ESTIMATING EVAPORATION FROM WATER SURFACES

(With emphasis on shallow water bodies)
INTRODUCTION

• Evaporation is rarely measured directly
• Estimating methods include:
  – pan coefficient × measured pan evaporation
  – water balance
  – energy balance
  – mass transfer
  – combination techniques
• Emphasis will be practical methods
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

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

![Graph showing the rate of energy storage over time with data points for different months and years. The x-axis represents months (M-03, J-03, S-03, N-03, M-04, J-04, S-04, N-04, M-05, J-05, S-05, N-05, J-06), and the y-axis represents the rate of energy storage in MJ m$^{-2}$ day$^{-1}$. The data points are differentiated by color: blue for estimated data and different colors for measured data from different years (2003, 2004, 2005).]
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).
Surface Temp - Lake Berryessa

°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
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

![Graph showing temperature trends from 2000 and 2004](image)

**American Falls Temperatures**

- **Year 2000**
- **Year 2004**

Legend:
- **Water Temp**
- **10 day mean Air Temp**
Evaporation ratio for Alfalfa Reference ET

American Falls, Evaporation/ETr ratios 2004

- ETrF from Am.Falls study 2004
- Aerodynamic ETrF from Tmean
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 $ET \times$ 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

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Lake Elsinore - Lake Okeechobee
$y = -0.000x^3 + 0.016x^2 - 0.056x + 0.623$

Ratio - Reservoir to Class A pan, Apr-Nov - Rohwer 1931
Rohwer - 1931

![Graph showing temperature trends from September to November, 2010, with peaks in July and August.](image)

- **Temp, ** C
- **Air temp-1-inch**
- **Water temp**

<table>
<thead>
<tr>
<th>Month</th>
<th>Air Temp</th>
<th>Water Temp</th>
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<tbody>
<tr>
<td>Sep</td>
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<td>Oct</td>
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<td>Nov</td>
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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 \( E = ET_0 \times K_w \)
  – 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)
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

<table>
<thead>
<tr>
<th>$ET_{ref} =$</th>
<th>$0.408 \Delta (R_n - G) + \gamma \left[\frac{900}{(T+273)}\right] u_2 (e_s - e_a)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta + \gamma (1 + 0.34 u_2)$</td>
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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
    – $ET_{ref} \times K_w$ also agrees with PM in November

• Results (May-October)
Home Lake, Alamosa, CO

Estimated evap, mm d⁻¹

E = ETo x 1.10

E - PM

Apr May Jun Jul Aug Sep Oct

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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.

<table>
<thead>
<tr>
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<th>Penman</th>
<th>NWS-33</th>
<th>$ET_{ref} \times 1.10$</th>
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<tr>
<td>PM</td>
<td>894</td>
<td>890</td>
<td>892</td>
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<tr>
<td>mm</td>
<td>906</td>
<td>(35.0)</td>
<td>(35.1)</td>
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<tr>
<td>(inches)</td>
<td>(35.7)</td>
<td>(35.0)</td>
<td>(35.1)</td>
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<tr>
<td>Percent of PM</td>
<td>100</td>
<td>100</td>
<td>99.8</td>
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<tr>
<td>All give similar values for May through October</td>
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ESTIMATED EVAPORATION
LAKE BERRYESSA (3 YR AVG)

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<td>PM</td>
<td>Penman</td>
<td>P-T</td>
<td>USBR original</td>
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<tr>
<td>mm</td>
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<tr>
<td>(inches)</td>
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<td>1,325</td>
<td>1,425</td>
<td>1,277</td>
<td>955</td>
<td></td>
</tr>
<tr>
<td>(52.2)</td>
<td>(56.1)</td>
<td>(50.3)</td>
<td>(37.7)</td>
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<tr>
<td>100</td>
<td>108</td>
<td>96</td>
<td>72</td>
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• 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