Droplet evaporation losses during sprinkler irrigation: an overview

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Abstract

A detailed understanding regarding the evaporation losses in sprinkler irrigation is important for developing as well as adopting appropriate water conservation strategies. To explain this phenomenon many theoretical and experimental studies have been conducted since the 1950's. Notwithstanding all these efforts, the contribution of droplet evaporation to the total evaporation losses during sprinkler irrigation is still a controversial issue in the irrigation community. There is a substantial difference among researchers regarding the magnitudes of the different components of the total evaporation in sprinkler irrigation especially droplet evaporation losses. Field studies reported that the droplet evaporation losses ranged from 2 – 45%, whereas theoretical studies indicated that it is less than 1%. This is due largely to the limitations of the traditional measurement methods. However, it is likely that these limitations can be overcome and accurate measurements obtained using the eddy covariance (ECV) technique.

Key words: Sprinkler irrigation, droplet evaporation, eddy covariance.

Introduction

Sprinkler irrigation is becoming a preferred method as the water available for irrigation around the world becomes increasingly scarce, especially in arid and semi arid regions. However, little is known about its performance in terms of water use efficiency under field conditions. The efficiency of sprinkler irrigation depends on the evaporation losses, which include the droplet evaporation, soil evaporation and canopy evaporation that occur from when water leaves the sprinkler nozzle until it reaches the root zone (Steiner *et al.* 1983). Among these, droplet evaporation (the water that evaporates directly from the droplets to the atmosphere during travel) is frequently assumed to be a major source of water loss. However, there is a substantial difference among the researchers regarding the losses. Evaporation loss is often cited by growers as a reason not to adopt sprinkler irrigation.

To tackle this problem, many theoretical and experimental studies have been conducted since the 1950s. Since these studies are not defined under same terms and conditions, the results vary a great deal with losses ranging from 2% to 40% (Kincaid *et al.* 1996; Kolh *et al.* 1987; Yazar 1984). Notwithstanding all the efforts, the phenomenon of droplet evaporation has not been adequately quantified and the technical literature provides conflicting results with a wide range of estimates for this loss. The reason is that the field techniques used to estimate the losses have severe limitations and large measurement uncertainties of traditional methods. However, due to the recent advancement of the eddy covariance (ECV) system it is hypothesized that the total evaporation during sprinkler irrigation can be partitioned into its different components using this technique in conjunction with additional measurements such as transpiration by the sap flow method and canopy evaporation by the energy balance method.

Water balance under sprinkler irrigation

Sprinkler irrigation is a method of applying water to the soil by sprinkling (discharged of water from nozzle) of water into air. In this method water emitted from the nozzle forms a water jet, which impacts against a deflector plate and disperses as a thin sheet or thin streams called ligaments. The ligaments then break up into droplets due to surface tension and aerodynamic drag forces as they travel from the nozzle point to the soil surface. During the travel some portion of the water evaporates from the droplets to the atmosphere (called droplet evaporation) and some drifts outside the irrigation area (drift loss) (McLean *et al.* 2000). The remainder of the water enters the canopy as precipitation. This portion of the water is partitioned between canopy interception and direct throughfall to the soil. Canopy interception can be further divided into the portion remaining on the leaves and another part dripping onto the lower leaves or the soil and running down the stem to the soil. The water remaining on the leaves (intercepted water) is then evaporated to meet the atmospheric demand and is called canopy evaporation (Wang *et al.* 2006). The soil water from direct throughfall is then partitioned into four component viz.: (i) the portion of water evaporated from the surface through evaporation (called soil evaporation), (ii) the portion that is lost by direct runoff, (iii) the portion of water which is available in the root zone for plant intake, and (iv) the portion of water lost by deep percolation. However, runoff and deep percolation can usually be considered negligible in sprinkler irrigation (Thomson 1986).

Physical process

Evaporation losses in sprinkler irrigation take place through the exchange of energy driven by the difference in temperature between droplets and their environment in three parts: (i) energy exchange between the water droplets and atmosphere above the canopy, (ii) exchange between water droplets and canopy, and finally (iii) exchange of energy between water droplets and soil (Thomson 1986).The evaporation of a liquid drop is essentially a combined process of mass and heat transfer. In this operation the heat for evaporation is transferred by conduction and convection from the environment to the surface of the droplet from which vapour is transferred by diffusion and convection back into the atmosphere (Ranz & Marshall 1952). Ranz & Marshall also mentioned that the rate of mass transfer per unit area of interface is a function of temperature, vapour pressure deficit, and the diameter & temperature of the droplets. Hardy (1947) described that when liquid is sprayed (discharged from the sprinkler nozzle) into the air which has a different temperature, the temperature of the droplets will change depending upon the rate at which the heat is transferred to, or from, the air both by convection and evaporation.

Factors affecting evaporation losses

There are many equipment-related factors (such as nozzle size, angle, operating pressure and height of the sprinkler) and climatic factors (like air temperature, air friction, relative humidity, solar radiation and wind velocity) that contribute to evaporation losses.

Frost and Schwalen (1955) found that evaporation losses are directly proportional to wind velocity and operating pressure and inversely proportional to relative humidity of the air and nozzle size. A close relationship between losses and vapour pressure deficit of the air was also obtained by Christiansen (1942) and Frost and Schwalen (1955). Hermsmeier (1973) suggested that air temperature and rate of application were more important factors responsible for evaporation losses than wind velocity or relative humidity. Abo-Ghobar (1993) reported that the evaporation losses increased with decreasing nozzle size, relative humidity and increased with air temperature and wind velocity. Lorenzini (2002) found that the evaporation losses greatly effect by air temperature with a logarithmic relation. Yazar (1984) observed that wind speed and vapour pressure deficit are the predominant factors that affect evaporation losses significantly during sprinkler irrigation. He concluded that the losses are exponentially correlated with wind speed and vapour pressure deficit. Operating pressure had very little effect on the evaporation losses.

Droplet size resulting from the nozzle is most important factor in evaporation losses. Kohl *et al.* (1987) reported that small droplets are more susceptible to evaporation. Equipment variables that affect the droplet diameter are the nozzle size, geometry, and operating pressure.

The size of droplets was found proportional to the nozzle diameter Kohl and Wright (1974) and Dadiao and Wallender (1985) and inversely proportional to the operating pressure.

Many researchers have reported that the diameter of the nozzle played a major role in the break up of the droplets and indirectly influenced the evaporation losses (Kohl and Wright 1974, Solomon *et al.* 1985). Frost and Schwalen (1955) found that a 25% increase of nozzle operating pressure increased the evaporation losses by 25%. They also noted that smaller nozzle diameters tended to break up the droplets leading to greater evaporation losses. Edling (1985) and Thompson *et al.* (1993) found that, the drift and evaporation losses are inversely proportional to the droplet diameter, whereas Lorenzini (2004) and De Wrachien and Lorenzini (2006) proposed that the evaporation losses are directly proportional to the droplet diameter.

Magnitude of the losses

Many studies (e.g. field tests, laboratory, analytic and physical-mathematical) have been conducted to quantify the magnitude of the evaporation and drift losses during water application by means of sprinkler irrigation. However, these studies were not defined under the same terms and conditions, had different accuracy levels, and attained results that varied greatly. Frost and Schwalen (1955) found that the droplet evaporation losses at the time of sprinkler irrigation were as high as 35-45% under extreme conditions. Kincaid *et al.* (1996), Kolh *et al.* (1987) and Yazar (1984) reported losses that varied from 2 to 40% (mostly 10-20%) from field tests. Analytic and laboratory investigations reported losses that ranged from 0.5 to 2% (Kohl *et al.* 1987). From laboratory tests Kincaid and Longley (1989) found that droplet evaporation losses in sprinkler irrigation are usually less than 2-3%, even under high air temperature and low relative humidity. Under normal conditions they were almost negligible. In comparison, under moderate evaporative condition the losses should not be more than be 5-10% (Keller & Bliesner 1990). Innoue and Jayasinghe (1962) calculated that the droplet loss during sprinkler irrigation should not be more than 6% considering the rate of heat flow into the droplet. Similarly, Thomson (1986) observed that the transfer of energy to droplets during flight is not sufficient for evaporating more than 1 to 2% of their volume. Using a modelling approach, Edling (1985) computed droplet evaporation losses during sprinkler irrigation ranging from 0.5-20% at different operating and climatic conditions. Thomson *et al.* (1993b, 1997) predicted that the droplet evaporation loss throughout the irrigation was less than 1%. They also pointed out that in some cases it is almost negligible. Most recently, Lorenzini (2004) estimated using an analytical model that the upper limit values of droplet evaporation varied from 3.7 to 8.6% for the droplet diameters ranging from 0.3 to 3mm.

Impacts of droplet evaporation on microclimate

Droplet evaporation during sprinkler irrigation is not only a direct loss of water, but it also has a significant effect on microclimate. It improves the microclimate of the irrigated area by reducing temperature (Thomson *et al.* 1993b; Tolk *et al.* 1995) and vapour pressure deficit (Chen 1996; Tolk *et al.* 1995) which leads to a decrease in the transpiration (Tolk *et al.* 1995) and soil evaporation. Norman and Campbell (1983) stated that during sprinkler irrigation, transpiration may be zero due to evaporation from intercepted water on leaves and soil. Reduction of crop transpiration and soil evaporation results in the conservation of soil water that would otherwise be depleted by the crop (McNaughton 1981; Steiner *et al.* 1983). It can reduce the gross interception loss by 6.6% via suppression of transpiration by 50% or more during irrigation (Tolk *et al.* 1995). Thomson *et al.* (1997) stated that the significant impact of sprinkler irrigation is the reduction of net evaporation losses by 7.2% and 2.6% for impact and spray type sprinkler nozzles respectively by depressing transpiration. More recently, Martinez-Cob *et al.* (2008) found a significant decrease in evapotranspiration (32-55%) and transpiration (58%) during irrigation compared to the dry (without irrigation) period.

Liu and Kang (2006) reported that field microclimate can be affected significantly by sprinkler irrigation not only during the period of irrigation but also during the irrigation intervals. They observed that VPD and air temperature above the canopy were lower in the sprinkler irrigated field compared to surface irrigated fields throughout the irrigation interval where the effect on temperature lasted 2-3 days after the irrigation. They revealed that the evaporation over this period was about 3-11% lower in a sprinkler irrigated field compared to the surface irrigated field during three winter seasons. Similarly, Kang *et al.* (2002) found that the cumulative surface evaporation on the top of the canopy under sprinkler irrigation was 12% lower than that under surface irrigation.

It is generally believed that the droplet evaporation and interception are not entirely losses since they partly contribute to decrease the crop water requirements. McNaughton (1981) indicated that the part of droplet evaporation replacing crop ET, should be regarded as crop consumptive and beneficial, whereas Burt *et al.* (1997) described it as consumptive but non beneficial.

Studies on evaporation losses during sprinkler irrigation

Experimental studies

The losses are conventionally determined in the field from volumetric or gravimetric measurement of water collected in catch-cans. The inherent problem in this method is that estimated droplet evaporation loss includes the water evaporated from the catch-cans during the irrigation. Accurate measurement of water that reaches the ground is also very difficult especially in windy conditions which increase the sampling area due to drift. To avoid these difficulties of measurement, wind drift loss are often included with the evaporation losses (McLean *et al.* 2000). Kohl *et al.* (1987) reported that measurements using catch-cans commonly have experimental errors. Jenson (1980) pointed out that investigators have applied corrections to account for these errors, but accurate measurements are difficult to achieve. Since there are no alternative methods to measure the loss, most of the studies have been conducted by this method. However, they differed in the details of the method.

Christiansen (1942) was the pioneer in both experimental and theoretical research concerning evaporation losses from sprinkler irrigation. He investigated the droplet evaporation losses from sprinklers by using catch-cans under different climatic and operating conditions at Davis, California. He also developed a theoretical equation to predict the evaporation losses during sprinkler irrigation on the basis of thermodynamic principles. He estimated from field tests that the losses ranged from less than 10 to 40% in the afternoon and approximately 4% in the morning. On the other hand, he predicted by his proposed equation that the evaporation losses from the droplets is negligible compared to the losses from crop canopy and soil.

Using the catch-cans technique, Frost and Schwalen (1955) estimated the droplet evaporation losses were as high as 35-50% during the day time under extreme conditions of bright sunlight, high air temperature and low humidity which prevail in Arizona.

To minimize the errors in the catch-cans method, George (1957) used an electrical conductivity (EC) method to estimate the droplet evaporation loss. He found that the losses ranged from 2% at a relative humidity of 48% with wind velocity 1.79 m/s to 15% at a relative humidity of 14% and wind speed of 9.95 m/s. Based on George's work, Hotes (1969) reported that the droplet evaporation losses during sprinkler irrigation may be 4% under most conditions. Hermsmeier (1973) carried out an experiment in the Imperial Valley of California using the electrical conductivity method and placing oil in the catch cans to reduce the evaporation from the catch container. He determined that the estimated evaporation loss was reduced by 17.2% from that measured without oil.

Myers *et al.* (1970) conducted an experiment in an environmental control chamber at Gaineville, Florida and estimated the losses as 0.2-1.1%, while the evaporation from the canopy surface varied from 3.5 to the 60% of the total volume applied. They also observed that evaporation loss during flight would not more than 5% under most conditions.

Using potassium ions as a chemical tracer in the irrigation water Kohl *et al.* (1987) measured the evaporation losses as 0.5 to 1.4% for smooth spray plates and 0.4 to 0.6% for coarse serrated plates in a low pressure sprinkler.

More recent studies predominantly in Europe (Bavi *et al.* 2009; Tarjuelo *et al.* 2000; Yazar 1984) have attempted to use the experimental data in regression models to quantify the interaction of the climatic and operating factors. However, quantifying the evaporation losses in sprinkler irrigation is very difficult due to a number of factors both climatic (air temperature, air friction, relative humidity, solar radiation, wind velocity etc.) and operating (droplet diameter, nozzle size, sprinkler height, operating pressure etc.). The problem is particularly acute with respect to separation of the components of losses. In that case, resorting to statistical (empirical) formulae often becomes the only way to circumvent the difficulties. However, the results in this approach are highly dependent on application of particular statistical techniques, which may vary from author to author. The statistical approach is adequate for describing empirical relationship but provides limited information on the physical processes involved.

Reviewing the available literature, it is concluded that the experimental studies have the following limitations:

i) there were differences in definition of the losses,
ii) the accuracy of experimental techniques,
iii) evaporation losses were over estimated due to inclusion of evaporation losses from catch-cans, and
iv) it was difficult to separate the different components.

Physical-mathematical modelling approach

Physical-mathematical models are developed on the basis of mathematical equations representing the physical process. These models, although requiring more extensive input data, provide a much better means of predicting actual evaluation avoiding laborious field or laboratory tests. The advantages of modelling over other technique (empirical equations) are: (i) it can minimize the knowledge gaps (ii) it can predicts the value accurately by minimizing experimental errors, and (iii) a proven model can be a valuable engineering and research tool for the scientists. The physical-mathematical modelling approach of droplet evaporation is based on combining the equations accounting for the water droplet evaporation with particle dynamics theory.

The droplet evaporation-trajectory model is developed mainly based on mass and heat transfer and ballistic equations. The first equation for mass transfer of a still droplet was given by Langmuir (1918). Hardy (1947) presented a modified equation similar to that of Langmuir for the rate of evaporation from the surface of a sphere accounting forced air convection as:

$$\frac{dD_p}{dt} = -2\left(\frac{D_v}{D_p}\right)\left(\frac{\rho_a}{\rho_1}\right)\left(\frac{M_v}{M_a}\right)\left(\frac{e_s - e_o}{P}\right)N_u' \quad \text{.............................. (1)}$$

Where, D_v is the mass diffusion of vapour in the gas,
D_p is the droplet diameter,
M_v and M_a are the molecular weight of vapour and air respectively,
ρ_a and ρ_l are the density of air and water droplet respectively,
(e_s-e_0) is the difference in the saturation pressure at wet and dry bulb temperature,
P is the partial pressure of air, and
N'_u is the Nusselt Number (Froessling 1938).

Various authors have developed droplet evaporation models based on the heat and mass transfer theory for numerous purposes such as chemical spray (application of hot gas through scattering a jet of droplets) drying, agricultural spray (application of pesticides through scatter in a mass or jet of droplets) as well as for sprinkler droplet evaporation. Ranz and Marshall (1952) first developed a model to estimate droplet evaporation using heat and mass transfer equations and presented an equation for molecular transfer rate during evaporation along the flight path of the droplet. They used the model in chemical spray drying for very small diameter droplets with low Reynolds Number (0-200). Most subsequent investigators have used the heat transfer theory to describe the evaporation from droplets and have referenced the work of Ranz and Marshal (1952). Starting from the equation of Marshall (1954), Goering *et al.* (1972) arrived at an equation similar to Hardy's for studying the change of diameter in smaller (15-135 micron) droplets.

Williamsom and Threadfill (1974) also used the mass diffusion equation in a form similar to Ranz and Marshall (1952) for agricultural spray, considering diameter ranging from 0.1 to 0.2 mm. They concluded that the results of their model were accurate under experimental conditions, when compared to horizontal and vertical displacements and change in droplet diameter due to evaporation.

Kincaid and Longley (1989) theorized an empirical model based on the above theory to predict the droplet evaporation and assess the role of changes in water temperature in the evaporation process. They assumed, and proved that, the temperature of the droplet does not necessarily reach the wet bulb temperature of the air instantaneously as the droplet leaves the nozzle, which was assumed by most previous researchers. They reported that this assumption may be correct for the spraying of agricultural chemicals where the drops are small (<0.55 mm). They also considered that diffusivity is a function of air temperature and pressure while others considered temperature only. Model predictions were reasonably accurate but there was a tendency for the model to under predict loss rates for the smallest drops measured (0.3 to 0.5 mm). Some of the difference may be due to experimental errors in measuring loss from the smaller drops.

Based on the principle of impulse momentum, Edling (1985) established a model for estimating kinetic energy, evaporation and wind drift of droplets from low pressure irrigation sprinklers in order to determine the influence of design and meteorological parameters on droplet behaviour. He concentrated mainly on the effect of droplet size and its impacts on soil erosion. He verified his predicted results with those of Williamsom and Threadfill (1974) and observed a similar trend for small droplet diameter. However, he recommended that additional verification is needed for the model through appropriate experimentation.

Thompson *et al.* (1993a) developed a unique comprehensive model (Cupid-DPEVAP) to assess water losses during sprinkler irrigation of a plant canopy under field conditions. The combination of equations governing water droplet evaporation based on the heat and mass transfer analogy used by Ranz and Marshall (1952), linked with temperature-droplet model presented by Longley and Kincaid (1989), and droplet ballistics equations (three dimensional) with a plant-environment energy model Cupid given by Norman (1982), were used in their model. Further they included droplet heat and water exchange above the canopy, along with the energy associated with cool water impinging on the canopy and soil. The model was able to give results in reasonable agreement with field measurements carried out in experimental plots equipped lysimeters. The model was also used to partition the water losses between droplet evaporation, evaporation from wetted canopy and soil, and transpiration during irrigation. The model was verified through field water balance measurements using monolithic lysimeters. However, the experimental values of total ET were lower than the predicted values in non irrigation period. Most importantly, they could not verify the predicted values of model during the irrigation, because they were not able to measure the ET during the irrigation through lysimetry. They attempted to verify the model by comparing predicted air temperature and vapour pressure above the canopy during irrigation with measurement of these parameters.

Most recently, Lorenzini (2004) developed an analytical model considering the effects of air friction (ignored in previous models) on droplet evaporation which is relevant in a turbulent flow (Reynolds Number > 1000). He did not consider the physical (mass and heat transfer) changes of droplet to develop the model. The model proved to fully match the kinematic results obtained by more complicated procedures of Edling (1985) and Thompson et al. (1993b). He made comparison of the field measurements and theoretical values in terms of travel distance for the model of Edling as well as Thompson et al. and for time-of-flight

(Thompson *et al.* 1993b). The observed data of Lorenzini and Edling showed reasonable agreement in two cases (droplet diameter 1.5 mm and 2.5 mm), but poor agreement with droplet diameter of 0.5 mm. A comparative analysis based on data from Thompson *et al.* (1993b) in terms of travel distance and time-of-flight made a difference with a droplet diameter of 0.3 mm. He recommended that the model still needs further verification to determine aerial water droplet evaporation.

Reviewing the comparative approaches, it is concluded that among the different procedures now available:

(i) the heat and mass transfer approach combined with ballistic theory offers a sound basis for the assessment of evaporation from falling droplets and the results are in reasonable agreement with experimental data for Reynolds Numbers (generally lower than 1000) that fall, mainly, under the laminar and/or intermediate flow laws,

(ii) the Lorenzini (2004) model has proved to be kinematically reliable to analyse the droplet evaporation losses from both a qualitative and quantitative point of view, particularly for small droplet diameters and large Reynolds Numbers (turbulent flow), and

(iii) considering all the parameters incorporated within the model Cupid-DPEVAP developed by Thompson *et al.* (1993a), it can be considered the most complete model available to quantify the evaporation losses in sprinkler irrigation.

However, these models should be validated through appropriate experimentation.

An alternative method for accurate measurement of sprinkler evaporation

Eddy covariance (ECV, also known as eddy correlation) is a direct, accurate and reliable micrometeorological mass transfer method for measuring evaporation and evapotranspiration (ET). It is being used successfully since the last decade to measure evaporation from watersheds, grasslands, lakes, surface and drip irrigated fields and has some significant advantages over the other methods. However, a review of the literature provided no instances of it being used to measure evaporation losses occurring during sprinkler irrigation. It is assumed that ECV technique can be an alternative approach to measure the droplet evaporation losses via the accurate measurement and partitioning of the total evaporation during sprinkler irrigation.

Eddy covariance (ECV) method to estimate evapotranspiration (ET) for partitioning

Although the partitioning of evaporation losses during sprinkler irrigation is an important issue before any improvements on the design of irrigation system, it was often ignored in the past research. However, accurate measurement of ET is the prime need to obtain reliable data to partition all the components. The most common methods of estimating field ET are hydrological approaches (such as field water balance and weighing lysimetry), and micrometeorological methods (e.g. eddy covariance, ECV; Bowen Ratio-Energy Balance, BREB). Regarding the first approach, the field water balance equation is a basic method of estimating ET by determining all other components of the equation. This method can generally be used to calibrate other ET estimation methods but it also has some disadvantages. For example, canopy interception is not often considered in the water balance equation (Li *et al.* 2008) and the other components are not easily determined accurately in the actual application of the equation (Shi *et al.* 2008). The lysimeter is not feasible for the measurement of ET during sprinkler irrigation due to simultaneous addition of water (Thomson *et al.* 1997). Lysimetry usually involves permanent installation, hence high cost and is less suitable for measuring short time ET. However, for situations with well-defined surface and lower boundary conditions, it is still a reliable method to calculate long term ET of crops (Rana & Katerji 2000).

With respect to micrometeorological methods, two of the most frequently used methods are Bowen Ratio-Energy Balance (BREB) and Eddy Covariance (ECV). However, the BREB assumption of equal eddy diffusivities for heat and water vapour is not always met (Barr *et al.* 1994). The method does not work under Bowen ratio values in the vicinity of -1 (Twine *et al.*

2000). Furthermore, the BREB method needs a large fetch requirement (hundreds of metres) which often makes it invalid and therefore of unknown accuracy (Craig & Hancock 2004).

Alternatively, ECV is generally considered as a standard direct micrometeorological method to measure the surface flux (Baldocchi 2003; Yu *et al.* 2006), which can be used for comparing with the other methods or models. It can measure water vapour and heat fluxes simultaneously and effectively 'at a point', thus avoiding the fetch requirement. The method offers an attractive alternative to other more cumbersome methods such as weighing lysimetry or potentially invalid methods such as BREB (Craig & Hancock 2004).

Prior to 1990, limitations in sensor performance and data acquisition systems restricted the duration of the eddy covariance studies to short campaigns during the growing season (Verma *et al.* 1986). However, during the past decade the eddy covariance method has emerged as an important tool for evaluating fluxes between terrestrial ecosystems and the atmosphere. At present, the method is being applied in a nearly continuous mode for the direct measurement of crop and grass land evaporation, forest evaporation and evaporation in irrigated fields.

Although it has some limitations such as relatively high equipment cost, complexity in use and requires steady environmental conditions, ECV is gaining popularity over other methods such as lysimetry and Bowen Ratio-Energy Balance (BERB) method because:

(i) it is the most reliable and accurate direct measuring method (Wang *et al.* 2006) avoiding the measurement of other components of the water budget and energy balance methods;

(ii) it offers several advantages over lysimetry by providing more areal integration, finer temporal resolution, less site disruption and by eliminating the need to estimate other terms of a water budget (precipitation, deep percolation, runoff, and storage etc.) (Sumner 2001);

(iii) no fetch requirement like BREB and rapid development of modern electronics makes the equipment a standard tool for researchers (Craig & Hancock 2004);

(iv) sonic anemometers make it possible to measure the sensible heat flux in wet conditions and to calculate evaporation as a residual of the energy balance (Gash *et al.* 1999),

(v) this technique emphasizes the influence of additional climatic factors on the intensity of the process (Assouline & Mahrer 1993);

(vi) the microcomputer data acquisition system has real time data processing of the digital turbulence data (Baladocchi 2002);

(vii) all the components of the energy budget can be measured simultaneously and thus errors can be identified, quantified and corrected by closing the energy balance (Villalobos *et al.* 2008);

(viii) averaging flux measurements over long periods reduces the random sampling error to relatively small values (Baladocchi 2002); and

(ix) ET can be measured for both short times and seasonal basis (Sammis *et al.* 2004).

Reviewing the comparative methods, it is concluded that eddy covariance (ECV) will be the most appropriate and reliable direct method for measuring evaporation and transpiration during sprinkler irrigation.

Conclusions

Partitioning of total evaporation during sprinkler irrigation into its different components is essential to the understanding of the phenomena, because of the conflicting results reported in literature. In many previous studies all other components except droplet evaporation were ignored due to difficulties in measurement. As a consequence, a study was conducted in the early 1990's to separate all these components through a modelling approach. Although, the components were successfully predicted, the predicted results were not verified experimentally due to the inadequacy of the measurement techniques. However, in recent advancement of ECV technique, it is hypothesized that the total evaporation during sprinkler irrigation can be partitioned into its different components using this technique in conjunction with additional measurements such as transpiration by the sap flow method and canopy evaporation by the energy balance method.

References

Abo-Ghobar HM (1993) Evaporation and drift losses from sprinkler irrigation system under hot and dry conditions, *J. King Saud Univ.*, 5, Agric Science 2, 153-164.

Assouline S & Mahrer Y (1993) Evaporation from lake Kinneret: Eddy correlation system measurement and budget estimation, *Water Resources Research*, 29 (4), 901-910.

Baladocchi DD (2002) Assessing the eddy covariance technique for evaluating the carbon balance of ecosystem, Ecosystem Science Division, Department of Environmental Science, Policy and Management, University of California, Berkeley.

Barr AG, King KM, Gillespie TJ, Den Hartog G & Neumann HH (1994) A comparison of Bowen ratio and eddy correlation sensible and latent heat flux measurements above a deciduous forest', *Boundary-Layer Meteorology*, 71, 21–41.

Bavi A, Kashkuli HA, Boromand S, Naseri A & Albaji M (2009) Evaporation losses from sprinkler irrigation system under various operating conditions, *Journal of Applied Sciences*, 9(3), 97-600.

Burt CM, Clemmens AJ, Strelkoff TS, Solomon KH, Bliesner RD, Howell TA & Eisenhauer DE (997) Irigation performance measures: Efficiency and uniformity', *J. Irrig. Drain. Eng.*, 123, (6), 423–442.

Christiansen JE (1942) *Irrigation by sprinkling*, California Agricultural Experimental Station Bulletin 670, University of California, Berkeley, California.

Craig I & Hancock NH 2004, *Methods for Assessing Dam Evaporation – An Introductory Paper*, Irrigation Association of Australia (IAA) 2004 Conference, May 11-13, Adelaide.

Dadio C & Wallender WW (1985) Droplet size distribution and water application with low-pressure sprinkler, *Transactions of the ASAE*, 28, 511-516.

De Wrachien, D & Lorenzini G (2006) Modelling Jet Flow and Losses in Sprinkler Irrigation: Overview and Perspective of a New Approach, *Biosystem Engineering*, 94(2), 297-309.

Edling RJ (1985) Kinetic energy, evaporation and wind drift of droplets from low pressure irrigation nozzles, *Transactions of the ASAE*, 28(5), 1543–1550.

Froessling N (1938) *Gerlands Beitr Geophysics*, 52, 170.

Frost KR & Schwalen HC (1955) Sprinkler evaporation losses, *Agricultural Engineering*, 36(8), 526-528.

Gash JHC, Valente F & David JC (1999) Estimates and measurements of evaporation from wet, sparse pine forest in Portugal, *Agric. For. Meteorol.*, 94, 149–158.

Goerge TJ (1957) Evaporation from irrigation sprinkler sprays as determined by electrical conductivity method, Unpublished M.S. thesis, University of California, Berkley.

Goering CE, Bode LE & Gebhard MR (1972) Mathematical modelling of spray droplet deceleration and evaporation, *Transactions of the ASAE*, 15(2), 220-225.

Hardy JK (1947) Evaporation of drops of liquid, Great Britain Aeronautical Research Council, Reports and Memoranda, No. 2805.

Hermsmeier LF (1973) Evaporation during sprinkler application in the desert climate, Unpublished Paper No. 73-216, presented at the Summer Meeting, ASAE, Lexington KY, 14.

Hotes FL (1969) Analysis of sprinkler irrigation losses, *Journal of the Irrigation and Drainage Division of ASCE*, 95, 218-223.

Innoue H & Jayasinghe SS (1962) *On size distribution and evaporation losses from spray droplets emitted by a sprinkler technical bulletin of faculty of agriculture*, Kagawa University, 12(2), 202-212.

Kang Y, Liu Hai-Jun & Liu Shi-Ping (2002) Effect of sprinkler irrigation on field microclimate, ASAE Annual International Meeting/CIGR XVth World Congress, Hyatt Regency Chicago, CHicagoo, Illinois, USA, July28-31, 2002.

Keller J & Bliesner RD (1990) *Sprinkler and Trickle Irrigation*. Van Nostrand Reinhold, NY.

Kincaid DC & Longley TS (1989) A water droplet evaporation and temperature model, *Transactions of the ASAE*, 32(2), 57 – 463.

Kincaid DC, Solomon KH & Oliphant JC (1996) Drop size distribution for irrigation sprinklers, *Trans. ASAE*, 39(3), 839-845.

Kohl RA & Wright JL (1974) Air temperature and vapour pressure changes caused by sprinkler irrigation, *Agron. J.*, 66, 85-88

Kohl KD, Kohl RA & De Boer DW (1987) Measurement of low pressure sprinkler evaporation loss, *Transactions of the ASAE*, 30, 1071-1074.

Langmuir I (1918) The evaporation of small spheres, *Physical Review*, Second series, 12, 368-370.

Lorenzini G (2002) Air temperature effect on spray evaporation in sprinkler irrigation, *Irrigation and Drainage*, 51(4), 301 – 309.

Lorenzini G (2004) Simpified Modelling of Sprinkler Droplet Dynamics, *Biosystems Engineering*, 87(1), 1-11.

Li S, Kang S, Zhang L, Li F, Zhu Z & Zhang B (2008) Comparision of three methods fro determining vineyard evapotranspiration in the arid desert regions of northwest China, *Hydrological Processes*, 22, 4554-4564.

Liu Hai-Jun & Kang Y (2006) Effect of sprinkler irrigation on microclimate in the winter wheat field in the North China Plain, *Agricultural Water Management*, 84, 3-19.

McLean RK, Sri Ranjan R & Klassen G (2000) Spray evaporation losses from sprinkler irrigation systems, *Canadian Agricultural Engineering*, 42(1).

McNaughton KG (1981) Net interception losses during sprinkler irrigation, *Agric. Meterol.*, 24, 11–27.

Marshall WR (1954) *Atomization and spray drying*, Chemical Engineering Progress. Monograph Series 4.2, Vol 50, American Institute of Chemical Engineers, New York.

Martinez-Cob A, Playan E, Zapata N, Cavero J, Medina ET & Puig, M (2008) Contribution of Evapotranspiration Reduction during Sprinkler Irrigation to Application Efficiency, *Journal of Irrigation and Drainage Division, ASCE*, 134(6), 745-756.

Mayers JM, Baird CD & Choate RE (1970) *Evaporation losses in sprinkler irrigation*, University of Florida Water Resources Center, Pub. No. 12.

Norman JM (1982) *Simulation of microclimates*, In "Bio-meteorology in integrated pest management" (J.L. Hatfield and I.J. Thomason, eds.), 65-99. Academic press, Inc. New York.

Norman JM & Campbell GS (1983) Application of the plant environment model to problems in irrigation, In *Advance in irrigation*, 2, 155-188. New York, N.Y.: Academic Press, Inc.

Rana G & Katerji N (2000) Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review, *European Journal of Agronomy*, 13, 125–153.

Ranz WE & Marshall WR (1952) Evaporation from drops, *Chemical Engineering Progress*, 48(4), 141-146, 173-179.

Sammis TW, Mexal JG & Miller DR (2004) Evapotranspiration of flood-irrigated pecans, *Agric. Water Manage.* 69, 179–190.

Shi T, Guan D, Wang A, Wu J, Jin C & Han S (2008) Comparison of three models to estimate evapotranspiration for a temperature mixed forest, *Hydrological Processes*, 22, 3431-3443.

Solomon KH, Kincaid DC & Bezdek JC (1985) Drop size distribution for irrigation spray nozzles, *Transactions of the ASAE*, 28(6), 1966-1974.

Steiner JL, Kanemasu ET & Clark RN (1983) Spray losses and partitioning of water under a center pivot sprinkler system, *Trans. ASAE*, 26, 1128–1134.

Sumner DM (2001) *Evapotranspiration from a cypress and pine forest subjected to natural fires in Volusia County, Florida, 1998–1999*, US Geological Survey Water-Resources Investigations Report 01–4245, 12–13.

Tarjuelo JM, Ortega JF, Montero J & De Juan JA (2000) Modelling evaporation and drift losses in irrigation with medium size impact sprinklers under semi-arid conditions, *Agricultural Water Management*, 43(3), 263-284.

Thomson AL (1986) Sprinkler water droplet evaporation simulated above plant a canopy, PhD thesis, The University of Nebraska, Lincoln.

Thompson AL, Gilley JR & Norman JM (1993a) A sprinkler water droplet evaporation and plant canopy model: I. Model development, *Transactions of the ASAE*, 36(3), 735-741.

Thompson AL, Gilley JR & Norman JM (1993b) A sprinkler water droplet evaporation and plant canopy model: II. Model application, *Transactions of the ASAE*, 36(3), 743-750.

Thomson AL, Martin DL, Norman JM, Tolk JA, Howel TA, Gilley JR & Schneider AD (1997) Testing of water loss distribution model for moving sprinkler system, *Transaction of ASAE*, 40(1), 81-88.

Tolk JA, Howell TA, Steiner JL, Krieg DR & Schneider AD (1995) Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency, *Irrigation Science*, 16(2), 89-95.

Twine TE, Kustas WP, Norman JM, Cook DR, Houser PR, Meyers TP, Prueger JH, Starks PJ & Wesely ML (2000) Correcting eddy-covariance flux underestimates over grassland, *Agricultural and Forest Meteorology*, 103, 279–300.

Verma SB, Baladocchi DD, Anderson DE *et al.* (1986) Eddy flux of CO_2, water vapour and sensible heat over deciduous forest, *Boundary Layer Meteorology*, 36, 71-91.

Villalobos FJ, Test L & Moreno-Perez MF (2008) Evaporation and canopy conductance of citrus orchards, *Agricultural Water Management*, 96(4), 565-573.

Wang J, Miller DR, Sammis TW, Gutschick VP & Simmons LJ (2006) Measurement and Simple Model for Pecan Water Use Efficiency, *Agric. Water Manage.*, submitted for publication.

Wang Qing-Gai, Kang Y, Liu Hai-Jun & Liu Shi-Ping (2006) Method for Measurement of Canopy Interception under Sprinkler Irrigation, *Journal of Irrigation and Drainage Engineering*, 132(2), 185-187.

Williamson RE & Threadgill ED (1974) A simulation for the dynamics of evaporation spray droplets in agricultural spraying, *Transactions of the ASAE*, 17(2), 254-261.

Yazar A (1984) Evaporation and drift losses from sprinkler irrigation systems under various operating conditions, *Agricultural Water Management*, 8, 439-449.

Yu GR, Wen XF, Sun XM, Tanner BD, Lee X & Chen JY (2006) Overview of China FLUX and evaluation of its eddy covariance measurement, *Agricultural and Forest Meteorology*, 137, 125–137.