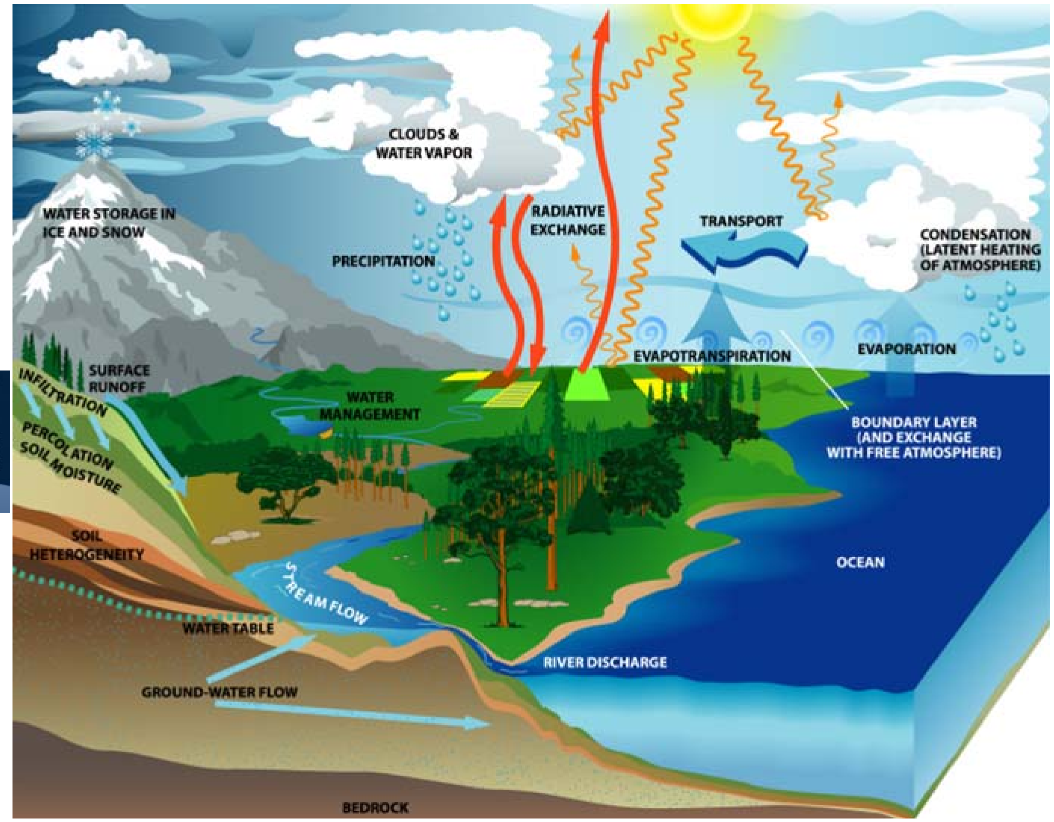
VIC Hydrology Model Training Workshop – Part I: About the VIC model

11-12 Oct 2011

Centro de Cambio Global
Pontificia Universidad Católica de Chile



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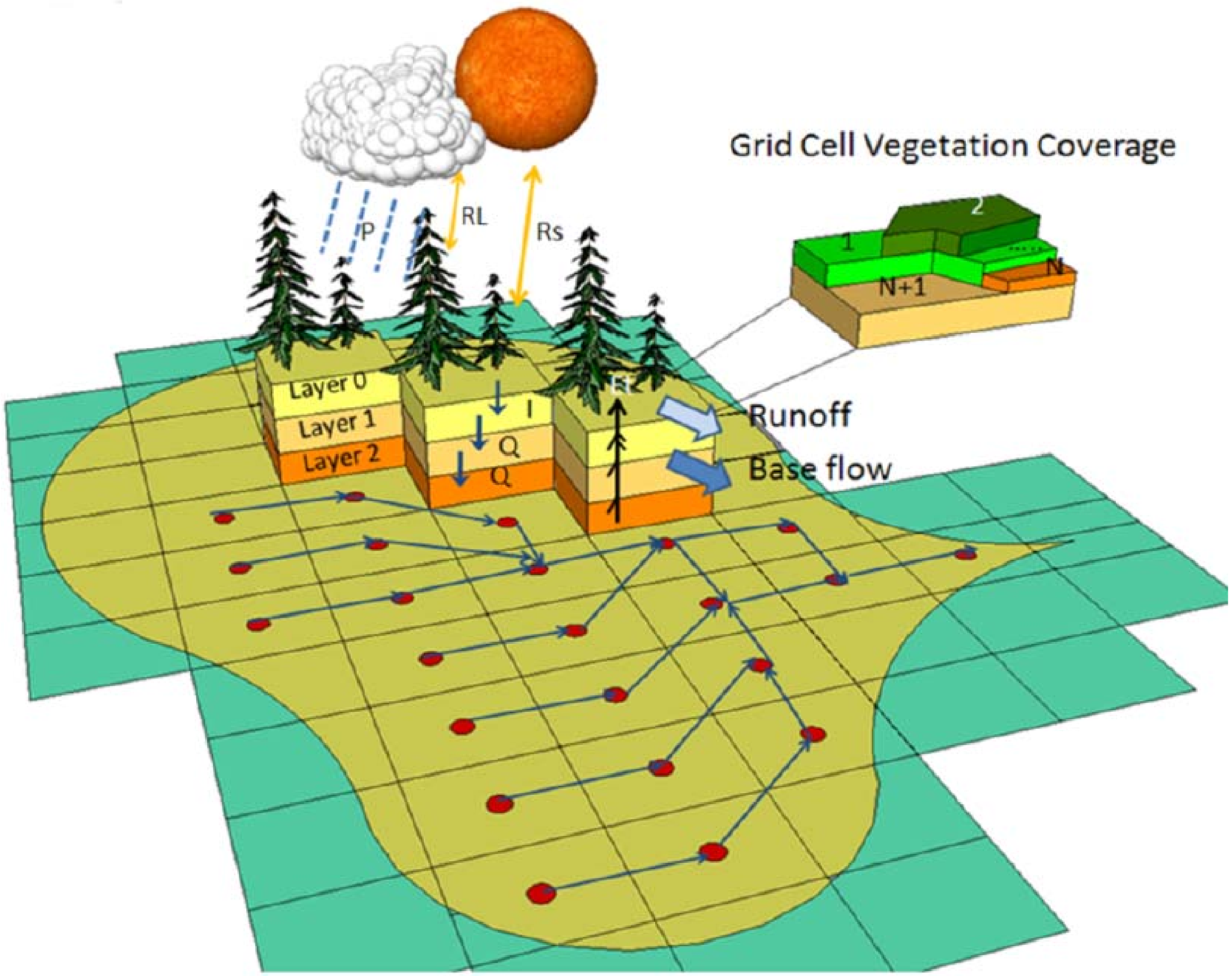
Based on original workshop materials generously provided by Alan Hamlet, U. Washington, with contributions by A. Wood, J. Adam, T. Bohn, and F. Su.

VIC Background



Source: Carrasco and Hamlet, Final Report for the Columbia Basin Climate Change Scenarios Project, Chapter 6, 2010.

- Grid-based land surface representation.
- Simulates land surface-atmosphere exchanges of <u>moisture</u> and <u>energy</u>
- Developed for coupled simulations
  - Only recently used
- Off-line simulations for most uses:
  - Debugging, model improvement
  - Calibration
  - Module development

Differences between land surface hydrology models (like VIC) and traditional hydrology models

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

Origin of the VIC Model

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

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Department of Civil Engineering and Operations Research, Princeton University, Princeton, New Jersey

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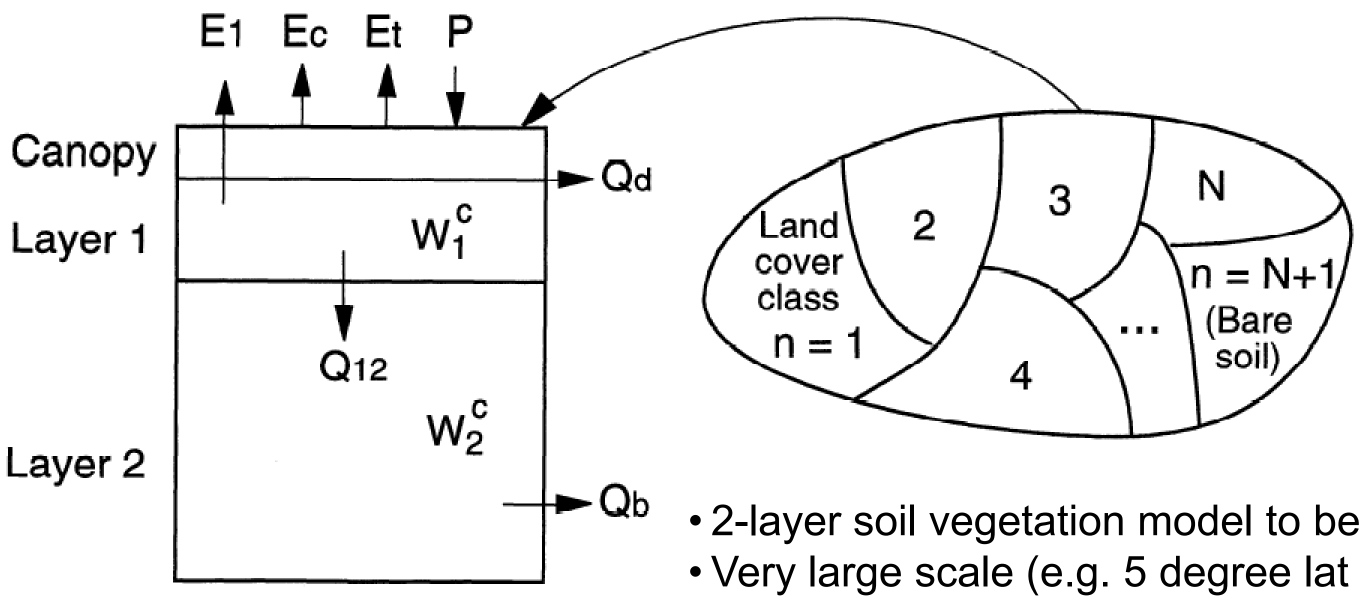
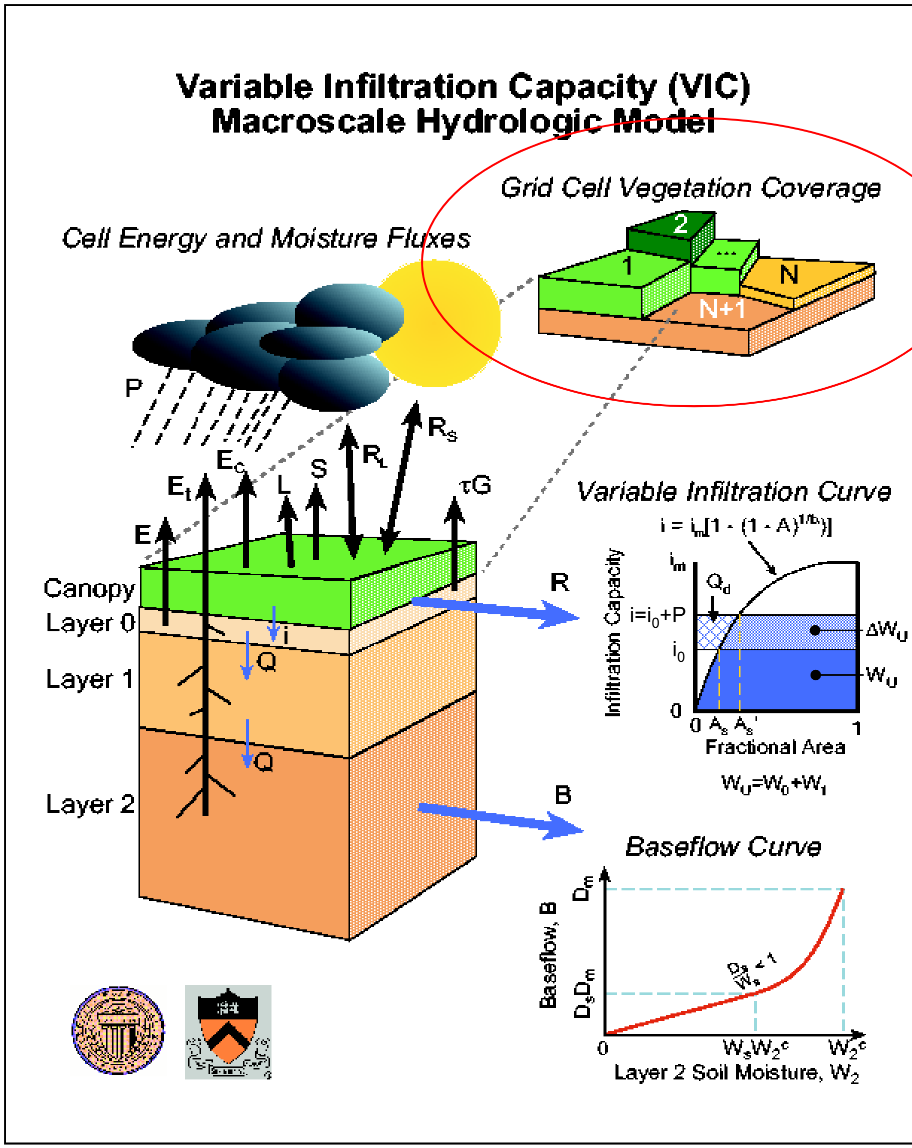


- 2-layer soil vegetation model to be coupled to climate models
- Very large scale (e.g. 5 degree lat lon resolution)
- Parameterized infiltration and base flow schemes
- Single layer energy balance snow model
- Physically-based vegetation model including canopy effects
- Physically-based evaporation based on the Penman/Monteith approach

VIC Grid Cell Representation



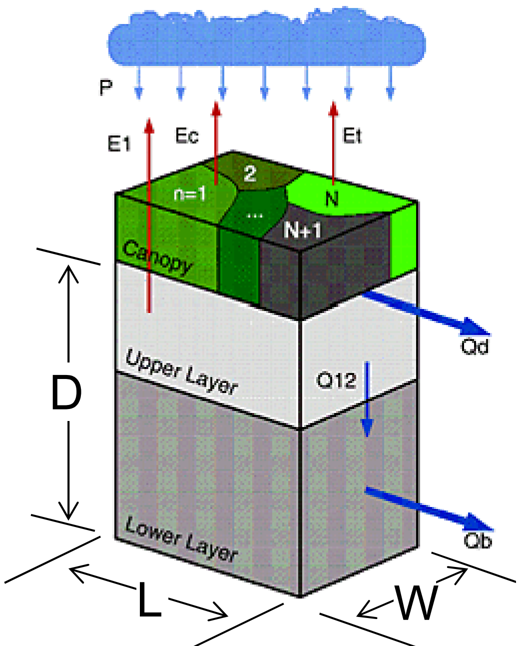
VIC assumptions related to Grid Cell Size

Grid cells do not interact with each other, except in river routing (no sub-surface moisture transfer, no recharge to soil from rivers)

This requires several assumptions, one of which is: vertical fluxes are much larger than horizontal, e.g.:

ET*L*W >> Q*(2L+2W)*D

Grid cells 1 km to 2° (~200 km) or larger per side



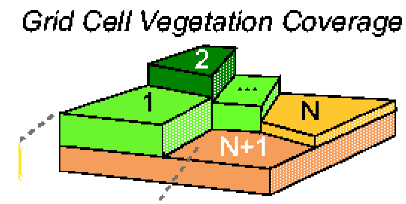
http://www.geog.umd.edu/

Other assumptions related to grid cell size

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

These are usually satisfied if grid cells are large.

Sub Grid Vegetation/Land Cover Description



Example: 33% tall coniferous trees and 36% with grassland (100-33-36 = 31% bare soil)

Each portion has different parameters, for example:

- leaf area index
- Rooting depth
- surface roughness
- etc.

Energy and water balance terms computed independently for each coverage class (vegetation and bare soil)

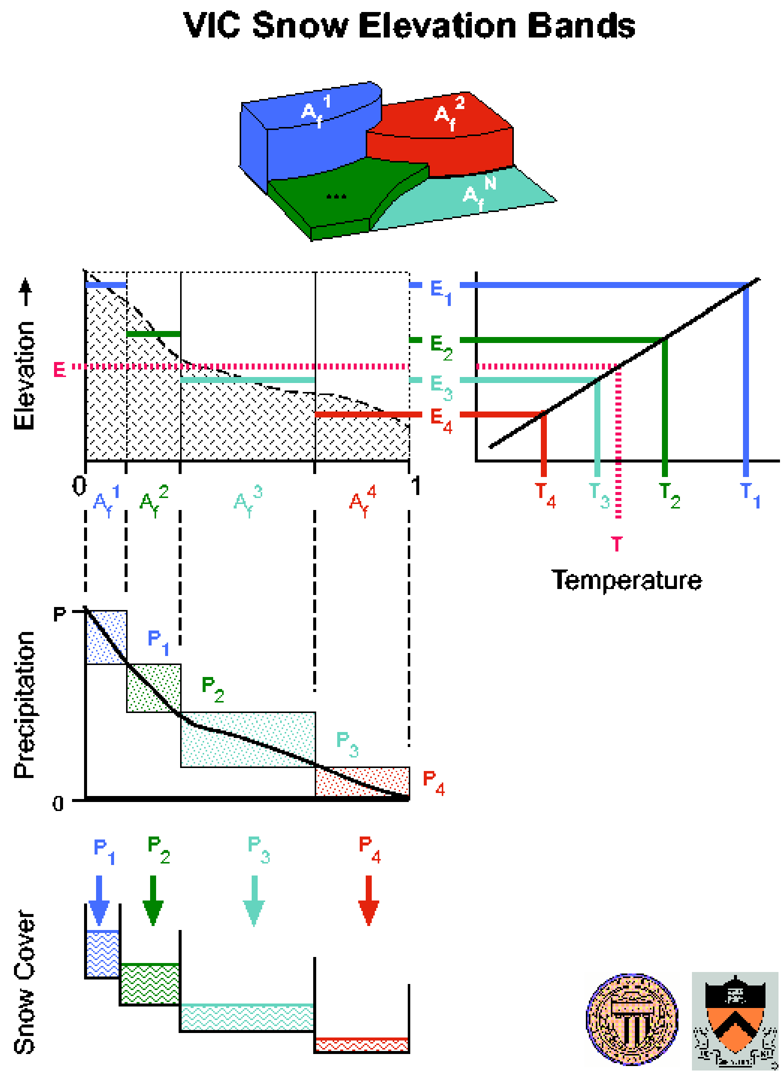
Vegetation characteristics:

Parameters for vegetation types specified in vegetation library (e.g. from national classification schemes)

Distribution over the land surface area is specified in vegetation parameter file

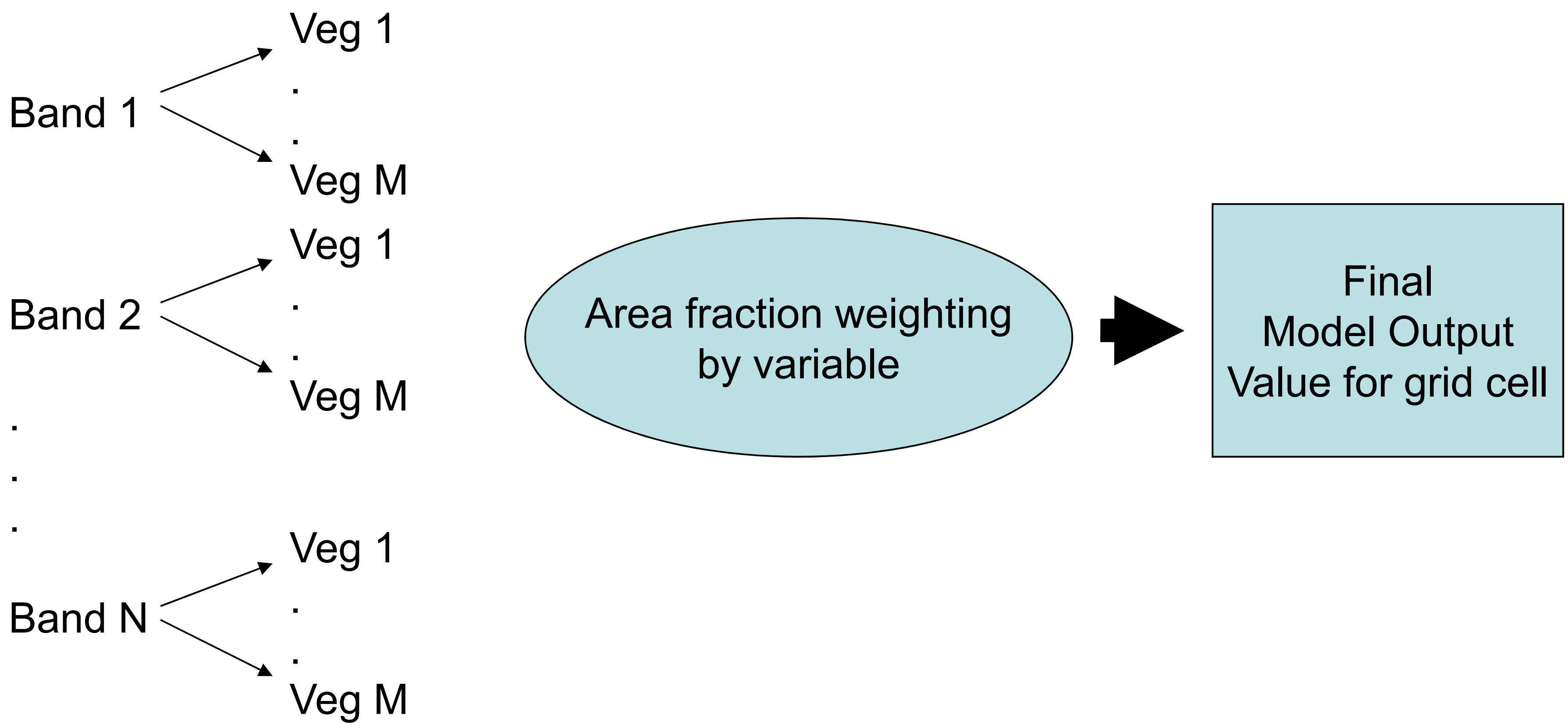
Sub grid elevation variability

- Effect of sub-grid topography on snow accumulation and melt through orographic controls on precipitation and temperature.
- Important for representing the offset in melt timing between high and low elevations.
- User specifies a variable number of snow bands with a fractional area and elevation associated with each band.
- Mean pixel temperature is lapsed to each elevation band
- The increase in precipitation with elevation is specified through precipitation fractions specified by user
- Precipitation falls as snow or rain depending on the lapsed temperature.
- Specified vegetation fractions are repeated for each snow band -- the snow model must be run independently for each vegetation type for each snow band: **model run time will increase accordingly!**



Model Combinatorial Algorithm – within a grid cell

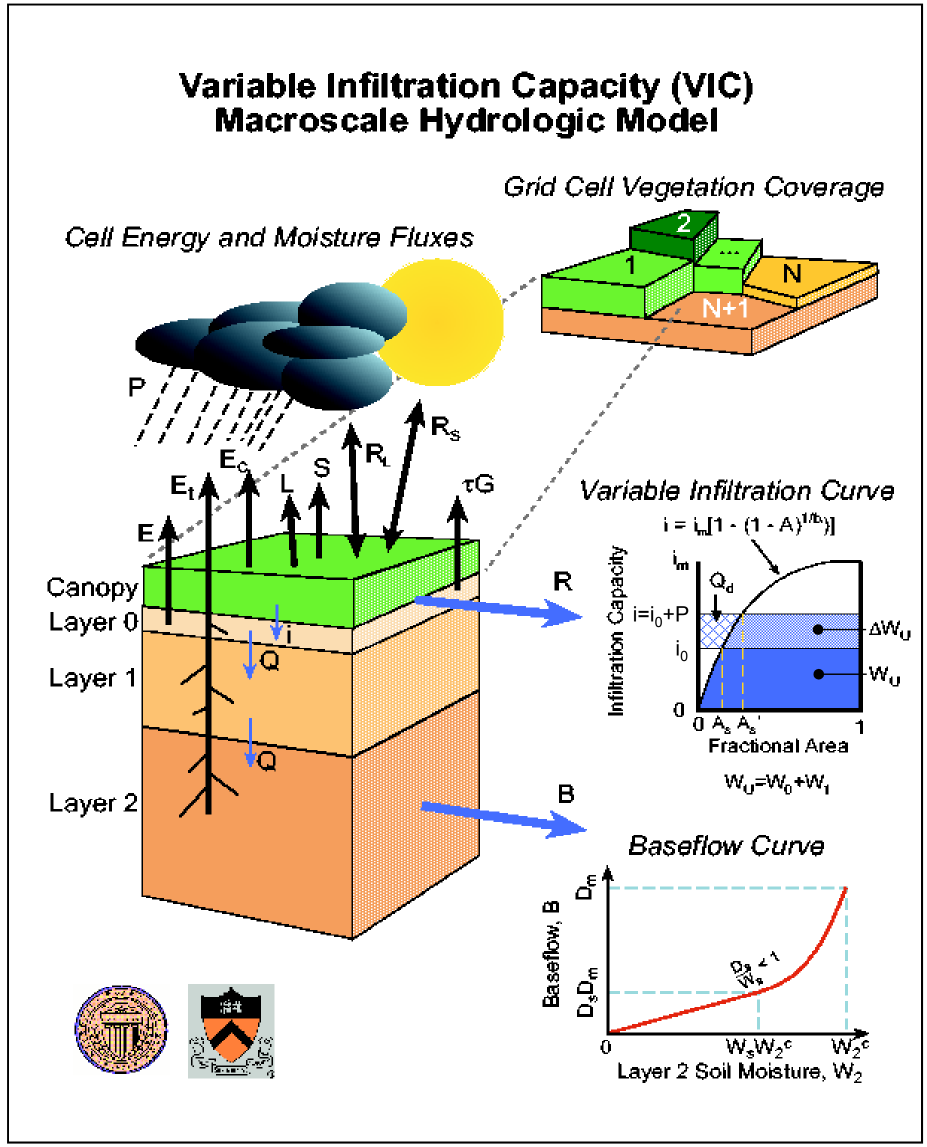
Each cell is completely independent of the others. The model solves the water and energy balance independently for each elevation band and vegetation type within the cell (plus bare soil).



Then in each time step the model creates a linear combination of each variable according to the fraction of the cell area that is associated with each band and veg type.

Hydrologic Process Representation

- Detailed parameterizations important for many climate-sensitive regions
- Modules and options to capture specific processes



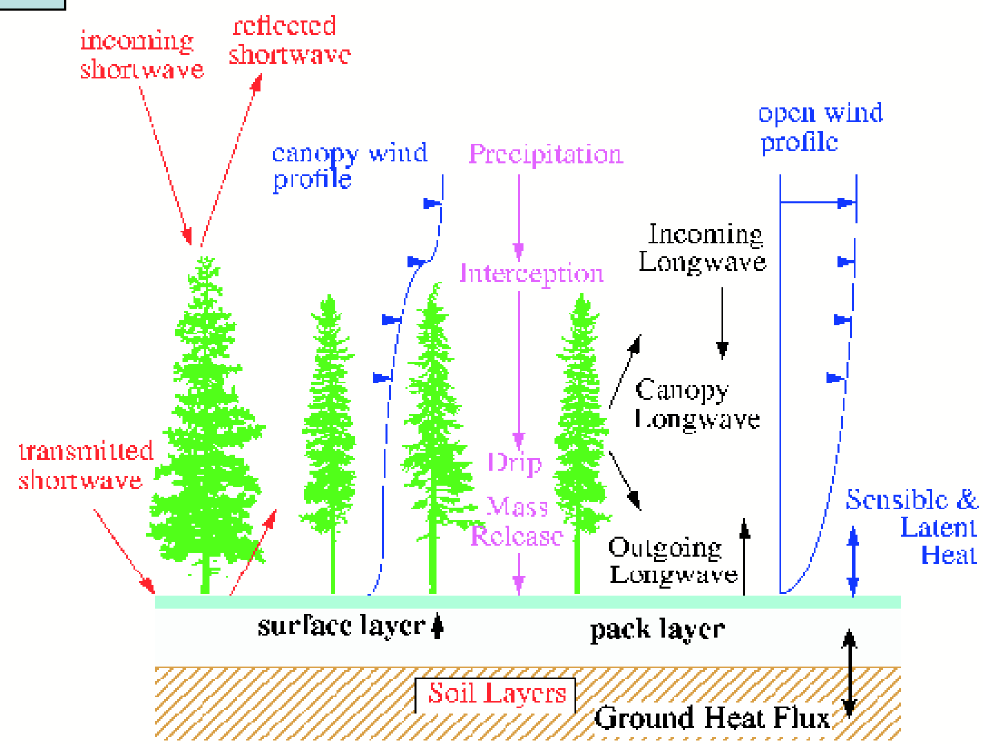
Representation of the Vegetation Canopy

Precipitation

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

Canopy Storage
(determined by LAI)

Canopy “throughfall” occurs when additional precipitation exceeds the storage capacity of the canopy (rain or snow) in the current time step.



Snow Simulation in VIC

Snow on Vegetation Canopy

Amount intercepted is related to leaf area index (LAI)

Sublimation, drip and release to ground

Ground Snowpack

Uses two-layer energy-balance model at the snow surface (a thin surface layer and the pack layer) for accumulation and ablation

Longwave, shortwave, sensible and latent heat, convective energy included.

Water can be added as rain, snow, or drip/throughfall from the canopy

Albedo evolves with snow age

Calibrating the snow model

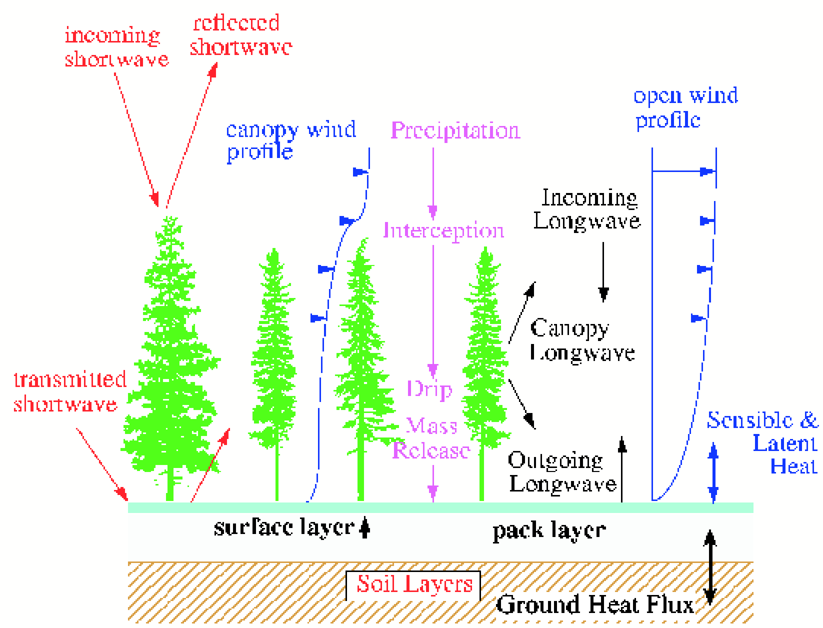
3 main parameters for snow without overstory:

1) Maximum air temperature at which snowfall occurs

2) Minimum air temperature at which rainfall occurs

3) the snow surface roughness.

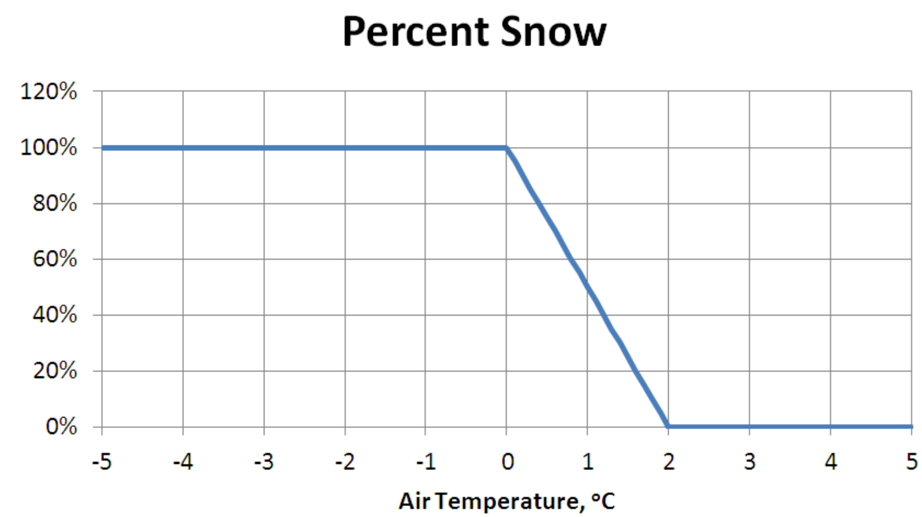
VIC Snow Algorithm



http://www.ce.washington.edu/pub/WRS/WRS161.pdf

Partitioning of Rain and Snow

The model currently uses a very simple partitioning method to determine the initial form of the precipitation.



E.g.

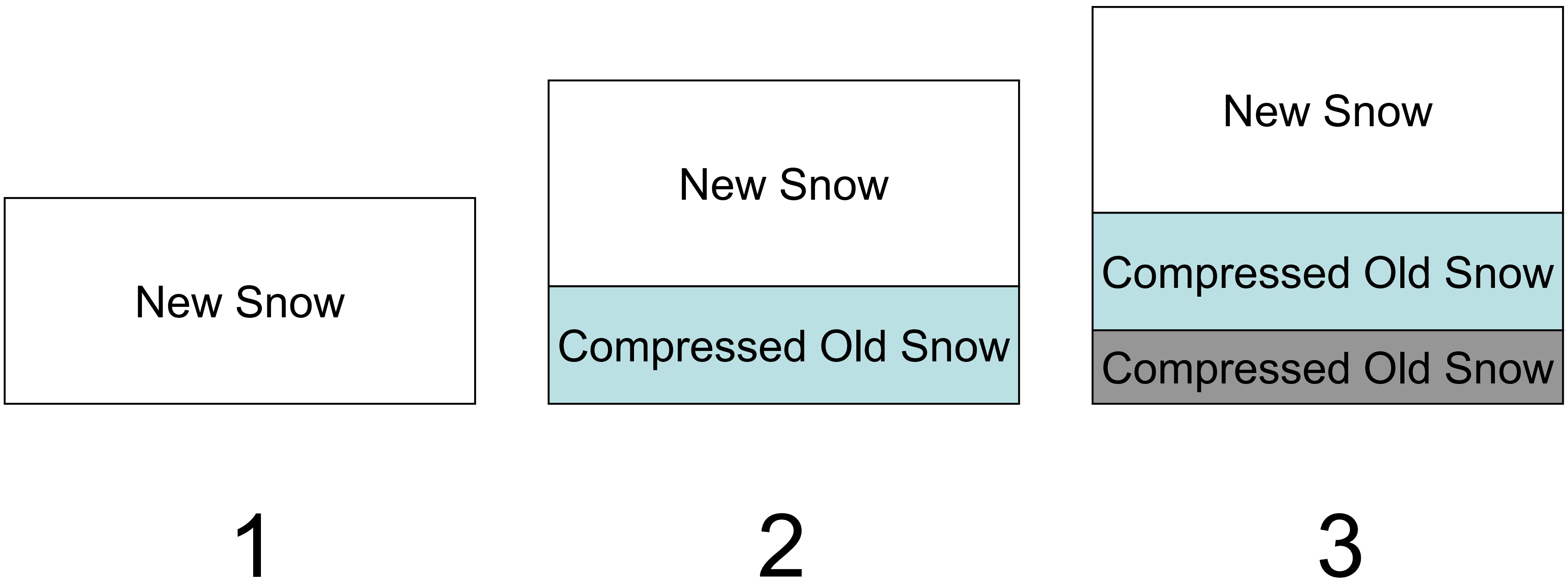
RainMin= 0.0 C
SnowMax = 2.0 C

If T <= RainMin then 100% snow

If T >= SnowMax the 100% rain.

Values in between are a linear interpolation between the two values. E.g. simulated precipitation at 0.5 degrees C would produce 75% snow, 25% rain.

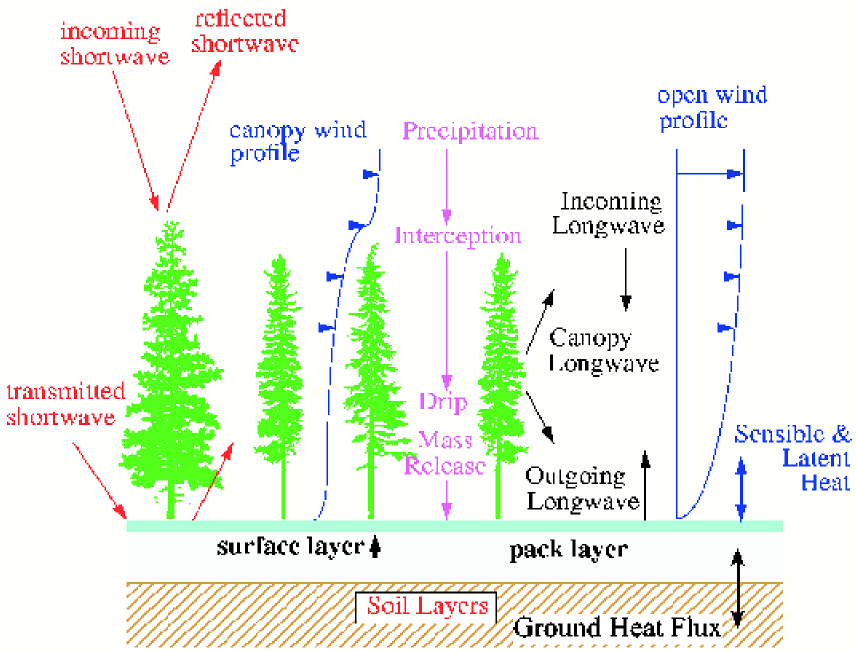
Simulated new snow accumulation compresses the existing pack using a recursive algorithm.



The model also simulates declining snow surface albedo with age of the pack as the snow surface becomes dirty.

Effects of Forest Canopy on Snow Accumulation

Loss of canopy increases the snow water equivalent and increases the rate of melt.



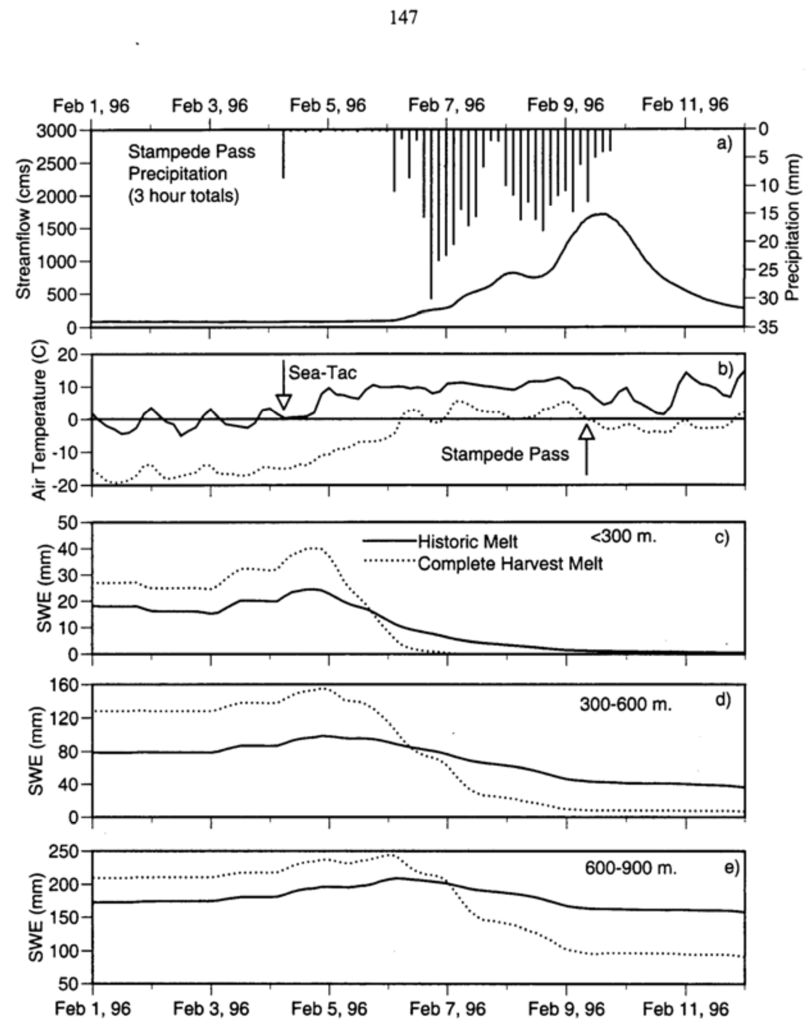


Figure 7.14. Observed micrometeorology, streamflow and predicted snowmelt during the February 1996 ROS event: a) Observed precipitation at Stampede Pass and observed streamflow at Snoqualmie at Carnation, b) observed air temperature at Seattle Tacoma International Airport and Stampede Pass, c) Predicted snow melt for the historic vegetation cover and complete harvest scenario at elevations less than 300 meters, d) same as c, but for the 300-600 m elevation band, e) same as c and d, but for the 600-900 m elevation band.

Source: Storck, P., 2000, Trees, Snow and Flooding: An Investigation of Forest Canopy Effects on Snow Accumulation and Melt at the Plot and Watershed Scales in the Pacific Northwest, Water Resources Series Technical Report No. 161, Dept of CEE, University of Washington.
http://www.ce.washington.edu/pub/WRS/WRS161.pdf

Evapotranspiration in VIC

$$E = \beta E_p$$

Three components in each elevation band and for each vegetation type:

ET

- **wet canopy evaporation**
- **dry canopy transpiration**
- **bare soil surface evaporation**

Evaporation and Transpiration

Evaporation from wet vegetation and transpiration from dry vegetation are estimated by the physically-based **Penman Monteith** approach

net radiation term, a function of incoming solar radiation (cloudiness)

vapor pressure deficit term, a function of the humidity and air temperature, with aerodynamic resistance (wind speed and surface roughness)

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

terms associated with canopy resistance and aerodynamic resistance

Bare soil calculations are similar but include a resistance term related to the soil's ability to deliver moisture to the surface (a function of upper layer moisture content and soil characteristics)

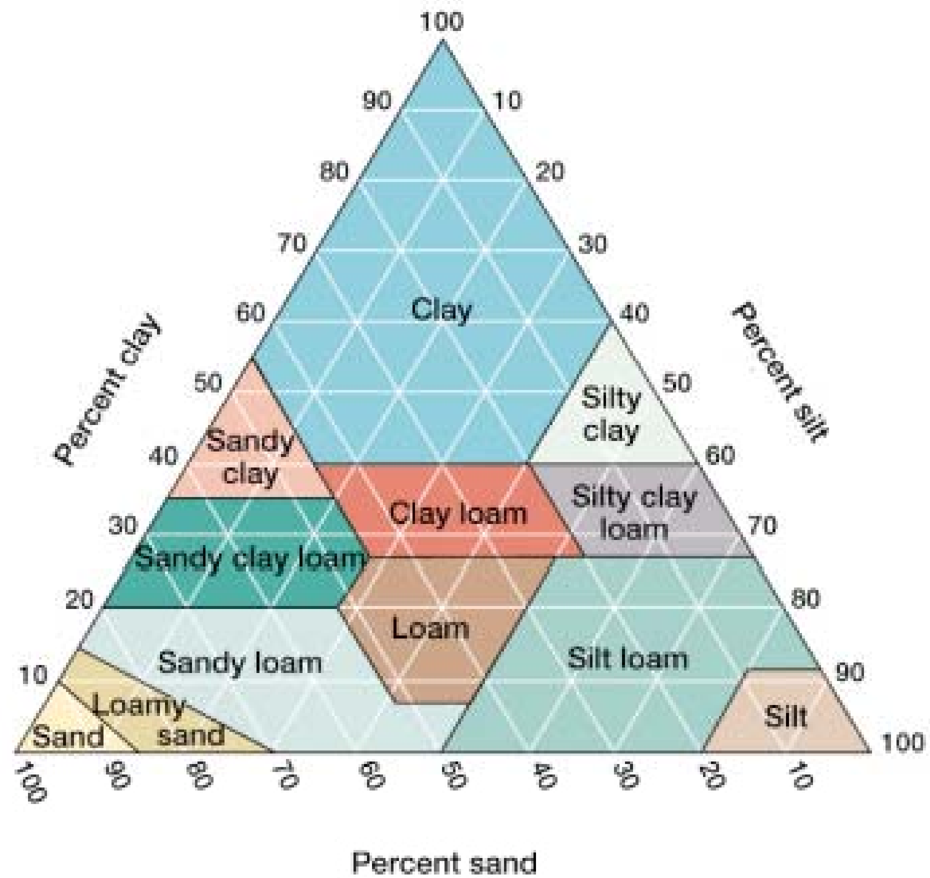
Parameterization of Soils

Soil data is poorly known. Soil texture can be obtained from USDA, FAO, etc.

Soil composition (texture) is used to estimate:

•Porosity
•Ksat
•field capacity
•wilting threshold
•residual capacity
•other soil characteristics for unsaturated flow parameterization

Use published pedo-transfer relationships



Pedo Transfer Functions

(Field Capacity) ↓ (Wilting Point) ↓

Saturated hydraulic conductivity (K_s) classified by USDA soil texture classes and porosity (Rawls et al., 1998)

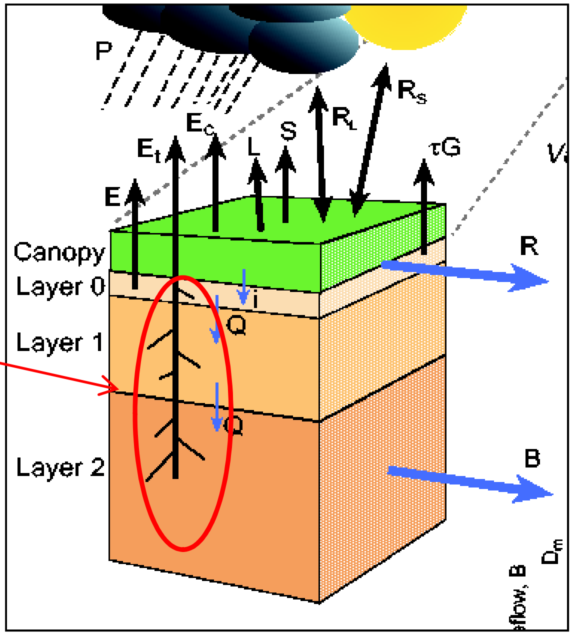
USDA Soil texture class	Geometric mean K_s[a] ($mm\ h^{-1}$)	Porosity ($m^3\ m^{-3}$)	Water retained at at −33 kPa ($m^3\ m^{-3}$)	Water retained at −1500 kPa ($m^3\ m^{-3}$)	Sand (%)	Clay (%)	Sample size
Sand	181.9 (266.8–96.5)	0.44	0.07	0.03	92	4	39
	91.4 (218.5–64.0)	0.39	0.09	0.02	91	4	30
Fine sand	141.3 (236.1–118.1)	0.49	0.07	0.03	89	3	14
	100.0 (219.8–68.1)	0.39	0.07	0.02	92	4	9
Loamy sand	123.0 (195.5–83.8)	0.45	0.09	0.04	82	6	19
	41.4 (77.6–30.5)	0.37	0.14	0.06	82	7	28
Loamy fine sand	62.2 (122.0–35.6)	0.46	0.11	0.06	82	6	18
	12.8 (116.0–6.8)	0.37	0.2	0.12	68	12	112
Sandy loam	55.8 (129.6–30.5)	0.47	0.23	0.1	65	11	75
	12.8 (31.3–5.1)	0.37	0.2	0.12	68	13	112
Fine sandy loam	22.4 (35.6–9.8)	0.45	0.24	0.1	70	14	24
	8.2 (17.0–3.4)	0.36	0.21	0.11	69	14	36
Loam	3.9 (28.4–1.6)	0.47	0.3	0.15	38	23	44
	6.2 (16.5–2.8)	0.39	0.28	0.13	43	22	65
Silt loam	14.4 (37.1–7.6)	0.49	0.34	0.14	18	19	61
	3.4 (9.9–1.0)	0.39	0.31	0.14	21	20	46
Sandy clay loam	7.7 (50.5–2.0)	0.44	0.31	0.2	56	26	20
	2.8 (10.9–1.0)	0.37	0.29	0.21	58	26	53
Clay loam	4.2 (13.1–2.2)	0.48	0.32	0.22	29	35	20
	0.7 (3.8–0.2)	0.4	0.34	0.25	35	35	53
Silty clay loam	3.7 (10.4–2.3)	0.50	0.37	0.23	10	34	26
	4.9 (14.0–2.3)	0.43	0.36	0.23	10	32	33
Sandy clay	0.9 (2.5–0.3)	0.39	0.3	0.22	51	36	14
Silty clay	1.8 (7.5–0.5)	0.53	0.41	0.27	4	49	10
Clay	2 (6.0–0.9)	0.48	0.4	0.31	18	53	20
	1.8 (6.9–0.3)	0.4	0.36	0.3	26	50	21

[a]K_s = saturated hydraulic conductivity; first line is mean value; in brackets are 25 and 75% percentile values.

Rooting depths in soil

Rooting distribution is user-specified for each vegetation type in each grid cell.

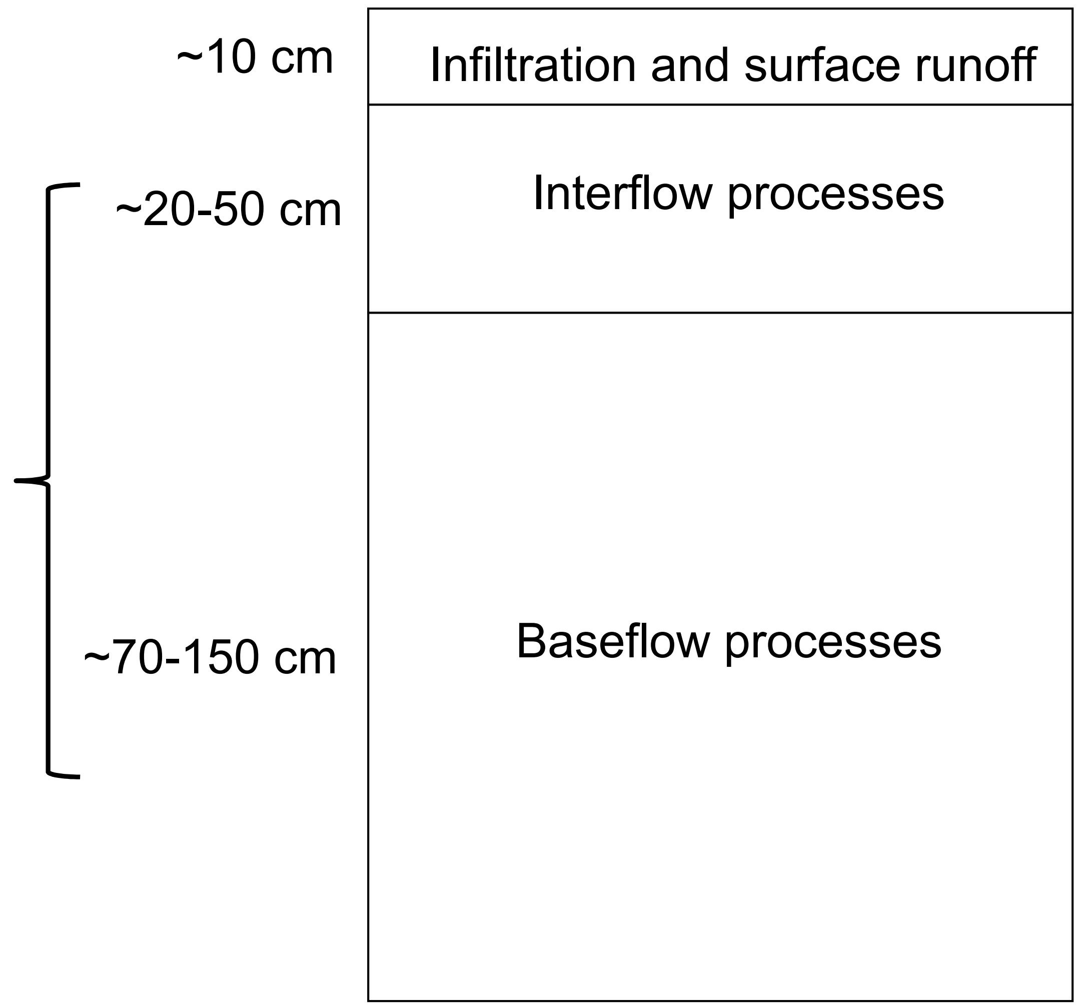
Rooting depths are independent of soil layer depths



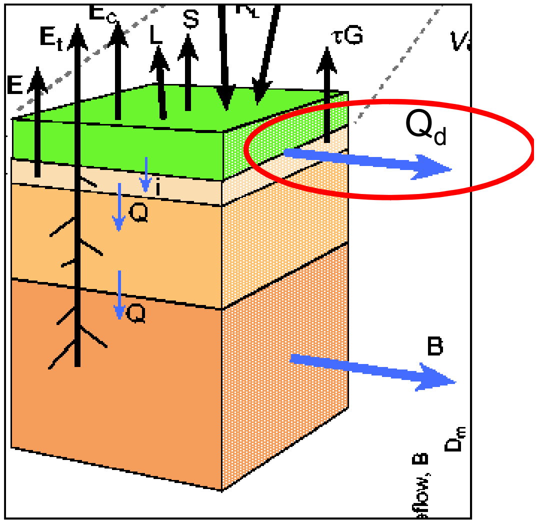
Typical Layer Depths in the Soil Column

No theoretical limit, but typical ranges are shown

Lower layer depths adjusted during calibration



Direct Runoff - Soil Infiltration



Variable infiltration curve

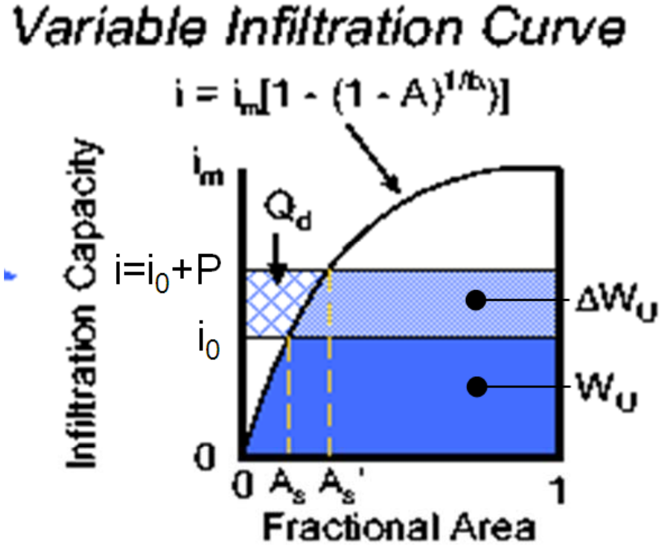
Scales maximum infiltration by non-linear function of fractional saturated gridcell area

Enables runoff calculations for subgrid-scale areas (e.g. multiple vegetation classes)

Curve defined by:

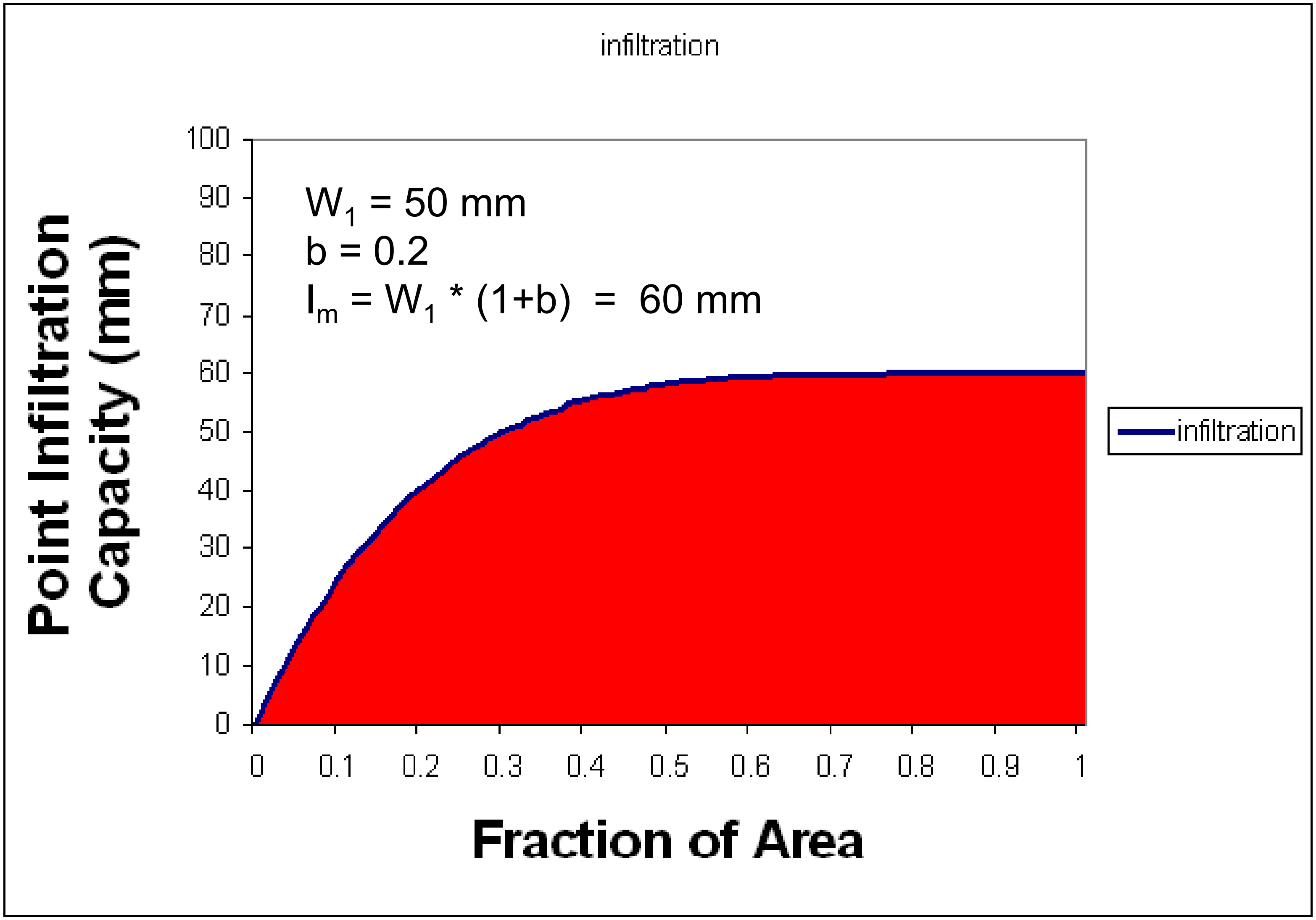
b_{inf} - [>0 to ~0.4] defines the shape of the curve. It describes the amount of available infiltration capacity as a function of relative saturated gridcell area.

A higher value of b_{inf} gives lower infiltration and yields higher rapid runoff, Q_d.



The Variable Infiltration Capacity Curve

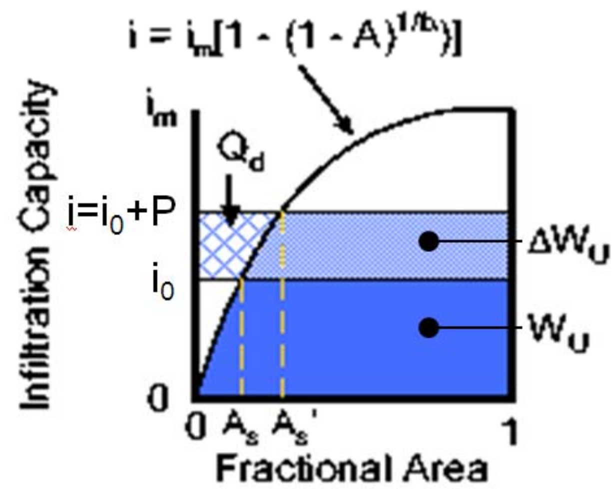
W_1 is determined by the soil depth and porosity. Selecting b determines I_m (I_{max})



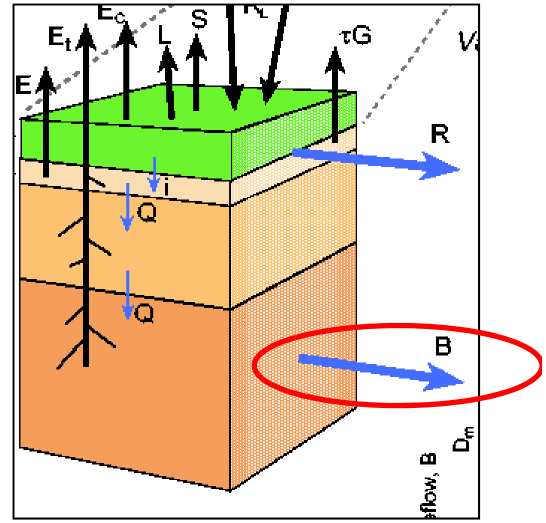
Spreadsheet exercise 1 – Infiltration curve

Using the supplied spreadsheet, vary the input data as follows, and compare the influence on direct runoff

I_o, mm	Precip, mm	b	Q_d, Direct runoff, mm
25	15	0.2	
25	15	0.5	
25	15	0.05	
25	45	0.2	
25	45	0.5	
45	15	0.2	



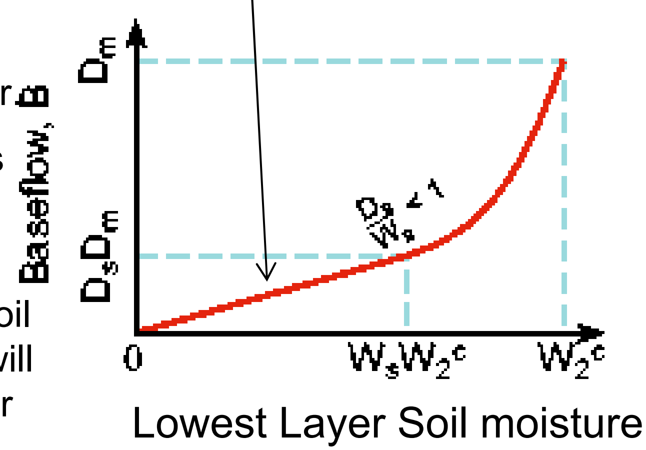
VIC Soil Drainage



Arno Baseflow Curve

- Baseflow as a function of soil moisture in the lowest soil layer
- Non-linear at high soil moisture contents, produces rapid baseflow response in wet conditions.
- Becomes linear reducing the responsiveness of baseflow in dry conditions

$$B = \frac{D_s \cdot D_{s\max}}{W_s W_2^c} \cdot W_2$$



Curve defined by:

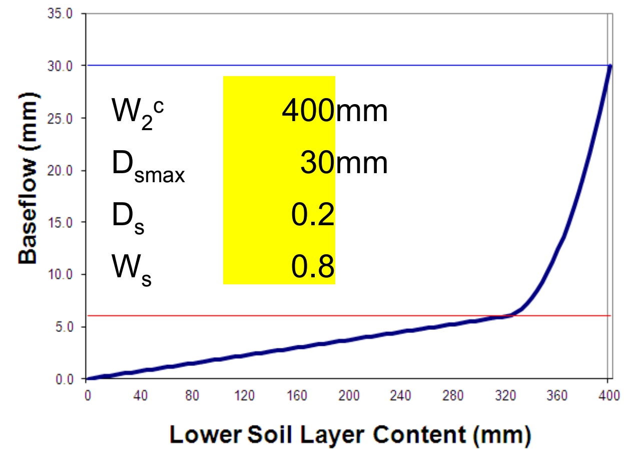
Ds - [>0 to 1] This is the fraction of Ds_{max} where non-linear (rapidly increasing) baseflow begins. With a higher value of Ds, the baseflow will be higher at lower water content in lowest soil layer.

Ds_{max} (or D_m)- [>0 to ~30, depends on hydraulic conductivity] This is the maximum baseflow that can occur from the lowest soil layer (in mm/day).

W_s - [>0 to 1] Fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs. A higher value of Ws will raise the water content required for rapidly increasing, non-linear baseflow, which will tend to delay runoff peaks.

Spreadsheet Exercise with Non-linear Baseflow Relationship

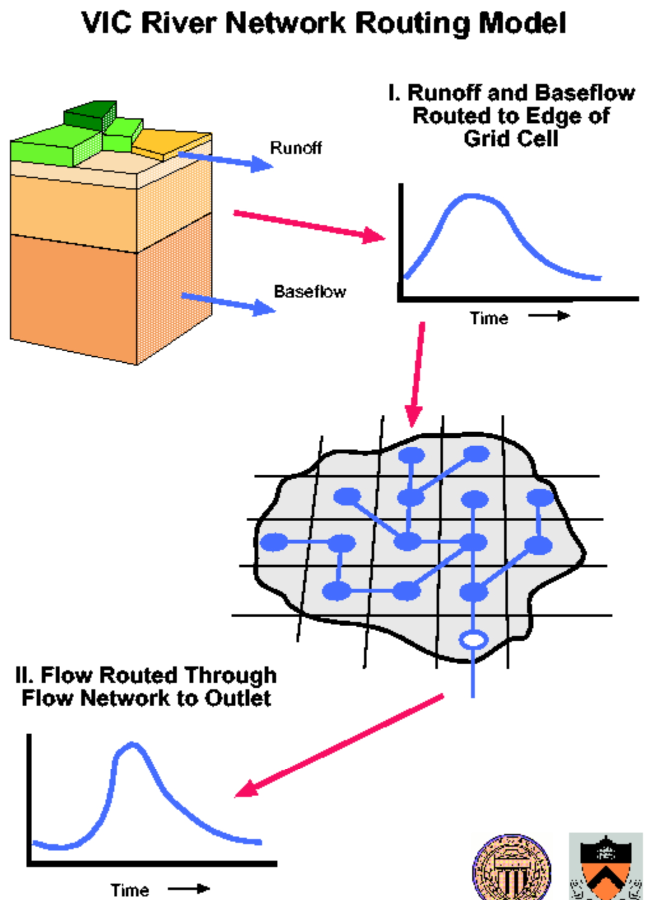
1) W_2^c (or W_m, W_{max}) is defined by soil parameters (porosity * soil column depth)
2) Select values for D_{smax}, D_s, W_s. Constraint: $D_s \leq W_s$ (Note, when $D_s = W_s$, linear relationship exists)
3) Assume during one time step the lowest layer soil moisture changes from 300 to 310 mm. Investigate the change in baseflow rate for different parameter values, for example:



D_{smax}, mm	D_s	W_s	ΔQ_{base}, mm/d
30	.2	.8	
30	.2	.6	
30	.05	.8	
5	.05	.6	
5	.4	.8	
5	.4	.6	

What combination produces higher sensitivity to moisture levels? What combination of values might produce more of a baseflow-dominated system?

Translating Runoff to Streamflow



Daily grid cell runoff routed to edge of grid cell

Daily grid cell outflow routed through river network to observation point.

Monthly hydrographs of routed daily flows can be compared to observations

Optional processes that are available in VIC

Spatially Distributing Precipitation

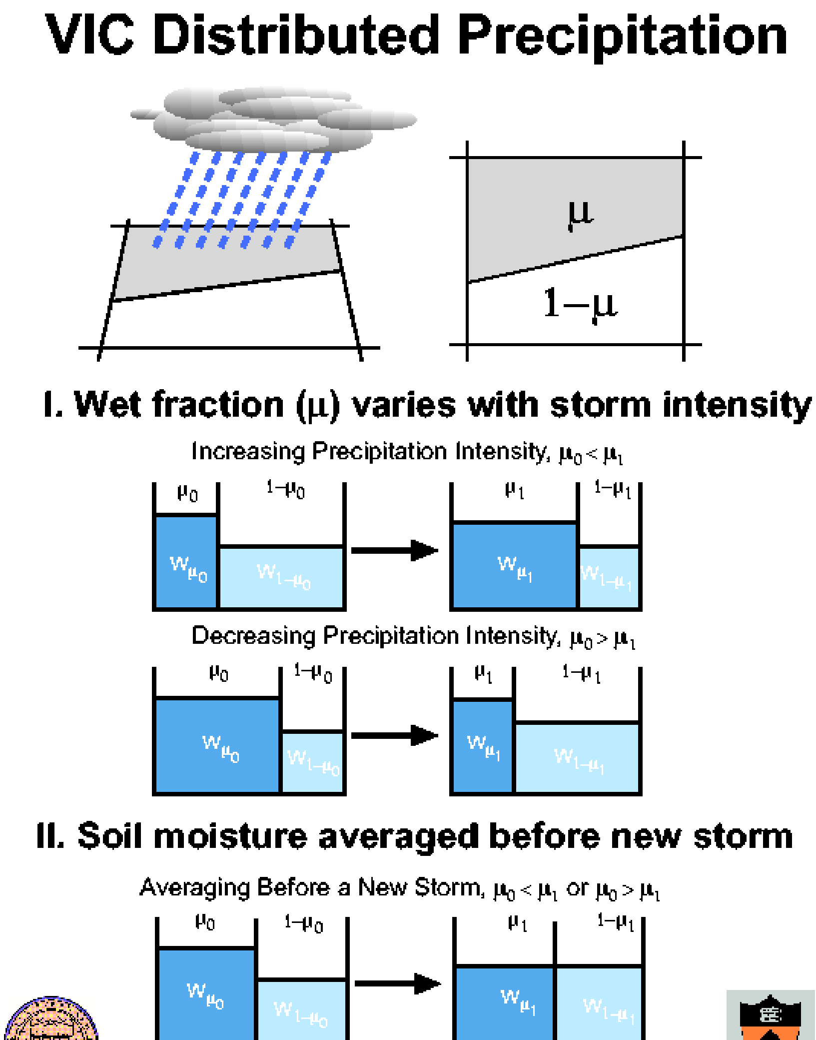
Sub-grid scale variability in precipitation

Precipitation distributed throughout all or a portion of a grid cell, as a function of the intensity of the precipitation event.

Fractional coverage of a grid cell by a precipitation event is determined based on an exponential relationship

As storm intensity increases, fractional coverage of the grid cell by the storm increases

Before a new storm event, the soil water content throughout the grid cell is set to the average value for the grid cell.



Frozen Soils

Important in cold regions

Effects of frozen soil can reduce the amount of precipitation and snow melt that can infiltrate the surface

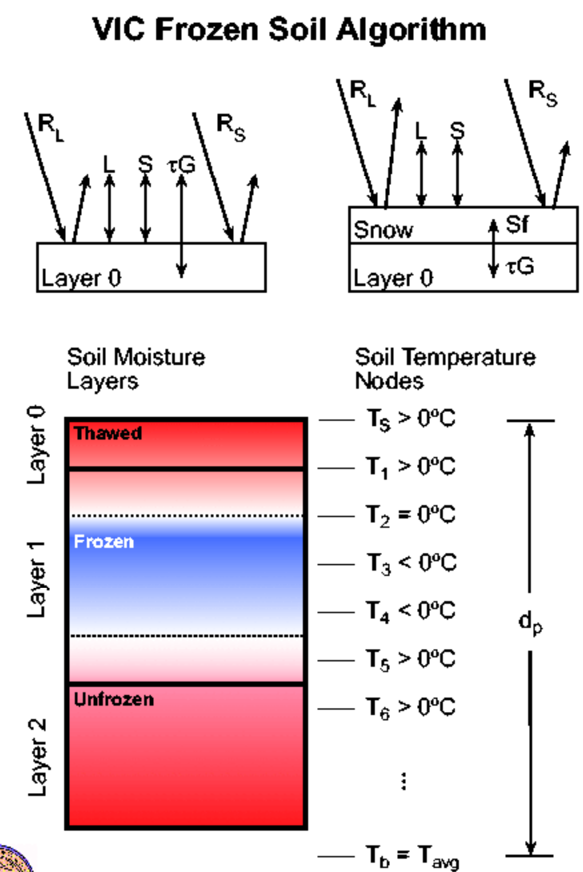
a high ice content can make the soil nearly impermeable.

Frozen soil stores more soil moisture through the winter.

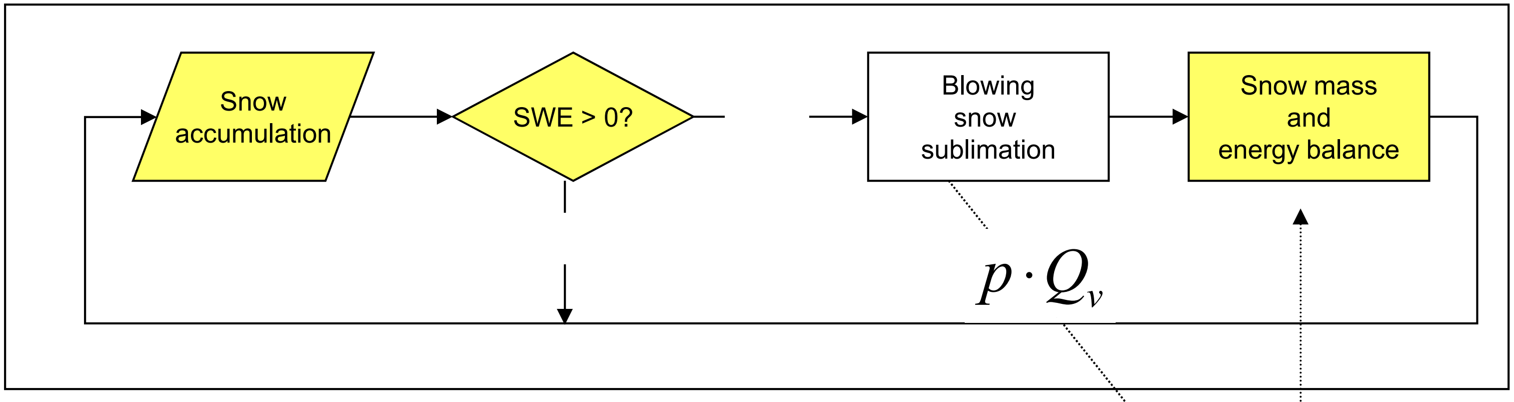
Frozen soil moisture cannot drain, or be evaporated, so spring soil moisture contents will be significantly higher in regions with frozen soil.

Soil temperatures are solved for at serveal "thermal nodes" through the soil column. The number and location of which can be defined by the user.

VIC solves the energy balance through the soil column -- surface temperature is solved iteratively to close the energy balance.



Sublimation from blowing snow



• Derived from existing small-scale blowing snow models (Pomeroy et al. 1993 and Liston and Sturm 1998).

• Particle sublimation rate proportional to the undersaturation of water vapor.

$$\frac{dW_e}{dt} = P - M - p \cdot Q_v - Q_e$$

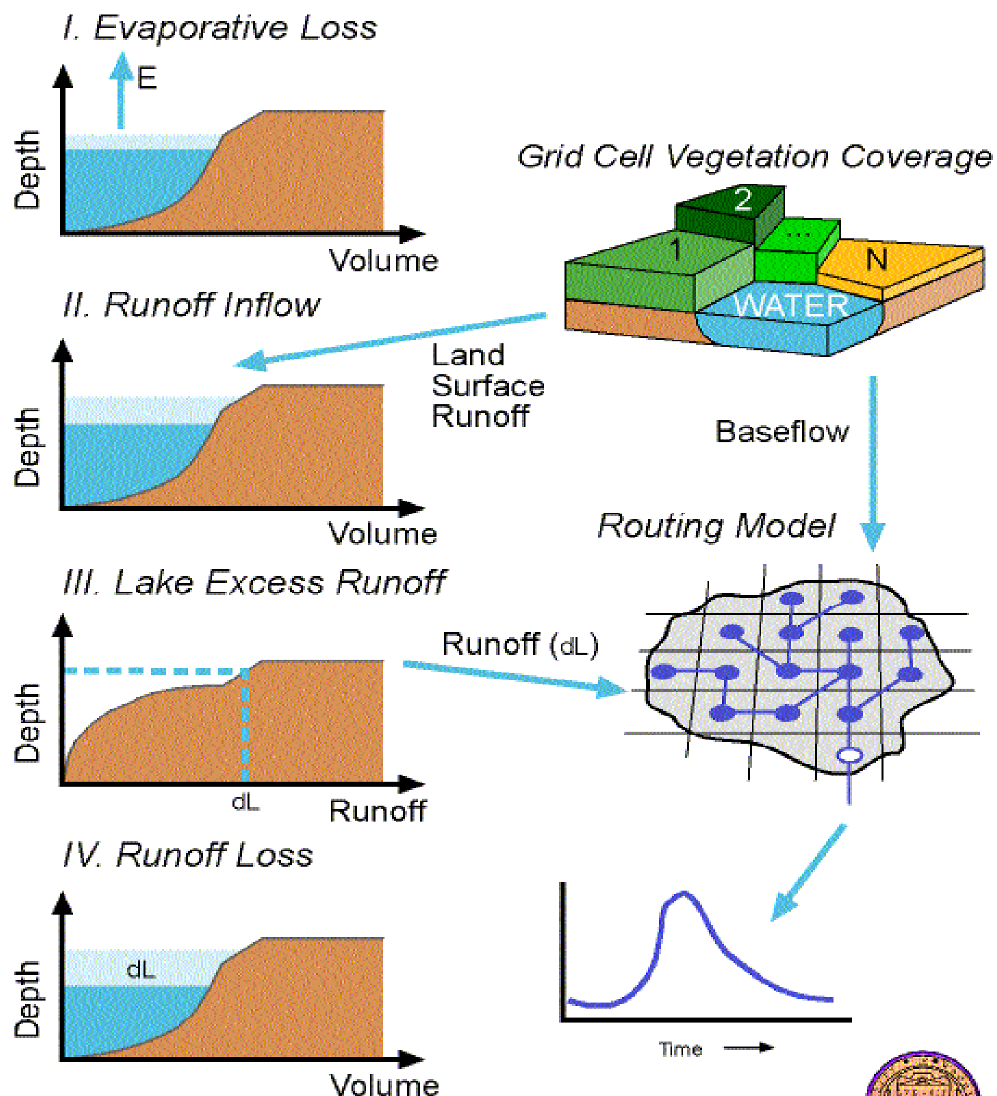
= VIC snow model

Source: L. Bowling, Purdue U.

Bowling, L. C., J. W. Pomeroy, D. P. Lettenmaier, 2004: Parameterization of Blowing-Snow Sublimation in a Macroscale Hydrology Model. *J. Hydrometeor*, **5**, 745–762.

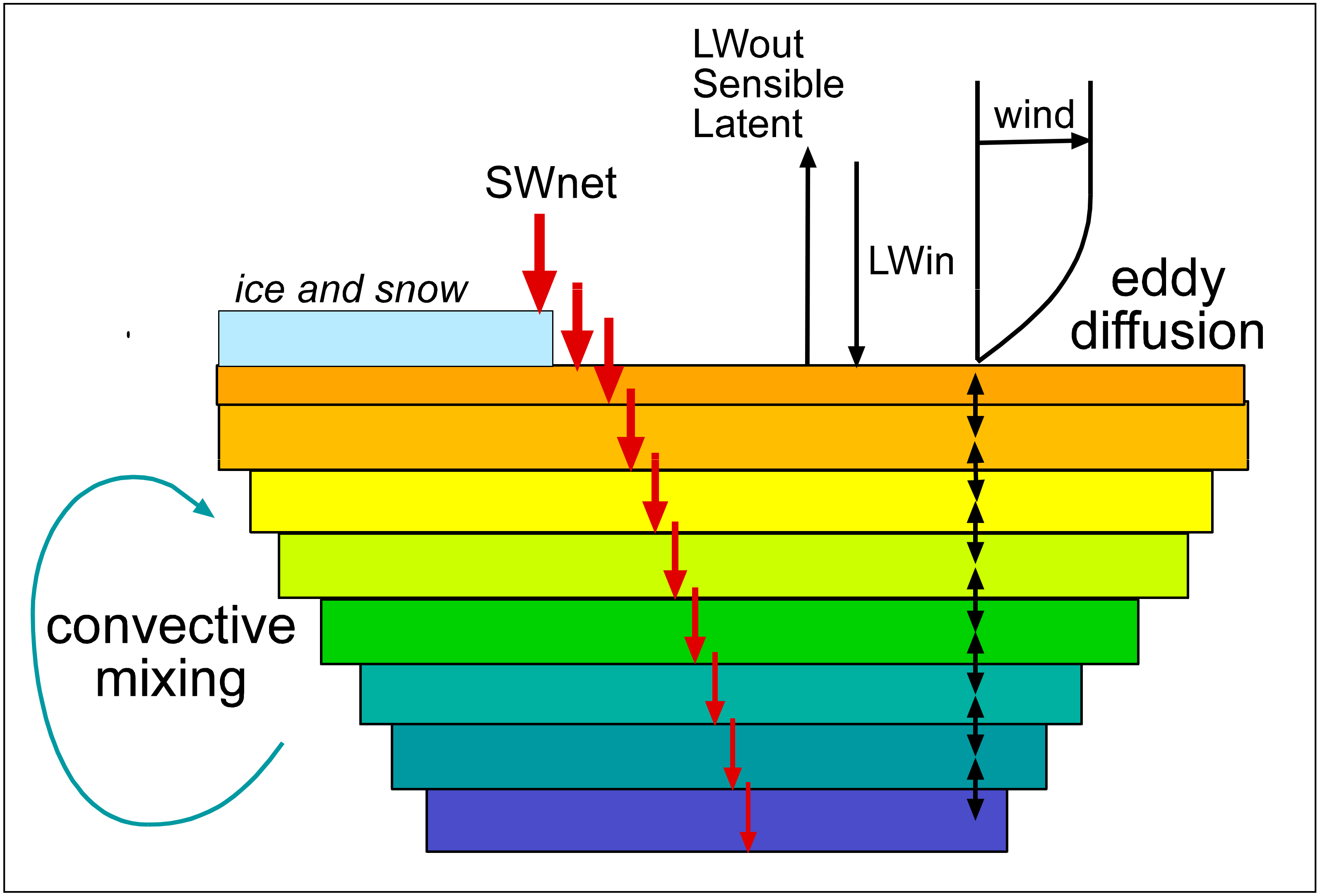
Representing Lakes and Wetlands

- Lake energy balance based on:
  - Hostetler and Bartlein (1990)
  - Hostetler (1991)
- Lake ice cover (Patterson and Hamblein)
- Assumptions:
  - One “effective” lake for each grid cell;
  - Laterally-averaged temperatures.



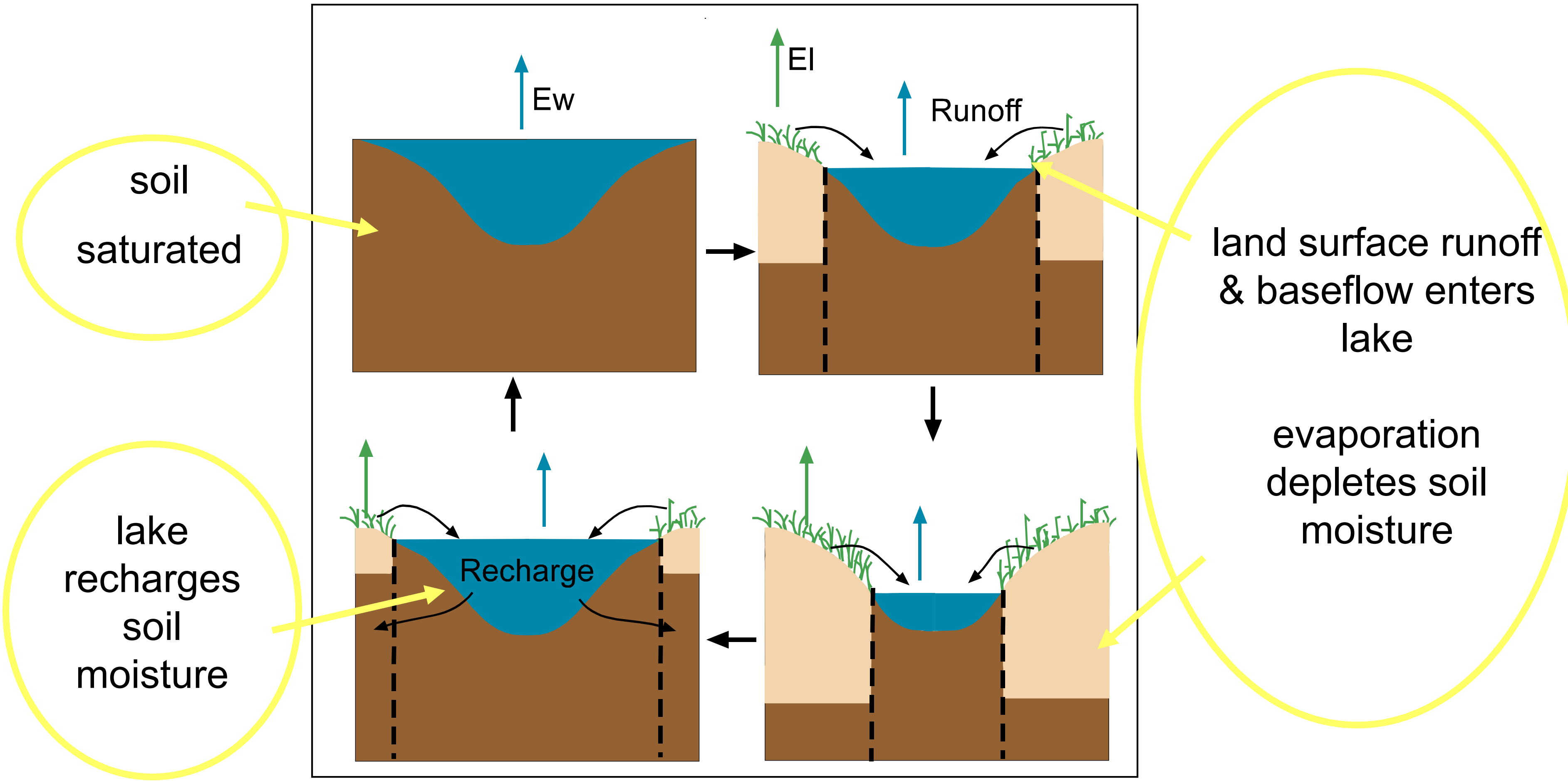
Bowling, Laura C., Dennis P. Lettenmaier, 2010: Modeling the Effects of Lakes and Wetlands on the Water Balance of Arctic Environments. *J. Hydrometeor*, **11**, 276–295

Lake energy balance



Source: L. Bowling, Purdue U.

Wetland Algorithm



Source: L. Bowling, Purdue U.

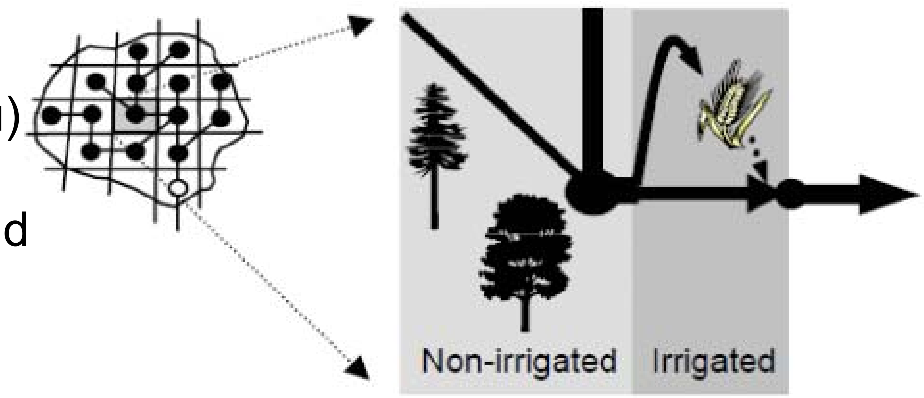
Other VIC Features and Developments

Met data preprocessor to construct full suite of hydrologic variables from limited observed driving data (precip, tmax, tmin, wind speed) (Nijssen and O'Donnell)

Implementation of hydrologic state files (an important element of using the model for hydrologic forecasting)

Incorporation in ECHAM 5 (Schnur) GCM and MM-5 meso-scale climate model (Zhu)

Irrigation and reservoir scheme [Haddeland et al., J. Hydrology 324(1-4):210-223, 2006]



In Progress: Carbon cycle dynamics (Bohn), dynamic crops (WSU)

VIC Simulation Modes

***Water Balance Mode*:**
Assumes the surface temperature is equal to the air temperature and solves the water balance. The snow model, however, is always run as an energy balance computation (with independent time step).

***Full Energy*:**
Solves the surface energy balance to determine surface temperature. A number of options are available for simulating the subsurface heat budget and ground heat flux algorithms.

See:

http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Technical_Notes/NOTES_model_modes.html

Model Forcing Data

- **Sub-daily air temperature (°C)**
- **Surface albedo (fraction)**
- **Atmospheric density (kg/m^3)**
- **Precipitation (mm)**
- **Atmospheric pressure (kPa)**
- **Shortwave radiation (W/m^2)**
- **Daily maximum temperature (°C)**
- **Daily minimum temperature (°C)**
- **Atmospheric vapor pressure (kPa)**
- **Wind speed (m/s)**

Required

Common Driving Meteorological Data Formats

ASCII
Binary (4-byte floats)
Custom Binary (2-byte integers)

Description of 2-byte integer conversion:

Precipitation: multiply by 40 and archive as a 2-byte unsigned integer value.

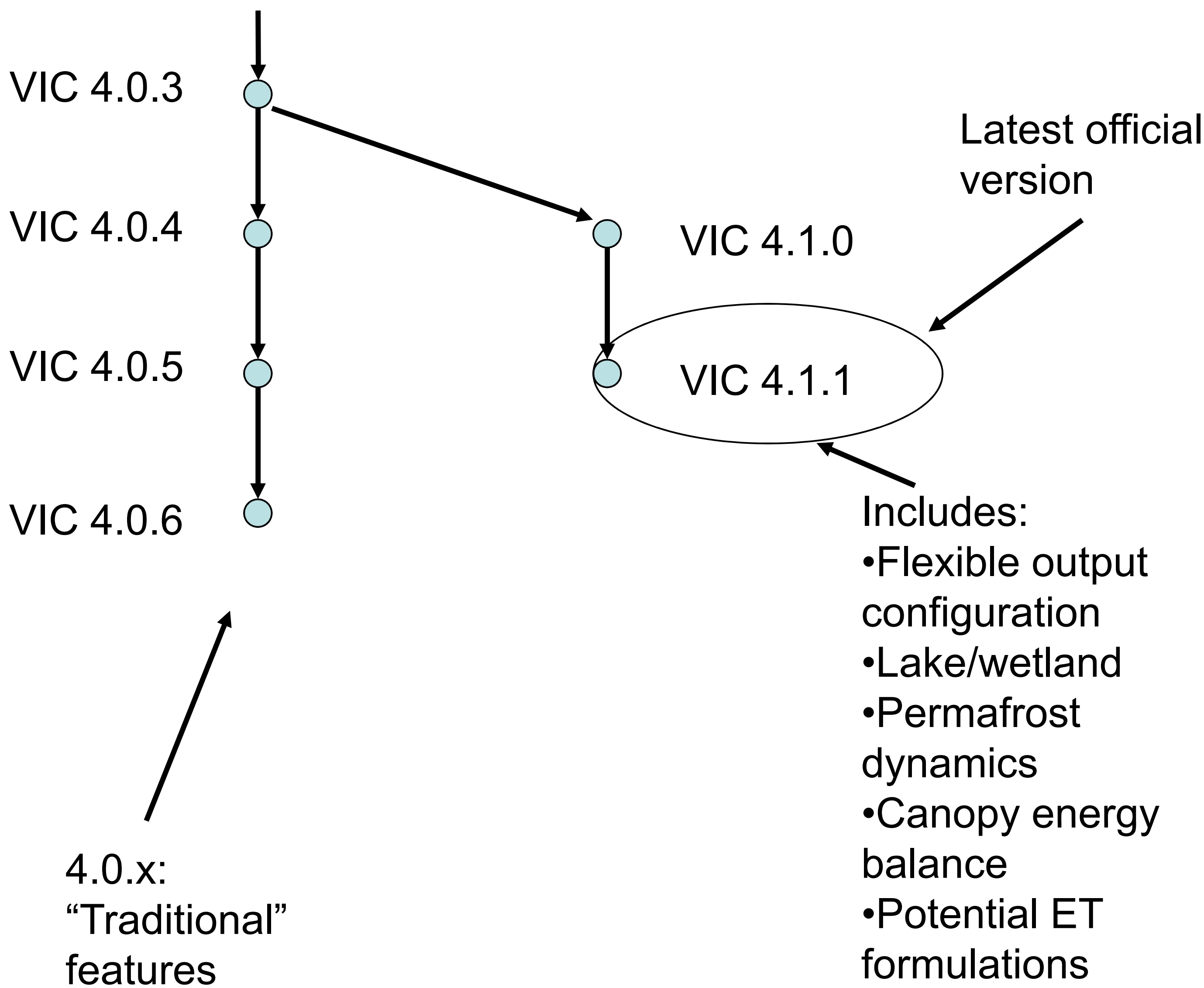
(e.g. 25.6 mm is archived as the integer value 1024)

Temperature and wind speed: multiply by 100 and archive as a 2-byte signed integer value.

(e.g. -13.567 C is archived as the integer value -1357)

Note that precision is intentionally limited in the case of the 2-byte binary format.

Versions of VIC



Computer Issues

VIC runs cell by cell, and can be very efficiently parallelized by dividing the run into separate runs for sub-groups of cells that together cover the entire area of interest.

VIC is typically run using the UNIX operating system (LINUX). LINUX clusters are also being used frequently, but because the runs are executed cell by cell there is not necessarily a great advantage to doing so.

VIC typically uses about 5 meg of RAM when running and RAM usage does not increase with basin size! Considerable disk storage is required for driving data and output, however, and these are dependent on basin size, output time step, etc.

The Gnu free C compiler is specified in the VIC make file and there is little reason to deviate from this choice. Use of another compiler may work, but requires testing.

The model can be successfully run on MS Windows machines using CYGWIN, which emulates a UNIX environment. Many pre-processing and post-processing scripts produced by UW and others require the C shell, which is not identical to the shell used by CYGWIN.

VIC Web Site

http://www.hydro.washington.edu/SurfaceWaterGroup/Models.html

Use the most recent versions of the VIC code and data processing code

Many pre- and post-processing routines are available at the same site