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Title:
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Date:
2016-11-01

Citation:
McMahon, T. A., Finlayson, B. L. & Peel, M. C. (2016). Historical developments of models for estimating evaporation using standard meteorological data. Wiley Interdisciplinary Reviews Water, 3 (6), pp.788-818. https://doi.org/10.1002/wat2.1172.

Persistent Link:
https://hdl.handle.net/11343/123756

Historical developments of models for estimating evaporation using standard meteorological data

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Abstract

Evaporation plays a key role in the hydrology of a catchment. World-wide actual terrestrial evaporation is approximately 2/3 of terrestrial precipitation. Evaporation is the focus of this study in which we describe the historical developments of models for estimating evaporation from standard meteorological data. Although Aristotle and Descartes made early contributions to understanding evaporation, Perrault is credited with having made the first experimental measurement of evaporation in about 1674 though in fact what he measured was sublimation by recording the loss of weight of a block of ice through time. In 1686 Halley carried out the first direct measurement of the evaporation of liquid water. Following a detailed set of experiments, Dalton in 1802 published an essay describing the relationship between evaporation, vapour pressure deficit and wind speed which is the forerunner of the mass-transfer equation to estimate open-water evaporation. In 1921, Cummings proposed an approximate energy balance equation which in 1948 Penman combined with a mass-transfer equation based on Dalton's work to develop the Penman equation. A key input was the Bowen ratio published in 1926. Following Penman, the next major development was by Monteith in 1965. He modified Penman's equation for a single leaf to deal with a canopy which led to the Penman-Monteith model and is the basis of the FAO56 Reference Crop model. Priestley and Taylor introduced their model in 1972, which is based on the energy

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/wat2.1172

term in Penman's equation, and underpins other models. The application of the Complementary Relationship to estimating regional evaporation is credited separately to Brutsaert and Stricker and to Morton. Budyko offered two important contributions. Firstly, he developed a potential evaporation equation in which the evaporating surface temperature was estimated by iteration, whereas Penman approximated a value from the Clausius-Clapeyron equation. Budyko's second contribution is a simple relationship to estimate runoff and, in turn, mean actual evaporation.

Keywords: evaporation; historical review; evaporation models; actual evaporation; potential evaporation; reference evaporation; open-water evaporation.

1 Introduction

Evaporation plays a key role in the hydrology of a catchment. World-wide actual terrestrial evaporation is approximately 2/3 of terrestrial precipitation.[1,2] Compared with streamflow and precipitation, the magnitude of actual evaporation is more difficult to measure directly in the field or to estimate by computation based on standard meteorological observations. This paper deals with the latter aspect and examines the development of the estimation of evaporation through mathematical models using readily available meteorological measurements. Although the first evaporation formulation can be attributed to Dalton[3] in 1802, this review examines our understanding of evaporation from classical times through to the present day.

The objectives of this paper are:

- to provide an account of the development of evaporation equations that use standard meteorological data to estimate annual, monthly or daily actual (terrestrial, open water and deep lake), potential, reference crop and pan evaporation;
- to understand the history of the development of key models in order to appreciate their form and, therefore, their potential use; and
- to outline where, and by whom, the models were developed in order to appreciate their applicability across space and time scales.

Our review includes models that are based mainly on standard meteorological data (radiation, temperature, vapour pressure and wind). For deep lakes water temperature data are required and, in some terrestrial models, a vegetation resistance parameter is required. We have also included models that allow mean actual catchment evaporation to be estimated from mean catchment precipitation and runoff known as Budyko-like models[4].

1.1 Defining terms

When explaining the confusion around the terms evapotranspiration and evaporation, Howell and Evett[5] noted that Monteith argued the term evapotranspiration was unnecessary and its components (evaporation and transpiration) were strictly congruous (see appendix of Monteith[6]). However, they also noted that the term evapotranspiration *"is too ingrained in U.S. literature … to move back to a more correct term, evaporation*" (5, page 3). Despite this, we use the term 'evaporation' in this paper to include evapotranspiration except where an author uses the terms 'evapotranspiration' or 'reference (crop) evapotranspiration'.

'Potential evaporation' is considered to be the most confusing of the evaporation terms. Its history begins with Thornthwaite[7] in 1948 who coined the name. Prior to Thornthwaite, Oldekop[8] in 1911, writing in Russian, had suggested the concept of "maximum possible evaporation, only dependent on climate", but had not used the specific term 'potential evaporation'.[9] Penman in 1956(10, page 18) defined potential evaporation "*as the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water".* A decade later van Bavel[11] extended the definition to any surface that imposes no restriction to the evaporation process. In 1983, based on the Complementary Relationship (Section 5.3), Morton[12] introduced 'wet environment areal evapotranspiration' and noted his definition was the same as *"the conventional definition for potential evapotranspiration*"(13, page 29). According to Morton this occurs when the soil-vegetation surfaces are saturated and water supply is unlimited. In 1984, McIlroy[14] (confirmed by Garrett[15]) brought together the elements of the definition of potential evaporation: maximum possible evaporation from leaves and soil surfaces where the air-surface interface is saturated and the environmental state is specified by net surface radiation, soil heat flux, aerodynamic resistance and vapour pressure deficit. In discussing potential evaporation from a forest, Byrne et al.[16] noted that r_s / r_a (the ratio of surface to aerodynamic resistance) should be set to a minimum to obtain potential evaporation. Potential evaporation is described by Shuttleworth(17, page 4.2) in terms of a "*free water surface under existing atmospheric conditions*" and Granger(18, Table 1) argued there should be constant atmospheric and surface temperature conditions. Dingman(19, page 299) and Lhomme(20, Abstract) observed that the saturated area should be sufficiently extensive to nullify local advection effects. According to Pereira et al.(21, Footnote 2), the term is now reserved "*to represent the ET rate from any nonstressed crop*". In summary, we define potential evaporation as the upper limit of evaporation under constant meteorological and surface temperature conditions from a surface (vegetation, bare soil, or open-water) that is saturated and of such extent to negate effects of local advection.

In order to avoid using the confusing term potential evapotranspiration, Doorenbos and Pruitt[22] in 1977 were among the first researchers to replace the term with 'reference crop evapotranspiration' which they defined as "*the rate of evapotranspiration from an extended surface of 8 to 15 cm tall grass cover of uniform height, actively growing, completely shading the ground and not short of water*"(22, page 4).

'Actual evaporation' occurs from terrestrial environments (including natural and irrigated landscapes) and from water bodies (small and large lakes, both shallow and deep).

With respect to 'open-water evaporation', we include lakes sufficiently shallow that seasonal heat storage can be ignored. Based on a literature review, McMahon et al.[23] concluded that in estimating lake evaporation, shallow lakes are, on average, less than 2 m deep. For deeper lakes, heat storage needs to be accounted for.

The final evaporation term is 'pan evaporation'. This refers to the estimate of water losses from a standard evaporation pan which for many countries is the Class-A pan[24].

1.2 A road map

Figure 1 is an appropriate setting for this paper. It represents as a time-line the key developments in evaporation theory and practice, concentrating on activity during the twentieth century. Our paper follows these developments but with the methodologies from

1948 being reviewed by application rather than by time. The paper is divided into seven sections. Following this introduction, Section 2 identifies recent reviews. Section 3 deals with the pre-Dalton (pre-1800) period in which Perrault influenced our understanding of evaporation. Key developments in the period from Dalton to pre-Penman (1947) are discussed in Section 4. In Section 5 there are seven sub-sections where we describe the developments in evaporation methodology and models from 1948. The models are summarised in Table 1 where those that are discussed in Section 5 are shaded. A general discussion follows in Section 6 and in the Conclusion, Section 7, we summarise the major milestones in this process.

2 Reviews

There have been several reviews and performance comparisons of evaporation models over the past two decades[23,25-44]. In the main these reviews were for specific purposes and were limited either in the range of evaporation models considered or the time period covered in the review. Furthermore, we saw the need to show how evaporation theory has developed from pre-19th century to the present day and to identify the influence that several key researchers have had on present day evaporation estimation techniques using standard meteorological data.

Our review is based on an examination of 166 evaporation models published from 1802 to the present. The details of most of the pre-1910 models were extracted from Livingston's[45] 1909 extraordinary annotated bibliography on evaporation consisting of 850 references. Of the 166 models, 143 are identified in Table 1 (see Table S1, Supplementary Material for model equations) and the remaining 23 are simple mass-transfer equations with different empirical coefficients[19,46-67].

In Table 1 we have categorised the models by year, reference, type, and application. Applications are categorised into six classes: potential evaporation, reference evaporation, actual evaporation in terrestrial environments, open-water evaporation, deep lakes, and pan evaporation. The models in Table 1 are further typed into the following 10 classes: models based on mass-transfer (so-called Dalton equation), temperature models, radiation-temperature models, energy balance methods, single-source (vegetation, soil or water) combination methods, multi-source combination methods, multivariate models, models based on the Complementary Relationship, Budyko-like models, and miscellaneous models. Table 2 is a matrix summary of all 166 models. Table 3 to be discussed later shows the linkages between the 57 models that are closely connected to Penman-1948, Penman-Monteith or Priestley-Taylor. Some observations about the contents of the tables are presented in Section 6.

3 Pre-Dalton (pre-19th century)

"*All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come; thither they return again*". Ecclesiastes 1:7

There are many discourses available in the literature that describe beliefs about evaporation, and hydrology in general, in classical times[68-71]. Middleton(69, page 2) puts this material into perspective when he states: "*Probably everything written about the hydrometeors before the seventeenth century should be classified as speculation rather than theory.*". The English word 'evaporation' is derived from the Latin 'evaporare', to disperse in vapour[72]. Klein[72] also reports uses of the word in its modern meaning from as early as 1567.

Despite the extensive writing that referred to hydrology and provided insights into the state of knowledge on the subject in classical times, it is mainly through the writings of Aristotle that this material, or at least some version of it, made its way into the scholarly works of the late Middle Ages when his works were rediscovered. They were highly influential in driving scientific thought until the late seventeenth century[68]. Brutsaert argues that the dominance of Aristotle's theory of two exhalations, in which heat is claimed to drive evaporation and wind has no effect, since Aristotle did not consider wind to be moving air, was a setback to the development of understanding of evaporation in this period[68].

While the two exhalations theory of Aristotle was not universally accepted by his contemporaries, Aristotle's writings were rediscovered in the 12th century and became very influential. It was the French polymath Rene Descartes who provided the basis to break away from the concepts of Aristotle with the publication of his book "The Meteors" in 1637[73]. Petrescu summarises the approach taken by Descartes as: "*....Descartes wanted to publish a sample of non-scholastic physics that uses mechanical explanations instead of hylomorphic* *notions*."(74, page 25) Here, the hylomorphism is central to Aristotle's philosophy of nature, consisting of two intrinsic principles of qualities and substantial forms.

In 1974 UNESCO, the WMO and the IAHS hosted a conference in Paris entitled "Three Centuries of Scientific Hydrology"[75]. This places the start of scientific hydrology at 1674. The only indication in the conference publication of why this date was chosen is given by Dumitrescu and Nemec[76], who, in their chapter in the conference proceedings, state that scientific hydrology began with the publication of Perrault's "De l'origine des fontaines" (On the origin of springs) in 1674[77]. Perrault's book was published anonymously and Nace ascribes this to the authoritarian intellectual climate of the time under which it could be considered heresy to differ from the prevailing orthodoxy, even on scientific matters[71]. In about 1674 Perrault made estimates of the rainfall in the area drained by the Seine and the flow of the river and showed that there was more than enough rainfall to provide the flow in the river. It is this, along with his clear description of the hydrological cycle, that places him at the start of scientific hydrology.

Perrault (1611-1680) is credited with having made the first experimental measurement of evaporation, though in fact what he measured was sublimation by recording the loss of weight of a block of ice through time. His description of the process of evaporation explains his choice of experiment: "*Although Aristotle and all the other Philosophers give only one cause for the evaporation of water, namely heat, I could find two more, the one cold, its opposite, and the other the movement of the parts of the air*."(77, page 110) As Nace points out, cold and heat were perceived at this time as separate entities[71]. Perrault described the particles involved as rising and separating without changing and in this he preceded Lavoisier by 100 years in identifying water as a chemical compound that was consistent in whatever state it occurred[71].

Perhaps the first direct measurement of the evaporation of liquid water was carried out by Edmund Halley in 1686 when he measured the loss of water from a heated pan[78]. He placed a pan of water over hot coals and heated it to the temperature of the air in summer and measured the loss of water by evaporation by measuring the change in the weight of the pan. From this he made a number of reasonable deductions about the water balance of the oceans. In a subsequent paper[79] he gave an account of how heat drives evaporation by heating the atoms of water so that they become less dense than the air and rise, proceeding to say that as they cool they will then descend as rainfall.

Halley then extended his analysis of evaporation with an experiment, the results of which he presented in a paper[80] to the Royal Society in 1694. He measured evaporation by recording loss of weight of a pan of water and also recorded the temperature of the water and the atmospheric pressure. Since this appears to be the first example of the measurement of evaporation in something roughly equivalent to modern open pans we present Halley's results here (Figure 2). Halley attempted to shelter his pan from the sun and the wind though his discussion suggests that he was not able to exclude wind entirely. Halley does not identify the temperature scale he used and there were many in use at that time. He also recorded the atmospheric pressure each day, but of course there is no correlation between evaporation and pressure in his data. Interestingly, in a regression analysis of evaporative water loss on temperature (Figure 2), temperature explains 63% of the variance in evaporation. Temperature is therefore shown to be a reasonably good predictor of evaporation though Halley appears not to have explored this possibility. There was a total of 8 inches (203 mm) evaporated in the year of his observations which he considers to be too low, given the amount of rainfall recorded in a year and concludes that the wind must also have a significant effect on evaporation. Modern evaporation (tank) data show that the location of his experiment, Gresham College (London), has an annual evaporation of ~400 mm[81]. Other direct measurements of evaporation soon followed those of Perrault and Halley. For example, the French scientist Sedileau measured rainfall and evaporation for three years at Versailles, from 1688 to 1690, as part of an examination of the water supply to the gardens of the Palace of Versailles[68].

A central component of the discussions about hydrology at this time was the need to account for the Biblical flood, both in terms of the source of the waters that produced the flood and its fate after the flood receded. This led to a belief that the water flowing in rivers had a subterranean source, and could not be explained by rainfall alone. The writings of John Keill, a contemporary of Halley at Oxford, reveal some of this debate, and it is obvious from his work that there was some scepticism developing about the subterranean source of the water in rivers[82]. This, combined with ongoing development of actual measurements as a means of testing these theories, led to an increasing focus on the means of accurately estimating the variables involved, of which evaporation was important as the postulated source of the water in rain.

The eighteenth century saw the development of ideas that had a bearing on the subsequent understanding of the process of evaporation, even though many were not conceived for that purpose. Brutsaert[68] points out that the main issues in the debate about evaporation in the eighteenth century were focussed on matters already present in Halley's paper[79] presented to the Royal Society in 1686. The key issues were: is evaporation a solution process?; that warmer air could dissolve more water; that the air can become saturated with water; that if saturated air cools it precipitates water; and that evaporation causes cooling.

Experimentation similar to that carried out by Halley and his contemporaries continued through the eighteenth century. Dobson[83] measured evaporation over a four-year period (1772-1775) in a manner similar to that of Halley and showed also a close relationship between evaporation and temperature. He considered that the rate of evaporation was a more accurate test of the moisture or dryness of the atmosphere than the quantity of rain. Even at this date, the process of evaporation was generally conceived as the solution of water in air. This aspect of the theorising on evaporation was effectively ended by the experiments of de Luc[84] in 1792 who showed that evaporation in a vacuum chamber proceeded at the same rate as in the air. This was the precursor to the idea of partial pressures of gases in the atmosphere, subsequently formalised as Dalton's Law.

Also during this period there were experiments and discussions about the absorption of heat during evaporation that led to the concept of latent heat. Joseph Black (1728-1799) carried out experiments on latent heat and presented his results at a literary society meeting in the University of Glasgow in 1762 and also included this material in his lectures to students[85]. He did not publish this work himself. Lavoisier also described latent heat in 1777 and it is not clear whether he developed these ideas independently or was familiar with Black's work. Brutsaert ascribes the discovery of the concept of latent heat to Black[68]. Furthermore, in discussing natural evaporation, Black argued that "*… wind greatly promotes natural evaporation …*"(85, page 195).

Dalton has become universally recognised as one of the major figures in the development of theory about evaporation[68,86]. Dalton devoted Essay III of his 1802 paper "*Experimental essay on the constitution of mixed gases*" to evaporation[3]. He begins that essay by refuting the notion that evaporation is a solution process and goes on to summarise what has already been determined about evaporation by others as follows: *"1. Some fluids evaporate much more quickly than others. 2. The quantity evaporated is in direct proportion to the surface exposed, all other circumstances alike. 3. An increase of temperature in the liquid is attended with an increase of evaporation, not directly proportionable. 4. Evaporation is greater where there is a stream of air than where the air is stagnant. 5. Evaporation from water is greater the less the humidity previously existing in the atmosphere, all other circumstances the same."*(3, page 576) He then sets out "*to obtain a true theory of evaporation*"(3, page 577) in terms of the effect of variation in temperature, the evaporability of different fluids, and the effect of humidity in the air. Following a series of experiments where he measured the rate of evaporation by loss in weight using tin pans heated over a fire he concludes that *"the evaporating force must be universally equal to that of the temperature of the water, diminished by that already existing in the atmosphere."*(3, page 581) The water existing in the atmosphere he refers to as the *'force of the vapour'*, effectively relative humidity.

Dalton did not continue work on evaporation but proceeded to turn his attention to chemistry where he made major contributions. Despite this, his work on evaporation can be seen as the progenitor of much that followed in this field.

4 Dalton to Penman (1800 – 1948)

Post Dalton, progress in understanding the evaporation process was slow. In 1867, Symons in referring to the Astronomer Royal's description of meteorology "*as one of the most desperate sciences with which we have to do*"(87, page 9) commented that "*the most desperate branch of this desperate science is evaporation*"(87, page 9).

Dalton's[3] evaporation relationship was expressed as a table rather than an equation. Dines in 1870, as noted by Livingston[45], related evaporation to vapour pressure deficit but it appears that Weilenmann[88] in 1877 was one of the first to derive an equation relating evaporation to vapour pressure deficit and wind speed as follows:

$$E_{OW} = \left[\frac{a}{\Delta + c} (1 + bu) \right] \left(v_a^* - v_a \right) \tag{1}$$

where E_{OW} is the estimate of open-water evaporation, $\left(v_a^* - v_a \right)$ is vapour pressure deficit, v_a^* is the saturation vapour pressure of the air, v_a is the vapour pressure of the air, u is wind speed, Δ is the slope of the saturation vapour pressure curve, and a, b and c are constants. According to Helfrich et al.[89] (see also Sartori[30]), the usual form of the Dalton mass-transfer equation is:

$$E_{OW} = (a + bu)\left(v_s^* - v_a \right) \tag{2}$$

where v_s^* is the saturated vapour pressure at the evaporating surface temperature, and the remaining variables are defined earlier. From our investigation about S of the evaporation models, developed during the past 215 years, are based directly on Dalton's relationship. Nearly all were used to estimate open-water evaporation (Tables 1 and 2).

During the period 1800–1947, the non-Dalton evaporation models were based on aridity analysis, on energy as radiation or degree-days, or on atmospheric turbulence. The models included the aridity-based Budyko-like[4] procedures of Schreiber[90] in 1904 and Oldekop[8] in 1911, the energy model of Cummings and Richardson[91] in 1927 and the degree-days equation of Lowry and Johnson[92] in 1942. Marvin, in 1909, developed a generalised equation more complex than Dalton but concluded that "*further solution ... must be deferred until some new data are available*"(93, page 61).

Thornthwaite and Holzman[94] provide a useful overview of the researches into applying atmospheric turbulence to evaporation processes from about 1920 to 1939. Jeffreys's[95] and Giblett's[96] researches were limited to water bodies, the former examined evaporation as a diffusion process whereas the latter was concerned mainly with how evaporation reduced in large water bodies relative to an upwind location.

The first half of the 20th century was devoted mainly to empiricism as indicated by the large number of Dalton derived equations that had been parameterised. Nevertheless, there were several important non-empirical developments, the key one being the introduction in 1926 of the Bowen Ratio[97 (see also 98-99)] which is defined for a water body as the ratio of the energy used for sensible heat divided by the energy used for latent heat (evaporation):

$$\text{Bowen Ratio } (B) = 0.46 \frac{(T_w - T_a)}{(v_w - v_a)} \frac{P_a}{760} \quad (3)$$

where T_w is the temperature of the air in contact with the evaporating surface (°C), T_a is the temperature of air passing over the water body (°C), v_w is the vapour pressure of the air in contact with water body (mm Hg), v_a is the vapour pressure of the air passing over the water body (mm Hg), and P_a is the atmospheric pressure (mm Hg).

A second development was by Cummings and Richardson[91] (in 1927) who described how lake evaporation could be estimated using the energy balance equation incorporating Bowen's ratio. This method has become known as BREB (Bowen ratio energy balance)[100]. The BREB equation is:

$$E_{DL} = \frac{R_n - S - A_o}{\lambda(1+B)} \quad (4)$$

where E_{DL} is evaporation from a deep lake, R_n is the net radiation at the evaporating surface but at air temperature, S is the rate of heat storage change in the lake, A_o is the heat advected into the lake, λ is the latent heat of vaporisation, and B is the Bowen Ratio.

Because atmospheric turbulence processes were sufficiently understood through the theoretical treatments of Taylor, Prandtl, von Kármán and Rossby (see discussion by Thornthwaite and Holzman[94]), in 1936 Sverdrup[101] was able to provide new insights into the mechanism of evaporation. Both Sverdrup[102] and Millar[103] considered moisture gradients in both laminar and turbulent layers but their analyses were limited by lack of data. Based on the works of Rossby[104], Rossby and Montgomery[105] and Sverdrup[106], in 1939 Thornthwaite and Holzman[94] combined moisture concentration in the atmosphere, wind speed and roughness length for estimating actual evaporation, E_A, through a transfer coefficient:

$$E_A = \frac{K_{von}^2 \rho_a u_2}{\ln\left(\frac{h_2}{h_1}\right)\ln\left(\frac{h_2}{z_0}\right)}\left(q_1 - q_2\right) \qquad (5)$$

where K_{von} is von Kármán's constant, ρ_a is the density of air, u_2 is the wind speed at height h_2, q_1 and q_2 are the moisture contents at levels h_1 and h_2, and z_0 is the roughness coefficient. Thornthwaite and Holzman[94] simplified Equation (5) (the Thornthwaite-Holzman model) to:

$$E_A = \frac{17.1\left(u_2 - u_1\right)}{T_a + 459.4}\left(v_1 - v_2\right) \qquad (6)$$

where u_1 and u_2 are the wind speeds, v_1 and v_2 are the actual vapour pressures, both variables measured at different heights, and T_a is the air temperature.

Over the past 100 years the usual form of the Dalton equation (Equation 2) as a linear function of vapour pressure deficit and wind speed has been progressively modified. Details are provided in Table S1, Supplementary Material. Other than several variations of the wind function, the major developments that occurred were: Sill[107] included variables in the Dalton model to address forced convection; Sartori[108] included the distance for full turbulent flow to develop; Lee and Swancar[109] improved the model by adding an atmospheric stability term; and, McJannet et al.[40] incorporated lake surface area in their open water equation. Because of the empirical nature of these equations, their applicability is site-specific.

5 Penman (1948) to present

According to Howell and Evett(5, page 3) Monteith, in a 1985 keynote address, commented that *"because Penman got the physics right, his formula has provided a basis for many theoretical and experimental studies*". However, it was some years after Penman's 1948 contribution[48] that his research was appreciated. According to Monteith(110, page 2), in 1950 Pasquill[111] wrote "*in view of the restricted empirical basis of the method and the special circumstances of the test, it seems doubtful that the method can be applied with confidence outside the* *circumstances of the test.*" Nevertheless, Penman's equation (Equation 7) underpins many evaporation models (see Table 3 and Section 6). The Penman-48 equation[48] is:

$$E_{OW} = \frac{\Delta}{\Delta + \gamma}\frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma}E_a \tag{7}$$

where Δ is slope of the saturation vapour pressure curve, γ is the psychrometric constant, and λ is the latent heat of vaporisation. $E_a = (a + bu_2)(v_a^* - v_a)$ is considered an estimate of the drying power of the atmosphere. The remaining variables are defined earlier. The E_a equation is similar to Dalton (Equation 2) except that v_a^* (the saturation vapour pressure of air) replaces v_s^* (the saturation vapour pressure at the water surface). The Penman-48 equation is the first combination equation in which a radiation term (1st term in Equation 7) is combined with an aerodynamic component (2nd term).

The post-Penman period was one of embedding the science of evaporation on a solid foundation followed by a range of theoretical analyses that culminated in models that are used to estimate potential evaporation, reference crop evapotranspiration, actual evaporation in terrestrial environments, and evaporation from shallow (open-water) and deep lakes, and evaporation from Class-A evaporation pans. We next explore briefly each of these developments. (The models to be discussed in this section are highlighted by shading in Table 1.)

5.1 Potential evaporation

We define potential evaporation as the maximum evaporation that can occur under constant meteorological and surface temperature conditions in which the evaporating surface (vegetation and/or bare soil, or open-water) is saturated and is large enough to negate local advection effects. Approximately 13% (22 models) of those listed in Table 1 are identified as potential evaporation models (Table 1, column 3), in which temperature and/or radiation are the key variables.

Because of confusion with the term 'potential evaporation', by the mid-1970s the terms reference or reference crop evapotranspiration were adopted in discussions of crop water requirements (see Section 1.1). However, the term potential evaporation is still used under specific circumstances as discussed in Section 5.3. In addition to the Thornthwaite model, the two key potential evaporation models are Penman-Monteith and Priestley-Taylor. These along with other potential evaporation equations are discussed below.

The Thornthwaite method is the most important of five procedures to estimate potential evaporation that are based only on temperature; the others are Blaney-Criddle developments (Blaney-Criddle, Blaney-Criddle-70 and Modified Blaney-Criddle) and the Behnke-Maxey model (Table 1, column 3). The Blaney-Criddle models incorporate a constant which depends on crop type and stage of growth. Unlike many other applications, Thornthwaite[7] developed his equations to estimate *mean monthly* potential evapotranspiration.

Seven potential evaporation models using radiation and temperature have been identified (Table 1, column 3): Makkink, Turc, Jensen-Haise, Stephens-Stewart-P, Camargo-71, Priestley-Taylor, and Makkink-Hansen. Makkink and Priestley-Taylor are similar and incorporate the slope of the saturation vapour pressure curve (at air temperature) with solar radiation, whereas Turc, Jensen-Haise and Stephens-Stewart relate potential evaporation to solar radiation and air temperature. Camargo-71 is based on extra-terrestrial radiation and air temperature. The key model in this group is Priestley and Taylor[112] from 1972:

$$E_P = \alpha_{PT}\left[\frac{\Delta}{\Delta+\gamma}\frac{\left(R_n - G\right)}{\lambda}\right] = \alpha_{PT} E_{Eq} \qquad (8)$$

where G is the heat flux into the ground, α_{PT} is the Priestley-Taylor coefficient, the term in square brackets is known as equilibrium evaporation (E_{Eq}), and the remaining variables are defined earlier.

According to Allen[26] "*Priestley and Taylor (1972) presented a shortened variation of the Penman equation for use in humid regions where advective transport of heat is low*". Priestley and Taylor[112] outlined a general framework for the development of their model where α_{PT} equals 1.26 based on field experiments where there is no advection. An extensive list of α_{PT} values are presented in McMahon et al.(23, Table S8) in which α_{PT} varies from 0.53 to 1.57. In Equation (8), the term equilibrium evaporation (E_{Eq}), a concept developed by Slatyer and McIlroy(113, page 3-73), is related to the equilibrium temperature defined by Edinger et al.(114, page 1139) *"as the surface temperature ... at which the net rate of heat exchange ... would be zero*". Although the Priestley-Taylor equation is an empirical one, de Bruin[115] observed that on a regional basis Priestley-Taylor can be derived by taking into account that evaporation and saturation deficit are dependent variables. According to McNaughton and Spriggs[116] α_{PT} will shift above or below 1 depending on the amount of entrainment of dry warmer air into the planetary boundary layer. Modifications to the Priestley-Taylor approach are offered by Agam et al.[117] and Ding et al.[118].

It should be pointed out that the Makkink[119] model from 1957 is very similar to Priestley-Taylor except that Priestley-Taylor inputs net radiation and Makkink inputs solar radiation. Furthermore, Makkink has two empirical coefficients whereas Priestley-Taylor has only one although Hansen[120] modified the Makkink model to incorporate only one parameter[120,121]. Nearly all references to the Makkink equation quote Makkink[122] which is incorrect. An appropriate reference is Makkink[119] (see McMahon et al.[123]).

As listed in Table 1, column 3, seven single-source combination models have been used to estimate potential evaporation. The Budyko(4, page 198) model uses a recursive approach to estimate the evaporating surface temperature whereas Penman uses a finite difference form of the Clausius-Clapeyron equation for a wet surface[124], to eliminate the unknown surface temperature. Although the McIlroy-P model resembles Penman[48] (which we have classified as an open-water model), McIlroy-P incorporates terms for heat flux into the ground and the albedo of the vegetation, thus with these variables McIlroy-P is considered a potential evaporation model[125].

The Penman-Monteith-P model has the following form:

$$E_P = \frac{1}{\lambda}\left[\frac{\Delta\left(R_n - G\right) + \rho_a c_a \dfrac{\left(v_a^* - v_a\right)}{r_a}}{\Delta + \gamma}\right] \tag{9}$$

where ρ_a is the density of air, c_a is the specific heat of air, r_a is the aerodynamic resistance to water vapour transport, and the remaining variables are defined earlier. Monteith (110, footnote page 8) points out that this equation for estimating the evaporation for a single leaf was first derived by Penman[126] in 1953, although according to Monteith its development is often attributed to himself. It is noted by de Bruin[115] that Rijtema[127] derived a similar formula (the Rijtema model) independently in 1965. Monteith[128] applied Equation (9) in 1965 to estimate evaporation from the vegetation canopy.

Although the van Bavel model is a Penman-48[48] equation with a modified wind function, it is considered a potential evaporation model as it was applied to well-watered alfalfa in a lysimeter. van Bavel[11] concluded the model *"is not only accurate but also practical and generally applicable*". Tegos et al.[129] developed in 2015 a parametric model (known as Parametric) based on the Penman-Monteith-P model incorporating extra-terrestrial radiation and air temperature requiring three regionally calibrated parameters.

5.2 Reference evapotranspiration (crop or grass)

The terms 'reference crop evaporation', introduced by Doorenbos and Pruitt[22], and 'reference evaporation', which appeared in 1985 (Snyder and Pruitt[130]), represents evapotranspiration from a defined vegetated surface. Since the mid-nineteen-seventies, many models to estimate crop (including grass) water requirements have been developed. These are listed in Table 1, column 4 under the headings: temperature, radiation-temperature, combination and multi-variate models. For more detailed reviews, see Allen[26], ASCE[31], Jacobs and Satti[131], Bandyopadhyay et al.[42], Tabari et al.[43] and Samaras et al.[132].

Two temperature-based reference models are Linacre-77V (a simplified version of the Penman model) and PMT. The latter model is a simplified version of FAO56-RC (discussed later in this section) in that solar radiation is a simple function of extra-terrestrial radiation, actual vapour pressure is a function of minimum temperature, and wind speed is fixed at 2 m s^{-1}.[133]

Five of the eight radiation-temperature reference crop procedures are based on Hargreaves research. The Hargreaves-85 model[134] (also known as the Hargreaves-Samani model[135]) is an extension of the Hargreaves radiation model. It is included here as reference evapotranspiration because Hargreaves and Allen[134] pointed out that the model coefficient was based on grass reference evapotranspiration. As well as radiation and temperature, the

Modified Hargreaves model incorporates precipitation and the Improved Hargreaves model of Meek and Phene[136] includes vapour pressure deficit[137]. Of the three non-Hargreaves radiation-temperature models, the Jones-Ritchie model includes only solar radiation and temperature, the Adjusted Turc model incorporates also wind speed, and the FAO24-radiation model, which according to Jensen[37] is based on the Makkink model, requires radiation and air temperature plus humidity and wind speed to evaluate one of the two coefficients. The latter model was updated by FAO56-RC[133] which is described next.

Reference crop evapotranspiration is related to a hypothetical crop of grass or alfalfa. In developing the FAO56-RC in 1998, Allen et al.[133] relied heavily on FAO24-radiation[21]. The successful adoption of FAO56-RC by users and researchers of evaporation models is described by Pereira et al.[21]. In 2000, the ASCE published a similar model (designated here as ASCE-PM) and documented parameters for both short and tall reference crops[31]. The ASCE-PM model is:

$$E_{RC} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T_a + 273} u_2 (v_a^* - v_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{10}$$

where E_{RC} is the reference crop evapotranspiration, C_n and C_d are constants that change with reference type and model time-step, and the remaining variables are defined earlier. In FAO56-RC values for C_n and C_d are fixed at 900 and 0.34 respectively.

The Kimberley-Penman model, which is the earliest (1982) of the nine single-source combination reference crop models (Table 1, column 4), is equivalent to the Penman model except that the wind function is seasonally varying. Following expert consultation over several years, the recommended reference crop model is FAO56-RC in which the reference crop is defined as a short crop 0.12 m high (similar to grass) and a surface resistance of 70 s m^{-1}.[133] The ASCE Task Committee on Standardization of Reference Evapotranspiration adopted this definition and added a tall reference crop 0.5 m high (similar to alfalfa)[31]. For crops other than the standard reference crop, FAO56-RC is regarded as a two-step procedure requiring the reference crop evapotranspiration to be adjusted by a crop coefficient:

$$E_C = K_C E_{RC} \tag{11}$$

where E_C is an estimate of evapotranspiration from a well-watered crop, E_{RC} is the reference crop evapotranspiration and K_C is the crop coefficient. Values of K_C are tabulated in Allen et al.[133].

Another in this group of reference crop models is the Todorovic model[138], which is based on Penman-Monteith-P, and incorporates a canopy resistance r_c that varies with weather conditions. For r_c = 70 s m^{-1}, the model results were consistent with those from FAO56-RC. Valiantzas[139-144] published several models that are simplifications of the Penman-48 and the FAO56-RC models without requiring the input of wind information.

In 2009, Shuttleworth and Wallace[145] proposed the Matt-Shuttleworth model as a one-step model "*on the grounds that this approach is consistent with present-day understanding of the evaporation process*"(145, page 1895). In their approach, they incorporate crop r_s (surface resistance) and the method is recommended for typically arid, windy regions. In their paper[145] they provide values of r_s for a range of crops.

The FAO24-Blaney-Criddle reference grass model is a multi-variate procedure operating at a monthly time-step and has been used world-wide for estimating reference evapotranspiration but as the model has been adjusted for local climate conditions, care is required in its application[146,147].

5.3 Actual evaporation from non-saturated surfaces

Thirty-four models were identified as procedures that estimate actual evaporation and are listed in Table 1, column 5. The key developments are based on McIlroy[113], Penman-Monteith[128] and Priestley-Taylor[112] models, and on the Complementary Relationship[148,12,13]. As well, the seven Budyko-like models[149] are included here.

Penman[150], in 1950, introduced the idea of a drying power relationship in the soil to represent the decrease in actual compared to potential evaporation. In 1965, Monteith[128] explored theoretically the relationship between actual and potential evaporation from leaves and developed the following model (Penman-Monteith-A):

$$E_A = \left[\frac{\Delta + \gamma}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \right] E_P \tag{12}$$

where E_A is an estimate of actual evaporation and E_P is the evaporation from thoroughly wet leaves ($r_s = 0$) (Equation (9)), and the remaining variables are defined earlier.

In the Katerji-Perrier model, Katerji and Perrier[151] estimated the ratio $\frac{r_s}{r_a}$ in Equation (12) by relating it to a ratio $\frac{r^*}{r_a}$ through an empirical procedure where r^* is the critical resistance and can be determined from weather variables. Armstrong et al.[152] questioned whether this minimum reference resistance is always applicable due to plant state changes. In this context we note Dunin and Aston's(153, page 308) comment about surface resistance: "*Surface resistance, which reflects stomatal regulation of water loss by vegetation, varies both diurnally with meteorological conditions and seasonally with phenological development. A further cause for temporal variation in surface resistance involves the supply of soil water for transpiration*".

In the Penman-48[48] model the slope of the saturation vapour pressure–temperature relationship at the temperature of the evaporating surface is estimated at air temperature. To overcome this assumption, Lascano and van Bavel[154] (see also Lascano and Evett[155]) compared the explicit solution of Penman's equation with a recursive one (PenmanR-act model) in which the evaporating surface temperature is estimated. Following Penman[48], McIlroy (Slatyer and McIlroy[113]) developed a combination equation (McIlroy-A) to estimate actual evaporation from standard meteorological data. The difficulty with this model is estimating the wet-bulb temperature depression for a non-saturated evaporating surface(128, page 209). To overcome Penman's linearization of the saturation vapour pressure function, Paw U and Gao[156] and Milly[157] presented more exact non-linear solutions.

Following Penman's[48] approach, in 1989 Granger and Gray[158] developed a combination equation, the Granger-Gray model, utilising the Bowen ratio and the aerodynamic boundary layer-surface roughness equation (see Kalma et al.[159, page 429]) to estimate actual evaporation from non-saturated surfaces. A relative drying power function moderates the potential evaporation resulting in an estimate of actual evaporation.

Verstraeten et al.(160, page 83) observe that "*For sparse canopies, the Penman-Monteith 'big-leaf' approach no longer holds. Under these boundary conditions, soil evaporation must be incorporated in the modelling approach*". As listed in Table 1 (column 5) it is observed that since 1985, eight complex models (Shuttleworth-Wallace, Four-layer, Weighted Penman-Monteith, Clumped three-source, MORECS, Two-layer, Clumped, and n-component canopies) have been developed to deal with actual evaporation from vegetation and soil; evaporation from open-water is included in the Weighted Penman-Monteith model. All seven models are based on the single-source Penman-Monteith model. The basic assumption in Penman-Monteith is that "*there is numerical similarity between bulk stomatal resistance and an integration of component stomatal-resistances in dry conditions*"(161, page 830). These multi-source models are structured somewhat similarly in that the total evaporation is the sum of evaporation from vegetation, soil and water, all appropriately weighted in terms of input energy or area, and is dependent on surface resistance variables of vegetation and bare soil, and on the aerodynamic resistance between soil and vegetation. In this context the warning by Cleverly et al.(162, page 1562) is pertinent: *"Accurate prediction of evapotranspiration E depends upon representative characterization of meteorological conditions in the boundary layer"*.

Another approach to understanding of evaporation processes relates to Bouchet's[148] 1963 Complementary Relationship in which potential and actual evaporation depend on each other in a complementary manner through feedbacks between land and atmosphere:

$$E_A = 2E_{We} - E_{Po} \tag{13}$$

where E_A is actual evaporation, E_{We} is areal potential or wet-environment evapotranspiration, and E_{Po} is point potential evapotranspiration where heat and water vapour have no effect on the overpassing air. The background, development, validity and asymmetry of the Complementary Relationship are beyond the scope of this review. Readers are referred to Seguin[163], Le Drew[164], Morton[165], Granger[18], Lhomme[20], Szilagyi[166], Ramírez et al.[167], Ozdogan et al.[168], Lhomme and Guilioni[169], Szilagyi[170], Pettijohn and Salvucci[171], Yu et al.[172], Huntington et al.[173] and Brutsaert[174] for details.

Over two decades, starting from about 1965, F.I. Morton developed three models based on the Complementary Relationship to estimate actual catchment evapotranspiration, shallow lake evaporation and deep lake evaporation[12,13,175]. The CRAE (Complementary Relationship Areal Evapotranspiration) model estimates actual catchment evaporation. This model is based on modified versions of Penman[48] and Priestley and Taylor[112] models. A key element is that the temperature of the evaporating surface is estimated. Furthermore, Morton(12, page 25) did not incorporate wind because its inclusion "*does not significantly reduce error*" in evaporation estimates, a view adopted by Cummings[175] in 1921 (see Cummings and Richardson[91]). Morton used a global set of catchments and lakes to calibrate his models. The CRAE model was extensively tested by Morton[12] and, independently, by others (for example, Hobbins et al.[177]).

In 1979, Brutsaert & Stricker[178] substituted the Priestley-Taylor and Penman equations into E_{We} and E_{Po} of Equation 13 respectively. Hobbins et al.[177] tested the Brutsaert-Stricker method and found it slightly underestimated actual evaporation. Szilagyi and Jozsa[179] and Szilagyi[170] (Szilagyi-Jozsa model) followed the Brutsaert & Stricker[178] approach but evaluated the Penman equation using an iteratively estimated equilibrium temperature of the evaporating surface. Testing indicated the model performed better than the Brutsaert-Stricker model. In 2014, Szilagyi[180] argued that because Priestley-Taylor was parameterised under humid conditions, a temperature correction is required to avoid over-estimating evapotranspiration. In the Modifed A-A model of 2010, Crago et al.[181] modified the Brutsaert–Stricker model by 1) estimating the relative humidity from minimum temperature rather than from observed humidity data; and 2) replacing Penman's aerodynamic component with a term based on Monin-Obukhov similarity theory[182] incorporating $K_{von}B_H^{-1}$ where B_H is the Stanton number[183].

Based on the Complementary Relationship, Han et al.[184] proposed a variation of the Granger-Gray and Brutsaert-Stricker models, designated as the Granger A-A model. Initial testing of the model suggests it effectively expresses the relationship between E_{Act} / E_{Pen} and E_{Rad} / E_{Pen} where E_{Act} is actual evaporation, E_{Pen} is Penman's 1948 evaporation, and E_{Rad} is the Penman radiation term. Han et al.[185] extended the previous development and proposed a nonlinear function approach for the normalized Complementary Relationship evaporation model. Anayah and Kaluarachchi[186] evaluated the Morton CRAE, Brutsaert-Stricker and Granger-Gray models at 34 world-wide FLUXNET sites and concluded that a variation of the Granger-Gray model designated as GG18 "*showed a step forward toward predicting ET in large river basins with limited data and requiring no calibration*".

Following Zhang et al.[187], the seven Budyko-like models (Schreiber; Oldekop; Turc-Pike; Budyko-annual; Fu-Zhang; Zhang; Potter-Zhang listed in Table 1, column 5), which were developed to estimate mean catchment runoff, can be used to estimate mean catchment evaporation. These simple equations, based on mean precipitation and the aridity index, provide plausible estimates of mean catchment runoff and, therefore, mean actual catchment evaporation.

5.4 Open-water, shallow lake and pond evaporation

Approximately 30% of the evaporation models were developed to estimate open-water evaporation (Table 1, column 6). Again, the key model is Penman[48] although the majority of the open-water models are based on a mass-transfer approach. Ferguson's 1952 contribution[188] to estimating open-water evaporation using a mass-transfer approach is especially innovative in that he combined the heat and mass-transfer equations through a relationship between the heat and the mass-transfer coefficients[189].

Five radiation-temperature models – Lane, Stewart-Rouse and de Bruin-Keijman[190] (the latter two are based on Priestley-Taylor), Linacre-92 and Linacre-93 models[191] (the latter two are based on Penman-48) – were identified to estimate open-water evaporation. The first three models are calibrated to meet field observations.

The Penman[48] equation with the Penman[10] 1956 wind function is the major development in open-water evaporation modelling using a combination equation. According to Allen[26], there were enhancements to Penman's wind function (Penman and Long[192]; Monteith[128]; van Bavel[11]) and the incorporation of the resistance formulations into the equation (Monteith[128]; Thom and Oliver[193]). In 2006, Valiantzas[139], making a series of assumptions, was able to simplify Penman-48 to an expression that does not include wind, producing the Valiantzas-OW model.

According to Sellers[194], the main difference between the Budyko[4] and Penman[48] procedures for computing evaporation is that Penman eliminates the surface temperature by adopting air temperature whereas in 1956 Budyko(4, page 198 in the English translation) used a trial and error technique to estimate the temperature of the evaporating surface. We have identified two other procedures that follow a trial and error approach, Ferguson[188] (discussed above) and the PenmanR-ow model. The iterative solution adopted in the latter model follows Lascano and van Bavel[154] in which the Murray[195] equation is combined with the Penman-48 model.

Because the characteristics of radiation absorption and vapour pressure between land and water are different, Morton[13] converted the CRAE model to the Morton CRWE (Complementary Relationship Wet-surface Evaporation) model by adjusting the empirical coefficients in a stability factor term and two other coefficients in computing open-water evaporation.

5.5 Lake evaporation where heat storage is taken into account

The difference in estimating evaporation from a deep lake compared with open-water (shallow lake) is that the heat storage in the lake must be taken into account. A deep lake tends to take up heat during the hotter months and release it as latent heat during the cooler months, resulting in a seasonal phase shift in evaporation. Models in this category are listed in Table 1, column 7.

According to Chow[70], Schmidt[196] in 1915 was the first to apply an energy balance to estimating evaporation from a water surface (ocean). Cummings and Richardson[91] were early contributors (1927) to estimating lake evaporation by energy balance utilising the Bowen ratio to account for the unknown sensible heat variable. Two studies that illustrate the energy balance method incorporating the Bowen ratio are Lake Hefner[197] and Lake Mead[198]. The Anderson model used in the Lake Hefner study is:

$$E_{DL} = \frac{R_s - R_{os} + R_{il} - R_{ol} - Q_{bs} + Q_v - Q_x}{\rho_e\left[\lambda(1+B) + c_w(T_e - T_b)\right]} \tag{14}$$

where R_s is the incident shortwave solar radiation, R_{os} is the reflected shortwave solar radiation, R_{il} is the incident long wave radiation from the atmosphere, R_{ol} is the reflected longwave radiation, Q_{bs} is the longwave radiation emitted by the lake, Q_v is the net energy advected by streamflow, groundwater and precipitation, Q_x is the change in stored energy, λ is the latent heat of vaporisation, c_w is the specific heat of water, ρ_e is the density of evaporating water, T_e is the temperature of the evaporated water, T_b is the reference base temperature, and B is the Bowen ratio. Variations of the energy balance method were developed by Webb[199] (Lake Eucumbene, New South Wales) and Lenters et al.[200] (Sparkling Lake, Wisconsin).

Of the six single-source combination models to estimate lake evaporation, five models – Weather Bureau, Kohler-Parmele, Keijman, Vardavas-Fountoulakis and Finch – are based on the 1948 Penman model, whereas the McJannet procedure is based on the Penman-Monteith model. The contribution of Kohler and Parmele[201] was to add a term to the Penman equation to account for net water-advected energy and the change in energy stored in the lake. In the Vardavas-Fountoulakis model the change in heat storage was added to the net radiation and the coefficients in the Penman wind function were based on four Australian reservoirs[202].

The concept of equilibrium temperature (see Section 5.1) appears to have been first introduced to the estimation of evaporation from large water bodies by Edinger et al.[114] in 1968 and applied by Keijman[203] and Fraedrich et al.[204]. In the Keijman model to estimate lake evaporation, the Penman equation was modified by incorporating the heat capacity of the water layer, assuming the lake was not thermally stratified, and then combined with the Bowen ratio to estimate the daily equilibrium temperature and the daily water temperature. The model uses only standard meteorological data. To account for heat storage, in 2001 Finch[205] also adopted the equilibrium temperature concept in the Finch model in which he follows Keijman[203] and de Bruin[206]. Because the estimation of equilibrium temperature is not explicit, the procedure is not regarded as a simple, quick method. Based on the 1965 Penman-Monteith model and applying the equilibrium temperature concept, the McJannet-PM model[207] offers a method to estimate evaporation not only for deep lakes but also for shallow water bodies. The general approach is similar to Finch[205].

Morton's deep lake model[175] (Morton CRLE model – Complementary Relationship Lake Evaporation) is based on CRWE in which the energy term includes the solar and water inputs for the current and previous months.

5.6 Modelling evaporation pans

Although an evaporation pan is regarded as a crude instrument to measure evaporation[208], Roderick et al.[209] commented "*that the pan evaporation record provides the only direct measurement of changing evaporative demand*" which is important in climate change studies. Evaporation pan data have been used in the past to estimate lake evaporation,[210] open-water evaporation,[211] reference evaporation,[133,212,213] and potential evaporation[214] and pan data have also been used in the interpretation of the Complementary Relationship.[167]

In developing a model to estimate Class-A pan evaporation, Linacre[215] in 1994 modified his simplified version[191] of the 1948 Penman equation and called the model Penpan. A little more than a decade later, Rotstayn et al.[216] combined features of the aerodynamic component of Thom et al.[59] with the radiative component of Linacre[215] to develop another Class-A pan evaporation model known as PenPan. (Readers should note there is a difference between the designations Penpan and PenPan.) Both models have been shown to perform well across a range of climates[23 Supplementary Material,216-218].

5.7 Miscellaneous techniques across all applications

A small number of models have been allocated to this class, and they include two interesting models. The first is a finite difference approach (Finch-Gash model) to estimate evaporation from a lake where there is heat storage[219]. The second interesting model is by de Bruin,[220] who combined the Penman and Priestley-Taylor equations thus eliminating the net radiation term, to yield the de Bruin model from which open-water evaporation can be estimated without recourse to radiation data. de Bruin[220] observed that the model is very sensitive to the value of Priestley-Taylor α_{PT}.

5.8 Interception evaporation

In water balance studies, interception and, therefore, interception evaporation are key processes. A review of the interception process is beyond the scope of this review. Readers are referred to Muzylo et al.[221] and to McMahon et al.[23]. Suffice to say that there are two important interception models, Rutter[222,223] and Gash[224]. Penman[10] is incorporated in the Rutter model and Penman-Monteith is used in the Gash model.

6 Discussion

6.1 Model types

From our analysis, summarised in Table 2, we observe that models based on mass-transfer approaches (35%), single-source combination models (21%) and radiation-temperature models (14%) make up approximately 70% of the evaporation models. Furthermore, more than half the mass-transfer models were found to follow the general form of Equation (2) and, generally, are locally calibrated where field observations of evaporation rates are available. Other models include: those based on the Complementary Relationship (5%) and on temperature alone (5%), multi-source combinations (5%) and Budyko-like models (4%).

6.2 Key modellers and modelling

From the time of Dalton's work (~1800) to the middle of the 20th century, there was little theoretical development in advancing the relationship based on Dalton's work. Analysts adopted an empirical mass-transfer approach in establishing an evaporation equation to fit their data. Nevertheless, several important non-Dalton developments occurred including the Bowen ratio and understanding the evaporation processes through atmospheric turbulence.

But in contrast to that 150 year period, over the past 65 years there has been continuous development of evaporation models in which the works of Penman[48], in 1948, Monteith[128], in 1965, and Priestley and Taylor[112], in 1972, have provided the starting points for development. The Penman combination equation is the basis of many non-Dalton and non-Budyko models. Monteith(110, page 2) wrote that "*The thermodynamic and aerodynamic aspects of evaporation* *were not fully reconciled until, in 1948, Howard Penman published a paper which has become one of the major classics of microclimatology; 'Natural evaporation from open water, bare soil and grass.' The Penman formula was soon adopted by hydrologists and irrigation engineers, but meteorologists were more cautious*". To illustrate the importance of the Penman model in estimating evaporation, Table 3 shows the time-sequence of the Penman, Penman-Monteith and Priestley-Taylor developments. The 56 models listed evolved from Penman and eighteen combination models followed from Penman-Monteith.

Given that the Priestley-Taylor work is the basis of 14 evaporation models (Table 3), it is noteworthy that Monteith[110] argued that the Priestley-Taylor formula was inadequate for two reasons: 1) there is no theoretical explanation why α_{PT} should be approximately constant at 1.26; 2) that the equation "*takes no account of the aerodynamic properties and physiological behaviour of the (evaporating) surface*"(110, page 23). Since the Priestley and Taylor publication in 1972 there have been many measured estimates of α_{PT} ranging from 0.53-1.57(23, Table S8). Also, there have also been a number of theoretical and analytical studies dealing with α_{PT} (20,117,225). For example, according to Pereira[226]

$$\alpha_{PT} = \Omega^{-1} = \left[1 + \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a} \right] \qquad (15)$$

where Ω is termed the decoupling factor[227]. Lhomme[20] concluded that α_{PT} is Hl for a saturated area surrounded by water, Hl.3 for saturated grass surrounded by well-watered grass and is >3 for saturated forest surrounded by forest. The Agam et al.[117] paper illustrated how the Priestley and Taylor model[112] can be applied to modelling a combination of soil and canopy transpiration, the latter being an exponential function of LAI (leaf area index).

Monteith[128] modified Penman's 1953 equation[126] for a single leaf to deal with a canopy. Also he was an early contributor to estimating actual evaporation by adjusting potential evaporation as shown in Equation 12. The Complementary Relationship defined by Equation 13 is the basis of the development of five important models (Brutsaert-Stricker, Morton CRAE, Morton CRWE, Morton CRLE and Szilagyi-Jozsa) to estimate actual evaporation from terrestrial environments and lakes. Both Morton and Brutsaert played key roles in these developments.

6.3 Temperature of evaporating surfaces

For more than 50 years, attempts have been made to estimate computationally the temperature of an evaporating surface. Penman bypassed this issue by assuming the slope of the vapour pressure-temperature curve could be computed using the atmospheric temperature rather than the unknown surface evaporating temperature. It is probable that Budyko was one of the first to estimate the surface temperature[194], but Budyko would have been hampered by the lack of computational power to find a solution by iteration. Assuming there is no thermal stratification in a lake, Keijman[203] and de Bruin[206] used an equilibrium temperature (T_e) concept to estimate the surface water temperature. Morton[12] approached the problem by equating the energy-balance and the vapour transfer equations and solving iteratively for T_e. With small variations, Finch[205] and McJannet et al.[207] followed the same approach as de Bruin[206] and Keijman[203] to estimate the equilibrium surface temperature. Finally, Szilagyi and Jozsa[179] in their model used an iterative procedure based on the Bowen ratio to estimate T_e.

6.4 Reducing input data

Continuing attempts have been made to reduce the number of variables and hence meteorological data required to estimate evaporation by the Penman or Penman-Monteith models. Linacre developed four models - Linacre[228] for both lakes and well-watered vegetation, Linacre[191] for lakes, Linacre[215] for a class-A evaporation pan. Valiantzas[139] produced two models, one for a reference crop and the other for open-water. These models perform satisfactorily, although they have not been extensively tested.

6.5 Model applications

The 166 evaporation models which were surveyed for this review are mainly used for estimating open-water evaporation and estimating actual terrestrial evaporation. Of the 47 models to estimate open-water evaporation listed in Table 1, 15 are non-mass-transfer techniques which offer a wide range of procedures. However, the key methods are Penman-48 and Morton CRWE. In terms of meteorological data, Penman-48 requires the four standard elements (radiation, temperature, humidity, and wind) whereas Morton does not require wind. Although several of the mass-transfer open-water models were probably calibrated to deep lake evaporation, procedures to estimate lake evaporation, where heat storage needs to be accounted for, are based on energy balance, combination models and the complementary relationship. It is recognised that estimating actual terrestrial evaporation is difficult, yet excluding the seven Budyko-like models, 27 models have been developed to estimate actual evaporation. A number of these do require additional information over and above standard meteorological data; for a terrestrial environment, canopy resistance is the main additional data required.

7 Conclusions

Over the past 350 years there have been many researchers who have made significant contributions to the science of evaporation. From this review of 166 evaporation models, we identified several key dates and researchers who have been at the forefront of evaporation modelling. Three dates standout – 1674, 1802 and 1948. The earliest date credits Perrault with being the first to experimentally measure evaporation. The establishment by Dalton of the principles that led to the mass-transfer equation occurred in 1802. In 1921, Cummings proposed an approximate energy balance equation which, in 1948, Penman combined with Dalton's mass-transfer equation to develop the Penman combination equation. A key input in this history is the Bowen ratio[97], published in 1926, which was a year prior to the Cummings and Richardson[91] paper on evaporation from lakes.

Following Penman, the next major development was by Monteith[128] in 1965. He modified Penman's 1953 equation for a single leaf to deal with the canopy which led to the Penman-Monteith model(110, footnote page 8). This model is the basis of the FAO56 Reference Crop model and ASCE standardized Reference Evapotranspiration Equation. 1972 saw the introduction of the Priestley and Taylor model which underpins a number of subsequent models.

Although Morton introduced the application of the Complementary Relationship to estimating regional evaporation in 1965, his final model was not published until 1983. In the meantime, more than a decade earlier, Brutsaert and Stricker provided an equation to estimate actual regional evaporation using the Complementary Relationship.

Budyko made two important contributions. Firstly, he developed a potential evaporation equation, similar to Penman's combination equation, in which the temperature of the evaporating surface was estimated by iteration. Budyko's second contribution relates to the Budyko-like models where he developed a simple relationship to estimate runoff and in turn mean annual actual evaporation.

The time-line in Figure 1 highlights these contributions.

Acknowledgements

Murray Peel is the recipient of an Australian Research Council Future Fellowship (FT120100130). We are grateful to our colleague, Justin Costelloe, who pointed out the quotation from Ecclesiastes 1:7.

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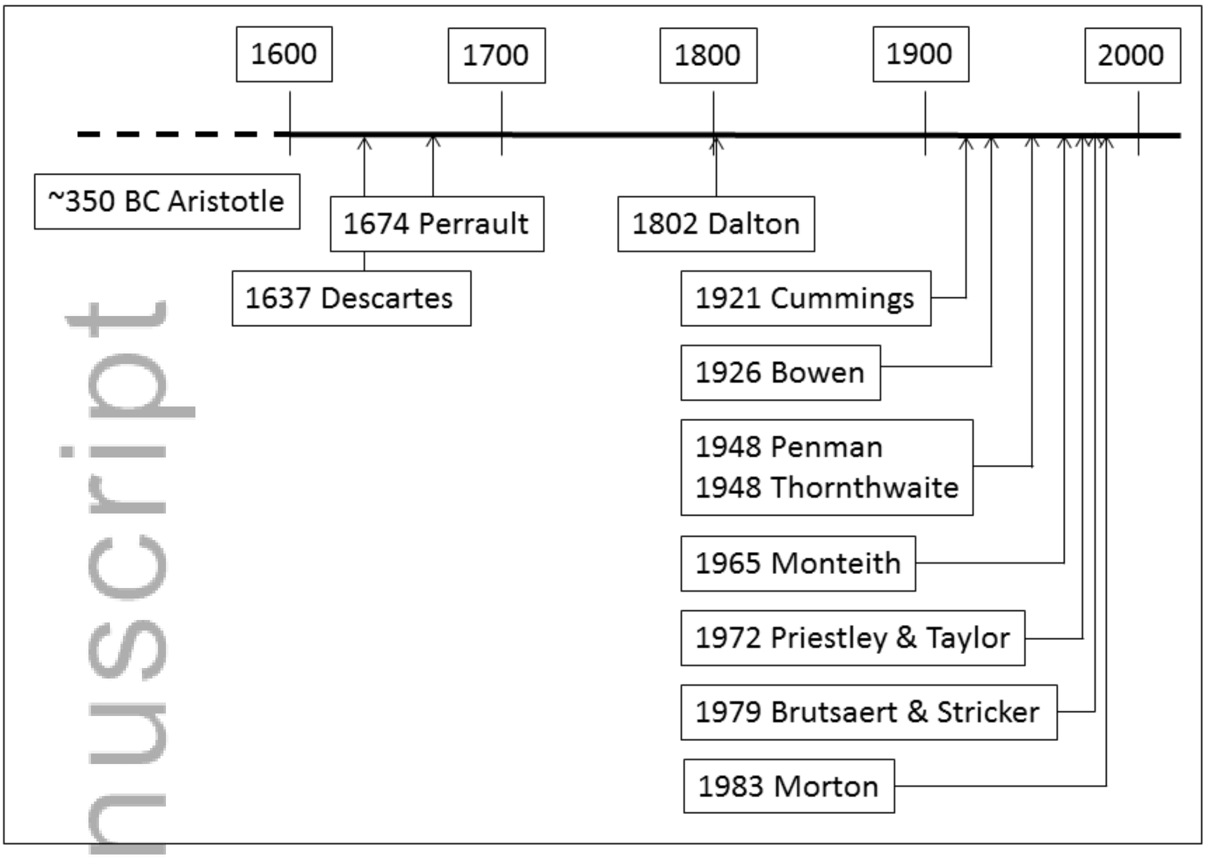
Figure Legends

Figure 1. Time-line showing key evaporation and modelling processes. (Specific references to these contributors are noted in the text and listed in the reference list.)

Figure 2. The relation between evaporation and temperature in Edmund Halley's evaporation data for the year 1693. The temperature scale used is not known but appears to have the freezing point of water at 0° and based on mid-summer temperatures in London[81] the upper end of his data would be ~20°C. 1 grain = 0.065 grams. (Source of data: Halley, 1694)[80].



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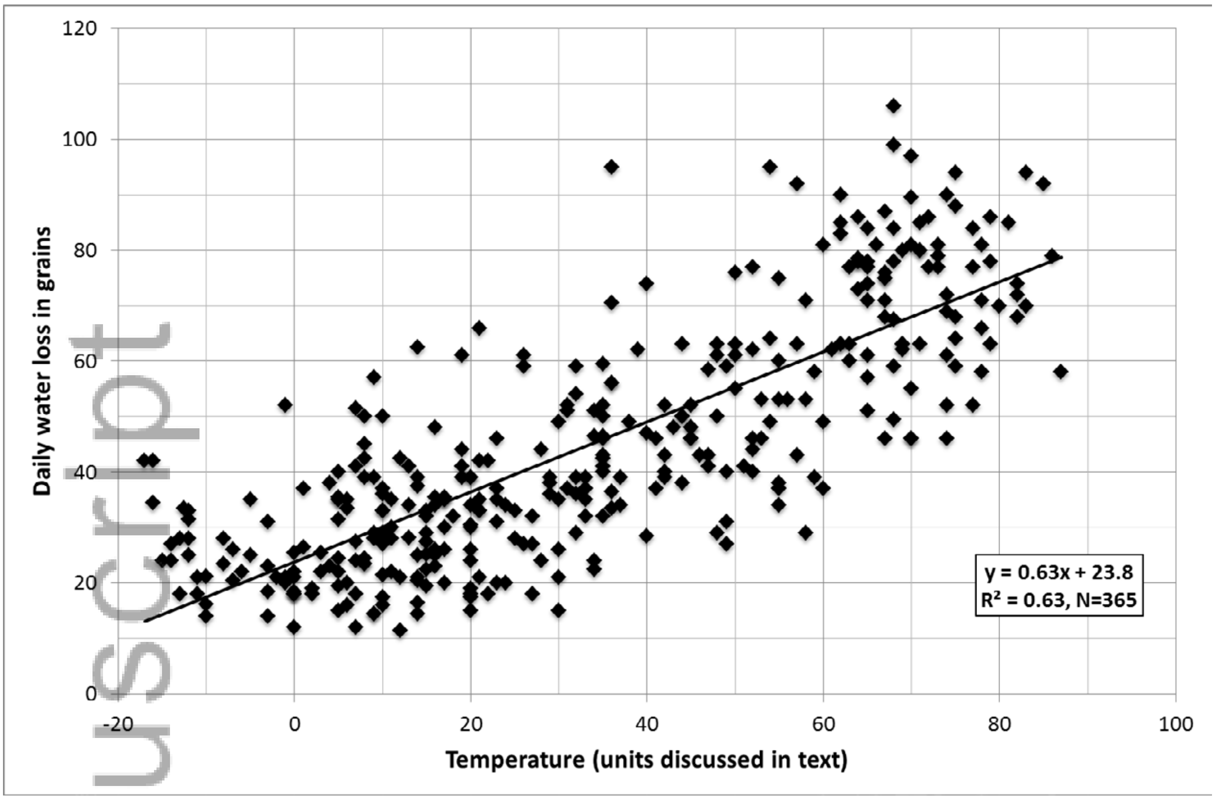

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Table 1. List of 143 evaporation models categorised by type, application and date (This list does not include 23 simple mass-transfer equations with different empirical coefficients. Models highlighted as shading are discussed in Section 5. A more complete set of references to the models and the relevant equations are listed in the Table S1, Supplementary Material).

Year (1)	Reference (2)	Potential Evaporation (3)	Reference (grass, crop) and related evapotranspiration (4)	Actual evaporation from non-saturated surfaces (5)	Open water, shallow lake and pond evaporation (6)	Lake/storage (heat storage explicitly accounted) evaporation (7)	Class-A pan or other (8)
Models based on mass-transfer (Dalton's relationship)							
1802	Dalton (1802)[3]				Dalton		
1871	Livingston (1909)[45]				Mann		
1877	Livingston (1909)[45]				Weilenmann		
1880	Livingston (1909)[45]				Masure		
1886	Rohwer (1931)[229]				Fitzgerald		
1889	Rohwer (1931)[229]				Carpenter		
1896	Livingston (1909)[45]				Trabert		
1902	Livingston (1909)[45]				Schwalbe		

1909	Marvin (1909)[93]				Marvin		
1919	Rohwer (1931)[229]				Horton		
1921	Giblett (1921)[96]				Giblett		
1931	Rohwer (1931)[229]						Rohwer
1937	Marciano & Harbeck (1954)[230]				Sverdrup-37		
1937	Marciano & Harbeck (1954)[230]				Millar		
1939	Thornthwaite & Holzman (1939)[94]			Thornthwaite-Holzman			
1946	Marciano & Harbeck (1954)[230]				Sverdrup-46		
1952	Ferguson (1952)[188]				Ferguson		
1955	Bormann (2011)[39]				Haude		
1955	Kohler et al. (1955)[210]						Kohler
1957	Helfrich et al. (1982)[89]				Rimsha-Donchenko		
1958	Harbeck & Kohler				Lake Mead-58		

	(1958)[231]	
1960	Webb (1960)[199]	Webb
1962	Harbeck (1962)[232]	Harbeck
1963	Bormann (2011)[39]	Brockamp-Wenner
1968	Singh & Xu (1997)[28]	Konstantinov
1969	Helfrich et al. (1982)[89]	B-G-G
1973	Helfrich et al. (1982)[89]	Ryan-Harleman
1975	Helfrich et al. (1982)[89]	Weisman
1976	Helfrich et al. (1982)[89]	G-S-McC
1983	Sill (1983)[107]	Sill
1983	Szeicz & McMonagle (1983)[233]	Szeicz-McMonagle
1989	Sartori (2000)[30]	Sartori
1994	Sartori (2000)[30]	Hahne-Kuber
1997	Lee & Swancar (1997)[109]	Lee-Swancar
2012	McJannet et al. (2012)[40]	McJannet-OW

Temperature models							
1945	Blaney & Criddle (1962) [234]	Blaney-Criddle					
1948	Thornthwaite (1948) [7]	Thornthwaite					
1969	Behnke & Maxey (1969) [235]	Behnke-Maxey					
1970	Nichols et al. (2004) [236]	Blaney-Criddle-70					
1977	Linacre (1977) [228]				Linacre-77W		
1977	Linacre (1977) [228]		Linacre-77V				
1994	Feddes & Lenselink (1994) [237]	Modified Blaney-Criddle					
1998	Allen et al. (1998) [133]		PMT				
Radiation-temperature models							
1957	Makkink (1957a) [119]	Makkink					
1961	Alexandris et al. (2008) [238]	Turc					
1963	Jensen and Haise (1963)	Jensen-Haise					

	[239]						
1963	Stephens & Stewart (1963) [240]	Stephens-Stewart-P					
1963	Stephens & Stewart (1963) [240]						Stephens-Stewart-pan
1964	Cruff & Thompson (1967) [241]				Lane		
1971	Camargo & Camargo (2000) [242]	Camargo-71					
1972	Priestley and Taylor (1972) [112]	Priestley-Taylor					
1973	Davies & Allen (1973) [243]			Davies-Allen			
1975	Hargreaves (1975) [244]		Hargreaves radiation				
1976	Stewart & Rouse (1976) [245]				Stewart-Rouse		
1977	Doorenbos and Pruitt (1977) [22]		FAO24-radiation				

1979	de Bruin & Keijmann (1979) [190]				de Bruin-Keijman
1979	Barton (1979) [246]			Barton	
1984	Hansen (1984) [120]	Makkink-Hansen			
1985	Hargreaves & Allen (2003) [134]; Hargreaves & Samani (1985) [135]		Hargreaves-85 (also designated as Hargreaves-Samani)		
1990	Sahoo et al. (2012; 2013) [247,248]		Jones-Ritchie		
1991	Meek & Phene (1991) [136]		Improved Hargreaves		
1992	Linacre (1992) [249]				Linacre-92
1993	Linacre (1993) [191]				Linacre-93
2002	Droogers & Allen (2002) [250]		Modified Hargreaves		
2009	Trajkovic & Kolakovic (2009) [251]		Adjusted Turc		
2012	Ravazzani et al. (2012) [252]		Modified HS		

Energy balance methods							
1927	Cummings & Richardson (1927)[91]					Cummings-Richardson	
1954	Anderson (1954)[197]					Anderson	
2005	Lenters et al. (2005)[200]					Lenters	
Combination methods – single source models							
1948	Penman (1948)[48]				Penman-48		
1955	Kohler et al. (1955)[210]					Weather Bureau	
1956	Penman (1956)[10]				Penman-56		
1956	Lascano & van Bavel (2007)[154]				PenmanR-ow		
1956	Lascano & van Bavel (2007)[154]			PenmanR-act			
1956	Budyko (1956)[4]	Budyko-56					
1960	Slatyer & McIlroy (1961)[113]	McIlroy-P					
1960	Slatyer & McIlroy			McIlroy-A			

	(1961)[113]						
1964	Sellers (1964)[194]	Sellers					
1965	Monteith (1965)[128]	Penman-Monteith-P					
1965	Monteith (1965)[128]			Penman-Monteith-A			
1965	Keijman (1981)[253]	Rijtema					
1966	van Bavel (1966)[11]	van Bavel					
1967	Kohler & Parmele (1967)[201]					Kohler-Parmele	
1974	Keijman (1974)[203]					Keijman	
1982	Wright (1982)[254]		Kimberly-Penman				
1983	Shi et al. (2008)[255]			Katerji-Perrier			
1988	Paw U and Gao (1988)[156]			PawU-Gao			
1989	Granger and Gray (1989)[158]			Granger-Gray			
1991	Milly (1991)[157]			Milly			
1994	Linacre (1994)[215]						Penpan

1996	Vardavas & Fountoulakis (1996)[202]					Vardavas-Fountoulakis	
1998	Allen et al. (1998)[133]		FAO56-RC				
1999	Todorovic (1999)[138]		Todorovic				
2000	ASCE (2000)[31]; Allen et al. (2005)[256]		ASCE-PM				
2001	Finch (2001)[205]					Finch	
2006	Valiantzas (2006)[139]				Valiantzas-OW		
2006	Valiantzas (2006)[139]		Valiantzas-RC				
2006	Rotstayn et al. (2006)[216]						PenPan
2008	McJannet et al. (2008)[207]					McJannet-PM	
2009	Shuttleworth & Wallace (2009)[145]		Matt-Shuttleworth				
2013	Valiantzas (2013c)[142]		Fo-PM (Rs,T,RH)				
2013	Valiantzas (2013c)[142]		Fo-PM (Ra,T,RH)				
2015	Tegos et al. (2015)[129]	Parametric					

2015	Valiantzas (2015)[144]		Fo-HUMID(R_s,T)				
Combination methods – multi-models							
1985	Shuttleworth & Wallace (1985)[161]			Shuttleworth-Wallace			
1988	Choudhury & Monteith (1988)[257]			Four-layer			
1994	Wessel & Rouse (1994)[258]			Weighted Penman-Monteith			
1997	Brenner & Incoll (1997)[259]			Clumped three-source			
1997	Hough & Jones (1997)[260]			MORECS			
2012	Lhomme et al. (2012)[261]			Two-layer			
2012	Lhomme et al. (2012)[261]			Clumped			
2013	Lhomme et al. (2013)[262]			n-component canopies			
Multi-variable models							

1960	Christiansen (1960, 1966) [263, 264]					Christiansen
1964	Christiansen (1966) [264]		Grassi			
1965	Christiansen (1966) [264]					Mehta
1966	Griffiths (1966) [265]					Griffiths
1977	Doorenbos and Pruitt (1977) [22]	FAO24-Blaney-Criddle				
Models based on the Complementary Relationship						
1979	Brutsaert and Stricker (1979) [178]		Brutsaert-Stricker			
1983	Morton (1983a) [12]		Morton CRAE			
1983	Morton (1983b) [13]			Morton CRWE		
1986	Morton (1986) [175]				Morton CRLE	
2007	Szilagyi and Jozsa (2008) [179]		Szilagyi-Jozsa			
2010	Crago et al. (2010) [181]		Modified A-A			
2011	Han et al. (2011) [184]		Granger A-A			

2012	Han et al. (2012) [185]	Han NLF		
2014	Anayah and Kaluarachchi (2014) [186]	GG18		
Budyko-like models				
1904	McMahon et al. (2013) [23]	Schreiber		
1911	Oldekop (1911) [8]	Oldekop		
1954	Pike (1964) [266]	Turc-Pike		
1956	Budyko (1956) [4]	Budyko-annual		
1981	Zhang et al. (2004) [187]	Fu-Zhang		
2001	Zhang et al. (2001) [267]	Zhang		
2009	Potter & Zhang (2009) [268]	Potter-Zhang		
Miscellaneous models				
1908	Bigelow (1908) [269]		Bigelow	
1940	Prescott (1940) [270]			Prescott
1942	Cruff & Thompson	Lowry-Johnson		

	(1967)[241]			
1961	Hamon (1961)[271]	Hamon		
1961	Singh & Xu (1997)[28]		Romanenko	
1966	Reid et al. (1976)[272]	Papadakis		
1967	Eagleman (1967)[273]	Eagleman		
1967	Bormann (2011)[39]		Schendel	
1978	de Bruin (1978)[220]		de Bruin	
2002	Finch & Gash (2002)[219]			Finch-Gash

Table 2. Distribution of types and applications of 166 evaporation models.

Model type	Application						Percentage of total models
	Potential	Reference crop	Actual	Open-water	Lakes/Storage	Pan	
Mass-transfer	0	0	1	55	0	2	34.9
Temperature	5	2	0	1	0	0	4.8
Radiation-temperature	7	8	2	5	0	1	13.9
Energy balance	0	0	0	0	3	0	1.8
Combination-single source	7	9	7	4	6	2	21.1
Combination-multi-source	0	0	8	0	0	0	4.8
Multivariate	0	1	1	0	0	3	3.0
Models based on CR	0	0	7	1	1	0	5.4
Budyko-like	0	0	7	0	0	0	4.2
Miscellaneous	3	0	1	4	1	1	6.0
Percentage of total models	13.3	12.0	20.5	42.2	6.6	5.4	100

Table 3. Linkages between models that are based on or have the same form as Penman, Penman-Monteith or Priestley-Taylor models.

Year	Penman	Penman-Monteith	Priestley-Taylor
1948	**Penman-48**		
1955	Weather Bureau		
1956	Penman-56		
1956	PenmanR-ow		
1956	PenmanR-act		
1960	McIlroy-P		
1960	McIlroy-A		
1965	**Penman-Monteith** →	Penman-Monteith-P	
1965		Penman-Monteith-A	
1965		Ritjema (developed independently of P-M model)	
1966	van Bavel		
1967	Kohler-Parmele		
1972	**Priestley-Taylor** →		Priestley-Taylor
1973			Davis-Allen
1974	Keijman		
1976			Stewart-Rouse
1977	Linacre-77V		
1977	Linacre-77W		
1978	De Bruin		De Bruin
1979	Bruisaert-Stricker		Bruisaert-Stricker
1979			De Bruin-Keijman
1979			Barton
1982	Kimberley-Penman		

1983	Morton CRAE		Morton CRAE
1983	Morton CRWE		Morton CRWE
1983		Katerji-Perrier	
1985		Shuttleworth-Wallace	
1986	Morton CRLE		Morton CRLE
1988		Four-layer	
1989	Granger-Gray		
1993	Linacre-92		
1993	Linacre-93		
1994	Penpan		
1994		Weighted Penman-Monteith	
1996	Vardavas-Fountoulakis		
1997		Clumped three source	
1997		MORECS	
1998		FAO56-RC	
1998		PMT	
1999		Todorovic	
2000		ASCE-PM	
2001	Finch		
2006	Valiantzas-OW		
2006	Valiantzas-RC		
2006	PenPan		
2007	Szilagyi-Jozsa		Szilagyi-Jozsa
2008		McJannet	
2009		Matt-Shuttleworth	
2010	Modified A-A		Modified A-A
2011	Granger A-A		Granger A-A

2012	Han-NLF		
2012		Two-layer	
2012		Clumped	
2013		n-component canopies	
2013		Fo-PM (variations)	
2013	GG18		GG18
2015		Fo-HUMID(Rs,T)	

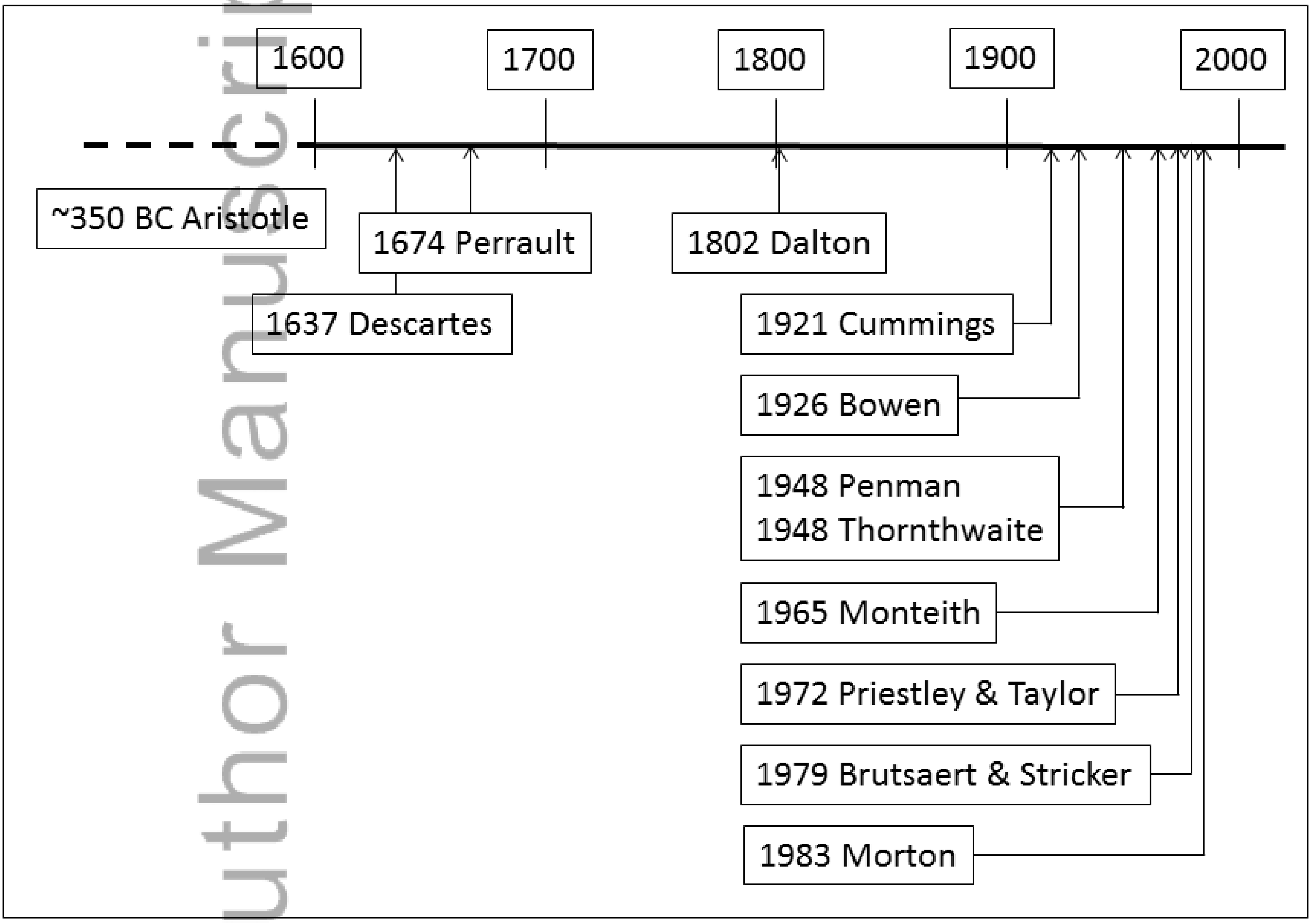
1600
1700
1800
1900
2000
~350 BC Aristotle
1674 Perrault
1637 Descartes
1802 Dalton
1921 Cummings
1926 Bowen
1948 Penman
1948 Thornthwaite
1965 Monteith
1972 Priestley & Taylor
1979 Brutsaert & Stricker
1983 Morton

Figure 1.tif

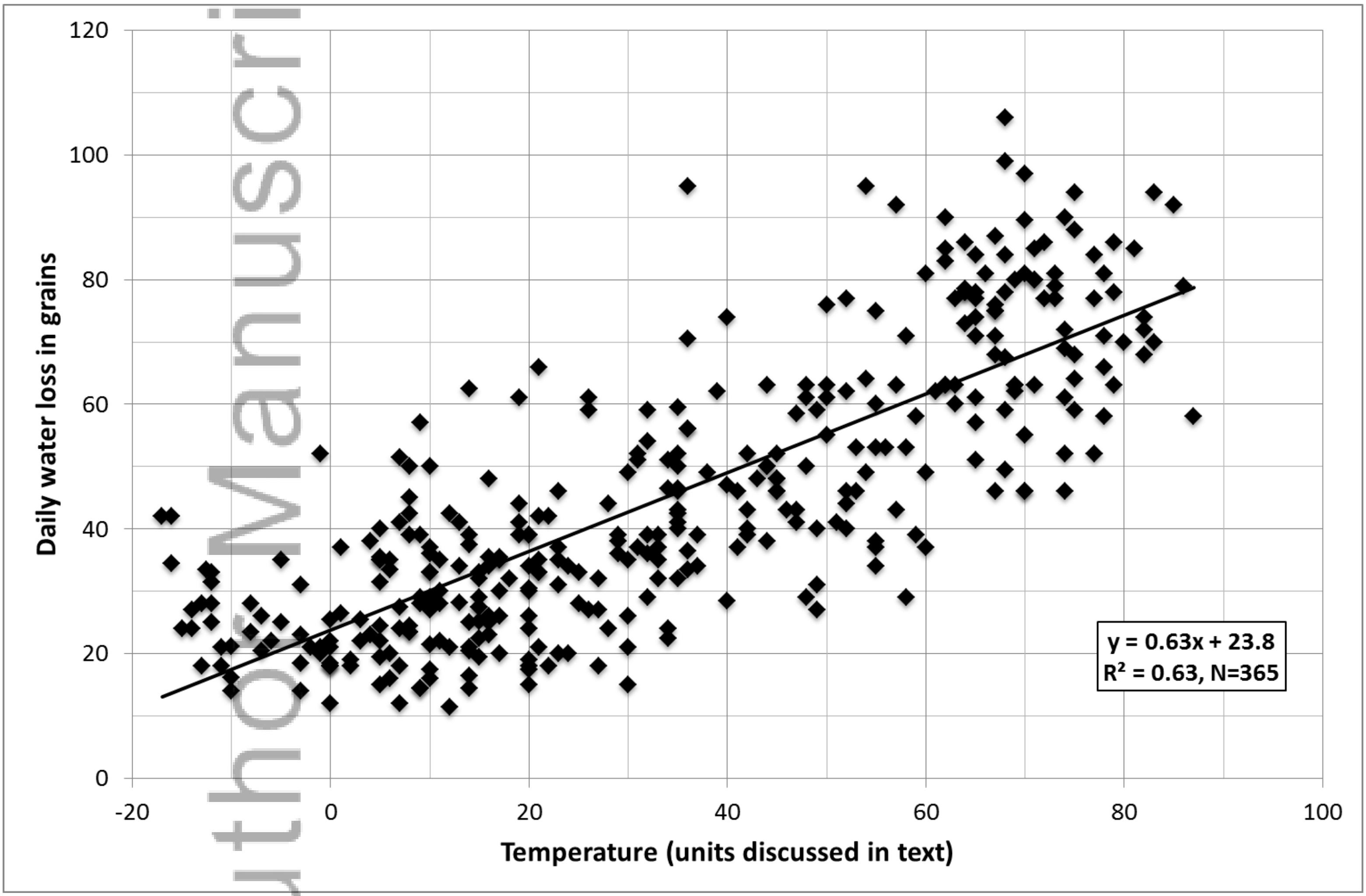
Daily water loss in grains
Temperature (units discussed in text)
120
100
80
60
40
20
0
-20
0
20
40
60
80
100
y = 0.63x + 23.8
R² = 0.63, N=365

Figure 2.tif

Historical developments of models for estimating evaporation using standard meteorological data

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Abstract

Evaporation plays a key role in the hydrology of a catchment. World-wide actual terrestrial evaporation is approximately 2/3 of terrestrial precipitation. Evaporation is the focus of this study in which we describe the historical developments of models for estimating evaporation from standard meteorological data. Although Aristotle and Descartes made early contributions to understanding evaporation, Perrault is credited with having made the first experimental measurement of evaporation in about 1674 though in fact what he measured was sublimation by recording the loss of weight of a block of ice through time. In 1686 Halley carried out the first direct measurement of the evaporation of liquid water. Following a detailed set of experiments, Dalton in 1802 published an essay describing the relationship between evaporation, vapour pressure deficit and wind speed which is the forerunner of the mass-transfer equation to estimate open-water evaporation. In 1921, Cummings proposed an approximate energy balance equation which in 1948 Penman combined with a mass-transfer equation based on Dalton's work to develop the Penman equation. A key input was the Bowen ratio published in 1926. Following Penman, the next major development was by Monteith in 1965. He modified Penman's equation for a single leaf to deal with a canopy which led to the Penman-Monteith model and is the basis of the FAO56 Reference Crop model. Priestley and Taylor introduced their model in 1972, which is based on the energy term in Penman's equation, and underpins other models. The application of the Complementary Relationship to estimating regional evaporation is credited separately to

Brutsaert and Stricker and to Morton. Budyko offered two important contributions. Firstly, he developed a potential evaporation equation in which the evaporating surface temperature was estimated by iteration, whereas Penman approximated a value from the Clausius-Clapeyron equation. Budyko's second contribution is a simple relationship to estimate runoff and, in turn, mean actual evaporation.

Keywords: evaporation; historical review; evaporation models; actual evaporation; potential evaporation; reference evaporation; open-water evaporation.

1 Introduction

Evaporation plays a key role in the hydrology of a catchment. World-wide actual terrestrial evaporation is approximately 2/3 of terrestrial precipitation.[1,2] Compared with streamflow and precipitation, the magnitude of actual evaporation is more difficult to measure directly in the field or to estimate by computation based on standard meteorological observations. This paper deals with the latter aspect and examines the development of the estimation of evaporation through mathematical models using readily available meteorological measurements. Although the first evaporation formulation can be attributed to Dalton[3] in 1802, this review examines our understanding of evaporation from classical times through to the present day.

The objectives of this paper are:

- to provide an account of the development of evaporation equations that use standard meteorological data to estimate annual, monthly or daily actual (terrestrial, open water and deep lake), potential, reference crop and pan evaporation;
- to understand the history of the development of key models in order to appreciate their form and, therefore, their potential use; and
- to outline where, and by whom, the models were developed in order to appreciate their applicability across space and time scales.

Our review includes models that are based mainly on standard meteorological data (radiation, temperature, vapour pressure and wind). For deep lakes water temperature data are required and, in some terrestrial models, a vegetation resistance parameter is required. We have also included models that allow mean actual catchment evaporation to be estimated from mean catchment precipitation and runoff known as Budyko-like models[4].

1.1 Defining terms

When explaining the confusion around the terms evapotranspiration and evaporation, Howell and Evett[5] noted that Monteith argued the term evapotranspiration was unnecessary and its components (evaporation and transpiration) were strictly congruous (see appendix of Monteith[6]). However, they also noted that the term evapotranspiration *"is too ingrained in U.S. literature … to move back to a more correct term, evaporation*" (5, page 3). Despite this, we use the term 'evaporation' in this paper to include evapotranspiration except where an author uses the terms 'evapotranspiration' or 'reference (crop) evapotranspiration'.

'Potential evaporation' is considered to be the most confusing of the evaporation terms. Its history begins with Thornthwaite[7] in 1948 who coined the name. Prior to Thornthwaite, Oldekop[8] in 1911, writing in Russian, had suggested the concept of "maximum possible evaporation, only dependent on climate", but had not used the specific term 'potential evaporation'.[9] Penman in 1956(10, page 18) defined potential evaporation "*as the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water".* A decade later van Bavel[11] extended the definition to any surface that imposes no restriction to the evaporation process. In 1983, based on the Complementary Relationship (Section 5.3), Morton[12] introduced 'wet environment areal evapotranspiration' and noted his definition was the same as *"the conventional definition for potential evapotranspiration*"(13, page 29). According to Morton this occurs when the soil-vegetation surfaces are saturated and water supply is unlimited. In 1984, McIlroy[14] (confirmed by Garrett[15]) brought together the elements of the definition of potential evaporation: maximum possible evaporation from leaves and soil surfaces where the air-surface interface is saturated and the environmental state is specified by net surface radiation, soil heat flux, aerodynamic resistance and vapour pressure deficit. In discussing potential evaporation from a forest, Byrne et al.[16] noted that r_s / r_a (the ratio of surface to aerodynamic resistance) should be set to a minimum to obtain potential evaporation. Potential evaporation is described by Shuttleworth(17, page 4.2) in terms of a "*free water surface under existing atmospheric conditions*" and Granger(18, Table 1) argued there should be constant atmospheric and surface temperature conditions. Dingman(19, page 299) and Lhomme(20, Abstract) observed that the saturated area should be sufficiently extensive to nullify local advection effects. According to Pereira et al.(21, Footnote 2), the term is now reserved "*to represent the ET rate from any nonstressed crop*". In summary, we define potential evaporation as the upper limit of evaporation under constant meteorological and surface temperature conditions from a surface (vegetation, bare soil, or open-water) that is saturated and of such extent to negate effects of local advection.

In order to avoid using the confusing term potential evapotranspiration, Doorenbos and Pruitt[22] in 1977 were among the first researchers to replace the term with 'reference crop evapotranspiration' which they defined as "*the rate of evapotranspiration from an extended surface of 8 to 15 cm tall grass cover of uniform height, actively growing, completely shading the ground and not short of water*"(22, page 4).

'Actual evaporation' occurs from terrestrial environments (including natural and irrigated landscapes) and from water bodies (small and large lakes, both shallow and deep).

With respect to 'open-water evaporation', we include lakes sufficiently shallow that seasonal heat storage can be ignored. Based on a literature review, McMahon et al.[23] concluded that in estimating lake evaporation, shallow lakes are, on average, less than 2 m deep. For deeper lakes, heat storage needs to be accounted for.

The final evaporation term is 'pan evaporation'. This refers to the estimate of water losses from a standard evaporation pan which for many countries is the Class-A pan[24].

1.2 A road map

Figure 1 is an appropriate setting for this paper. It represents as a time-line the key developments in evaporation theory and practice, concentrating on activity during the twentieth century. Our paper follows these developments but with the methodologies from 1948 being reviewed by application rather than by time. The paper is divided into seven sections. Following this introduction, Section 2 identifies recent reviews. Section 3 deals with the pre-Dalton (pre-1800) period in which Perrault influenced our understanding of evaporation. Key developments in the period from Dalton to pre-Penman (1947) are discussed in Section 4. In Section 5 there are seven sub-sections where we describe the developments in evaporation methodology and models from 1948. The models are summarised in Table 1 where those that are discussed in Section 5 are shaded. A general discussion follows in

Section 6 and in the Conclusion, Section 7, we summarise the major milestones in this process.

2 Reviews

There have been several reviews and performance comparisons of evaporation models over the past two decades[23,25-44]. In the main these reviews were for specific purposes and were limited either in the range of evaporation models considered or the time period covered in the review. Furthermore, we saw the need to show how evaporation theory has developed from pre-19th century to the present day and to identify the influence that several key researchers have had on present day evaporation estimation techniques using standard meteorological data.

Our review is based on an examination of 166 evaporation models published from 1802 to the present. The details of most of the pre-1910 models were extracted from Livingston's[45] 1909 extraordinary annotated bibliography on evaporation consisting of 850 references. Of the 166 models, 143 are identified in Table 1 (see Table S1, Supplementary Material for model equations) and the remaining 23 are simple mass-transfer equations with different empirical coefficients[19,46-67].

In Table 1 we have categorised the models by year, reference, type, and application. Applications are categorised into six classes: potential evaporation, reference evaporation, actual evaporation in terrestrial environments, open-water evaporation, deep lakes, and pan evaporation. The models in Table 1 are further typed into the following 10 classes: models based on mass-transfer (so-called Dalton equation), temperature models, radiation-temperature models, energy balance methods, single-source (vegetation, soil or water) combination methods, multi-source combination methods, multivariate models, models based on the Complementary Relationship, Budyko-like models, and miscellaneous models. Table 2 is a matrix summary of all 166 models. Table 3 to be discussed later shows the linkages between the 57 models that are closely connected to Penman-1948, Penman-Monteith or Priestley-Taylor. Some observations about the contents of the tables are presented in Section 6.

3 Pre-Dalton (pre-19th century)

"*All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come; thither they return again*". Ecclesiastes 1:7

There are many discourses available in the literature that describe beliefs about evaporation, and hydrology in general, in classical times[68-71]. Middleton(69, page 2) puts this material into perspective when he states: "*Probably everything written about the hydrometeors before the seventeenth century should be classified as speculation rather than theory.*". The English word 'evaporation' is derived from the Latin 'evaporare', to disperse in vapour[72]. Klein[72] also reports uses of the word in its modern meaning from as early as 1567.

Despite the extensive writing that referred to hydrology and provided insights into the state of knowledge on the subject in classical times, it is mainly through the writings of Aristotle that this material, or at least some version of it, made its way into the scholarly works of the late Middle Ages when his works were rediscovered. They were highly influential in driving scientific thought until the late seventeenth century[68]. Brutsaert argues that the dominance of Aristotle's theory of two exhalations, in which heat is claimed to drive evaporation and wind has no effect, since Aristotle did not consider wind to be moving air, was a setback to the development of understanding of evaporation in this period[68].

While the two exhalations theory of Aristotle was not universally accepted by his contemporaries, Aristotle's writings were rediscovered in the 12th century and became very influential. It was the French polymath Rene Descartes who provided the basis to break away from the concepts of Aristotle with the publication of his book "The Meteors" in 1637[73]. Petrescu summarises the approach taken by Descartes as: *"....Descartes wanted to publish a sample of non-scholastic physics that uses mechanical explanations instead of hylomorphic notions.*"(74, page 25) Here, the hylomorphism is central to Aristotle's philosophy of nature, consisting of two intrinsic principles of qualities and substantial forms.

In 1974 UNESCO, the WMO and the IAHS hosted a conference in Paris entitled "Three Centuries of Scientific Hydrology"[75]. This places the start of scientific hydrology at 1674. The only indication in the conference publication of why this date was chosen is given by Dumitrescu and Nemec[76], who, in their chapter in the conference proceedings, state that scientific hydrology began with the publication of Perrault's "De l'origine des fontaines" (On the origin of springs) in 1674[77]. Perrault's book was published anonymously and Nace ascribes this to the authoritarian intellectual climate of the time under which it could be considered heresy to differ from the prevailing orthodoxy, even on scientific matters[71]. In about 1674 Perrault made estimates of the rainfall in the area drained by the Seine and the flow of the river and showed that there was more than enough rainfall to provide the flow in the river. It is this, along with his clear description of the hydrological cycle, that places him at the start of scientific hydrology.

Perrault (1611-1680) is credited with having made the first experimental measurement of evaporation, though in fact what he measured was sublimation by recording the loss of weight of a block of ice through time. His description of the process of evaporation explains his choice of experiment: "*Although Aristotle and all the other Philosophers give only one cause for the evaporation of water, namely heat, I could find two more, the one cold, its opposite, and the other the movement of the parts of the air.*"(77, page 110) As Nace points out, cold and heat were perceived at this time as separate entities[71]. Perrault described the particles involved as rising and separating without changing and in this he preceded Lavoisier by 100 years in identifying water as a chemical compound that was consistent in whatever state it occurred[71].

Perhaps the first direct measurement of the evaporation of liquid water was carried out by Edmund Halley in 1686 when he measured the loss of water from a heated pan[78]. He placed a pan of water over hot coals and heated it to the temperature of the air in summer and measured the loss of water by evaporation by measuring the change in the weight of the pan. From this he made a number of reasonable deductions about the water balance of the oceans. In a subsequent paper[79] he gave an account of how heat drives evaporation by heating the atoms of water so that they become less dense than the air and rise, proceeding to say that as they cool they will then descend as rainfall.

Halley then extended his analysis of evaporation with an experiment, the results of which he presented in a paper[80] to the Royal Society in 1694. He measured evaporation by recording loss of weight of a pan of water and also recorded the temperature of the water and the atmospheric pressure. Since this appears to be the first example of the measurement of evaporation in something roughly equivalent to modern open pans we present Halley's results here (Figure 2). Halley attempted to shelter his pan from the sun and the wind though his discussion suggests that he was not able to exclude wind entirely. Halley does not identify the temperature scale he used and there were many in use at that time. He also recorded the atmospheric pressure each day, but of course there is no correlation between evaporation and pressure in his data. Interestingly, in a regression analysis of evaporative water loss on temperature (Figure 2), temperature explains 63% of the variance in evaporation. Temperature is therefore shown to be a reasonably good predictor of evaporation though Halley appears not to have explored this possibility. There was a total of 8 inches (203 mm) evaporated in the year of his observations which he considers to be too low, given the amount of rainfall recorded in a year and concludes that the wind must also have a significant effect on evaporation. Modern evaporation (tank) data show that the location of his experiment, Gresham College (London), has an annual evaporation of ~400 mm[81]. Other direct measurements of evaporation soon followed those of Perrault and Halley. For example, the French scientist Sedileau measured rainfall and evaporation for three years at Versailles, from 1688 to 1690, as part of an examination of the water supply to the gardens of the Palace of Versailles[68].

A central component of the discussions about hydrology at this time was the need to account for the Biblical flood, both in terms of the source of the waters that produced the flood and its fate after the flood receded. This led to a belief that the water flowing in rivers had a subterranean source, and could not be explained by rainfall alone. The writings of John Keill, a contemporary of Halley at Oxford, reveal some of this debate, and it is obvious from his work that there was some scepticism developing about the subterranean source of the water in rivers[82]. This, combined with ongoing development of actual measurements as a means of testing these theories, led to an increasing focus on the means of accurately estimating the variables involved, of which evaporation was important as the postulated source of the water in rain.

The eighteenth century saw the development of ideas that had a bearing on the subsequent understanding of the process of evaporation, even though many were not conceived for that purpose. Brutsaert[68] points out that the main issues in the debate about evaporation in the eighteenth century were focussed on matters already present in Halley's paper[79] presented to the Royal Society in 1686. The key issues were: is evaporation a solution process?; that warmer air could dissolve more water; that the air can become saturated with water; that if saturated air cools it precipitates water; and that evaporation causes cooling.

Experimentation similar to that carried out by Halley and his contemporaries continued through the eighteenth century. Dobson[83] measured evaporation over a four-year period (1772-1775) in a manner similar to that of Halley and showed also a close relationship between evaporation and temperature. He considered that the rate of evaporation was a more accurate test of the moisture or dryness of the atmosphere than the quantity of rain. Even at this date, the process of evaporation was generally conceived as the solution of water in air. This aspect of the theorising on evaporation was effectively ended by the experiments of de Luc[84] in 1792 who showed that evaporation in a vacuum chamber proceeded at the same rate as in the air. This was the precursor to the idea of partial pressures of gases in the atmosphere, subsequently formalised as Dalton's Law.

Also during this period there were experiments and discussions about the absorption of heat during evaporation that led to the concept of latent heat. Joseph Black (1728-1799) carried out experiments on latent heat and presented his results at a literary society meeting in the University of Glasgow in 1762 and also included this material in his lectures to students[85]. He did not publish this work himself. Lavoisier also described latent heat in 1777 and it is not clear whether he developed these ideas independently or was familiar with Black's work. Brutsaert ascribes the discovery of the concept of latent heat to Black[68]. Furthermore, in discussing natural evaporation, Black argued that "… *wind greatly promotes natural evaporation* …"(85, page 195).

Dalton has become universally recognised as one of the major figures in the development of theory about evaporation[68,86]. Dalton devoted Essay III of his 1802 paper "*Experimental essay on the constitution of mixed gases*" to evaporation[3]. He begins that essay by refuting the notion that evaporation is a solution process and goes on to summarise what has already been determined about evaporation by others as follows: *"1. Some fluids evaporate much more quickly than others. 2. The quantity evaporated is in direct proportion to the surface exposed, all other circumstances alike. 3. An increase of temperature in the liquid is attended with an increase of evaporation, not directly proportionable. 4. Evaporation is greater where there is a stream of air than where the air is stagnant. 5. Evaporation from water is greater the less the humidity previously existing in the atmosphere, all other circumstances the same."*(3, page 576) He then sets out "*to obtain a true theory of evaporation*"(3, page 577) in terms of the effect of variation in temperature, the evaporability of different fluids, and the effect of humidity in the air. Following a series of experiments where he measured the rate of evaporation by loss in weight using tin pans heated over a fire he concludes that *"the evaporating force must be universally equal to that of the temperature of the water, diminished by that already existing in the atmosphere."*(3, page 581) The water existing in the atmosphere he refers to as the *'force of the vapour'*, effectively relative humidity.

Dalton did not continue work on evaporation but proceeded to turn his attention to chemistry where he made major contributions. Despite this, his work on evaporation can be seen as the progenitor of much that followed in this field.

4 Dalton to Penman (1800 – 1948)

Post Dalton, progress in understanding the evaporation process was slow. In 1867, Symons in referring to the Astronomer Royal's description of meteorology "*as one of the most desperate sciences with which we have to do*"(87, page 9) commented that "*the most desperate branch of this desperate science is evaporation*"(87, page 9).

Dalton's[3] evaporation relationship was expressed as a table rather than an equation. Dines in 1870, as noted by Livingston[45], related evaporation to vapour pressure deficit but it appears that Weilenmann[88] in 1877 was one of the first to derive an equation relating evaporation to vapour pressure deficit and wind speed as follows:

$$E_{OW} = \left[\frac{a}{\Delta + c}\left(1 + bu\right)\right]\left(v_a^* - v_a\right) \qquad (1)$$

where E_{OW} is the estimate of open-water evaporation, $\left(v_a^* - v_a\right)$ is vapour pressure deficit, v_a^* is the saturation vapour pressure of the air, v_a is the vapour pressure of the air, *u* is wind speed, Δ is the slope of the saturation vapour pressure curve, and *a*, *b* and *c* are constants. According to Helfrich et al.[89] (see also Sartori[30]), the usual form of the Dalton mass-transfer equation is:

$$E_{OW} = \left(a + bu\right)\left(v_s^* - v_a\right) \qquad (2)$$

where v_s^* is the saturated vapour pressure at the evaporating surface temperature, and the remaining variables are defined earlier. From our investigation about S of the evaporation models, developed during the past 215 years, are based directly on Dalton's relationship. Nearly all were used to estimate open-water evaporation (Tables 1 and 2).

During the period 1800–1947, the non-Dalton evaporation models were based on aridity analysis, on energy as radiation or degree-days, or on atmospheric turbulence. The models included the aridity-based Budyko-like[4] procedures of Schreiber[90] in 1904 and Oldekop[8] in 1911, the energy model of Cummings and Richardson[91] in 1927 and the degree-days equation of Lowry and Johnson[92] in 1942. Marvin, in 1909, developed a generalised equation more complex than Dalton but concluded that "*further solution ... must be deferred until some new data are available*"(93, page 61).

Thornthwaite and Holzman[94] provide a useful overview of the researches into applying atmospheric turbulence to evaporation processes from about 1920 to 1939. Jeffreys's[95] and Giblett's[96] researches were limited to water bodies, the former examined evaporation as a diffusion process whereas the latter was concerned mainly with how evaporation reduced in large water bodies relative to an upwind location.

The first half of the 20th century was devoted mainly to empiricism as indicated by the large number of Dalton derived equations that had been parameterised. Nevertheless, there were several important non-empirical developments, the key one being the introduction in 1926 of the Bowen Ratio[97] (see also 98-99) which is defined for a water body as the ratio of the energy used for sensible heat divided by the energy used for latent heat (evaporation):

$$\text{Bowen Ratio } (B) = 0.46 \frac{(T_w - T_a)}{(v_w - v_a)} \frac{P_a}{760} \tag{3}$$

where T_w is the temperature of the air in contact with the evaporating surface (°C), T_a is the temperature of air passing over the water body (°C), v_w is the vapour pressure of the air in contact with water body (mm Hg), v_a is the vapour pressure of the air passing over the water body (mm Hg), and P_a is the atmospheric pressure (mm Hg).

A second development was by Cummings and Richardson[91] (in 1927) who described how lake evaporation could be estimated using the energy balance equation incorporating Bowen's ratio. This method has become known as BREB (Bowen ratio energy balance)[100]. The BREB equation is:

$$E_{DL} = \frac{R_n - S - A_o}{\lambda(1 + B)} \tag{4}$$

where E_{DL} is evaporation from a deep lake, R_n is the net radiation at the evaporating surface but at air temperature, S is the rate of heat storage change in the lake, A_o is the heat advected into the lake, λ is the latent heat of vaporisation, and B is the Bowen Ratio.

Because atmospheric turbulence processes were sufficiently understood through the theoretical treatments of Taylor, Prandtl, von Kármán and Rossby (see discussion by Thornthwaite and Holzman[94]), in 1936 Sverdrup[101] was able to provide new insights into the mechanism of evaporation. Both Sverdrup[102] and Millar[103] considered moisture gradients in both laminar and turbulent layers but their analyses were limited by lack of data. Based on the works of Rossby[104], Rossby and Montgomery[105] and Sverdrup[106], in 1939 Thornthwaite and Holzman[94] combined moisture concentration in the atmosphere, wind speed and roughness length for estimating actual evaporation, E_A, through a transfer coefficient:

$$E_A = \frac{K_{von}^2 \rho_a u_2}{\ln\left(\frac{h_2}{h_1}\right)\ln\left(\frac{h_2}{z_0}\right)}(q_1 - q_2) \tag{5}$$

where K_{von} is von Kármán's constant, ρ_a is the density of air, u_2 is the wind speed at height h_2, q_1 and q_2 are the moisture contents at levels h_1 and h_2, and z_0 is the roughness coefficient. Thornthwaite and Holzman[94] simplified Equation (5) (the Thornthwaite-Holzman model) to:

$$E_A = \frac{17.1(u_2 - u_1)}{T_a + 459.4}(v_1 - v_2) \tag{6}$$

where u_1 and u_2 are the wind speeds, v_1 and v_2 are the actual vapour pressures, both variables measured at different heights, and T_a is the air temperature.

Over the past 100 years the usual form of the Dalton equation (Equation 2) as a linear function of vapour pressure deficit and wind speed has been progressively modified. Details are provided in Table S1, Supplementary Material. Other than several variations of the wind function, the major developments that occurred were: Sill[107] included variables in the Dalton model to address forced convection; Sartori[108] included the distance for full turbulent flow to develop; Lee and Swancar[109] improved the model by adding an atmospheric stability term; and, McJannet et al.[40] incorporated lake surface area in their open water equation. Because of the empirical nature of these equations, their applicability is site-specific.

5 Penman (1948) to present

According to Howell and Evett(5, page 3) Monteith, in a 1985 keynote address, commented that *"because Penman got the physics right, his formula has provided a basis for many theoretical and experimental studies*". However, it was some years after Penman's 1948 contribution[48] that his research was appreciated. According to Monteith(110, page 2), in 1950 Pasquill[111] wrote "*in view of the restricted empirical basis of the method and the special circumstances of the test, it seems doubtful that the method can be applied with confidence outside the circumstances of the test.*" Nevertheless, Penman's equation (Equation 7) underpins many evaporation models (see Table 3 and Section 6). The Penman-48 equation[48] is:

$$E_{OW} = \frac{\Delta}{\Delta+\gamma}\frac{R_n}{\lambda} + \frac{\gamma}{\Delta+\gamma}E_a \qquad (7)$$

where Δ is slope of the saturation vapour pressure curve, γ is the psychrometric constant, and λ is the latent heat of vaporisation. $E_a = (a + bu_2)(v_a^* - v_a)$ is considered an estimate of the drying power of the atmosphere. The remaining variables are defined earlier. The E_a equation is similar to Dalton (Equation 2) except that v_a^* (the saturation vapour pressure of air) replaces v_s^* (the saturation vapour pressure at the water surface). The Penman-48 equation is the first combination equation in which a radiation term (1st term in Equation 7) is combined with an aerodynamic component (2nd term).

The post-Penman period was one of embedding the science of evaporation on a solid foundation followed by a range of theoretical analyses that culminated in models that are used to estimate potential evaporation, reference crop evapotranspiration, actual evaporation in terrestrial environments, and evaporation from shallow (open-water) and deep lakes, and evaporation from Class-A evaporation pans. We next explore briefly each of these developments. (The models to be discussed in this section are highlighted by shading in Table 1.)

5.1 Potential evaporation

We define potential evaporation as the maximum evaporation that can occur under constant meteorological and surface temperature conditions in which the evaporating surface (vegetation and/or bare soil, or open-water) is saturated and is large enough to negate local advection effects. Approximately 13% (22 models) of those listed in Table 1 are identified as potential evaporation models (Table 1, column 3), in which temperature and/or radiation are the key variables.

Because of confusion with the term 'potential evaporation', by the mid-1970s the terms reference or reference crop evapotranspiration were adopted in discussions of crop water requirements (see Section 1.1). However, the term potential evaporation is still used under specific circumstances as discussed in Section 5.3. In addition to the Thornthwaite model, the two key potential evaporation models are Penman-Monteith and Priestley-Taylor. These along with other potential evaporation equations are discussed below.

The Thornthwaite method is the most important of five procedures to estimate potential evaporation that are based only on temperature; the others are Blaney-Criddle developments (Blaney-Criddle, Blaney-Criddle-70 and Modified Blaney-Criddle) and the Behnke-Maxey model (Table 1, column 3). The Blaney-Criddle models incorporate a constant which depends on crop type and stage of growth. Unlike many other applications, Thornthwaite[7] developed his equations to estimate *mean monthly* potential evapotranspiration.

Seven potential evaporation models using radiation and temperature have been identified (Table 1, column 3): Makkink, Turc, Jensen-Haise, Stephens-Stewart-P, Camargo-71, Priestley-Taylor, and Makkink-Hansen. Makkink and Priestley-Taylor are similar and incorporate the slope of the saturation vapour pressure curve (at air temperature) with solar radiation, whereas Turc, Jensen-Haise and Stephens-Stewart relate potential evaporation to solar radiation and air temperature. Camargo-71 is based on extra-terrestrial radiation and air temperature. The key model in this group is Priestley and Taylor[112] from 1972:

$$E_P = \alpha_{PT}\left[\frac{\Delta}{\Delta+\gamma}\frac{(R_n - G)}{\lambda}\right] = \alpha_{PT}E_{Eq} \qquad (8)$$

where G is the heat flux into the ground, α_{PT} is the Priestley-Taylor coefficient, the term in square brackets is known as equilibrium evaporation (E_{Eq}), and the remaining variables are defined earlier.

According to Allen[26] "*Priestley and Taylor (1972) presented a shortened variation of the Penman equation for use in humid regions where advective transport of heat is low*". Priestley and Taylor[112] outlined a general framework for the development of their model where α_{PT} equals 1.26 based on field experiments where there is no advection. An extensive list of α_{PT} values are presented in McMahon et al.(23, Table S8) in which α_{PT} varies from 0.53 to 1.57. In Equation (8), the term equilibrium evaporation (E_{Eq}), a concept developed by Slatyer and McIlroy(113, page 3-73), is related to the equilibrium temperature defined by Edinger et al.(114, page 1139) *"as the surface temperature ... at which the net rate of heat exchange ... would be zero*". Although the Priestley-Taylor equation is an empirical one, de Bruin[115] observed that on a regional basis Priestley-Taylor can be derived by taking into account that evaporation and saturation deficit are dependent variables. According to McNaughton and Spriggs[116] α_{PT} will shift above or below 1 depending on the amount of entrainment of dry warmer air into the planetary boundary layer. Modifications to the Priestley-Taylor approach are offered by Agam et al.[117] and Ding et al.[118].

It should be pointed out that the Makkink[119] model from 1957 is very similar to Priestley-Taylor except that Priestley-Taylor inputs net radiation and Makkink inputs solar radiation. Furthermore, Makkink has two empirical coefficients whereas Priestley-Taylor has only one although Hansen[120] modified the Makkink model to incorporate only one parameter[120,121]. Nearly all references to the Makkink equation quote Makkink[122] which is incorrect. An appropriate reference is Makkink[119] (see McMahon et al.[123]).

As listed in Table 1, column 3, seven single-source combination models have been used to estimate potential evaporation. The Budyko(4, page 198) model uses a recursive approach to estimate the evaporating surface temperature whereas Penman uses a finite difference form of the Clausius-Clapeyron equation for a wet surface[124], to eliminate the unknown surface temperature. Although the McIlroy-P model resembles Penman[48] (which we have classified as an open-water model), McIlroy-P incorporates terms for heat flux into the ground and the albedo of the vegetation, thus with these variables McIlroy-P is considered a potential evaporation model[125].

The Penman-Monteith-P model has the following form:

$$E_P = \frac{1}{\lambda}\left[\frac{\Delta\left(R_n - G\right) + \rho_a c_a \dfrac{\left(v_a^* - v_a\right)}{r_a}}{\Delta + \gamma}\right] \qquad (9)$$

where ρ_a is the density of air, c_a is the specific heat of air, r_a is the aerodynamic resistance to water vapour transport, and the remaining variables are defined earlier. Monteith (110, footnote page 8) points out that this equation for estimating the evaporation for a single leaf was first derived by Penman[126] in 1953, although according to Monteith its development is often attributed to himself. It is noted by de Bruin[115] that Rijtema[127] derived a similar formula (the Rijtema model) independently in 1965. Monteith[128] applied Equation (9) in 1965 to estimate evaporation from the vegetation canopy.

Although the van Bavel model is a Penman-48[48] equation with a modified wind function, it is considered a potential evaporation model as it was applied to well-watered alfalfa in a lysimeter. van Bavel[11] concluded the model *"is not only accurate but also practical and generally applicable*". Tegos et al.[129] developed in 2015 a parametric model (known as Parametric) based on the Penman-Monteith-P model incorporating extra-terrestrial radiation and air temperature requiring three regionally calibrated parameters.

5.2 Reference evapotranspiration (crop or grass)

The terms 'reference crop evaporation', introduced by Doorenbos and Pruitt[22], and 'reference evaporation', which appeared in 1985 (Snyder and Pruitt[130]), represents evapotranspiration from a defined vegetated surface. Since the mid-nineteen-seventies, many models to estimate crop (including grass) water requirements have been developed. These are listed in Table 1, column 4 under the headings: temperature, radiation-temperature, combination and multi-variate models. For more detailed reviews, see Allen[26], ASCE[31], Jacobs and Satti[131], Bandyopadhyay et al.[42], Tabari et al.[43] and Samaras et al.[132].

Two temperature-based reference models are Linacre-77V (a simplified version of the Penman model) and PMT. The latter model is a simplified version of FAO56-RC (discussed later in this section) in that solar radiation is a simple function of extra-terrestrial radiation, actual vapour pressure is a function of minimum temperature, and wind speed is fixed at 2 m s^{-1}.[133]

Five of the eight radiation-temperature reference crop procedures are based on Hargreaves research. The Hargreaves-85 model[134] (also known as the Hargreaves-Samani model[135]) is an extension of the Hargreaves radiation model. It is included here as reference evapotranspiration because Hargreaves and Allen[134] pointed out that the model coefficient was based on grass reference evapotranspiration. As well as radiation and temperature, the Modified Hargreaves model incorporates precipitation and the Improved Hargreaves model of Meek and Phene[136] includes vapour pressure deficit[137]. Of the three non-Hargreaves radiation-temperature models, the Jones-Ritchie model includes only solar radiation and temperature, the Adjusted Turc model incorporates also wind speed, and the FAO24-radiation model, which according to Jensen[37] is based on the Makkink model, requires radiation and air temperature plus humidity and wind speed to evaluate one of the two coefficients. The latter model was updated by FAO56-RC[133] which is described next.

Reference crop evapotranspiration is related to a hypothetical crop of grass or alfalfa. In developing the FAO56-RC in 1998, Allen et al.[133] relied heavily on FAO24-radiation[21]. The successful adoption of FAO56-RC by users and researchers of evaporation models is described by Pereira et al.[21]. In 2000, the ASCE published a similar model (designated here as ASCE-PM) and documented parameters for both short and tall reference crops[31]. The ASCE-PM model is:

$$E_{RC} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{C_n}{T_a + 273} u_2\left(v_a^* - v_a\right)}{\Delta + \gamma\left(1 + C_d u_2\right)} \qquad (10)$$

where E_{RC} is the reference crop evapotranspiration, C_n and C_d are constants that change with reference type and model time-step, and the remaining variables are defined earlier. In FAO56-RC values for C_n and C_d are fixed at 900 and 0.34 respectively.

The Kimberley-Penman model, which is the earliest (1982) of the nine single-source combination reference crop models (Table 1, column 4), is equivalent to the Penman model except that the wind function is seasonally varying. Following expert consultation over several years, the recommended reference crop model is FAO56-RC in which the reference crop is defined as a short crop 0.12 m high (similar to grass) and a surface resistance of 70 s m^{-1}.[133] The ASCE Task Committee on Standardization of Reference Evapotranspiration adopted this definition and added a tall reference crop 0.5 m high (similar to alfalfa)[31]. For crops other than the standard reference crop, FAO56-RC is regarded as a two-step procedure requiring the reference crop evapotranspiration to be adjusted by a crop coefficient:

$$E_C = K_C E_{RC} \qquad (11)$$

where E_C is an estimate of evapotranspiration from a well-watered crop, E_{RC} is the reference crop evapotranspiration and K_C is the crop coefficient. Values of K_C are tabulated in Allen et al.[133].

Another in this group of reference crop models is the Todorovic model[138], which is based on Penman-Monteith-P, and incorporates a canopy resistance r_c that varies with weather conditions. For r_c = 70 s m^{-1}, the model results were consistent with those from FAO56-RC. Valiantzas[139-144] published several models that are simplifications of the Penman-48 and the FAO56-RC models without requiring the input of wind information.

In 2009, Shuttleworth and Wallace[145] proposed the Matt-Shuttleworth model as a one-step model "*on the grounds that this approach is consistent with present-day understanding of the evaporation process*"(145, page 1895). In their approach, they incorporate crop r_s (surface resistance) and the method is recommended for typically arid, windy regions. In their paper[145] they provide values of r_s for a range of crops.

The FAO24-Blaney-Criddle reference grass model is a multi-variate procedure operating at a monthly time-step and has been used world-wide for estimating reference evapotranspiration but as the model has been adjusted for local climate conditions, care is required in its application[146,147].

5.3 Actual evaporation from non-saturated surfaces

Thirty-four models were identified as procedures that estimate actual evaporation and are listed in Table 1, column 5. The key developments are based on McIlroy[113], Penman-Monteith[128] and Priestley-Taylor[112] models, and on the Complementary Relationship[148,12,13]. As well, the seven Budyko-like models[149] are included here.

Penman[150], in 1950, introduced the idea of a drying power relationship in the soil to represent the decrease in actual compared to potential evaporation. In 1965, Monteith[128] explored theoretically the relationship between actual and potential evaporation from leaves and developed the following model (Penman-Monteith-A):

$$E_A = \left[\frac{\Delta + \gamma}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \right] E_P \qquad (12)$$

where E_A is an estimate of actual evaporation and E_P is the evaporation from thoroughly wet leaves (r_s = 0) (Equation (9)), and the remaining variables are defined earlier.

In the Katerji-Perrier model, Katerji and Perrier[151] estimated the ratio $\frac{r_s}{r_a}$ in Equation (12) by relating it to a ratio $\frac{r^*}{r_a}$ through an empirical procedure where r^* is the critical resistance and can be determined from weather variables. Armstrong et al.[152] questioned whether this minimum reference resistance is always applicable due to plant state changes. In this context we note Dunin and Aston's(153, page 308) comment about surface resistance: "*Surface resistance, which reflects stomatal regulation of water loss by vegetation, varies both diurnally with meteorological conditions and seasonally with phenological development. A further cause for temporal variation in surface resistance involves the supply of soil water for transpiration*".

In the Penman-48[48] model the slope of the saturation vapour pressure–temperature relationship at the temperature of the evaporating surface is estimated at air temperature. To overcome this assumption, Lascano and van Bavel[154] (see also Lascano and Evett[155]) compared the explicit solution of Penman's equation with a recursive one (PenmanR-act model) in which the evaporating surface temperature is estimated. Following Penman[48], McIlroy (Slatyer and McIlroy[113]) developed a combination equation (McIlroy-A) to estimate actual evaporation from standard meteorological data. The difficulty with this model is estimating the wet-bulb temperature depression for a non-saturated evaporating surface(128, page 209). To overcome Penman's linearization of the saturation vapour pressure function, Paw U and Gao[156] and Milly[157] presented more exact non-linear solutions.

Following Penman's[48] approach, in 1989 Granger and Gray[158] developed a combination equation, the Granger-Gray model, utilising the Bowen ratio and the aerodynamic boundary layer-surface roughness equation (see Kalma et al.[159, page 429]) to estimate actual evaporation from non-saturated surfaces. A relative drying power function moderates the potential evaporation resulting in an estimate of actual evaporation.

Verstraeten et al.(160, page 83) observe that "*For sparse canopies, the Penman-Monteith 'big-leaf' approach no longer holds. Under these boundary conditions, soil evaporation must be incorporated in the modelling approach*". As listed in Table 1 (column 5) it is observed that since 1985, eight complex models (Shuttleworth-Wallace, Four-layer, Weighted Penman-Monteith, Clumped three-source, MORECS, Two-layer, Clumped, and n-component canopies) have been developed to deal with actual evaporation from vegetation and soil; evaporation from open-water is included in the Weighted Penman-Monteith model. All seven models are based on the single-source Penman-Monteith model. The basic assumption in Penman-Monteith is that "*there is numerical similarity between bulk stomatal resistance and an integration of component stomatal-resistances in dry conditions*"(161, page 830). These multi-source models are structured somewhat similarly in that the total evaporation is the sum of evaporation from vegetation, soil and water, all appropriately weighted in terms of input energy or area, and is dependent on surface resistance variables of vegetation and bare soil, and on the aerodynamic resistance between soil and vegetation. In this context the warning by Cleverly et al.(162, page 1562) is pertinent: *"Accurate prediction of evapotranspiration E depends upon representative characterization of meteorological conditions in the boundary layer"*.

Another approach to understanding of evaporation processes relates to Bouchet's[148] 1963 Complementary Relationship in which potential and actual evaporation depend on each other in a complementary manner through feedbacks between land and atmosphere:

$$E_A = 2E_{We} - E_{Po} \tag{13}$$

where E_A is actual evaporation, E_{We} is areal potential or wet-environment evapotranspiration, and E_{Po} is point potential evapotranspiration where heat and water vapour have no effect on the overpassing air. The background, development, validity and asymmetry of the Complementary Relationship are beyond the scope of this review. Readers are referred to Seguin[163], Le Drew[164], Morton[165], Granger[18], Lhomme[20], Szilagyi[166], Ramírez et al.[167], Ozdogan et al.[168], Lhomme and Guilioni[169], Szilagyi[170], Pettijohn and Salvucci[171], Yu et al.[172], Huntington et al.[173] and Brutsaert[174] for details.

Over two decades, starting from about 1965, F.I. Morton developed three models based on the Complementary Relationship to estimate actual catchment evapotranspiration, shallow lake evaporation and deep lake evaporation[12,13,175]. The CRAE (Complementary Relationship Areal Evapotranspiration) model estimates actual catchment evaporation. This model is based on modified versions of Penman[48] and Priestley and Taylor[112] models. A key element is that the temperature of the evaporating surface is estimated. Furthermore, Morton(12, page 25) did not incorporate wind because its inclusion "*does not significantly reduce error*" in evaporation estimates, a view adopted by Cummings[175] in 1921 (see Cummings and Richardson[91]). Morton used a global set of catchments and lakes to calibrate his models. The CRAE model was extensively tested by Morton[12] and, independently, by others (for example, Hobbins et al.[177]).

In 1979, Brutsaert & Stricker[178] substituted the Priestley-Taylor and Penman equations into E_{We} and E_{Po} of Equation 13 respectively. Hobbins et al.[177] tested the Brutsaert-Stricker method and found it slightly underestimated actual evaporation. Szilagyi and Jozsa[179] and Szilagyi[170] (Szilagyi-Jozsa model) followed the Brutsaert & Stricker[178] approach but evaluated the Penman equation using an iteratively estimated equilibrium temperature of the evaporating surface. Testing indicated the model performed better than the Brutsaert-Stricker model. In 2014, Szilagyi[180] argued that because Priestley-Taylor was parameterised under humid conditions, a temperature correction is required to avoid over-estimating evapotranspiration. In the Modifed A-A model of 2010, Crago et al.[181] modified the Brutsaert–Stricker model by 1) estimating the relative humidity from minimum temperature rather than from observed humidity data; and 2) replacing Penman's aerodynamic component with a term based on Monin-Obukhov similarity theory[182] incorporating $K_{von}B_H^{-1}$ where B_H is the Stanton number[183].

Based on the Complementary Relationship, Han et al.[184] proposed a variation of the Granger-Gray and Brutsaert-Stricker models, designated as the Granger A-A model. Initial testing of the model suggests it effectively expresses the relationship between E_{Act}/E_{Pen} and E_{Rad}/E_{Pen} where E_{Act} is actual evaporation, E_{Pen} is Penman's 1948 evaporation, and E_{Rad} is the Penman radiation term. Han et al.[185] extended the previous development and proposed a nonlinear function approach for the normalized Complementary Relationship evaporation model. Anayah and Kaluarachchi[186] evaluated the Morton CRAE, Brutsaert-Stricker and Granger-Gray models at 34 world-wide FLUXNET sites and concluded that a variation of the Granger-Gray model designated as GG18 "*showed a step forward toward predicting ET in large river basins with limited data and requiring no calibration*".

Following Zhang et al.[187], the seven Budyko-like models (Schreiber; Oldekop; Turc-Pike; Budyko-annual; Fu-Zhang; Zhang; Potter-Zhang listed in Table 1, column 5), which were developed to estimate mean catchment runoff, can be used to estimate mean catchment evaporation. These simple equations, based on mean precipitation and the aridity index, provide plausible estimates of mean catchment runoff and, therefore, mean actual catchment evaporation.

5.4 Open-water, shallow lake and pond evaporation

Approximately 30% of the evaporation models were developed to estimate open-water evaporation (Table 1, column 6). Again, the key model is Penman[48] although the majority of the open-water models are based on a mass-transfer approach. Ferguson's 1952 contribution[188] to estimating open-water evaporation using a mass-transfer approach is especially innovative in that he combined the heat and mass-transfer equations through a relationship between the heat and the mass-transfer coefficients[189].

Five radiation-temperature models – Lane, Stewart-Rouse and de Bruin-Keijman[190] (the latter two are based on Priestley-Taylor), Linacre-92 and Linacre-93 models[191] (the latter two are based on Penman-48) – were identified to estimate open-water evaporation. The first three models are calibrated to meet field observations.

The Penman[48] equation with the Penman[10] 1956 wind function is the major development in open-water evaporation modelling using a combination equation. According to Allen[26], there were enhancements to Penman's wind function (Penman and Long[192]; Monteith[128]; van Bavel[11]) and the incorporation of the resistance formulations into the equation (Monteith[128]; Thom and Oliver[193]). In 2006, Valiantzas[139], making a series of assumptions, was able to simplify Penman-48 to an expression that does not include wind, producing the Valiantzas-OW model.

According to Sellers[194], the main difference between the Budyko[4] and Penman[48] procedures for computing evaporation is that Penman eliminates the surface temperature by adopting air temperature whereas in 1956 Budyko(4, page 198 in the English translation) used a trial and error technique to estimate the temperature of the evaporating surface. We have identified two other procedures that follow a trial and error approach, Ferguson[188] (discussed above) and the PenmanR-ow model. The iterative solution adopted in the latter model follows Lascano and van Bavel[154] in which the Murray[195] equation is combined with the Penman-48 model.

Because the characteristics of radiation absorption and vapour pressure between land and water are different, Morton[13] converted the CRAE model to the Morton CRWE (Complementary Relationship Wet-surface Evaporation) model by adjusting the empirical coefficients in a stability factor term and two other coefficients in computing open-water evaporation.

5.5 Lake evaporation where heat storage is taken into account

The difference in estimating evaporation from a deep lake compared with open-water (shallow lake) is that the heat storage in the lake must be taken into account. A deep lake tends to take up heat during the hotter months and release it as latent heat during the cooler months, resulting in a seasonal phase shift in evaporation. Models in this category are listed in Table 1, column 7.

According to Chow[70], Schmidt[196] in 1915 was the first to apply an energy balance to estimating evaporation from a water surface (ocean). Cummings and Richardson[91] were early contributors (1927) to estimating lake evaporation by energy balance utilising the Bowen ratio to account for the unknown sensible heat variable. Two studies that illustrate the energy balance method incorporating the Bowen ratio are Lake Hefner[197] and Lake Mead[198]. The Anderson model used in the Lake Hefner study is:

$$E_{DL} = \frac{R_s - R_{os} + R_{il} - R_{ol} - Q_{bs} + Q_v - Q_x}{\rho_e\left[\lambda(1+B) + c_w(T_e - T_b)\right]} \qquad (14)$$

where R_s is the incident shortwave solar radiation, R_{os} is the reflected shortwave solar radiation, R_{il} is the incident long wave radiation from the atmosphere, R_{ol} is the reflected longwave radiation, Q_{bs} is the longwave radiation emitted by the lake, Q_v is the net energy advected by streamflow, groundwater and precipitation, Q_x is the change in stored energy, λ is the latent heat of vaporisation, c_w is the specific heat of water, ρ_e is the density of evaporating water, T_e is the temperature of the evaporated water, T_b is the reference base temperature, and B is the Bowen ratio. Variations of the energy balance method were developed by Webb[199] (Lake Eucumbene, New South Wales) and Lenters et al.[200] (Sparkling Lake, Wisconsin).

Of the six single-source combination models to estimate lake evaporation, five models – Weather Bureau, Kohler-Parmele, Keijman, Vardavas-Fountoulakis and Finch – are based on the 1948 Penman model, whereas the McJannet procedure is based on the Penman-Monteith model. The contribution of Kohler and Parmele[201] was to add a term to the Penman equation to account for net water-advected energy and the change in energy stored in the lake. In the Vardavas-Fountoulakis model the change in heat storage was added to the net radiation and the coefficients in the Penman wind function were based on four Australian reservoirs[202].

The concept of equilibrium temperature (see Section 5.1) appears to have been first introduced to the estimation of evaporation from large water bodies by Edinger et al.[114] in 1968 and applied by Keijman[203] and Fraedrich et al.[204]. In the Keijman model to estimate lake evaporation, the Penman equation was modified by incorporating the heat capacity of the water layer, assuming the lake was not thermally stratified, and then combined with the Bowen ratio to estimate the daily equilibrium temperature and the daily water temperature. The model uses only standard meteorological data. To account for heat storage, in 2001 Finch[205] also adopted the equilibrium temperature concept in the Finch model in which he follows Keijman[203] and de Bruin[206]. Because the estimation of equilibrium temperature is not explicit, the procedure is not regarded as a simple, quick method. Based on the 1965 Penman-Monteith model and applying the equilibrium temperature concept, the McJannet-PM model[207] offers a method to estimate evaporation not only for deep lakes but also for shallow water bodies. The general approach is similar to Finch[205].

Morton's deep lake model[175] (Morton CRLE model – Complementary Relationship Lake Evaporation) is based on CRWE in which the energy term includes the solar and water inputs for the current and previous months.

5.6 Modelling evaporation pans

Although an evaporation pan is regarded as a crude instrument to measure evaporation[208], Roderick et al.[209] commented "*that the pan evaporation record provides the only direct measurement of changing evaporative demand*" which is important in climate change studies. Evaporation pan data have been used in the past to estimate lake evaporation,[210] open-water evaporation,[211] reference evaporation,[133,212,213] and potential evaporation[214] and pan data have also been used in the interpretation of the Complementary Relationship.[167]

In developing a model to estimate Class-A pan evaporation, Linacre[215] in 1994 modified his simplified version[191] of the 1948 Penman equation and called the model Penpan. A little more than a decade later, Rotstayn et al.[216] combined features of the aerodynamic component of Thom et al.[59] with the radiative component of Linacre[215] to develop another Class-A pan evaporation model known as PenPan. (Readers should note there is a difference between the designations Penpan and PenPan.) Both models have been shown to perform well across a range of climates[23 Supplementary Material,216-218].

5.7 Miscellaneous techniques across all applications

A small number of models have been allocated to this class, and they include two interesting models. The first is a finite difference approach (Finch-Gash model) to estimate evaporation from a lake where there is heat storage[219]. The second interesting model is by de Bruin,[220] who combined the Penman and Priestley-Taylor equations thus eliminating the net radiation term, to yield the de Bruin model from which open-water evaporation can be estimated without recourse to radiation data. de Bruin[220] observed that the model is very sensitive to the value of Priestley-Taylor α_{PT}.

5.8 Interception evaporation

In water balance studies, interception and, therefore, interception evaporation are key processes. A review of the interception process is beyond the scope of this review. Readers are referred to Muzylo et al.[221] and to McMahon et al.[23]. Suffice to say that there are two important interception models, Rutter[222,223] and Gash[224]. Penman[10] is incorporated in the Rutter model and Penman-Monteith is used in the Gash model.

6 Discussion

6.1 Model types

From our analysis, summarised in Table 2, we observe that models based on mass-transfer approaches (35%), single-source combination models (21%) and radiation-temperature models (14%) make up approximately 70% of the evaporation models. Furthermore, more than half the mass-transfer models were found to follow the general form of Equation (2) and, generally, are locally calibrated where field observations of evaporation rates are available. Other models include: those based on the Complementary Relationship (5%) and on temperature alone (5%), multi-source combinations (5%) and Budyko-like models (4%).

6.2 Key modellers and modelling

From the time of Dalton's work (~1800) to the middle of the 20th century, there was little theoretical development in advancing the relationship based on Dalton's work. Analysts adopted an empirical mass-transfer approach in establishing an evaporation equation to fit their data. Nevertheless, several important non-Dalton developments occurred including the Bowen ratio and understanding the evaporation processes through atmospheric turbulence.

But in contrast to that 150 year period, over the past 65 years there has been continuous development of evaporation models in which the works of Penman[48], in 1948, Monteith[128], in 1965, and Priestley and Taylor[112], in 1972, have provided the starting points for development. The Penman combination equation is the basis of many non-Dalton and non-Budyko models. Monteith(110, page 2) wrote that "*The thermodynamic and aerodynamic aspects of evaporation were not fully reconciled until, in 1948, Howard Penman published a paper which has become one of the major classics of microclimatology; 'Natural evaporation from open water, bare soil and grass.' The Penman formula was soon adopted by hydrologists and irrigation engineers, but meteorologists were more cautious*". To illustrate the importance of the Penman model in estimating evaporation, Table 3 shows the time-sequence of the Penman, Penman-Monteith and Priestley-Taylor developments. The 56 models listed evolved from Penman and eighteen combination models followed from Penman-Monteith.

Given that the Priestley-Taylor work is the basis of 14 evaporation models (Table 3), it is noteworthy that Monteith[110] argued that the Priestley-Taylor formula was inadequate for two reasons: 1) there is no theoretical explanation why α_{PT} should be approximately constant at 1.26; 2) that the equation "*takes no account of the aerodynamic properties and physiological behaviour of the (evaporating) surface*"(110, page 23). Since the Priestley and Taylor publication in 1972 there have been many measured estimates of α_{PT} ranging from 0.53-1.57(23, Table S8). Also, there have also been a number of theoretical and analytical studies dealing with α_{PT} (20,117,225). For example, according to Pereira[226]

$$\alpha_{PT} = \Omega^{-1} = \left[1 + \frac{\gamma}{\Delta + \gamma} \frac{r_c}{r_a} \right] \tag{15}$$

where Ω is termed the decoupling factor[227]. Lhomme[20] concluded that α_{PT} is Hl for a saturated area surrounded by water, Hl.3 for saturated grass surrounded by well-watered grass and is >3 for saturated forest surrounded by forest. The Agam et al.[117] paper illustrated how the Priestley and Taylor model[112] can be applied to modelling a combination of soil and canopy transpiration, the latter being an exponential function of LAI (leaf area index).

Monteith[128] modified Penman's 1953 equation[126] for a single leaf to deal with a canopy. Also he was an early contributor to estimating actual evaporation by adjusting potential evaporation as shown in Equation 12. The Complementary Relationship defined by Equation 13 is the basis of the development of five important models (Brutsaert-Stricker, Morton CRAE, Morton CRWE, Morton CRLE and Szilagyi-Jozsa) to estimate actual evaporation from terrestrial environments and lakes. Both Morton and Brutsaert played key roles in these developments.

6.3 Temperature of evaporating surfaces

For more than 50 years, attempts have been made to estimate computationally the temperature of an evaporating surface. Penman bypassed this issue by assuming the slope of the vapour pressure-temperature curve could be computed using the atmospheric temperature rather than the unknown surface evaporating temperature. It is probable that Budyko was one of the first to estimate the surface temperature[194], but Budyko would have been hampered by the lack of computational power to find a solution by iteration. Assuming there is no thermal stratification in a lake, Keijman[203] and de Bruin[206] used an equilibrium temperature (T_e) concept to estimate the surface water temperature. Morton[12] approached the problem by equating the energy-balance and the vapour transfer equations and solving iteratively for T_e. With small variations, Finch[205] and McJannet et al.[207] followed the same approach as de Bruin[206] and Keijman[203] to estimate the equilibrium surface temperature. Finally, Szilagyi and Jozsa[179] in their model used an iterative procedure based on the Bowen ratio to estimate T_e.

6.4 Reducing input data

Continuing attempts have been made to reduce the number of variables and hence meteorological data required to estimate evaporation by the Penman or Penman-Monteith models. Linacre developed four models - Linacre[228] for both lakes and well-watered vegetation, Linacre[191] for lakes, Linacre[215] for a class-A evaporation pan. Valiantzas[139] produced two models, one for a reference crop and the other for open-water. These models perform satisfactorily, although they have not been extensively tested.

6.5 Model applications

The 166 evaporation models which were surveyed for this review are mainly used for estimating open-water evaporation and estimating actual terrestrial evaporation. Of the 47 models to estimate open-water evaporation listed in Table 1, 15 are non-mass-transfer techniques which offer a wide range of procedures. However, the key methods are Penman-48 and Morton CRWE. In terms of meteorological data, Penman-48 requires the four standard elements (radiation, temperature, humidity, and wind) whereas Morton does not require wind. Although several of the mass-transfer open-water models were probably calibrated to deep lake evaporation, procedures to estimate lake evaporation, where heat storage needs to be accounted for, are based on energy balance, combination models and the complementary relationship. It is recognised that estimating actual terrestrial evaporation is difficult, yet excluding the seven Budyko-like models, 27 models have been developed to estimate actual evaporation. A number of these do require additional information over and above standard meteorological data; for a terrestrial environment, canopy resistance is the main additional data required.

7 Conclusions

Over the past 350 years there have been many researchers who have made significant contributions to the science of evaporation. From this review of 166 evaporation models, we identified several key dates and researchers who have been at the forefront of evaporation modelling. Three dates standout – 1674, 1802 and 1948. The earliest date credits Perrault with being the first to experimentally measure evaporation. The establishment by Dalton of the principles that led to the mass-transfer equation occurred in 1802. In 1921, Cummings proposed an approximate energy balance equation which, in 1948, Penman combined with Dalton's mass-transfer equation to develop the Penman combination equation. A key input in this history is the Bowen ratio[97], published in 1926, which was a year prior to the Cummings and Richardson[91] paper on evaporation from lakes.

Following Penman, the next major development was by Monteith[128] in 1965. He modified Penman's 1953 equation for a single leaf to deal with the canopy which led to the Penman-Monteith model(110, footnote page 8). This model is the basis of the FAO56 Reference Crop model and ASCE standardized Reference Evapotranspiration Equation. 1972 saw the introduction of the Priestley and Taylor model which underpins a number of subsequent models.

Although Morton introduced the application of the Complementary Relationship to estimating regional evaporation in 1965, his final model was not published until 1983. In the meantime, more than a decade earlier, Brutsaert and Stricker provided an equation to estimate actual regional evaporation using the Complementary Relationship.

Budyko made two important contributions. Firstly, he developed a potential evaporation equation, similar to Penman's combination equation, in which the temperature of the evaporating surface was estimated by iteration. Budyko's second contribution relates to the Budyko-like models where he developed a simple relationship to estimate runoff and in turn mean annual actual evaporation.

The time-line in Figure 1 highlights these contributions.

Acknowledgements

Murray Peel is the recipient of an Australian Research Council Future Fellowship (FT120100130). We are grateful to our colleague, Justin Costelloe, who pointed out the quotation from Ecclesiastes 1:7.

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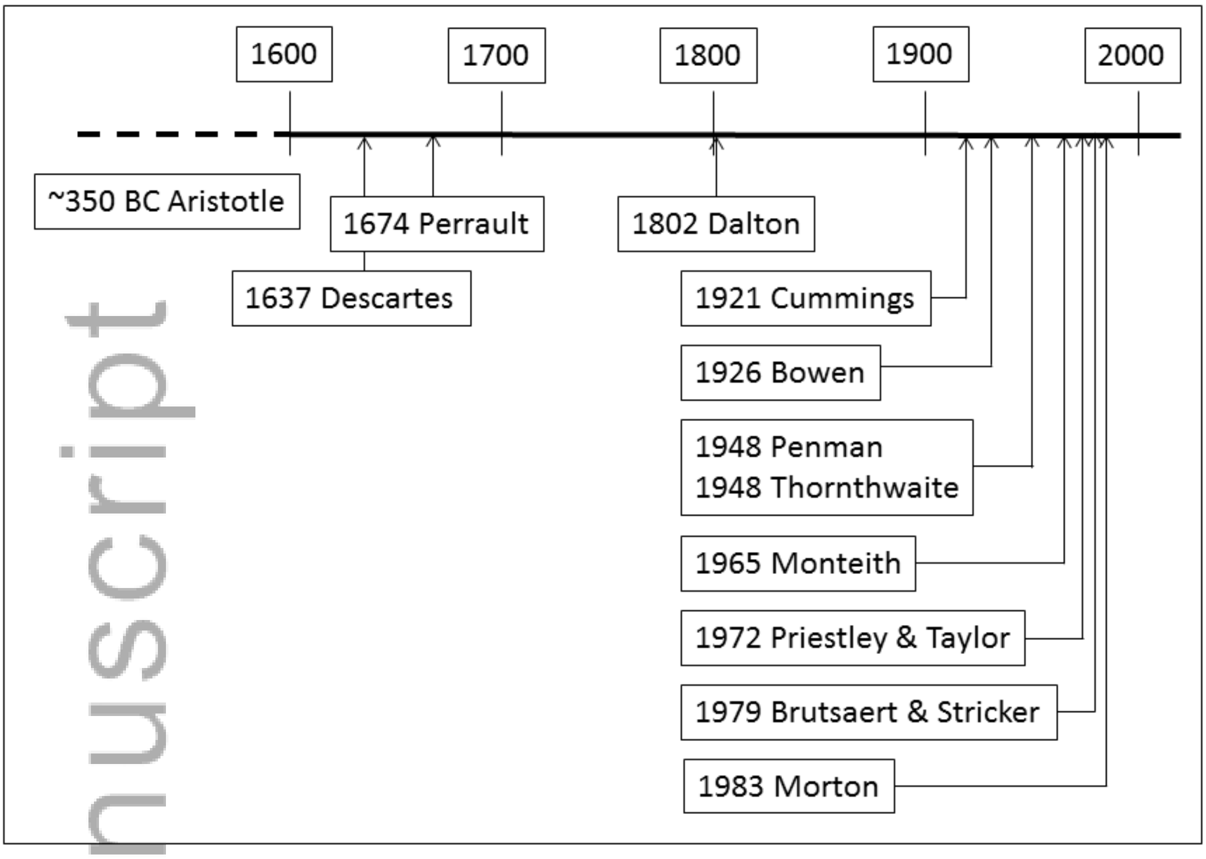
Figure Legends

Figure 1. Time-line showing key evaporation and modelling processes. (Specific references to these contributors are noted in the text and listed in the reference list.)

Figure 2. The relation between evaporation and temperature in Edmund Halley's evaporation data for the year 1693. The temperature scale used is not known but appears to have the freezing point of water at 0° and based on mid-summer temperatures in London[81] the upper end of his data would be ~20°C. 1 grain = 0.065 grams. (Source of data: Halley, 1694)[80].



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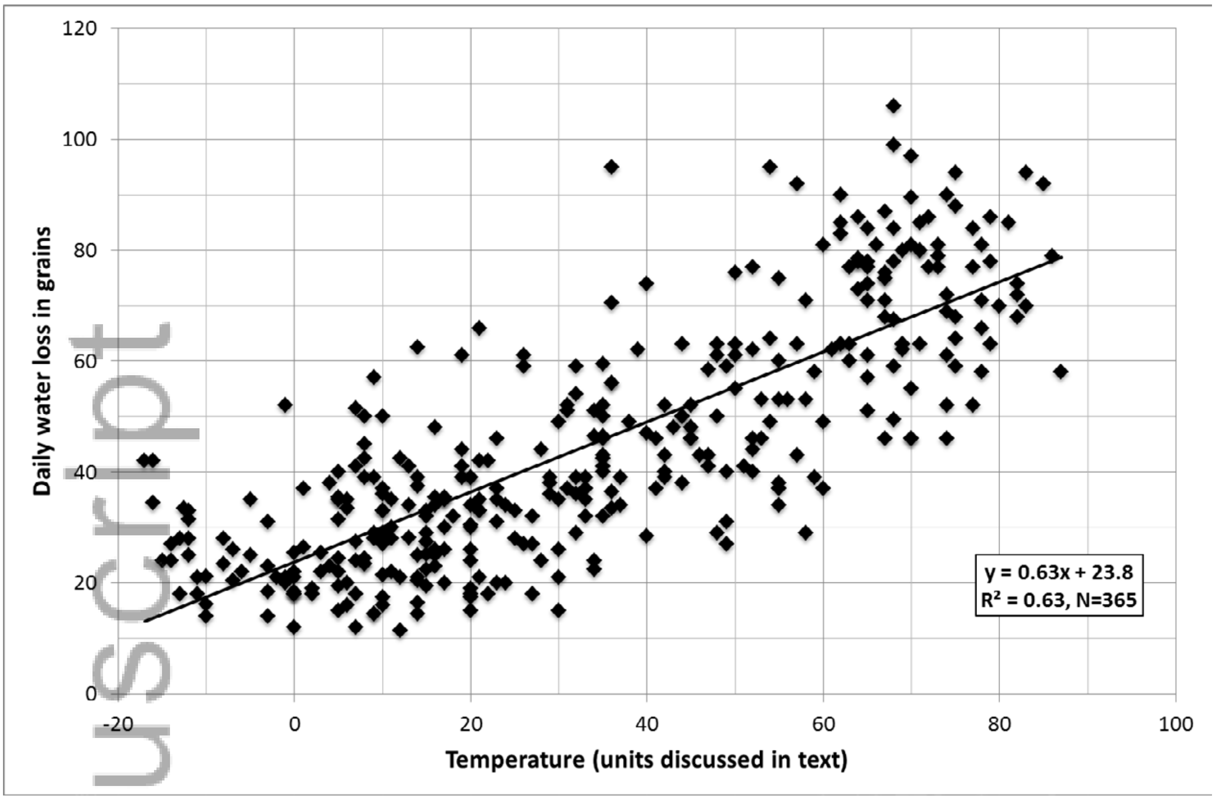

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Table 1. List of 143 evaporation models categorised by type, application and date (This list does not include 23 simple mass-transfer equations with different empirical coefficients. Models highlighted as shading are discussed in Section 5. A more complete set of references to the models and the relevant equations are listed in the Table S1, Supplementary Material).

Year (1)	Reference (2)	Potential Evaporation (3)	Reference (grass, crop) and related evapotranspiration (4)	Actual evaporation from non-saturated surfaces (5)	Open water, shallow lake and pond evaporation (6)	Lake/storage (heat storage explicitly accounted) evaporation (7)	Class-A pan or other (8)
Models based on mass-transfer (Dalton's relationship)							
1802	Dalton (1802)[3]				Dalton		
1871	Livingston (1909)[45]				Mann		
1877	Livingston (1909)[45]				Weilenmann		
1880	Livingston (1909)[45]				Masure		
1886	Rohwer (1931)[229]				Fitzgerald		
1889	Rohwer (1931)[229]				Carpenter		
1896	Livingston (1909)[45]				Trabert		
1902	Livingston (1909)[45]				Schwalbe		
1909	Marvin (1909)[93]				Marvin		
1919	Rohwer (1931)[229]				Horton		

1921	Giblett (1921) [96]		Giblett	
1931	Rohwer (1931) [229]			Rohwer
1937	Marciano & Harbeck (1954) [230]		Sverdrup-37	
1937	Marciano & Harbeck (1954) [230]		Millar	
1939	Thornthwaite & Holzman (1939) [94]	Thornthwaite-Holzman		
1946	Marciano & Harbeck (1954) [230]		Sverdrup-46	
1952	Ferguson (1952) [188]		Ferguson	
1955	Bormann (2011) [39]		Haude	
1955	Kohler et al. (1955) [210]			Kohler
1957	Helfrich et al. (1982) [89]		Rimsha-Donchenko	
1958	Harbeck & Kohler (1958) [231]		Lake Mead-58	
1960	Webb (1960) [199]		Webb	
1962	Harbeck (1962) [232]		Harbeck	
1963	Bormann (2011) [39]		Brockamp-Wenner	

1968	Singh & Xu (1997) [28]		Konstantinov
1969	Helfrich et al. (1982) [89]		B-G-G
1973	Helfrich et al. (1982) [89]		Ryan-Harleman
1975	Helfrich et al. (1982) [89]		Weisman
1976	Helfrich et al. (1982) [89]		G-S-McC
1983	Sill (1983) [107]		Sill
1983	Szeicz & McMonagle (1983) [233]		Szeicz-McMonagle
1989	Sartori (2000) [30]		Sartori
1994	Sartori (2000) [30]		Hahne-Kuber
1997	Lee & Swancar (1997) [109]		Lee-Swancar
2012	McJannet et al. (2012) [40]		McJannet-OW
Temperature models			
1945	Blaney & Criddle (1962) [234]	Blaney-Criddle	
1948	Thornthwaite (1948) [7]	Thornthwaite	
1969	Behnke & Maxey (1969) [235]	Behnke-Maxey	

1970	Nichols et al. (2004) [236]	Blaney-Criddle-70					
1977	Linacre (1977) [228]				Linacre-77W		
1977	Linacre (1977) [228]		Linacre-77V				
1994	Feddes & Lenselink (1994) [237]	Modified Blaney-Criddle					
1998	Allen et al. (1998) [133]		PMT				
Radiation-temperature models							
1957	Makkink (1957a) [119]	Makkink					
1961	Alexandris et al. (2008) [238]	Turc					
1963	Jensen and Haise (1963) [239]	Jensen-Haise					
1963	Stephens & Stewart (1963) [240]	Stephens-Stewart-P					
1963	Stephens & Stewart (1963) [240]						Stephens-Stewart-pan
1964	Cruff & Thompson (1967) [241]				Lane		
1971	Camargo & Camargo (2000) [242]	Camargo-71					

1972	Priestley and Taylor (1972) [112]	Priestley-Taylor			
1973	Davies & Allen (1973) [243]			Davies-Allen	
1975	Hargreaves (1975) [244]		Hargreaves radiation		
1976	Stewart & Rouse (1976) [245]				Stewart-Rouse
1977	Doorenbos and Pruitt (1977) [22]		FAO24-radiation		
1979	de Bruin & Keijmann (1979) [190]				de Bruin-Keijman
1979	Barton (1979) [246]			Barton	
1984	Hansen (1984) [120]	Makkink-Hansen			
1985	Hargreaves & Allen (2003) [134]; Hargreaves & Samani (1985) [135]		Hargreaves-85 (also designated as Hargreaves-Samani)		
1990	Sahoo et al. (2012; 2013) [247,248]		Jones-Ritchie		
1991	Meek & Phene (1991) [136]		Improved Hargreaves		
1992	Linacre (1992) [249]				Linacre-92

1993	Linacre (1993) [191]				Linacre-93		
2002	Droogers & Allen (2002) [250]		Modified Hargreaves				
2009	Trajkovic & Kolakovic (2009) [251]		Adjusted Turc				
2012	Ravazzani et al. (2012) [252]		Modified HS				
Energy balance methods							
1927	Cummings & Richardson (1927) [91]					Cummings-Richardson	
1954	Anderson (1954) [197]					Anderson	
2005	Lenters et al. (2005) [200]					Lenters	
Combination methods – single source models							
1948	Penman (1948) [48]				Penman-48		
1955	Kohler et al. (1955) [210]					Weather Bureau	
1956	Penman (1956) [10]				Penman-56		
1956	Lascano & van Bavel (2007) [154]				PenmanR-ow		
1956	Lascano & van Bavel			PenmanR-act			

	(2007) [154]					
1956	Budyko (1956) [4]	Budyko-56				
1960	Slatyer & McIlroy (1961) [113]	McIlroy-P				
1960	Slatyer & McIlroy (1961) [113]			McIlroy-A		
1964	Sellers (1964) [194]	Sellers				
1965	Monteith (1965) [128]	Penman-Monteith-P				
1965	Monteith (1965) [128]			Penman-Monteith-A		
1965	Keijman (1981) [253]	Rijtema				
1966	van Bavel (1966) [11]	van Bavel				
1967	Kohler & Parmele (1967) [201]					Kohler-Parmele
1974	Keijman (1974) [203]					Keijman
1982	Wright (1982) [254]		Kimberly-Penman			
1983	Shi et al. (2008) [255]			Katerji-Perrier		
1988	Paw U and Gao (1988) [156]			PawU-Gao		
1989	Granger and Gray			Granger-Gray		

	(1989)[158]					
1991	Milly (1991)[157]		Milly			
1994	Linacre (1994)[215]					Penpan
1996	Vardavas & Fountoulakis (1996)[202]				Vardavas-Fountoulakis	
1998	Allen et al. (1998)[133]	FAO56-RC				
1999	Todorovic (1999)[138]	Todorovic				
2000	ASCE (2000)[31]; Allen et al. (2005)[256]	ASCE-PM				
2001	Finch (2001)[205]				Finch	
2006	Valiantzas (2006)[139]			Valiantzas-OW		
2006	Valiantzas (2006)[139]	Valiantzas-RC				
2006	Rotstayn et al. (2006)[216]					PenPan
2008	McJannet et al. (2008)[207]				McJannet-PM	
2009	Shuttleworth & Wallace (2009)[145]	Matt-Shuttleworth				
2013	Valiantzas (2013c)[142]	Fo-PM (Rs,T,RH)				
2013	Valiantzas (2013c)[142]	Fo-PM (Ra,T,RH)				

2015	Tegos et al. (2015) [129]	Parametric					
2015	Valiantzas (2015) [144]		Fo-HUMID(R_s,T)				
Combination methods – multi-models							
1985	Shuttleworth & Wallace (1985) [161]			Shuttleworth-Wallace			
1988	Choudhury & Monteith (1988) [257]			Four-layer			
1994	Wessel & Rouse (1994) [258]			Weighted Penman-Monteith			
1997	Brenner & Incoll (1997) [259]			Clumped three-source			
1997	Hough & Jones (1997) [260]			MORECS			
2012	Lhomme et al. (2012) [261]			Two-layer			
2012	Lhomme et al. (2012) [261]			Clumped			
2013	Lhomme et al. (2013) [262]			n-component canopies			
Multi-variable models							
1960	Christiansen (1960, 1966) [263, 264]						Christiansen

1964	Christiansen (1966) [264]			Grassi			
1965	Christiansen (1966) [264]						Mehta
1966	Griffiths (1966) [265]						Griffiths
1977	Doorenbos and Pruitt (1977) [22]		FAO24-Blaney-Criddle				
Models based on the Complementary Relationship							
1979	Brutsaert and Stricker (1979) [178]			Brutsaert-Stricker			
1983	Morton (1983a) [12]			Morton CRAE			
1983	Morton (1983b) [13]				Morton CRWE		
1986	Morton (1986) [175]					Morton CRLE	
2007	Szilagyi and Jozsa (2008) [179]			Szilagyi-Jozsa			
2010	Crago et al. (2010) [181]			Modified A-A			
2011	Han et al. (2011) [184]			Granger A-A			
2012	Han et al. (2012) [185]			Han NLF			
2014	Anayah and Kaluarachchi (2014) [186]			GG18			
Budyko-like models							

1904	McMahon et al. (2013) [23]			Schreiber			
1911	Oldekop (1911) [8]			Oldekop			
1954	Pike (1964) [266]			Turc-Pike			
1956	Budyko (1956) [4]			Budyko-annual			
1981	Zhang et al. (2004) [187]			Fu-Zhang			
2001	Zhang et al. (2001) [267]			Zhang			
2009	Potter & Zhang (2009) [268]			Potter-Zhang			
Miscellaneous models							
1908	Bigelow (1908) [269]				Bigelow		
1940	Prescott (1940) [270]						Prescott
1942	Cruff & Thompson (1967) [241]			Lowry-Johnson			
1961	Hamon (1961) [271]	Hamon					
1961	Singh & Xu (1997) [28]				Romanenko		
1966	Reid et al. (1976) [272]	Papadakis					
1967	Eagleman (1967) [273]	Eagleman					
1967	Bormann (2011) [39]				Schendel		

1978	de Bruin (1978) [220]		de Bruin		
2002	Finch & Gash (2002) [219]			Finch-Gash	

Table 2. Distribution of types and applications of 166 evaporation models.

Model type	Application						Percentage of total models
	Potential	Reference crop	Actual	Open-water	Lakes/Storage	Pan	
Mass-transfer	0	0	1	55	0	2	34.9
Temperature	5	2	0	1	0	0	4.8
Radiation-temperature	7	8	2	5	0	1	13.9
Energy balance	0	0	0	0	3	0	1.8
Combination-single source	7	9	7	4	6	2	21.1
Combination-multi-source	0	0	8	0	0	0	4.8
Multivariate	0	1	1	0	0	3	3.0
Models based on CR	0	0	7	1	1	0	5.4
Budyko-like	0	0	7	0	0	0	4.2
Miscellaneous	3	0	1	4	1	1	6.0
Percentage of total models	13.3	12.0	20.5	42.2	6.6	5.4	100

Table 3. Linkages between models that are based on or have the same form as Penman, Penman-Monteith or Priestley-Taylor models.

Year	Penman	Penman-Monteith	Priestley-Taylor
1948	**Penman-48**		
1955	Weather Bureau		
1956	Penman-56		
1956	PenmanR-ow		
1956	PenmanR-act		
1960	McIlroy-P		
1960	McIlroy-A		
1965	**Penman-Monteith** →	Penman-Monteith-P	
1965		Penman-Monteith-A	
1965		Ritjema (developed independently of P-M model)	
1966	van Bavel		
1967	Kohler-Parmele		
1972	**Priestley-Taylor** →		Priestley-Taylor
1973			Davis-Allen
1974	Keijman		
1976			Stewart-Rouse
1977	Linacre-77V		
1977	Linacre-77W		
1978	De Bruin		De Bruin
1979	Bruisaert-Stricker		Bruisaert-Stricker
1979			De Bruin-Keijman
1979			Barton
1982	Kimberley-Penman		
1983	Morton CRAE		Morton CRAE
1983	Morton CRWE		Morton CRWE

1983		Katerji-Perrier	
1985		Shuttleworth-Wallace	
1986	Morton CRLE		Morton CRLE
1988		Four-layer	
1989	Granger-Gray		
1993	Linacre-92		
1993	Linacre-93		
1994	Penpan		
1994		Weighted Penman-Monteith	
1996	Vardavas-Fountoulakis		
1997		Clumped three source	
1997		MORECS	
1998		FAO56-RC	
1998		PMT	
1999		Todorovic	
2000		ASCE-PM	
2001	Finch		
2006	Valiantzas-OW		
2006	Valiantzas-RC		
2006	PenPan		
2007	Szilagyi-Jozsa		Szilagyi-Jozsa
2008		McJannet	
2009		Matt-Shuttleworth	
2010	Modified A-A		Modified A-A
2011	Granger A-A		Granger A-A
2012	Han-NLF		
2012		Two-layer	
2012		Clumped	
2013		n-component canopies	

2013		Fo-PM (variations)	
2013	GG18		GG18
2015		Fo-HUMID(Rs,T)	