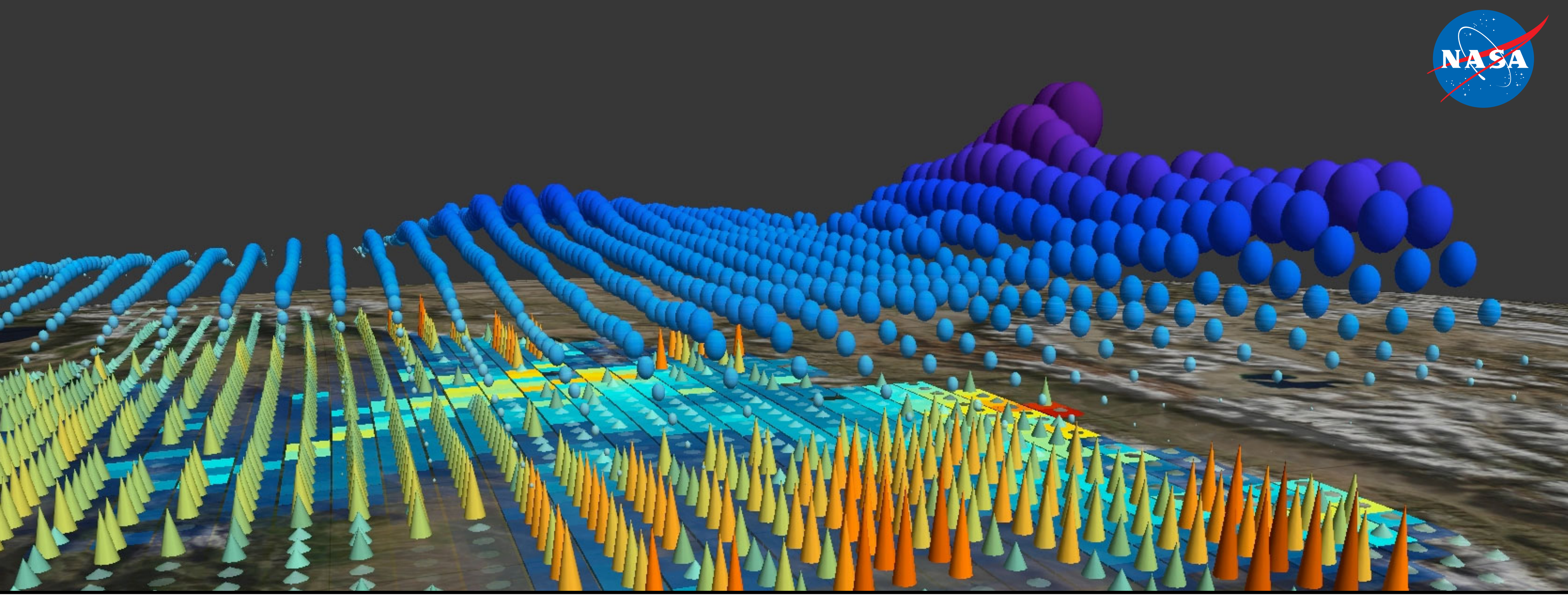


Introduction to Using the VIC Model with NASA Earth Observations

Amita Mehta & Kel Markert (SERVIR Science Coordination Office)

February 15, 22, and March 1, 2018

Image Credit: AralDIF, University of Washington

Training Objective

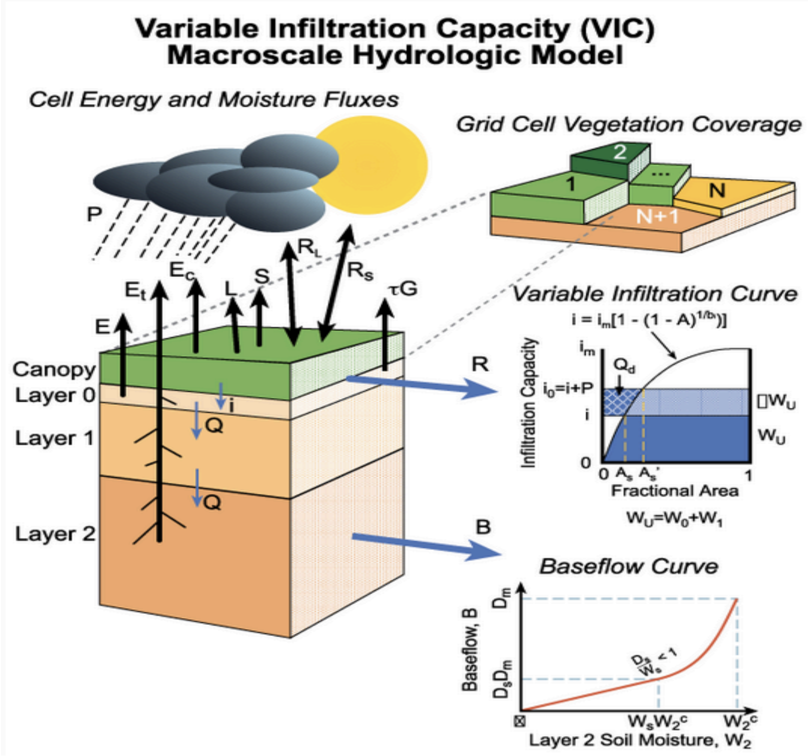
By the end of this training attendees will learn how to:

- download and install the VIC model
- setup VIC for a watershed or river basin using remote sensing data inputs
- analyze the output water resources components

Training Outline

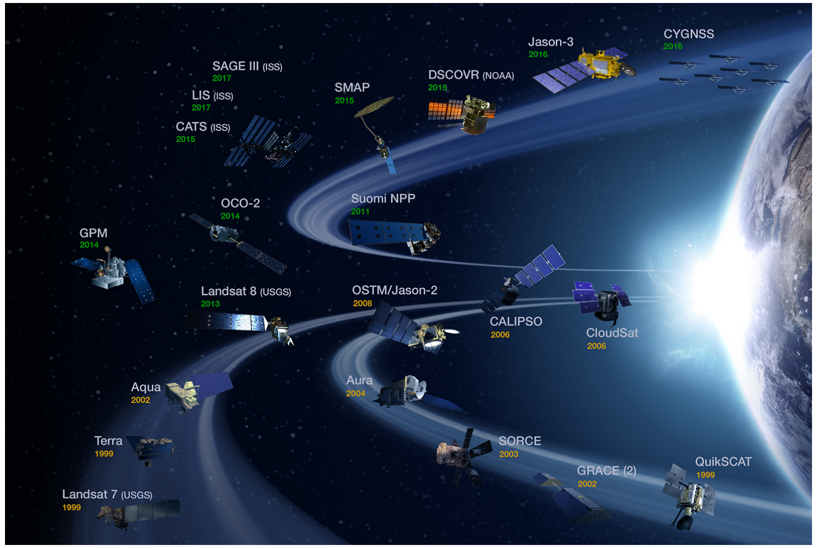
Three Sessions, 09:00-10:00 or 18:00-19:00 EST (UTC-5)

Session 1: Feb 15, 2018



Introduction to the VIC Hydrological Model

Session 2: Feb 22, 2018



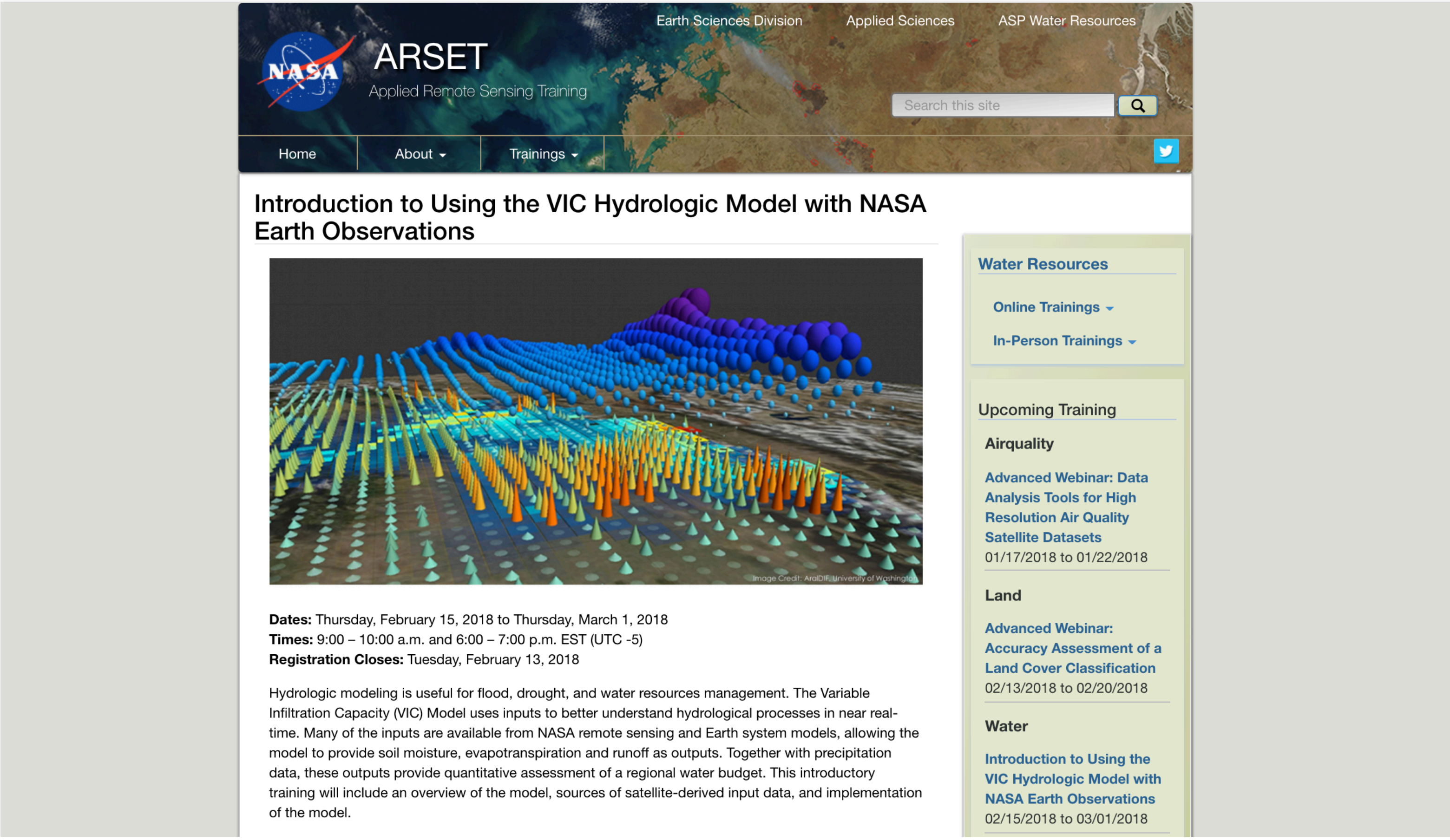
Overview of Remote Sensing-Based Input Data for VIC

Session 3: Mar 1, 2018

Overview of VIC Implementation for a River Basin

Course Material

Webinar presentations and recording are available at:
https://arset.gsfc.nasa.gov/water/webinars/VIC18

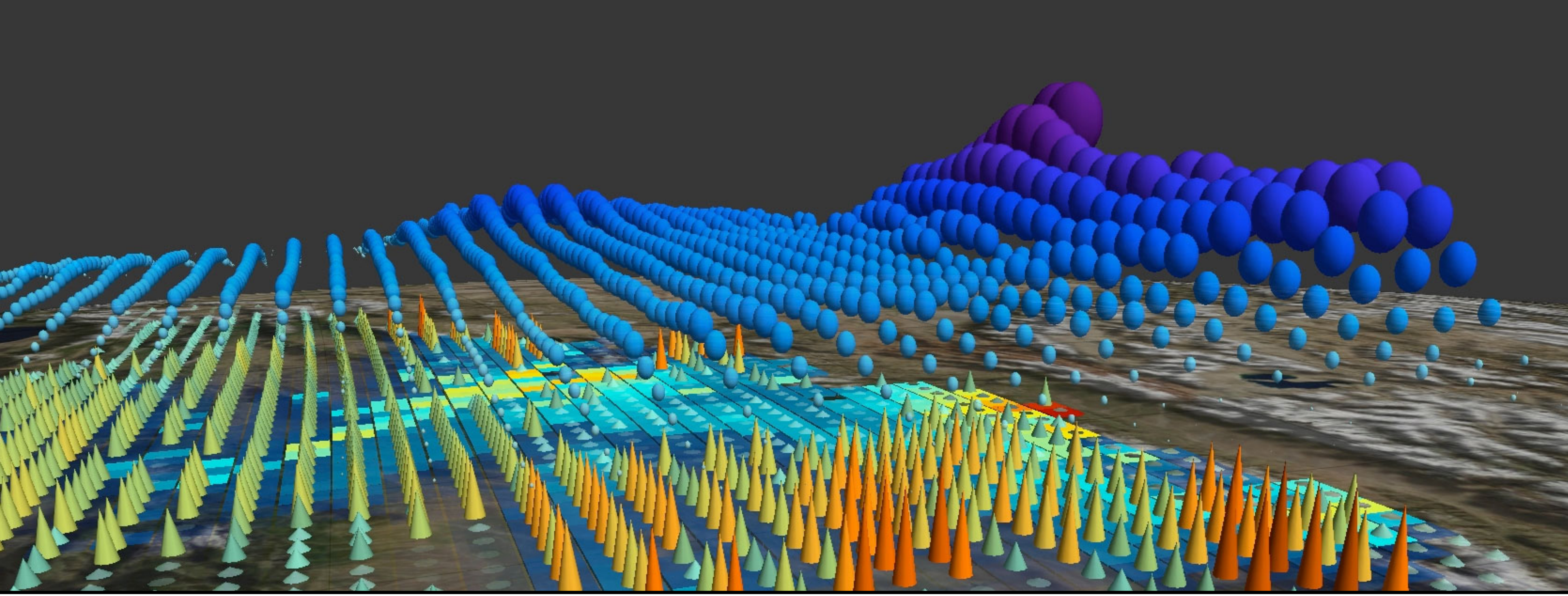


Homework and Certificates

- Homework will be available after Session-3 from https://arset.gsfc.nasa.gov/water/webinars/VIC18
  - **Answers must be submitted via Google Form**
- Certificate of Completion:
  - Attend all webinars
  - Complete homework assignment by the deadline (16 March 2018)
  - You will receive certificates approx. two months after the completion of the course from: marines.martins@ssaihq.com

Session 1 Outline

- Applied Remote Sensing Training (ARSET) Program
- Overview of the VIC Model
  - Features
  - Processes
  - Routing Model



Applied Remote Sensing Training Program (ARSET)

Image Credit: AralDIF, University of Washington

NASA's Applied Remote Sensing Training Program (ARSET)

http://arset.gsfc.nasa.gov/

- **Mission: To empower the global community through remote sensing training**
- Team of 15 NASA scientists, students and other support staff at 3 NASA centers
- Part of NASA's Applied Sciences/Capacity Building Program
- Target audience: policy makers and environmental professionals in the public and private sectors
- Trainings areas:

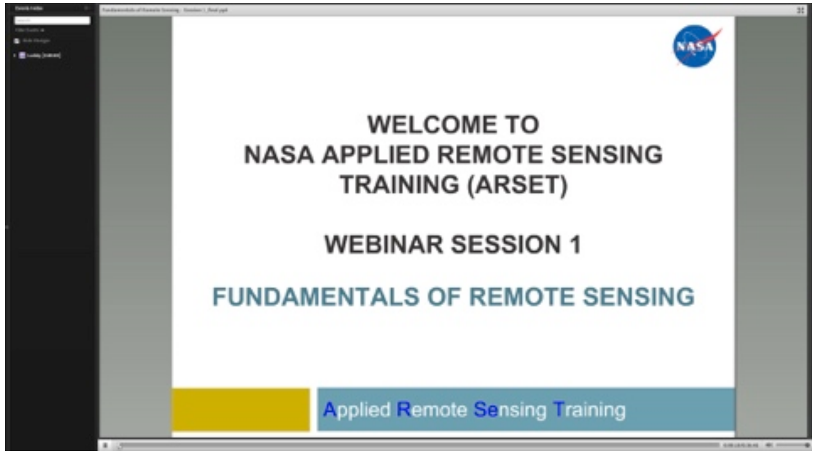
Disasters

Land

Health & Air Quality

Water Resources

ARSET Training Formats



Online

- Live and recorded
- 4-6 hours of instruction
- Advanced training includes image processing

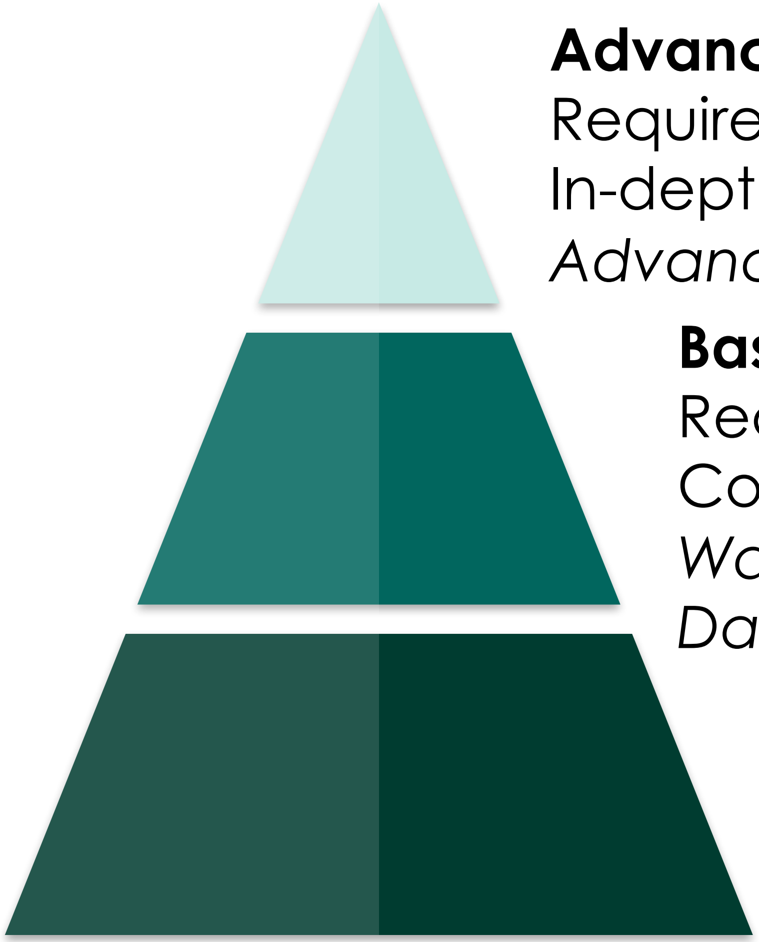
In-Person

- 2-7 days in length
- Held in a computer lab
- Mixture of lectures and exercises
- Locally relevant case studies

Train the Trainers

- Online training and manuals
- For organizations seeking to develop a remote sensing training program

ARSET Training Levels



Advanced (Level 2)
Requires level 1 training or equivalent knowledge
In-depth and highly focused topics
Advanced Webinar: Remote Sensing of Drought

Basic (Level 1)
Requires level 0 training or equivalent knowledge
Covers specific applications
Water Resource Management Using NASA Earth Science Data

Fundamentals (Level 0)
Assumes no prior knowledge of remote sensing
Fundamentals of Remote Sensing

All presentations and exercises are freely available in English & Spanish. Some recordings are delivered in both languages

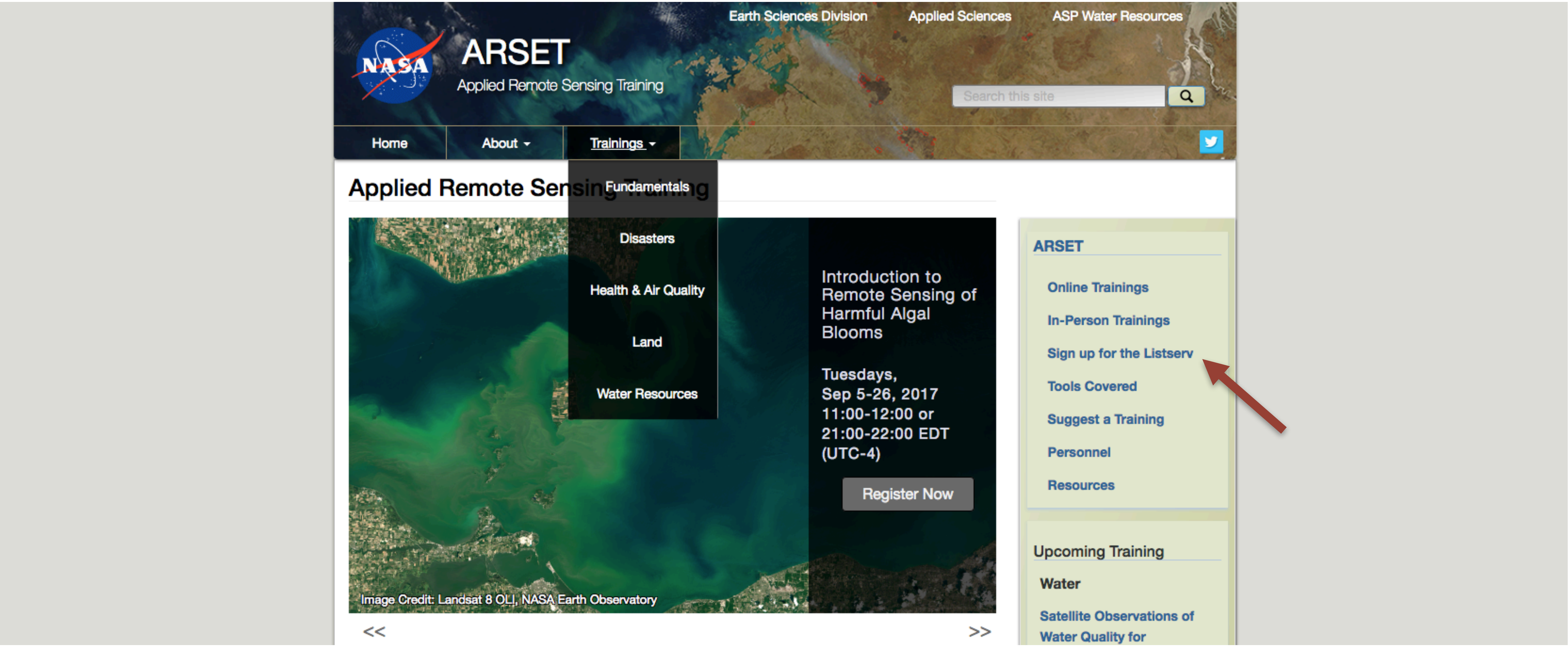
Global Participation

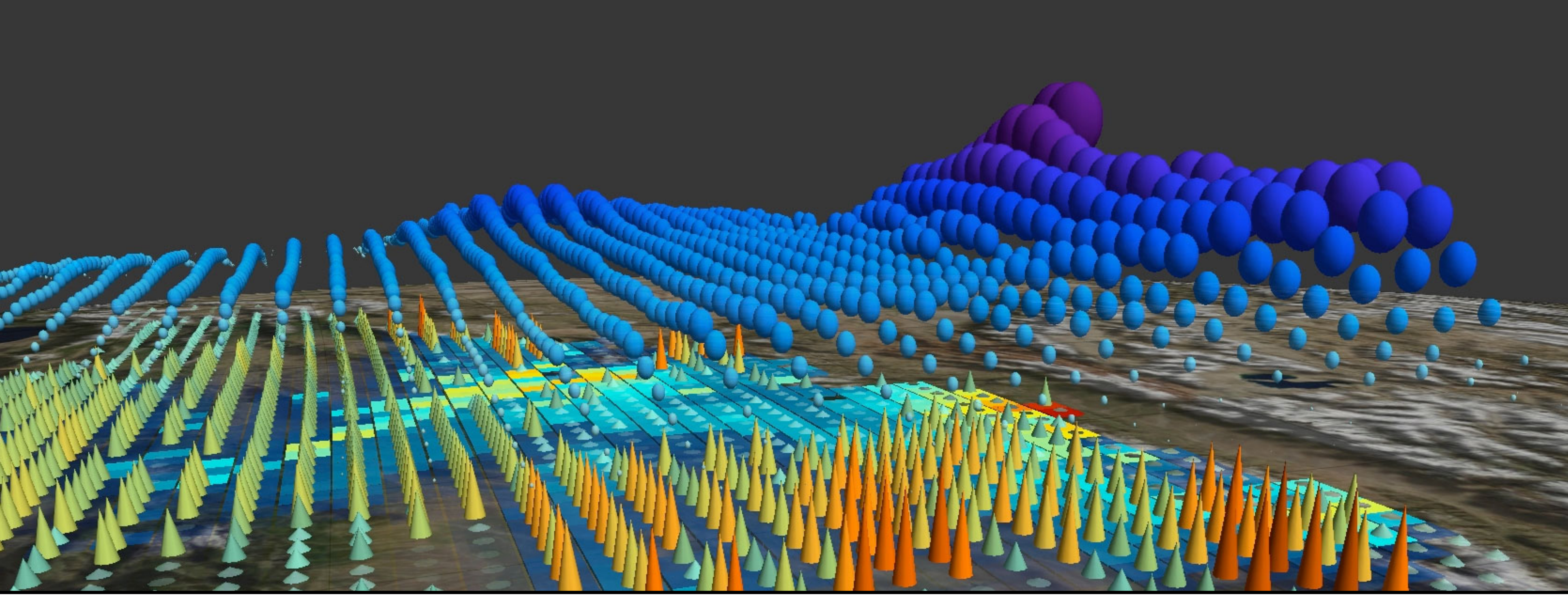
Number of participants (2009-2016)

- 100 trainings (since 2009)
- 13,000+ participants
- 159 countries, all US states
- 3,700+ unique organizations

ARSET Website and ListServ

http://arset.gsfc.nasa.gov/



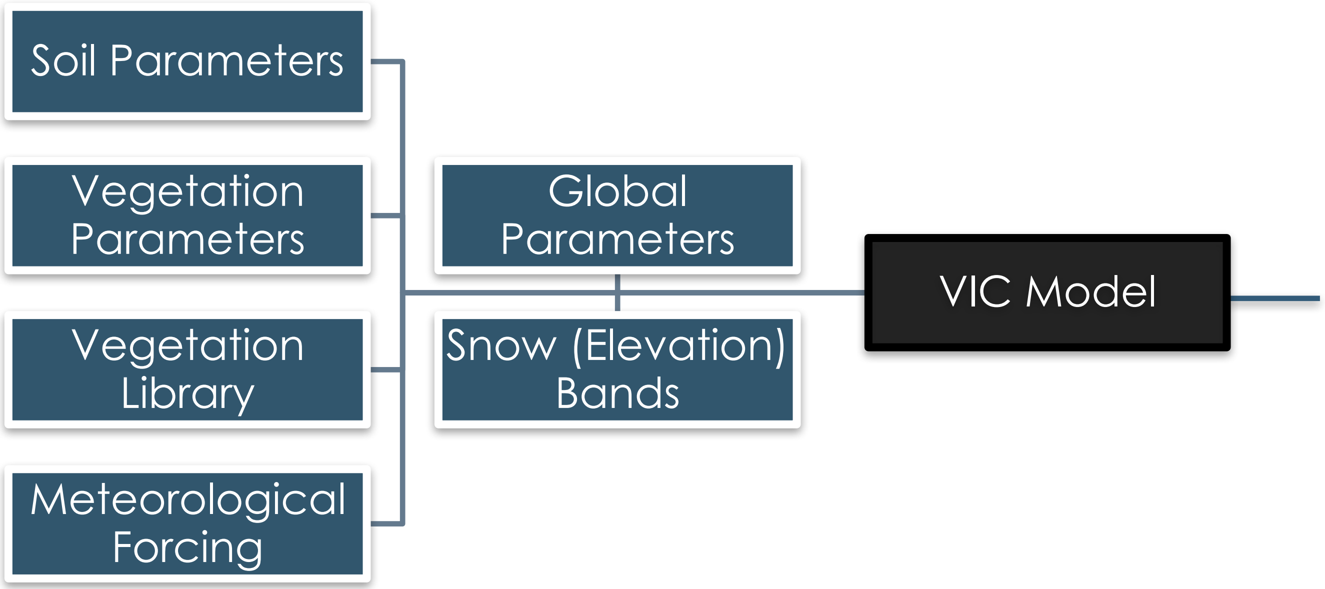


Introduction to the VIC Model

Image Credit: AralDIF, University of Washington

The VIC Model Workflow

Inputs



Outputs

- Soil Moisture
- Evapotranspiration
- Runoff/Streamflow
- Snow Water Equivalent

Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview

An Overview of the VIC Model

- Hydrology model comparison/selection
- VIC model features
  - Cell size
  - Sub-grid representations
- VIC model processes
  - Vegetation
  - Snow
  - Evapotranspiration
  - Runoff/Infiltration
  - Baseflow
- Routing Model

The VIC Model

- The **Variable Infiltration Capacity (VIC)** Model
- **Grid-based** land surface representation
- Simulates land surface-atmosphere fluxes of **moisture** and **energy**
- Developed for coupled Land surface Model (LSM) – Global Circulation Model (GCM) simulations
  - Considered **a research model**
- **Open-source** development

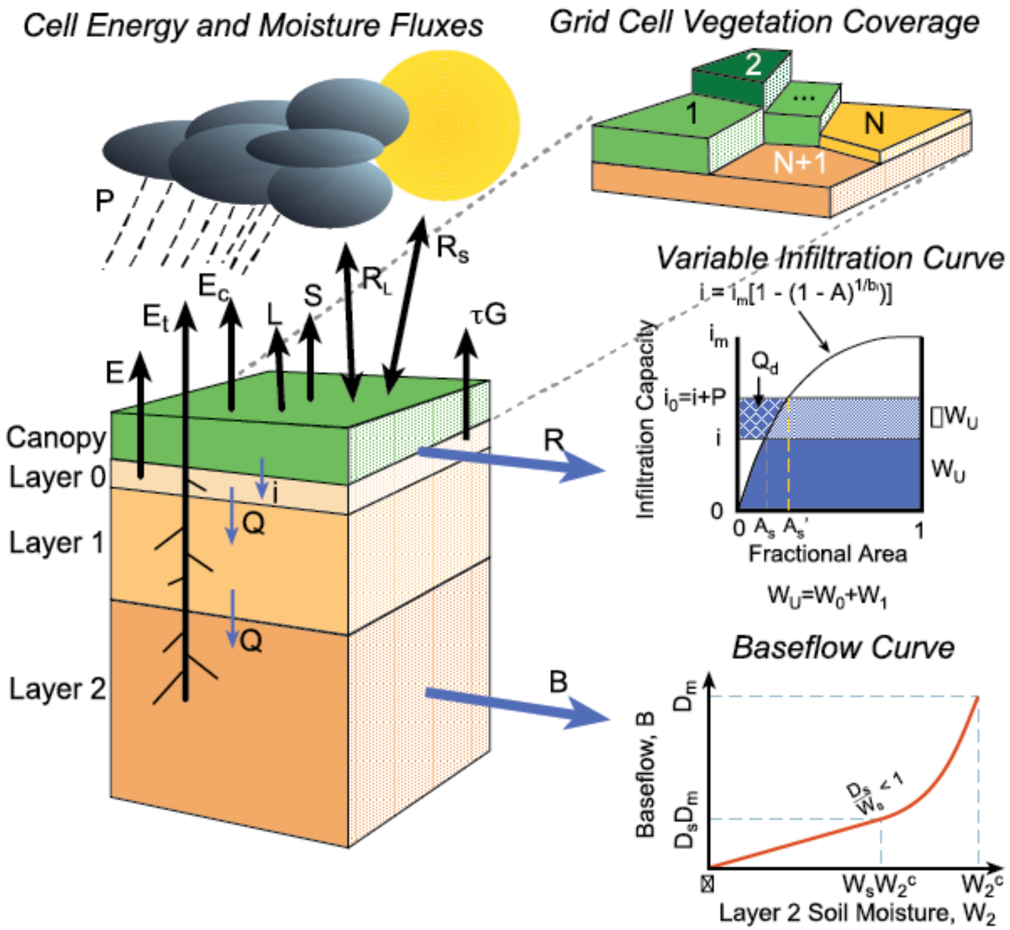


Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview

LSM - Traditional Hydro Model Difference

	Traditional Hydrology Model	LSM Scheme
Purpose	Flood forecasting, water supply	For inclusion in a GCM as a land surface scheme
Fluxes	Only water balance in important	Both water and energy balance is important
Model representation	Mainly conceptual models (parameters are not physically based such as the CN method)	More physically based formulation (e.g. hydraulic conductivity)
Vegetation	Implicitly simulated	Explicitly simulated
Run	Lumped parameters or fully distributed	Grid-based
Function	Off-line simulations	Dynamic coupling with GCM or off-line simulations

Hydrology Model Selection

- Model selection depends largely on application of model
  - Somewhat based on technical expertise
- Many studies have investigated model selection, parameterization, and calibration effects on results
  - Model selection has a major effect
  - Should understand model components and physical representations for application

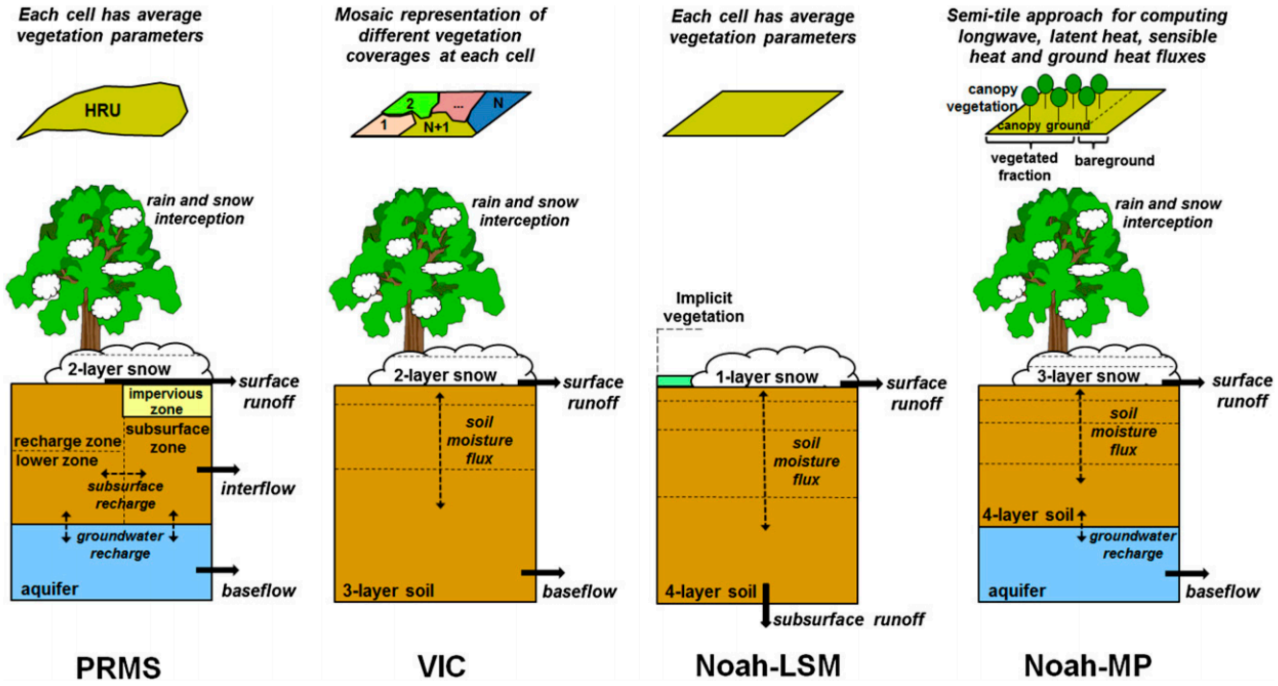
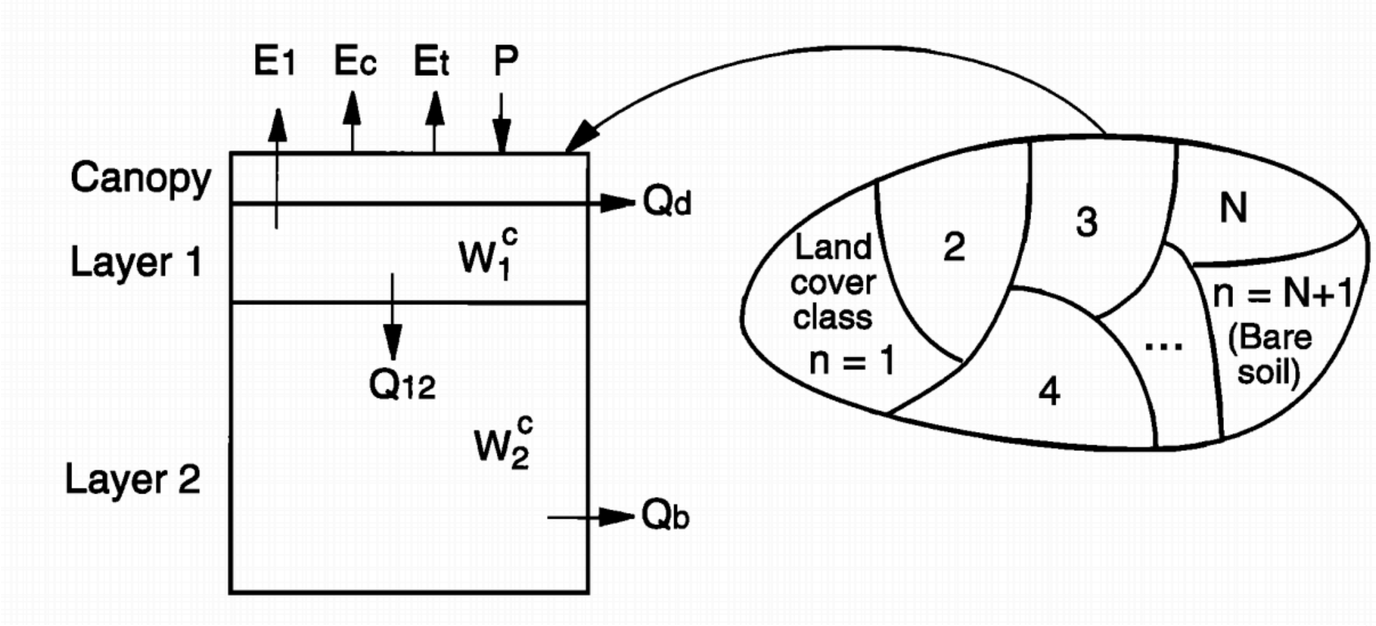
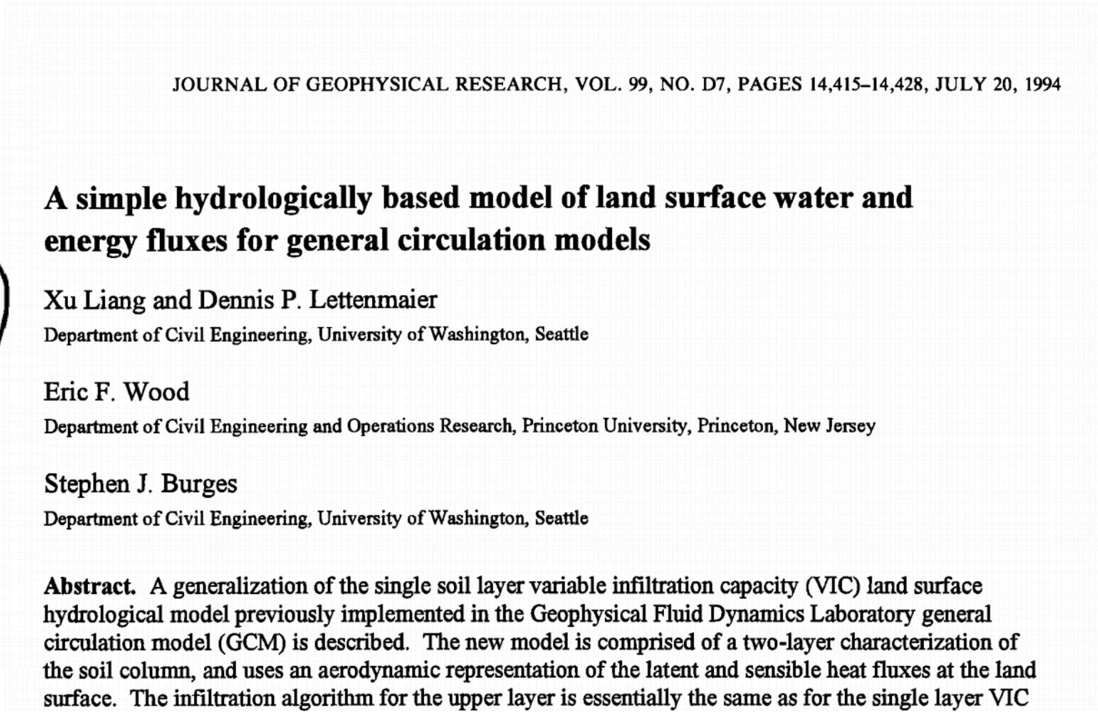


Image from Mendoza et al., 2015 (Open access J. Hydromet. Article): http://journals.ametsoc.org/doi/pdf/10.1175/JHM-D-14-0104.1

Origins of VIC

- Developed by *Liang et al.* [1994]
- Two-layer soil-vegetation model
- **Physically-based model** to be coupled with climate models




JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. D7, PAGES 14,415–14,428, JULY 20, 1994

A simple hydrologically based model of land surface water and energy fluxes for general circulation models

Xu Liang and Dennis P. Lettenmaier
Department of Civil Engineering, University of Washington, Seattle

Eric F. Wood
Department of Civil Engineering and Operations Research, Princeton University, Princeton, New Jersey

Stephen J. Burges
Department of Civil Engineering, University of Washington, Seattle

Abstract. A generalization of the single soil layer variable infiltration capacity (VIC) land surface hydrological model previously implemented in the Geophysical Fluid Dynamics Laboratory general circulation model (GCM) is described. The new model is comprised of a two-layer characterization of the soil column, and uses an aerodynamic representation of the latent and sensible heat fluxes at the land surface. The infiltration algorithm for the upper layer is essentially the same as for the single layer VIC

Image from *Liang et al.* [1994] (Open access article): http://onlinelibrary.wiley.com/doi/10.1029/94JD00483/epdf

VIC Features

- Each grid cell is simulated independently
  - Only water entering cell is from atmosphere (precipitation)
- Can represent sub-grid vegetation/land cover
- Can represent sub-grid elevation variability (snow bands)
- Daily or sub-daily time step
- Multiple soil layer depths
- Routing of streamflow is performed independently using a separate model
  - Typically the Lohmann et al. [1996; 1998] routing model
- Deep groundwater is not considered within the model

VIC Grid Cell Size

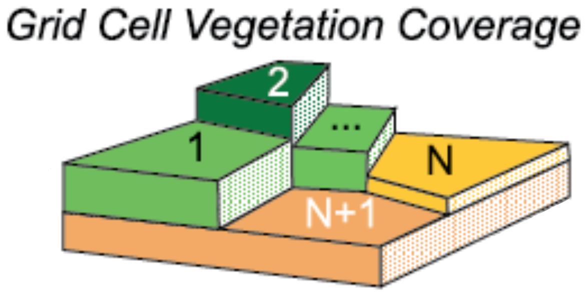
- Grid cells are simulated independently of each other
  - No channel flow, sub-surface flow, or recharge to soil from rivers
- Assumes: **vertical fluxes are much larger than horizontal fluxes**
- Assumption satisfied with **large grid cell (>3km to ~2° resolution)**

- Additional assumptions:
  - Groundwater flow is small relative to surface and near-surface flow
  - Lakes/wetlands do not have significant channel flow
  - Flooding (over banks) is insignificant

- All are usually satisfied if the grid cell is large enough

Sub-Grid Representation: Vegetation

- Spatial distribution and parameters for vegetation classes are specified within input files
- Energy and water balance terms are **computed independently for each vegetation class**
- Each class has **different parameterization:**
  – Leaf-Area Index
  – Rooting Depth
  – Surface Roughness
  – etc.



- Classes **must add up to 100% area** or VIC's **bare soil scheme is used for the remainder**
- Example: 33% Forest, 36% Grassland
  - o (100 – 33 – 36 = 31% bare soil)

Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview/

Sub-Grid Representation: Elevation

- Simulates **orographic effects** on precipitation/snowfall and snow pack processes
- Important for representing the differences in **snow accumulation and snow melt timing** between high and low elevations
- **User specified** snow (elevation) bands
  - Fractional area and mean elevation for each band
- Mean pixel **temperature is lapsed to each elevation band**
  - Precipitation falls as either liquid or solid depending on the lapsed temperature

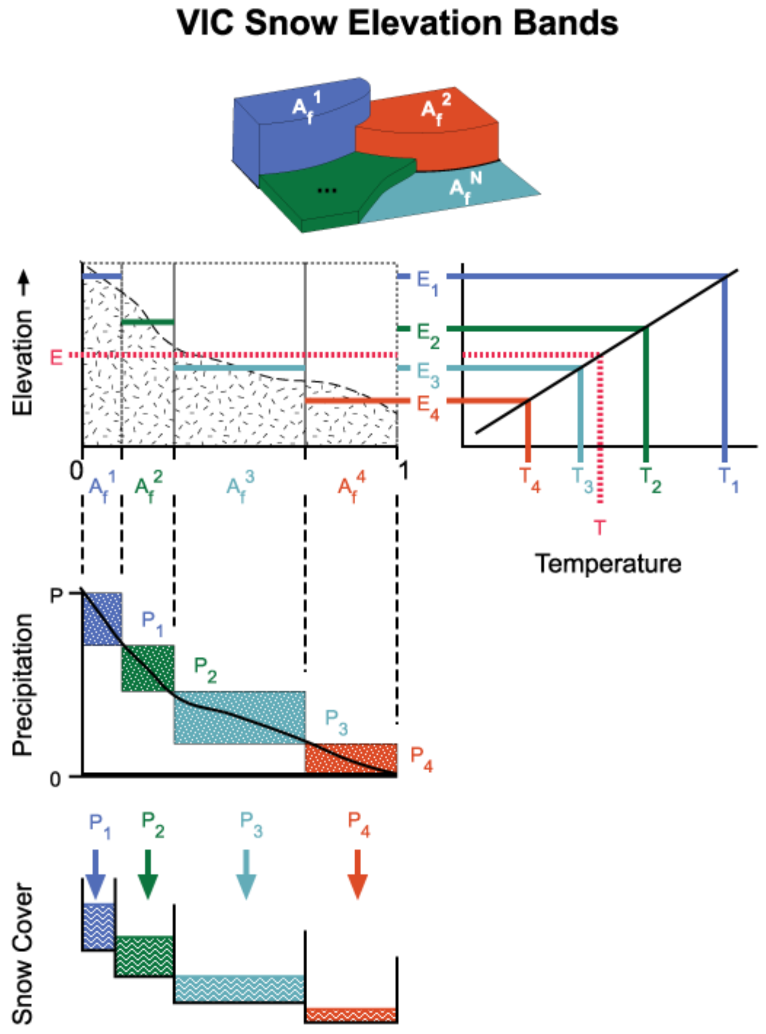
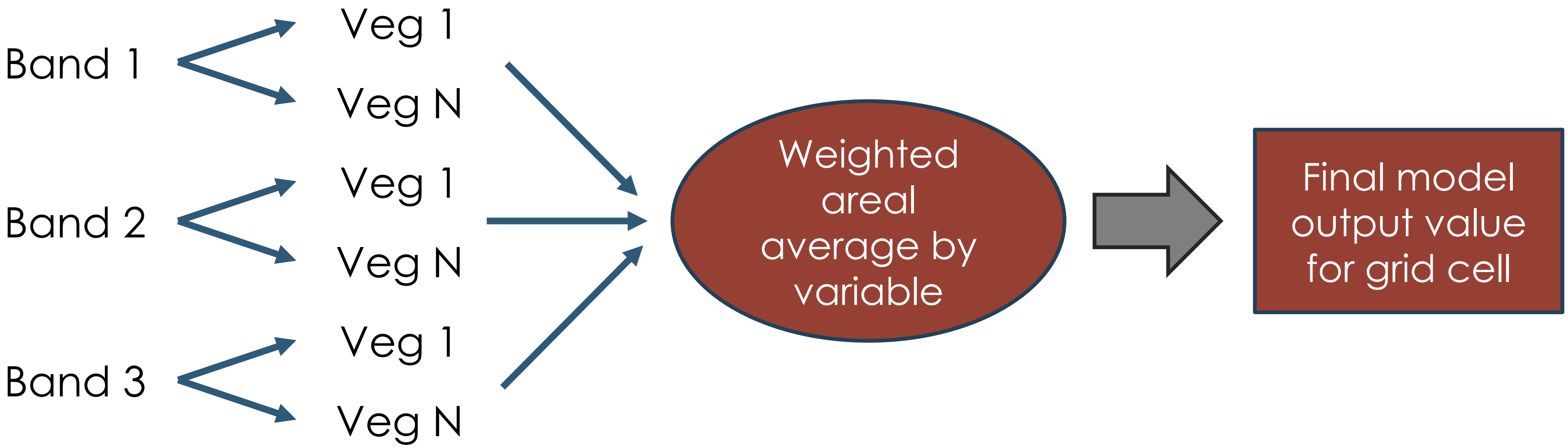


Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview/

Sub-Grid Representation: Aggregation

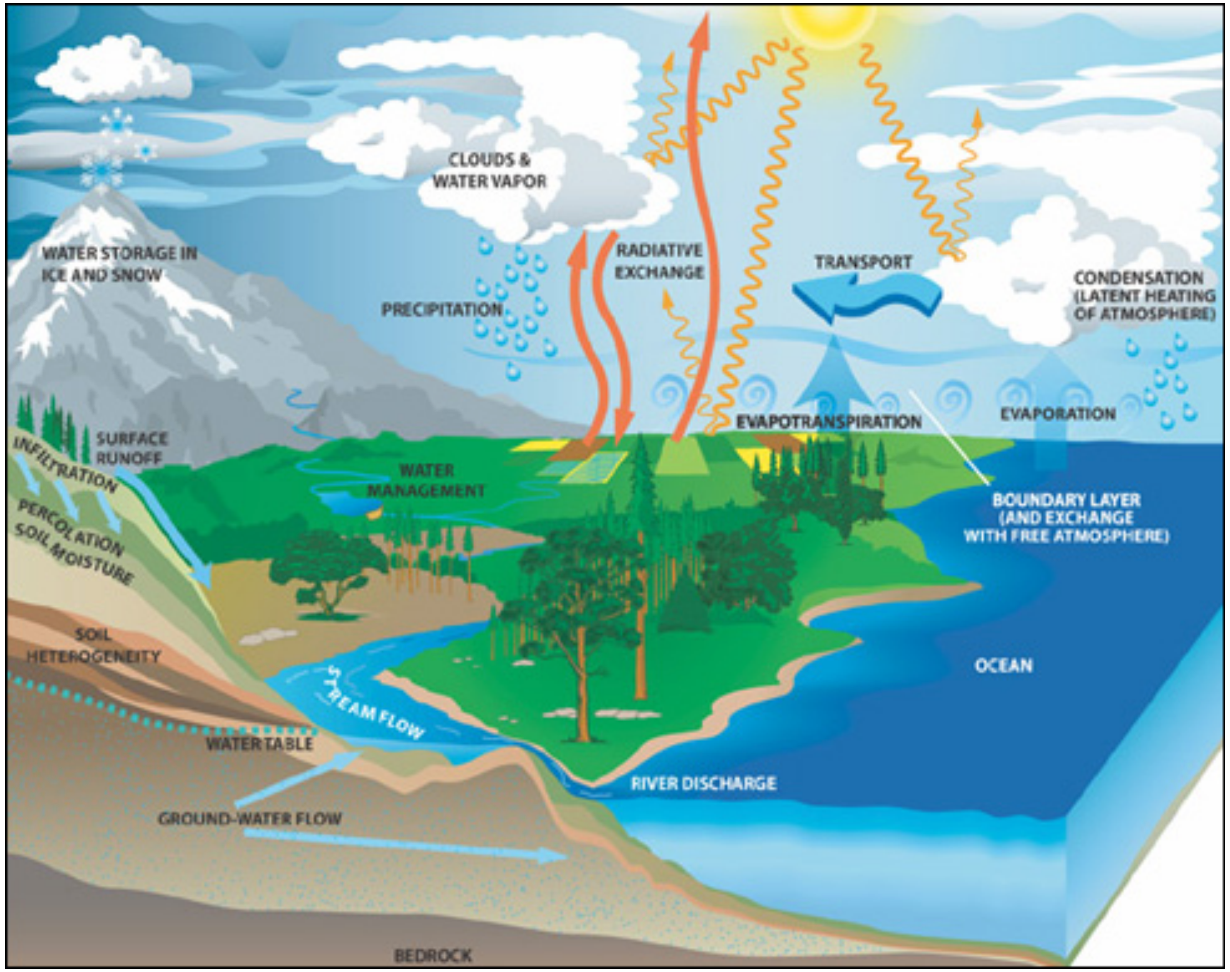
- Sub-grid processes are combined through **weighted areal average**
- Computed by elevation bands and then vegetation cover
  - **Order of operations is important**



- More elevation bands and vegetation types significantly increase computation time!

Hydrologic Process Representation

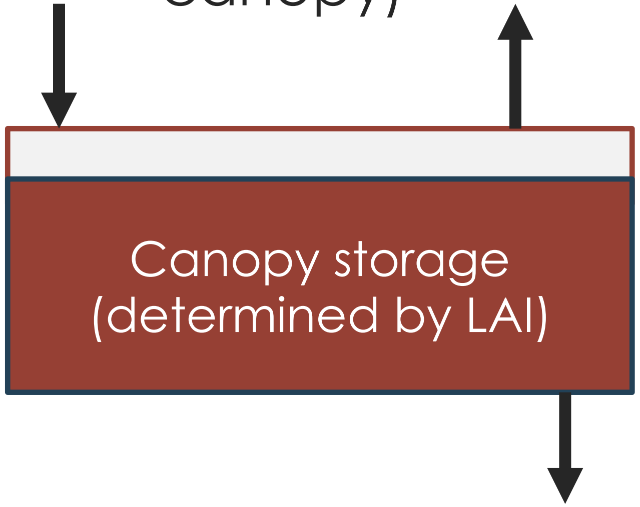
- Requires detailed parameterization
  - Important for climate-sensitive regions
- Contains modules and options to capture specific processes



Vegetation Canopy

Precipitation

Canopy evap (wet canopy or snow) Transpiration (dry canopy)



Canopy "throughfall" occurs when additional precipitation exceeds the canopy storage capacity in the current time step

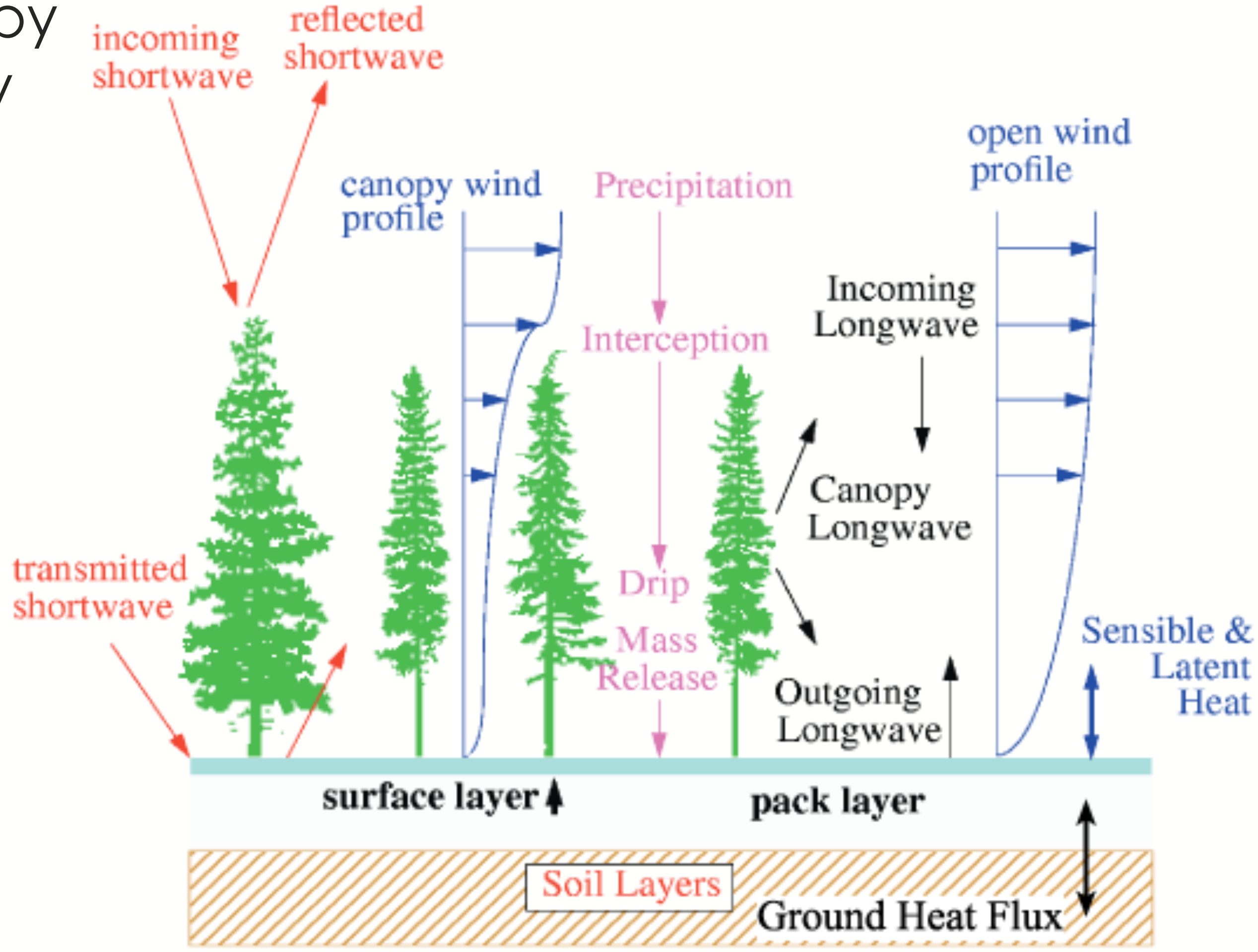
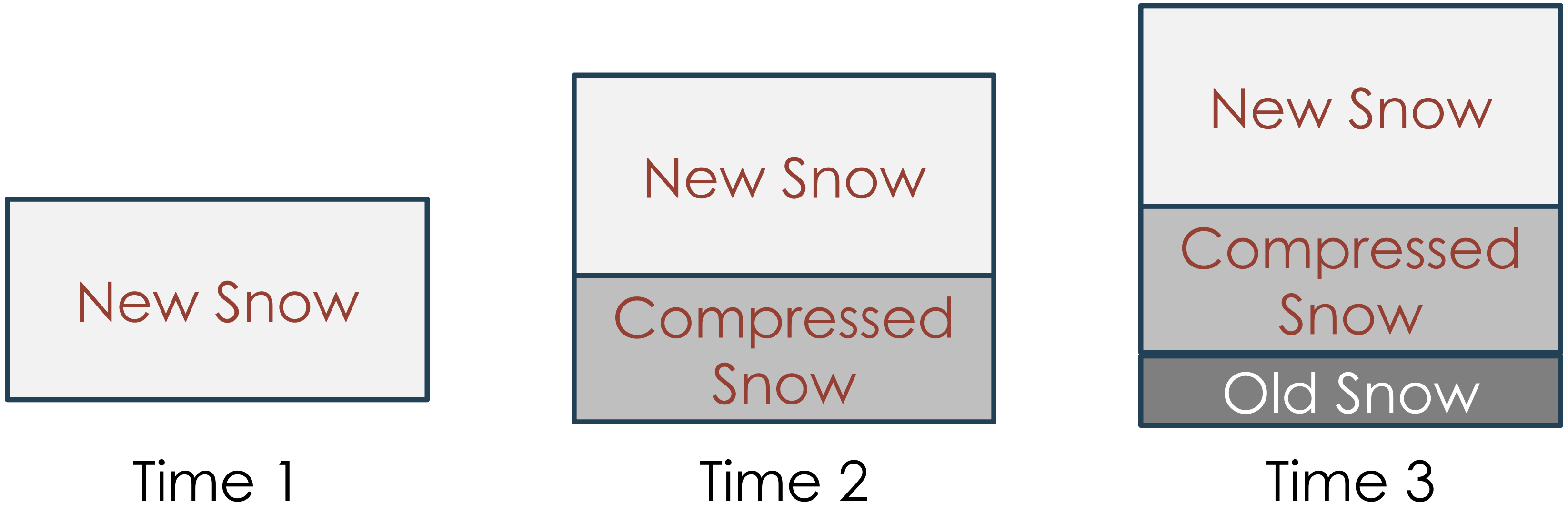


Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview

Snow Simulations

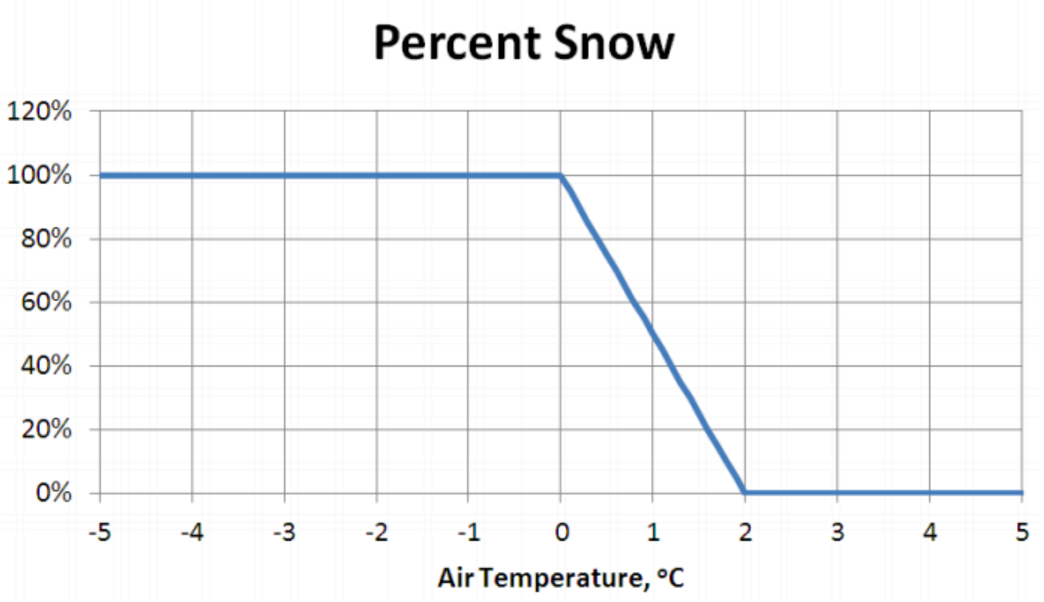
- Snow within the vegetation canopy is directly related to LAI
- Uses two-layer energy balance model at snow surface
  – Thin surface layer
  – Pack layer
- Albedo and snow pack size evolves with snow ages
- Requires calibration of snow surface roughness and albedo



Rain-Snow Partitioning

- VIC used a **simple (linear) method** to determine the **percentage of liquid (rain) or solid (snow) precipitation**
- Example: Rain Minimum = 0.0 °C
  Snow Maximum = 2.0 °C
- Requires calibration of the rain minimum and snow maximum parameters

- For this example, 0.5°C would produce – 75% snow and 25% rain



Evapotranspiration Simulation

- Physically-based **Penman Monteith approach** [*Monteith*, 1965]

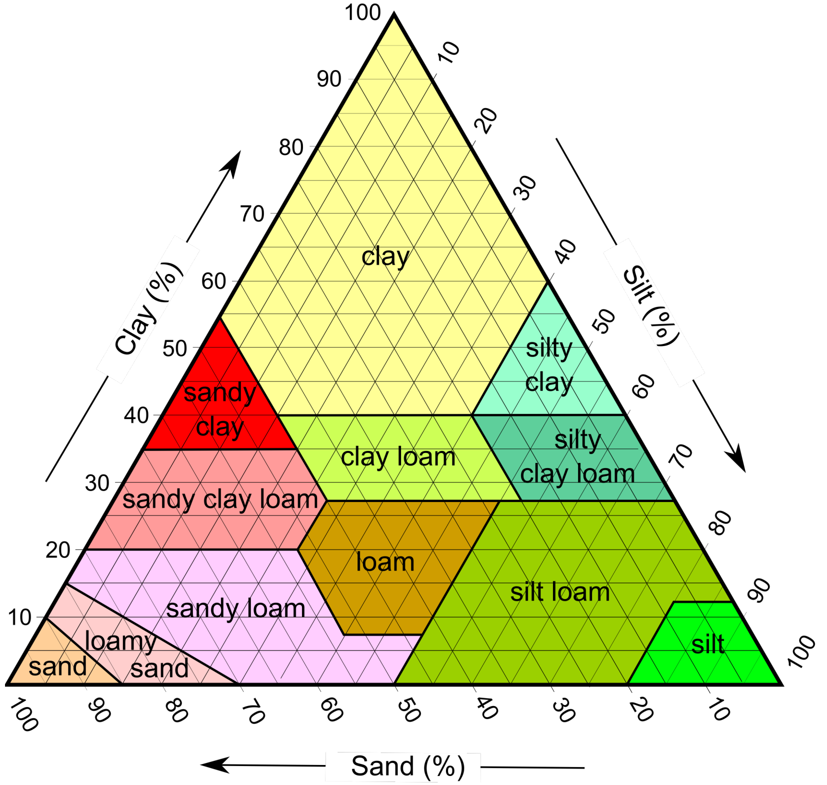
$$E_p = \frac{s(R_n - G) + pc_p d_a / r_a}{s + \gamma(1 + r_s / r_a)}$$

- Made up of three components for each elevation band and vegetation type

- Bare soil calculations are similar but include resistance terms for soil-atmosphere moisture transfer

Parameterization of Soils

- Soil information is poorly known
- **Pedotransfer functions**
  - Changing what we have into what we need
  - Soil texture info to physical units
  - Soil pedotransfer table
- Soil texture information is used to estimate:
  - Porosity
  - Ksat
  - Field capacity
  - Wilting point
  - Residual capacity
  - And other soil characteristics

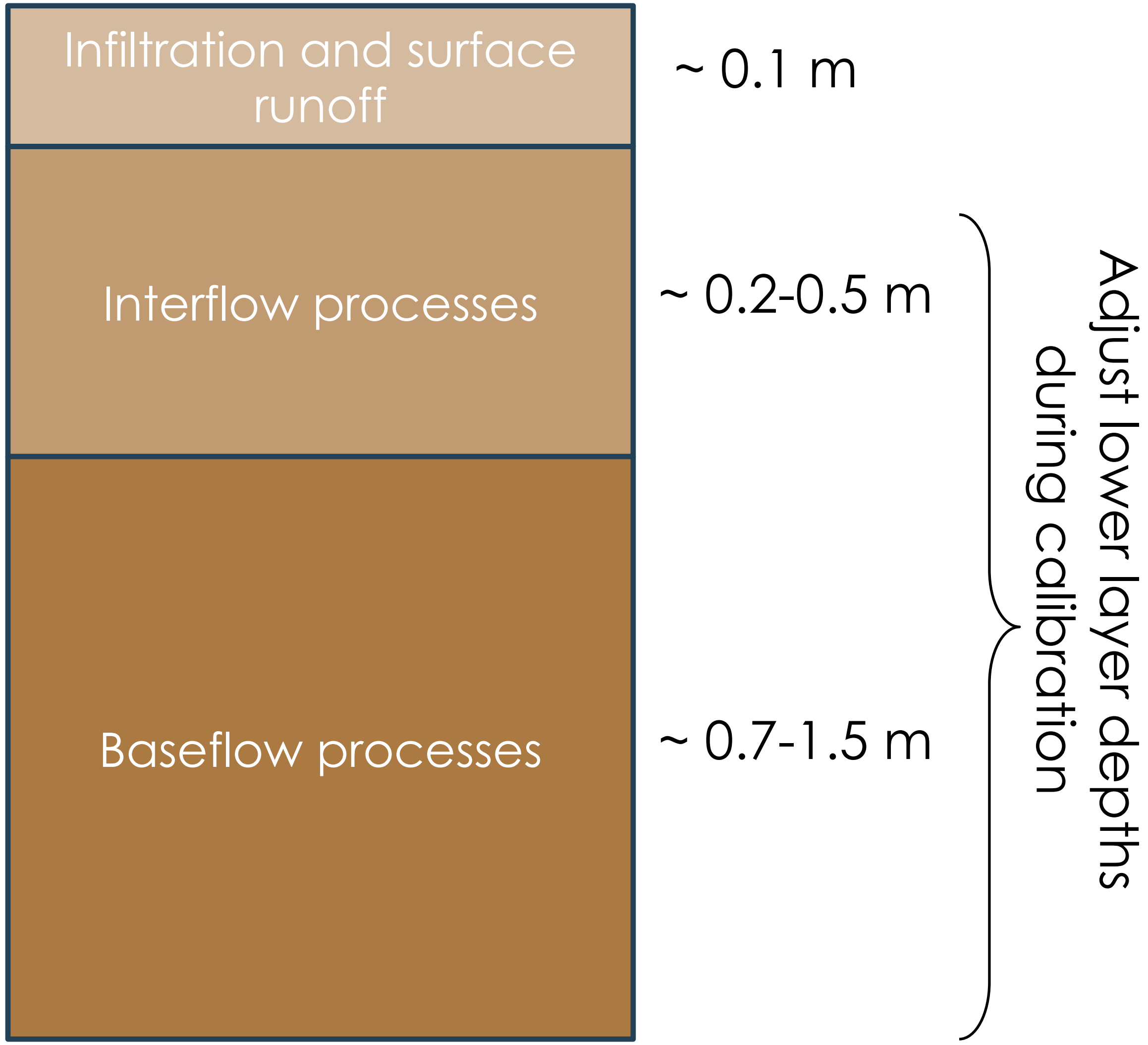


USDA Class	Soil Type	% Sand	% Clay	Bulk Density g/cm^3	Field Capacity cm^3/cm^3	Wilting Point cm^3/cm^3	Porosity fraction	Saturated Hydraulic Conductivity cm/hr	Slope of Retention Curve (in log space) b**
1	s	94.83	2.27	1.49	0.08	0.03	0.43	38.41	4.1
2	ls	85.23	6.53	1.52	0.15	0.06	0.42	10.87	3.99
3	sl	69.28	12.48	1.57	0.21	0.09	0.4	5.24	4.84
4	sil	19.28	17.11	1.42	0.32	0.12	0.46	3.96	3.79

Image Credit: USDA

Soil Column

- Parameterize arbitrary number of soil layers at different depths
  - Model requires **at least two soil layers** for water balance calculations and three soil layers for energy balance calculations
  - No theoretical limit to the number of layers
- **Typically, three layers** are defined for simulations
  - NLDAS VIC 3 layers (approx 0-0.15, 0.15-0.55, and 0.55-1.35 m)
  - GLDAS VIC 3 layers (0-0.1, 0.1-1.6, and 1.6-1.9 m)



Rooting Depths

- Rooting depths are **independent of soil layer** depths
- Rooting depths and distributions are **user-defined**
  - Defined for each vegetation type in each grid cell
- Important parameterization for vegetation transpiration calculations
  - Determines available water at soil depths for uptake by vegetation
- Rooting parameterization **taken from literature or estimated**

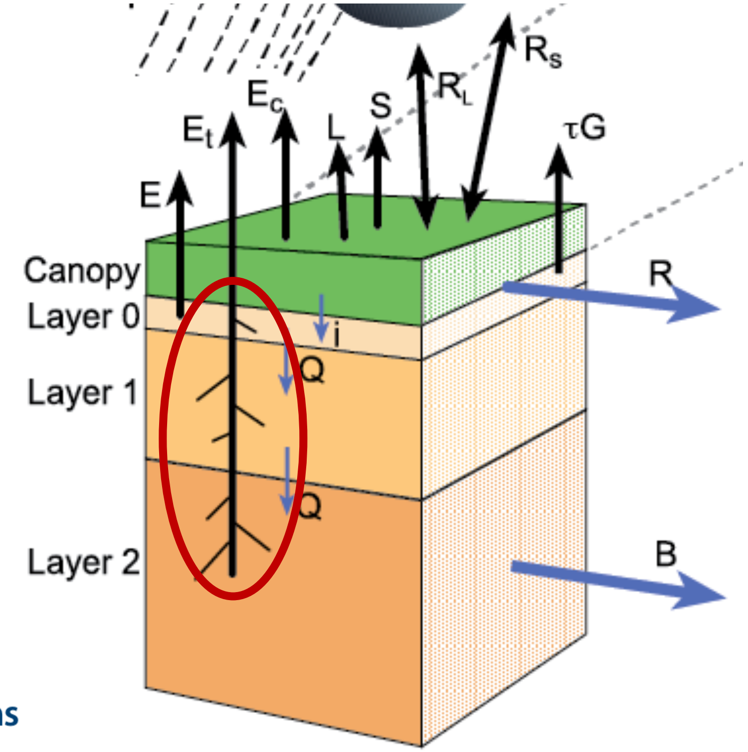


Image from Open Access VIC Documentation

Global estimation of effective plant rooting depth: Implications for hydrological modeling

Yuting Yang[1], Randall J. Donohue[1,2], and Tim R. McVicar[1,2]

[1]CSIRO Land and Water, Canberra, Australia, [2]Australian Research Council Centre of Excellence for Climate System Science, Sydney, Australia

Abstract Plant rooting depth (Z_r) is a key parameter in hydrological and biogeochemical models, yet the global spatial distribution of Z_r is largely unknown due to the difficulties in its direct measurement. Additionally, Z_r observations are usually only representative of a single plant or several plants, which can differ greatly from the effective Z_r over a modeling unit (e.g., catchment or grid-box). Here, we provide a global

Runoff-Soil Infiltration

- Surface runoff/soil infiltration defined by the variable infiltration curve [Wood et al., 1992]
- Scales maximum infiltration with a **non-linear function** of fractional saturated area
  - Enables runoff calculations **for subgrid-scale areas**
- Curve shape defined by b_{inf} parameter (typically >0 - ~0.4)
  - Amount of infiltration capacity relative to the saturated gridcell area
- Greater value of b_{inf} yields lower infiltration and more runoff (Q_d)

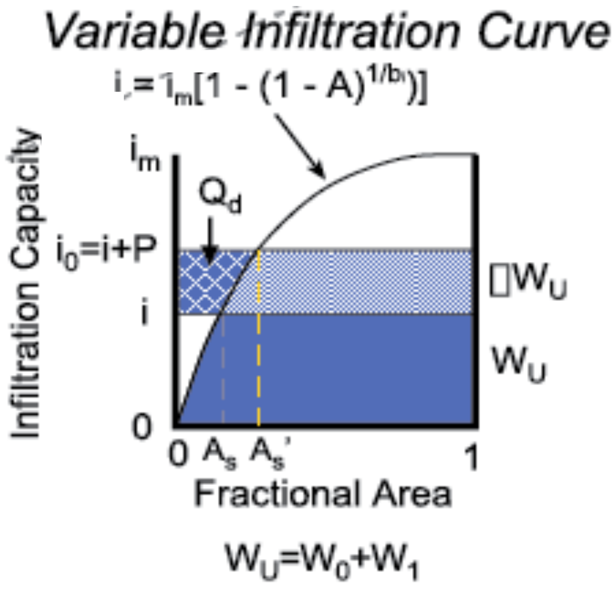


Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview

Sub-surface Flow

- Subsurface flow (baseflow) is estimated using the Arno baseflow model [Francini and Paccinai, 1991]
- **Function of soil moisture in the lowest layer**
- Linear at low soil moisture content
  – Reduces responsiveness of baseflow during dry conditions
- Non-linear at high soil moisture content
  – Rapid baseflow response during wet conditions

Linear baseflow: $B = \frac{D_s \cdot D_{smax}}{W_s W_n^c} \cdot W_n$

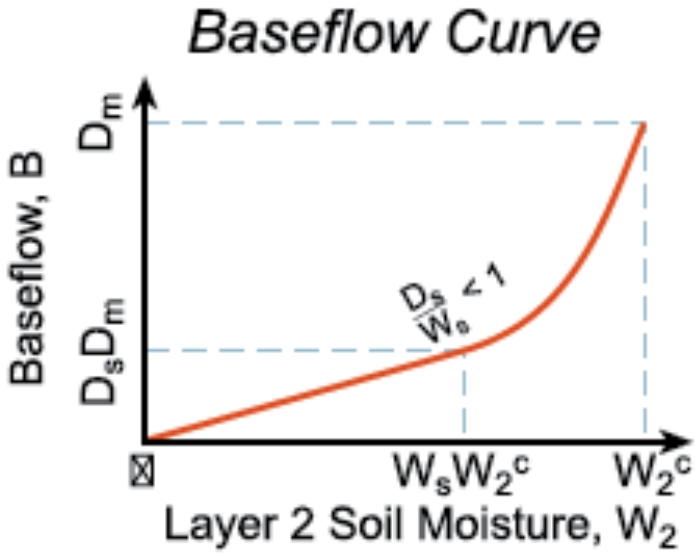


Image from Open Access VIC Documentation: http://vic.readthedocs.io/en/master/Overview/ModelOverview/

Baseflow Formulation

- Important to **understand baseflow dynamics and parameterization for calibration**
- Baseflow calculation example: https://goo.gl/5qFCKM
- Assume one time step (t1 to t2) and the lowest layer's soil moisture increases from 300 to 310 mm. Find the change in baseflow for the time step using different parameterization
  – Change model parameters to for different results

A	B	C	D	E	F	G
Dsmax [mm]	**Ds [-]**	**Ws [-]**	**Wnc [mm]**	**Qbase(t1) [mm day-1]**	**Qbase(t2) [mm day-1]**	***ΔQbase [mm day-1]***
30	0.2	0.8	50	45	46.5	*1.5*
30	0.2	0.6	50	60	62	*2*
30	0.05	0.8	50	11.25	11.625	*0.375*
5	0.05	0.6	50	2.5	2.583333333	*0.08333333333*
5	0.4	0.8	50	15	15.5	*0.5*
5	0.4	0.6	50	20	20.66666667	*0.6666666667*
Soil moisture(t1) [mm]	**Soil moisture(t2) [mm]**					
300	310					

- W_n^c (or W_s, D_{smax}) parameters defined by soil parameters
  - W_n^c = porosity * soil depth

Streamflow Routing

- Streamflow routing performed after LSM scheme simulations
- Developed **specifically to be coupled with LSM** [*Lohmann et al.*, 1996; 1998]
- Grid-based routing scheme based on the **unit hydrograph approach**
  – Creates an **Impulse Response Function (IRF)** for each grid
  – Calculates percent water contribution to outlet from each grid cell at each time step

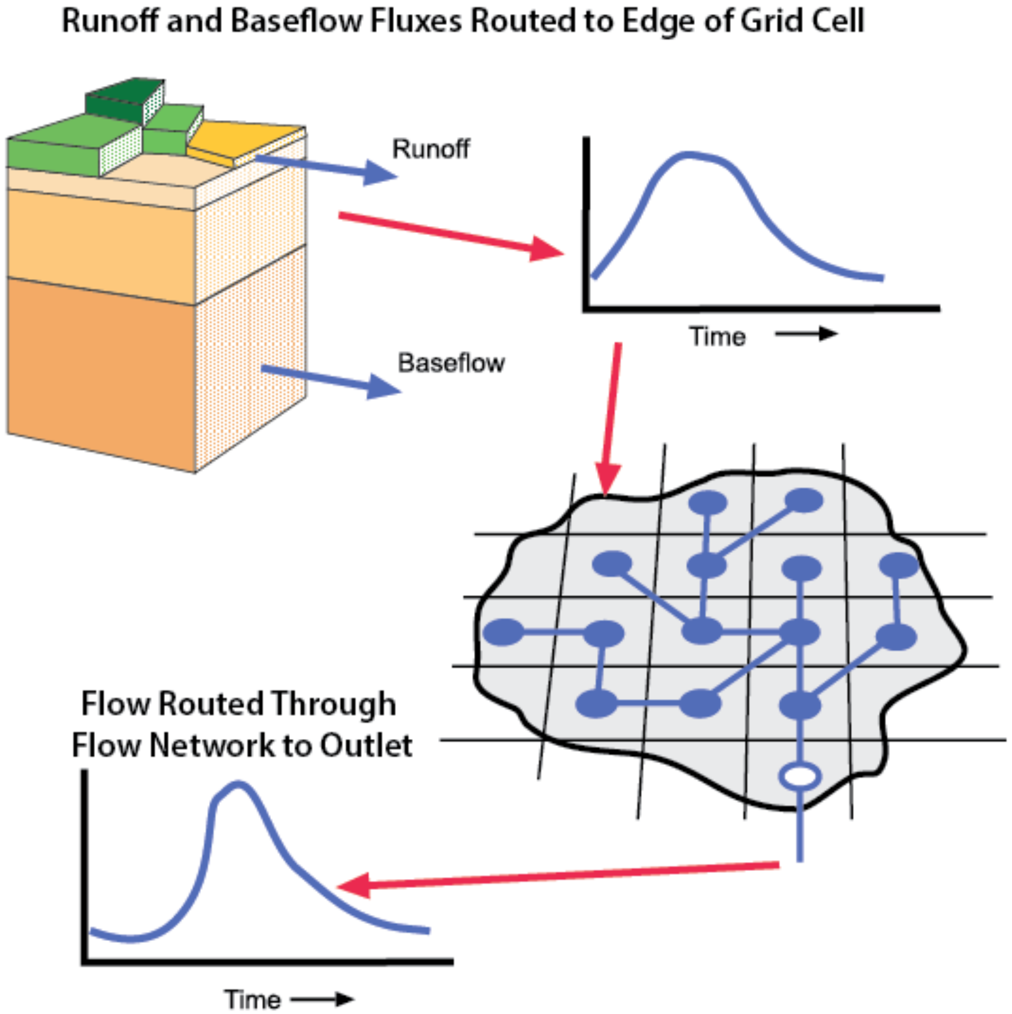


Image from Open Access VIC Documentation

Computational Considerations

- Compiled using free GNU C compilers
  - Can use other compilers but needs to be tested
- Simulation runs cell by cell, can be very **efficiently parallelized by dividing the domain into separate runs**
- VIC is typically run using **UNIX/LINUX operating systems**
  - Possible to run using Windows OS but not supported
- Simulations usually use about 5 MB of RAM
  - Memory usage does not increase with basin size but simulation time does!
- **Need considerable amount of storage** for I/O data
  - Dependent on basin size, time step, etc.

VIC Resources

- Old VIC Website:
  - http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Overview/ModelOverview.shtml

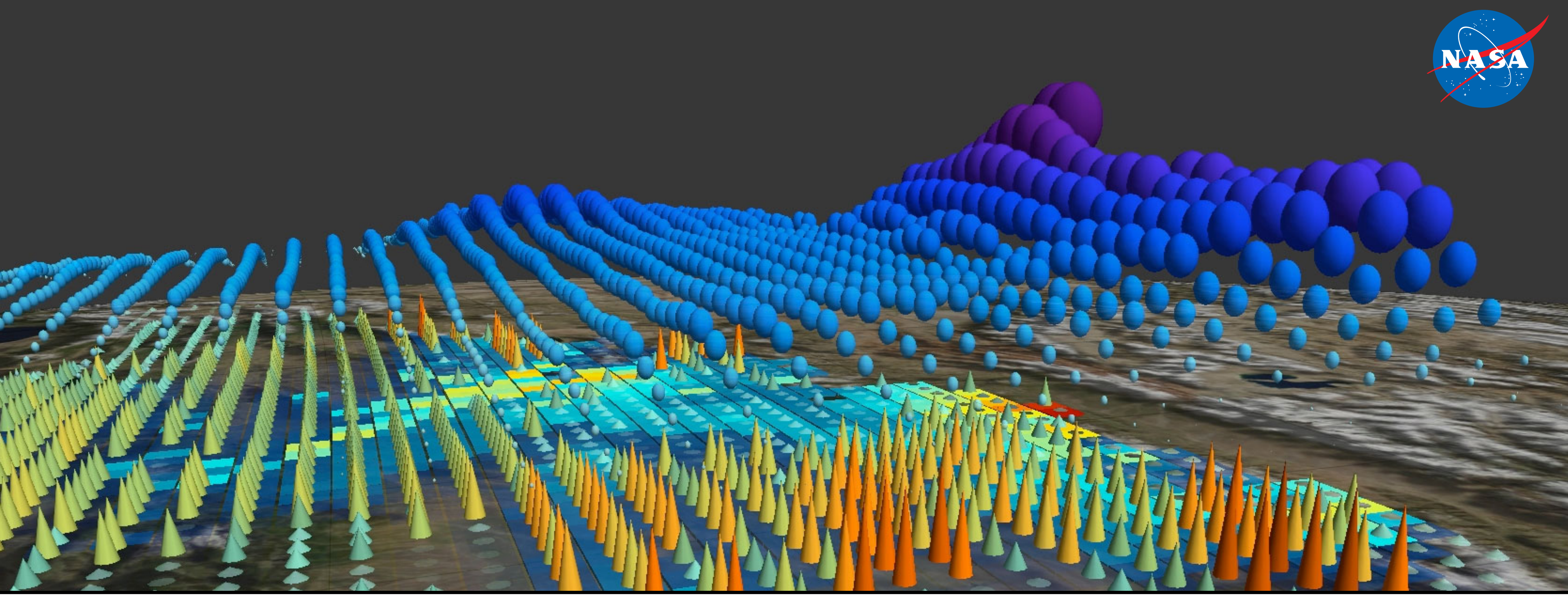
- **Current VIC Website:** http://vic.readthedocs.io/en/master/

- **Routing Model Website:** http://rvic.readthedocs.io/en/latest/

- Source Code Availability:
  - VIC GitHub: https://github.com/UW-Hydro/VIC
  - RVIC GitHub: https://github.com/UW-Hydro/RVIC/

References

- Francini, M., and M. Pacciani, (1991) Comparative analysis of several conceptual rainfall-runoff models, J. Hydrol., 122, 161-219
- Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res., 99, 14415-14428
- Lohmann, D., R. Nolte-Holube, and E. Raschke, (1996), A large-scale horizontal routing model to be coupled to land surface parametrization schemes, Tellus, 48, 708-721.
- Lohmann, D., E. Raschke, B. Nijssen and D. P. Lettenmaier (1998), Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, Hydrol. Sci. J., 43, 131-141.
- Maurer, E. (2011), VIC Hydrology Model Training Workshop-Part I: About the VIC Model, Presentation, url: http://www.engr.scu.edu/~emaurer/chile/vic_taller/01_vic_training_overview_processes.pdf
- Monteith, J. L. (1965), Evaporation and the environment, in The state of movement of water in living organisms, pp 205-234, 19th Symposia of the Society for Experimental Biology. Cambridge Univ. Press, London, UK
- Wood, E. F., D. P. Lettenmaier, and V. G. Zartarian (1992), A land-surface hydrology parameterization with subgrid variability for general circulation models, J. Geophys. Res., 97, 2717-2728



Thank you!

Amita Mehta & Kel Markert (SERVIR Science Coordination Office)

February 15, 22, and March 1, 2018

Image Credit: AralDIF, University of Washington

Thank You