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Article

Simulation of Soil Hydrological Components in Chuncheon over 30 years Using E-DiGOR Model

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The hydrological components of a sandy loam soil of nearly level in Chuncheon over 30 years were computed using the E-DiGOR model. Daily simulations were carried out for each year during the period of 1980 to 2009 using standard climate data. Reference evapotranspiration and potential soil evaporation based on Penman -Montheith model were higher during May to August because of the higher atmospheric evaporative demand. Actual soil evaporation was mainly found to be a function of the amount and timing of rainfall, and presumably soil wetness in addition to atmospheric demand. Drainage was affected by rainfall and increased with a higher amount of precipitation and soil water content. Excess drainage occurred throughout rainy months (from July to September), with a peak in July. Therefore, leaching may be a serious problem in the soils all through these months. The 30-year average annual reference evapotranspiration and potential soil evaporation were 951.5 mm and 714.2 mm, respectively. The actual evaporation from bare soil varied between 396.9-528.4 mm and showed comparatively lesser inter-annual variations than drainage. Annual drainage rates below 120 cm soil depth ranged from 477.8 to 1565.9 mm. The long-term mean annual drainage-loss was approximately two times higher than actual soil evaporation.

Key words: Soil-water balance, E-DiGOR model, Reference evapotranspiration, Chuncheon

Introduction

Quantification of water loss through evaporation and drainage from bare fields is very important for an effective soil-water management and sustainable productivity in rainfed-agriculture, although the calculation of actual soil evaporation poses a serious dilemma. In many regions, evaporation from the soil surface constitutes a large fraction of the total water loss not only from bare soils but also from cropped fields. It has been reported that direct evaporation from the soil surface ranged from 30 to more than 80% of the total rainfall (Onder et al., 2009). Soil water evaporation is also an important component of the surface water balance and the surface energy balance; therefore, the estimation of evaporation is critical in the physics of land-surface processes on regional and global scales (Bittelli et al., 2008; Allen, 2011; Xiao et al, 2011). For example, Agam et al. (2004) concluded that latent heat flux played a major role in the dissipation of the net radiation during the dry season in a desert. The evaporation from the soil is the link between atmosphere and soil surface in the hydrologic cycle and as a result is a key issue in many fields of hydrological sciences. The problem was widely investigated in the last decades and a very large number of possible solutions were proposed; unfortunately, none of them appeared to be completely satisfactory, because the applicability of the different methods strongly depends on space and time scale of the involved phenomena (Romano and Giudici, 2009). Evaporation from the soil is affected by soil water content, type, and tillage; the presence or absence of surface mulches, and the environmental conditions being imposed on the soil (Burt et al., 2005).

The exchange of water between the soil and the atmosphere plays a more critical role in soil hydrologic processes which are linked to water fluxes in the soil, such as deep percolation and leaching processes. Small relative errors in the estimation of evaporation result in large relative errors in the estimated deep percolation (Vanderborght et al., 2010). In order to overcome such problems, Aydin (2008) proposed an interactive way (called E-DiGOR

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model by the author) for predicting daily actual soil evaporation, soil water storage and drainage rates, since these components are strongly interdependent. The applicability of E-DiGOR model to a wide range of environments has been tested by different researchers using field-based measurements (Aydin, 2008; Aydin et al., 2008; Kurt, 2011). Similarly, the model had been successfully applied to different environmental conditions in Turkey, Japan and Sri Lanka (Aydin et al., 2005; Onder et al., 2009; Aydin et al., 2012). Like most studies about evaporation (Burt et al., 2005), it should be noted that E-DiGOR model does not consider the influence of shallow groundwater on evaporation, and soil evaporation is presented as a natural dry-down phenomenon. However, the model is relatively simple and requires readily available input-parameters. In addition, Aydin and Polat (2010) developed a computer program for a functional implementation of the E-DiGOR model.

Many studies have been carried out for estimating reference evapotranspiration (ET_r) in Korea to contribute to water resources planning, irrigation schedule, and environmental management (i.e., Kim and Kim, 2008; Kim, 2010a; 2010b). Rim (2008) investigated the effects of climate change owing to urbanization on ET_r at different locations all over Korea, using weather data of 21 meteorological stations from 1970 to 2004. The author concluded that urbanization affected ET_r, and increasing ET_r trends had been observed in Korea during the study period. On the other hand, Rim (2010) emphasized that yearly and monthly effects of urbanization on ET_r were closely related to solar radiation, relative humidity, wind speed and change in temperature. Lee and Park (2008) calculated daily-based ET_r at 23 meteorological stations in Korea for the period of 1997-2006. Similarly, Choi et al. (2010) compared measured and model-based ET_r using weather data in Seoul for 29 years. However, to our knowledge, there is no data available on water balance components of bare soils, including actual soil evaporation and drainage rates, and daily changes in soil water storage for a long time in Korea. Therefore, in this study, the hydrological components of a sandy loam soil in Chuncheon over 30 years were computed using the E-DiGOR model.

Materials and Methods

Description of the model Evaporation is often divided, time-wise, into two or three stages that characterize the form or nature of control on the evaporation process and rate (Ritchie, 1972). During first stage, the soil surface is sufficiently wet so that water is transported to the surface at least at a rate equal to the evaporation potential, and evaporation is mainly controlled by the atmospheric evaporative demand. During second stage, the evaporation is limited by the actual soil water content, as a consequence, driven by the hydraulic capacity of the soil. Occasionally, for example, with deep-cracking soils, a third evaporation stage is added, where a low and long-term evaporation rate is supplied by water from deep and exposed cracks (Ventura et al., 2006; Aydin, 2008; Allen, 2011).

In general, soil evaporation is modeled by limiting potential evaporation (e.g., from Penman-Monteith equation) with a surface resistance of zero (Allen et al., 1994; Wallace et al., 1999; Aydin et al., 2005):

$$E_p = \frac{\Delta(R_n - G_s) + 86.4 c_p \rho \delta / r_a}{\lambda(\Delta + \gamma)} \tag{1}$$

where E_p is potential soil evaporation (E_p=kg m^{-2} day^{-1} ≈ mm day^{-1}), Δ is the slope of vapor pressure-temperature curve (kPa ℃$^{-1}$), R_n is the net radiation (MJ m^{-2} day^{-1}), G_s is the soil heat flux (MJ m^{-2} day^{-1}), ρ is the air density (kg m^{-3}), C_p is the specific heat of air (kJ kg^{-1} ℃$^{-1}$=1.013), δ is the vapor pressure deficit of the air (kPa), r_a is the aerodynamic resistance (s m^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}), γ is the psychrometric constant (kPa ℃$^{-1}$), and 86.4 is the factor for conversion from kJ s^{-1} to MJ day^{-1}.

The evaporation rate during second stage progressively decreases with time. A simplified model originally proposed by Aydin (1998), referred as Aydin equation, for estimating actual evaporation from bare soils was tested by Aydin et al. (2005) under different environmental conditions:

$$E_a = \frac{Log|\psi| - Log|\psi_{ad}|}{Log|\psi_{tp}| - Log|\psi_{ad}|} E_p \tag{2}$$

If $|\Psi| \leq |\Psi_{tp}|$ then E_a=E_p or E_a/E_p=1

For $|\Psi| \geq |\Psi_{tp}|$, E_a=0.

Remember that $E_p \geq 0$.

where E_a and E_p are actual and potential evaporation rates (mm day^{-1}), respectively, $|\Psi_{tp}|$ is the absolute value of soil water potential (matric potential) at which actual evaporation starts to drop below potential one (cm of water), $|\Psi_{ad}|$ is the absolute value of soil water potential at air-dryness (cm), and $|\Psi|$ is the absolute value of soil water potential at the surface layer (cm).

Although Aydin equation appeared to be useful; however, the objective measurement of soil water potential near the surface of the profile was difficult, especially for dried upper layer. In order to overcome such difficulties, Aydin and Uygur (2006) devised a simple model for predicting soil water potential at the top surface layer:

$$\psi = -\left[\frac{(1/\alpha)(10\sum E_p)^3}{2(\theta_{fc}-\theta_{ad})(D_{av}t/\pi)^{1/2}}\right] \tag{3}$$

where Ψ is soil water potential (cm of water) at the top surface layer, α is a soil specific parameter (cm) related to flow path tortuosity in the soil, ΣE_p is cumulative potential soil evaporation (cm), θ_{fc} and θ_{ad} are volumetric water content (cm^3 cm^{-3}) at field capacity and air-dryness, respectively, D_{av} is average hydraulic diffusivity (cm^2 day^{-1}) determined experimentally, t is time (day) and π is 3.1416.

In very dry range (in which the flow is entirely as vapor), either resistance models or a Fickian equation should be used (Konukcu, 2007) to estimate water transport through the slow process of moisture diffusion. On the other hand, the water potential at dry soil surface can be derived from the Kelvin equation (Brown and Oosterhuis, 1992; Aydin et al., 2005; Aydin, 2008):

$$\psi_{ad} = \frac{R_g T}{mg}\ln H_r \tag{4}$$

where Ψ_{ad} is the water potential for air-dry conditions (cm of water), T is the absolute temperature (K), g is the acceleration due to gravity (981 cm s^{-2}), m is the molecular weight of water (0.01802 kg mol^{-1}), H_r is the relative humidity of the air (fraction), and R_g is the universal gas constant (8.3143×10^4 kg cm^2 s^{-2} mol^{-1} K^{-1}).

The soil water storage (S) on any day can be imposed on the difference between rainfall (P, in case) and actual evaporation on the consecutive day. Symbolizing this produced variable as W, and assuming a negligible runoff from nearly level soils, the following expression can be written (Aydin, 2008):

$$\begin{aligned}&W^{(j)} = S^{(j-1)} + P^{(j)} - E_a^j\\&\text{If } W^{(j)} \langle \theta_{fc}Z, \text{ then } S^{(j)} = W^{(j)}\\&\text{If } W^{(j)} \geq \theta_{fc}Z, \text{ then } S^{(j)} = \theta_{fc}Z.\end{aligned} \tag{5}$$

In practice, soil water storage between the soil surface (0) and a given depth (Z) is calculated by integrating water content of individual soil layers ($\int_0^z \theta_i dz$).

Drainage is simply calculated by the mass balance. The cumulative drainage until day j can be expressed as follows (Aydin, 2008):

$$\left[\sum D\right]^{(j)} = \int_0^z \theta_i dz + \left[\sum P\right]^{(j)} - \left[\sum E_a\right]^{(j)} - S^{(j)} \tag{6}$$

where ΣD is cumulative drainage (mm) out of storage depth since the first day of simulation period, ΣP is total rainfall (mm), and ΣE_a is cumulative actual soil evaporation (mm). Thus, from the differences between the consecutive days, drainage rates (D = mm day^{-1}) can be easily calculated, if any: $D^{(j)} = [\Sigma D]^{(j)} - [\Sigma D]^{(j-1)}$.

Although the performance of the E-DiGOR was satisfactory at plot scale (Aydin and Kececioglu, 2010), there was still a need to improve the model since it lacked the estimation of runoff. The model is additionally updated to provide a method of assessing runoff losses (equation not shown) with an acronym DERSim (Aydin, 2012).

The input variables of the E-DiGOR computer program (runoff module not included) are climate data (sunshine duration, air-temperature, relative humidity, wind speed and precipitation) and soil properties (albedo, tortuosity, average diffusivity for drying soil, volumetric water content at field capacity, profile depth, initial water content of the profile) to account for specific soil-climate combinations (Aydin and Polat, 2010).

With standardized height for wind speed, temperature and humidity measurements at 2 m; an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23, the reference evapotranspiration can be calculated using the FAO Penman-Monteith equation as follows (Allen et al., 1998):

$$ET_r = \frac{0.408\Delta(R_n - G_s) + \gamma\dfrac{900}{T_a + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{7}$$

where ET_r is grass reference evapotranspiration (mm day^{-1}), T_a is mean daily air temperature (℃), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa).

Table 1. Monthly mean climatic data of Chuncheon for the period of 1980 to 2009.

Month	Mean temperature (°C)	Mean relative humidity (%)	Mean radiation (MJ $m^{-2}day^{-1}$)	Mean wind speed (m s^{-1})	Rainfall (mm)
January	-4.6	69.3	7.3	1.2	19.4
February	-1.5	65.3	10.2	1.4	22.6
March	4.5	63.0	13.0	1.6	40.1
April	11.6	59.5	16.1	1.7	66.3
May	17.1	66.0	17.6	1.5	102.7
June	21.7	72.0	17.4	1.3	123.5
July	24.4	79.8	14.4	1.2	387.3
August	24.5	79.8	14.9	1.2	308.6
September	19.2	78.0	13.7	1.1	148.9
October	12.4	75.3	10.8	1.0	44.3
November	5.0	73.4	7.4	1.1	44.9
December	-1.8	71.8	6.3	1.1	20.2

Study location Study site-Chuncheon (37°54′ N, 127°44′ E, Altitude: 76.8 m) is located in the middle of Korea. Daily climate data for the study area were obtained from Korea Meteorological Service. Chuncheon has cold winters and hot summers. Severe cold of less than 20 below zero is sometimes recorded in winter. The mean annual temperature and relative humidity at the site was 11.1℃ and 71%, respectively, based on the meteorological data for the period of 1980-2009. The annual precipitation was an average of 1329.2 mm during the same period, and was concentrated in summer (Table 1).

Simulations of water balance components were done for a sandy loam soil with a nearly level and bare (non -plant-covered) surface, since the soils in the region are predominantly gravelly loam or sandy loam (Jo, 2002). However, daily computations of evaporation (or evapotranspiration) were carried out not only for a bare plot but also for a grass reference surface during the period of 1980 to 2009. It was assumed that infiltration rate of the flat soil was enough high and no surface runoff occurred. Volumetric water content at field capacity and soil profile depth were taken as 0.18 cm^3 cm^{-3} and 120 cm, respectively. Albedo of the bare soil was assumed to be 0.15 (van Dam et al., 1997; Ács, 2003; Aydin, 2008). The tortuosity parameter, which can be defined as the actual round about flow path for the soils, was taken as 1.1 cm (Onder et al., 2009). The volumetric water content under air-dry conditions and hydraulic diffusivity of the soil were assumed to be 0.005 cm^3 cm^{-3} and 20 cm^2 day^{-1}. The threshold potential is always greater than 15 cm (for sand) and may exceed 60 cm (for clay soil) as reported by Aydin et al. (2005). We used 20 cm of water as a threshold for the sandy loam soil.

Results and Discussion

Simulations of daily ET_r, E_p, E_a, D and S were conducted for each year during the period from 1980 to 2009. As known, the evaporation rate from pans filled with water (Epan) is widely used to estimate reference evapotranspiration practically (Xu et al., 2006). Therefore, the relation between Epan and calculated ET_r has also been demonstrated using their daily values (from April to October) for the studied period (Fig. 1). A strong correlation between them was observed (R^2=0.673, P<0.001); however, the ET_r rates were usually overestimated. Although the pan responds in a similar fashion to the same climatic factors affecting reference evapotranspiration, several factors produce significant differences in loss of water from a water surface and from a cropped surface (Allen et al.,

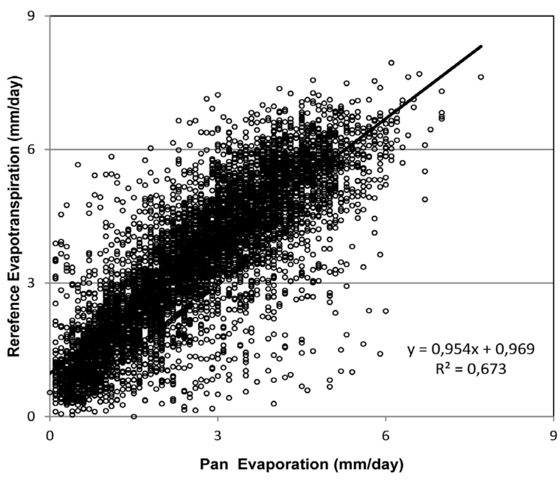


Fig. 1. The relation between pan evaporation and calculated reference evapotranspiration based on the data of 1980 to 2009.

1998). Variations of annual precipitation and ET_r for 30 years in Chuncheon are shown in Fig. 2. Annual precipitation increased gradually, although it denoted noticeable inter-annual fluctuations. Yearly ET_r calculated from the observed climate data tended to increase according to trend line. Increasing ET_r trends in Korea have already been reported by Rim (2008).

Graphical illustration of daily P, ET_r, E_p, E_a, D and S values for the entire period would have required a lot of space. For this reason, daily changes in the variables in 2009 were given as representative examples in Fig. 3 and 4. Drainage occurred on some rainy days (and/or on the consecutive days). Drainage rates below a soil depth of 120 cm were high during rainy months with a maximum value of 196.5 mm day-1 in July. Drainage was affected by rainfall and increased with a higher amount of precipitation and soil water content (Fig. 3). The ET_r and E_p rates were higher during warm period because of the higher atmospheric evaporative demand. However, the E_a rates were mainly found to be a function of the amount and timing of rainfall, and presumably soil wetness in addition to atmospheric demand. When the soil became drier, water could not be supplied to the soil surface fast enough to meet the evaporative demand. Soil water storage varied daily depending on the intensity and frequency of precipitation events and on evaporation rates. The water stored in the soil reached field capacity during the wet periods. However, the water storage decreased continuously during the dry periods (Fig. 4), with a lowest level in October.

In order to demonstrate the relationships among the variables, monthly variations of ET_r, E_p, E_a, and D along with precipitation for a period of 30 years are depicted in Fig. 5. Reference evapotranspiration and potential soil evaporation were higher during May to August due to higher evaporative demand of the atmosphere. The rates of ET_r were overestimated when compared with those of

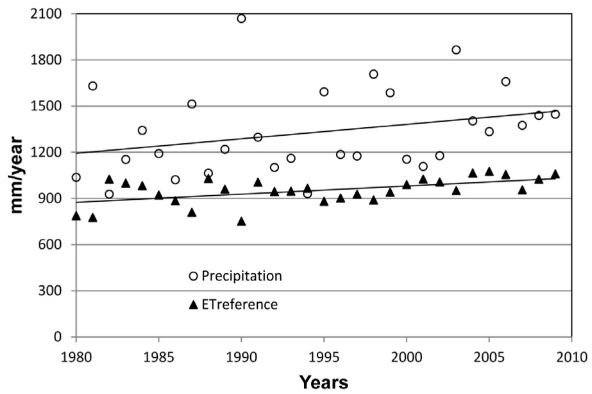


Fig. 2. Variations of annual precipitation and reference evapotranspiration from 1980 to 2009.

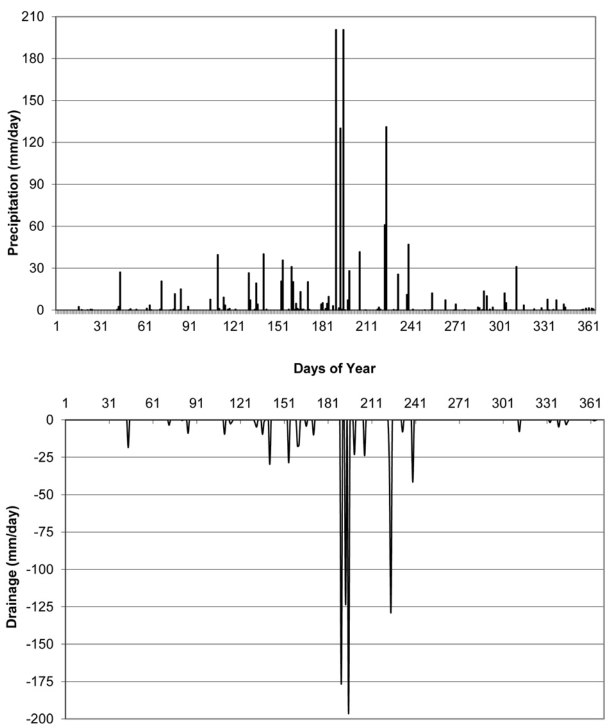


Fig. 3. Drainage rates below a soil depth of 120 cm along with precipitation in 2009.

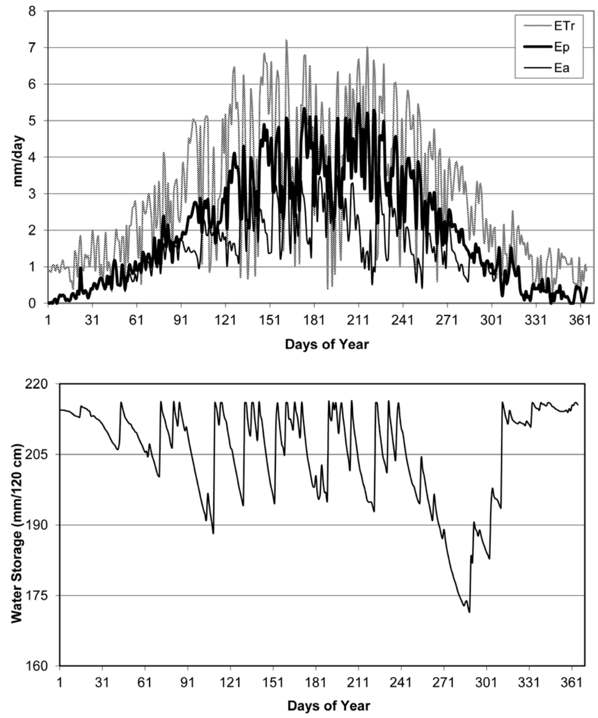
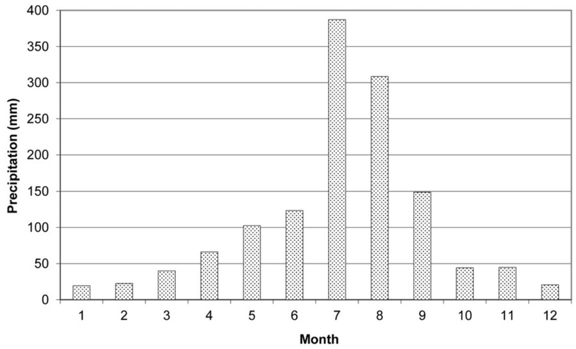


Fig. 4. Comparison of reference evapotranspiration (ETr), potential (Ep) and actual (Ea) soil evaporation, and water storage in the soil profile of 120 cm in 2009.

E_p. In contrast, E_a rates were very low in the dry periods and high in the wet months and depended on the rainfall pattern and soil wetness. In other words, actual soil evaporation was mainly a function of soil wetness in addition to atmospheric demand (Fig. 5). In a warm climate with lesser precipitation, an increased evaporative demand of the atmosphere favors soil dryness. Excess drainage occurred during rainy months (from July to September), with a peak in July. Therefore, leaching may be a serious problem in the soils all through these months.



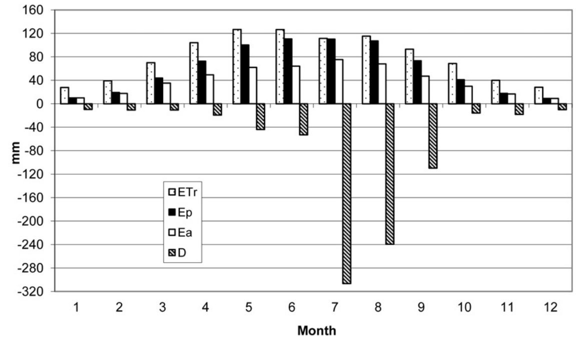


Fig. 5. Monthly mean precipitation, reference evapotranspiration (ET_r), potential (E_p) and actual (E_a) evaporation from bare soil along with drainage below a soil depth of 120 cm over a period of 30 years starting from 1980.

Table 2. Annual quantities of soil-water balance components in Chuncheon.

Year	Precipitation (mm)	Reference ET (mm)	Potential soil evaporation (mm)	Actual soil evaporation (mm)	Drainage (mm)
1980	1037.5	788.1	644.3	466.2	574.0
1981	1630.8	776.7	641.5	477.0	1159.6
1982	927.6	1025.4	755.7	442.3	477.8
1983	1153.7	999.6	750.3	508.8	654.9
1984	1342.2	982.9	734.1	475.1	859.6
1985	1191.5	922.2	703.6	482.2	706.6
1986	1021.6	884.3	684.7	489.9	532.4
1987	1513.2	809.8	647.6	480.2	1045.3
1988	1064.1	1030.1	757.1	446.6	630.3
1989	1219.2	960.5	727.9	507.8	686.6
1990	2069.2	751.8	655.0	500.1	1565.9
1991	1298.0	1005.6	741.6	492.1	805.6
1992	1101.5	944.6	718.1	500.5	600.2
1993	1161.0	947.0	711.9	500.4	660.2
1994	930.9	966.2	730.2	447.0	489.1
1995	1593.1	880.8	664.1	486.4	1105.9
1996	1185.7	902.7	703.3	448.5	736.3
1997	1175.7	927.2	720.8	458.7	718.0
1998	1707.6	889.8	706.2	506.5	1202.5
1999	1586.9	940.4	738.1	477.3	1106.1
2000	1154.9	990.0	724.2	473.5	680.0
2001	1108.0	1025.7	735.8	396.9	718.1
2002	1177.7	1006.6	725.6	504.9	665.2
2003	1865.8	950.7	702.7	528.4	1340.1
2004	1404.0	1065.5	733.4	484.2	918.6
2005	1334.2	1076.0	737.8	492.4	840.1
2006	1659.4	1055.6	741.9	502.9	1159.1
2007	1374.9	955.5	708.4	519.7	854.5
2008	1439.4	1025.5	730.8	510.1	928.8
2009	1446.9	1059.3	749.3	496.0	949.8
Average	1329.2	951.5	714.2	483.4	845.7

Annual quantities of water balance components for 30 years are summarized in Table 2. Annual precipitation, reference evapotranspiration and potential soil evaporation had noticeable inter-annual variations. The 30-year average annual reference evapotranspiration and potential soil evaporation were 951.5 mm and 714.2 mm, respectively. E_p rates were lower than ET_r values (E_p=0.75×ET_r), because the evaporation from bare soils depended not only on the atmospheric conditions but also on soil properties. Aydin et al. (2008) found a similar relationship between E_p and ET_r. Kroes et al. (1999) reported that ET_r rates could be multiplied by a coefficient value of 0.5 to 1.5 to obtain E_p. The actual evaporation from bare soil varied between 396.9-528.4 mm and showed comparatively lesser inter-annual variations than drainage. Annual drainage rates below 120 cm soil depth ranged from 477.8 to 1565.9 mm and depended on the intensity and frequency of rainfall events and especially soil water storage from the preceding dry periods. A similar trend in drainage was also reported by Eilers et al. (2007), Aydin (2008). The long-term mean annual drainage-loss was approximately two times higher than actual soil evaporation.

Conclusions

The long-term mean annual actual soil evaporation and drainage in a nearly level soil, as calculated by the model, accounted for about 36 and 64% of the total precipitation in Chuncheon, respectively. These results demonstrate that the *D* component cannot be neglected when dealing with water conservation and leaching. Thus soil water storage should be facilitated by the management practices favoring soil moisture retention. The findings may be instructive in terms of prevention of water loss through evaporation and drainage from bare soils and adoption of an effective management strategy for the soil water. Further studies are needed to quantify the components of soil water balance in the other regions of Korea; and the model outputs should be compared with field-based measurements.

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