Water Resource Analysis

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Water Resources Analysis

- Soil and Water are strategic resources in the near future
- How much water there is in the world?
- Hydrological cycle: from planetary scale to the farm
- How to measure some components of hydrological cycle with different technologies
- How we can measure rain and evapotranspiration in a farm with low level technology
- Soil hydrology: some fundamental soil properties in relation to irrigation
- CROPWAT

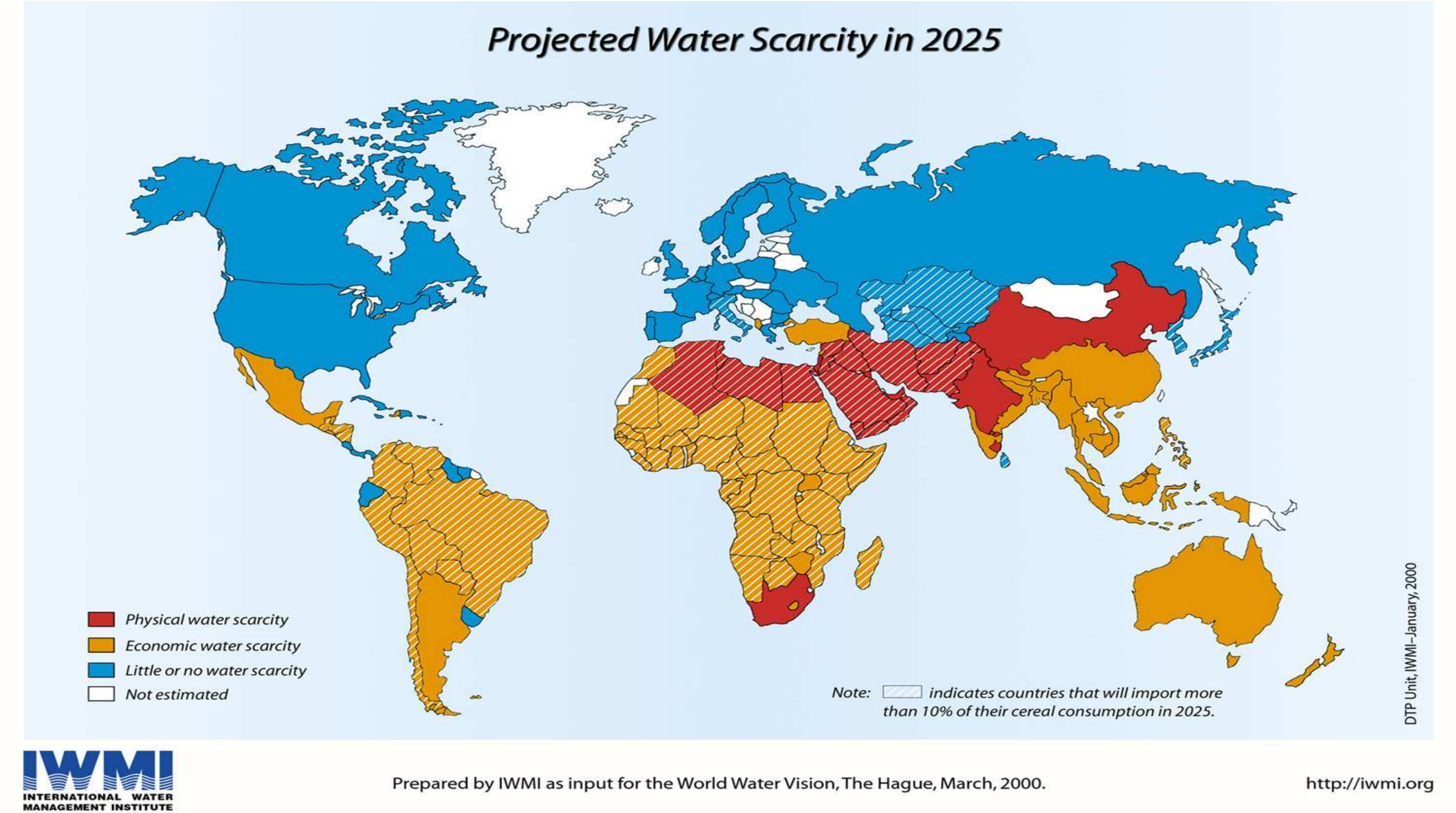
Water =

Limited resource, but a strategic one

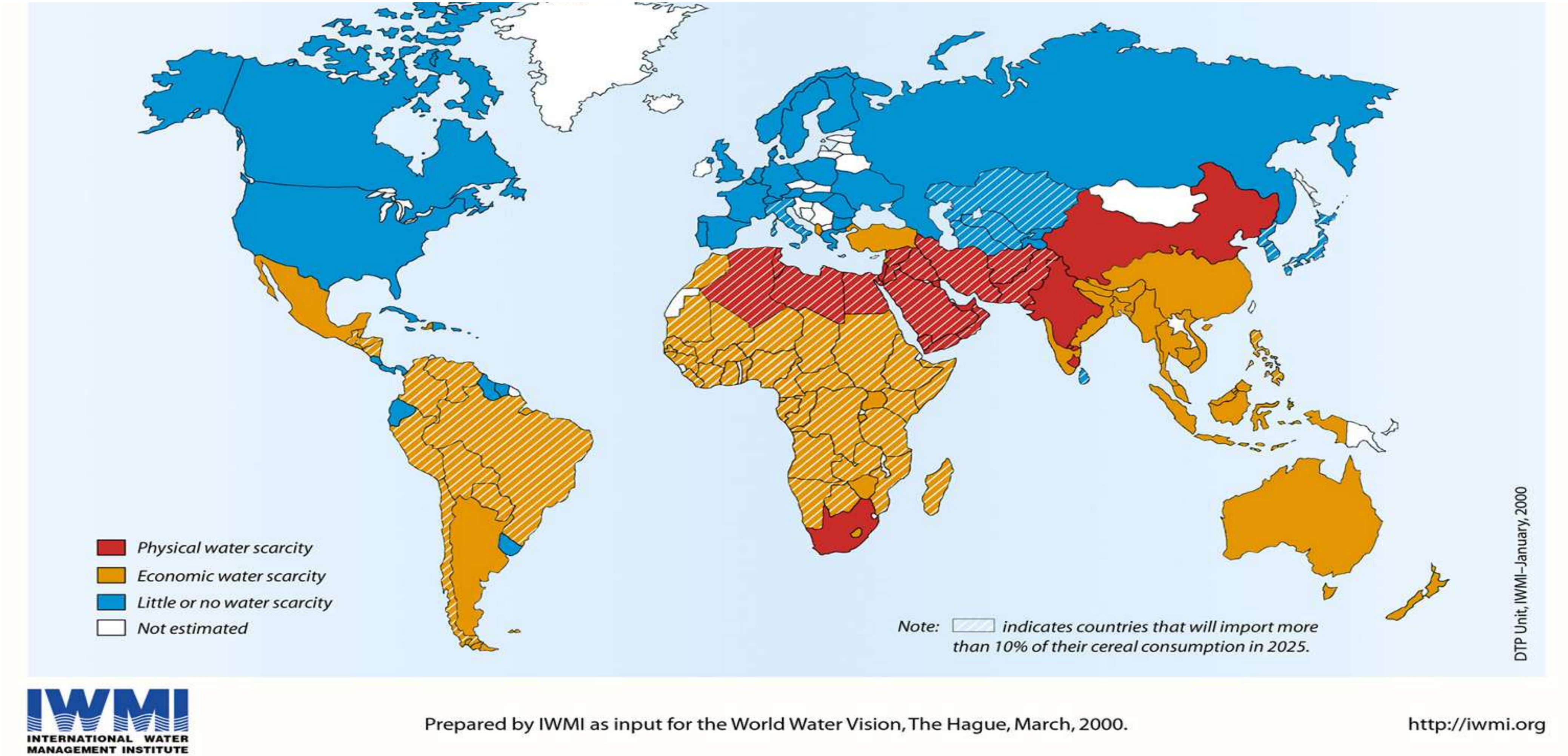
How much water do we use?

- Global average per capita consumption is suggested as 50 l/d.
- Consumption vary widely among different countries.
- 75 % of the population in Africa live on less than 40 l/d.
- 85% of the population in Asia live on less than 80 l/d.
- Consumption in Japan is between 300 – 400 l/d
- Average consumption in USA is over 700 l/d
- Consumption is related to water availability as well as economic state of a country

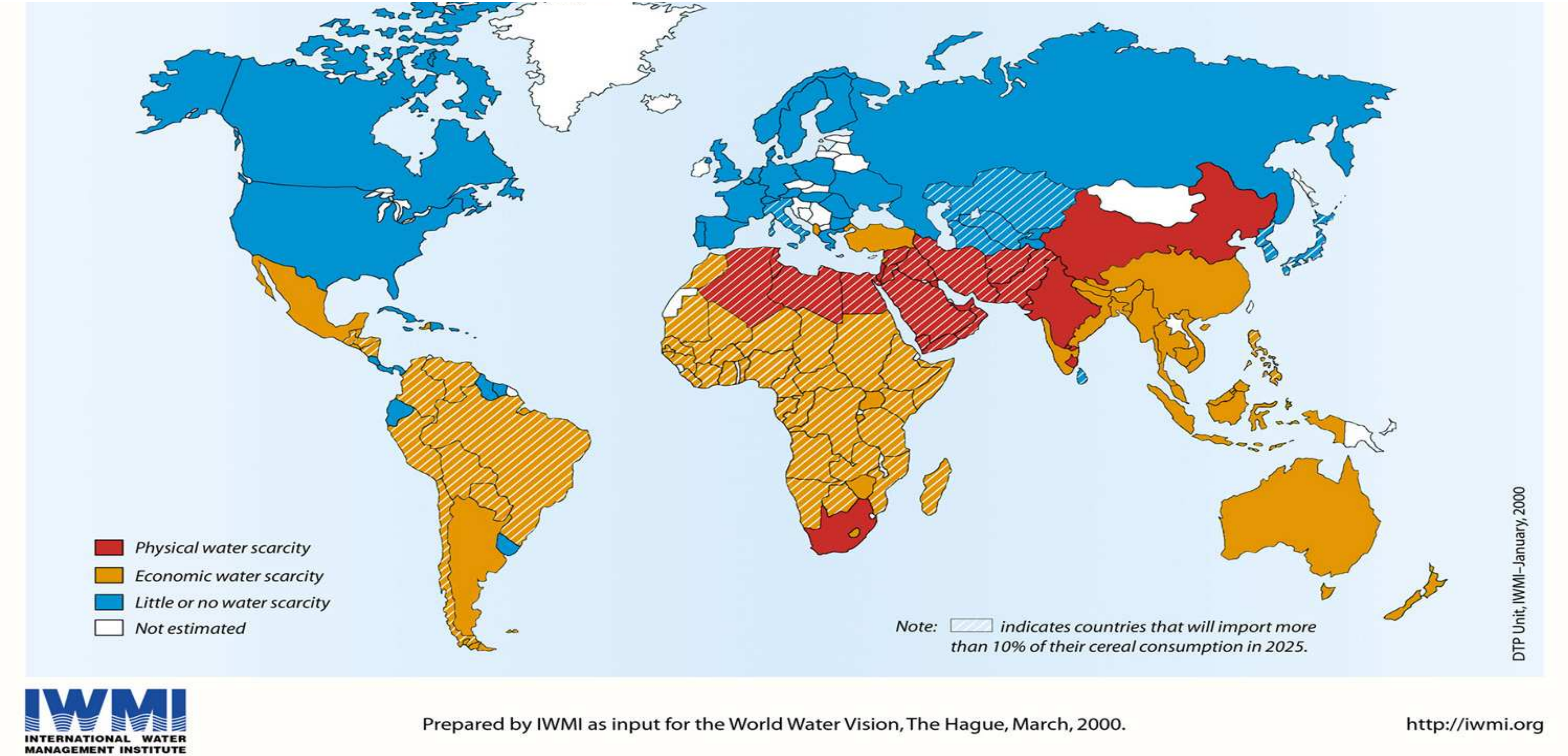
The prediction



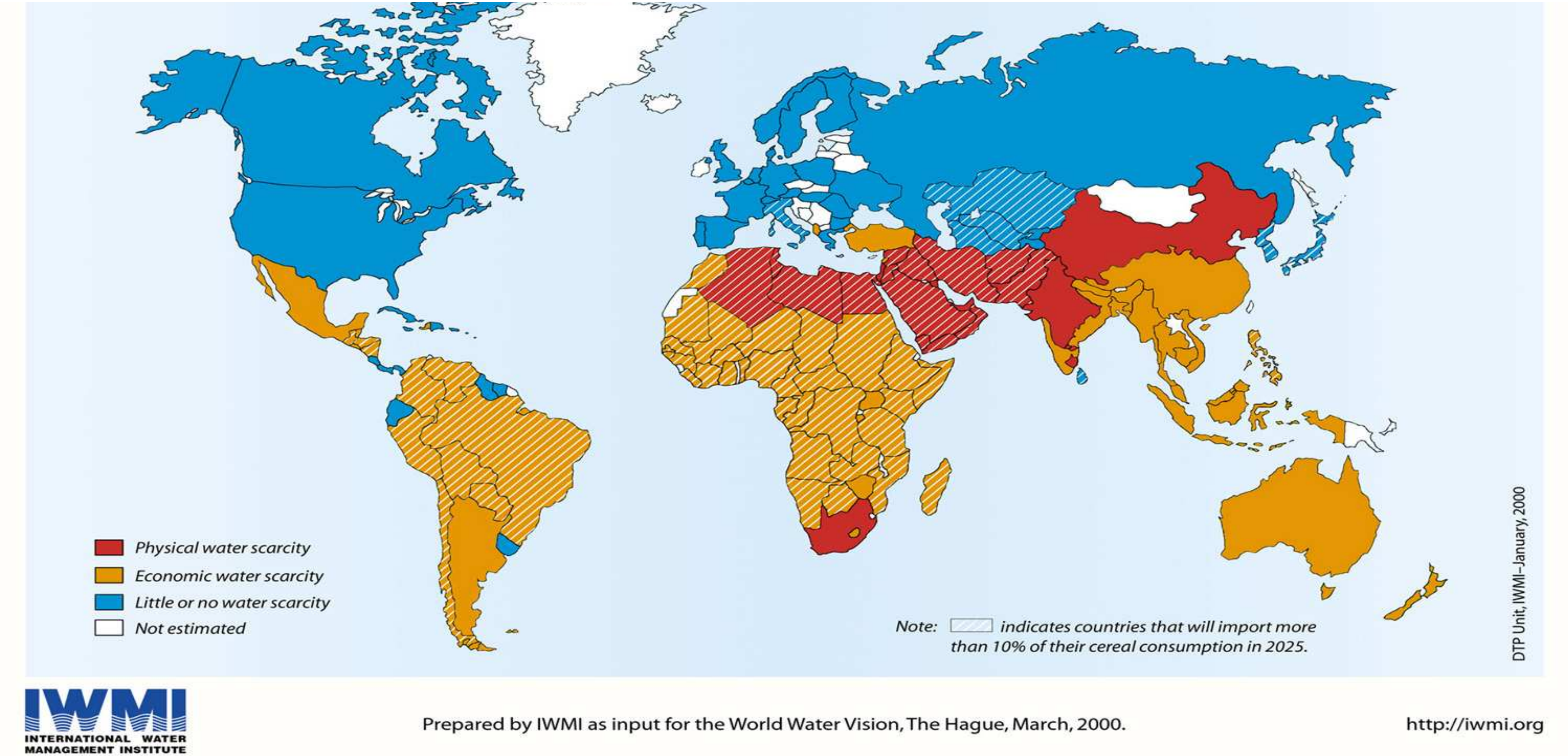
- **The crosshatched** countries on this map are countries that are projected to import over 10 percent of their total cereal consumption in 2025.

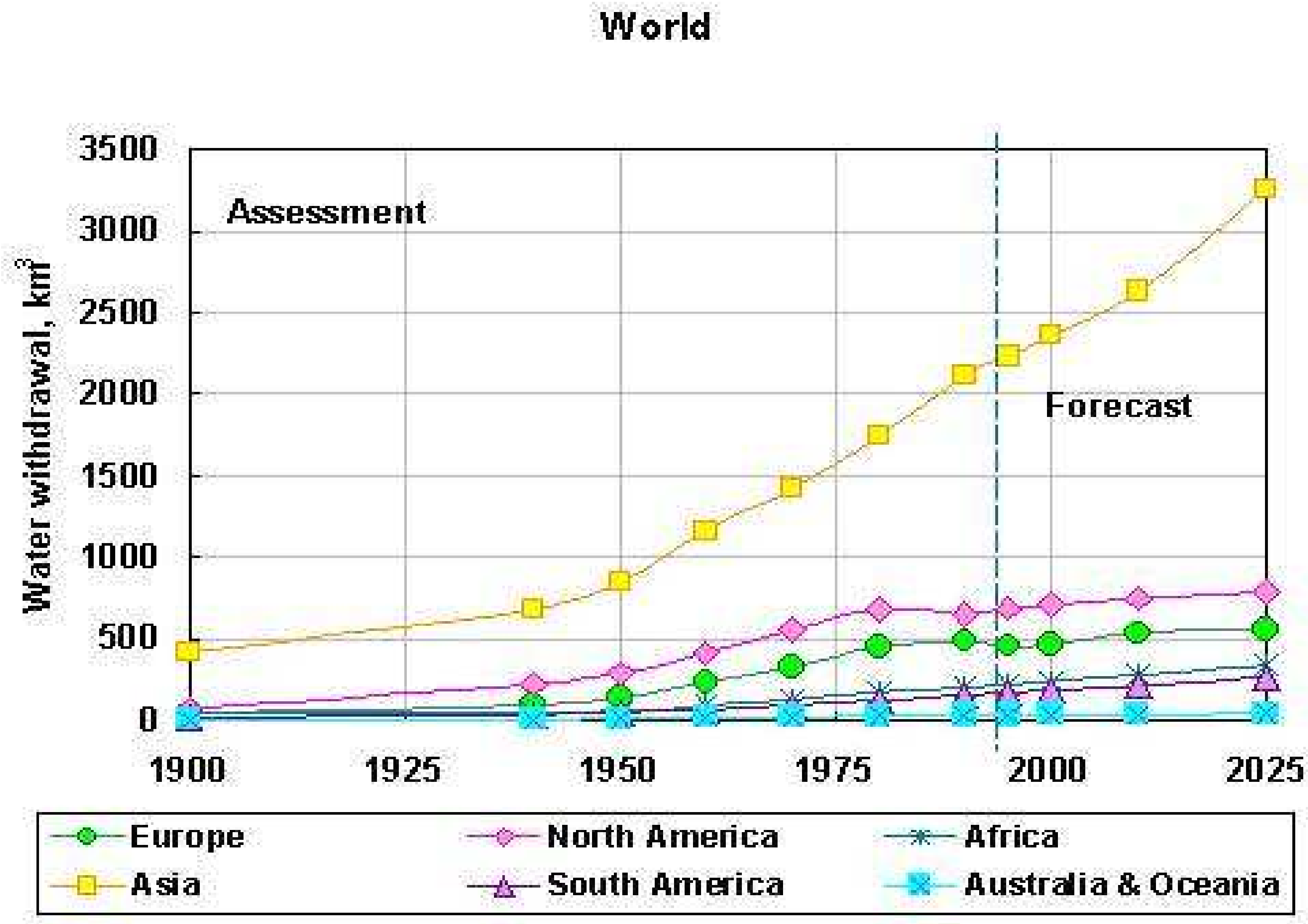


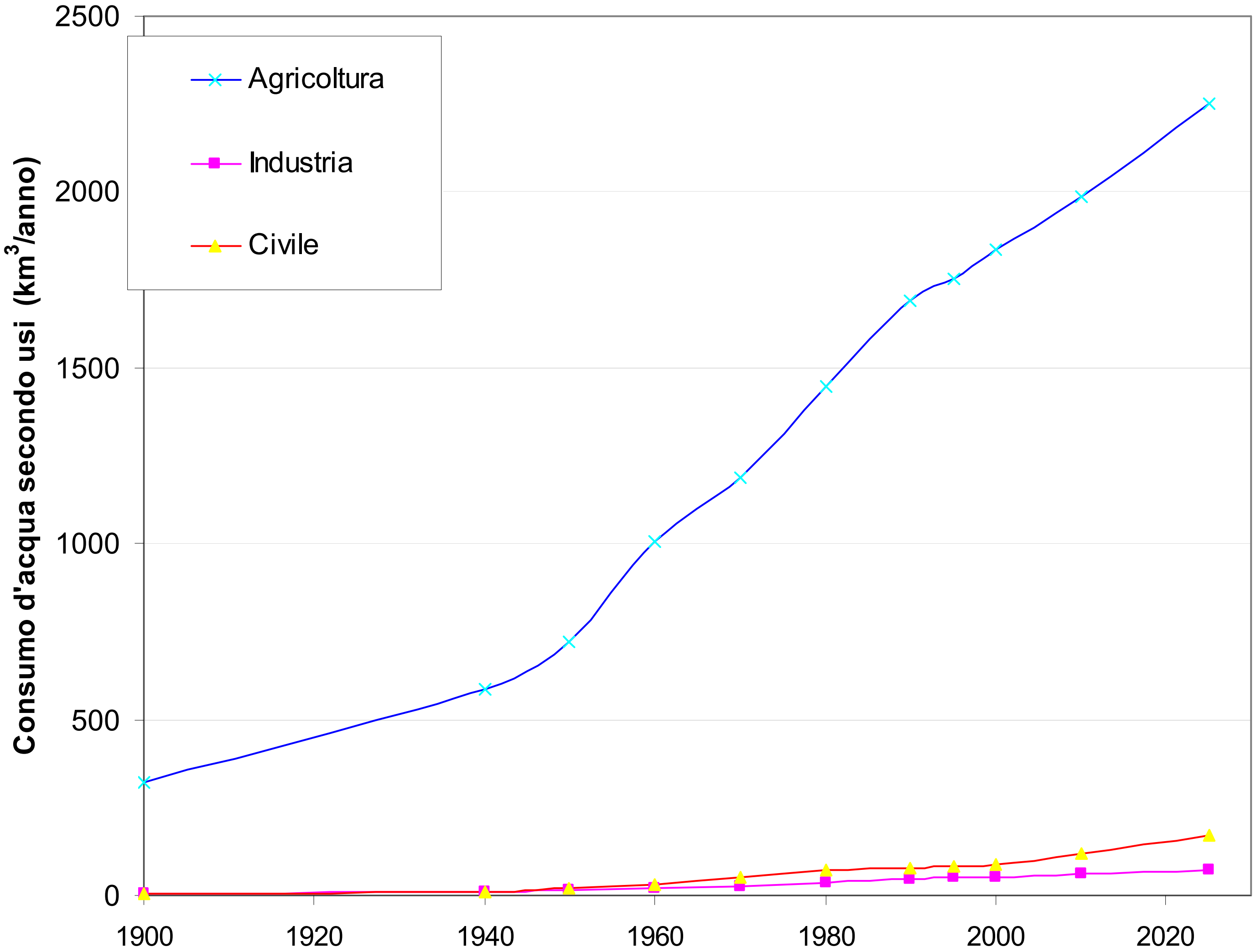
• **Group I** represents countries that face *physical water scarcity* in 2025. This means that, even with the highest feasible efficiency and productivity of water use, these countries do *not have sufficient water resources* to meet their agricultural, domestic, industrial and environmental needs in 2025. Indeed, many of these countries cannot even meet their present needs. The only options available for these countries are to invest in expensive desalinization plants and/or reduce the amount of water used in agriculture, transfer it to the other sectors and import more food.



- **Group II** represents countries that face economic water scarcity in 2025. These countries have sufficient water resources to meet 2025 needs but which will have to increase water supplies through additional storage, conveyance and regulation systems by 25 percent or more to meet their 2025 needs.
- Many of these countries face severe *financial and development capacity* problems in meeting their water needs.




World
Assessment
Forecast
Water withdrawal, km^3
3500
3000
2500
2000
1500
1000
500
0
1900
1925
1950
1975
2000
2025
Europe
North America
Africa
Asia
South America
Australia & Oceania



Consumo d'acqua secondo usi (km3/anno)
2500
2000
1500
1000
500
0
1900
1920
1940
1960
1980
2000
2020
Agricoltura
Industria
Civile

World food production will have to double within the next 30 years (OECD)

- Amount of water needed to produce food for a balanced diet is 2000 $m^3/(person \cdot year)$
- Currently 40% of world food supplies come from irrigated agriculture
- 40% of water supply of irrigated agriculture is irrigation water (World Resources Institute, 1994)
- ...that makes 320 $m^3/(person \cdot year)$ irrigation water

The concept of sustainability: use or *abuse*

The Aral Sea:

a case-study on unsustainable irrigation development.

Sustainable irrigation

In some basins, excessive diversion of river water for irrigation (and other uses) has brought environmental and ecological disasters to downstream areas, and groundwater pumping at unsustainable rates has contributed to the lowering of groundwater tables.

The ARAL SEA


Kazakhstan
Aral Sea
Uzbekistan
Syr Darya
Kyrgyzstan
Turkmenistan
Amu Darya
Tajikistan
Afghanistan

The ARAL SEA

The beginning of irrigated agriculture in the region dates back to the 6^{th}-7^{th} centuries B.C. and coincides with flourishing the most ancient civilization where irrigation was a major decisive factor of historical and socio-economic development.

During the last 50 years it has intensified rapidly. The area brought under irrigation has increased from about 5 million hectares in 1950 to some 8 million hectares today.

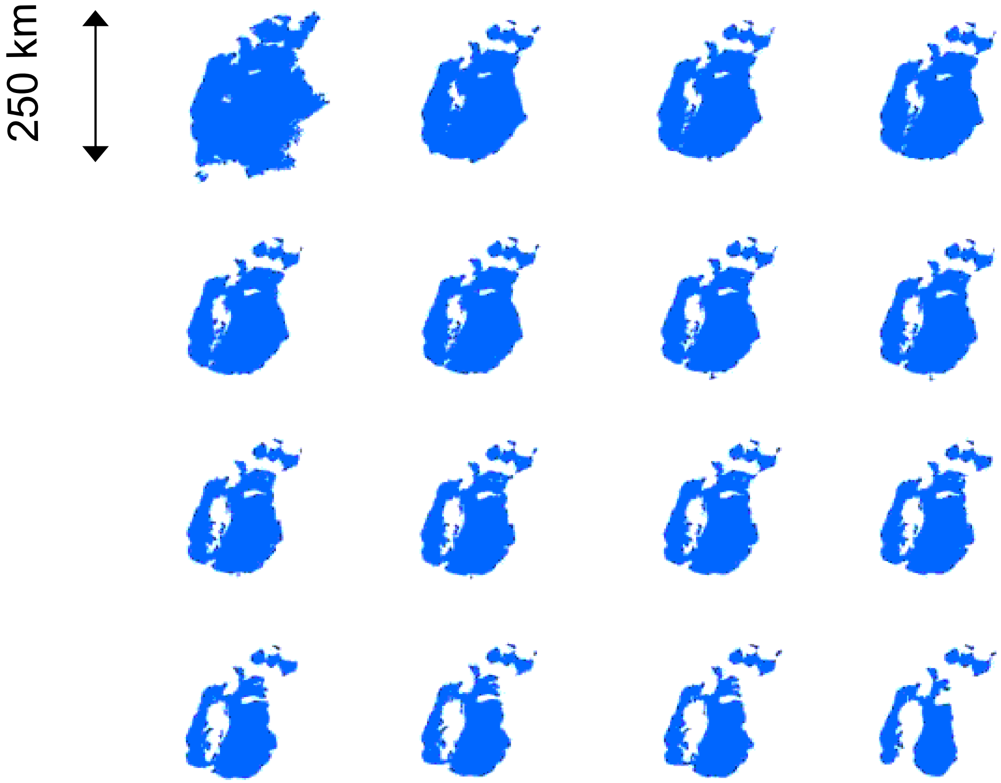
To irrigate the 8 million hectares, water was taken from the two main rivers, the AmuDarya and SyrDarya. Both discharge into the Aral Sea, an inland sea with no outlet.

Parallel to this development, the population in the region has increased from about 14 million in 1960 to some 40 million in 1999.

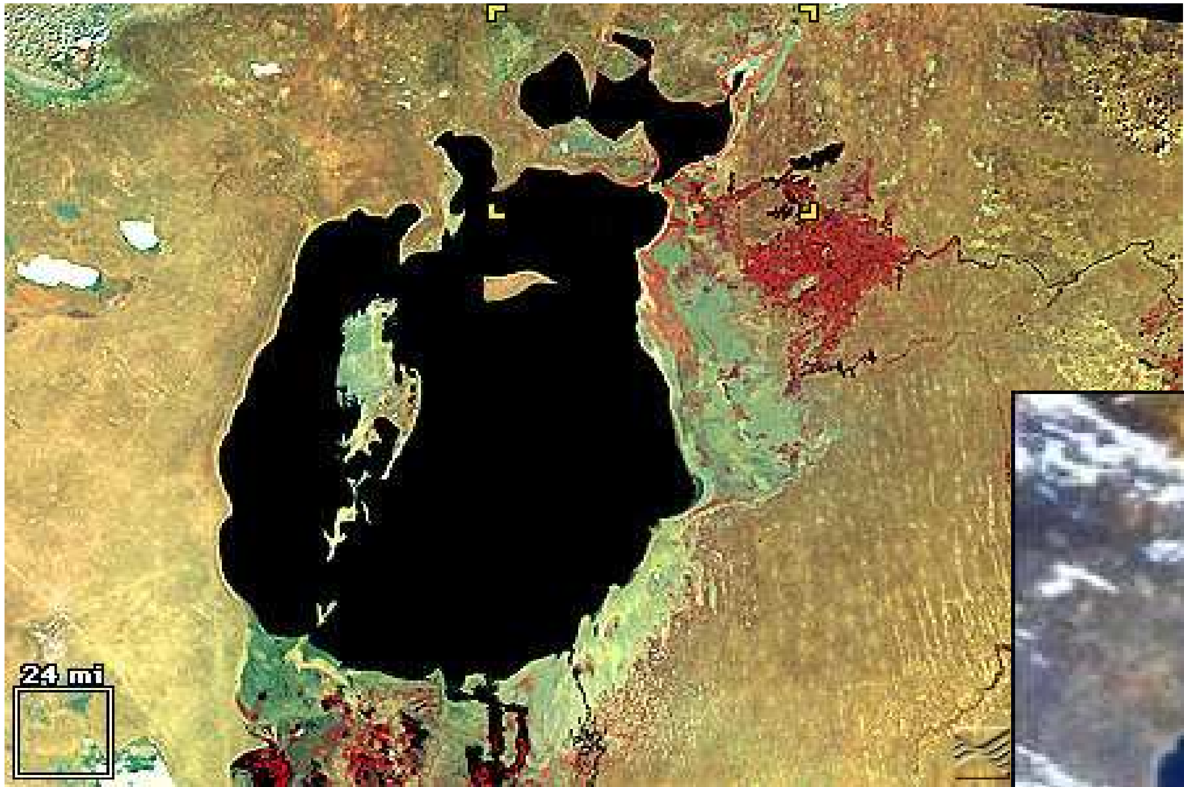
Indicator	Unit of measurement	1960	1970	1980	1990	1999
Population	mln.	14.1	20	26.8	33.6	39.9
Irrigated land area	thous. hect	4510	5150	6920	7600	7900
Summary water intake	cub. km per year	64.7	83.5	120.7	118.1	107.6
For irrigation	cub. km per year	55.2	74	108.5	106	96.3
Specific intake per 1 hect. of irrigation	cub.m per hect	12240	14370	15680	13950	12190
Specific intake per capita	cub. m per capita per year	4590	4174	4500	3515	2700

The ARAL SEA disappearance

1950



2000



1987

2003

The ARAL SEA disappearance

Year			Average level (m)	Average area (km^2)	Average volume (km^3)	Average salinity (grams/litre)
1960			53.4	66,900	1090	10
1971			51.1	60,200	925	11
1976			48.3	55,700	763	14
Separation	1994	Large Sea	36.8	28,856	273	>35
		Small Sea	40.8	3,082	25	~25
	2000	Large Sea	33.4	21,776	186	>60
		Small Sea	41.6	3,441	26	~20

Consequences: pollution

Over 33,000 square kilometres of exposed seabed have created vast salt plains inundated with agricultural chemicals. Salt and residues from pesticides and fertilizers are scoured off and blown hundreds of kilometres by harsh winds, settling in deposits that contribute further to the desertification of the region.

Consequences: climate changing

In the past the Aral was considered a regulator mitigating cold winds from Siberia and reducing the summer heat. Climate changes have led to a dryer and shorter summer in the region, and longer and colder winters.

Consequences: climate changing

The vegetative season has been reduced to 170 days. The pasture productivity has decreased by a half, and meadow vegetation destruction has decreased meadow productivity 10 times.

On the shores of the Aral Sea precipitation was reduced several times.

Consequences: human conditions

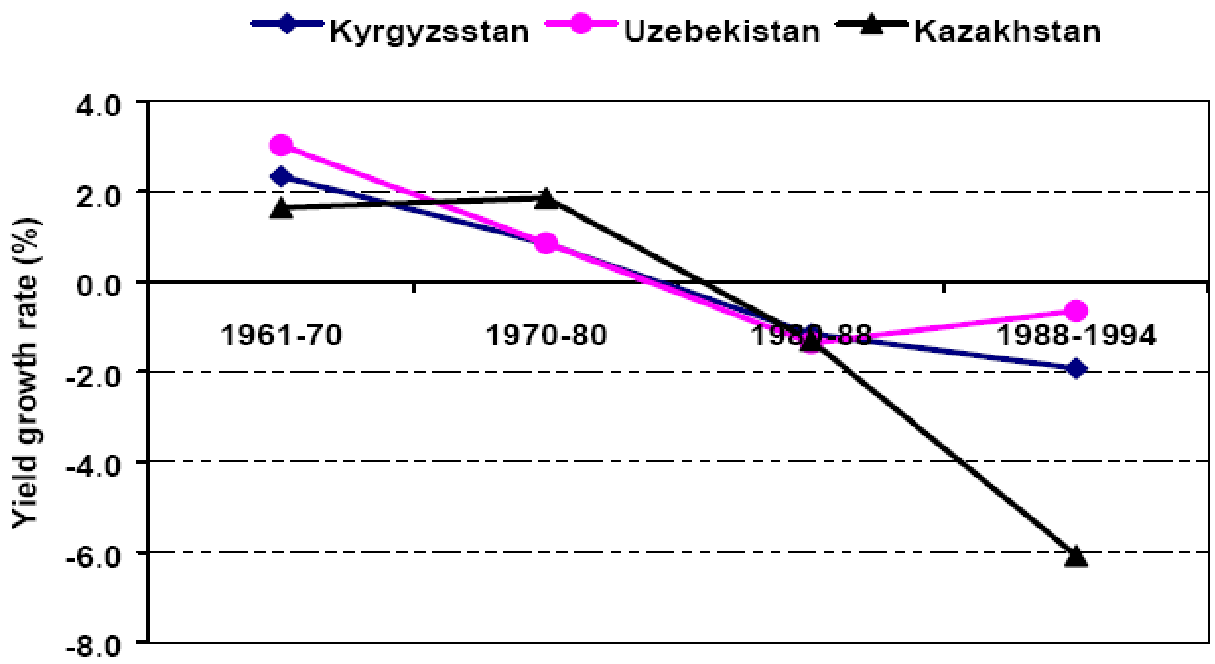
The region has the highest child mortality rate in the former USSR (75 children per 1000 newly born), high level of maternity death: about 120 women per 10,000 births.

Anemia, disfunction of thyroid, kidney and liver diseases are wide spread. Blood, oncological diseases, heart diseases are progressing.

Medical research proves that the incidence and growth of these diseases are directly dependent on ecological disaster.

Consequences: economy

One indicator of the increasing environmental deterioration in the basin was the change in crop yields, as irrigation-induced water quality and soil quality problems led to a reduction in yields.



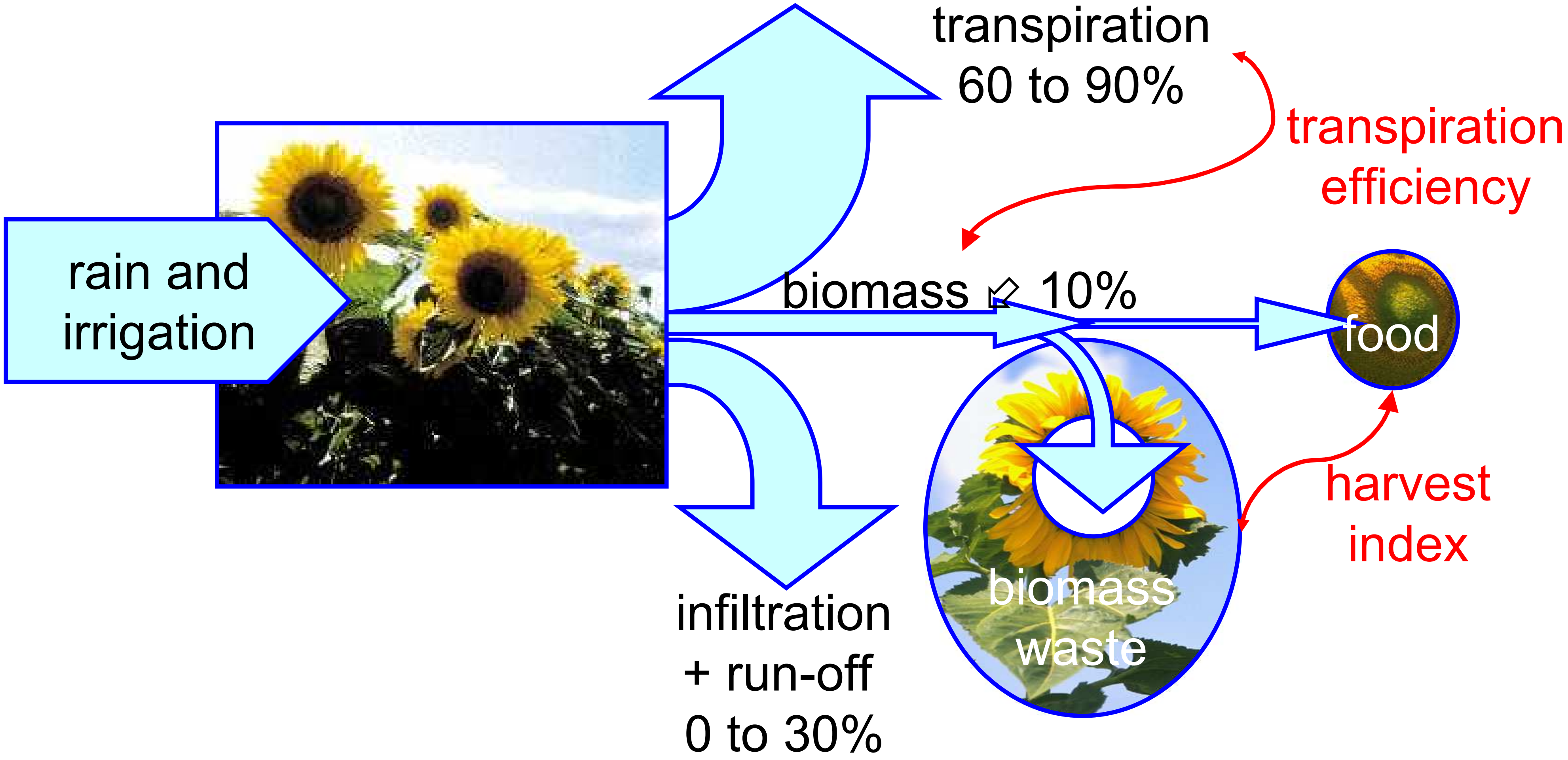
Consequences: economy

The salinity of the Aral Sea has steadily increased from 10 g/l in 1960 to 34.4. g/l in 1992.

This has wiped out a flourishing marine ecosystem that once supported 24 species of fish of commercial significance.

Nowadays, the Aral Sea has lost its fishery completely.

Water Use Efficiency (WUE)



Water Use Efficiency of crops (WUE)... WUE = transpiration efficiency × harvest index

Litres of water per dry kg of…	
Potatoes	500
Wheat	900
Tomato	1000
Maize	1400
Rice	2000
Chicken	*3500*
Beef	*>20000*

(OECD, 1999; Stanhill, 1980)

... is affected by genotype

With 5% dry matter this is about 50 litres per kg tomato

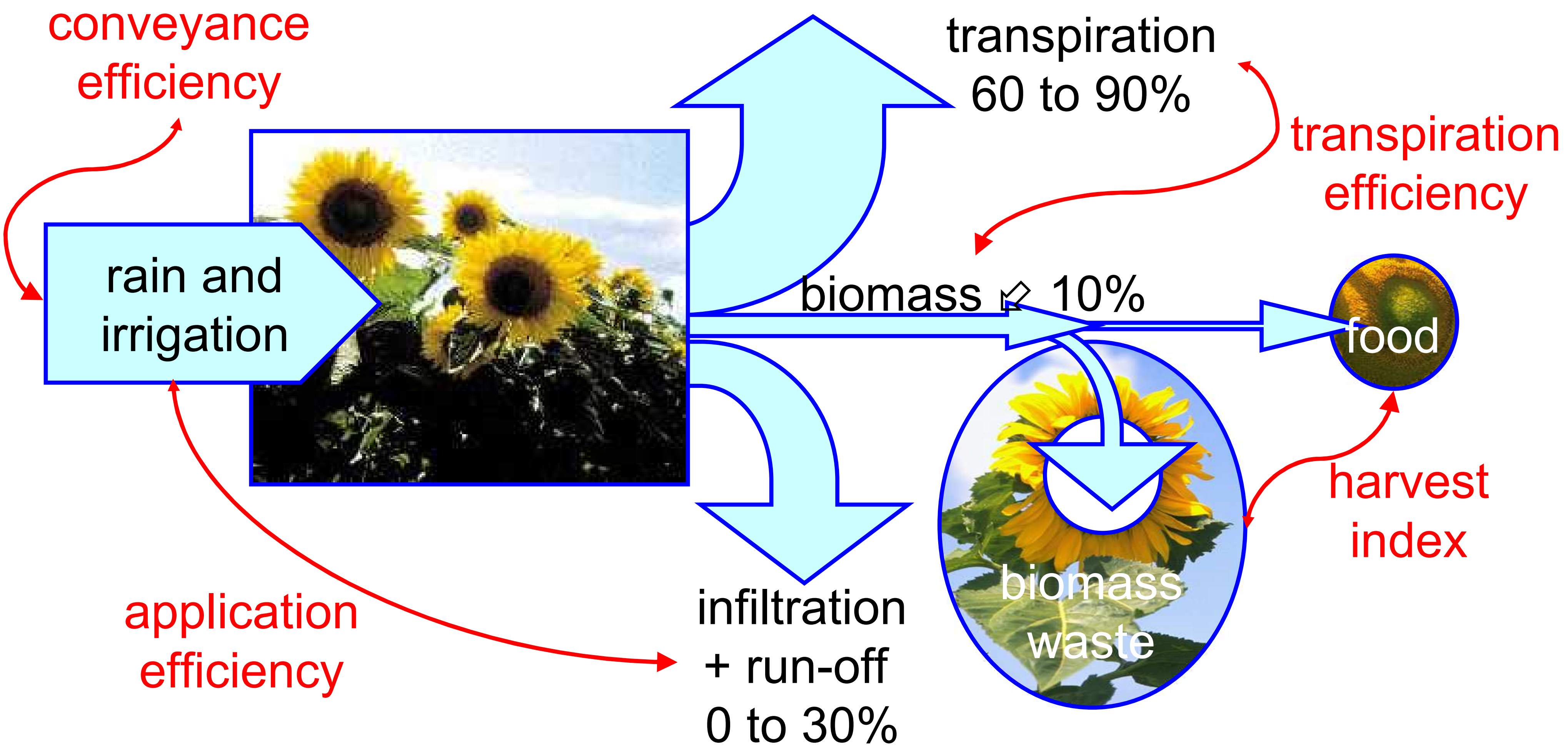
Efficiency of Water Use (EWU) is affected by genotype, environment ...

Litres of water per kg of fresh tomatoes in…	
Israel (field)	60
Spain (unheated plastic house)	40
Israel (unheated glasshouse)	30
Holland (climate-controlled glasshouse)	22

Increasing technology content

(Stanhill, 1980; Castilla and Fereres, 1990; Stanghellini, 1994)

Efficiency of Water Use (EWU)



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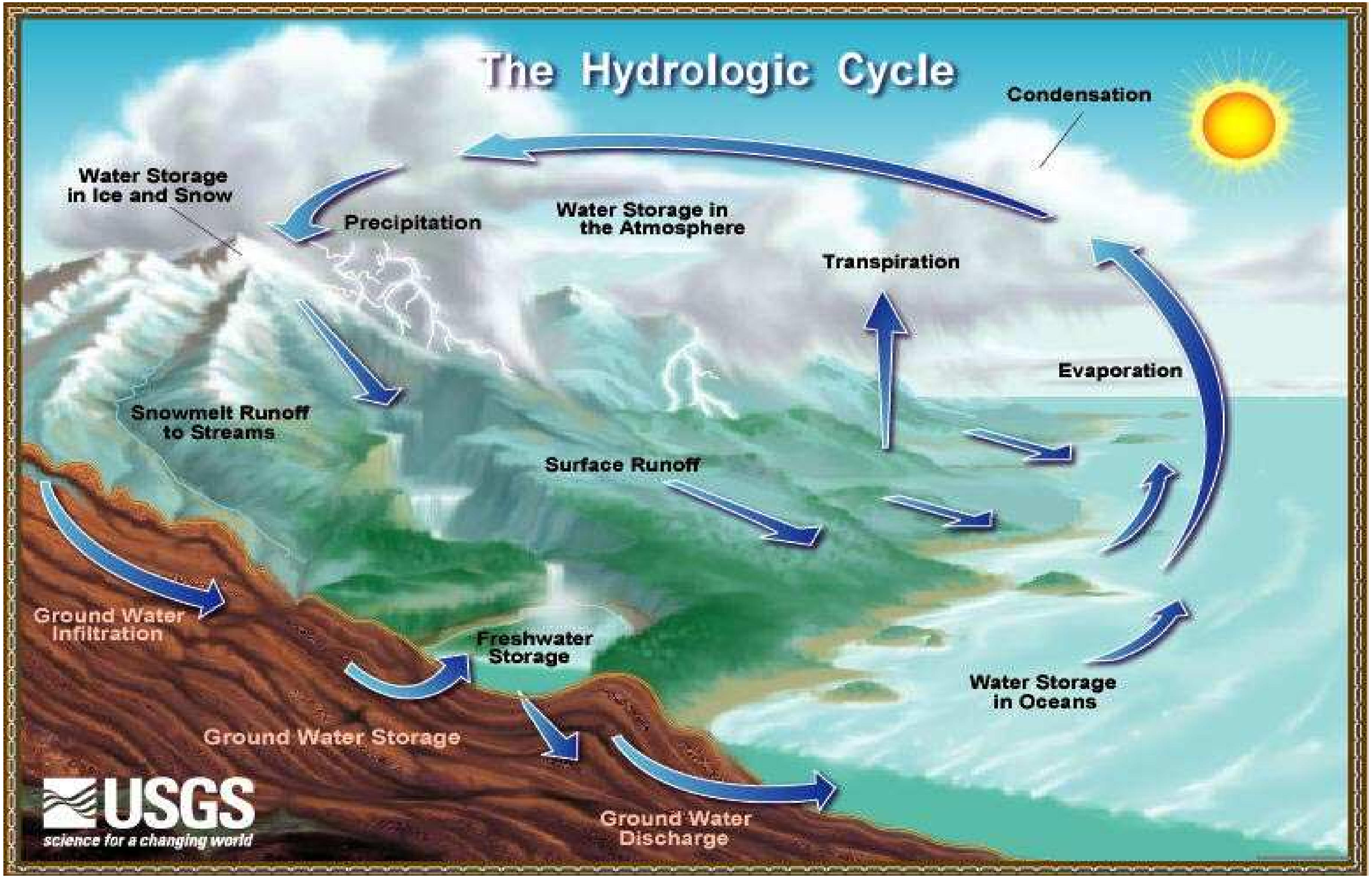
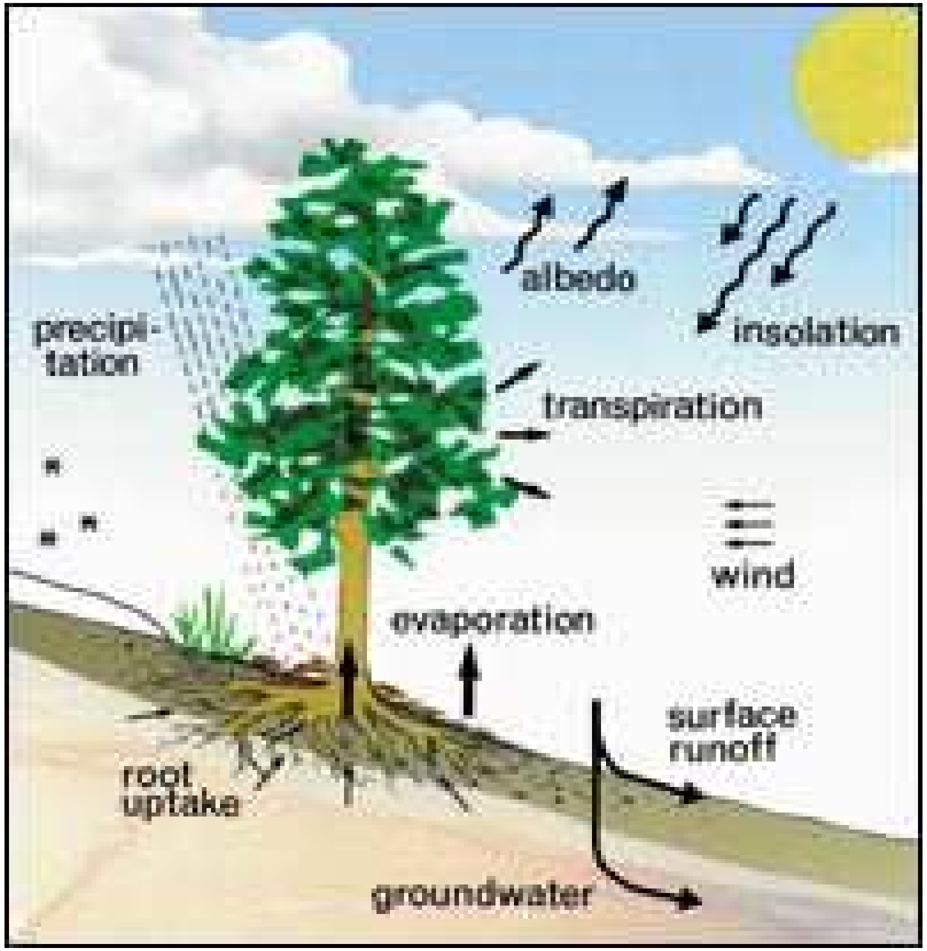

The Hydrologic Cycle
Condensation
Water Storage
in Ice and Snow
Precipitation
Water Storage in
the Atmosphere
Transpiration
Evaporation
Snowmelt Runoff
to Streams
Surface Runoff
Ground Water
Infiltration
Freshwater
Storage
Water Storage
in Oceans
Ground Water Storage
Ground Water
Discharge
USGS
science for a changing world

Pedon scale



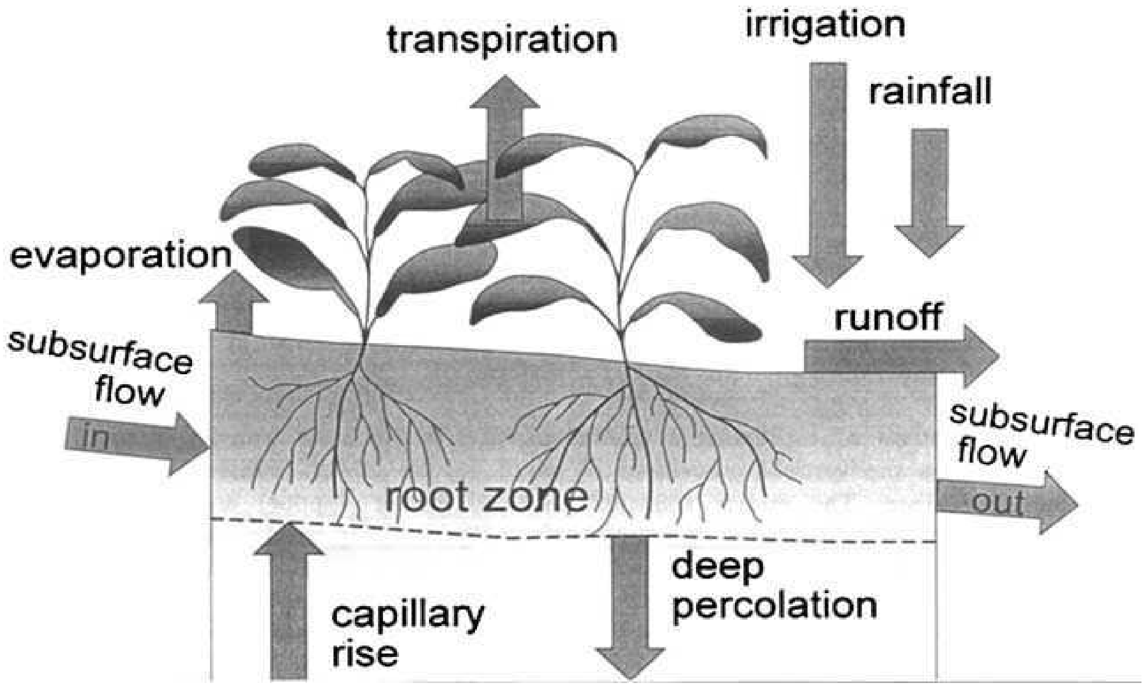
albedo
insolation
precipi-
tation
transpiration
wind
evaporation
surface
runoff
root
uptake
groundwater

The Water Balance

- 62% of precipitation that falls on the continents is evaporated
- Understanding and predicting climate change
- Q=P-ET. P-ET is the water available for use
- ET "loss" supports ecosystems and agriculture
- Reservoir losses
- The antecedent "wetness" that determines what happens to runoff depends on ET
- Even during a single storm ET may exceed runoff

Physical principles used

- Conservation of mass
- Conservation of energy
- Latent heat of phase change (vaporization)
- Turbulent transfer near the ground



$$\frac{\Delta W}{\Delta t} = P_n + I_n - E_s - T + v$$

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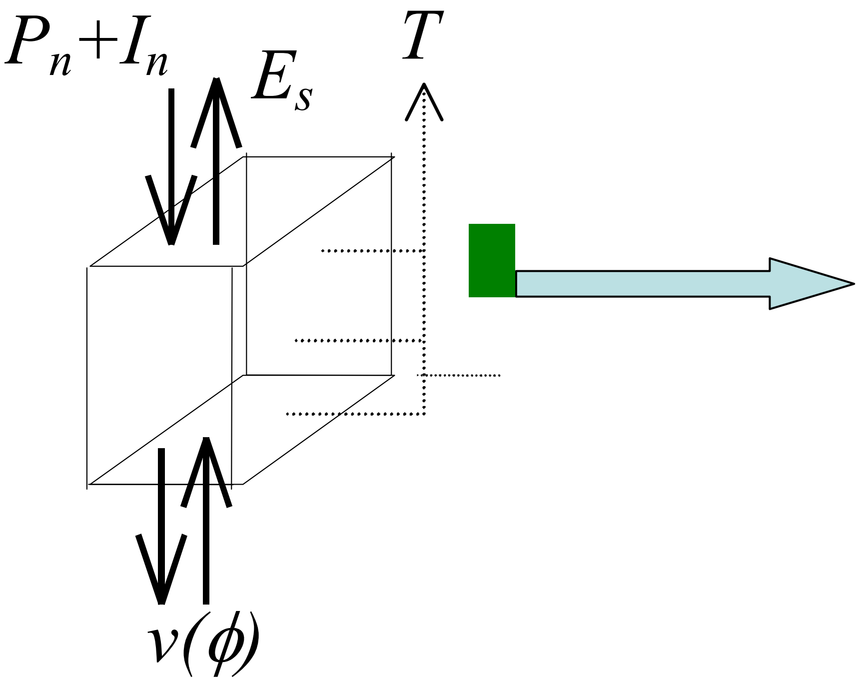
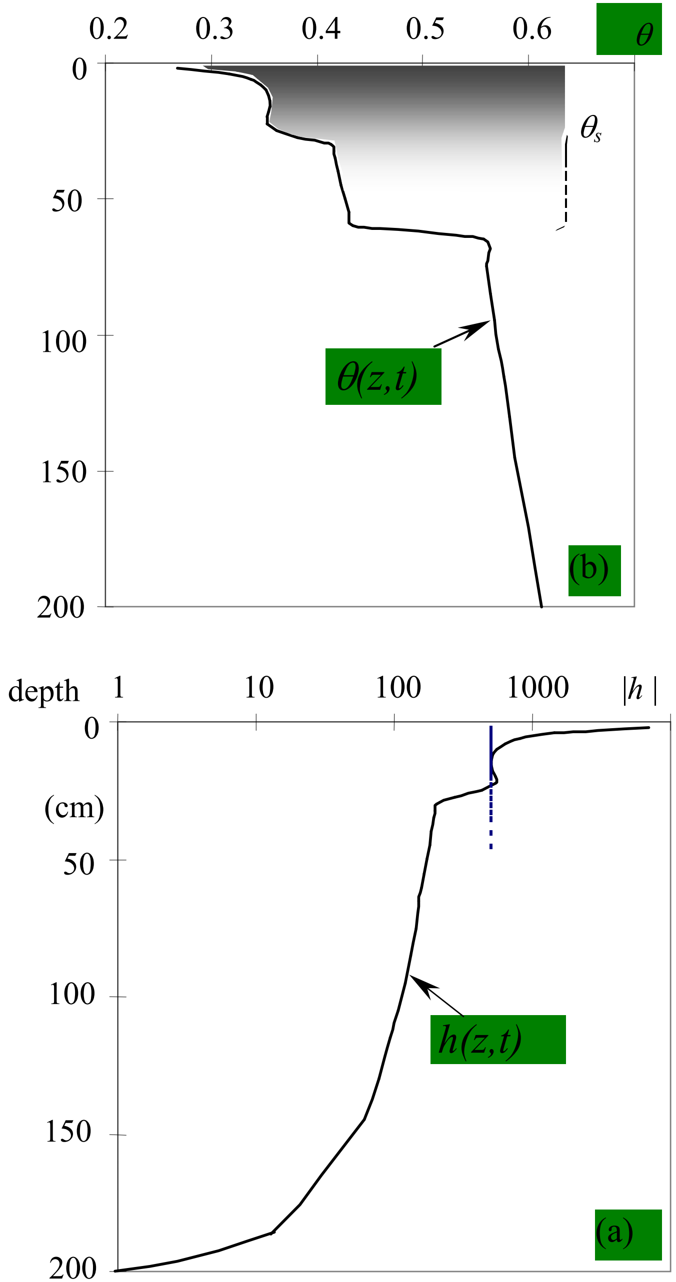
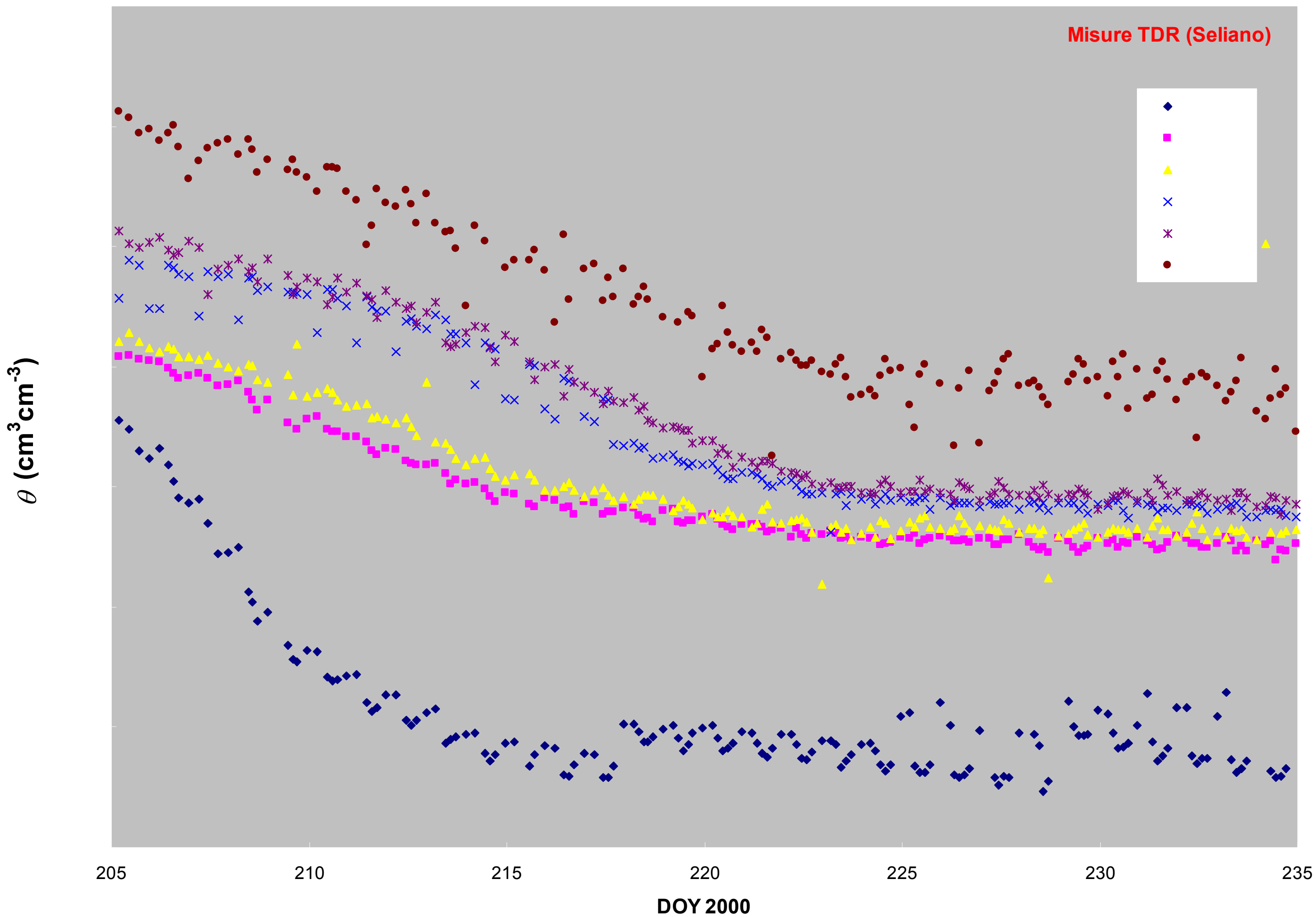


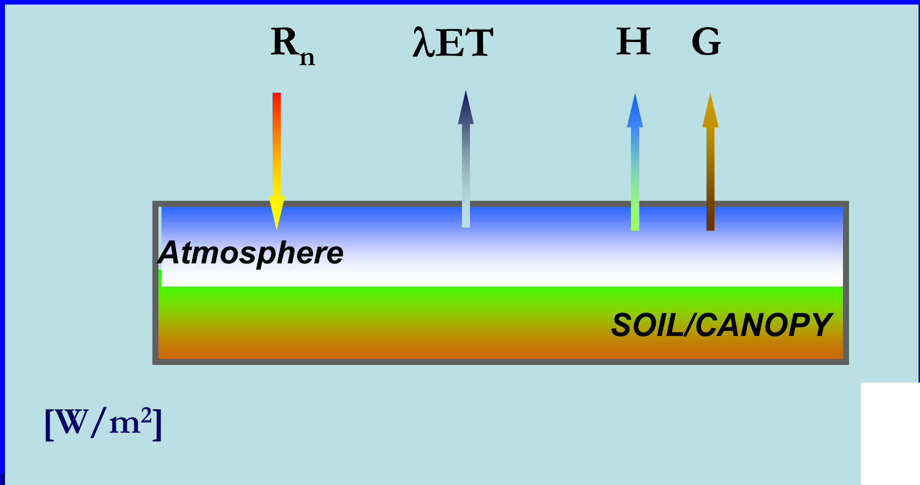


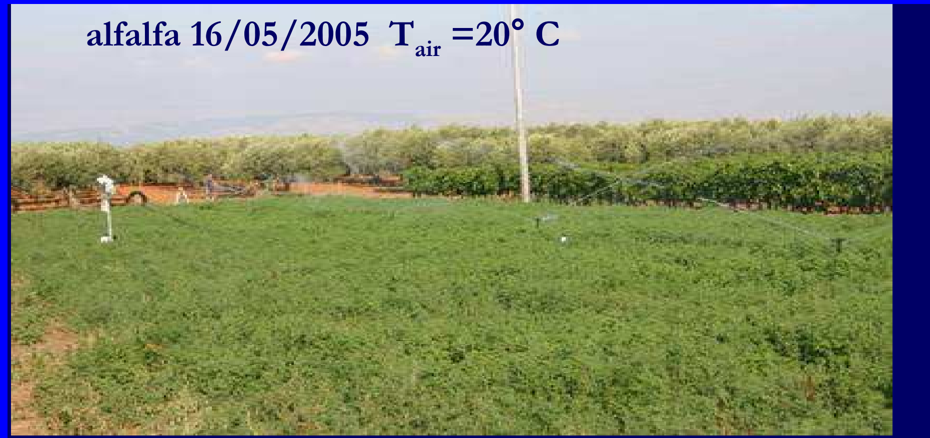
Measurement of soil water content at different depths during several days of no rainfall, July 2000, South Italy

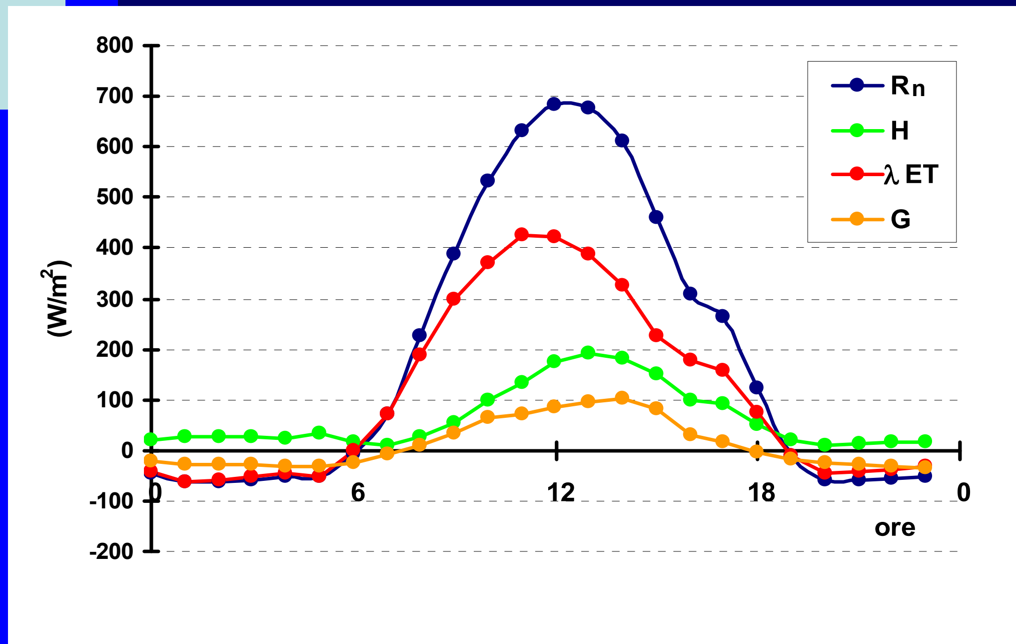


Conservation of energy

$$R_n - \lambda ET - H - G = 0$$







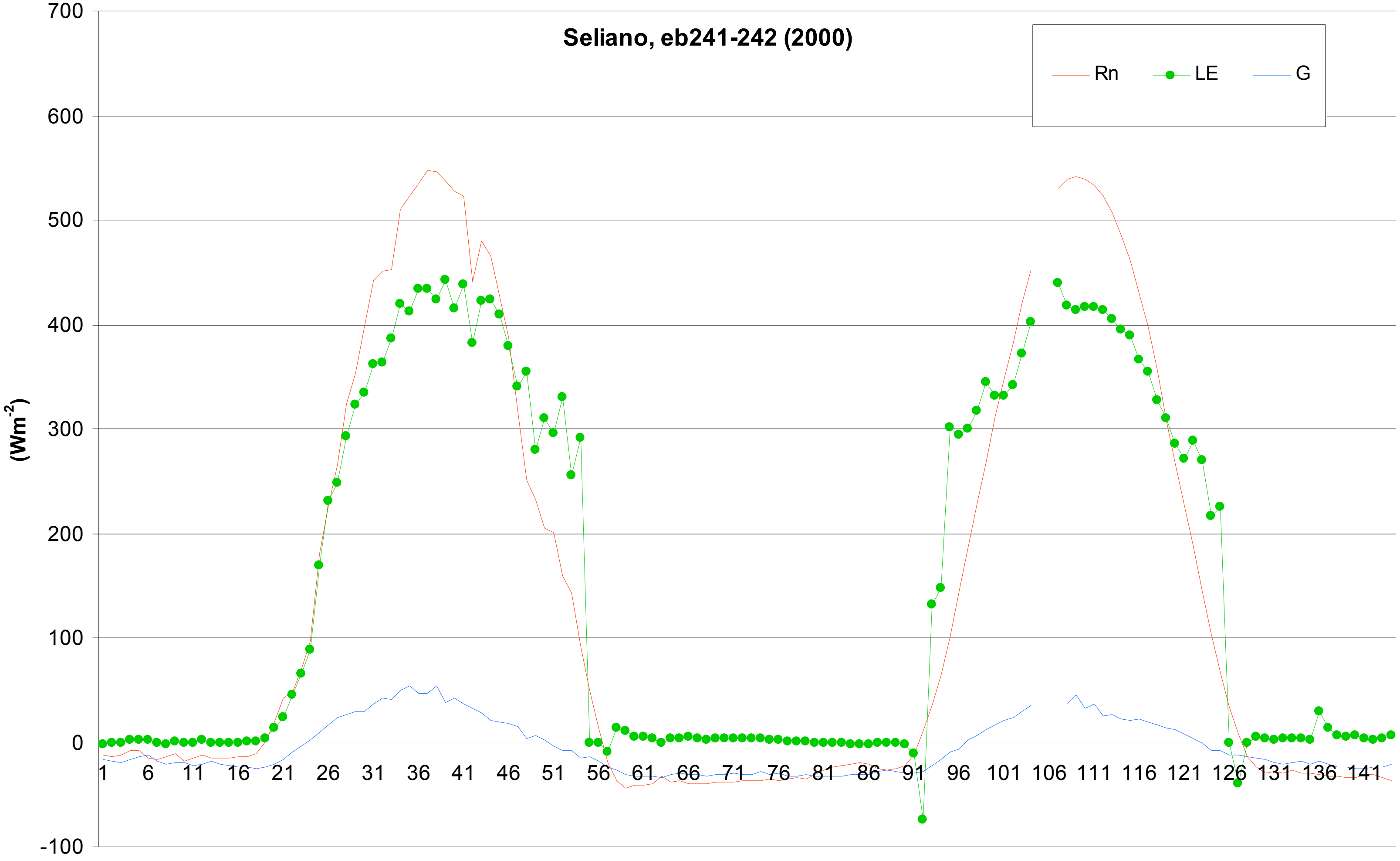
R_n = Net RADIATION

λET = Latent HEAT flux

H = Sensigle heat flux

G = Soil Heat flux

Measurement of energy balance component during two days, July 2000, South Italy



Precipitation

- Occurs when three conditions are met:
  - #1. Atmosphere is saturated
  - #2. Small particles are present
    - Dust
    - Ocean salt
  - #3. Drops are big enough to reach the surface
    - Have to over come updrafts
- The movement and collision of air masses lead to atmospheric instability
  - The result is often precipitation

Precipitation Data

- Necessary for most land use plans
  - Municipal / industrial / agricultural / forestry / flood prevention / recreation
- Data collection by State and Federal agencies
  - Much of the data is now on-line via the internet
- Precipitation records report amounts
  - Yearly / monthly / daily / hourly

Rainfall

- Large variation depending on
  - Location and time of year
    - Some deserts get 0 rain
    - Cherrapunji, India has gotten 20 000 mm/yr
    - Combined orographic effects and monsoons
- Units of measurement ➔ depth (in. / mm / etc.)
  - Can get volume easily by multiplying by area
  - Accuracy of measurement ➔ 0.1-0.2 mm
    - Mis-leading since no two rain gages will ever record the same amount of rain even if they are side by side!

Rainfall Measurement

- Standard rain gages are point samples only
  - Generally a high degree of variation in any rainfall
  - Rain gages are usually cylindrical with circular top
    - Therefore least subjected to edge effect errors
  - Mounted vertically
  - Height of 2 m
  - 2:1 obstruction rule
    - If top of object is 10 m above gage
    - Place gage 20 m away
    - Eliminates obstructions that may affect rainfall capture

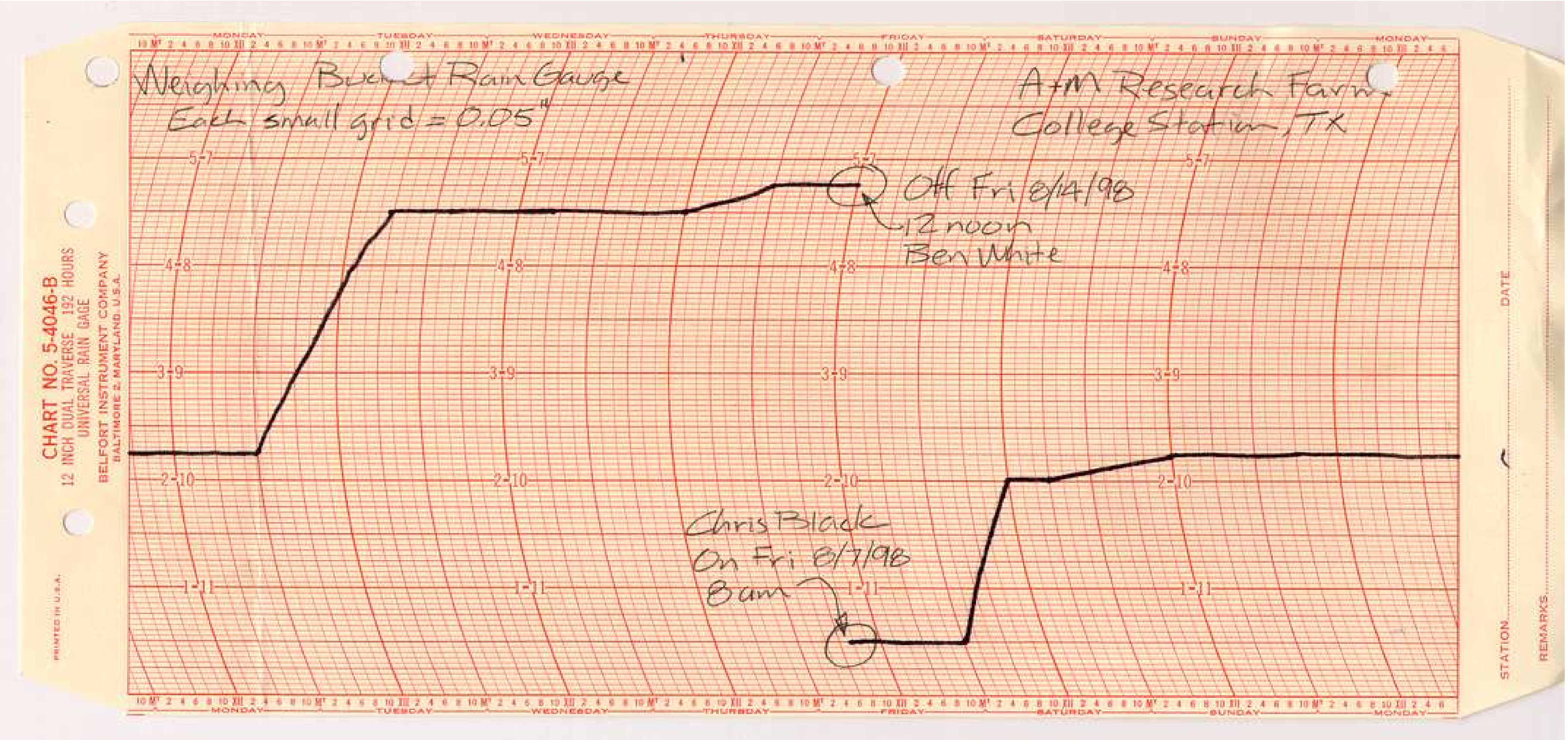
Rainfall Measurement

- Two types of rain gages
  - Non-recording
    - Low cost / maintenance free
    - Accuracy = 0.2 mm
  - Recording
    - Paper only
    - Paper and electronic data collection
      - Some type of datalogger required
    - Electronic only
  - Good strategy → mix of both for redundancy

Rainfall Measurement

- Recording rain gages
  - Weighing bucket type
    - Good for large rainfall events
      - Can’t accurately measure (weigh) small rainfall events
  - Tipping bucket type
    - Good for small rainfall events
      - Can’t keep up during heavy rainfall events
    - Each tip = 0.1 mm

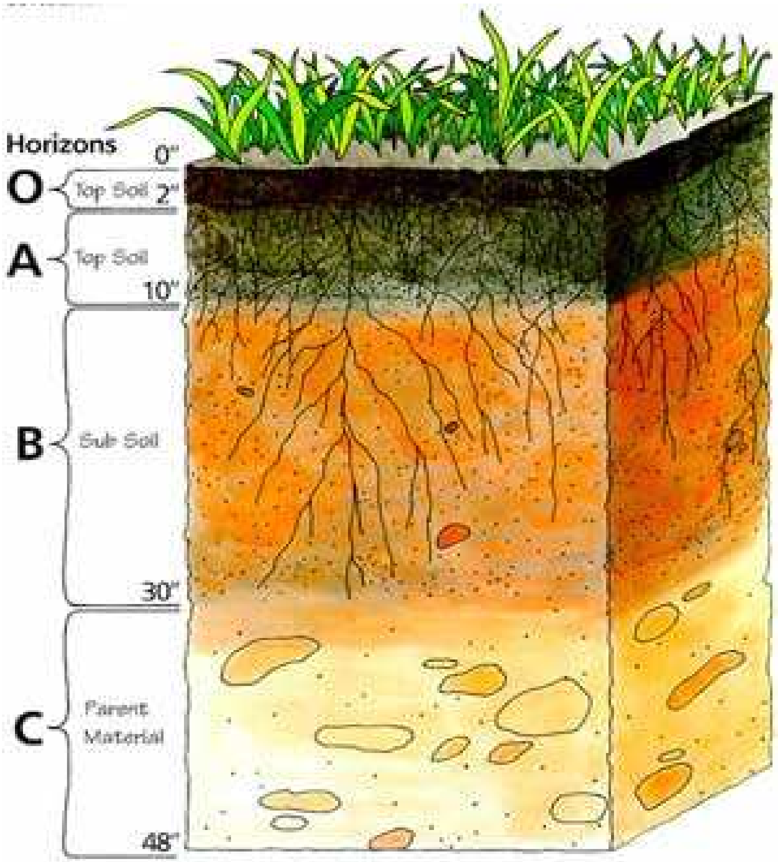
Weighing Bucket Rain Gage Chart
Each small grid = 0.05"

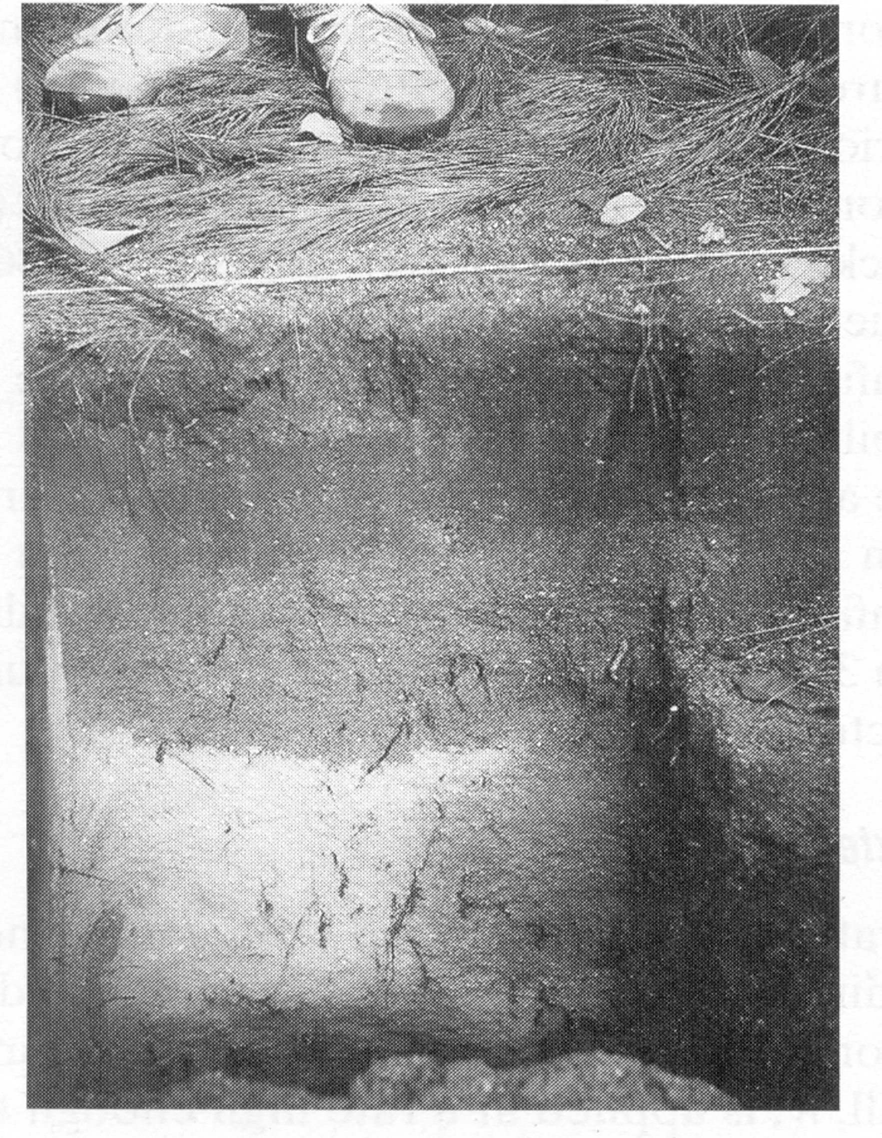


Rain Gauge

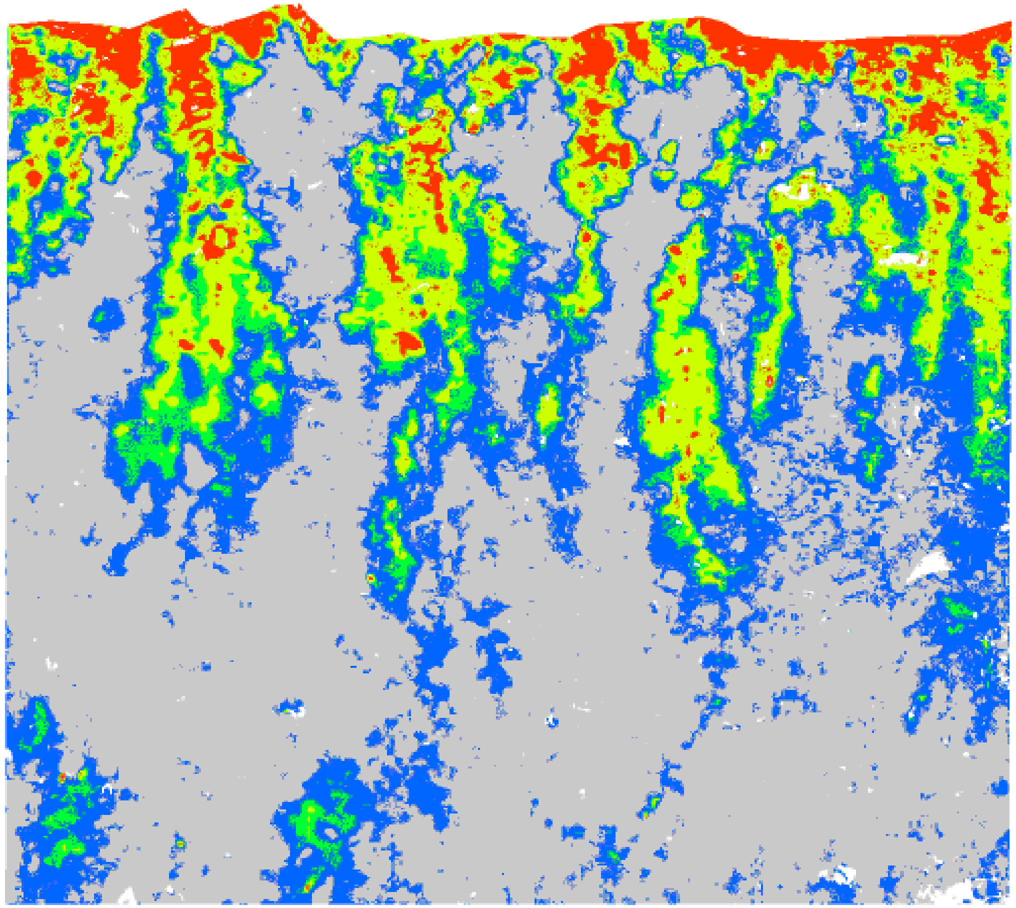
Infiltration

- The entry of water into the soil

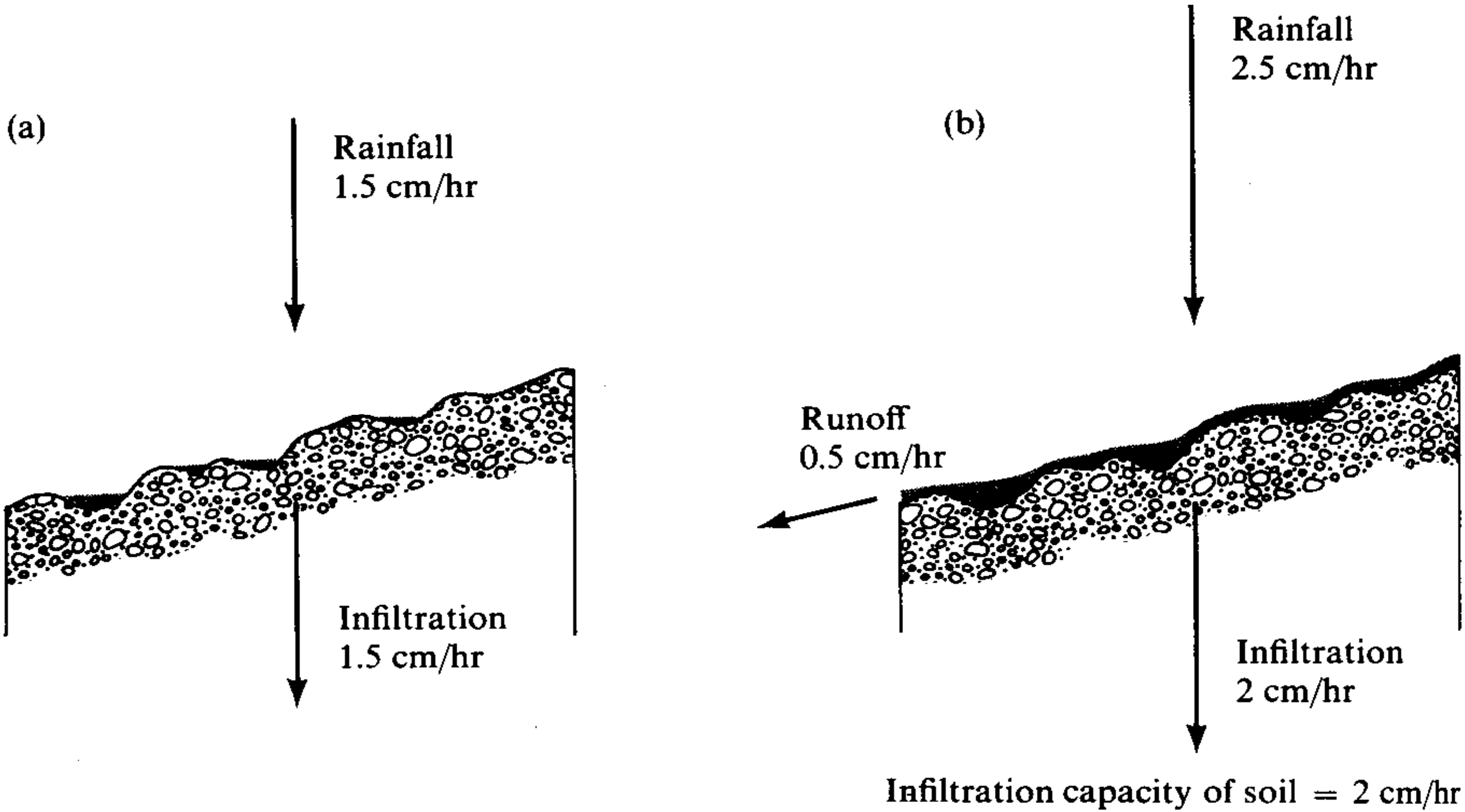




Wetting front in a sandy soil exposed after intense rain (from Dingman, 1994).



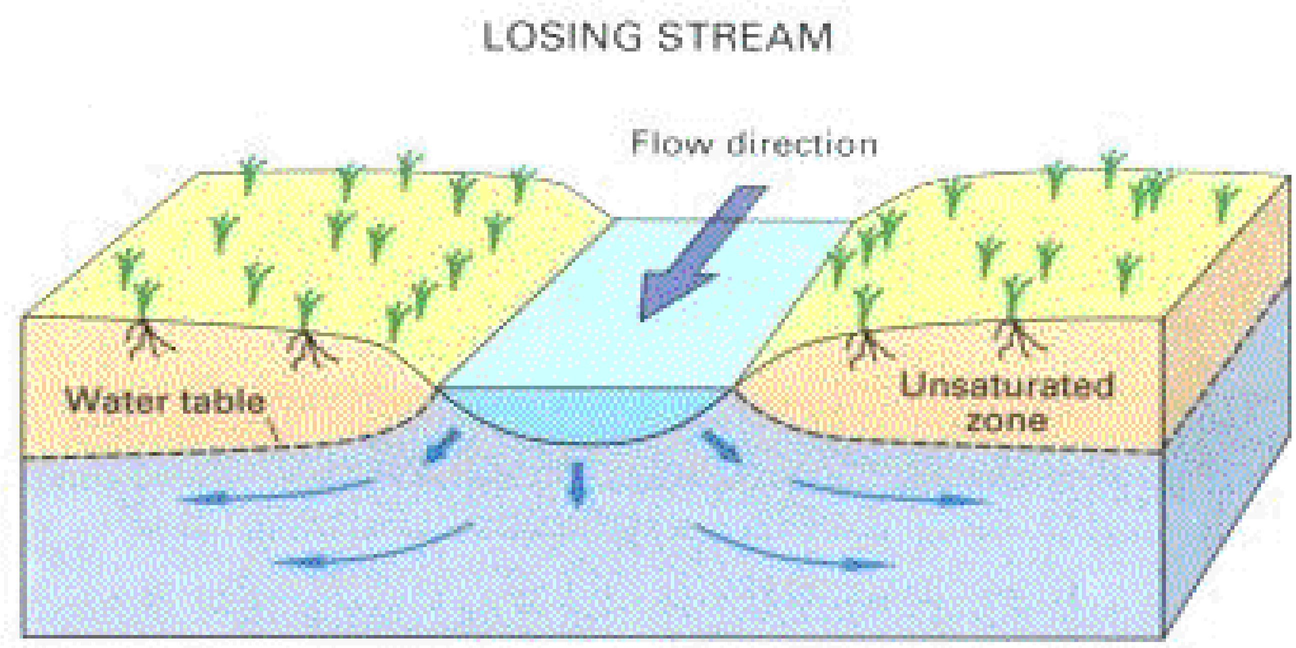
Preferential pathway infiltration (Markus Weiler, ETH Zurich)

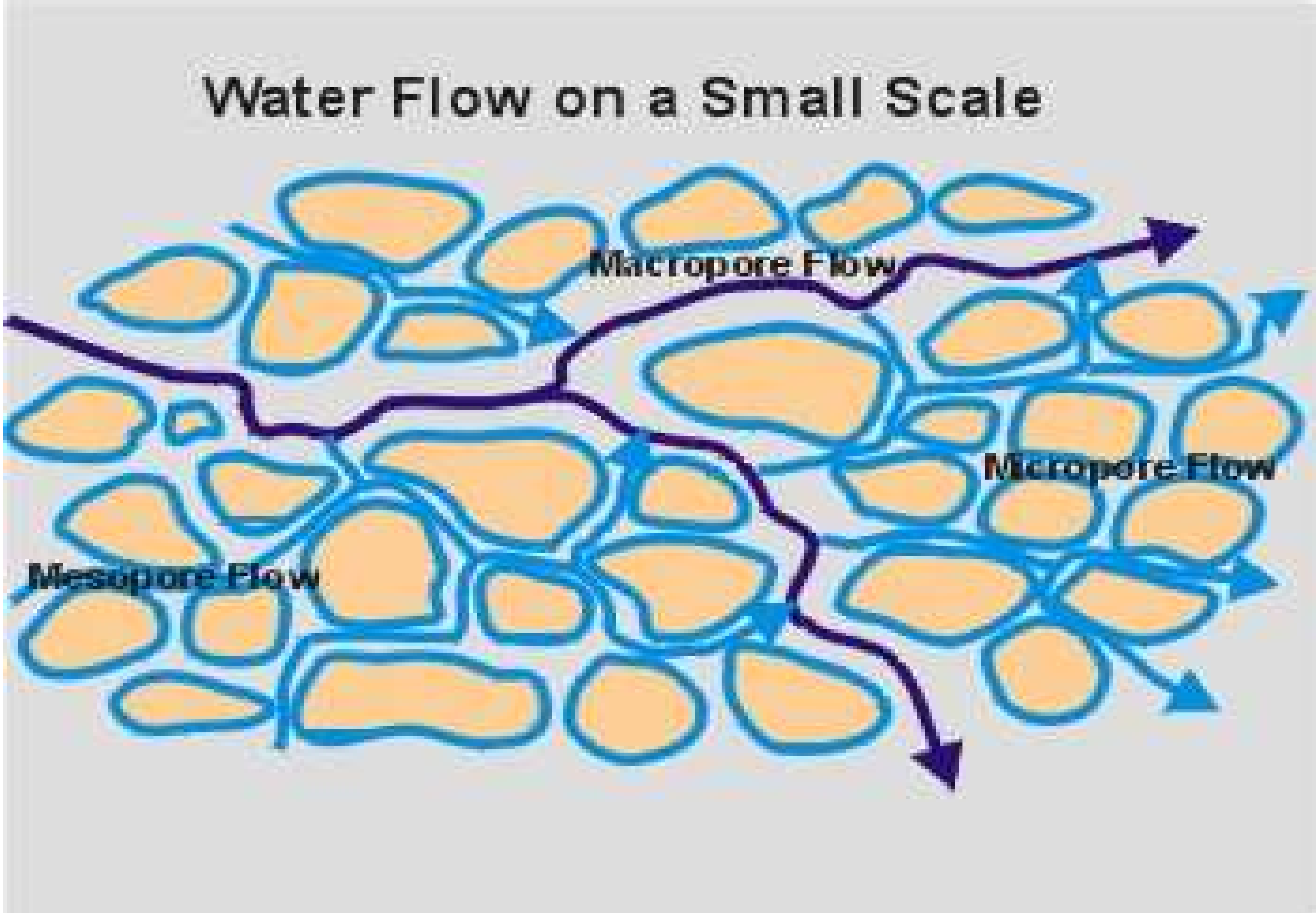


Surface Runoff occurs when surface water input exceeds infiltration capacity. (a) Infiltration rate = rainfall rate which is less than infiltration capacity. (b) Runoff rate = Rainfall intensity – Infiltration capacity. (from Dunne and Leopold, 1978)

Groundwater

- Groundwater recharged by:
  - Water that infiltrates past the root zone
  - "Losing" streams (in arid regions generally)
    - Groundwater is deeper than the stream
  - This is generally a vertical downward flow path





Water Flow on a Small Scale
Macropore Flow
Micropore Flow
Mesopore Flow

Groundwater Movement

- Rapid flow in caves represents karst flow
  - Karst: Topography formed over limestone, dolomite or gypsum and characterized by sinkholes and caverns
  - However, most groundwater flow is very slow
    - "Rate of Exchange" ➔ flow through the system
      - River systems = 11 days
      - Groundwater = 102,200 days (280 yrs)
- Saturated hydraulic conductivity
  - Clay = 1 x 10^{-6} m/s = 31 m/yr
  - Gravel = 3 x 10^{-2} m/s = 946 km/yr

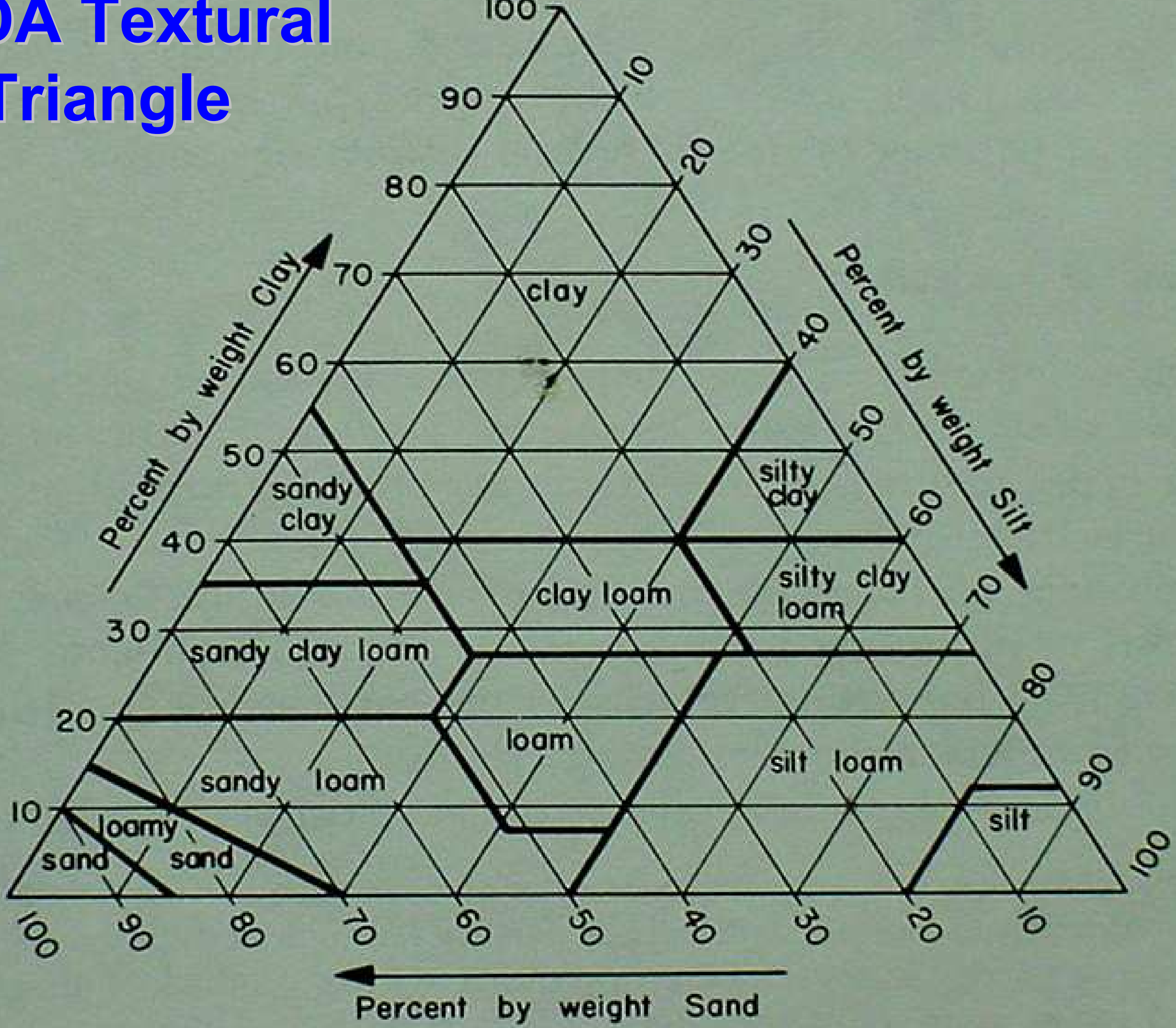
Infiltration

- Other factors that influence infiltration rate
  - Compaction ➔ reduces infiltration
  - Vegetation ➔ increases infiltration
  - Topography (slope) of land surface
  - Surface roughness
  - Human activity
    - Urban developments ➔ impervious surfaces
    - Agriculture

Soil Properties

- Texture
  - Definition: relative proportions of various sizes of individual soil particles
  - USDA classifications
    - Sand: 0.05 – 2.0 mm
    - Silt: 0.002 - 0.05 mm
    - Clay: <0.002 mm
  - Textural triangle: USDA Textural Classes
  - Coarse vs. Fine, Light vs. Heavy
  - Affects water movement and storage
- Structure
  - Definition: how soil particles are grouped or arranged
  - Affects root penetration and water intake and movement

USDA Textural Triangle



- Bulk Density (ρ_b)

$$\rho_b = \frac{M_s}{V_b}$$

  - ρ_b = soil bulk density, g/cm^3
  - M_s = mass of dry soil, g
  - V_b = volume of soil sample, cm^3
- Typical values: 1.1 - 1.6 g/cm^3

- Particle Density (ρ_p)

$$\rho_p = \frac{M_s}{V_s}$$

  - ρ_P = soil particle density, g/cm^3
  - M_s = mass of dry soil, g
  - V_s = volume of solids, cm^3
- Typical values: 2.6 - 2.7 g/cm^3

- Porosity (ϕ)

$$\phi = \frac{\text{volume of pores}}{\text{volume of soil}}$$

$$\phi = \left(1 - \frac{\rho_b}{\rho_p}\right) 100\%$$

- Typical values: 30 - 60%

Water in Soils

- Soil water content

$$\theta_m = \frac{M_w}{M_s}$$

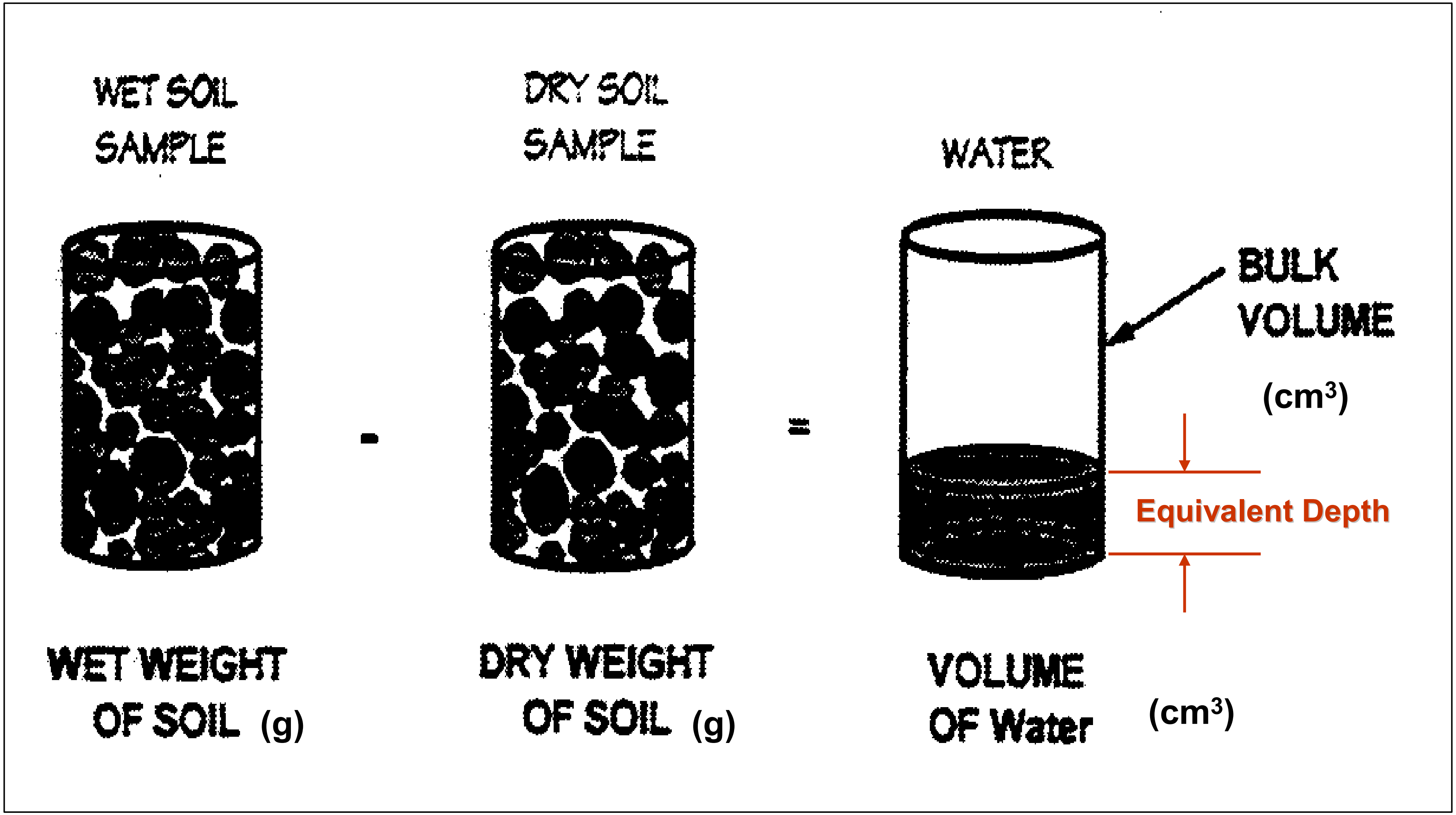
  - Mass water content (θ_m)
  - θ_m = mass water content (fraction)
  - M_w = mass of water evaporated, g (≥24 hours @ 105°C)
  - M_s = mass of dry soil, g

- Volumetric water content (θ_v)

$$\theta_v = \frac{V_w}{V_b}$$

  - θ_V = volumetric water content (fraction)
  - V_w = volume of water
  - V_b = volume of soil sample
  - At saturation, $\theta_V = \phi$
  - θ_V = As θ_m
  - As = apparent soil specific gravity = ρ_b/ρ_w (ρ_w = density of water = 1 g/cm^3)
  - As = ρ_b numerically when units of g/cm^3 are used
- Equivalent depth of water (d)
  - d = volume of water per unit land area = (θ_v A L) / A = θ_v L
  - d = equivalent depth of water in a soil layer
  - L = depth (thickness) of the soil layer

Volumetric Water Content & Equivalent Depth

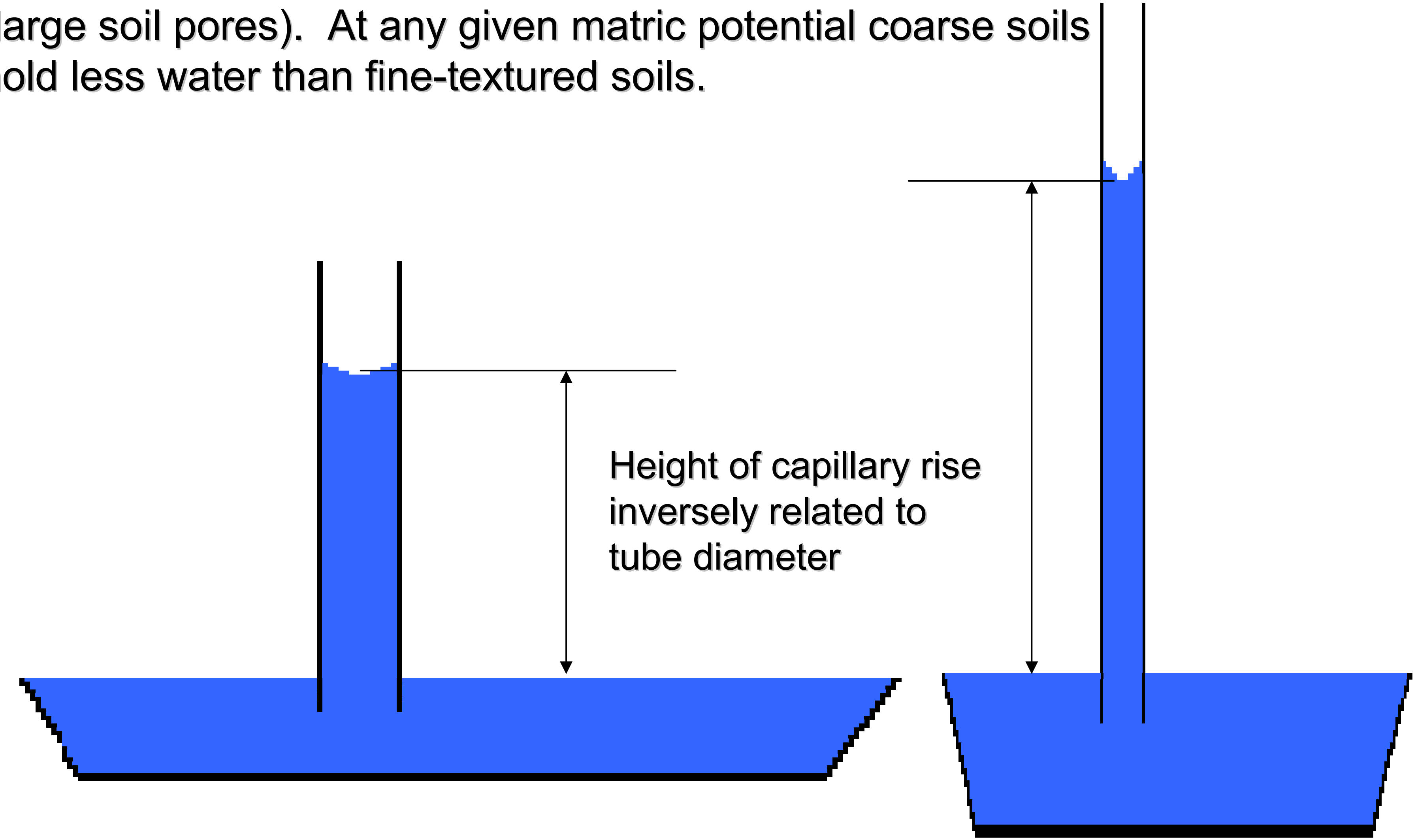


Soil Water Potential

- Description
  - Measure of the energy status of the soil water
  - Important because it reflects how hard plants must work to extract water
  - Units of measure are normally bars or atmospheres
  - Soil water potentials are negative pressures (tension or suction)
  - Water flows from a higher (less negative) potential to a lower (more negative) potential

Matric Potential and Soil Texture

The tension or suction created by small capillary tubes (small soil pores) is greater that that created by large tubes (large soil pores). At any given matric potential coarse soils hold less water than fine-textured soils.



- Field Capacity (FC or θ_{fc})
  - –Soil water content where gravity drainage becomes negligible
  - –Soil is not saturated but still a very wet condition
  - –Traditionally defined as the water content corresponding to a soil water potential of -1/10 to -1/3 bar
- Permanent Wilting Point (WP or θ_{wp})
  - –Soil water content beyond which plants cannot recover from water stress (dead)
  - –Still some water in the soil but not enough to be of use to plants
  - –Traditionally defined as the water content corresponding to -15 bars of SWP

Available Water

- Definition
  - Water held in the soil between field capacity and permanent wilting point
  - “Available” for plant use
- Available Water Capacity (AWC)
  - $AWC = \theta_{fc} - \theta_{wp}$
  - Units: depth of available water per unit depth of soil, “unitless” (in/in, or mm/mm)
  - Measured using field or laboratory methods (described in text)

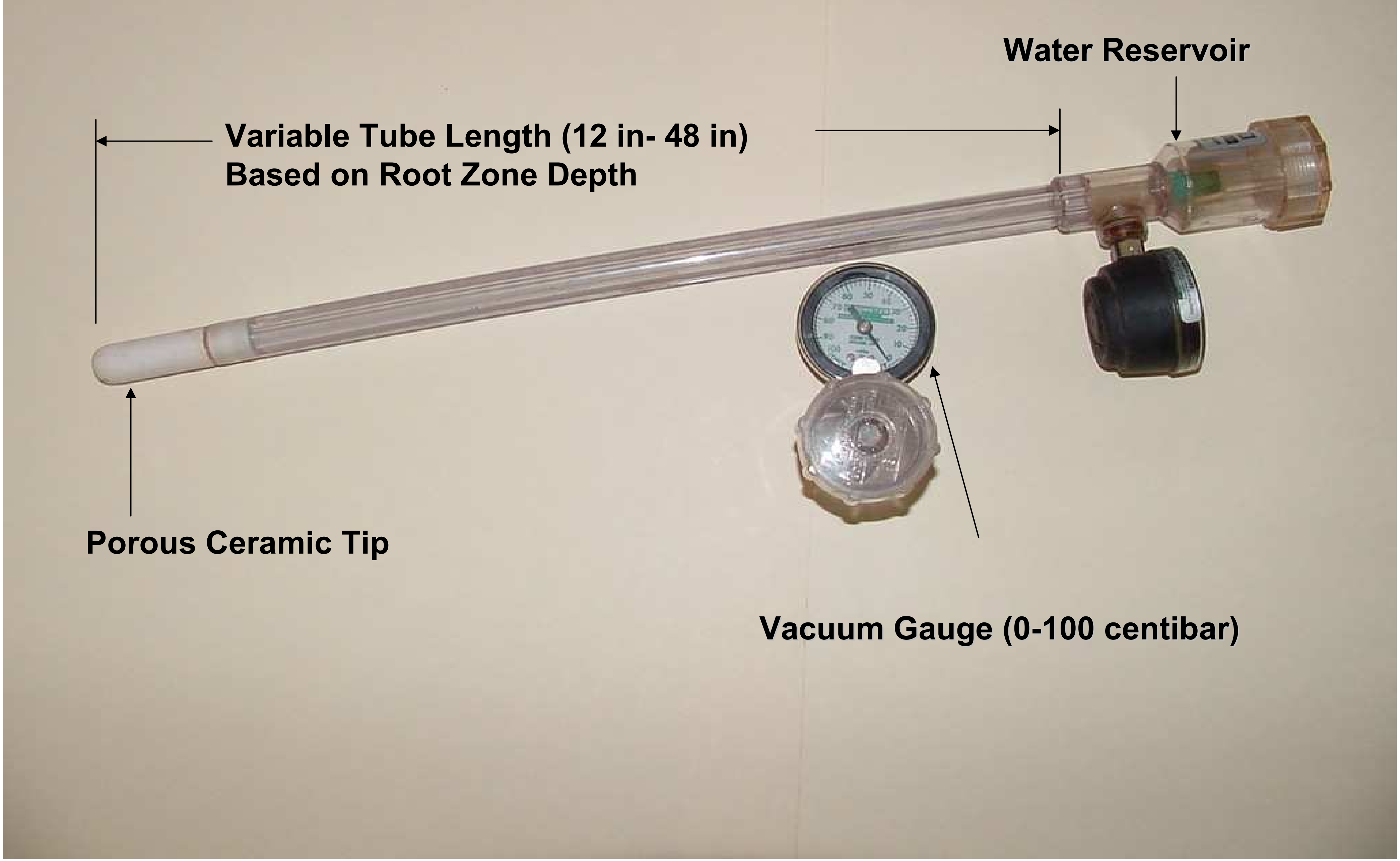
Soil Hydraulic Properties and Soil Texture

Table 2.3. Example values of soil water characteristics for various soil textures.*

Soil texture	θ_{fc}	θ_{wp}	AWC
	---------- in/in or m/m	---------	
Coarse sand	0.10	0.05	0.05
Sand	0.15	0.07	0.08
Loamy sand	0.18	0.07	0.11
Sandy loam	0.20	0.08	0.12
Loam	0.25	0.10	0.15
Silt loam	0.30	0.12	0.18
Silty clay loam	0.38	0.22	0.16
Clay loam	0.40	0.25	0.15
Silty clay	0.40	0.27	0.13
Clay	0.40	0.28	0.12

* Example values are given. You can expect considerable variation from these values within each soil texture.

Tensiometer for Measuring Soil Water Potential



Electrical Resistance Blocks & Meters

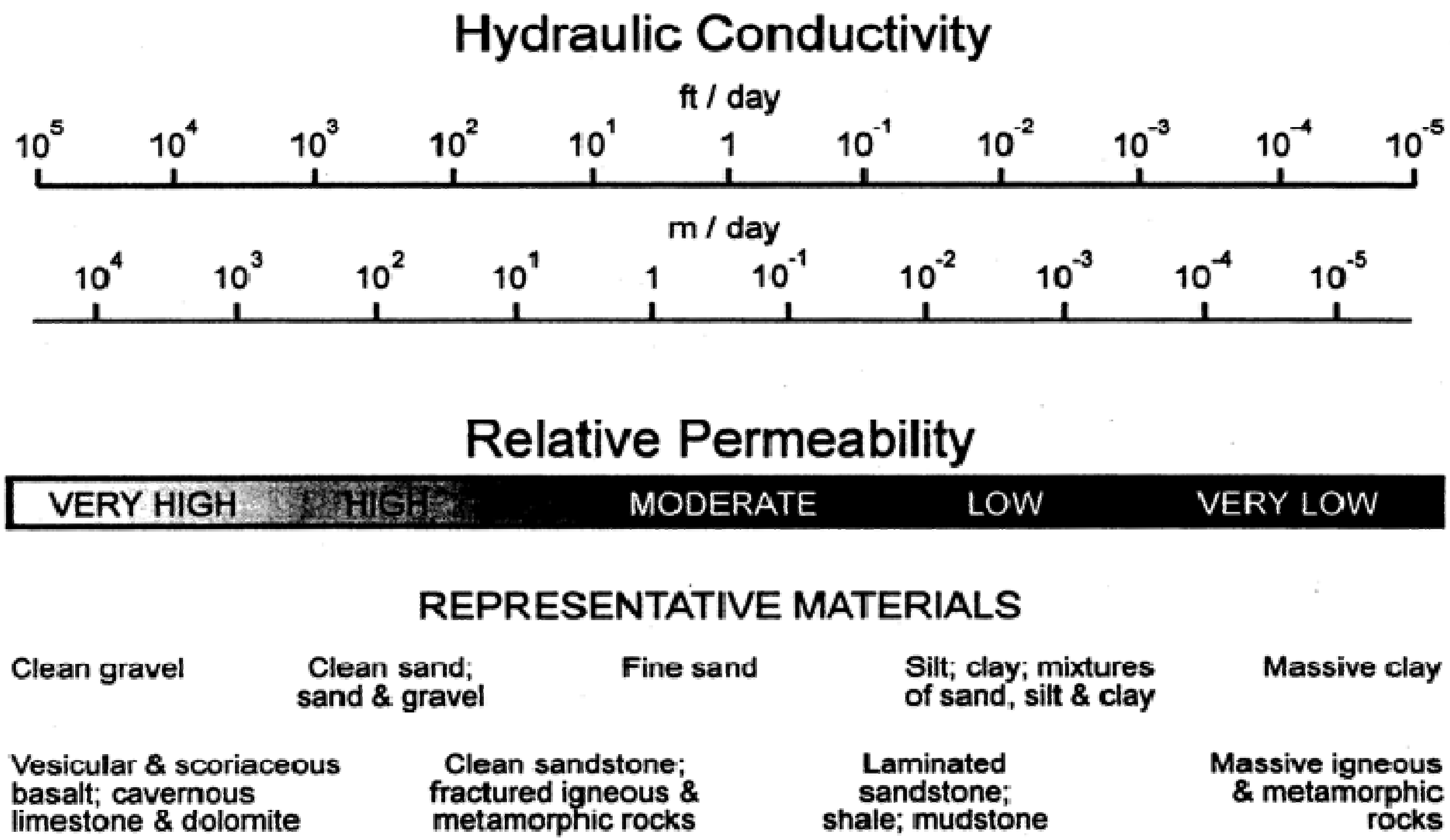
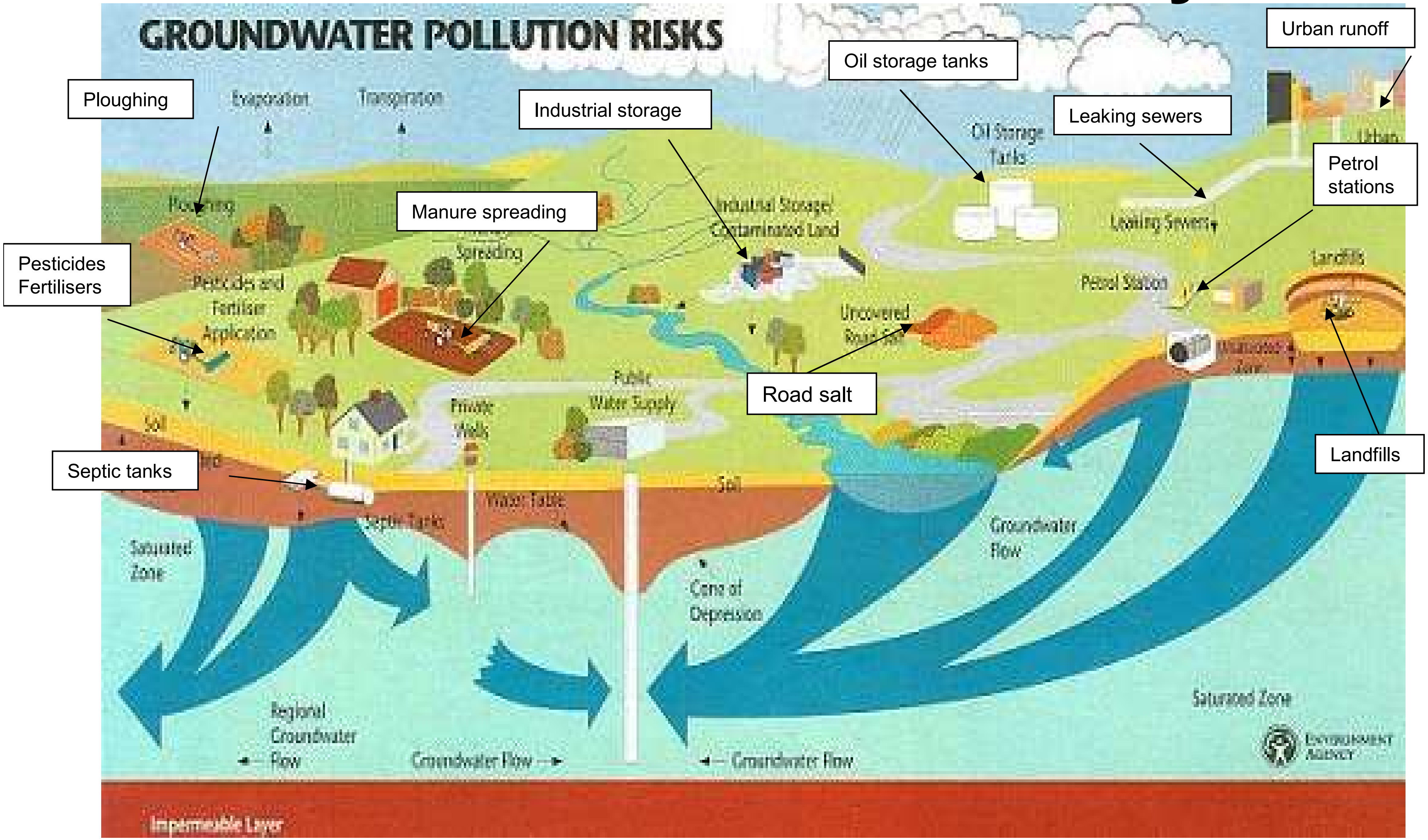


Figure 9.4. Bar chart showing hydraulic-conductivity values for various types of rock and sediment (modified from Bureau of Reclamation, 1977).

Groundwater Quality



A few more contaminant sources are missing from the cartoon: **saline intrusion** in coastal areas and **nuclear waste disposal** facilities.

Groundwater Quality

Groundwater quality is nowadays the issue number one in hydrogeological studies. Contamination can come from many different sources and the number of pollutants with different characteristics is extremely large.

- Some pollutants have immediate detrimental effect - e.g. they are **highly toxic**, such as arsenic.

- Some may have **long term poisonous** effects, such as lead or mercury.

- Some can **cause cancer**, such as many organic compounds, including hydrocarbons contained in fuel, or pesticides.

- Some can **harm particular categories** of people; one example is nitrate contamination and its relation to the blue baby syndrome.

- Finally, **pathogens** can still be a problem, especially when water is drawn from private wells with no suitable treatment.

The most instructive way to describe groundwater pollution problems is to classify them by source type.

Groundwater Quality

Pesticides is a general term to include insecticides, herbicides and fungicides.

The introduction of synthetic pesticides in the 1950s changed the face of agriculture forever. **DDT** is the best known of these new compounds, most of which are **organochlorines**, i.e. they contain atoms of chlorine in the organic molecule.

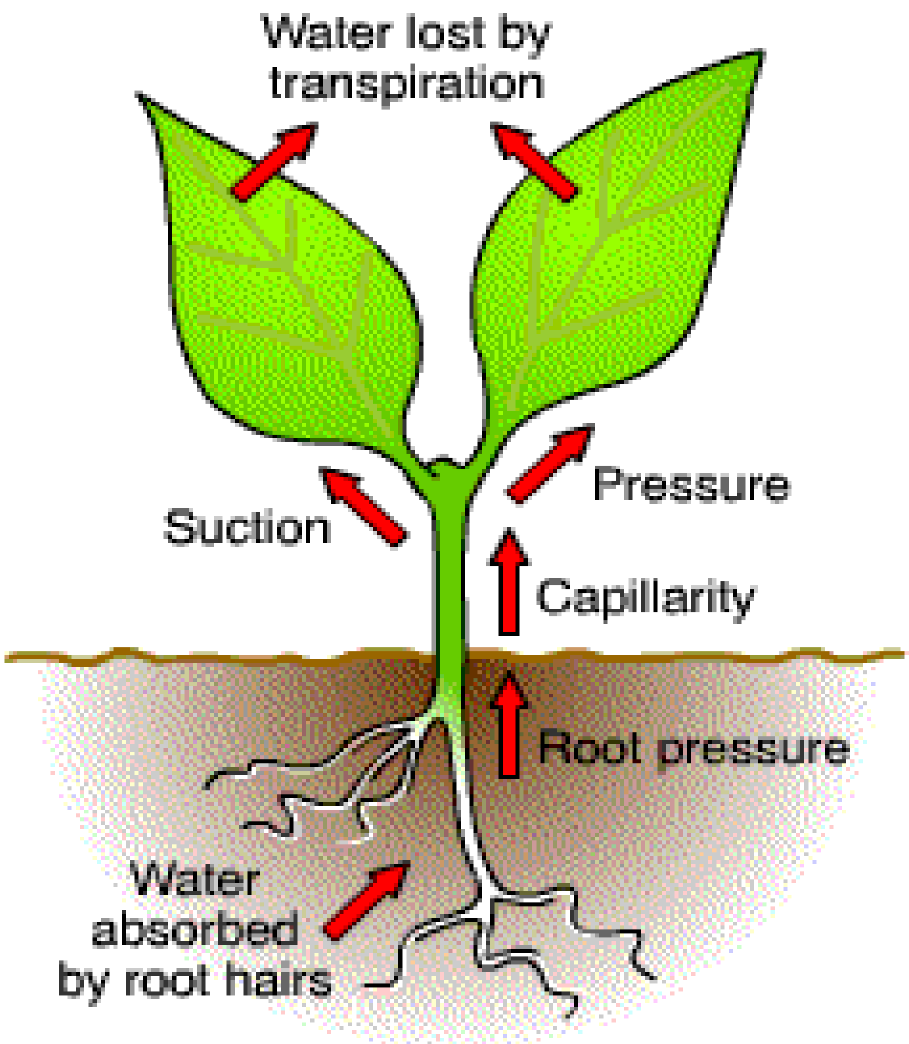
Organochlorines are **extremely persistent and accumulate in fat** tissues, thus concentrating in living animals that feed on contaminated land. The potential for contamination to the food chain is high. However, DDT and similar compounds are so **little soluble in water** that they are mostly retained adsorbed to the soil organic matter or to clay. Very small quantities of pesticides have been found in groundwater until the early 1980s. However, after that time their presence has been detected more and more commonly. Among the best known pesticides found in ground water is **atrazine** (a herbicide).

Only a **limited number of micro-organisms** have the capability to **degrade pesticides**. Often, the only treatment for water supply is chemical oxidation, very expensive.

Evapo-transpiration = 2 separate processes

- Evaporation
  - Water changes from a liquid to a vapor
  - Increases with increasing:
    - Air temp. / wind speed / solar radiation
  - Decreases with increasing relative humidity
    - Lots of moisture already in the air ➔ no room for more

- Transpiration

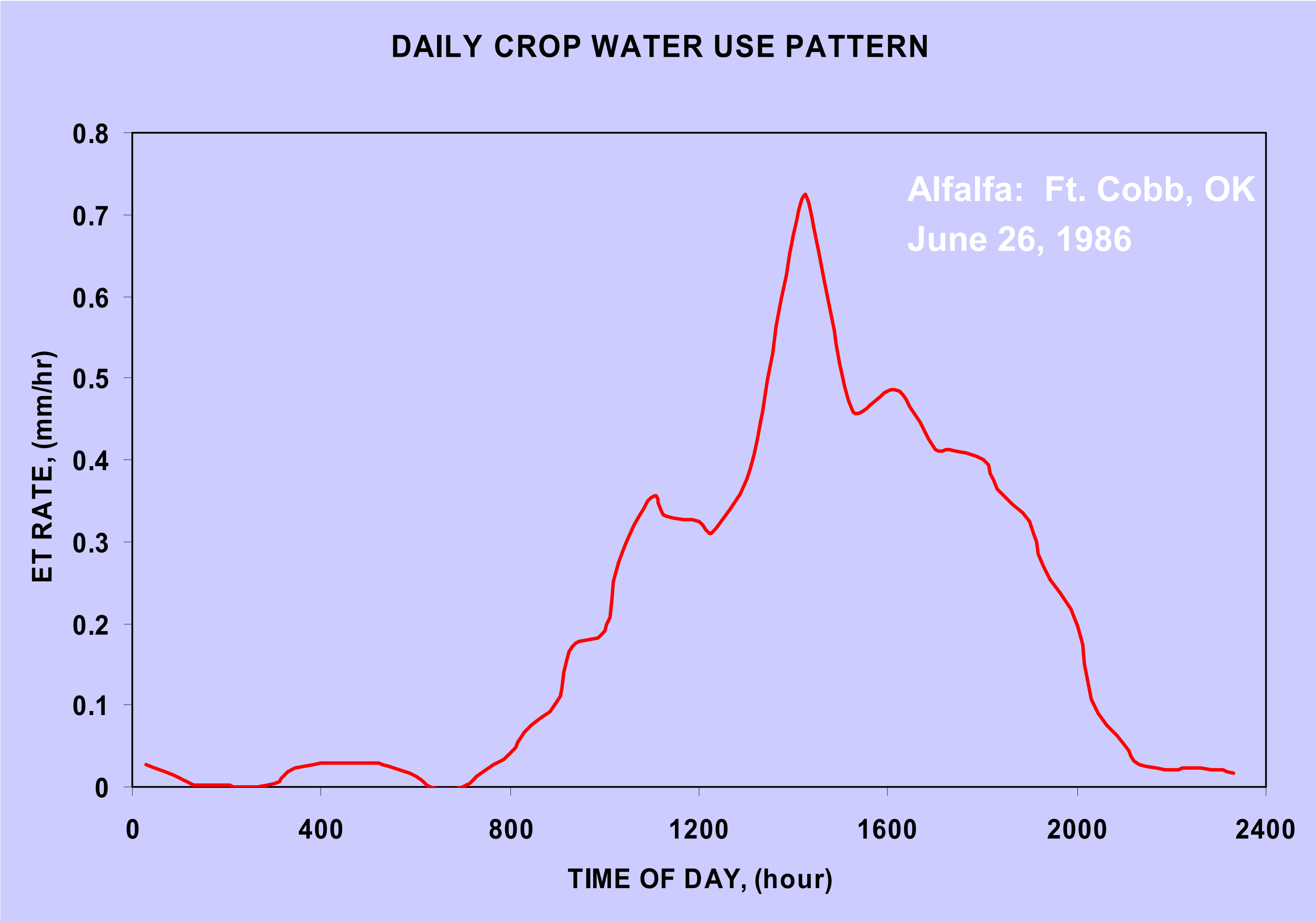


Magnitude of ET

- Generally 3-6 mm per day, or 800-1000 mm per growing season
- Varies with type of plant, growth stage, weather, soil water content, etc.
- Transpiration ratio
  - Ratio of the mass of water transpired to the mass of plant dry matter produced (g H_2O/g dry matter)
- Typical values: 250 for sorghum
  500 for wheat
  900 for alfalfa

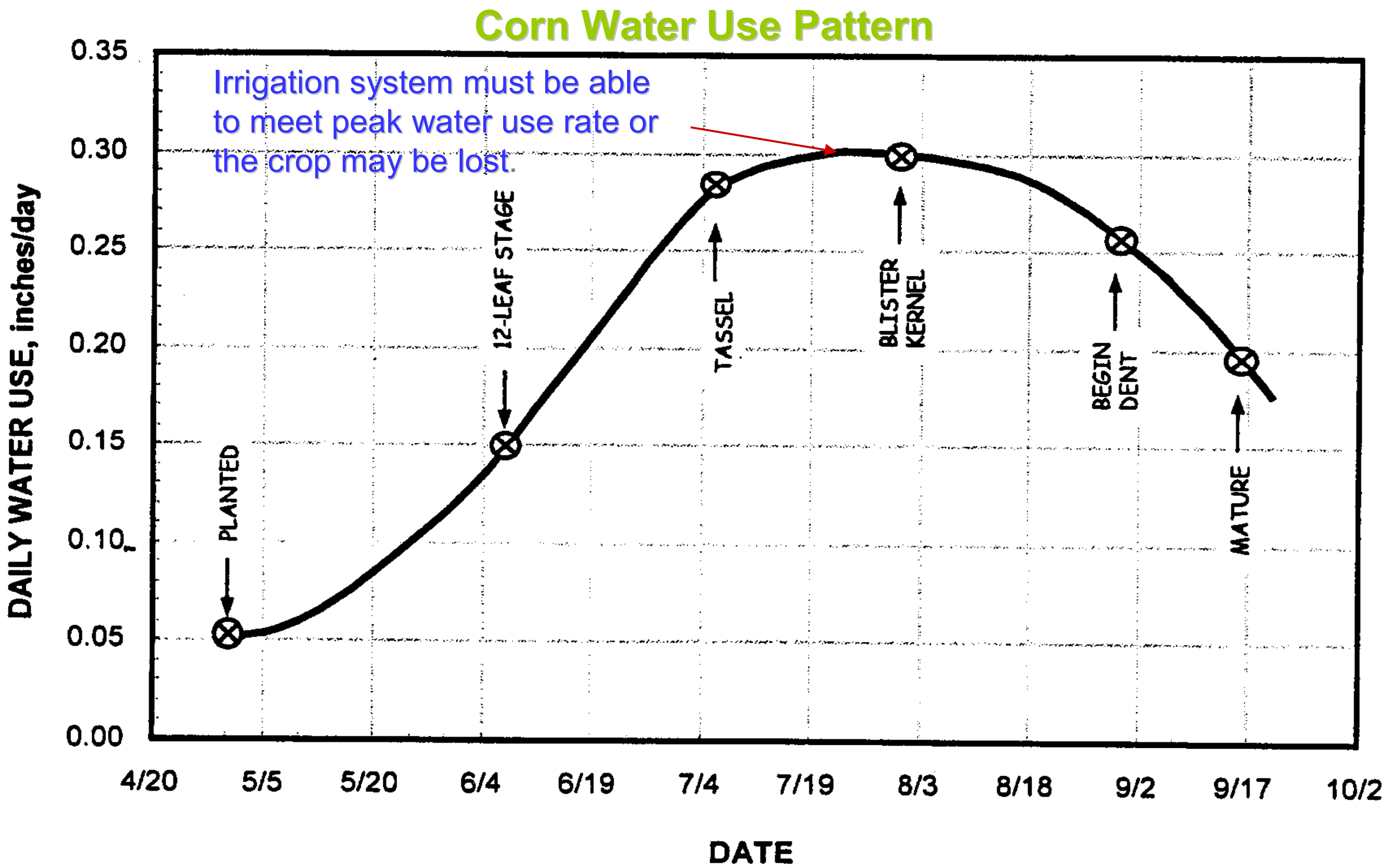
Plant Water Use Patterns

Daily Water Use: peaks late in afternoon; very little water use at night



Plant Water Use Patterns

- Seasonal Use Pattern: Peak period affects design



Evapotranspiration Modeling

- Estimation based on:
  - climate
  - crop
  - soil factors

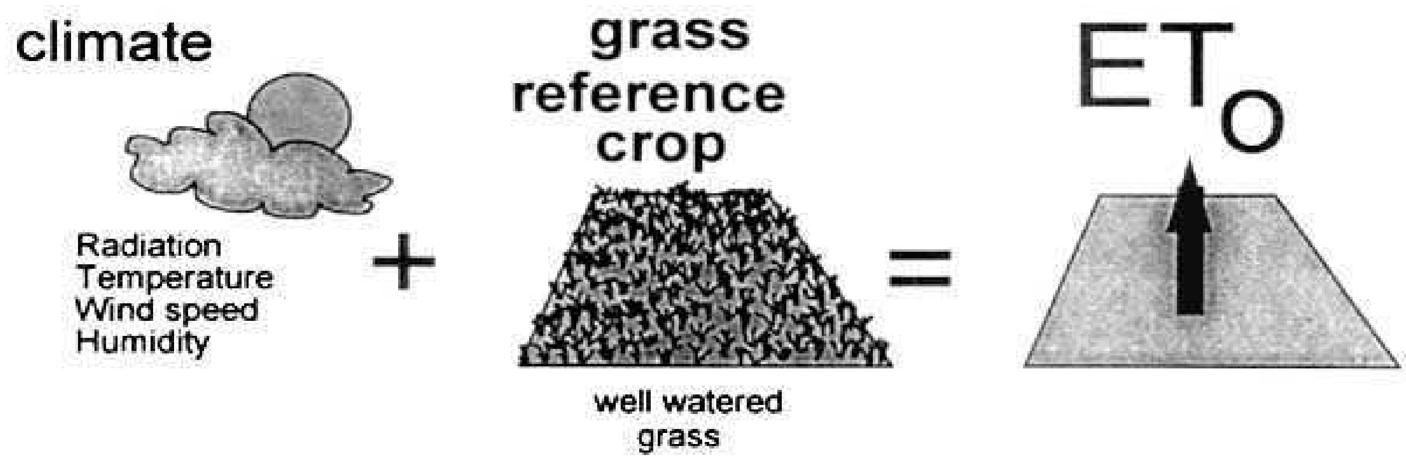
ETc = Kc ETo

- ETc = actual crop evapotranspiration rate
- ETo = the evapotranspiration rate for a reference crop
- Kc = the crop coefficient

Evapotranspiration Modeling

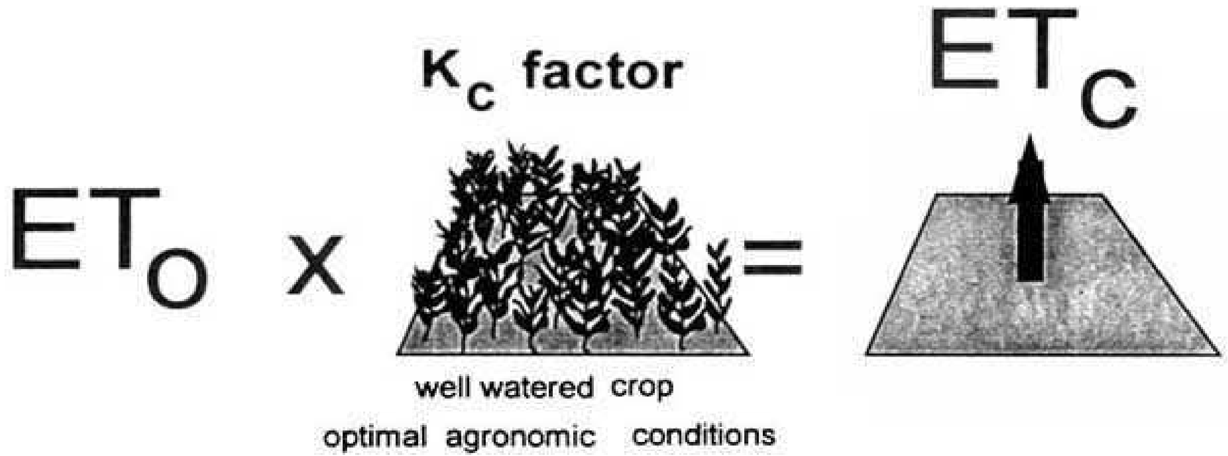
Reference ET (ETo)

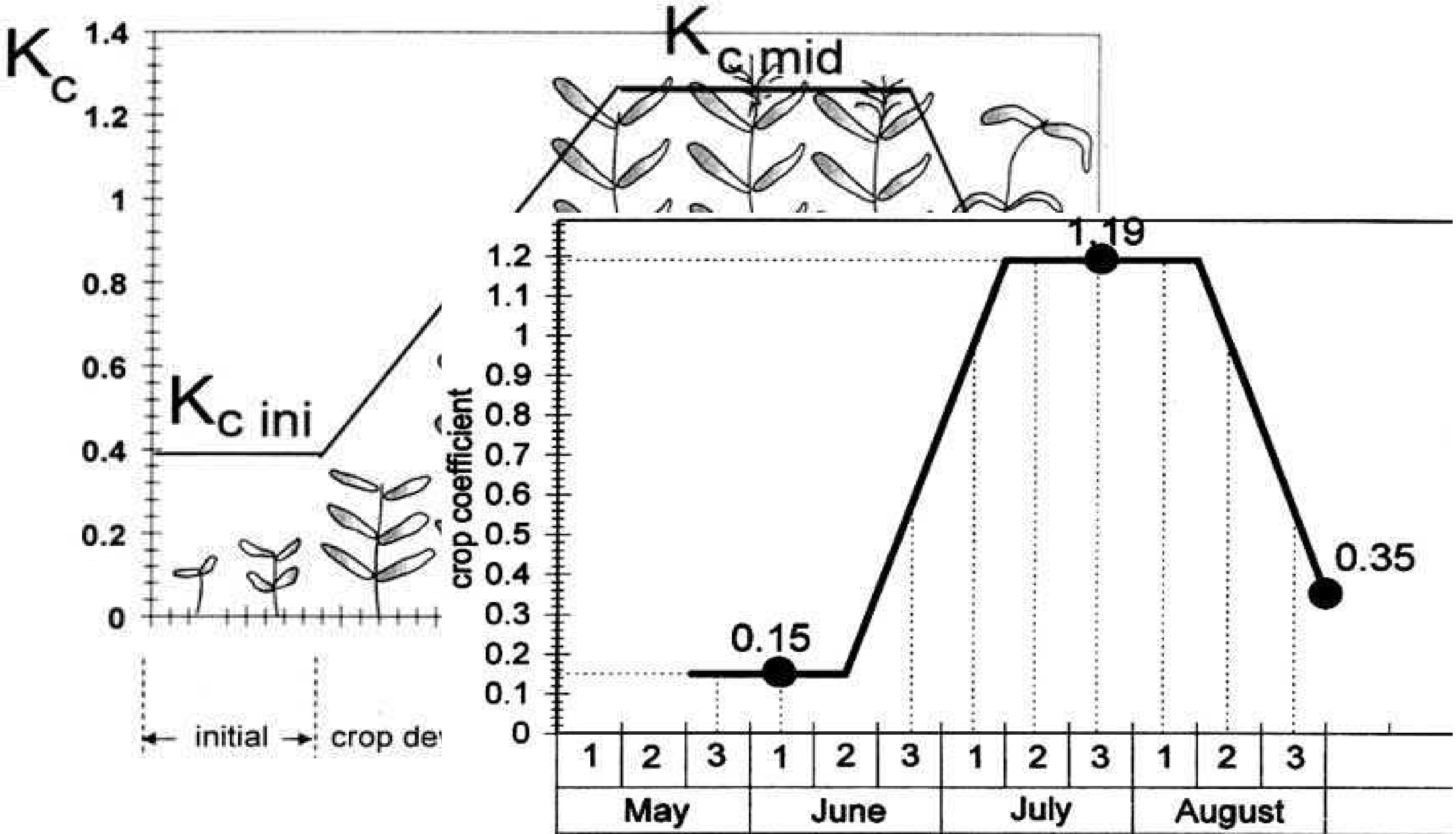
- ET rate of actively growing, well-watered, "*reference*" crop
- Grass or alfalfa used as the reference crop
- A measure of the amount of energy available for ET
- Many weather-based methods available for estimating ETo (FAO Blaney-Criddle; Jensen-Haise; Modified Penman; Penman-Monteith)



Evapotranspiration Modeling

- Crop Coefficient (Kc)
  - Empirical coefficient which incorporates type of crop & stage of growth
  - Kc values generally less than 1.0, but not always

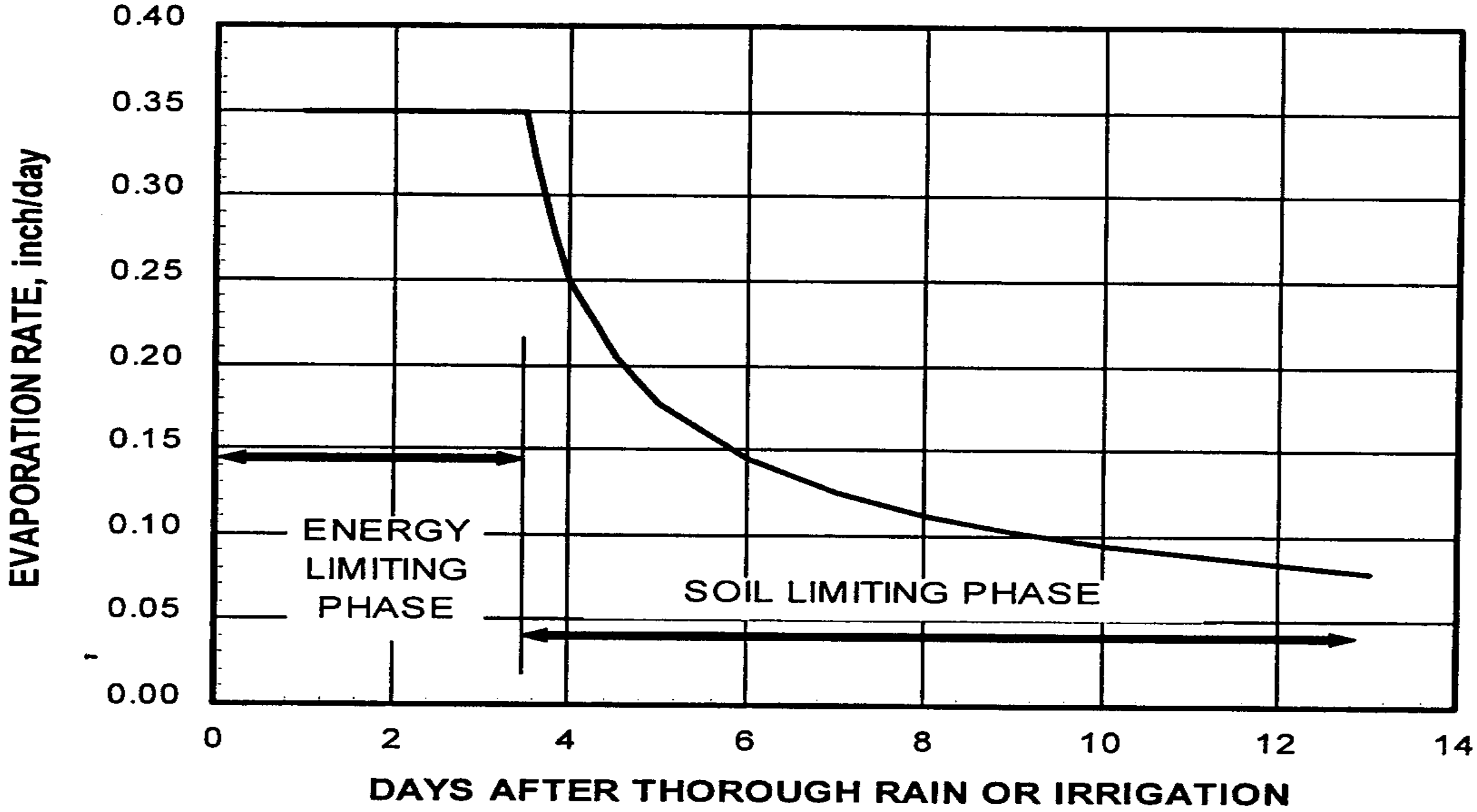




	May 3	June 1	June 2	June 3	July 1	July 2	July 3	August 1	August 2	August 3	
K_c	0.15	0.15	0.20	0.57	0.98	1.19	1.19	1.19	0.98	0.56	
ET_o	3.0	3.4	4.0	4.2	4.5	5.1	5.6	6.0	5.5	5.2	mm/day
ET_c	0.5	0.5	0.8	2.4	4.4	6.1	6.7	7.1	5.4	2.9	mm/day

Evaporation Rate and Time Since Irrigation

Energy or Water Availability as the Limiting Factor in ET Rate



- Easy-to-use tool with integrated climatic data base
- Speditive evaluations

ET References

- Shuttleworth, W. J., (1993), "Evaporation," in Handbook of Hydrology, Chapter 4, Edited by D. R. Maidment, McGraw-Hill, New York

- Dingman, S. L., (2002)
  - Chapter 7. Evapotranspiration
  - Appendix D.4. Physics of Evaporation
  - Appendix D.6. Physics of Turbulent Transfer near the ground.
  - Appendix E. Radiation on sloping surfaces

- Jensen, M. E., R. D. Burman and R. G. Allen, ed. (1990), Evapotranspiration and Irrigation Water Requirements, ASCE Manuals and Reports on Engineering Practice No. 70, New York

- Allen, R. G., L. S. Pereira, D. Raes and M. Smith, (1998), Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - Fao Irrigation and Drainage Paper 56, FAO - Food and Agriculture Organization of the United Nations, Rome, http://www.fao.org/docrep/x0490e/x0490e00.htm.