-based, hydro-ecological modeling framework designed to simulate carbon, water, and nutrient fluxes at landscape level.

- Functional or statistical approach to model spatio-temporal interaction between climate and vegetation.

- Allows the use of remote sensing and GIS for spatially distributed parameterization.

- Combines both a set of physically based process models and a methodology for partitioning and parameterizing the landscape.

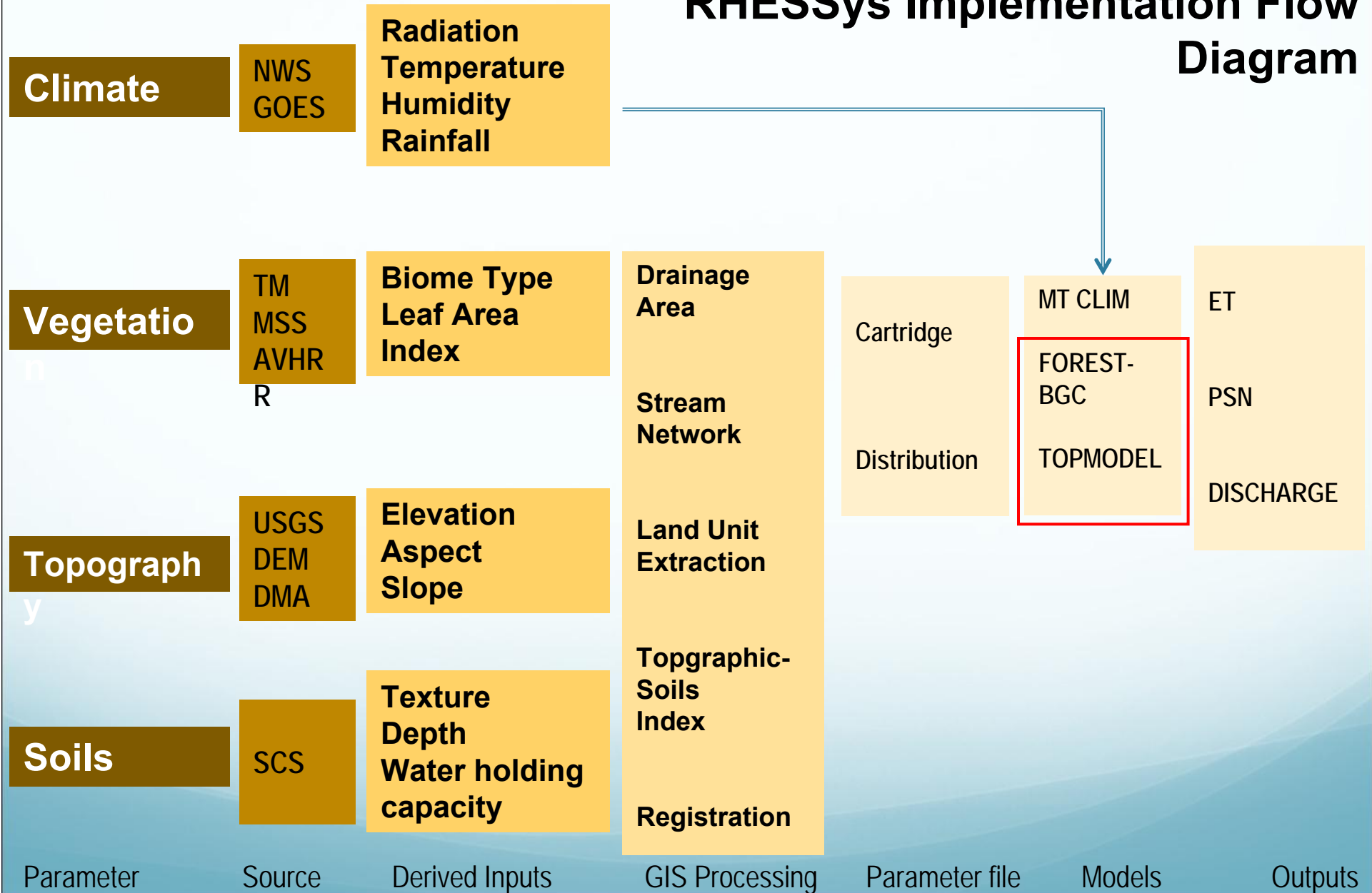- It has Structural, Parameterization, Simulation, Visualization components.
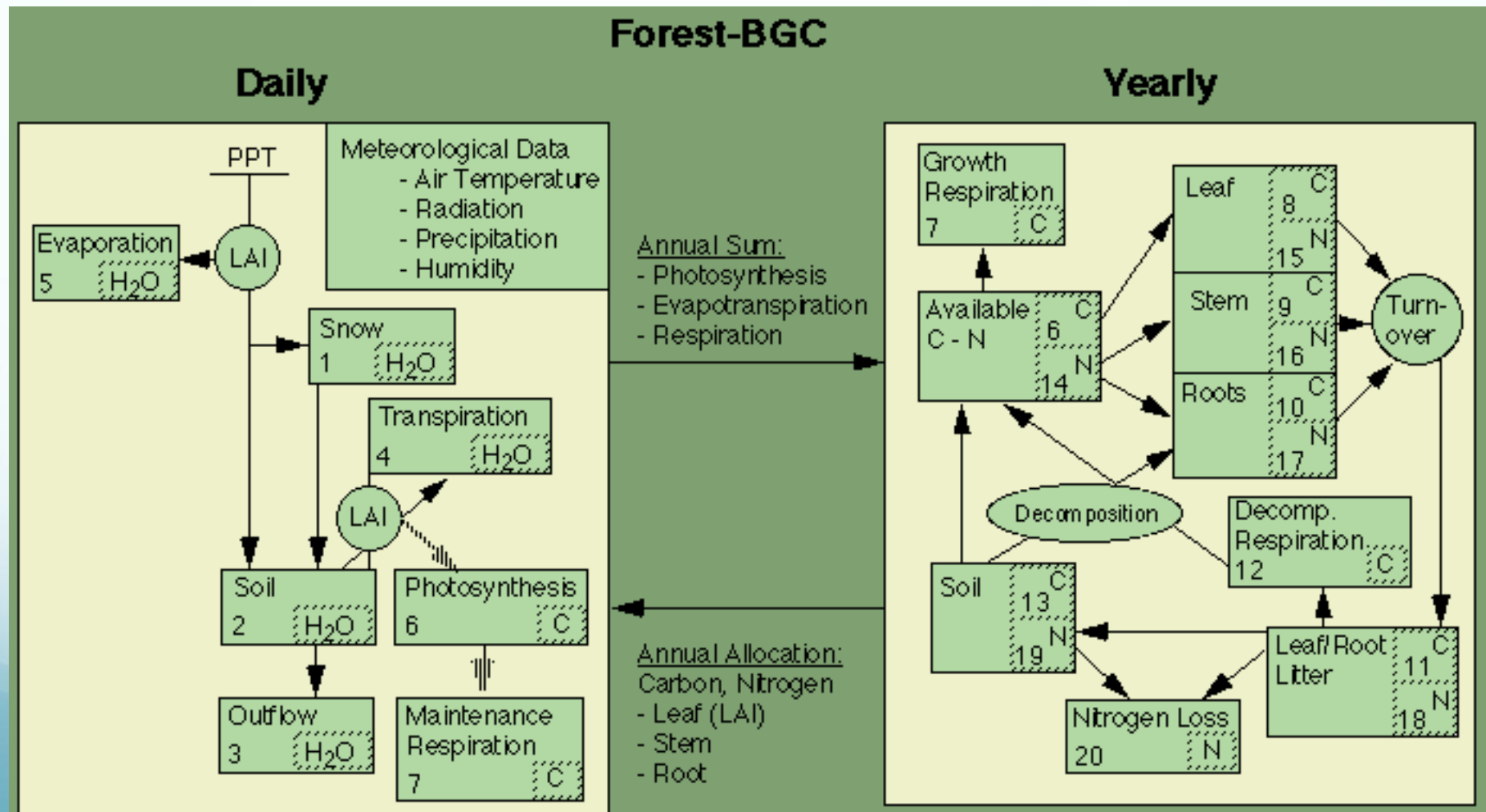
# RHESSys Framework

# What is RHESSys ?

## RHESSys Implementation Flow Diagram

| Parameter | Source | Derived Inputs | GIS Processing | Parameter file | Models | Outputs |
|-----------|--------|----------------|----------------|----------------|--------|---------|
| **Climate** | NWS GOES | **Radiation Temperature Humidity Rainfall** | | | | |
| **Vegetation** | TM MSS AVHRR | **Biome Type Leaf Area Index** | **Drainage Area** | Cartridge | MT CLIM | ET |
| | | | **Stream Network** | | FOREST-BGC | PSN |
| **Topography** | USGS DEM DMA | **Elevation Aspect Slope** | **Land Unit Extraction** | Distribution | TOPMODEL | DISCHARGE |
| **Soils** | SCS | **Texture Depth Water holding capacity** | **Topgraphic-Soils Index**<br><br>**Registration** | | | |

# Forest Ecosystem Processes Model (FOREST-BGC)

• Stand level simulation model of carbon, water and nitrogen budgets.

• Calculate forest ET and PSN.



Forest-BGC

Coughlan 1994

# Hydrological Model (TOPMODEL)

**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.

David Tenenbaum – EEOS 383 – UMass Boston

•Physically based, distributed watershed hydrological model.

•Simulate explicit groundwater/surface water interactions by predicting the movement of the water table.

•Use surface topography and soil information to simulate hydrologic fluxes of water (infiltration-excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration, and channel routing) through a watershed.

•Locations with large upslope contribution areas and lower slope maintain higher TMI (soil moisture or soil water) than location with smaller contribution areas and steeper slope. Soil water affect transpiration and productivity.

# TOPMODEL vs. BUCKET Model

Bucket Model is used for soil water budget

**Net Input to Soil Water Storage =**

$$\partial S_w = P - (I_c + I_l) + M - \mathrm{ET} - D$$

Where,
$\Delta S_w$ = change in soil water
$D$ = deep percolation
$M$ = snow melt
$P$ = precipitation
$I_c$ = canopy interception
$I_l$ = litter interception
$ET$ = Evapotranspitation

$S_w$ (Soil Water) > available soil water capacity (AWC, mm),  **runoff**
$S_w$ < = AWC,  **no runoff**

- Hydrology is restricted to vertical exchange
- Doesn't account soil water drainage
- Appropriate for landscape without gradient

Topmodel is used to calculate local soil water deficit

$$ln(aT_e/(T_i \tan \beta))$$

Where,
a = upslope contributing area
$\beta$ = slope or local gradient
$T_i$ = local soil transitivity
$T_c$ = transitivity index of catchment

$$S = S' + m\lambda - m \, ln\left(\frac{aT_e}{T_i \tan \beta}\right)$$

Where,
S = measured as a depth below saturation
S'=hillslope mean soil water deficit
$\lambda$ = mean value of TMI
m = soil specific parameter
$T_c$ = transitivity index of catchment

- Appropriate for landscape with gradient
- Account for soil water drainage and soil transitivity (redistribution of soil water)

# Advantages of including TOPMODEL in RHESSys

• Provides lateral subsurface drainage of soil water.

• Provides realistic outflow hydrographs (high degree of physical realism) in watershed than **bucket model** (depletion of soil water is not incorporated).

• Allow the representation of important topographic controls on canopy processes and forest growth through the zonation of soil moisture deficits.

• Help to maintain the observed assemblages of terrain, soil, and vegetation.

• Area with larger **a** and lower **tanβ** has higher value of $S_w$ that has impact on transpiration and productivity.

• This approach is very complementary to the conceptual level of FOREST-BGC model.

# Field Site

Soup Creek
Watershed on West
slope of Swan
Mountain Range,
Montana, USA



**Precipitation:** 850-2000mm, abundant snow prevents soils from freezing during winter.

**Soil:** Gravelly silty loam to extra gravelly silty loam or extra gravelly coarse sandy loam

**Extreme event:** 1988 Extreme drought (No data on snow cover)

**Vegetation:** Douglas fir *(Pseudotsuga menzeisii), red cedar (Thuja plicata), larch (Larix occidentalis), lodgepole pine (Pinus eontorta), subalpine fir (Abies lasiocarpa)* and engelmann spruce *(Picea englemannii)*. **Crown Cover:** 30- >70%

**Hydrology:** dependent on accumulated distributed of snowpack.

# Data Parameterization and Simulation

**Meteorological data:** (Temperature (Max and Min), Precipitation (Daily), and snow

**DEM:** (30m interpolated from the digitized contours of the Thunderbolt Mountain 7.5 min USGS topographic quadrangle)
= delineate watershed
= compute topographic soil moisture index (TMI)

**Digitized soil maps**
= topographic soils index

**Leaf Area Index (LAI):** estimated by using an empirical correlation of Thematic Mapper Bands 3, 4 and 5 (630-690nm, 760-900nm, 1550-1750nm resp.) with field estimated LAI

**Rooting zone ~ soil depth** (max 2m)
= calculate soil water storage in root zone for prediction of soil water potential $\Psi_{soil}$ & leaf water potential $\Psi_{leaf}$

# Simulation results

**Evaporation Transpiration (ET)**
*Bucket Model*
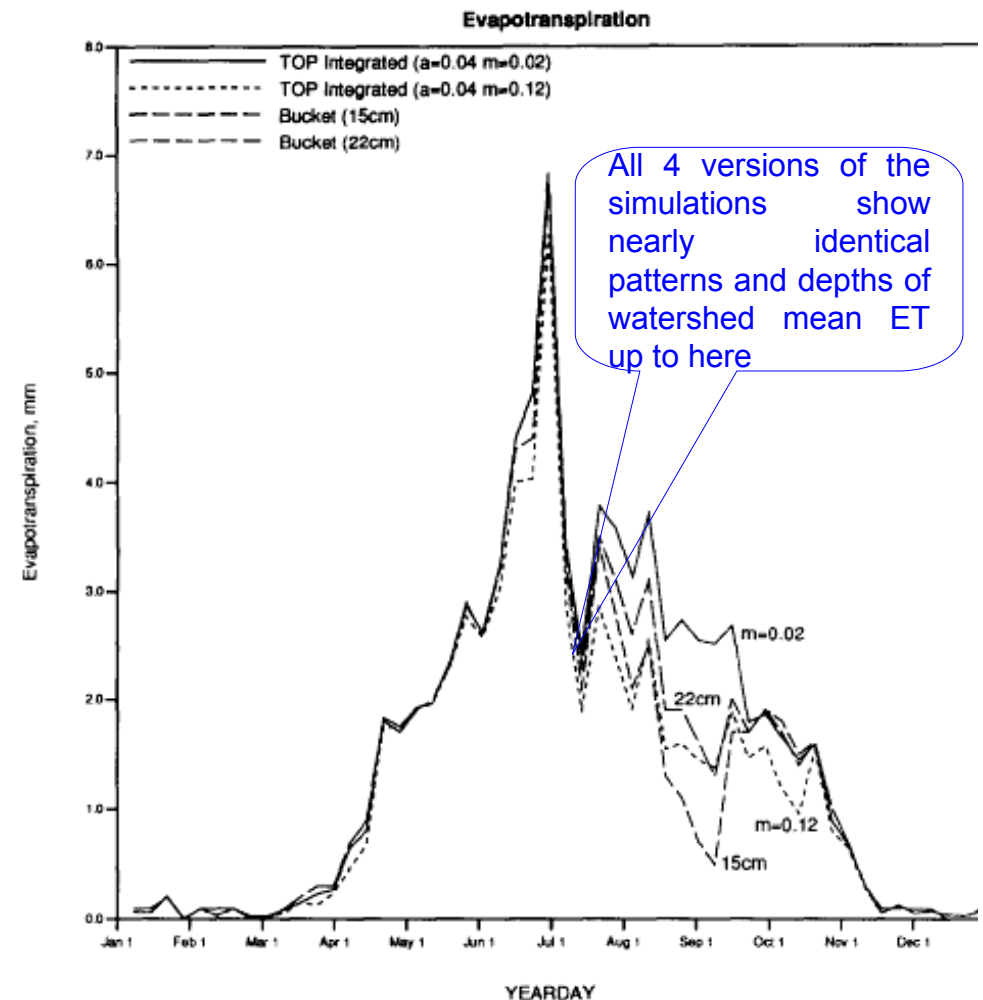•The 15 cm bucket shows more severe moisture limitations than the 22 cm bucket.

•No spatial variation of soil moisture within hillslopes.

•The moisture limited **ET** continues through September, when rainfall adequately recharges the soil.

*Topmodel*
•Redistributing soil water effect on topography can be seen in the variance of watershed ET.

•The lower interval values drain very rapidly (expand moisture stress and increase S') while the higher values remain saturated.



Evapotranspiration

All 4 versions of the simulations show nearly identical patterns and depths of watershed mean ET up to here

# Cumulative ET for different topography-soils indices simulated for a lower elevation, south facing slope of Soup Creek

•The higher index value zones maintain a high level of ET through the drought and contribute an annual ET ~ 3 times ET of the lower index values.

•The spread of ET is determined by soil water recharge and site LAI (above 6.5 soil water isn't limiting factor).

•Soil water redistribution prevents the impact of drought without the significant expansion of the saturation runoff pathway that will drain the hillslope soil water.

•In dry month, ET with lower *m* by TOPMODEL is 2X > than higher *m* and the 22cm bucket and ~6X than the 15cm bucket.



Evapotranspiration

interval 2.5
interval 4.5
interval 6.5
interval 8.5
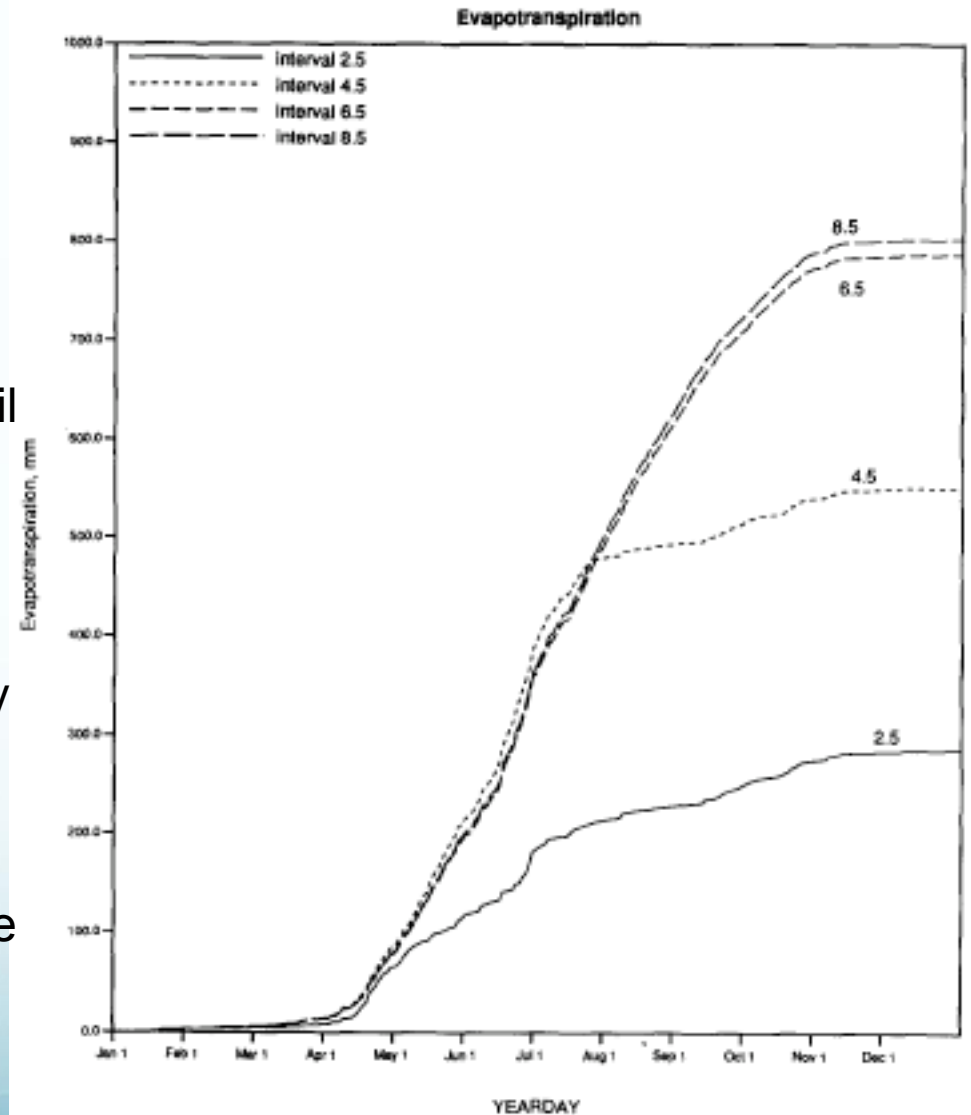
# Sensitivity of annual ET and watershed runoff to the parameter m

•Distribution of soil moisture increases with m, the increase in run off production is balanced by decrease in average ET.

•Partition of precipitation in ET and run off production is very sensitive to the representation of soil properties and drainage pathways.

•ET is limited by temperature and radiation (north and south facing slope) at higher elevations all the time (June & September).

•Lower elevation have uniform ET in June but variations is high in September.
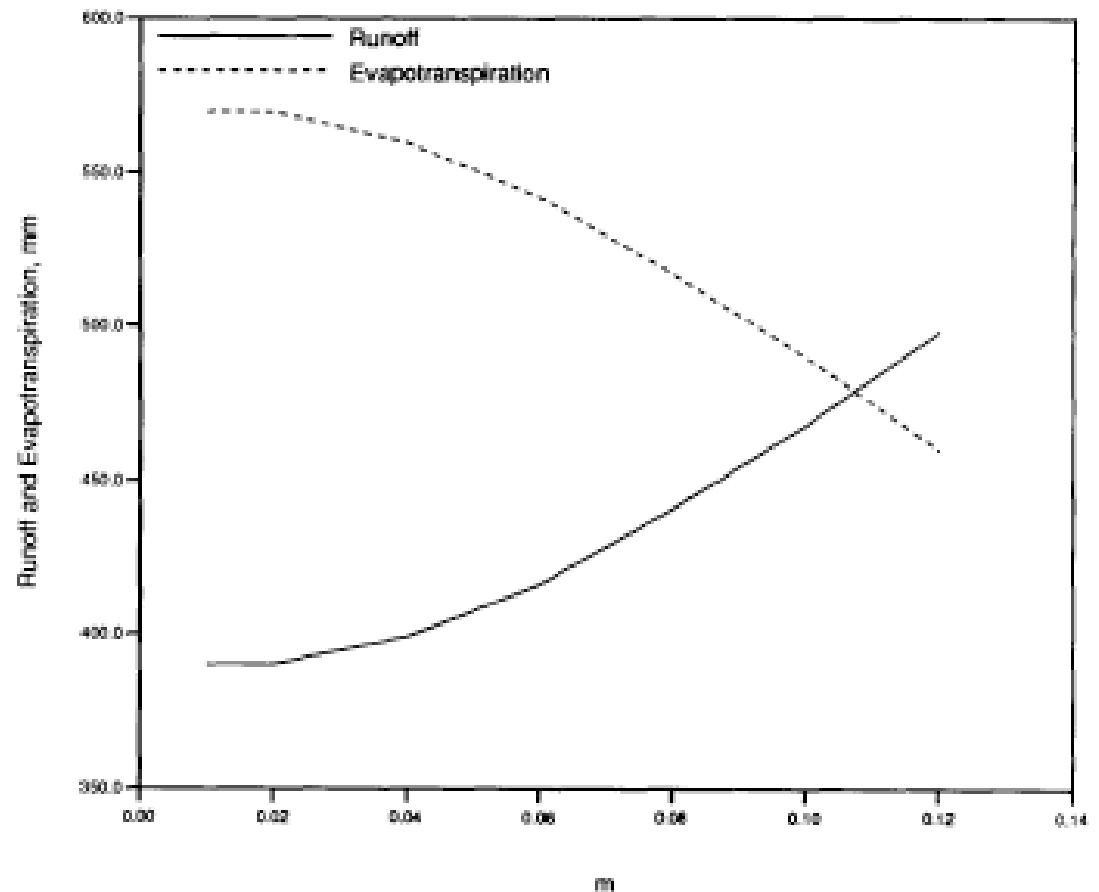
# Impact of drought on ecosystem (Bucket vs. TOPMODEL)

**Bucket Model,**
When bucket soil is depleted, soil water potential $\Psi_{soil}$ & leaf water potential $\Psi_{leaf}$ drop vary rapidly increasing stomatal resistance.

**TOPMODEL,**
Drop is restricted by lower value index intervals that close stomata restricting ET while higher index intervals are not stressed and still freely transpiring as higher value index interval remains saturated.



Leaf Water Potential
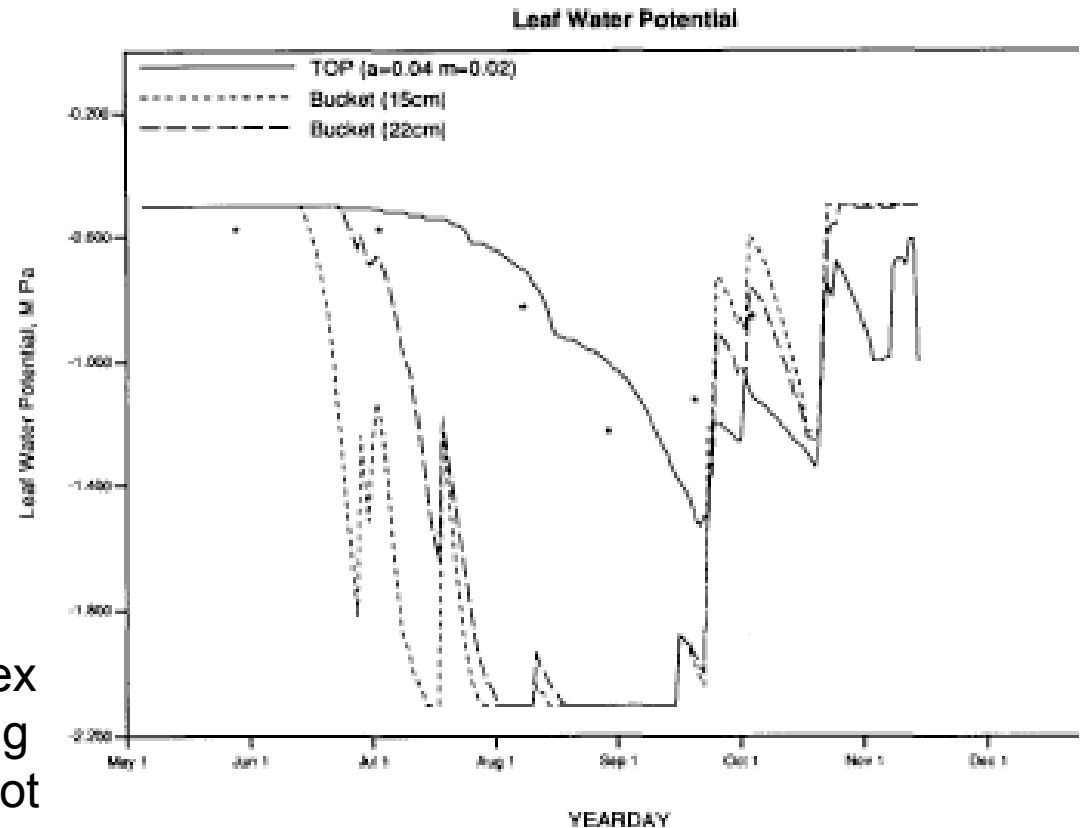
# Simulated discharge differences (Bucket vs. TOPMODEL)

Compare the hydrographs producing each methodology.
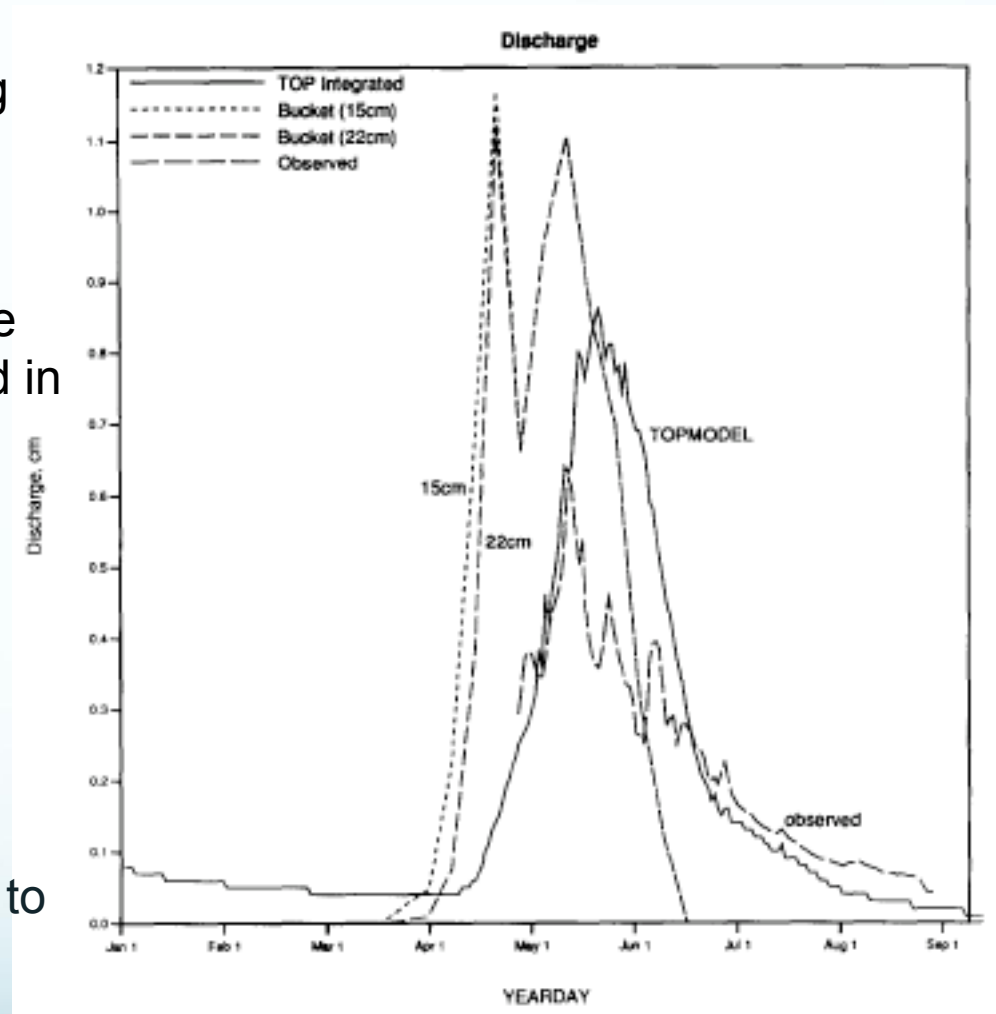
**Bucket Model,**
Soil water is greater than AWC, large outflows, the discharge series spiked in that day.

Soil water is lower than AWC, no outflows in that day, discharge discharge series dropped down.
Unrealistic !

**TOPMODEL**
Observed discharge pattern is close to TOPMODEL

# Seasonal carbon balance trends (Bucket vs. TOPMODEL)

PSN shows the similar pattern with ET in different models and different seasons.

PSN with m= 0.02 greatly exceeds the 15cm and 22cm bucket through the drought period.

When m = 0.12 for greater soil water distribution shows generally lower PSN rates throughout the year but crossover with 15cm bucket during drought.

High PSN rates with peak value on low elevation, south facing hillslopes (June). Reduction and variability of PSN (September) due to low temp. and water stress in low elevation.

Higher elevations have spatially uniform and moderate PSN rates.
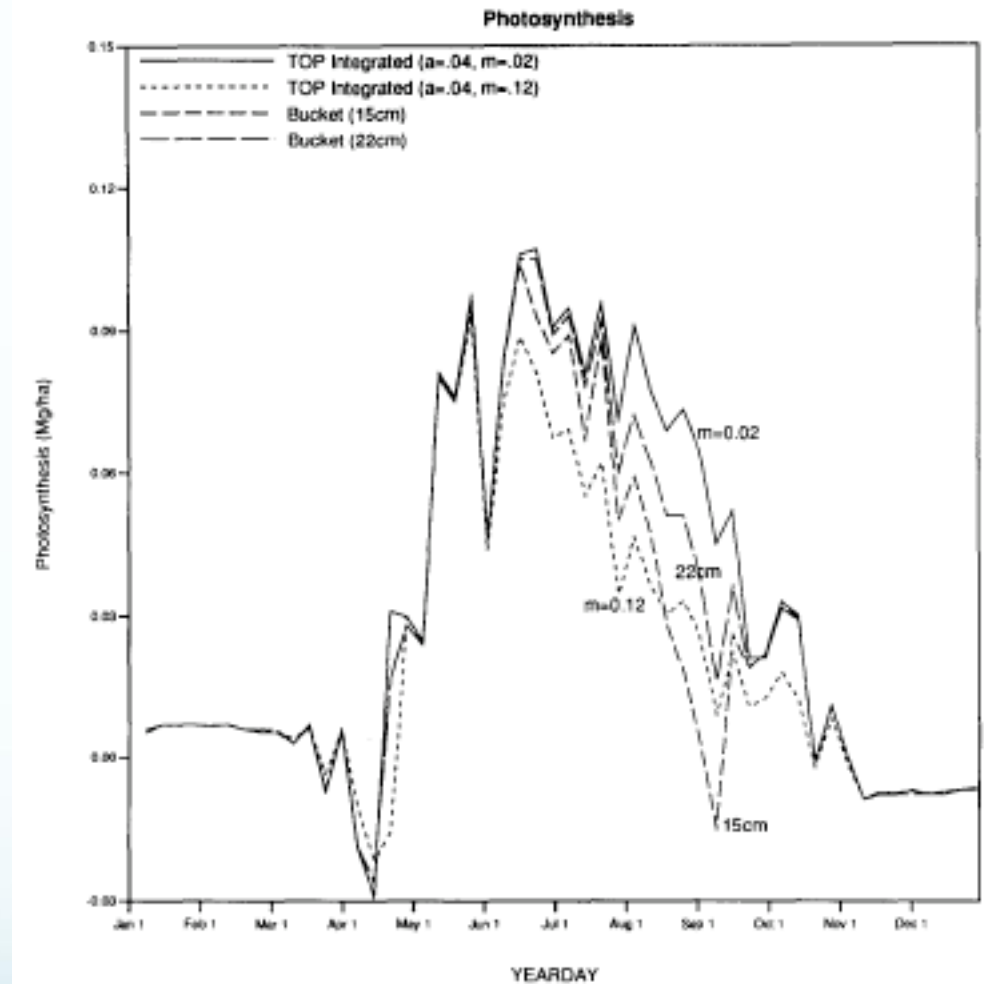
## Discussion and Conclusion

Integration of the distributed soil water strategy (TOPMODEL) with FOREST-BGC yield better results in comparison with limited field data and Bucket model.

Degree of simulated water distribution cause significant differences in ET & PSN.
This is due to a combination of the variable soil moisture patterns that develop within the hillslopes with TOP model along with the throughflow and runoff pathways.

TET and PSN in watershed is highly sensitive to soil moisture and canopy properties.

Combination of soil water recharge and high LAI can buffer the drought impact on areal ET and PSN rates.

Hydrograph produced by the bucket model is not useful for validation against gauged flow. TOPMODEL might not be suitable in flatter terrain.