A Review of the Hydrologic Cycle
(Foundation for the Wise Use of Natural Resources)

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Connecting with Ground Water - Minnesota Ground Water Association Spring Meeting
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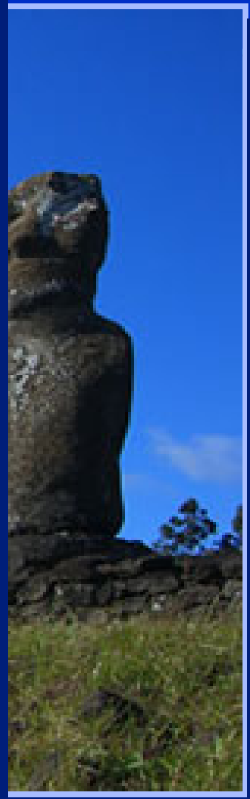
Lessons from Easter Island

(Jared Diamond - Collapse)

Brief History:

- Polynesian settlers: ~ 900 A.D.
- Statues ~ 1300 to 1600
- Peak population: 15,000 or more
- Population crash: ~1600
- 1st European explorer: 1722
- Small pox epidemics: ~ 1836
- 111 islanders by 1872



Most Famous Features:

- 887 statues (moia)
- 300 support structure (ahu)
- Average: 13 feet, 10 tons
- Largest: 32 feet, 87 tons
- In quarry: 70 feet, 270 tons

Wise Management of Resources?

Bad Times:

- Destruction of bird populations
- No canoes for fishing porpoises
- Large erosion, nutrient leaching
- Insufficient food supplies
- Larger statues for gods to improve prosperity
- Society collapses into civil war
- Cannibalism

Outline

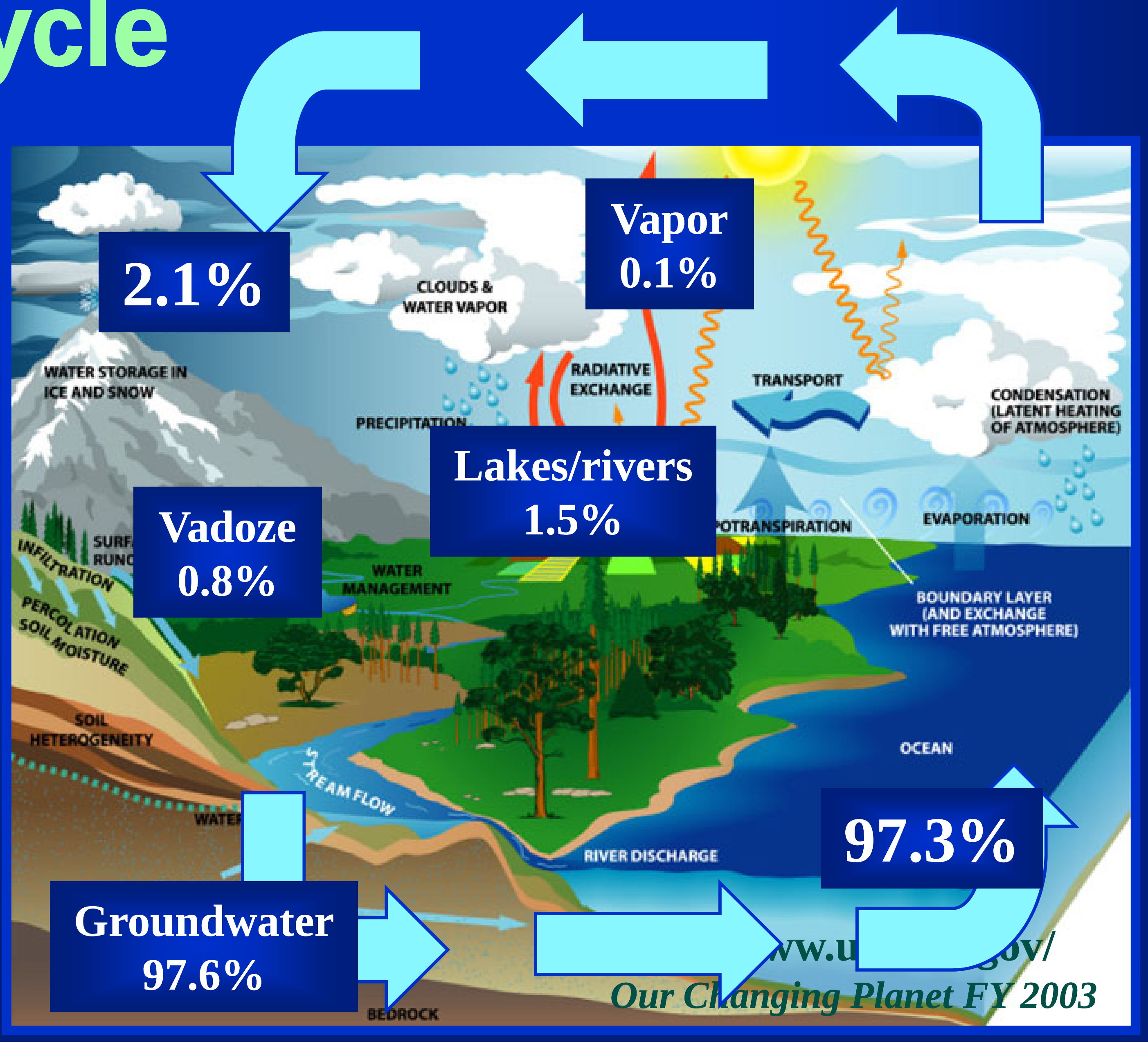
- The Cycle
- Water balance & applications
- Thoughts on modeling the Cycle
- Cold climate considerations

Water Cycle

Global Breakdown

Other < 1%

Freshwater Breakdown



Water Withdrawal

	Total (mgal/d)	Ground Water	Surface Water
U.S.	408,000 (1432 gal/d/person)	21%	79%
MN	3,870 (787 gal/d/person)	19%	81%

http://pubs.usgs.gov/circ/2004/circ1268/index.html

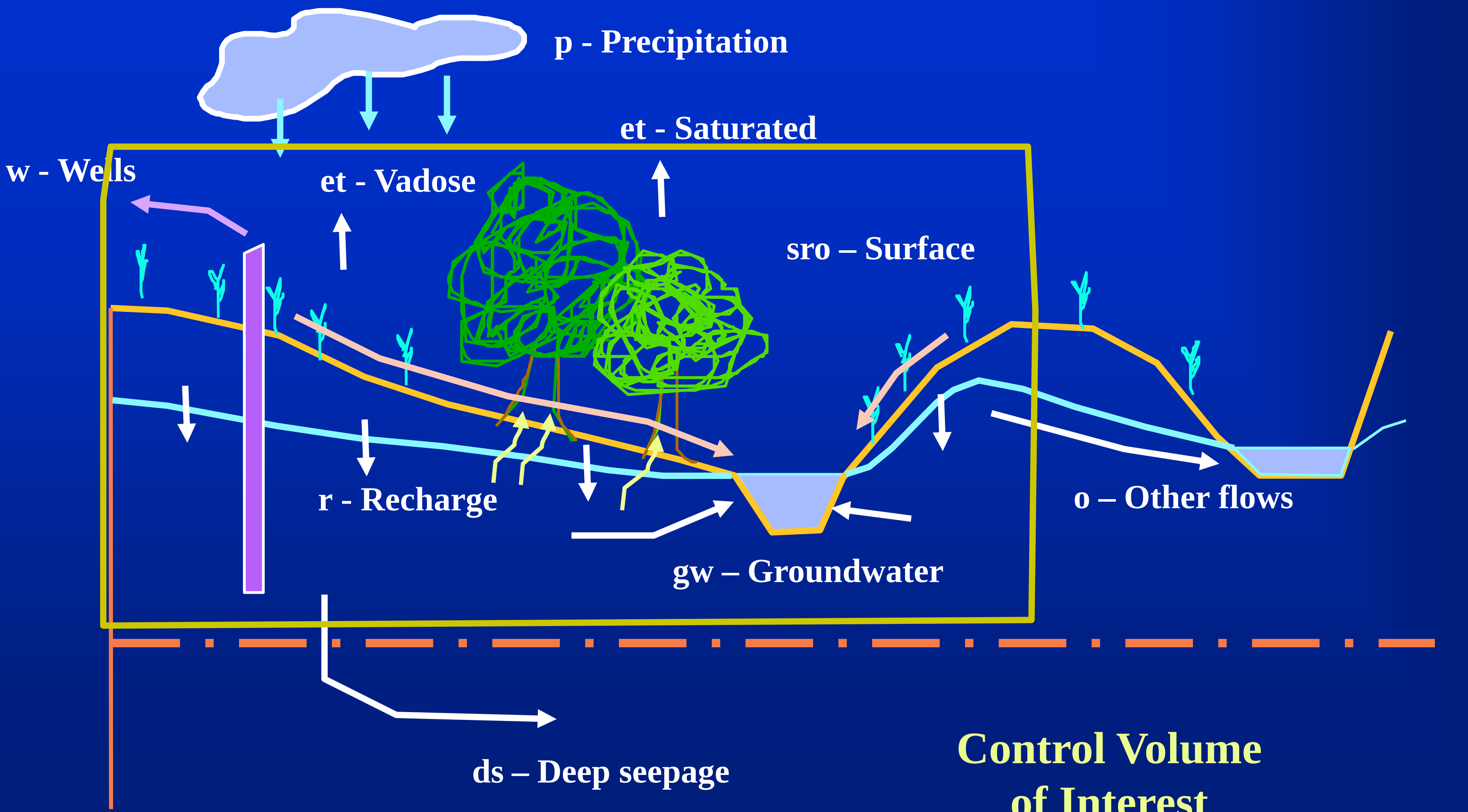
Freshwater Uses

Use	US	MN
Domestic (self-supplied)	1.0%	2.1%
Irrigation	39.7%	5.9%
Livestock	0.5%	1.4%
Industrial	5.4%	4.0%
Mining	0.6%	15.2%
Thermo Power	39.7%	58.6%
Public Supply (25+ people, 77% MN)	12.6% (179 gal/d/p, GW=37%)	12.9% (133 gal/d/p, GW=66%)

http://pubs.usgs.gov/circ/2004/circ1268/index.html

Water Balance

ro = Runoff = sro + gw



Control Volume
of Interest

Mass Balance: i – o = ds/dt

Instantaneous Rates

Inflows

Outflows

$$p - gw - sro - et - w - ds - o = \frac{ds}{dt}$$

Long-term Depths

$$\frac{1}{A_w}\left[\int_0^T p\,dt - \int_0^T gw\,dt - \int_0^T sro\,dt - \int_0^T et\,dt - \int_0^T w\,dt - \int_0^T ds\,dt - \int_0^T o\,dt\right] = \int_{S(0)}^{S(T)} ds$$

$$P - GW\left(\frac{A_{gw}}{A_w}\right) - SRO - ET - W - DS \approx 0$$

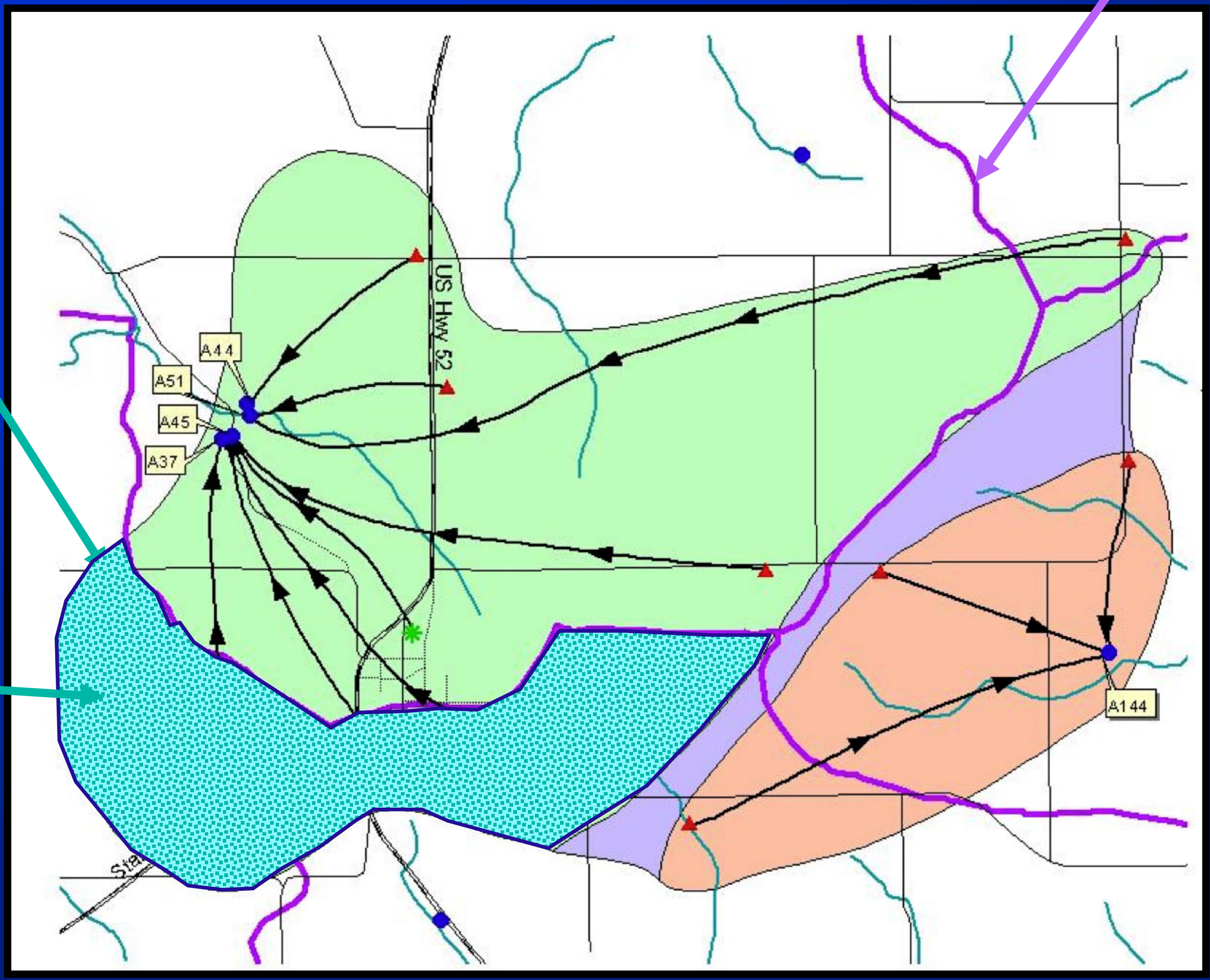
Area Fraction: $f_a = A_{gw} / A_w$

Area Fraction

Watershed Boundaries

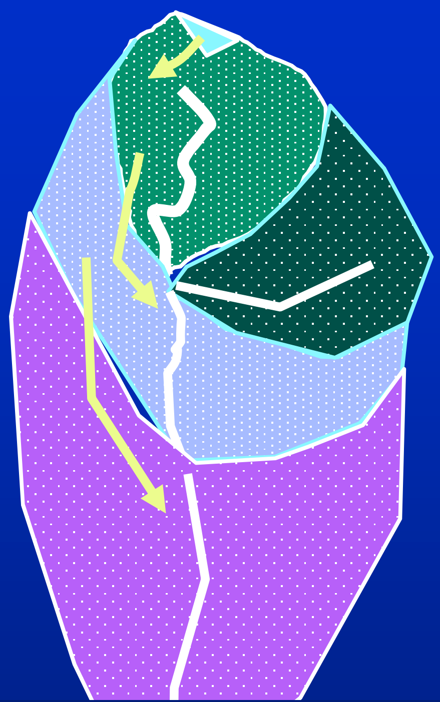
Springshed Boundaries

Additional Area



From S.C. Alexander, E.C. Alexander Jr.,A. Luhmann, J. Green & A. Peters

Scaling Issues (data from Harold et al, 1986)



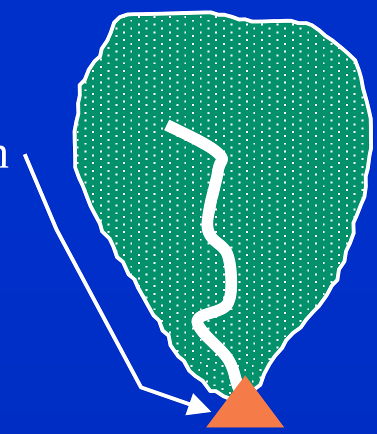
Area (ac)	Annual RO (in)	DS+O? (in)
10	6	9
50	10	5
100	12	3
300	13	2

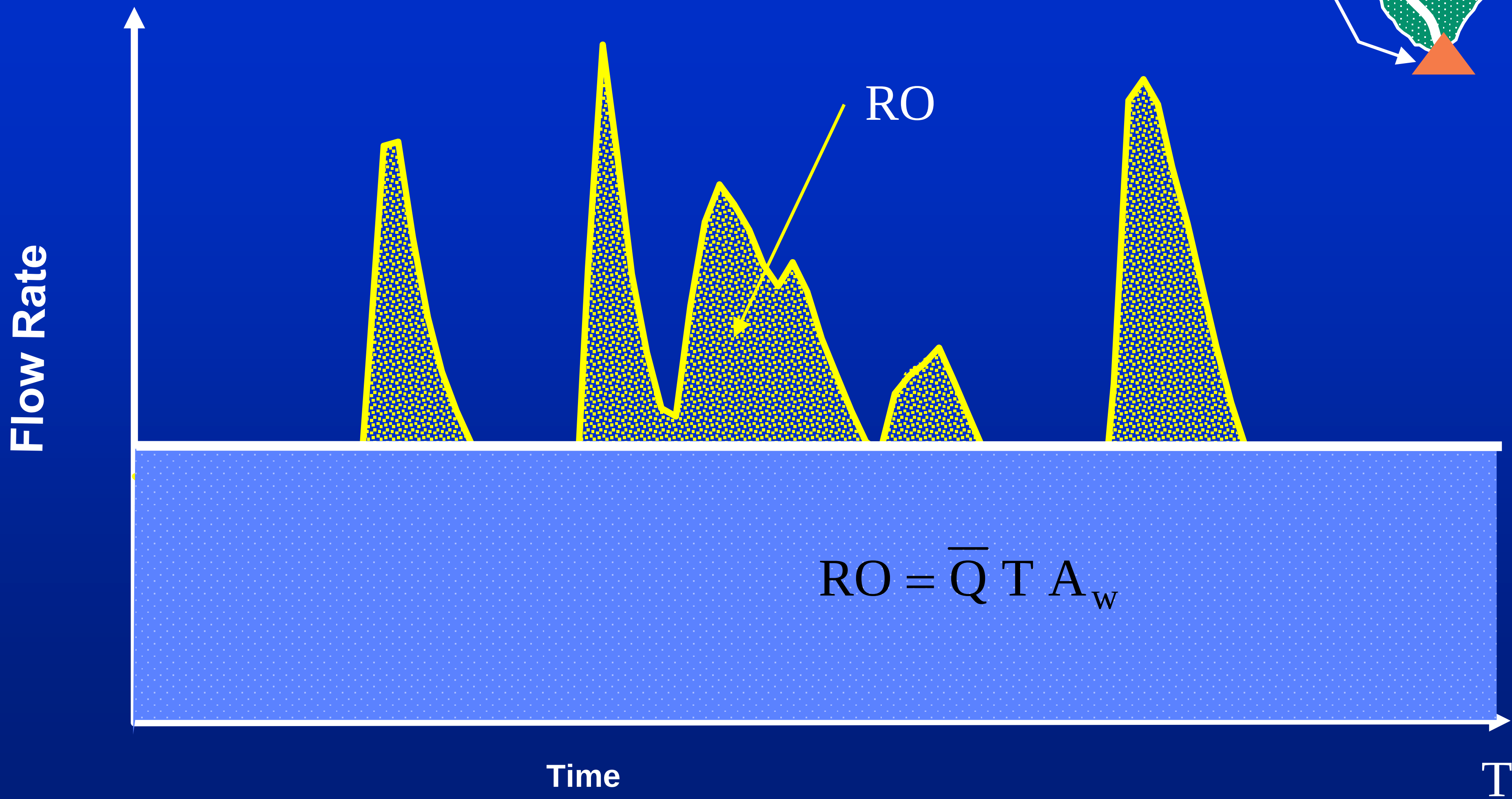
Wilson Intuition: Loss from one watershed is gained in another watershed. Likely negligible large area. Area fraction usually taken as one. DS frequently neglected.

Flow Data

Average Flow Rate

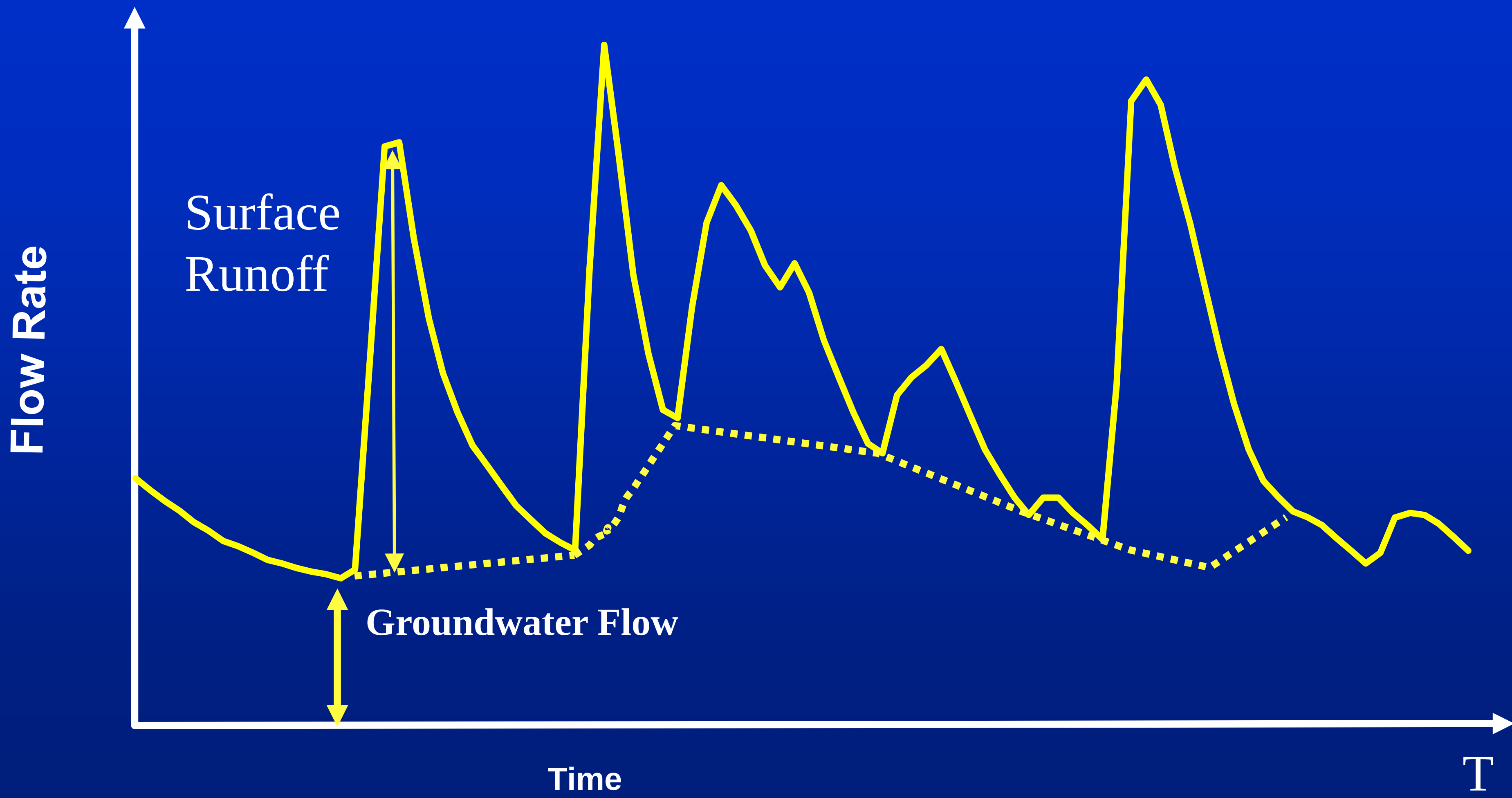
$$\overline{Q} = \frac{1}{TA_w}\left[\int_0^T ro\,dt\right] = \frac{RO}{TA_w}$$

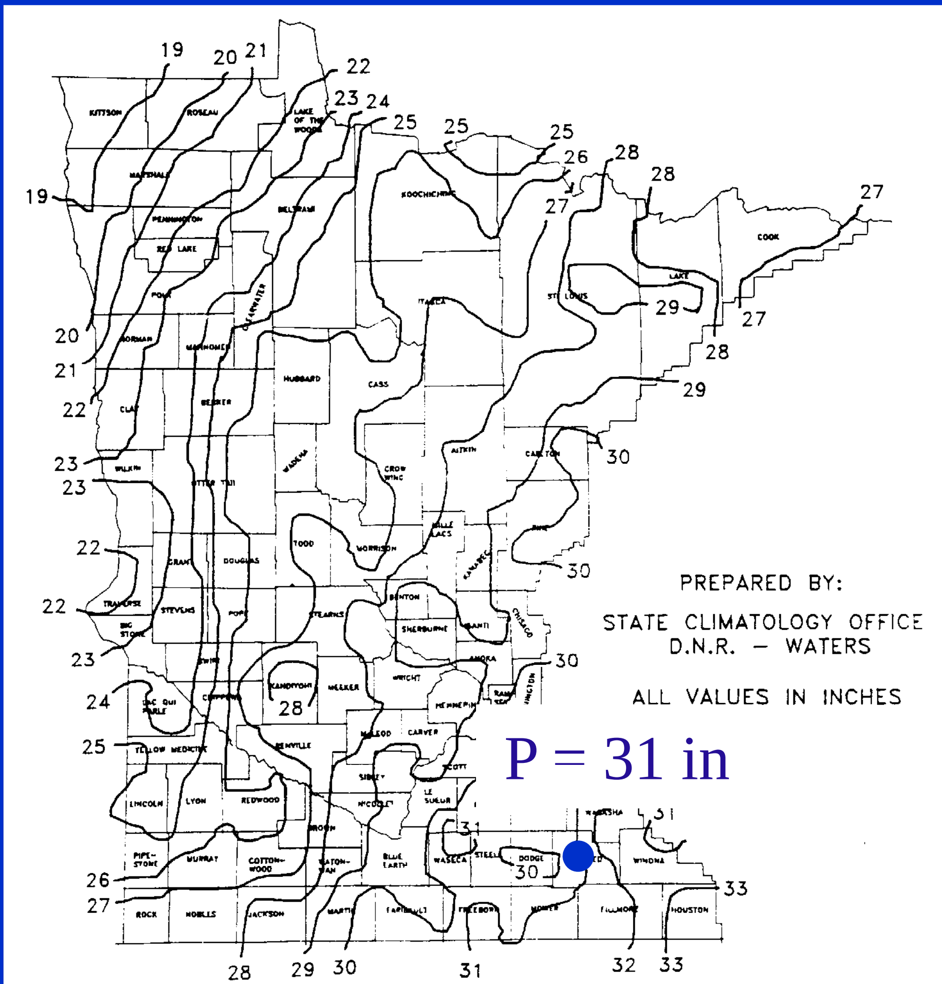


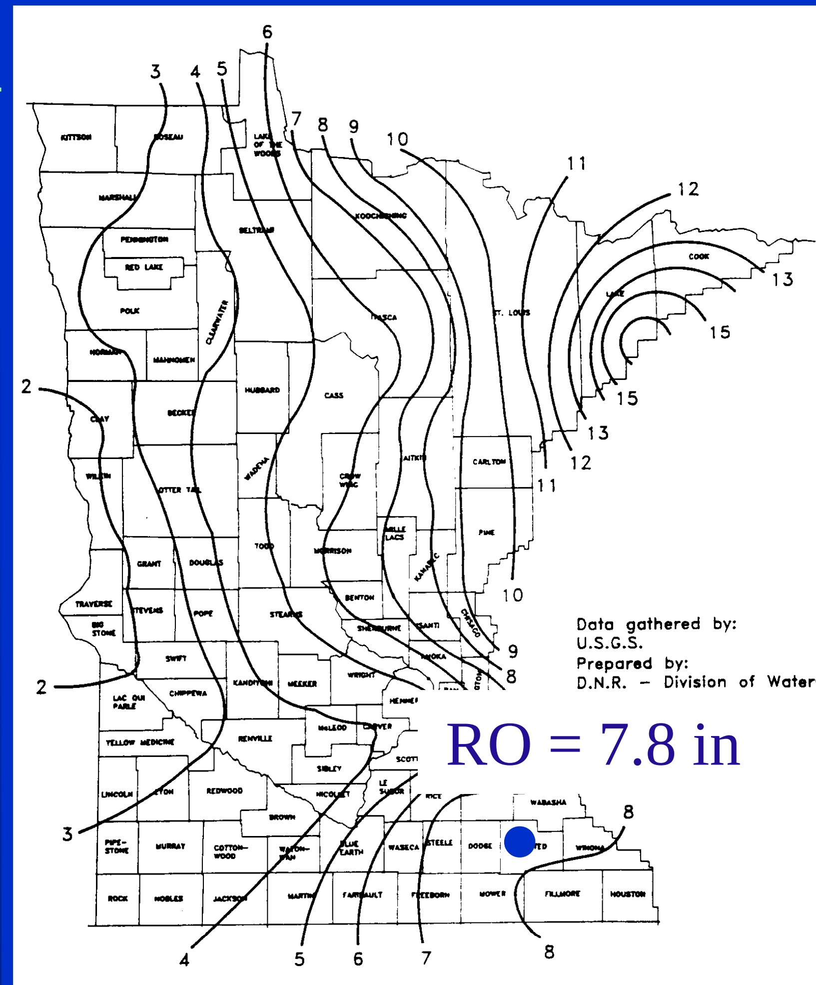


Groundwater Flow

GW = RO - SRO



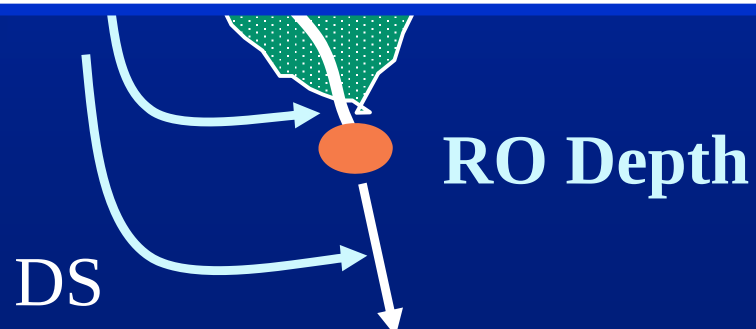




= ΔS

≅ 0

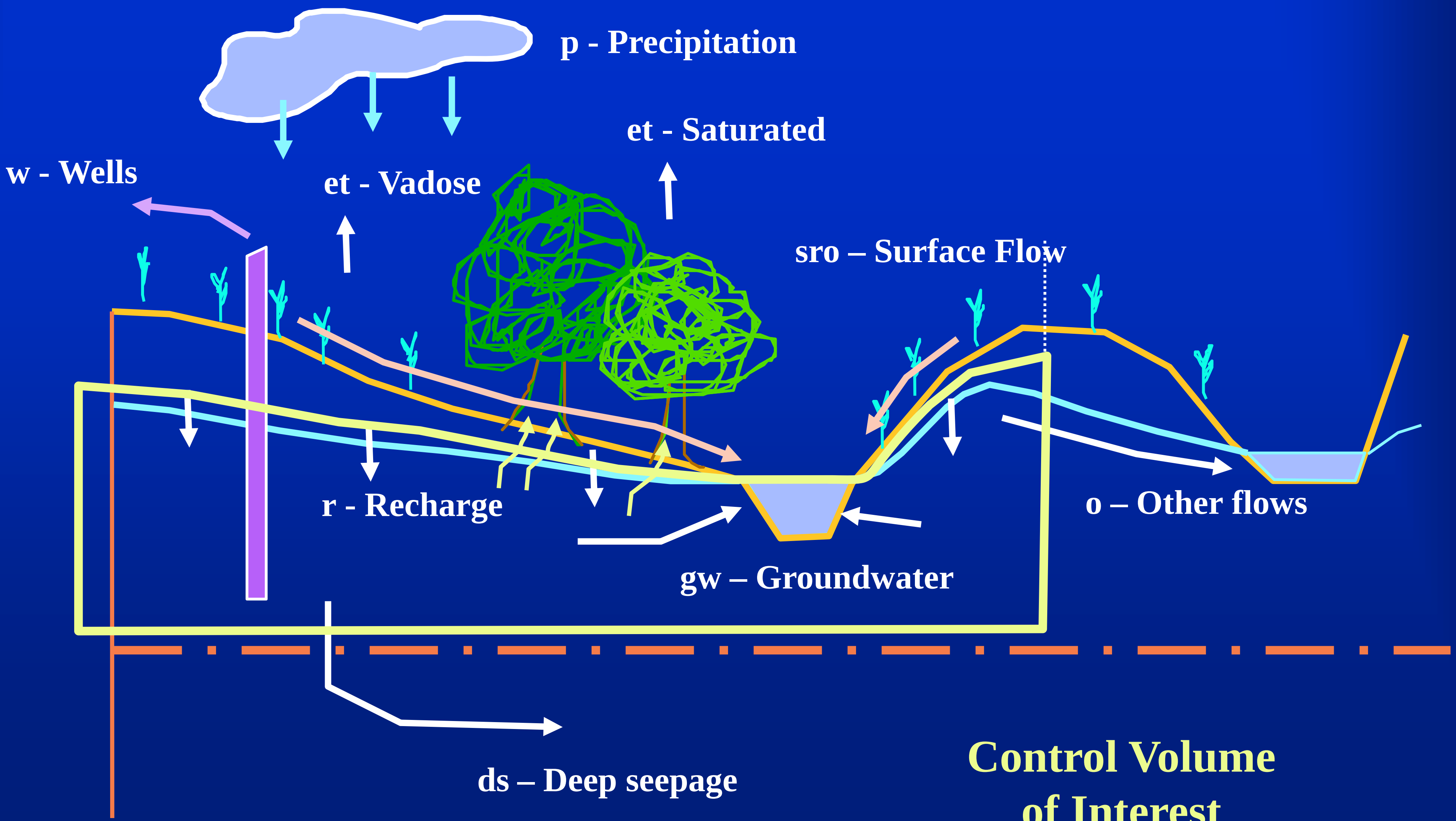
1



ET = P - RO

ET = 31 – 7.8 = 23.2 in (75% of P)

Water Balance - Revisited



Mass Balance: i – o = ds/dt

Instantaneous Rates

Inflows

Outflows

$$r - gw - et - w - ds - o = \frac{ds}{dt}$$

Long-term Depths

$$\frac{1}{A_w}\left[\int_0^T r\,dt - \int_0^T gw\,dt - \int_0^T et\,dt - \int_0^T w\,dt - \int_0^T ds\,dt - \int_0^T o\,dt\right] = \int_{S(0)}^{S(T)} ds$$

$$R - GW - ET - W - DS - O \approx 0$$

Recharge Estimates

Recharge: $$R = GW + ET + W + DS + O$$

Effective Recharge for sustainability?

$$R_e = R - ET = RO - SRO + W + DS + O$$

If SRO ≈ W + DS + O (underestimate), nearly maximum effective recharge rate:

$$r_e \approx \frac{RO}{T\,A_w} = \frac{\overline{Q}\,T\,A_w}{T\,A_w} = \overline{Q}$$

RechargeEvaluation of Terms

Recharge: $R = GW + ET + W + DS + O$

Wells (W): DNR Withdrawal Records

Groundwater depth (GW):

Annual Ave Flow

$$GW = RO - SRO$$

$$R = RO - SRO + ET + W + DS + O$$

if SRO ≈ W + DS + O + ET?

$$r \approx \frac{RO}{T A_w} = \frac{\bar{Q} T A_w}{T A_w} = \bar{Q}$$

Effective recharge for sustainability?

$$R_e = R - ET = RO - SRO + W + DS + O$$

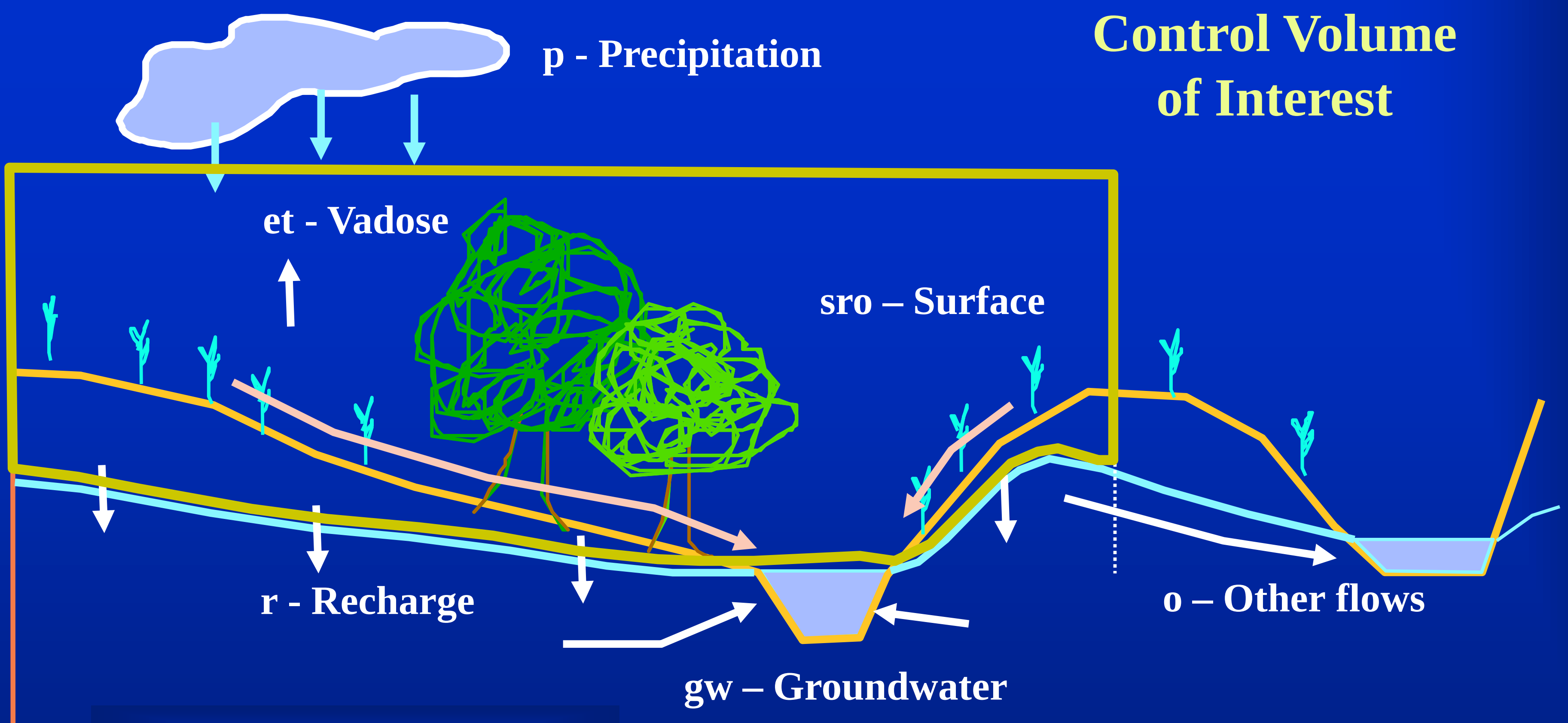
If DS ≈ O ≈ 0

$$r_e \approx \frac{RO - SRO + W}{T\,A_w}$$

If SRO ≈ W + DS + O (underestimate), nearly maximum effective recharge rate:

$$r_e \approx \frac{RO}{T\,A_w} = \frac{\overline{Q}\,T\,A_w}{T\,A_w} = \overline{Q}$$

More Water Balance



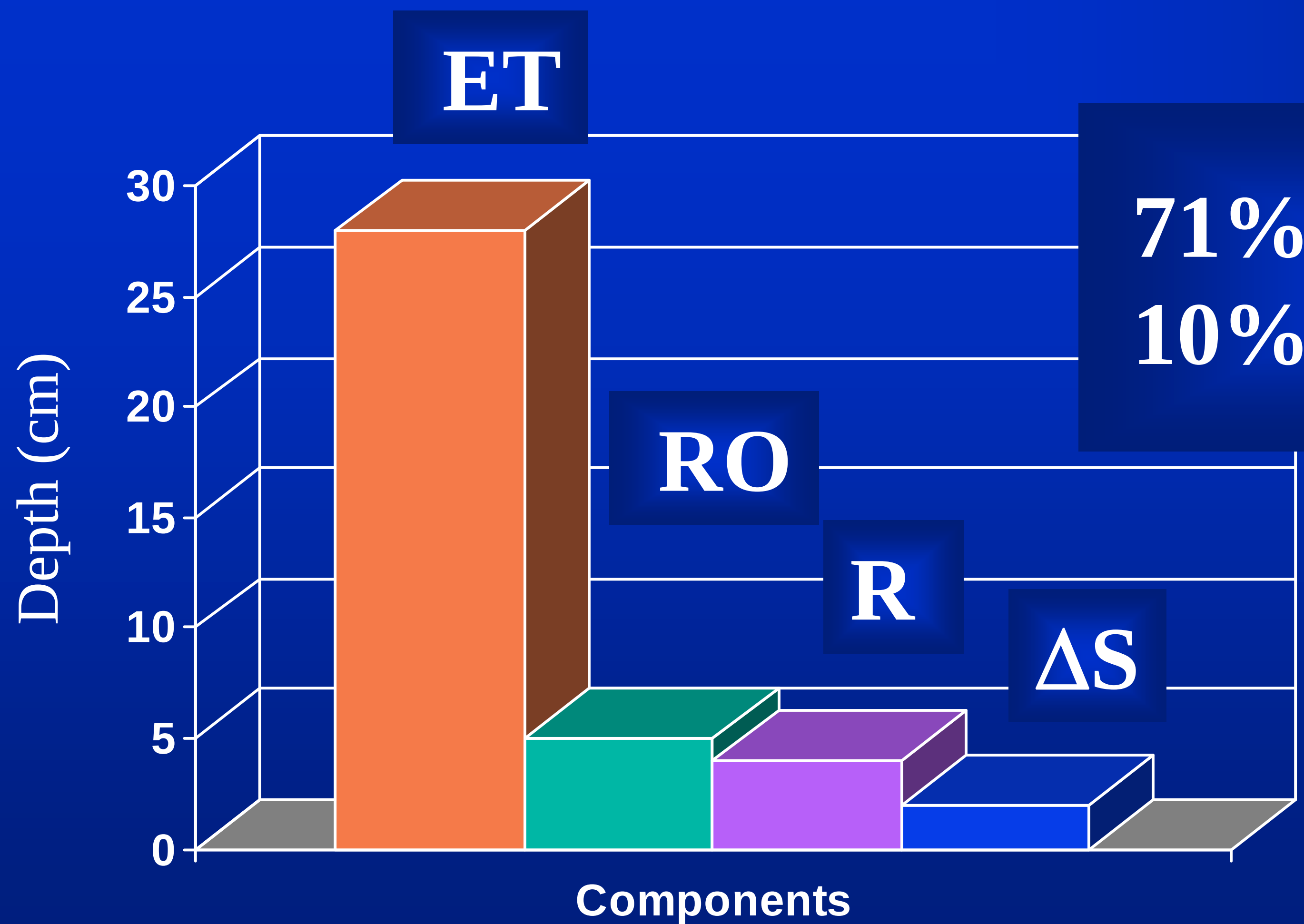
Water Balance

$$R = P - ET - RO - \Delta S$$

Depression Focused Recharge

Ag Field Results

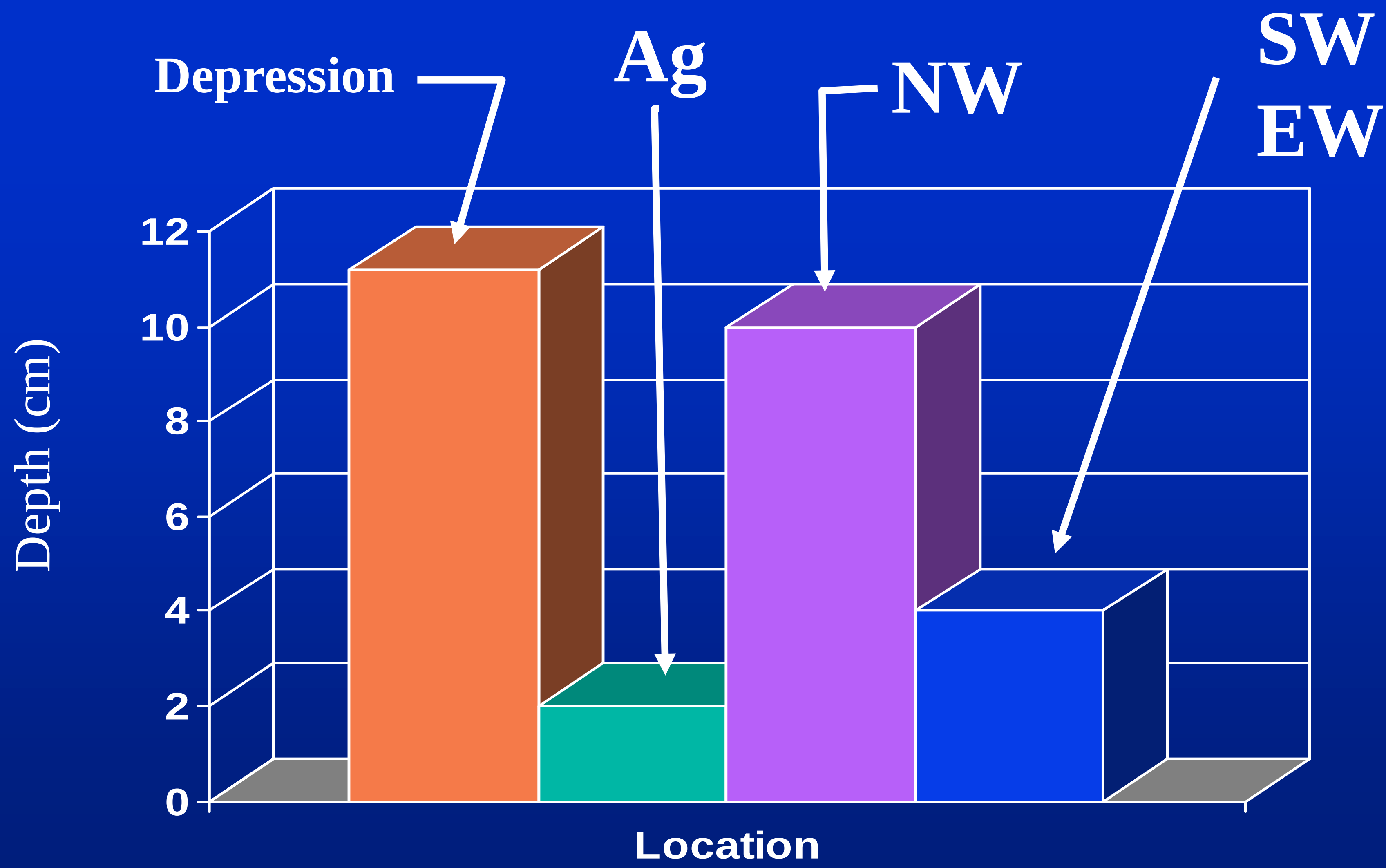
$$R = P - ET - RO - \Delta S$$



71% of P is ET

10% of P is R

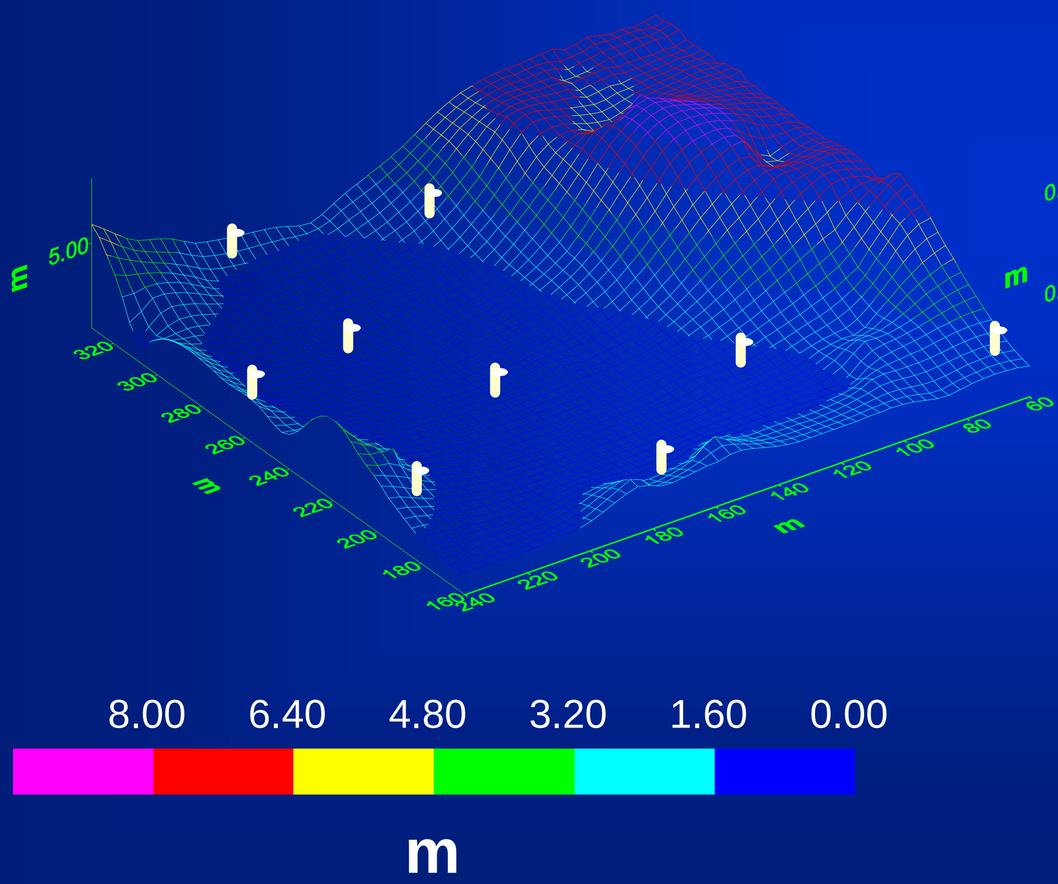
Spatially Varying Recharge



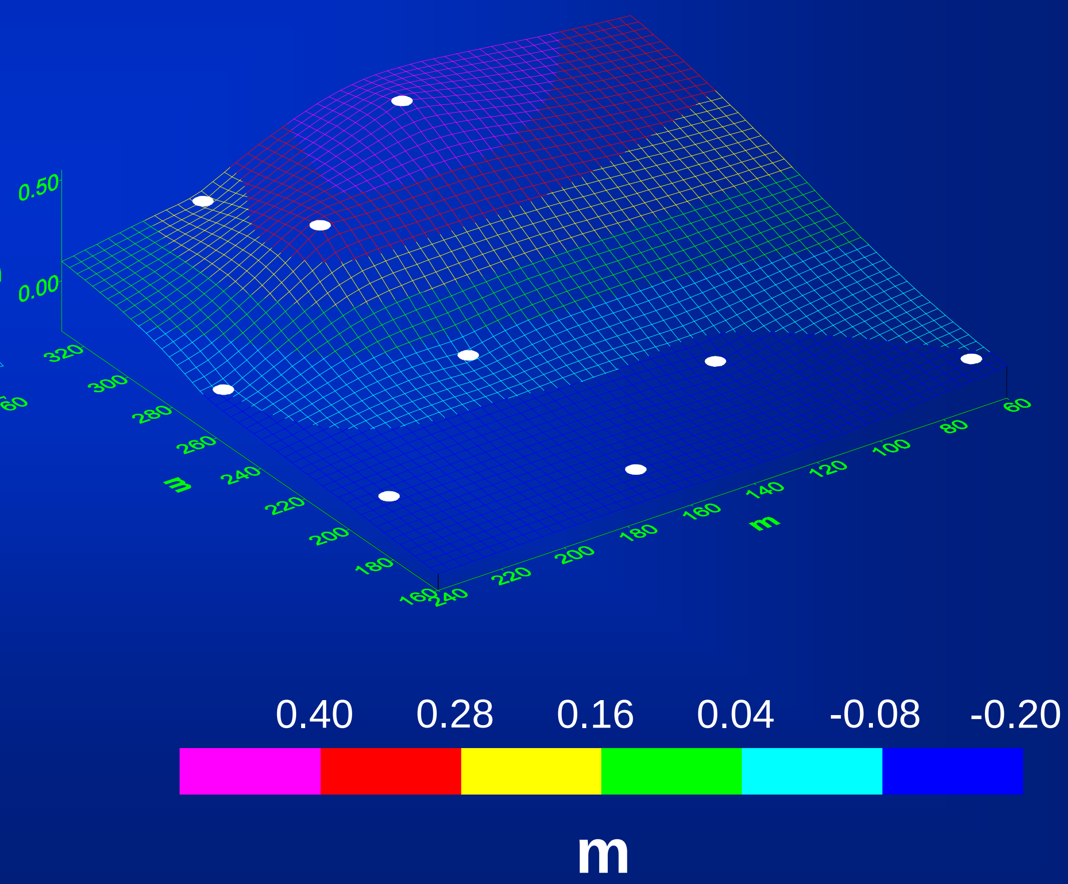
Ground Water Recharge

May 26,1994

Topography

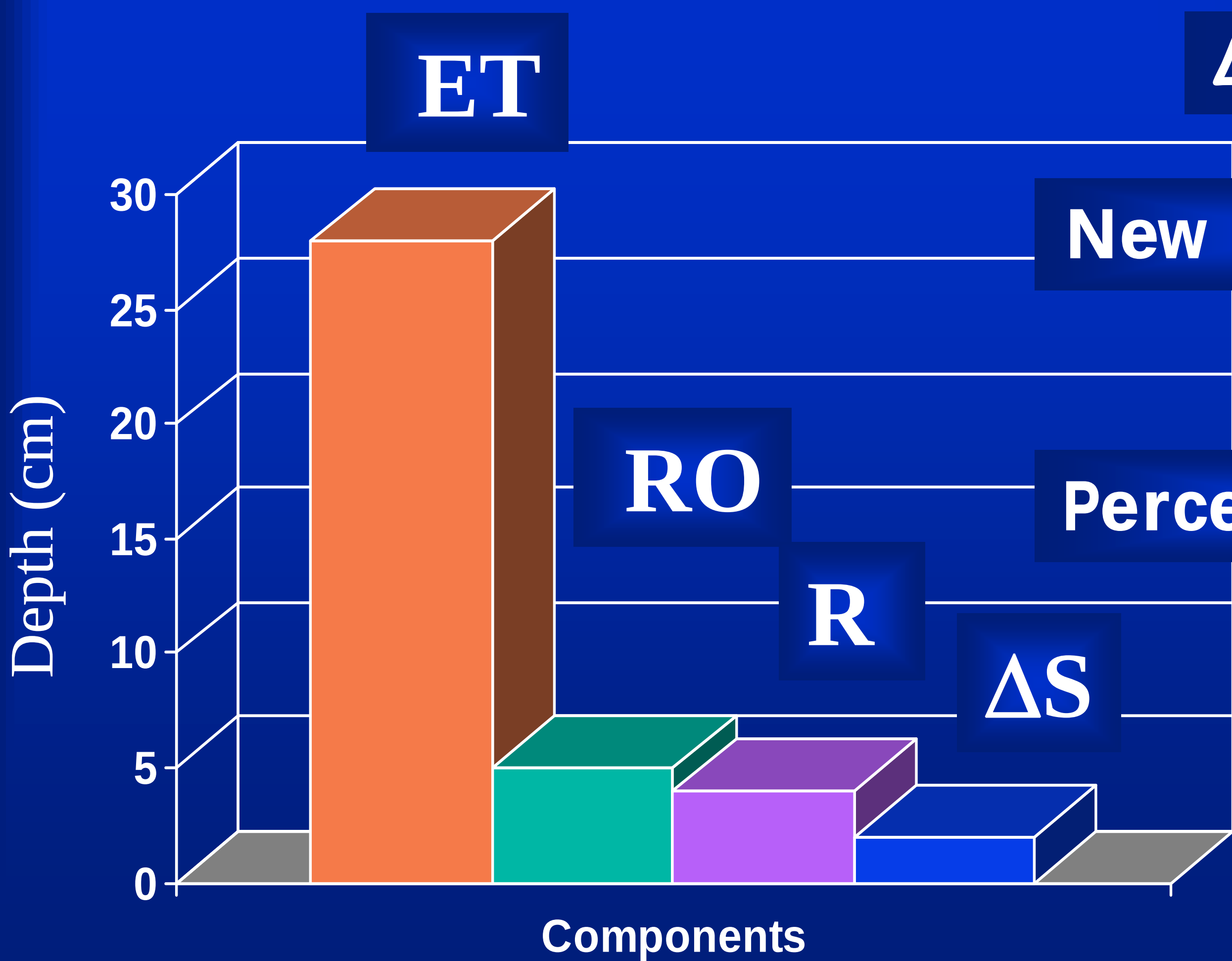


Water Table



Revisit Recharge Estimate

$$R = P - ET - RO - \Delta S$$



10% Error in ET

$\Delta ET = 0.10\ (28) = 2.8$ cm

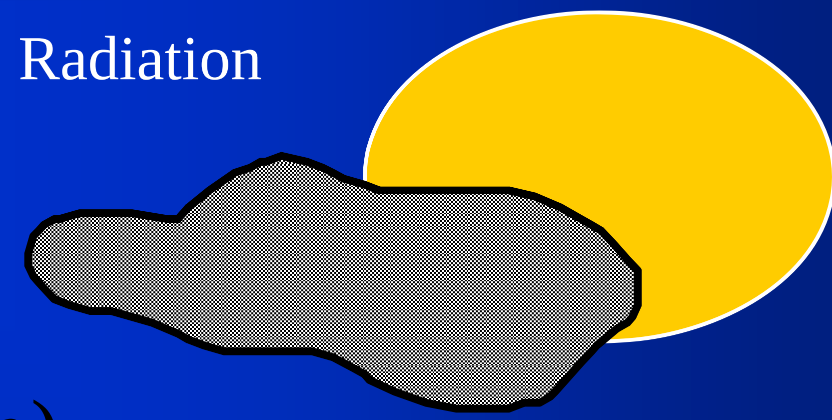
New Recharge

$R = 4 - 2.8 = 1.2$ cm

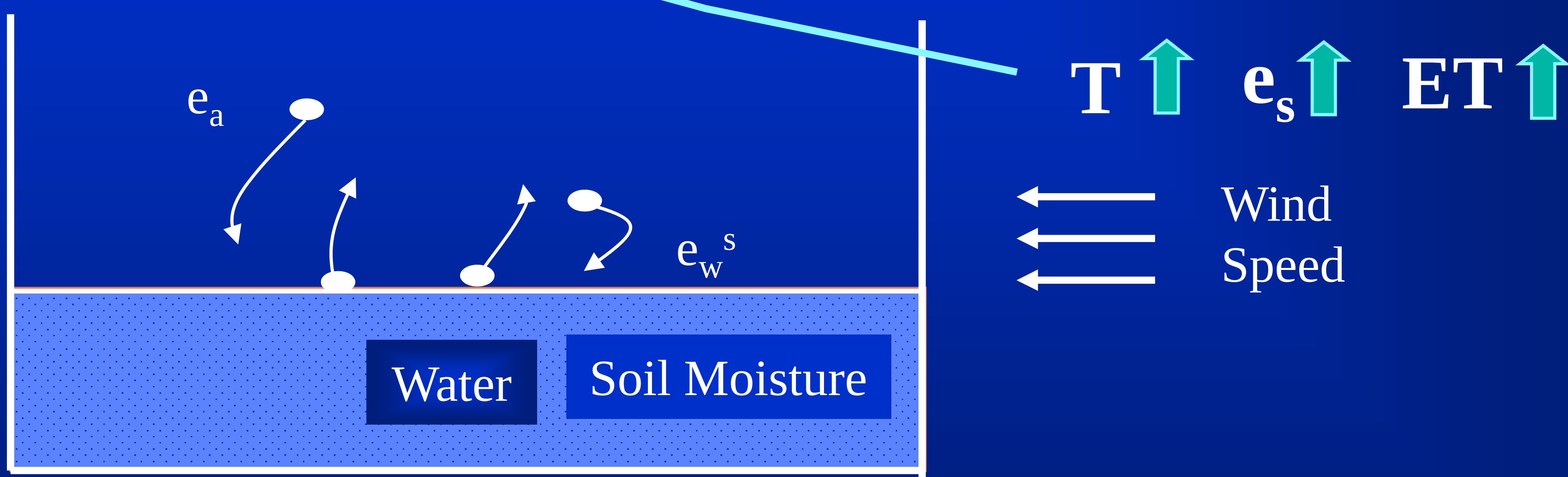
Percent Change

$\Delta R = 2.8/4 = -70\%$

Implication of Climate Change

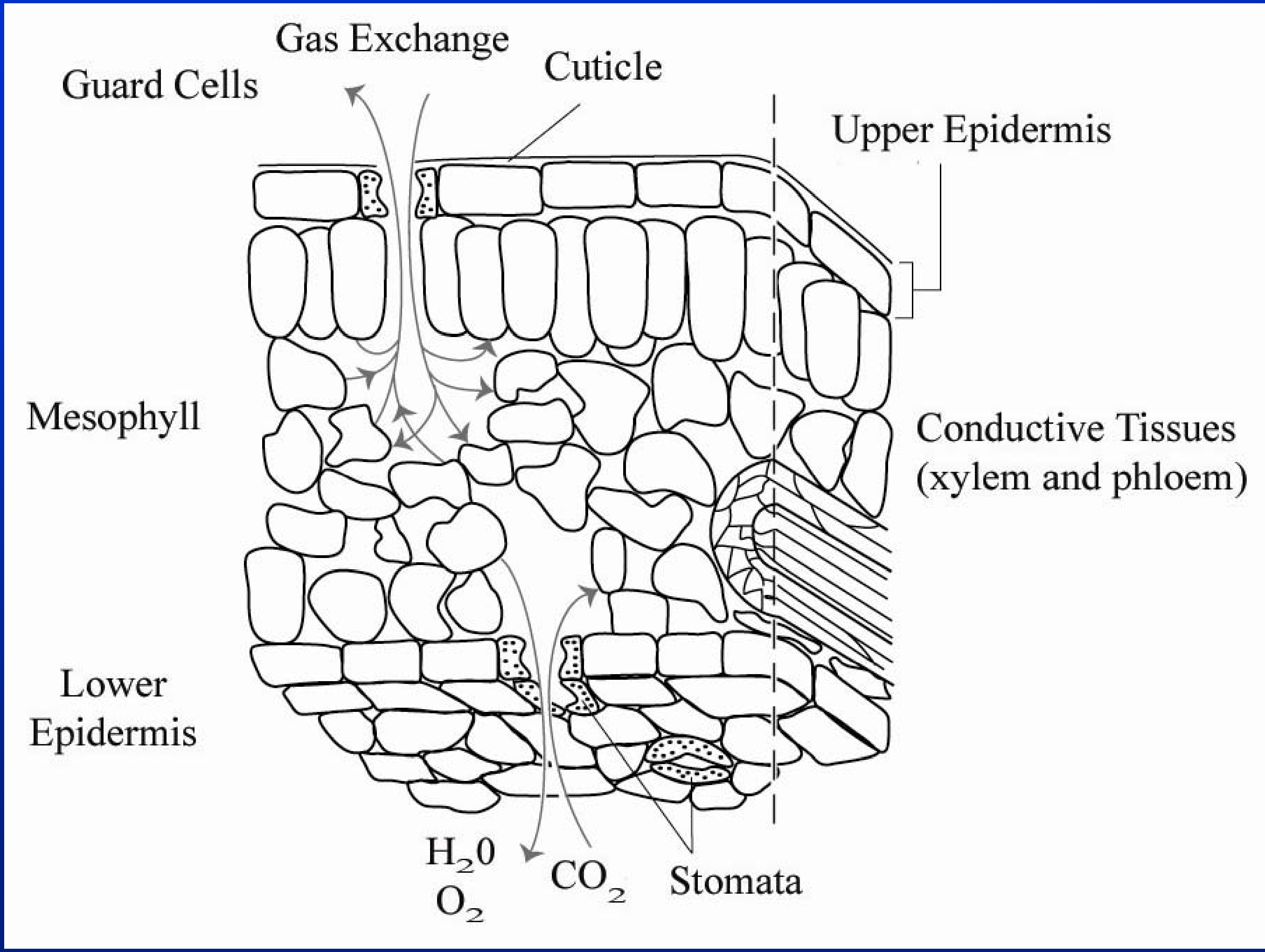


$$ET \propto e_s(1 - rh)$$



Does a 10% increase in ET correspond to 70% decrease in recharge?

Plant Response

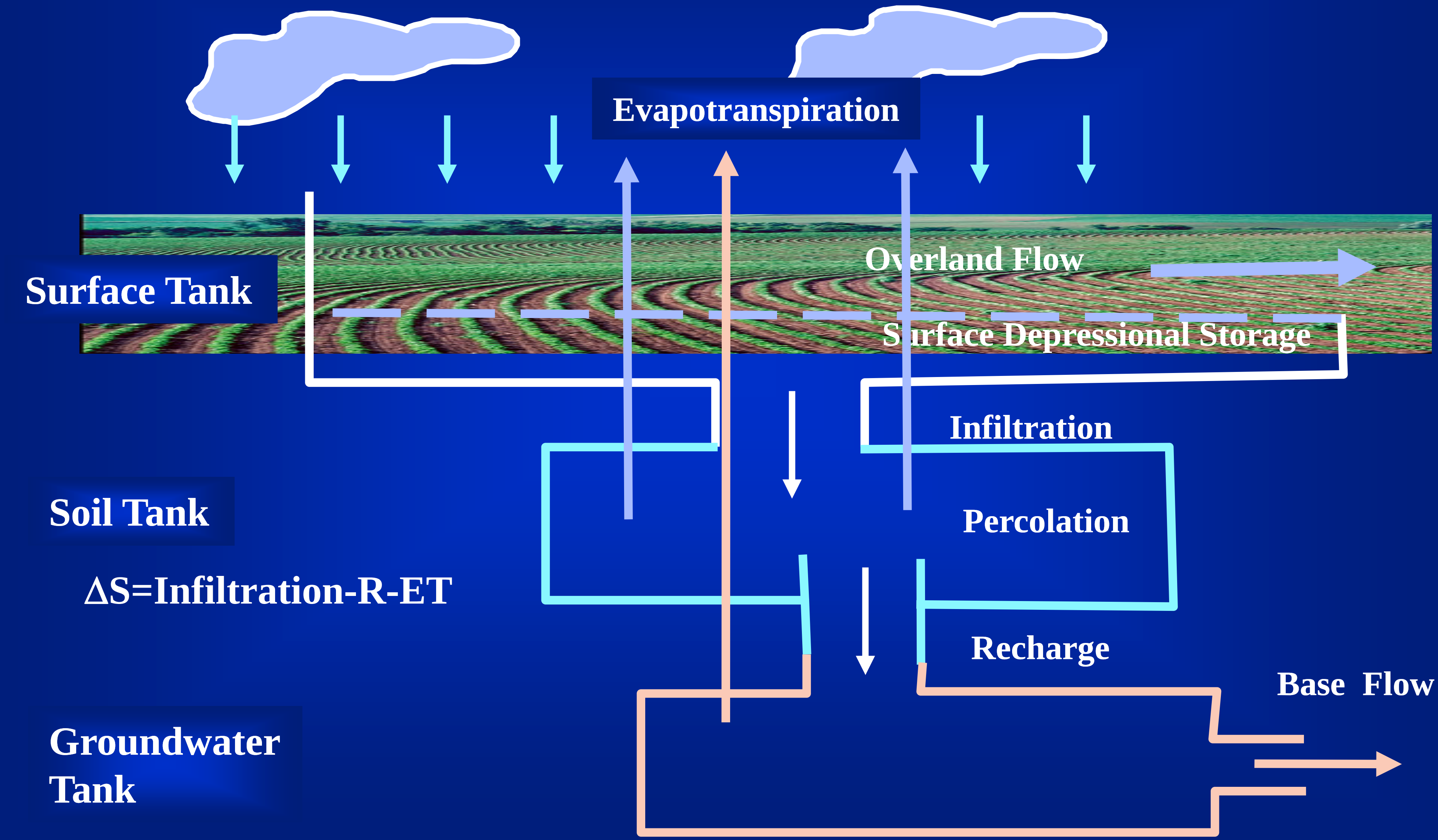


Stomata aperture decreases with increasing CO_2

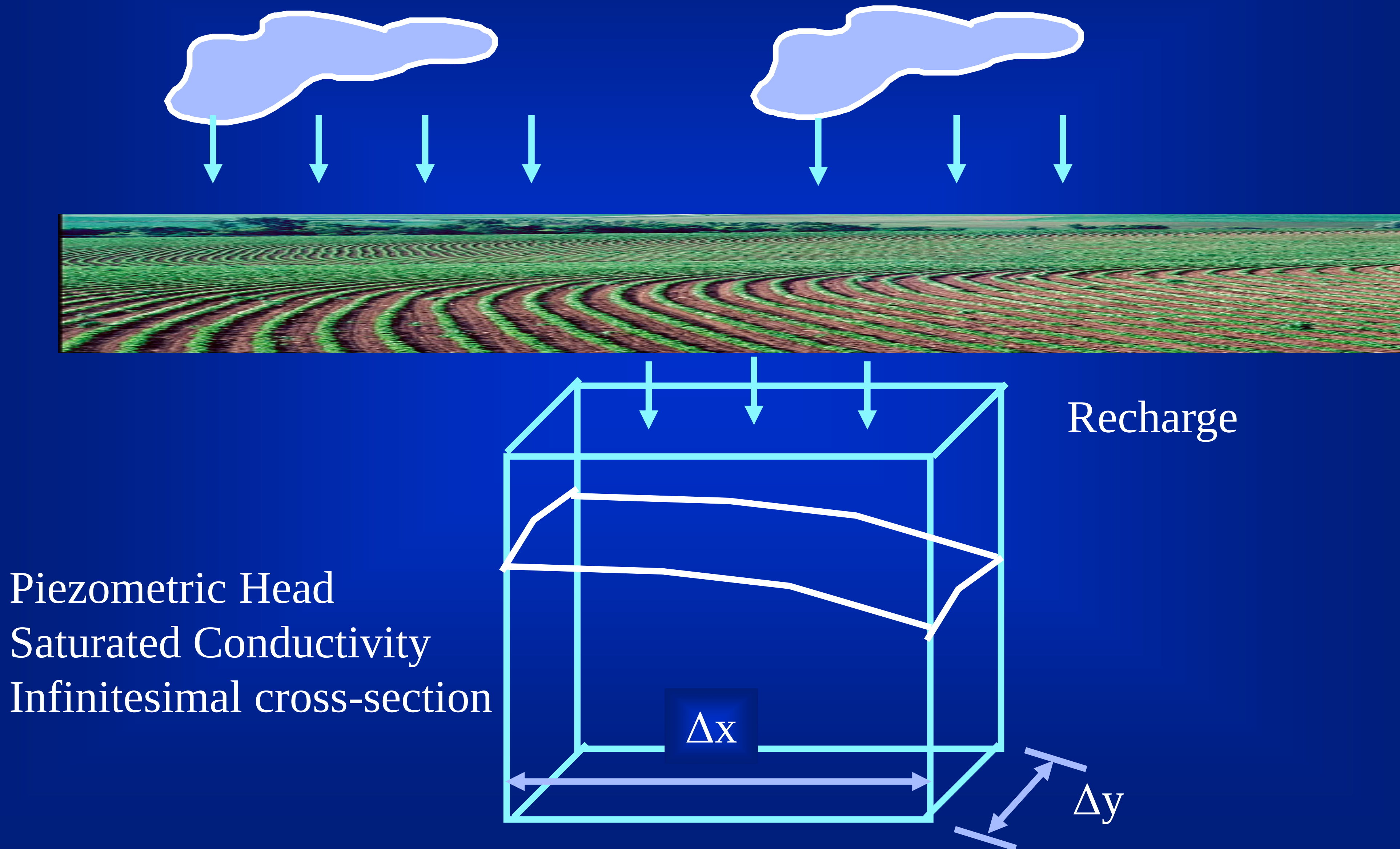
Increased stomatal resistance reduces transpiration

Increased CO_2 results in fewer stomata, but remaining maybe larger

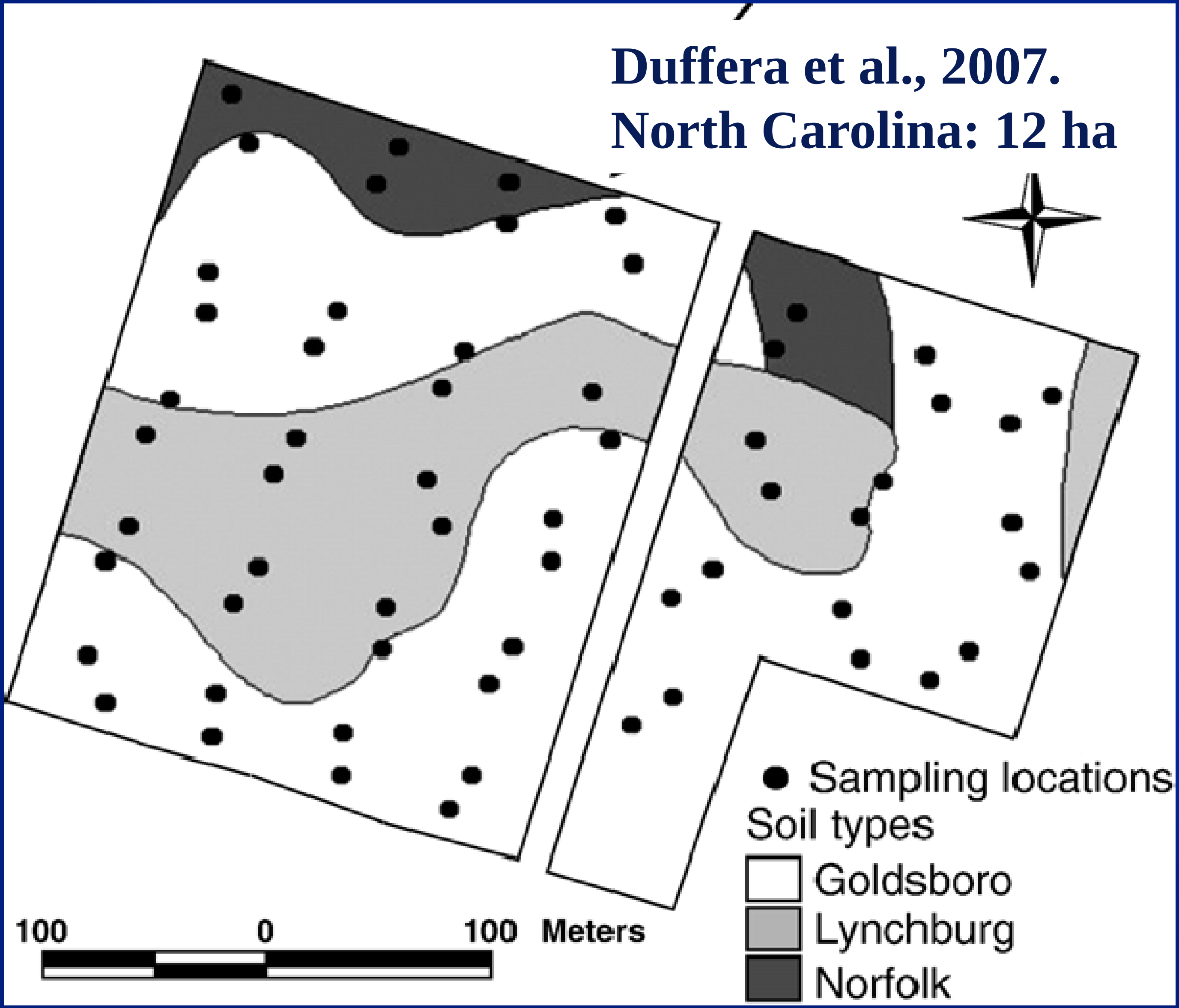
Hydrologic Cycle and Models



More Process-based Models



Variability in Parameters



Saturated Conductivity

Mean: 5.3 cm/h

Max: 22.9 cm/h

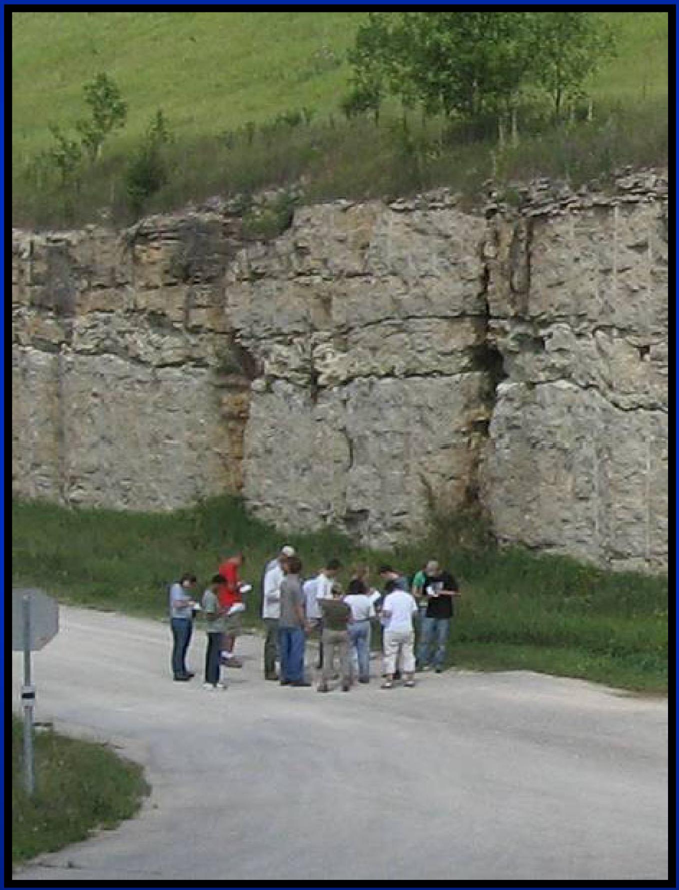
Min: 0.02 cm/h

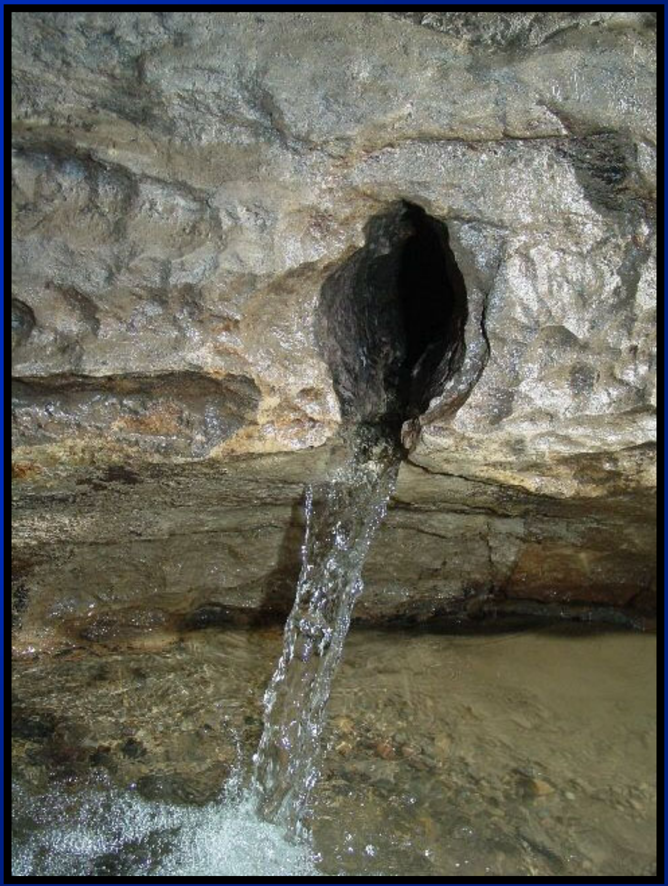
StDev: 5.4 cm/h

Variability in Parameters

Triple Porosity Aquifer

Matrix / Fractures & Bedding Planes / Conduits





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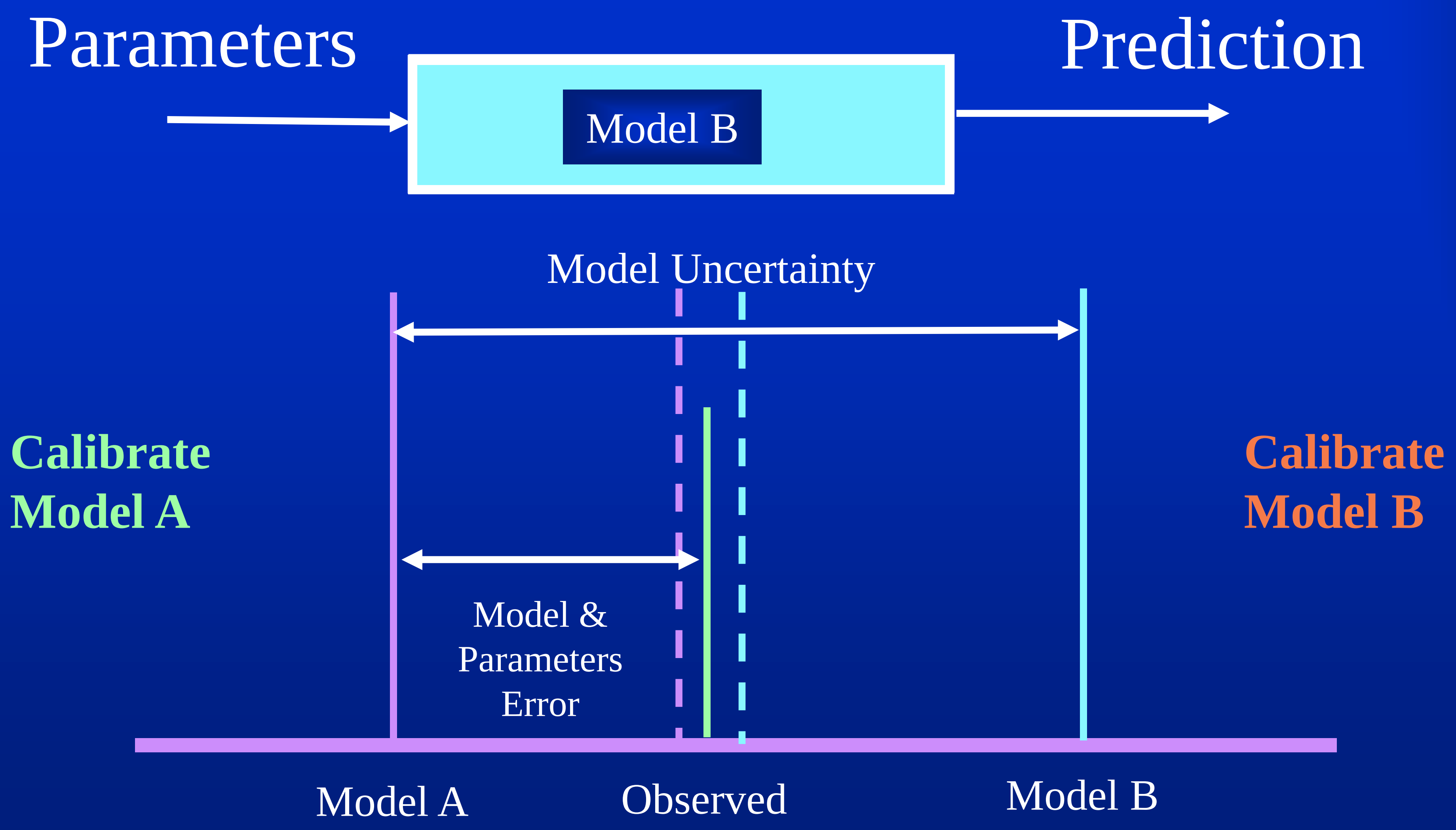
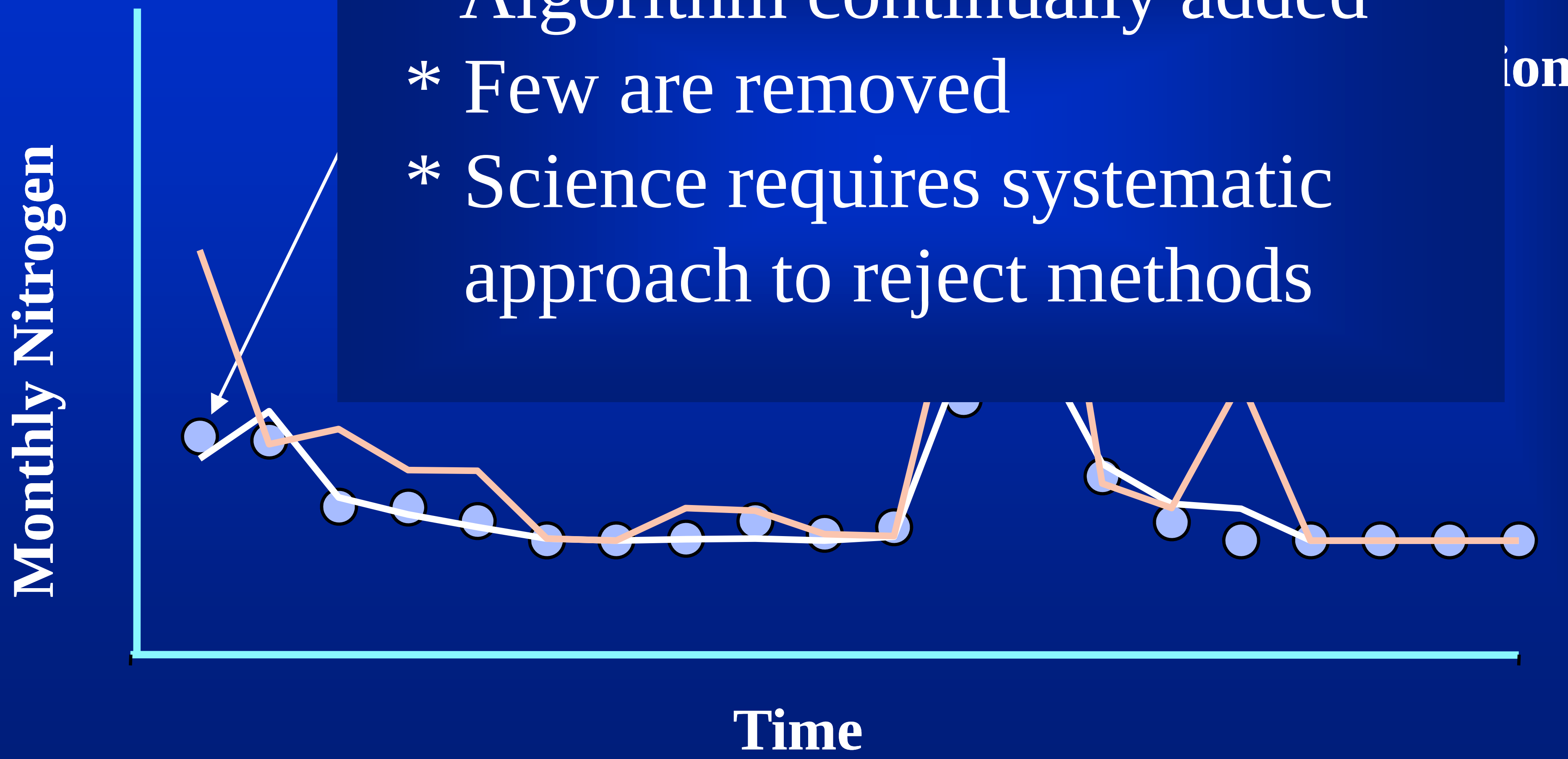
Modeling Issue

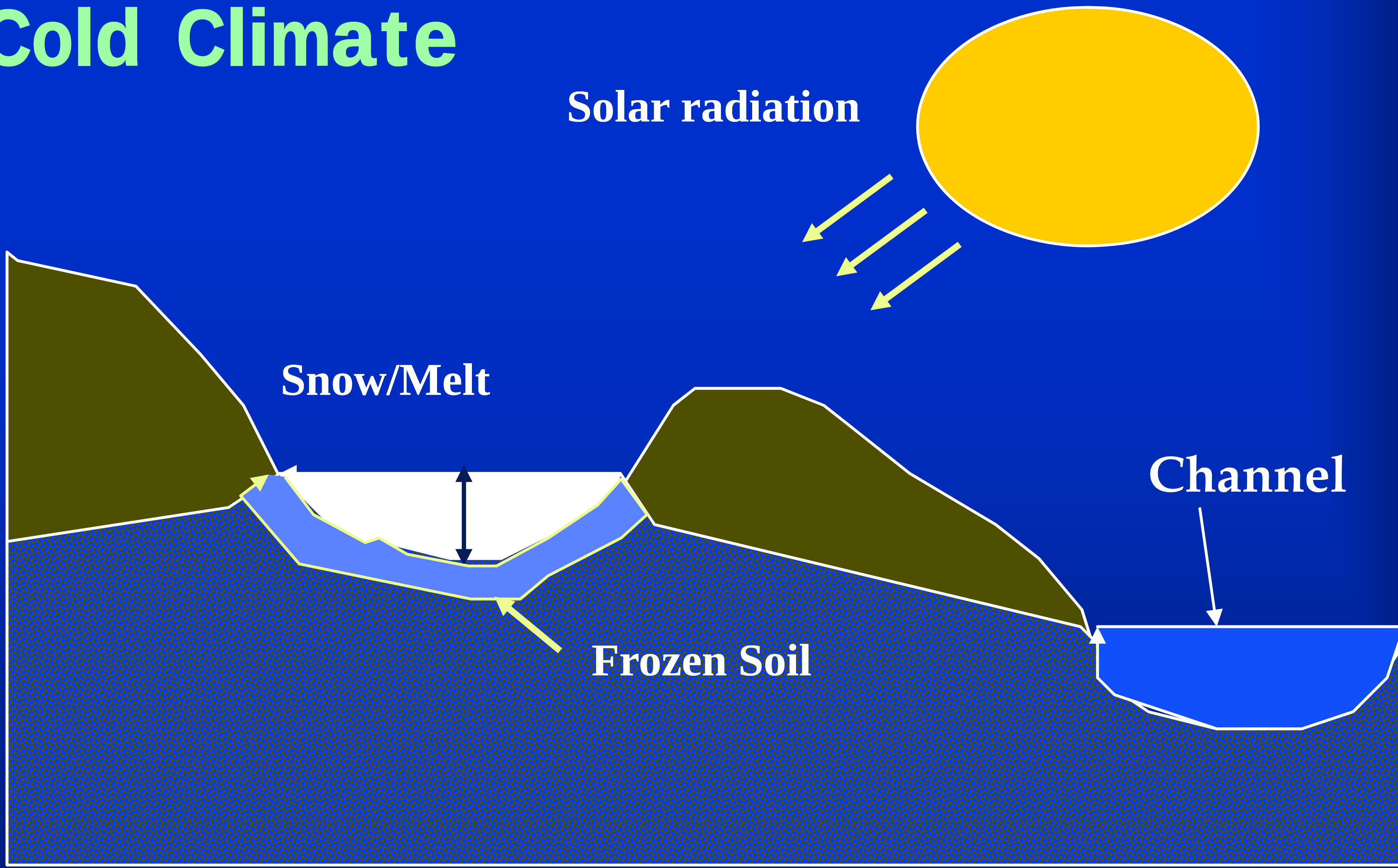


Model Non-Uniqueness

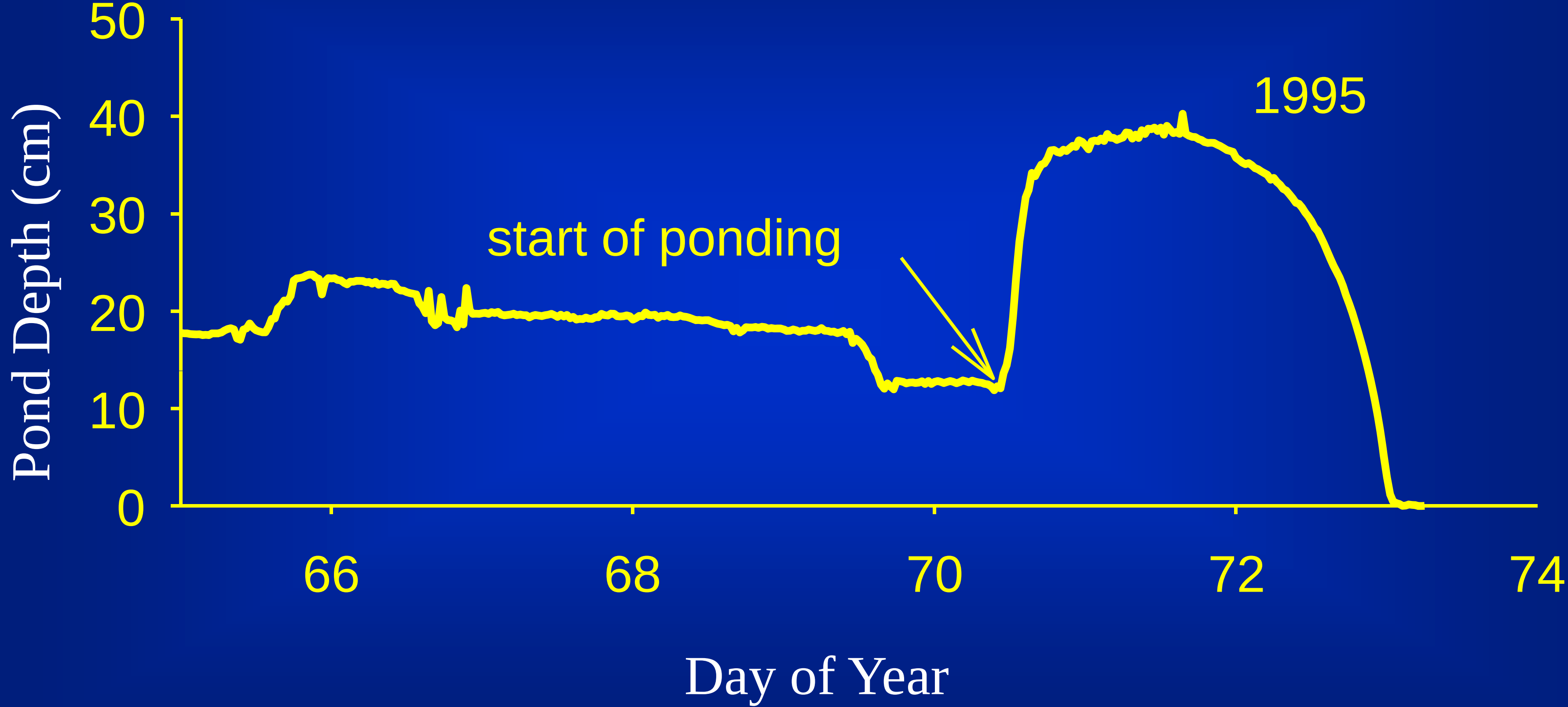
* Algorithm continually added
* Few are removed
* Science requires systematic approach to reject methods



Cold Climate



Snowmelt Event (Rosemount)



From John M. Baker, USDA-ARS, Soil, Water and Climate, U of MN

Summary and Conclusion

Wise management requires consideration of process of the hydrologic cycle

Water balances provide valuable insight

Recharge varies spatially

Models useful but limited by parameters

Cold climate important Minnesota

Questions and Comments