HISTORICAL EVOLUTION OF ET ESTIMATING METHODS[1]
A Century of Progress

by
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Introduction

This is a condensation of a more detailed paper that Allen and I prepared in 2000 (Jensen and Allen, 2000). I presented it at the 4th ASAE National Irrigation Symposium in Phoenix, AZ. In this paper, more emphasis is placed on my involvement or association with others in the development and dissemination of new technology for estimating ET in the U.S. My involvement began as I evaluated monthly coefficients for the Blaney-Criddle equation that had been prepared by researchers at USDA-ARS field stations in response to a request from Harry Blaney and Howard Haise. I reviewed current ET literature and older documents relating to the development of early evapotranspiration estimating methods in the USA. In this paper, I have included some history of the development of the ASCE Manual 70 Evapotranspiration and Water Requirements (Jensen et al. 1990), FAO-56 Crop Evapotranspiration (Allen et al. 1998), development of programs to calculate ET using satellite data (Bastiaanssen, 1998a,b, 1998; Allen et al. 2007), the new ASCE Standardized Reference ET Equation (ASCE-EWRI 2005), proposal for a one-step approach to estimating ET, and an update on the second edition of ASCE Manual 70. More detailed, but less personnel-oriented, on progress in measuring and modeling ET in agriculture can be found in a recent review article by Farahani et al. (2007).

Early Studies

With the rapid development of irrigation in the western USA after about 1850, efforts to reduce water losses from both beneficial and non-beneficial vegetation became more important. Measured water deliveries varied widely and often greatly exceeded consumptive use values because as Buffum (1892) stated, *over-irrigation was the first and most serious mistake made by early settlers*. Most early methods that were developed for estimating *evapotranspiration* (ET), or *consumptive use* (CU) for irrigated areas were for seasonal values based on observed or measured water deliveries. Air temperature was the main weather variable that was used. Solar radiation was not considered directly as a separate variable. For monthly values, crop stage of growth effects became important. As developers of empirical estimating methods adjusted and modified their temperature-based based methods, the methods tended to become more complex. A measured change in soil water content over periods of seven or more days was the main source of measured ET data before the 1950s. Reliable published data were scarce, especially measured ET rates by stage of crop growth.

My Involvement

My involvement in methods of estimating ET began in 1960. In the late 1950s, the Soil Conservation Service asked the USDA Agricultural Research Service (ARS) to develop monthly coefficients for the Blaney-Criddle (B-C) method. Howard Haise and Harry Blaney had

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[1] Presented at the CSU/ARS Evapotranspiration Workshop, Fort Collins, CO, 12-Mar-2010.

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requested ARS researchers to use their available data to calculate monthly coefficients for the B-C method. A stack of data sheets was collected when I arrived in Fort Collins in 1959. However, the data had not been analyzed before Harry Blaney went to Israel for a year and Howard Haise went to Davis, CA for a six-month sabbatical. I was asked to work on the data. I started reviewing the numbers–the results were highly variable. Researchers with little or no prior experience with the B-C method had calculated monthly coefficients. Many did not have the experience to judge good input data from bad data such drainage that may have occurred following rains. Also, some time periods were too short. The plotted monthly coefficients were widely scattered. I prepared a new questionnaire that was sent to ARS researchers by Howard Haise as he was well-known to ARS researchers at the time. As part of this task, I reviewed current literature and many early publications on development of irrigation and ET estimating methods. These reviews were never published, but served as a good personal reference and the main source of information for a later 1962 ET workshop report[3].

The main difference in the new questionnaire that I prepared was that we asked for basic soil water and weather data, mainly air temperature and precipitation along with supporting data and not the B-C coefficients that they had computed. We established criteria for reviewing data sets before making our own calculations. Where possible, we estimated solar radiation for each measurement period, usually from cloud cover at one or more nearby stations. We ended up with about 1,000 ET rates for periods of seven or more days. When searching for full crop cover ET data, we found only about 100 data sets represented reasonably reliable values. The general equation summarizing the ET rates and solar radiation (R_s) data from the full cover sets was:

$$ET = (0.014\ T - 0.37)\ R_s$$

where T is in °F and R_s is in mm/day or inches/day. A summary of the results tabulated was presented at an ARS-SCS CU workshop in March 1972 and later at the annual SSSA meeting[4]. The workshop report contained charts of the ratio of ET to solar radiation for seven crops vs. percent of the growing season and by cutting periods for alfalfa grown in lysimeters at Reno, NV, a summary of solar radiation relationships, and tabulated weekly mean solar radiation, mean air temperature and cloud cover for 20 locations in the west. Copies of the workshop report were sent to others involved in estimating ET who did not attend the workshop such as Jerry Christiansen at Utah State University and David Robb with the USBR in Denver.

The main results of my analyses were published in 1963 (Jensen and Haise 1963). The main purpose of that paper was to encourage engineers, soil scientists and agronomists to begin thinking about radiant energy as the primary source of energy for evaporation instead of air temperature which had been the practice for decades. Using the 1962 report, Dave Robb with the USBR developed a set of nine crop coefficient curves for use with the Jensen-Haise equation (Robb 1966).

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[3] Jensen, M.E., and H.R Haise. 1962. *Estimating Evapotranspiration from Solar Radiation*. Prel. Rept. for discussion at an ARS-SCS Consumptive Use Workshop, Phoenix, AZ, Mar. 6-8.

[4] Soil Science Society of America meeting, Aug. 20-24, 1962, Ithaca, NY.

Early Irrigation and CU Studies

Many books on irrigation had been written on irrigation in England, France and Italy from 1846 to 1888 along with reports on irrigation in California (Carpenter 1890). Joint USDA-Experiment Stations irrigation investigations were started in 1897 under the supervision of the Office of Experiment Stations (Teele 1904). These investigations continued for the next 55 years under various USDA departments, but were transferred to the Soil Conservation Service (SCS) in 1939 (Knoblauch et al. 1962). In 1902, the Bureau of Plant Industry was established in the USDA and detailed studies of transpiration were conducted by this organization in the early 1900s. From about 1890 to 1920 the term *duty of water* was used to describe water use in irrigation with no standard definition. Duty of water was sometimes reported as the number of acres that could be irrigated by a constant flow of water such as 1 cubic foot per second or as depth of water applied. Water measured at farm turnouts was referred to as net duty of water. Examples of early studies were those by Widstoe (1912) in Utah from 1902 to 1911 on 14 crops; Harris (1920) who summarized 17 years of study in the Cache Valley of Utah; Lewis (1919) who conducted studies near Twin Falls, ID from 1914 to 1916; Hemphill (1922) who summarized studies in the Cache La Poudre river valley of northern Colorado; Israelson and Winsor (1922) who made duty of water studies in the Sevier River valley in Utah from 1914 to 1918; and Crandall (1918**)** who worked in the Snake River area near Twin Falls in 1917 and 1918. An excellent summary of early seasonal CU studies was presented in a progress report of the Duty of Water Committee in the Irrigation Division of the American Society of Civil Engineers (ASCE). It was presented in 1927 by O.W. Israelson and later published (Anonymous 1930).

L.J. Briggs, a biophysicist, and H.L. Shantz, a plant physiologist, conducted highly significant studies of transpiration in eastern Colorado (Briggs and Shantz 1913, 1914, 1916a, 1916b). Briggs and Shantz recognized that solar radiation was the primary cause of cyclic change of environmental factors (Briggs and Shantz 1917). They developed hourly prediction equations using the vertical component of solar radiation and temperature rise, and solar radiation and vapor saturation deficit. They also recognized the significance of advected energy. A summary of the Briggs and Shantz 1910-1917 studies was later published by Shantz and Piemeisel (1927). Widstoe (1909) began studying the influence of various factors affecting evaporation and transpiration in 1902. Harris and Robinson (1916) conducted similar studies from 1912 through 1916. Widstoe and McLaughlin (1912) concluded that temperature is the most important factor, then sunshine and relative humidity.

Other studies conducted during the 1900-1920 period were concerned with the factors causing and controlling water loss under irrigation. During the next two decades emphasis was on developing procedures for estimating seasonal CU using available climatic data.

Early Estimating Methods

The U.S. Bureau of Reclamation began studying CU and temperature relationships in 1920 (Lowry and Johnson 1942). Hedke (1924) proposed a procedure for estimating valley CU based on heat available to the ASCE Duty of Water Committee in 1924. *Heat available* was estimated using degree-days. Radiant energy was not considered directly. The ASCE committee concluded in 1927 that there was an urgent need for a relatively simple method of estimating CU

(Anonymous 1930). Harry Blaney began measuring CU of crops in the 1920s based on soil samples. He worked on crops grown along the Pecos River for the Division of Irrigation and Water Conservation under the SCS-USDA which was established in 1935. His first procedure for estimating seasonal and annual CU used mean temperature, percent of annual daylight hours and average humidity (Blaney and Morin 1942). From 1937 to 1940, Lowry with the National Resources Planning Board, and Johnson with the USBR, developed a procedure for estimating seasonal CU using maximum temperature above 32° F during the growing season and annual inflow minus outflow data for irrigation projects (Lowry and Johnson 1942). Thornthwaite (1948) correlated mean monthly temperature with ET based on eastern river basin water balance studies and developed an equation for *potential evapotranspiration* which was widely used for years. Thornthwaite recognized the limitations of his equation pointing out the lack of understanding of why potential ET at a given temperature is not the same everywhere. Because of its simplicity the equation was applied everywhere and, in general, underestimated ET in arid areas. All of these early methods were based on correlations of measured or estimated CU data with various available or calculated climatic data. The resulting equations were relatively simple because computers were not available—only slide rules and perhaps hand-operated adding machines. This may be difficult for young people to comprehend today since they are very dependent on personal computers.

Numerous other reports and publications were prepared between 1920 and 1945 by various state and federal agencies. Many of them dealt with investigations of water requirements for specific areas and measured farm deliveries and not on techniques for estimating CU or ET. Bibliographies of publications on seasonal CU can be found in books such as Israelsen (1950) and Houk (1951).

Blaney-Criddle Method

The most widely known empirical ET estimating method used in the USA in the 1950s and 1960s was the Blaney-Criddle (B-C) method. The procedure was first proposed by Blaney and Morin in 1942 (Blaney and Morin 1942). It was modified later by Blaney and Criddle (1945[5], 1950, 1952). The equation should be well-known by this group, but if not it is:

$$U = KF = \sum kf$$

where:

U = estimated CU (or ET), inches, F = the sum of monthly CU factors, f, for the period ($f = t \cdot p/100$ where t = mean monthly air temperature, °F, and p = mean monthly percent of annual daytime hours (daytime is defined as the period between sunrise and sunset)

K = empirical CU coefficient (irrigation season or growing period)

k = monthly CU coefficient

For long-time periods mean air temperature was considered to be a good measure of solar radiation (B-C 1962). Phelan developed a procedure for adjusting monthly k values as a function

[5] Blaney, H.F., and W.D. Criddle. A method of estimating water requirements in irrigated areas from climatological data. June 1945 (mimeo). ___ pp.

of air temperature[6] which later became part of SCS publication on the B-C method (USDA-SCS 1970). Criddle (1952) also developed a table of daily peak ET rates as a function of depth of water to be replaced during irrigation. Hargreaves (1956) developed a procedure similar to the B-C method for transferring CU data to other areas of the globe. Christiansen and Hargreaves developed a series of regression equations for estimating monthly grass ET based on pan evaporation, air temperature and humidity data (Christiansen 1968; Christiansen and Hargreaves 1969). They initiated efforts to reduce weather data requirements to only air temperature, calculated extraterrestrial radiation and the difference between maximum and minimum air temperature to predict the effects of relative humidity and cloudiness. A culmination of these efforts was the well-known 1985 Hargreaves equation for grass reference ET (Hargreaves et al. 1985; Hargreaves and Samani 1985).

A summary of early studies and the B-C method was published in a USDA technical bulletin in cooperation with The Office of Utah State Engineer (Blaney and Criddle 1962). Criddle was Utah State Engineer at that time. This publication presented the B-C equation in English and metric units and updated records of measured CU by crops, percent of daytime hours of the year for latitudes of 0 to 65° N and 0-50° S, monthly CU factors by states, suggested monthly crop coefficients (k) for selected locations, monthly CU factors (f) and average precipitation in various foreign countries, and a summary of B-C method applications that were made by various consultants such as Claude Fly in Afghanistan, Tipton and Kalmbach in Egypt and West Pakistan. The B-C method is still used in some states because historical water records such as water rights have been based on this method.

Prior to about 1960 and U.S. engineers were usually taught only the Blaney-Criddle method of estimating CU or ET. Today, students and young engineers generally have had a fairly broad training in methods of estimating ET and ET-climate relationships.

It is unfortunate that Blaney and Criddle did not select extraterrestrial solar radiation as an index of solar energy instead percent of daytime hours. Daytime hours from sunshine tables of Marvin (1905) do not adequately account for solar angle effects, especially in higher latitudes as illustrated in fig. 1. *Smithsonian Meteorological Tables* would have had an equation for calculating total daily solar radiation at the top of the atmosphere and total daily at selected dates during the year at that time.

Transition Methods in the U.S.

Estimating methods in the U.S. began to change in the 1960s from methods based primarily on mean air temperature to methods considering both temperature and solar radiation as listed below.

$ET = (0.014\ T_f - 0.37)\ R_s$ (Alfalfa reference ET; Jensen and Haise 1963)
$ET = (0.0082\ T_f - 0.19)\ R_s$ (Grass reference ET, Florida; Stephens and Stewart 1963)
$ET = (0.0023\ TD_c^{0.5}\ (T_c + 17.8)\ R_s$ (Grass reference ET, Hargreaves and Samani 1985 and Hargreaves et al. 1985)

[6] Phelan, J.T. 1962. Estimating monthly "k" values for the Blaney-Criddle formula. ARS-SCS Workshop on Consumptive Use, Mar. 6-8 (mimeo).

where T_c is mean air temperature in °C, R_s is solar radiation in mm d^{-1} or in. d^{-1}, and *TD* is the difference between maxim and minimum daily air temperature.

Methods Based on Theory

The Bowen ratio the ratio of temperature to vapor pressure gradients, Δt/Δe, (Bowen 1926) and energy balance concepts were not incorporated at an early date into methods for estimating ET as they were for estimating evaporation from water surfaces. Examples of early work on evaporation from water using the Bowen ratio were those of Cummings and Richardson (1927), McEwen (1930), Richardson (1931), Cummings (1936), Kennedy and Kennedy (1936) and Cummings (1940).

In contrast to development of largely empirical methods in the U.S., Penman[7] (1948) in the UK took a basic approach and related ET to energy balance and rates of sensible heat and water vapor transfer. Penman♣s work was based on the physics of the processes, and it laid the foundation for current ET estimating methodology using standard weather measurements of solar radiation, air temperature, humidity, and wind speed. The Penman equation (Penman 1948, 1956b, 1963) stands out as the most commonly applied *physics-based* equation. Penman (1948) utilized the Bowen ratio principle in developing the well-known equation for estimating evaporation from a water surface along with reduction coefficients for grass. Later, a surface resistance term was added (Penman and Long 1960; Monteith 1965; and Rijtema 1965). Howell and Evett (2002) provide an excellent summary of the Penman equation and its evolution to the ASCE-EWRI standardized equation. The modern combination equation applied to standardized surfaces is currently referred to as the Penman-Monteith equation (PM). It represents the state of the art in estimating hourly and daily ET. When applied to standardized surfaces it is now called the Standardized Reference ET Equation (ASCE-EWRI 2005).

Other methods of estimating and measuring ET range from eddy covariance and energy balance using Bowen ratio or sensible heat flux based on surface temperature, radiosonde measurements of complete boundary layer profiles of temperature and humidity and energy balance estimates based on satellite imagery.

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[7] An excellent summary of Penman's life and work was prepared by J.L Monteith:
Howard Latimer Penman. 10 April 1909-13 October 1984. J.L. Monteith. *Biographical Memoirs of Fellows of the Royal Society*, Vol. 32 (Dec., 1986), pp. 379-404. Stable URL: http://www.jstor.org/stable/770117

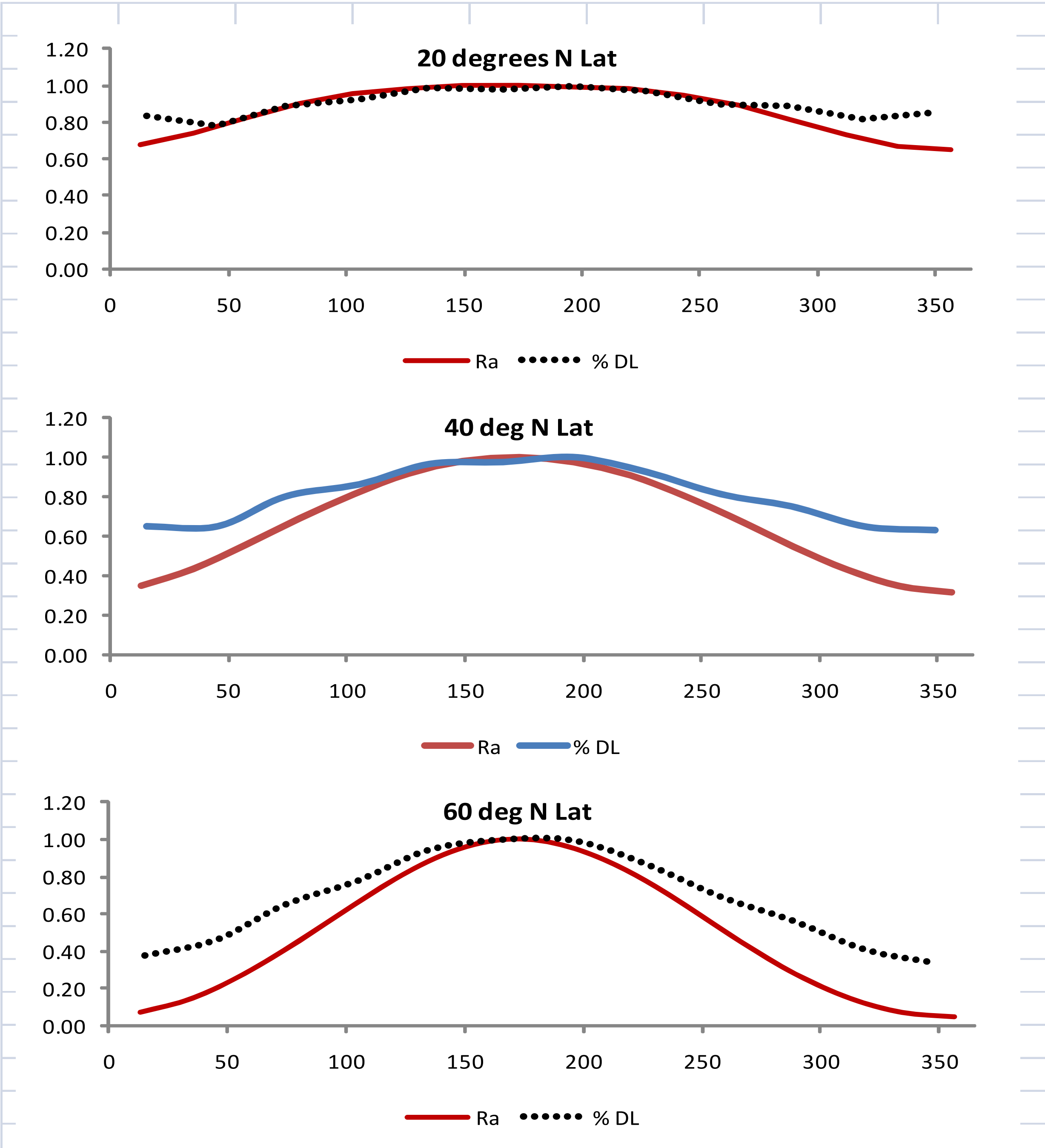

Figure 1. Change in relative solar radiation vs. change in relative percent daylight hours.

Other Methods

Many other equations were proposed during the 1950s and early 1960s, but have not been widely used in the U.S. Some of these are Halkias et al. (1955), Ledbedevich (1956), Romanov (1956), Makkink (1957) and Vitkevich (1958). In 1957, Makkink published a formula for estimating potential ET based on solar radiation and air temperature (Rijtema 1958) that is still used in Western Europe. Makkink utilized the energy-weighting term of the Penman equation, solar radiation and a small negative constant. The Makkink equation formed the basis of the subsequent *FAO Radiation* method that was included in FAO Irrigation and Drainage Paper No. 24 on crop water requirements by Doorenbos and Pruitt (1975, 1977). Turc developed a formula in 1960 which was later modified (Turc 1961). It was based on mean air temperature and solar radiation for 10-day periods. Rijtema (1958) proposed the Turc formula for individual crops using crop factors and length of growing season. Olivier (1961) in England developed a procedure for estimating average monthly CU for planning new projects where climatic data were limited. The equation used average monthly wet-bulb depression and a factor based on clear sky solar radiation values.

In 1968, I described the process of using the rate of ET from a well-watered crop with an aero-dynamically rough surface like alfalfa with 30-50 cm of growth as a measure of potential ET, or E_o (Jensen 1968). ET for a given crop could be related to E_o using a coefficient, now known as a crop coefficient:

$$E_t = K_c E_o$$

where K_c is a dimensionless coefficient similar to that proposed by van Wijk and de Vries (1954) representing the combined effects of resistance to water movement from the soil to the evaporating surfaces, resistance to diffusion of water vapor from the evaporating surfaces through the laminar boundary layer, resistance to turbulent transfer to the free atmosphere, and relative amount of radiant energy available as compared to the reference crop. At that time, methods other than those based on air temperature were not well known. In order to facilitate the understanding of the of the E_o x K_c process, illustrating the change in the K_c as crop cover develops enabled users to visualize how the coefficient changed from a value near 0.15 for bare soil to 1.0 at full cover.

Routine use of computers for estimating ET was in its infancy. Estimates of alfalfa reference ET, ET_r, that were used in our first computerized irrigation scheduling program (Jensen 1969) were calculated using the Penman method with alfalfa wind speed coefficients developed at Kimberly, ID (Jensen et al. 1970). Since we did not have a computer at Kimberly, ID we used a time-share computer located in Phoenix, AZ, and the telephone system with a teletype paper tape reader and printer at Kimberly. In 1970, copies of a FORTRAN computer program that Ben Pratt and I had written for estimating daily ET and scheduling irrigations using the Penman equation was widely distributed following an informal workshop at Kimberly, ID in 1970.

The method of using reference ET and crop coefficients has been widely used for nearly a half century. In general it has been relatively robust. For example, in 2004, Ivan Walter and I estimated ET for the Imperial Irrigation District in California using this approach. Our estimate for agricultural land for CY 1998 were 2% higher than that of SEBAL estimate for entire district and to 5% higher for agricultural crops for water year 1998[8] of 2.01 million ac-ft or 2.5 km^3. Whether the ET_{ref} x K_c method, also known as the two-step method, will be replaced by the direct PM method, or one-step method, in the near future is uncertain.

Various methods of measuring ET and methods of estimating ET were summarized during a conference held in Chicago following the ASAE winter meeting on Dec. 5-6, 1966. Leading researchers from many different organizations and disciplines presented papers on the current state of the art of estimating ET in the early 1960s. I was the conference chairman and program committee members represented ASCE, American Meteorological Society, Soil Science Society of America, International Commission of Irrigation and Drainage, and several Canadian organizations. W.O. Pruitt assisted in editing the proceedings (Jensen 1966).

Unfortunately, we not did get anyone to specifically discuss the Penman method. I tried to get Howard Penman to attend and present a paper, but he declined after several letters and a phone call. Leo Fritschen discussed the energy balance method, C.H.M. van Bavel discussed combination methods (van Bavel 1966a,b), and Champ Tanner discussed a comparison of energy balance and mass transfer methods for measuring ET (Tanner 1966). The proceedings contained pictures of the authors who were leaders in their field at the time and session chairmen.

Disseminating and Adopting New ET Estimating Technology

Disseminating and adopting advances in ET estimating technology has not been rapid as compared with many other fields because dissemination-adaption involves many disciplines such as meteorology, soils, and plants. Dissemination and adaption just does not occur rapidly as it does in single disciplines. The users of the technology, a half century ago, were mainly engineers.

Penman had a comprehensive understanding of the physical processes involved in ET. He presented an introductory paper at the informal meeting on physics that was held in The Netherlands in September 1955 (Penman 1956). He concluded with the sentence:

> ***Though the physicist still has some problems he can solve by himself, much of his future contribution to understanding evaporation in agriculture must be in collaboration with the biologist and the soil scientist.***

In my 1960 review of old and current literature, it was clear that new advances in estimating ET had to depart from the traditional use of temperature as the primary input variable. The Penman equation had been developed, but was not in general use by engineers designing and managing irrigation projects. Generally, the Penman equation was thought to be too complicated for use by engineers given the status of computational tools and weather data commonly collected at that time.

During the 1966 meeting of the Irrigation and Drainage Division of ASCE in Las Vegas, NV I was asked to chair the ASCE committee on Irrigation Water Requirements, formerly the

[8] Personal information from Bryan Thoreson, Davids Engineering, Nov. 2009.

committee on CU of Crops and Native Vegetation. The committee was charged with developing a manual on CU. The committee had been chaired by Harry Blaney, but it was not making much progress on this task. A few papers that had been prepared were reproductions old temperature-based methods of estimating ET. My one condition on accepting chairmanship was that I could bring in non-ASCE members into the committee such as Bill Pruitt. Bill, who was with the University of California at Davis and was not an ASCE member then, had been measuring ET using weighing lysimeters along with associated basic meteorological data. The committee had Control, Corresponding and Non-member advisors. Control members were: Robert Burman, University of Wyoming, Harlan Collins, SCS, Albert Gibbs, USBR, Marv Jensen (ARS-USDA), and Arnold Johnson, USGS. Harry Blaney remained on the committee, but never attended any of our meetings. We made progress and produced a report was the start of the ASCE manual on ET. The 1973 report, which we prepared as a camera-ready document at Kimberly, was printed as the ASCE report *Consumptive Use and Irrigation Requirements* (Jensen *ed.* 1974) and widely disseminated in the U.S. and in other countries like China.

I left the ET committee for three years when I became a member of the executive committee of the ASCE I&D Division in October 1974. Members of the ET committee continued to work on the manual. Several members served as ET committee chairman between October 1973 and 1986. In 1986, a subcommittee of the ET committee was formed. Its members were Rick Allen, Ron Blatchley, Bob Burman, Marv Jensen, Eldon Johns, Jack Stone and Jim Wright. I was designated as chairman. We were charged with the task of preparing the CU or ET manual. The first draft, which had both English and metric units, was completed for review by one or several ASCE committees in 1988. One reviewer suggested that we use only metric units. This was good advice, but delayed the manuscript another year as changes were made in the manuscript. The manual was published in 1990 as *ASCE Manual No. 70* (Jensen et al. 1990). The *ASCE PM* equation from ASCE Manual 70 has been widely accepted for standardized calculations such as in the Natural Resources Conservation Service *National Engineering Handbook* (Martin and Gilley 1993).

Allen et al. (1989) prepared a paper for publication in the Agronomy Journal to disseminate new information to soil scientists and agronomists. In 1990, the FAO needed to update its 1975-1977 publication on crop water requirements (FAO-24). It organized an experts consultation on the revision of FAO-24 in Rome 28-30 May 1990 (Smith et al. 1991). There were 10 participants from seven countries, John Monteith from the International Crops Research Institute for Semi-arid Tropics, D. Rijks from WMO, and several participants from FAO. USA participants were Rick Allen, Marv Jensen, and Bill Pruitt. At this conference several manuscript copies of the ASCE Manual 90 were made available and became a key reference. The revision of FAO-24 with major contributions by Rick Allen resulted in the well-known FAO-56 publication on crop evapotranspiration by Allen et al. (1998).

In the Netherlands, R.A. Feddes had been working on models of ET, plant root systems and soil water extraction (Feddes et al. 1993). In 1998, Bastiaanssen et al., including Feddes, published a paper describing a surface energy balance model for land (SEBAL) using satellite-based imagery (Bastiaassen et. al. 1998a,b). In the U.S., Allen et al. developed a high resolution mapping model with internalized calibration using principles and techniques used in the SEBAL model (Allen et al. 2007). It differs from SEBAL in that it uses a near-surface temperature gradient, *dT*, that is indexed to the radiometric surface. The METRIC technique uses the SEBAL technique for estimating *dT*. METRIC also uses weather-based reference ET to establish energy balance conditions for a *cold* pixel and is internally calibrated at two extreme conditions (wet and dry) using local available weather data. The autocalibration is done for each image using alfalfa-based reference ET. Both of these models are now being used in the U.S. to map ET at a high resolution.

In 2000 the Irrigation Association and landscape industry requested the ASCE Irrigation Water Requirements committee, now renamed Committee on Evapotranspiration in Irrigation and Hydrology, to recommend a single procedure for estimating reference ET for use in the United States. This request in part resulted in an ASCE task committee of the ET Committee consisting of engineers and scientists from around the U.S. They agreed on a single equation for estimating reference crop ET. The equation is a simplification of the ASCE PM equation. The request was made to help standardize the basis for the myriad of landscape (i.e., crop) coefficients that have been developed since the late 1980♣s. The task committee suggested applying the PM equation to both a tall reference crop like alfalfa and short reference crop like clipped grass by changing several coefficients in order to support usage in both agricultural and landscape industries. A reduced form of the PM equation was adopted for both reference types, with the grass form being the same as in the FAO-56 publication. This was done to promote agreement in usage between the U.S. and other countries. Sets of coefficients were presented in a table for estimating daily or hourly reference ET for the short and tall references. Details of that equation and its development were presented in separate papers at the 2000 ASAE National Irrigation Conference in Phoenix, AZ (Walter et al. 2000). The various forms and applications of the PM and Penman equations, as well as commonly used empirical equations, were implemented in REF-ET software (Allen 2000) that was available for free downloading from http://www.kimberly.uidaho.edu/ref-et. Rick Snyder also has several reference ET programs (monthly, daily, and hourly) for Exel spreadsheets on the web site http://biomet.ucdavis.edu/evapotranspiration.html.

A summary of the reference ET methodology and tables of mean and basal crop coefficients were published as a major chapter in the 2nd edition of the ASABE book *Design and Operation of Farm Irrigation Systems* (Allen et al. 2007). It contains a great deal of detail on factors controlling ET and on estimating ET. There are numerous recent publications on many different crop coefficients written by U.S. and foreign authors. Before using these coefficients the users need to carefully review how the calculations were made. FAO-56 crop coefficients have been refined incorporating the fraction of ground cover and plant height (Allen and Pereira 2009). Others have used remote sensing with ground-based or aircraft-based cameras, and satellite images to measure the normalized difference vegetation index (NDVI) and then related NDVI to ET_{ref}-based crop coefficients. The use of the reference ET and crop coefficient method is expected to continue because of the extensive collection of available crop coefficients.

Some scientists are suggesting a more direct approach to estimating crop water requirements such a one-step method or direct PM (Monteith 1985). Shuttleworth derived a Penman-Monteith based, one-step estimation equation that allows for different aerodynamic characteristics of crops in all conditions of atmospheric aridity to estimate crop ET from any crop of a specified height using standard 2-m climate data (Shuttleworth 2006). Not everyone agrees that the concept can adequately account of surface soil water conditions. Shuttleworth called for field studies to address the problem of effective values for surface resistance for different crops equivalent to that for crop coefficients. Shuttleworth and Wallace summarized a detailed study that was conducted in Australia using the one-step approach (Shuttleworth and Wallace 2009). I am not aware of any specific applications that have been made in the U.S. In the second edition of Manual 70 we have a chapter on Direct Penman-Monteith method.

The first edition of Manual 70 is out of print. In 2000, the ET committee decided to have a technical committee prepare a second edition. Marv Jensen and Rick Allen were designated co-chairmen. Other members were Terry Howell, Derrel Martin, Rick Snyder, and Ivan Walter. The second edition has been completely restructured. We are near having a final draft ready for review by ASCE committees. I hope that this can be completed this year.

Major progress on developing improved methods of estimating ET was made during the past third of a century because of the efforts of many Europe and U.S. individuals. Some are R. Feddes and W. Bastiaannsen in the Netherlands, L. Pereira in Portugal, and M. Smith with FAO who led the FAO effort. Many individuals in the U.S. were major contributors to ET development technology. Some of these are Rick Allen, Terry Howell, Bill Pruitt, Joe Ritchie, Rick Snyder and Jim Wright. Bill Pruitt measured ET in weighing lysimeters near Davis California along with detailed weather data for many years. His technical guidance and data were very valuable in the development of new technology. Jim Wright measured ET from various crops using a weighing lysimeter at Kimberly, ID over an eight year period and he developed the concept of the *basal crop coefficient* representing conditions when soil evaporation is minimal and most of the ET is transpiration (Wright 1982). Wright's measured data were also used to refine net radiation and crop coefficients.

Summary and Conclusions

This brief paper summarizes a century of progress in the development of modern methodology for accurately estimating daily and hourly evapotranspiration. Why did this process take so long? Evaporation from soil and plant services is a complex process involving plants, soils, local weather data like wind speed and humidity, solar and long-wave radiation. Its developments involved many disciplines. It's only been 200 years since hydrologic principles were first understood and described by Dalton so perhaps a century is not that unreasonable.

Most of the progress in developing new methodology in the U.S. was made during the last third of a century. Many scientists and engineers were involved in the evolution of ET-estimating technology. Scientists and engineers in Europe have also been instrumental in advancing the technology. In this paper, I tried to highlight major contributions of people many of whom I knew personally or at least had met them briefly. My involvement in the process of development better ET estimating technology and association with other engineers and scientists was a learning experience. It started me on a very rewarding career path. The experience that I gained working leading scientists and engineers over the past half century has been very rewarding personally. If I have emphasized my involvement too much it's because I have been associated with the development of ET estimating methods for the past 50 years. More detail on progress in measuring and modeling EY can be found in a review paper by Farahani et al. (2007).

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