Evapotranspiration Concepts and Irrigation Water Requirements

Thomas W. Ley PhD, PE
Chief Hydrographer
Colorado Division of Water Resources

Background

- Education
- "ET" related career highlites
  - Collaborated with Tom Spofford to develop crop water requirement data for the WA Irrigation Guide
  - Washington Public Agriculture Weather System (PAWS)
  - Historical crop water use analyses (KS v. CO)
  - New lysimeter at CSU Rocky Ford AVRC
  - Member ASCE ET in Irrigation and Hydrology Technical Committee and Crop Coefficient Task Committee
- What's a hydrographer?

Objectives

- Discuss irrigation water requirements and need for crop water use information
- Define evapotranspiration (ET) and consumptive use (CU)
- Overview of the physics of ET and factors affecting ET
- Methods of determining/estimating ET

Irrigation Water Requirements

- "…the quantity, or depth, of irrigation water in addition to precipitation required to produce the desired crop yield and quality and to maintain an acceptable salt balance in the root zone." (NEH, Part 623, Chap 2, Irrigation Water Requirements)
- affected by crop types, climate conditions, soil conditions

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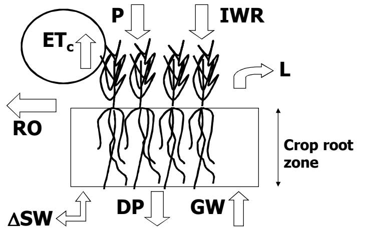
Irrigation Water Requirements

- Needed day-to-day
  - irrigation scheduling
  - other operational and management decisions
- Needed seasonally
  - sizing of irrigation system components (pipes, valves, ditches)
  - planning and development of irrigation projects
  - water rights issues
  - hydrologic studies

Soil-Water Balance

$$IWR = ET_c + DP + RO - P \pm \Delta SW - GW + L$$



Evapotranspiration and Consumptive Use

- In general, one and the same
- Crop water requirement is an equivalent term
- Consumptive use includes water retained in plant tissue at harvest, but this is generally minor relative to amount of ET

Evapotranspiration

- Combination of two separate processes

⇨ Evaporation from the soil surface

⇨ Transpiration by the crop

Physics of Evapotranspiration

- Evaporation is the process where liquid water is converted to water vapor

Evaporation is predominant when crop is small and water loss is primarily by soil evaporation, or under high frequency wetting when soil evaporation and evaporation of free water from plant surfaces can be high

Physics of Evapotranspiration

- Transpiration is the vaporization of liquid water in plant tissues and vapor removal to the atmosphere

--Vaporization occurs in intercellular spaces of the plant tissue, while exchange with the atmosphere occurs through and is controlled by plant stomata.

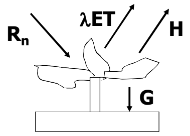
--Transpiration is predominant once the crop has developed and the canopy shades more and more of the surface

Physics of Evapotranspiration

- ET is an energy controlled process requiring the conversion of available radiation energy (sunshine) and sensible energy (heat contained in the air) into latent energy (energy stored in water vapor molecules)

Energy Balance

$$\mathbf{R_n = \lambda ET + H + G}$$



R_n is the net short and longwave radiation at the surface from sun and sky (main energy source)

λET is latent heat flux (energy used in the ET process)

H is sensible heat flux (transfer) to the air

G is sensible heat flux (transfer) to the ground or soil

Why not compute ET directly from the Energy Balance?

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

Pros: R_n and G can be directly measured or reliably estimated from climatic data

Cons: Only vertical fluxes are considered, and the net rate at which energy is transferred horizontally, **advection**, is ignored (a major problem in many areas of CO and elsewhere). Thus, this approach can only be applied to large, extensive surfaces of homogeneous vegetation. Measurement of sensible heat flux, H, is complex and not easily obtained.

Penman Combination Equation

$$\lambda E = \left(\frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} \lambda E_a \right)$$

- Penman (1948) developed the well-known combination equation, combining the energy balance with an aerodynamic function to account for heat and vapor exchange with the air

Penman Combination Equation

$$E_a = W_f \, (e^\circ - e_a)$$
$$W_f = (a + b \; u_2)$$

- Vapor transport flux term, E_a
    - empirical wind function, W_f
    - vapor pressure deficit, $(e^\circ - e_a)$

Factors Affecting Evapotranspiration

- Weather
- Crop characteristics
- Management
- Environmental conditions

Weather

- Solar radiation
- Air temperature
- Relative humidity
- Wind speed

Crop Characteristics

- Crop type and variety
    - Height, roughness, stomatal control, reflectivity, ground cover, rooting characteristics
- Stage of development

Management

- Irrigation method
- Irrigation management
- Cultivation practices
- Fertility management
- Disease and pest control

Environmental Conditions

- Soil type, texture, water-holding capacity
- Soil salinity
- Soil depth and layering
- Poor soil fertility
- Exposure/sheltering

Methods of Determining/Estimating ET

- Direct measurement
- Compute ET using a wide variety of empirical, semi-empirical, and physically-based equations using climate and weather data

Direct Measurement of ET

- Lysimetry
- Soil water depletion
- Energy balance and micro-meteorological methods—research applications only
    - Mass transfer / Bowen ratio
        - Vertical gradients of air temp and water vapor
    - Eddy correlation
        - gradients of wind speed and water vapor

Lysimetry

- Crop of interest grown under natural conditions in an isolated tank in large field of same crop
- Disturbed or undisturbed soil
- Terms in the soil water balance that are difficult to measure are carefully controlled and measured
- Many types of lysimeters: non-weighing drainage, non-weighing water table, weighing type

Lysimetry

- Direct measurement of ET
- Precision weighing lysimeters most accurate (resolution of 0.05 ET mm per hour or better)
- Soils inside and outside the tank must be similar
- Vegetation inside and outside the tank must perfectly match (height, leaf area, density, vigor)

Lysimetry

- Difficult and expensive to construct
- Require careful operation and maintenance
- Primarily research application
- Primary tool for evaluating weather effects on ET and evaluation of estimating methods

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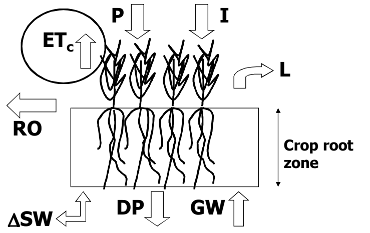
Soil-Water Depletion

$$ET_{c)1\rightarrow2} = (I - DP - RO - L) + P_e + \Delta SW_{1\rightarrow2} + GW$$



ET Concepts

- Reference ET (ET_{ref})
  - ET rate from a reference vegetative surface, actively growing, not short of water
  - measure of evaporative demand under current climate conditions
- Crop ET under standard conditions
- Crop ET under non-standard conditions

ET Concepts

- Reference ET (ET_{ref})
- Crop ET under standard conditions
  - ET of disease-free, well-fertilized crop not short of water achieving full production

ET_c = crop coefficient x ET_{ref}

  - Crop coefficients are determined experimentally by lysimeter or soil water balance methods as the ratio of measured crop ET (under optimal growing conditions) to reference crop ET across the growing season
- Crop ET under non-standard conditions

ET Concepts

- Reference ET (ET_{ref})
- Crop ET under standard conditions
- Crop ET under non-standard conditions
  - ET of crop considering "real-world" growing conditions (diseases, pests, fertility problems, salinity effects, water stress, management, etc.)
  - Use a water stress coefficient, K_s, and adjust crop coefficients for other stresses

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Estimating ET

- wide variety of empirical, semi-empirical, and physically-based equations/models
- generally categorized as:
  - temperature methods
  - radiation methods
  - combination methods
  - pan evaporation methods

Modified Blaney-Criddle Method

$$U = \Sigma(kf) = \Sigma[(0.0173\ t - 0.314)\ k_c\ (t\ p/100)]$$

- Originally developed in the 1920's and 1930's; modified in 1945, 1950, 1952, 1960, 1965, 1970
- ET of an actively growing crop with adequate soil moisture varies directly with the product of mean monthly air temperature and monthly percentage of annual daytime hours

Modified Blaney-Criddle Method

- Simple, easy to use
- Minimal data requirements—mean monthly air temperature
- Wide application across western US
- Widely used in CO water rights proceedings

Precautions/Limitations

- Not a reference ET method
- Crop growth stage coefficient, k_c
  - is specific to this method
  - not a true crop coefficient, i.e., shown to be dependent on climate/location
- Should not be used to compute ET on less than a monthly time step
- Underpredicts in arid climates, and under windy or high advection conditions

1985 Hargreaves Method

$$ET_o = 0.0023\,(T_{max} - T_{min})^{0.5}\ (T_{mean} + 17.8)\ R_a$$

- Originally developed in 1975
  - solar radiation and temperature data inputs
- Updated in 1982 and 1985
  - solar radiation estimated from extraterrestrial radiation
- Grass reference ET (ET_o)
- Can be used to compute daily estimates

1985 Hargreaves Method

- Simple, easy to use
- Minimal data requirements—maximum and minimum air temperature
- Better predictive accuracy in arid climates than modified Blaney-Criddle
  - Max-min temperature difference
  - Extra-terrestrial radiation

Precautions/Limitations

- Grass reference ET method
  - Convert to alfalfa basis before using alfalfa reference crop coefficients
  - Adds another level of uncertainty to crop ET estimates
- Accuracy improves when used over longer intervals, i.e., 10-days, monthly
- Still underpredicts in arid climates, and under windy or high advection conditions

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1982 Kimberly Penman

$$ET_r = \left(\frac{\Delta}{\Delta+\gamma}(R_n - G) + K_w \frac{\gamma}{\Delta+\gamma}(a_w + b_w u_2)(e_s - e_a) \right) / \lambda$$

- Developed at Kimberly ID
- Alfalfa reference ET (ET_r)
- Calibrated wind function (varies daily) attempts to account for seasonally- varying local and regional advection and daylength
- Calibrated net radiation function (varies daily)

1982 Kimberly Penman

- May be used for hourly or daily ET estimates
- Good predictive accuracy across a wide range of climates often ranking second only to the Penman-Monteith (ASCE Manual 70)
- Widely used across the western US

Crop Coefficients

- Specifically developed using the 1982 Kimberly Penman method
  - Wright (1982)
  - ASCE Manual 70 Tables 6.6 and 6.9
- Basal and "mean" coefficients
- Transferability of "mean" crop coefficients requires assessment of irrigation and rainfall patterns

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Precautions/Limitations

- Same weather data requirements as any other Penman-based equation
- Wind and net radiation functions calibrated to Kimberly ID climate
  - Aerodynamic term may lose accuracy in climates windier or more advective than those experienced at Kimberly
  - Net radiation function bias—underpredicts on high R_n days

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Penman-Montieth Equation

(ASCE Full-Form)

$$ET_{ref} = \left(\frac{\Delta (R_n - G) + K_{time} \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \right) / \lambda$$

- ET of a well-watered crop
- Physically-based, theoretically sound model
  - Neutral atmospheric stability
  - Logarithmic wind profile
- Most accurate on an hourly basis
- Standard of comparison for evaluating other models

Precautions/Limitations

- Often used in a reference crop approach (alfalfa, grass) due to limited data on bulk canopy surface resistance of other crops
- Same weather data requirements as any other Penman-based equation
- Empirical simplifications are introduced when using daily weather data
    - diurnal distributions of humidity, wind speed and net radiation

ASCE Manual 70 (1990) Studies

- 19 estimating methods evaluated
- Carefully screened lysimeter data from 11 worldwide locations representing a range of climatic (arid to humid) conditions
- Penman-Monteith found to be most accurate and consistent across all climates on both monthly and daily basis
- 1982 Kimberly Penman ranked second at arid sites and at all locations and ranked second in the evaluation of daily estimates

ASCE Standardized Penman-Montieth Equation

$$\boxed{ET_{sz} = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + C_d\,u_2)}}$$

- ET for hypothetical standardized reference crop
    - ET_{os}, short reference crop, like 12 cm tall grass with bulk surface resistance of 70 s/m
    - ET_{rs}, tall reference crop, like 50 cm tall alfalfa with bulk surface resistance of 45 s/m

ASCE Task Committee Evaluation of the Standardized P-M Equation

- Evaluated the predictive accuracy of 13 reference equations (including the standardized equation) at 49 sites across the US
- Standard of comparison was the (ASCE full form) Penman-Monteith equation
- ASCE standardized P-M equation performed well on hourly and daily basis
    - simplifications and standardized computations included in the ASCE standardized P-M equation considered acceptable

Penman Methods with Limited Climate Data

- Penman-type ET estimates using limited climate data and estimation procedures for missing data are considered more accurate than estimates computed using less data-intensive ET methods

Temperature Data

- Minimum data requirements are maximum and minimum air temperature
- Predict/estimate dewpoint temperature from minimum air temperature

$$T_{\mathbf{dew}} = T_{\mathbf{min}} - K_{\mathbf{o}}$$

where $K_{\mathbf{o}}$ ~ 2 – 4 °C in dry climates, and ~ 0 °C in humid climates

Solar Radiation

- Estimate solar radiation from
  - a regional station, or,
  - from max/min temps

Wind Speed

- Use data from a nearby station
- Estimate mean monthly wind speed

Description	Mean Wind Speed (at 2 m)
light winds	≤ 1.0 m s^{-1}
light to moderate winds	1-3 m s^{-1}
moderate to strong winds	3-5 m s^{-1}
strong winds	≥ 5 m s^{-1}

(adapted from FAO-56)

Precautions/Limitations

- Minimum data requirements are max/min air temperature
  - must be representative of, or measured in an irrigated area
- Using data from nearby stations
  - climate conditions, physiographic features, etc. at both locations should be similar, i.e., region should be homogeneous

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Precautions/Limitations

- Validate at regional level by comparing reference ET calculated using a full data set and a limited/estimated data set
- Not recommended for daily estimates, better suited for longer interval (10-days,monthly)
- Best reserved for filling in intervals of missing data or data of suspect quality at sites where all variables are measured

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Calibration

Why Consider Calibration?

- Period of record of electronic weather station (EWS) data may be limited
- Period of record at NOAA Coop Observer network (max/min/precip) stations often much longer
- With minimum 3 years of overlapping record (better if 5-7 years) it is desirable to calibrate the less data-intensive methods to compute more accurate historical crop ET estimates

Approach

- Compute calibration coefficients for some specific time interval during growing season (10-days, monthly)

$$\text{Calibration coeff.} = \frac{\text{Penman Crop ET}}{\text{Crop ET by method to be calibrated}}$$

- Compute average values for overlapping period of record

Precautions/Limitations

- Calibration coefficients should be computed by pairing each individual NOAA station with an electronic weather station
- Extent of areal representation of calibration coefficients limited by that of the EWS data

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Coefficients for one EWS-NOAA station pair generally not applicable at other NOAA stations when conditions at the NOAA sites are dissimilar

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Crop Coefficients

- dual crop coefficient approach

$$ET_{c)\ actual} = (K_s \; K_{cb} + K_e)\, ET_{ref}$$

  - K_s is a water stress coefficient used to account for effects of water stress on crop transpiration
  - K_{cb} is the basal crop coefficient and is the ratio of crop ET to reference ET when the soil is dry and the crop is transpiring at potential rates
  - K_e is a coefficient for wet soil evaporation
- use when daily crop ET estimates are needed

Crop Coefficients

- single crop coefficient approach

$$ET_{c)\ actual} = K_s \; K_c \; ET_{ref}$$

  - K_s is a water stress coefficient used to account for effects of water stress on crop transpiration
  - K_c is "average" or "mean" crop coefficient incorporating crop characteristics and averaged effects of soil evaporation

- for normal irrigation planning and management, hydrologic studies, etc., mean crop coefficients are applicable and easier to apply than the dual crop coefficient approach

Crop Coefficients

- Alfalfa or grass reference basis
- Method specific
- Geographical transferability

Crop Coefficients

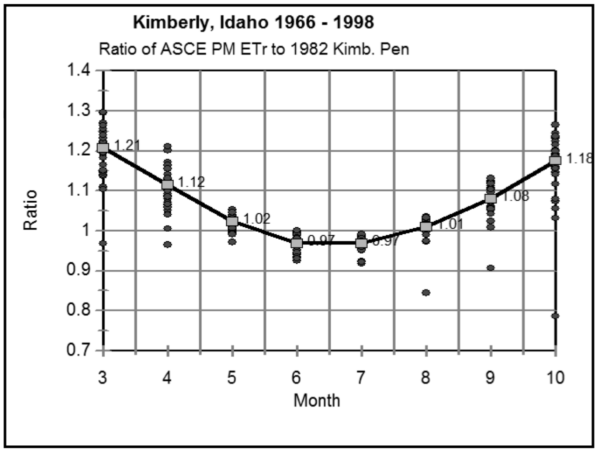
- Alfalfa or grass reference basis
  - Crop coefficients for the two references are not interchangeable without adjustment
  - ASCE Manual 70 used a ratio of 1.15 for alfalfa to grass reference ET to allow the extensive comparisons between methods and lysimeter sites
  - More recent work (Wright et al. 2000) indicates this ratio is climate, season and location dependent and should be determined on at least a monthly basis
- Method specific
- Geographical transferability

Crop Coefficients

- Alfalfa reference basis
  - ASCE Manual 70 Table 6.6 basal crop coefficients
  - ASCE Manual 70 Table 6.9 “mean” crop coefficients
- Grass reference basis
  - FAO 56: Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements
- Method specific
- Geographical transferability

Crop Coefficients

- Alfalfa or grass reference basis
- Method specific
  - Generally thought that K_c values developed for one method can be used with another method without adjustment, as long as the reference basis is the same and the two methods produce equivalent reference ET values
  - ASCE Standardized P-M method with a fixed crop height yields different alfalfa reference ET values than the 1982 Kimberly Penman
- Geographical transferability



Monthly ratios of 1982 Kimberly Penman to ASCE standardized Penman-Monteith alfalfa reference ET (adapted from Allen, 2001 unpublished paper).

Month	Vineland 1994-2000	Avondale 1994-2000	Rocky Ford 1993-2000
Mar	0.77	0.73	0.76
Apr	0.85	0.81	0.85
May	0.92	0.90	0.94
Jun	1.01	0.98	1.00
Jul	1.05	1.00	1.03
Aug	1.05	0.98	1.01
Sep	0.95	0.90	0.95
Oct	0.84	0.81	0.85

Crop Coefficients

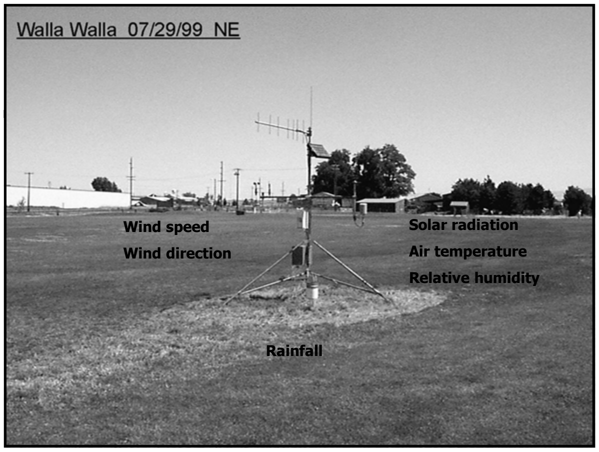
- On a seasonal basis differences between the two methods “average out”
- On a monthly basis the differences are large enough to warrant adjustment of the 1982 Kimberly Penman coefficients prior to use with the ASCE std P-M
- Allen and Wright (2002) conversion

Crop Coefficients

- Alfalfa or grass reference basis
- Method specific
- Geographical transferability
  - ET of well-watered crops is mainly dependent on available energy
  - Requires assessment of, and often adjustment for differences in growing period conditions between development and application sites
  - Transferability of “mean” crop coefficients requires assessment of irrigation and rainfall patterns
  - Climate differences between sites; primarily wind, humidity and advection considerations impact transferability

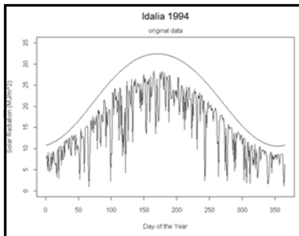
Weather Data Considerations

- Detailed weather data requirements
  - solar radiation
  - air temperature
  - relative humidity
  - wind speed at 2 m
- Weather data quality
- Data collection environment
- Weather station location and density



Weather Data Considerations

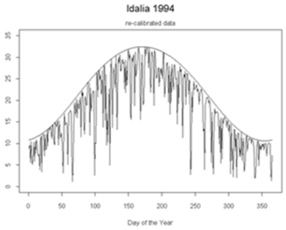
- Detailed weather data requirements
- Weather data quality
  - All data need quality assessment
  - Detailed QA/QC procedures available (e.g. EWRI, 2002; Allen, 1996)
- Data collection environment
- Weather station location and density

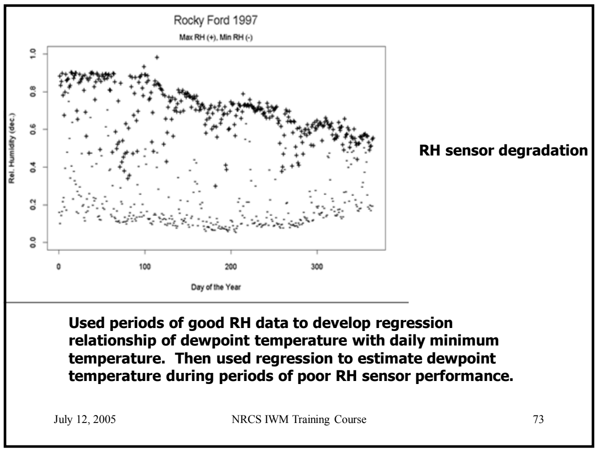


Original data plotted with clear sky solar radiation envelope

Calibration correction factor = 1.155

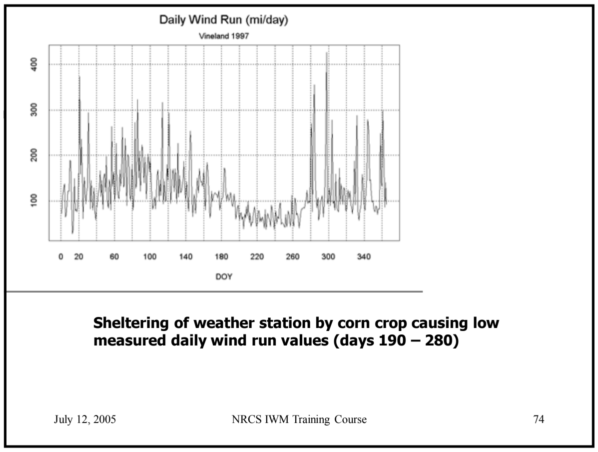
“Re-calibrated” data plotted with clear sky solar radiation envelope



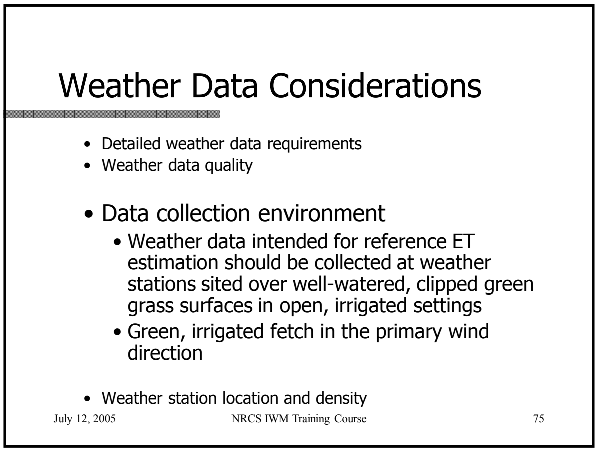


RH sensor degradation

Used periods of good RH data to develop regression relationship of dewpoint temperature with daily minimum temperature. Then used regression to estimate dewpoint temperature during periods of poor RH sensor performance.



Sheltering of weather station by corn crop causing low measured daily wind run values (days 190 – 280)



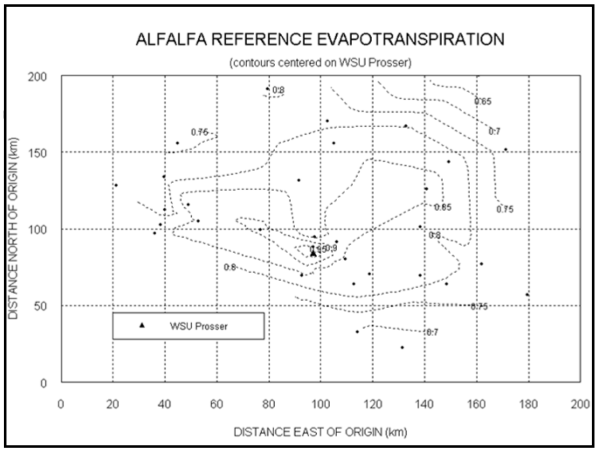
Weather Data Considerations

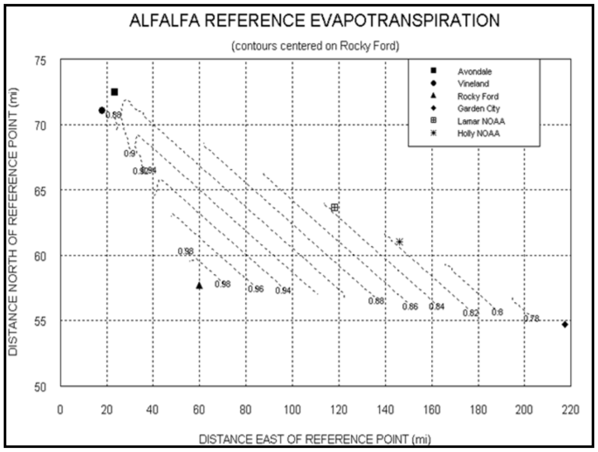
- Detailed weather data requirements
- Weather data quality
- Data collection environment
  - Weather data intended for reference ET estimation should be collected at weather stations sited over well-watered, clipped green grass surfaces in open, irrigated settings
  - Green, irrigated fetch in the primary wind direction
- Weather station location and density

Weather Data Considerations

- Detailed weather data requirements
- Weather data quality
- Data collection environment

- Weather station location and density
  - Various studies suggest weather station spacing of 20-40 miles to maintain 0.90 spatial cross-correlation for reference ET estimates
  - Highly dependent on topography, prevailing weather patterns, etc.





Summary

- ET is key component to determining irrigation water requirements
- Most direct methods have limited practical application
- Climate based ET estimation
- Penman-based ET methods:
  - carefully screened, good quality weather data,
  - collected under irrigated reference conditions,
  - spatially representative of the area of interest
- Crop coefficients