ESTIMATING EVAPORATION FROM WATER SURFACES

(With emphasis on shallow water bodies)

INTRODUCTION

- **Evaporation is rarely measured directly**
- **Estimating methods include:**
  - **pan coefficient *x* measured pan evaporation**
  - **water balance**
  - **energy balance**
  - **mass transfer**
  - **combination techniques**
- **Emphasis will be practical methods**

BACKGROUND

- **Evaporation theories – to the 8th century**
- **Dalton (1802), $E = f(\bar{u})\,(e_o - e_a)$**
- **Bowen (1926), the Bowen ratio, the ratio of sensible heat to latent heat gradients ($\Delta t/\Delta e$)**
- **Applications were made to lake evaporation by Cummings and Richardson 1927; McEwen 1930**

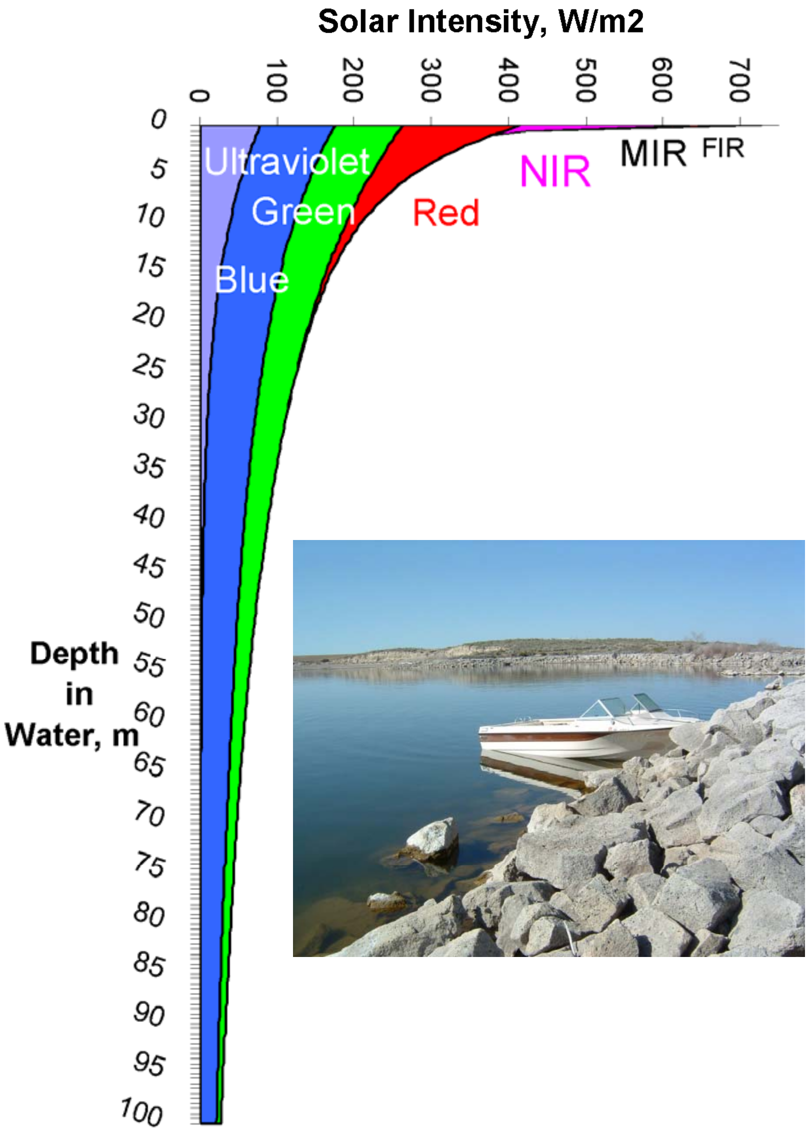
ENERGY CONSIDERATIONS

- **Evaporation requires a lot of energy**
- **Incoming solar radiation is the main source**
- **In contrast to land, not all net solar radiation is absorbed on the surface**
- **In pure water, about 70% is adsorbed in the top 5 m (16 ft)**
- **Solar radiation adsorbed below the surface is "stored energy"**

ENERGY (continued)

- **Estimating energy storage in water (Q_t) can be more difficult than estimating soil heat flux (G)**
- **Part of solar radiation may penetrate to great depths depending on the clarity of the water**
- **Stored energy affects the evaporation rate**
- **Example temperature profiles in deep water:**
  - **profiles during increasing solar cycle**
  - **profiles during decreasing solar cycle**

Solar Radiation Penetrates Deep in Water



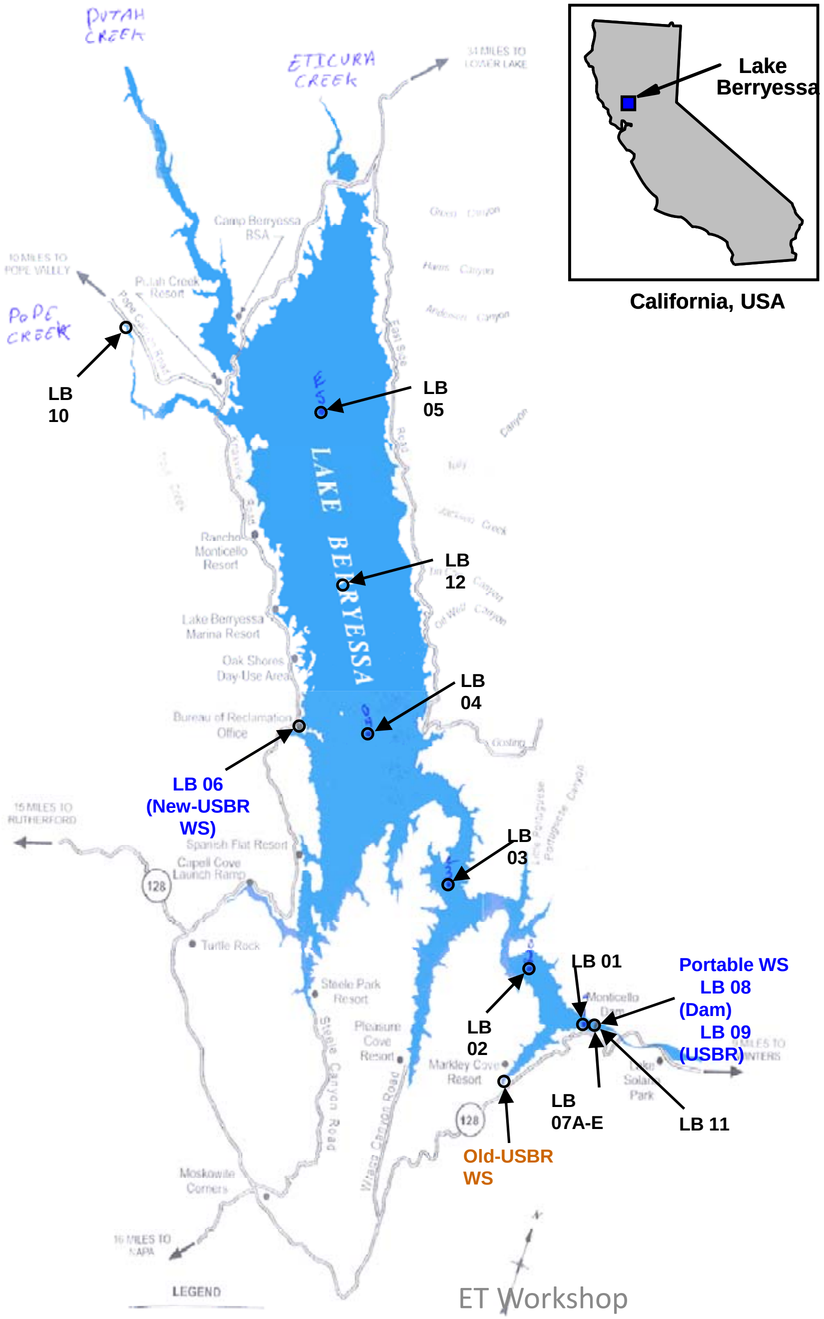
Pure Water

Evaporation pans are two shallow and hold too much “warmth” at the surface.
Therefore, they can overestimate the evaporation from large reservoirs and lakes.

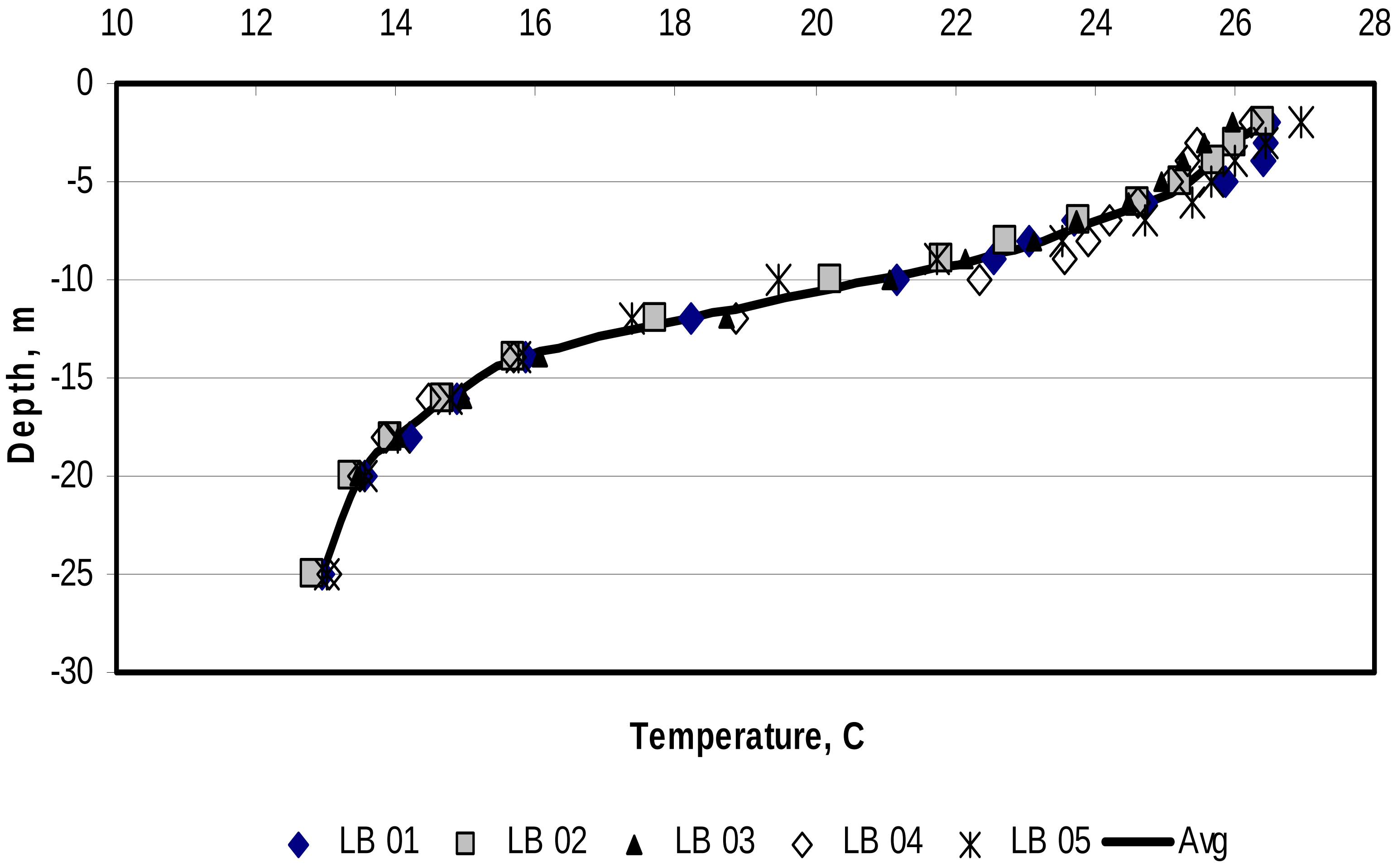
National Weather Service Class A Evaporation Pan
NOAA / NWS

ENERGY STORAGE & RELEASE

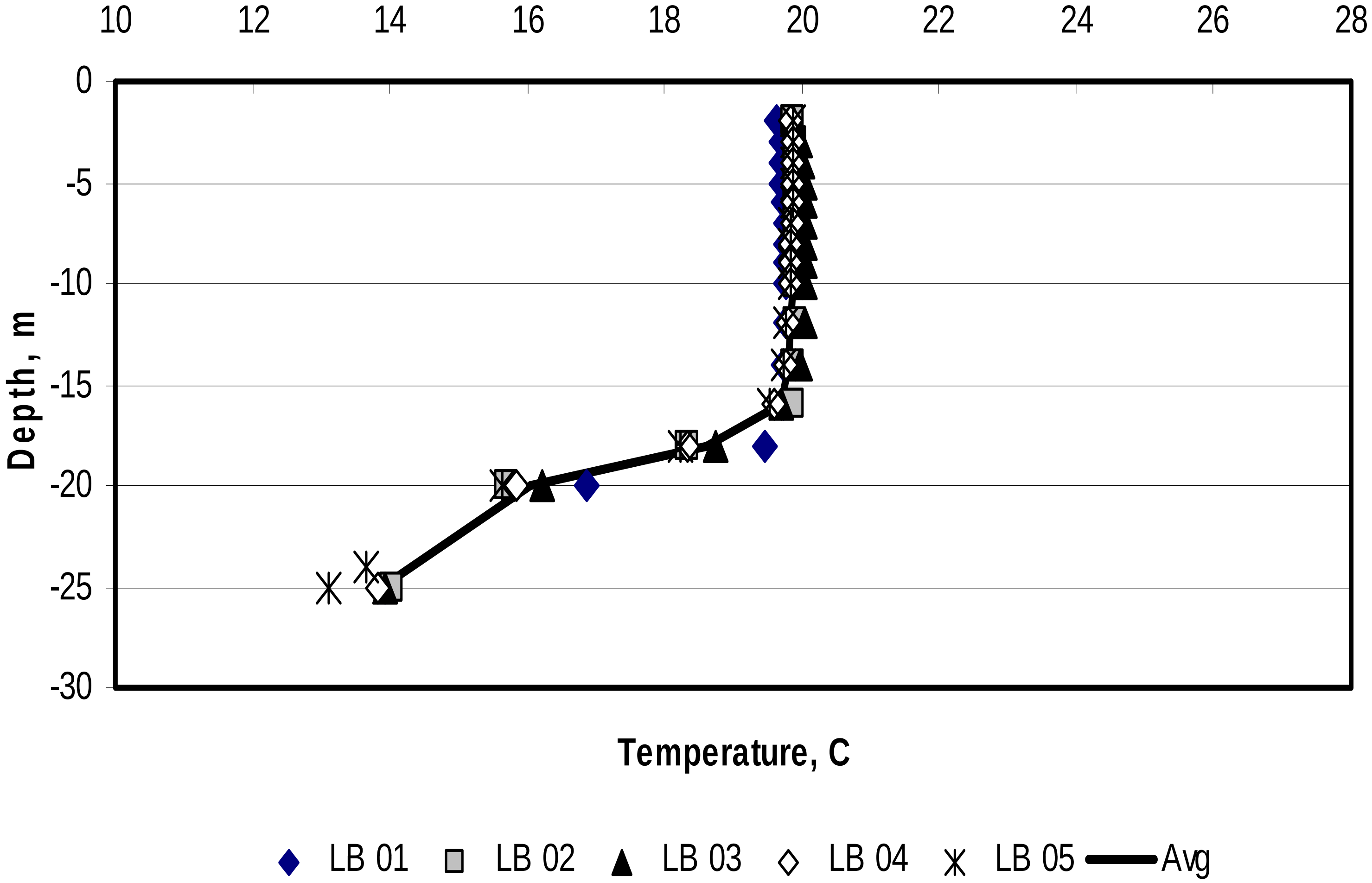
- Lake Berryessa, 8,100 ha (20,000 ac.) and 58 m (190 ft) deep, average 40 m
- Little or no inflow during the summer
- Thermal profiles during increasing R_s
- Thermal profiles during decreasing R_s
- Example temperatures by depth and time
- Reason for studying evaporation—improve estimates of evaporation to calculate inflow

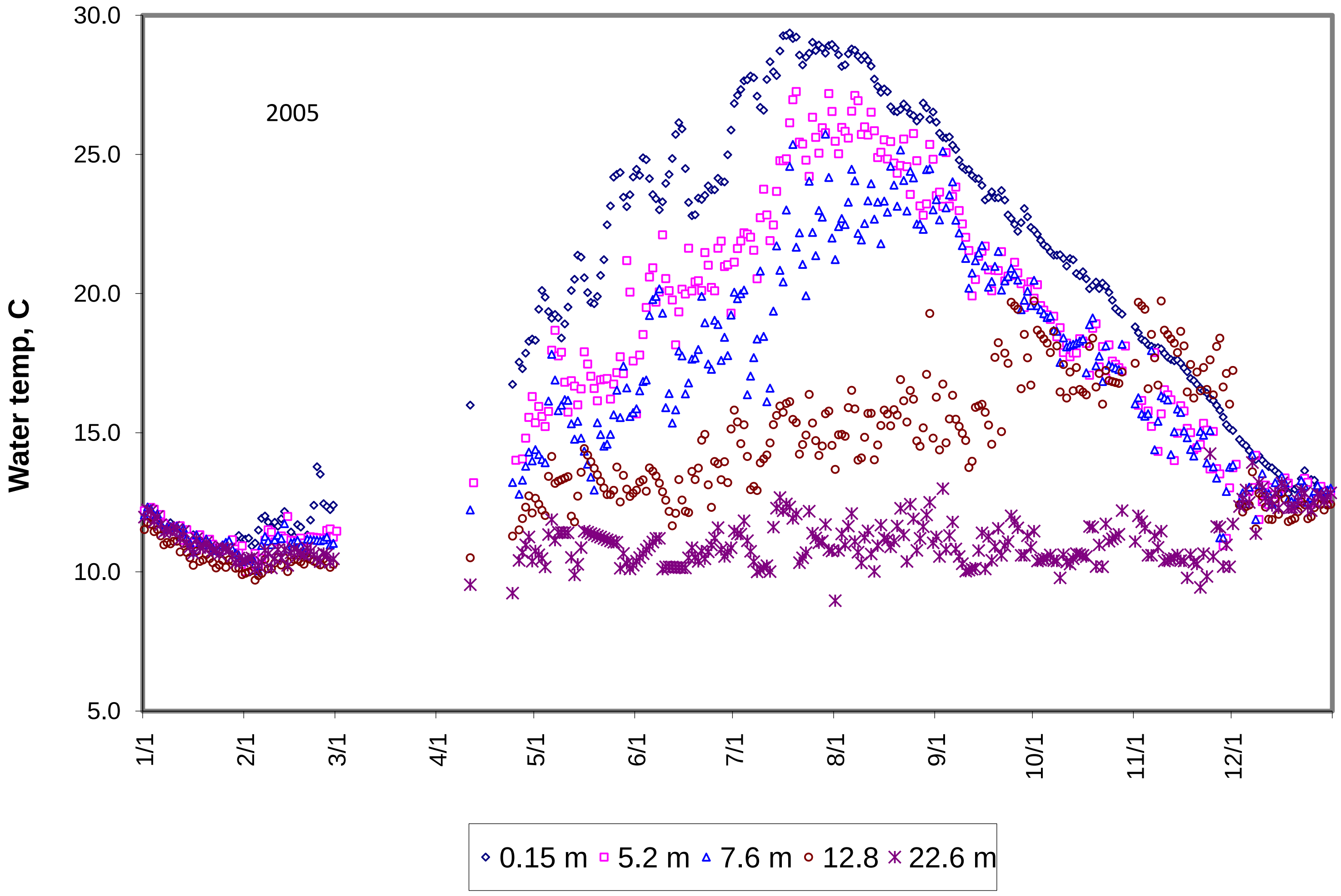
PUTAH CREEK
ETICURA CREEK
34 MILES TO LOWER LAKE
Lake Berryessa
California, USA
Camp Berryessa BSA
Green Canyon
Harris Canyon
Anderson Canyon
10 MILES TO POPE VALLEY
Putah Creek Resort
Pope Canyon Road
POPE CREEK
LB 10
LB 05
East Side Road
LAKE BERRYESSA
Rancho Monticello Resort
Jackson Creek
LB 12
Lake Berryessa Marina Resort
Oil Well Canyon
Oak Shores Day-Use Area
LB 04
Bureau of Reclamation Office
Gosling
LB 06 (New-USBR WS)
15 MILES TO RUTHERFORD
Spanish Flat Resort
Capell Cove Launch Ramp
128
Little Portuguese
Portuguese Canyon
LB 03
Turtle Rock
Steele Park Resort
LB 01
Portable WS
LB 08 (Dam)
LB 09 (USBR)
Monticello Dam
Pleasure Cove Resort
LB 02
Markley Cove Resort
Lake Solano Park
9 MILES TO WINTERS
LB 07A-E
LB 11
Steele Canyon Road
Wragg Canyon Road
128
Old-USBR WS
Moskowite Corners
16 MILES TO NAPA
LEGEND
N

Temperature Profile Data - 7/10/03



Temperature Profile Data - 10/30/03




2005
Water temp, C
30.0
25.0
20.0
15.0
10.0
5.0
1/1
2/1
3/1
4/1
5/1
6/1
7/1
8/1
9/1
10/1
11/1
12/1
◇ 0.15 m
□ 5.2 m
△ 7.6 m
○ 12.8
✕ 22.6 m

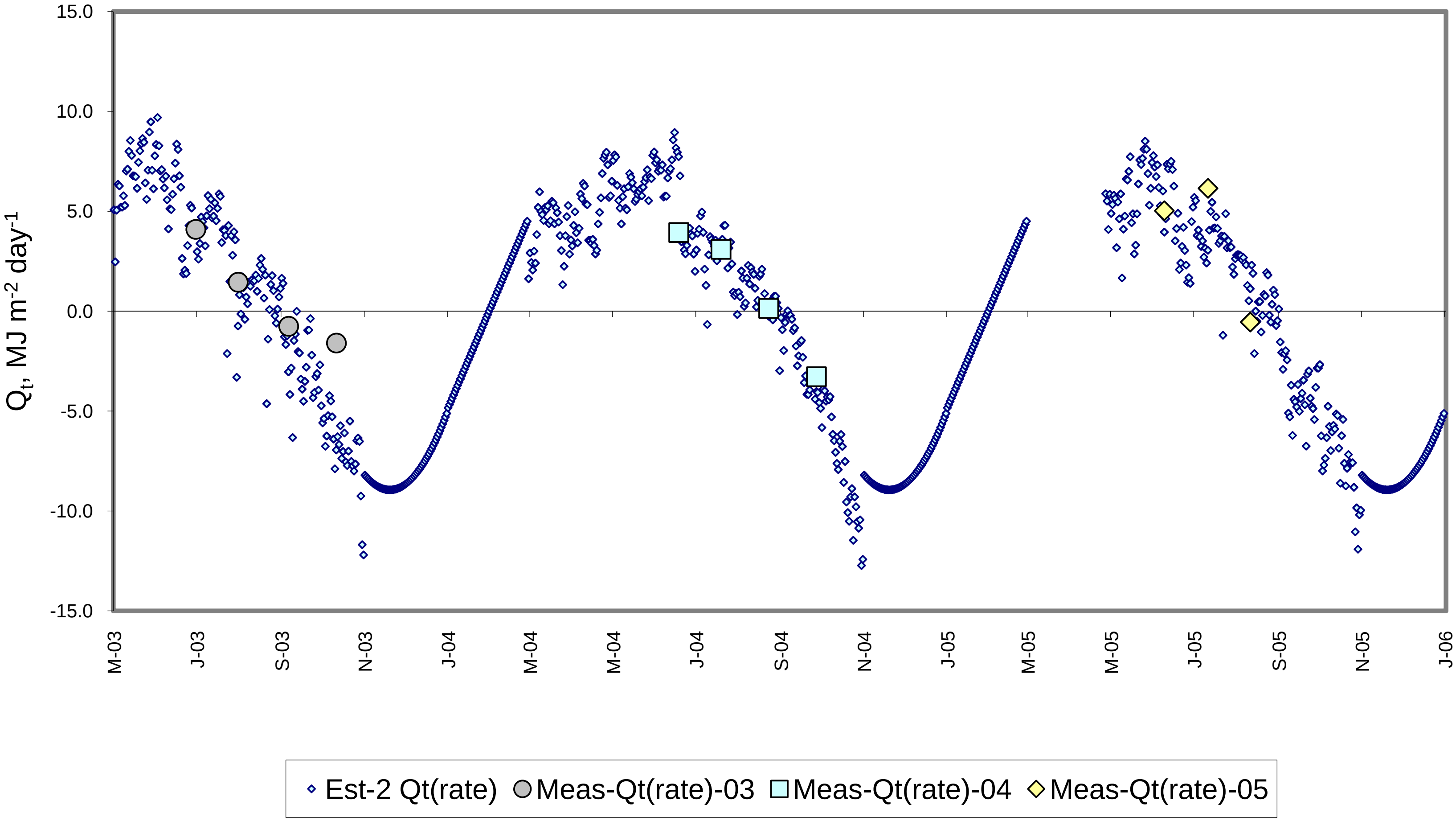
WHY STUDY EVAPORATION ON LB?

- The pan site was moved from the original site
- Measured pan evaporation *x* original coefficients underestimated reservoir evaporation and inflow
- Negative inflows were calculated during low and zero inflows late in the summer
- The obvious solution – move the pan site, and recheck the pan coefficients
- Data were needed to justify to the USBR the need to change the pan site
- View of the evaporation pan site
- Estimated rate of energy storage

Original USBR Pan Site

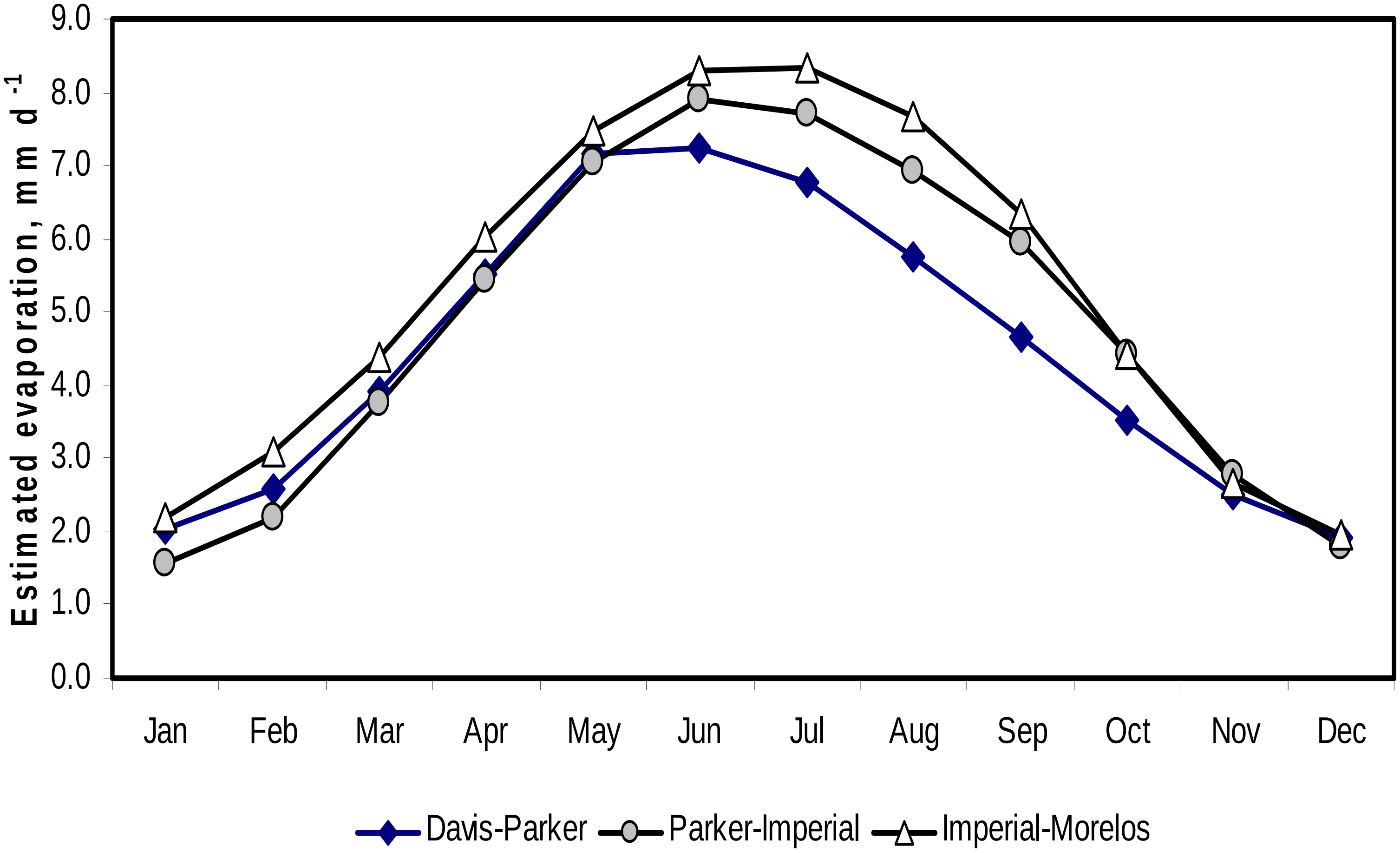
7 31 '01

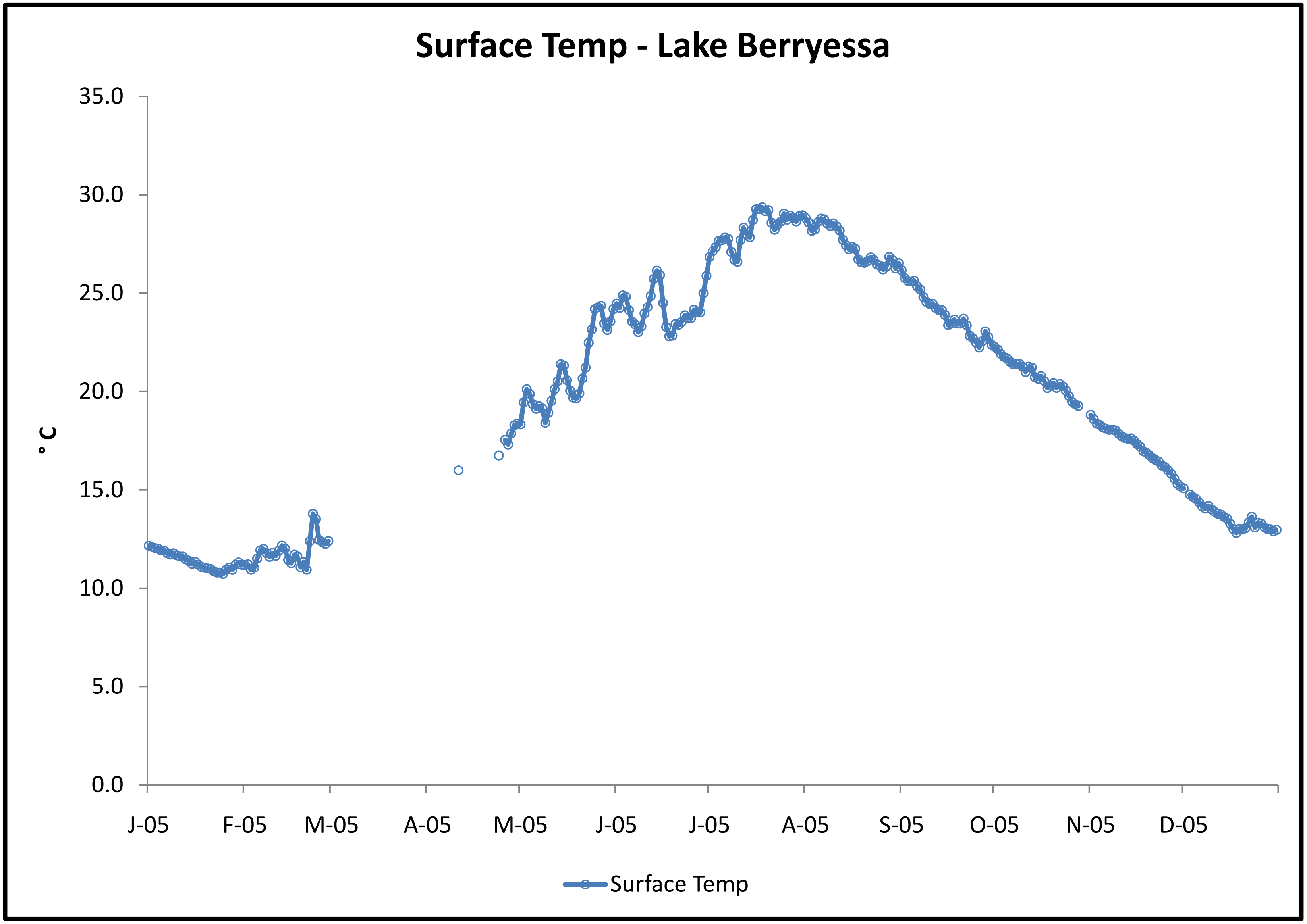
Rate of Energy Storage



ENERGY STORAGE EXAMPLES

- Maximum energy storage rates of 5 to 10 MJ m^{-2} d^{-1} to a depth of 25 m measured in Lake Berryessa and about 10 MJ m^{-2} d^{-1} to a depth of 45 m measured in Lake Mead
- Water surface temperatures reached a maximum in July in LB and in August in Lake Mead (lag is related to depth of water)
- Evaporation rate also lagged solar radiation
- Advected energy can be large in reservoirs on rivers (example along Colorado River)

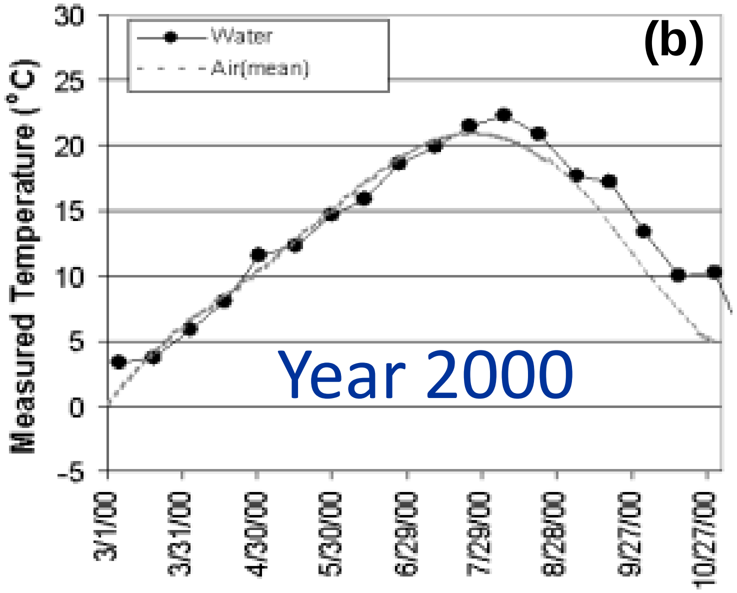

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Estimated evaporation, mm d -1
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Davis-Parker
Parker-Imperial
Imperial-Morelos

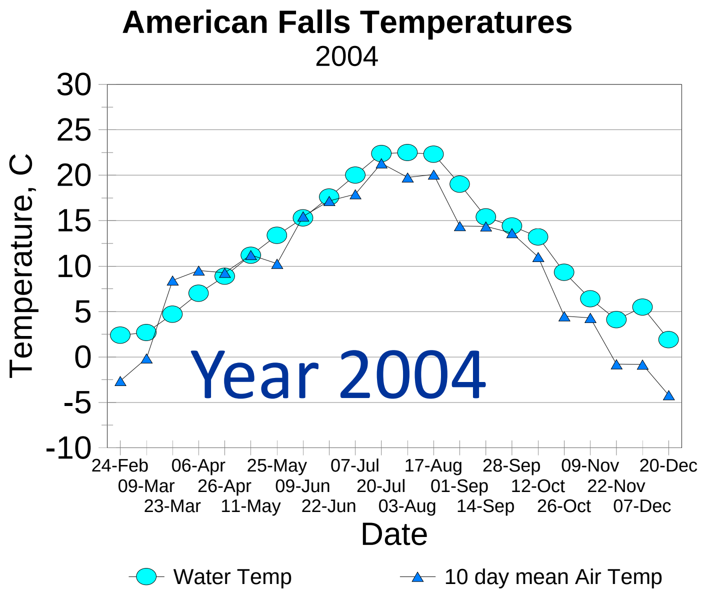

Surface Temp - Lake Berryessa
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
° C
J-05
F-05
M-05
A-05
M-05
J-05
J-05
A-05
S-05
O-05
N-05
D-05
Surface Temp

Other Methods

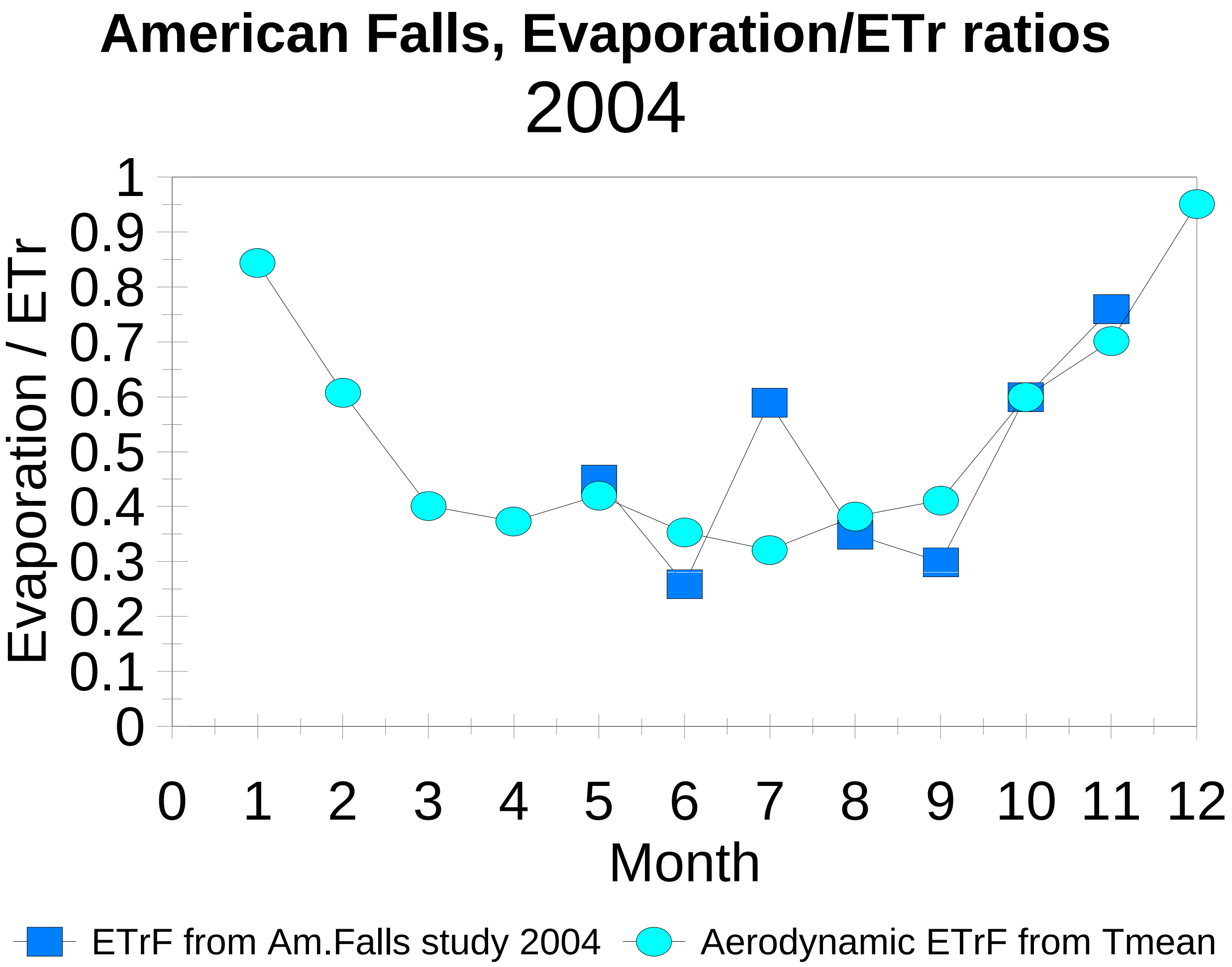
- Water budget procedure
- Aerodynamic methods
  - used mainly on large lakes and reservoirs
- Example – American Falls reservoir in Idaho by Allen et al.
  - estimates using water and air temperature
  - estimated evaporation relative to ET_r
- Why the low summer rate? Cold inflow water?

Temperature of water from American Falls outfall follows Temperature of Air





Evaporation ratio for Alfalfa Reference ET

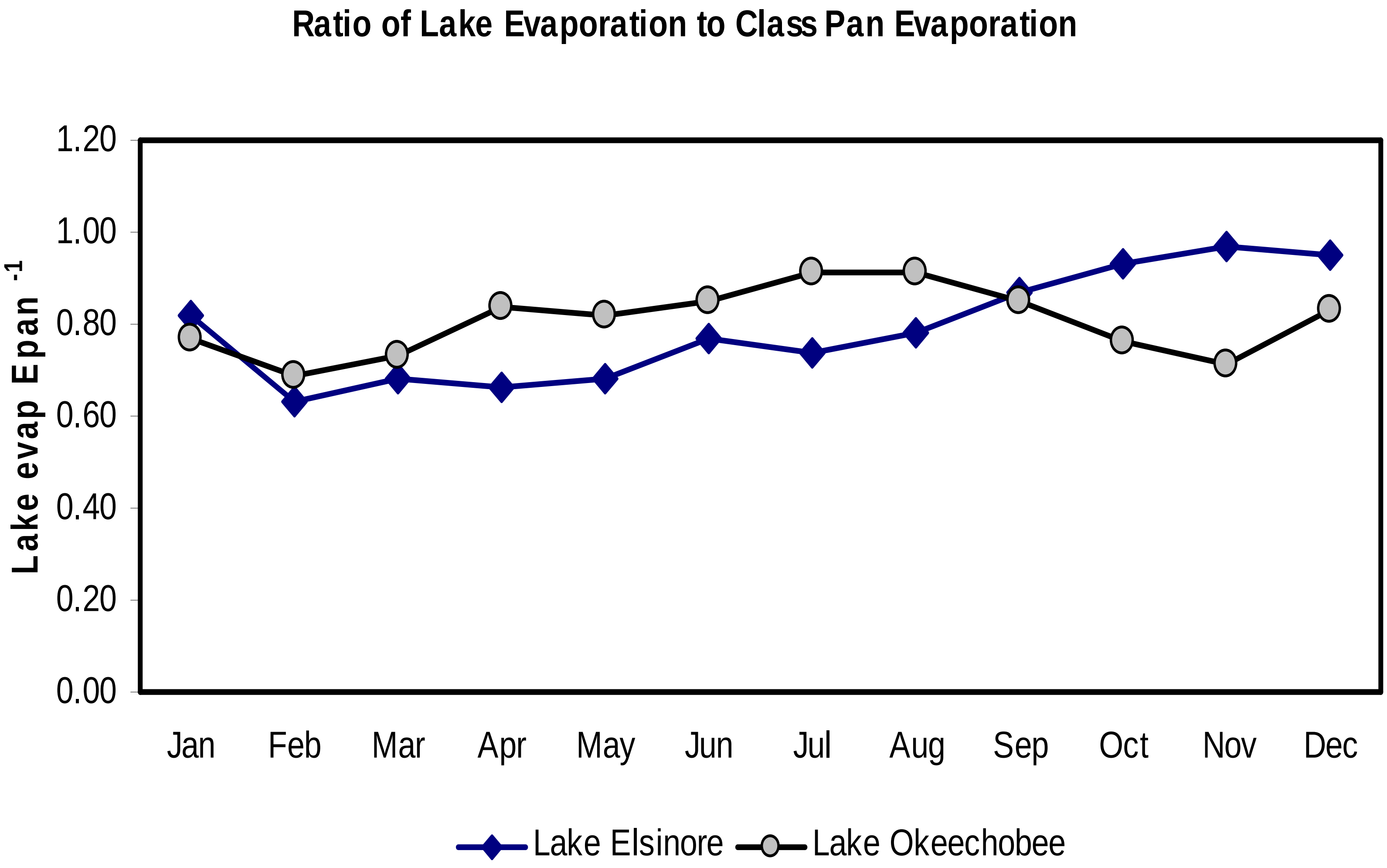


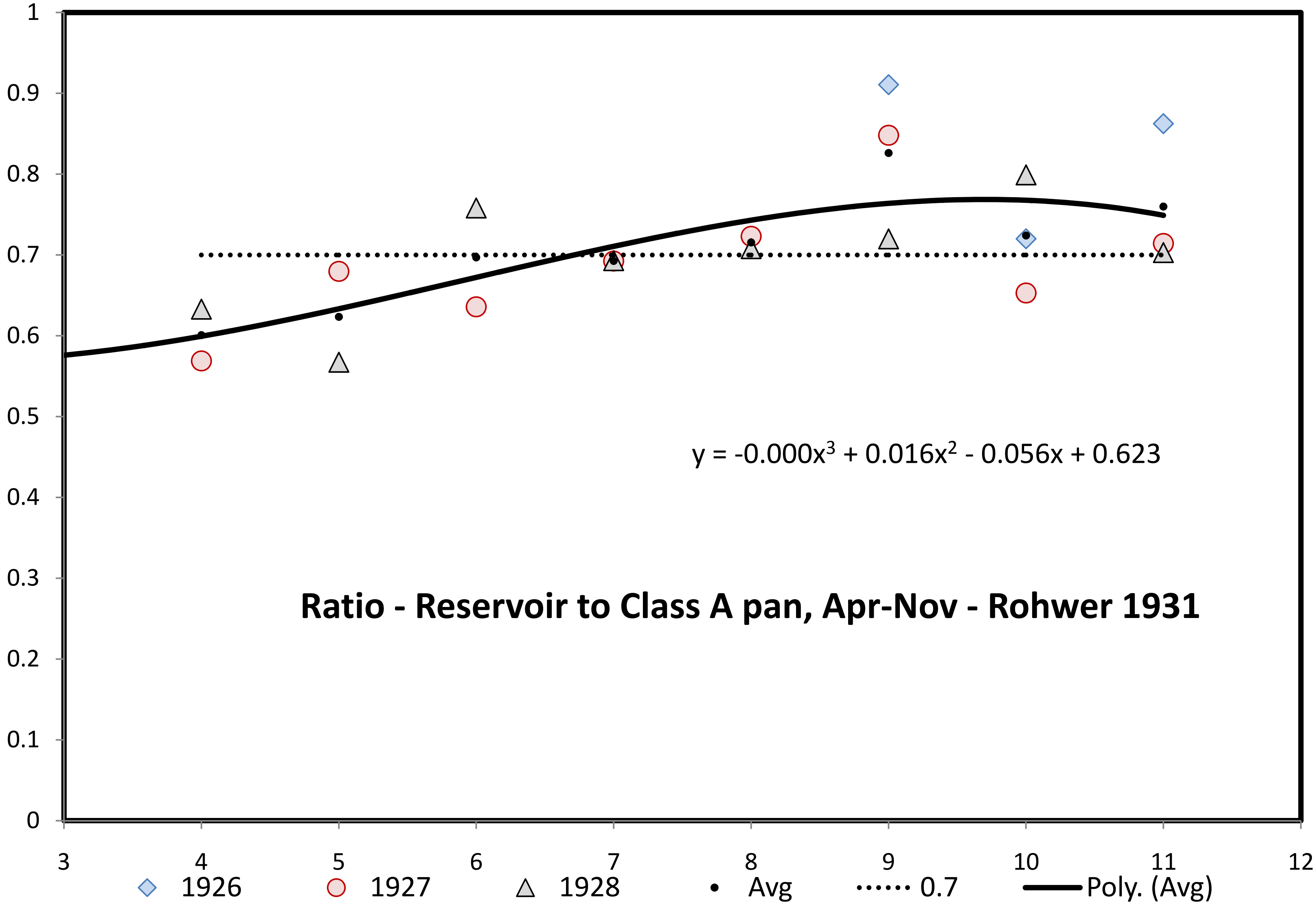
SHALLOW WATER BODIES

- Early estimating methods
  - Equilibrium temperature (Edlinger et al. 1968)
  - Further developed and tested by Keijman (1974), Fraederich et al. (1977), de Bruin (1982), and Finch (2001)
- Finite difference model (Finch and Gash, 2002)
- Pan evaporation *x* pan coefficient
- Energy balance and combination methods
- Reference *ET* x coefficient ($E = ET_o \times K_w$)

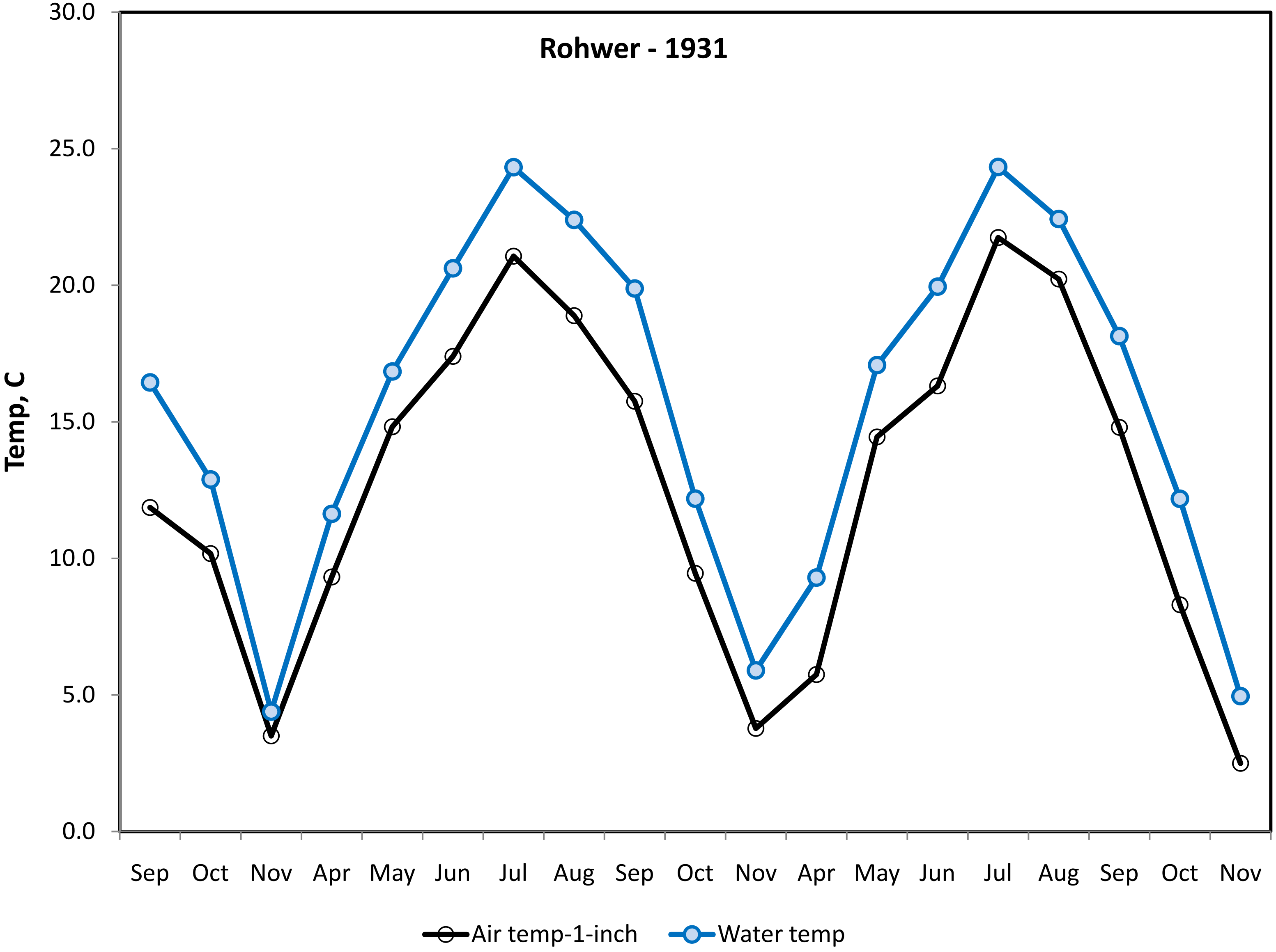
EVAPORATION PAN COEFFICIENTS

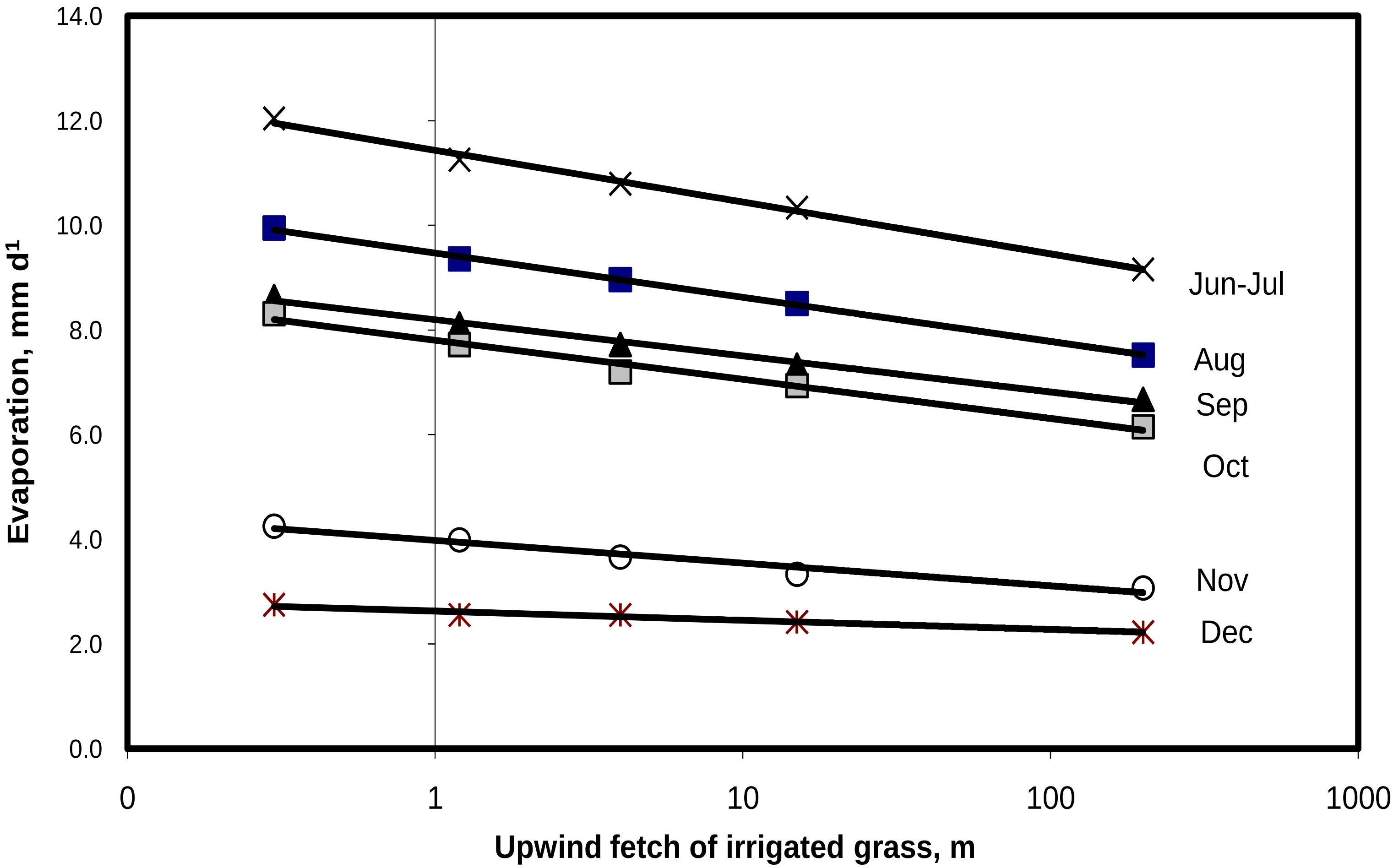
- **Pan coefficient studies**
- **Rohwer (1931) – a classic detailed study conducted on the CSU campus**
- **Rohwer compared evaporation from a Class A pan and an 85-diameter (26 m) reservoir**
- **Young (1947) also did a classic study in CA**
- **Others: Kohler (1954); Kohler et al. (1959); Farnsworth et al. (1982)**
- **Fetch effects and obstructions (fixed & variable)**


Ratio of Lake Evaporation to Class Pan Evaporation
Lake evap Epan -1
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Lake Elsinore
Lake Okeechobee



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
4
5
6
7
8
9
10
11
12
y = -0.000x³ + 0.016x² - 0.056x + 0.623
Ratio - Reservoir to Class A pan, Apr-Nov - Rohwer 1931
◇ 1926
○ 1927
△ 1928
• Avg
······ 0.7
━━ Poly. (Avg)


Rohwer - 1931
Temp, C
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Sep
Oct
Nov
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Air temp-1-inch
Water temp


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Evaporation, mm d¹
0
1
10
100
1000
Upwind fetch of irrigated grass, m
Jun-Jul
Aug
Sep
Oct
Nov
Dec

Obstructions

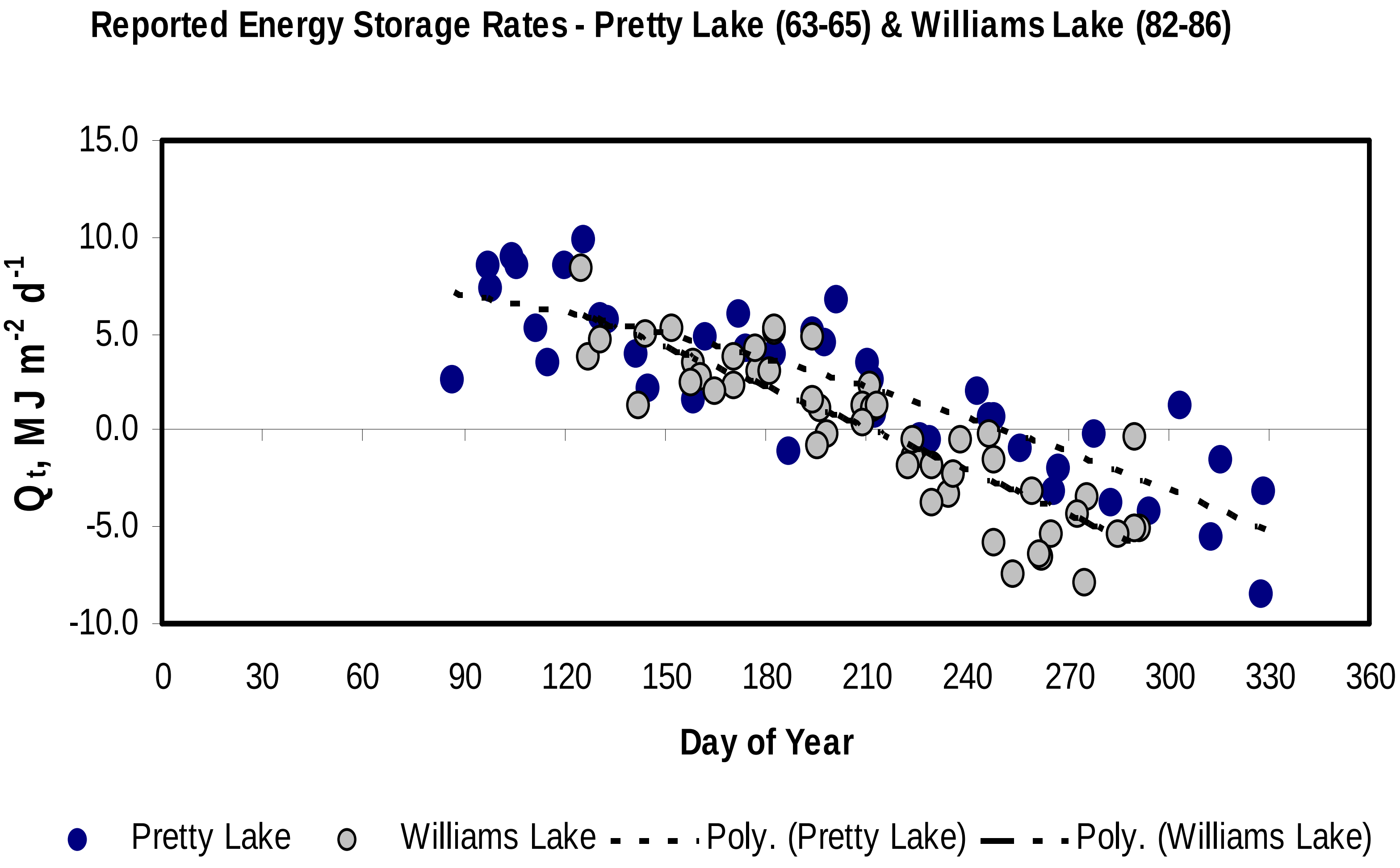
- Fixed
  - buildings
  - shelter belts
  - other (shown in previous example)
- Variable
  - adjacent corn field (most common), can have a major effect
  - weeds and other adjacent crops

OTHER ESTIMATING METHODS

- **Aerodynamic (used mainly on large water bodies)**
- **Energy balance (requires detailed measurements)**
- **Combination methods: Penman (1948, 1956, 1963); Penman-Monteith (1965); Priestley-Taylor (1972)**
- **All require estimating net radiation using standard equations and estimating energy storage (more difficult for deep water bodies)**
- **Reference ET x coefficient ($E = ET_o \times K_w$)**
  - **for shallow water bodies**
  - **for ice-free water bodies**

ENERGY STORAGE RATES

- Difficult to quantify without measurements
- Example rates of storage
  - peak rates can range from 5 to 10 MJ m^{-2} d^{-1}
  - equivalent to 2 to 4 mm d^{-1} evaporation
- Example rates calculated from lake studies
  - Pretty Lake in Indiana
  - Williams Lake in Minnesota


Reported Energy Storage Rates - Pretty Lake (63-65) & Williams Lake (82-86)
15.0
10.0
5.0
0.0
-5.0
-10.0
Q t, M J m-2 d-1
0
30
60
90
120
150
180
210
240
270
300
330
360
Day of Year
Pretty Lake
Williams Lake
Poly. (Pretty Lake)
Poly. (Williams Lake)

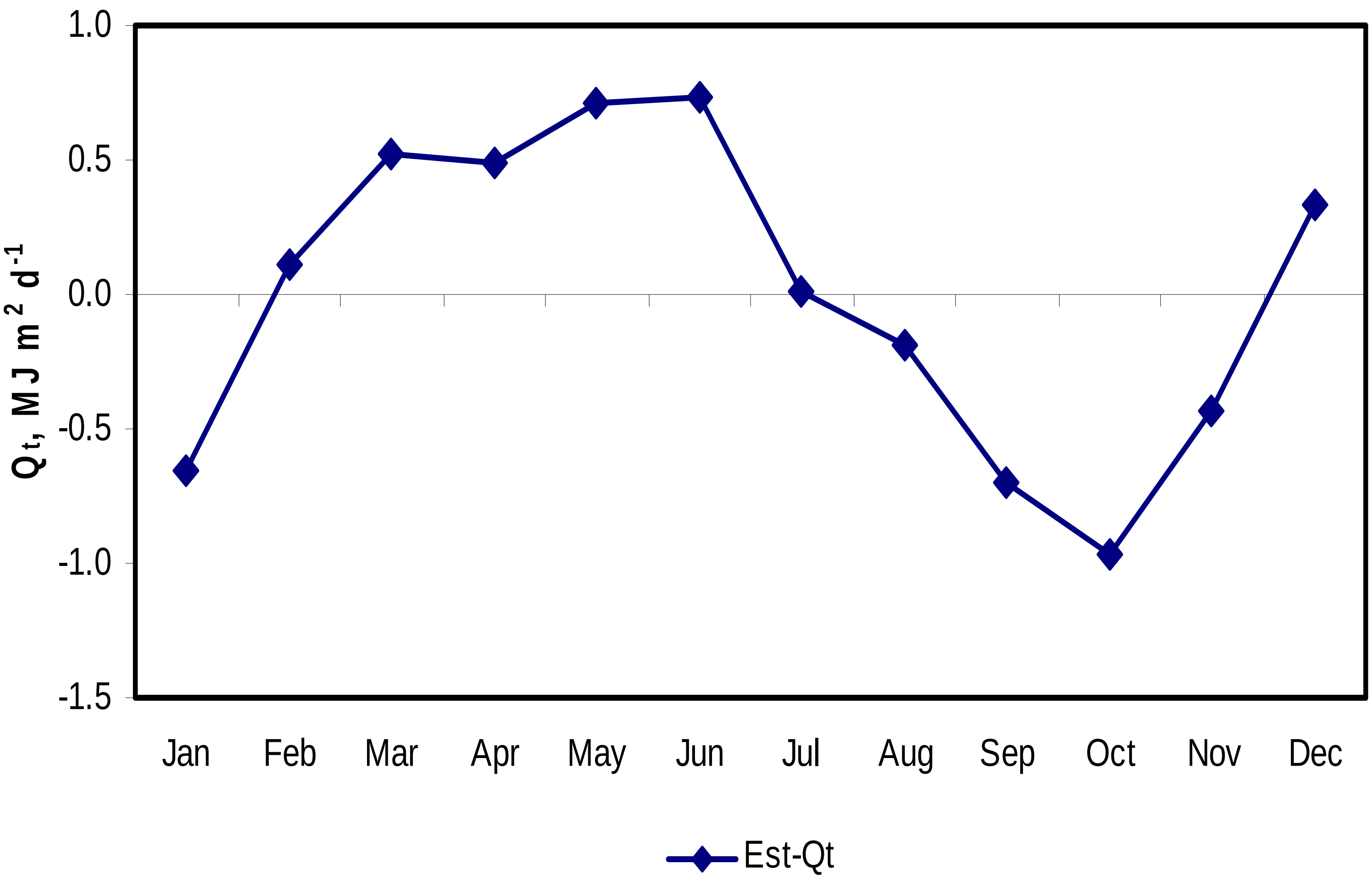
ASCE-EWRI REFERENCE ET

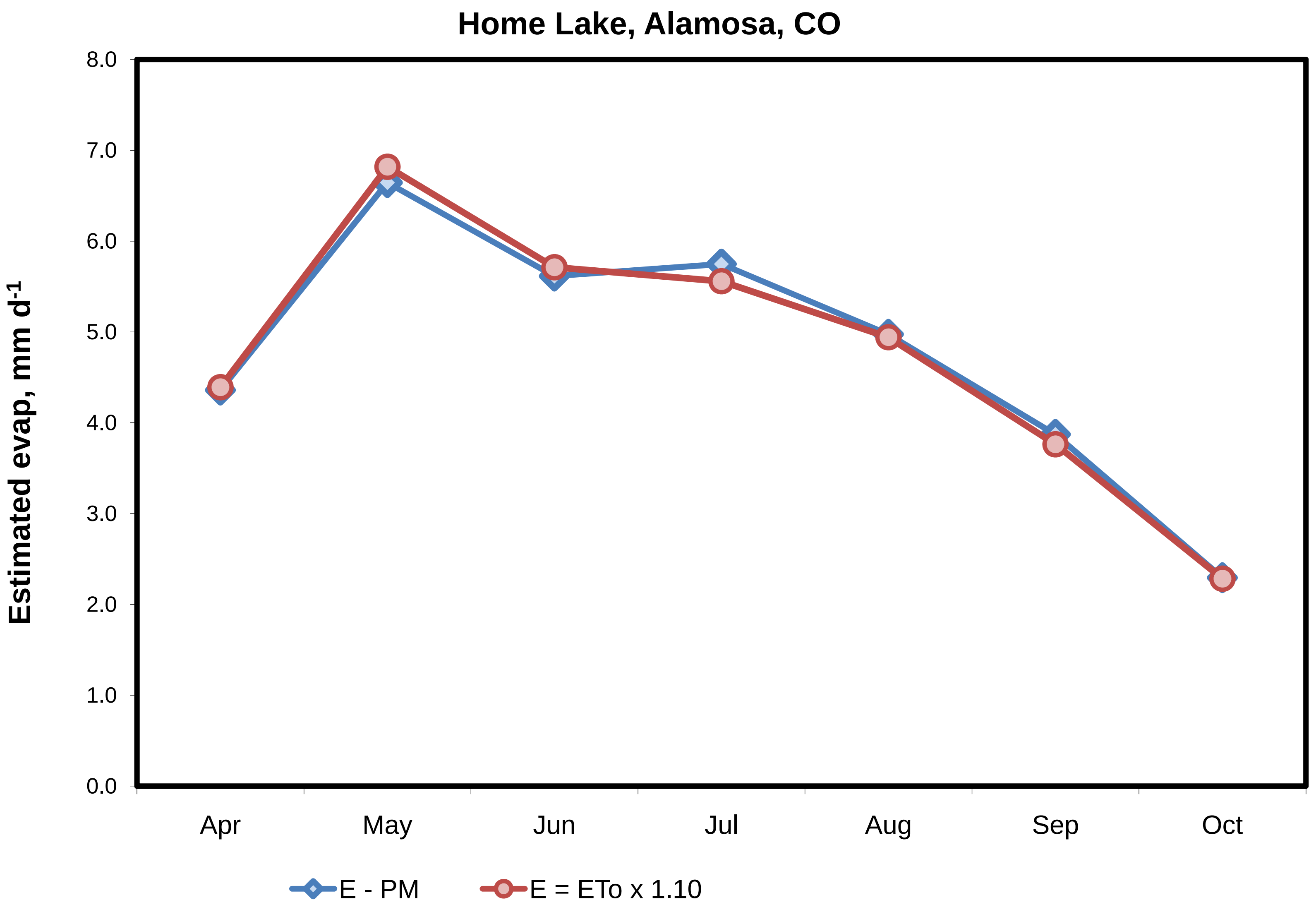
- **ASCE-EWRI (2005) and Allen et al. (1998)**
- **ET_{ref} *x* coefficient for open ice-free water (K_w)**
- **where ET_{ref} is for short grass (ET_{os}), mm d^{-1}**
- **First check input weather data for quality**

$$ET_{ref} = \frac{0.408\,\Delta(R_n - G) + \gamma\,[900/(T+273)]\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

EXAMPLE – HOME LAKE, CO

- **Location San Luis Valley**
  - **Elevation 2297 m (7536 ft) above sea level**
  - **Average depth, about 1.5 m (5 ft)**
- **Estimated energy storage**
- **Estimated evaporation**
  - **May-October**
  - **ET_{ref} x K_w also agrees with PM in November**
- **Results (May-October)**


1.0
0.5
0.0
-0.5
-1.0
-1.5
Q_t, MJ m^2 d^{-1}
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Est-Qt


Home Lake, Alamosa, CO
Estimated evap, mm d-1
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Apr
May
Jun
Jul
Aug
Sep
Oct
E - PM
E = ETo x 1.10

ROHWER'S CLASS A PAN COEFFICIENTS

- K_p **by months for Colorado:**
- **Based on mean ratios (polynomial)**

Apr	**0.60**	**August**	**0.75**
May	**0.63**	**September**	**0.78**
June	**0.67**	**October**	**0.77**
July	**0.71**		

  - **Average, April-October 0.70**

ESTIMATED EVAPORATION HOME LAKE – MAY-OCT.

- PM Penman NWS-33 ET_{ref} x 1.10
- mm
- (inches)
- 894 906 890 892
- (35.2) (35.7) (35.0) (35.1)
- Percent of PM
- 100 101 100 99.8
- All give similar values for May through October

ESTIMATED EVAPORATION LAKE BERRYESSA (3 YR AVG)

- PM Penman P-T USBR original
- mm
- (inches)
- 1,325 1,425 1,277 955
- (52.2) (56.1) (50.3) (37.7)
- 100 108 96 72
- The same R_n and Q_t used for first three methods
- Values confirm effects of “poor pan site”
- P-T equation does not have wind speed