available at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/agwat
ELSEVIER
Agricultural Water Management

Estimation of design water requirement using FAO Penman–Monteith and optimal probability distribution function in South Korea

Seung-Hwan Yoo[a], Jin-Yong Choi[b,*], Min-Won Jang[c]

[a] Department of Rural Systems Engineering, Seoul National University, Seoul, Republic of Korea
[b] Department of Rural Systems Engineering, Research Institute for Agriculture & Life Sciences, Seoul National University, Seoul, Republic of Korea
[c] Department of Agricultural Engineering, Gyeongsang National University, Jinju, Republic of Korea

ARTICLE INFO

Article history:
Received 18 July 2007
Accepted 18 February 2008
Published on line 18 April 2008

Keywords:
Design water requirement
Drought reference design year
Optimal probability distribution function
Net irrigation water requirement
Paddy rice
FAO Penman–Monteith
South Korea

ABSTRACT

Estimation of the design water requirement (DWR) is a key part of design and operation of agricultural water resource systems. DWR is determined from frequency analysis of crop water requirement, and the reference return period has been 10 years in South Korea. This study aimed to propose a guideline for determining DWR using Food and Agriculture Organization (FAO) Penman–Monteith method and optimal probability distribution function (PDF). To find an optimal PDF, nine types of PDF were tested using the Kolmogorov–Smirnov (K–S) and Probability Plot Correlation Coefficient (PPCC) goodness-of-fit methods. From the test, the Generalized Logistic (GLO) was selected and DWRs were estimated using the chosen optimal PDF. To demonstrate the DWR differences among the PDFs, DWR and drought reference design year were compared for the three selected PDFs, GLO, Generalized Extreme Values (GEV) and Weibull (WBU). The results would effect on the design and operation of the agricultural water resources structures in terms of capacity and capability in South Korea.

1. Introduction

Irrigation water management and development in South Korea have concentrated mainly on the protection of paddy rice fields from drought because rice self-sufficiency has been considered as the foremost priority. Forty-eight percent of the total water resources in South Korea are consumed for agricultural use, and it is decreasing in competition with other water demands (Park, 2004). Considering the difficulty of new water resource development due to the environmental impact from construction as well as the cost, the efficient management techniques of current water resources are significantly required to improve water application efficiency, and the first step is to understand the agricultural water demand according to time and location because this knowledge is quite necessary not only for water resource development but also for irrigation scheduling. Irrigation scheduling determines the amount and the time of water supply according to crop evapotranspiration which is a key component of water balance for crop water requirement. With the evapotranspiration of paddy rice counting with weather, crop growing stage and cultivation practices, it can be expected to achieve efficient irrigation management and reasonable design of agricultural water resource structures. The capacity of agricultural water structures is concluded from design water requirement, which is a function of crop water

* Corresponding author. Tel.: +82 28804583; fax: +82 28732087.
E-mail address: iamchoi@snu.ac.kr (J.-Y. Choi).
0378-3774/$ – see front matter
doi:10.1016/j.agwat.2008.02.010

requirement and the risk of water deficit with the drought frequency analysis.

Crop water requirement is decided from reference evapotranspiration estimation methods suggested by Food and Agriculture Organization (FAO) of the United Nations in usual. In 1977, FAO presented guidelines for predicting crop water requirements. The guidelines suggested methods to derive crop water requirements and discussed the application of crop water requirements data in irrigation project planning, design and operation. The use of four well-known methods for determining such requirements was defined to obtain reference crop evapotranspiration for different climatic conditions (Doorenbos and Pruitt, 1977). Jensen et al. (1990) examined 20 different evapotranspiration formulas and pointed out that the FAO modified-Penman method recommended by previous studies possibly overestimated the reference evapotranspiration. Thus, FAO concluded that the Penman–Monteith method, which had a stable tendency from humid to dry weather, can be the standard method for estimating the reference evapotranspiration. Since the publication of the FAO paper no. 56 (Allen et al., 1998), the Penman–Monteith method has been recognized as an accurate formula from various studies and has also been recommended by International Commission on Irrigation and Drainage (ICID) and World Meteorological Organization (WMO). Abdelhadi et al. (2000) estimated the crop water requirement in arid regions using FAO Penman–Monteith with derived crop coefficients from the phenomenological stages of Acala cotton. Ibrahim et al. (2002) compared crop factors and crop coefficients of FAO modified-Penman and FAO Penman–Monteith method for sorghum and groundnut under semi-arid conditions. Azevedo et al. (2003) evaluated the evapotranspiration during the 1999 fruiting cycle of a mango orchard and used the crop coefficient determined by a function of the days after flowering. Kuo et al. (2006) calculated the reference and actual crop evapotranspiration from field experiments and estimated the irrigation water requirements of different crops in Taiwan using CROPWAT model.

In South Korea, different studies have been conducted to develop accurate computational methods for crop evapotranspiration since the 1960s (MAF/ADC, 1987). The Institute of Agricultural Sciences and Development in Seoul National University (IASD-SNU) has classified transplanted paddy rice into early, middle and late maturing rice and estimated the consumptive water use for nine locations during 5 years from 1982 to 1986. The study estimated reference evapotranspiration using Blaney-Criddle, FAO modified-Penman and Class A-Pan methods, which were published in FAO paper no. 24 (Doorenbos and Pruitt, 1977), and the crop coefficients of transplanted paddy rice were also determined based on measured evapotranspiration using a lysimeter. These paddy rice crop coefficients have subsequently been used in agricultural water resources development and irrigation systems operation in South Korea.

Recently, FAO Penman–Monteith method began to be adopted for calculating evapotranspiration based on the FAO recommendation. Yoo et al. (2006) has proposed the crop coefficients of paddy rice applicable to FAO Penman–Monteith method and then it became possible to establish new methodology for agricultural water structure design and irrigation management based on FAO Penman–Monteith method.

Design water requirement derived from frequency analysis of crop water requirement and the reference return period has been 10 years (Koo et al., 1998). In design standard for the agricultural water resource development, plotting-position formulas including California and Weibull equation for finding design water requirement are suggested for frequency analysis. The formulas, which have commonly been accepted in the design process, are useful, although the methods oversimplify the probability distribution of water requirement and do not consider statistical characteristics of each region. However, due to the increasing risk of drought damage from the recent climate change, design water requirement reevaluation is required to adjust design and management of irrigation systems.

This study aims to reestablish water requirement estimation procedures using FAO Penman–Monteith method and frequency analysis, and to find an optimal probability distribution function for determining design water requirement at the drought reference design year in South Korea.

2. Material and methods

Design water requirement (DWR) is the subsequent process of net irrigation water requirement (NIWR) calculation and frequency analysis as shown in Fig. 1. Firstly, crop evapotranspiration is calculated using FAO Penman–Monteith method and the crop coefficient, and then an optimal probability distribution function is chosen from the time series of NIWR.

2.1. Site description

Nationwide nine locations in South Korea were selected for estimating DWR: Chuncheon, Seoul, Suwon, Cheongju, Daejeon, Jeonju, Gwangju, Daegu and Jinju (Fig. 2). Daegu shows the highest annual mean temperature among the target locations while the lowest temperature is in Chuncheon (Table 1). As for annual rainfall, the amount is the maximum in Jinju near by the south coast of the Korean Peninsula. Daegu would be expected to need the biggest amount of water requirement in that it has the maximum in terms of annual total sunshine duration, mean wind speed and mean temperature but the amounts of annual total rainfall and mean relative humidity are the smallest among nine locations.

2.2. Net irrigation water requirement (NIWR)

NIWR is defined as the depth of water to meet the water loss through crop evapotranspiration of a disease-free crop growing in large fields and to achieve the full production potential under the given growing environment.

NIWR for paddy rice is formulated by using a water balance concept as described by Eq. (1) (Jensen et al., 1990)

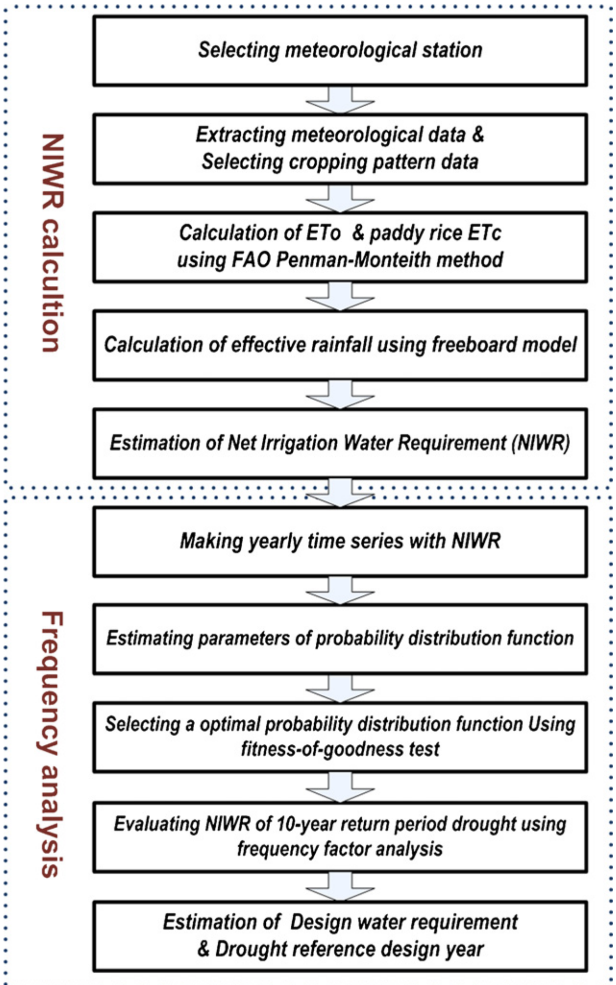

Fig. 1 – A procedure diagram for design water requirement calculation.

Fig. 2 – Locations of the nine study sites.

$$\mathrm{NIWR} = \mathrm{ETc} + \mathrm{DP} + \mathrm{LR} + \mathrm{MR} - \mathrm{EFR} \tag{1}$$

where ETc is crop evapotranspiration (mm), DP the deep percolation (mm), LR the leaching requirement (mm), MR the miscellaneous water requirement (mm) and EFR is the effective rainfall (mm) as we will define it below.

In general, the leaching requirement and the land preparation in ponding rice fields are negligible. Therefore, Eq. (2) is a simpler and more commonly used equation for computing NIWR in a paddy field.

$$\mathrm{NIWR} = \mathrm{ETc} + \mathrm{DP} - \mathrm{EFR} \tag{2}$$

2.2.1. *Crop evapotranspiration*

The estimation of consumptive use for irrigated crops is determined by the crop coefficient-reference evapotranspiration procedure. Reference evapotranspiration (ETo) is computed for a hypothetical reference crop according to the FAO paper no. 56 methodology (Allen et al., 1998) and is then multiplied by an empirical crop coefficient (K_c) to produce an estimate of crop evapotranspiration (ETc), as in Eq. (3),

$$\mathrm{ETc} = K_c \times \mathrm{ETo} \tag{3}$$

Accordingly, the ETo is calculated using the FAO Penman–Monteith method recommended in FAO paper no. 56 (Allen et al., 1998), which uses all parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters are measured or can be calculated from weather conditions. It requires daily, weekly and monthly meteorological data including air temperature, humidity, sunshine duration and wind speed (Allen et al., 1998).

The FAO Penman–Monteith equation used for 24-h calculations of ETo and using daily or monthly mean data can be simplified (Allen et al., 1998) as in Eq. (4)

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma(900/T + 273)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

Table 1 – Climatic characteristics by study locations

Location	Annual mean temperature (°C)	Annual mean wind speed (m/s)	Annual mean relative humidity (%)	Annual total sunshine duration (h)	Annual total rainfall (mm)
Chuncheon	10.9	1.4	72.3	2197.6	1266.8
Seoul	12.2	2.4	66.9	2114.1	1344.3
Suwon	11.6	1.6	72.2	2230.1	1268.1
Cheongju	12.0	1.9	71.0	2255.6	1225.1
Daejeon	12.3	1.7	71.3	2221.0	1353.8
Daegu	13.7	2.9	64.1	2290.0	1027.7
Jeonju	13.0	1.3	71.9	2105.4	1286.6
Gwangju	13.5	2.2	72.0	2213.9	1367.8
Jinju	13.1	1.7	71.5	2214.4	1490.0

where ETo is the reference evapotranspiration (mm/day), Δ the slope of saturated vapour pressure/temperature curve (kPa/°C), γ the psychrometric constant (kPa/°C), u_2 the wind speed at 2 m height (m/s), R_n the total net radiation at the crop surface (MJ/m^2 day), G the soil heat flux density (MJ/m^2 day), T the mean daily air temperature at 2 m height (°C), e_s the saturation vapor pressure (kPa) and e_a is the actual vapor pressure (kPa).

The ETc of paddy rice is calculated by multiplying 10-day crop coefficients and 10-day ETo values as defined by Eq. (3). Crop coefficients can be influenced by cultivation, local climatic conditions and seasonal differences in crop growth patterns (Kuo et al., 2006). The crop coefficients in this study were referred from the results of Yoo et al. (2006) as in Table 2. In this study, transplanting days and the irrigation period are defines as the end day of May and from June 1 to September 10.

2.2.2. *Deep percolation*

Deep percolation is influenced by changes in the conditions of paddy rice fields including soil texture and structure, top and subsoil thickness, standing water depth, water and soil temperature and salinity, depth to the ground water table, and other topographical conditions (Wickham and Singh, 1978). In South Korea, most paddy rice irrigation systems have been developed under soil conditions, which are clay textured and have relatively low percolation rates (Jang et al., 2007).

Previous studies showed that about 4–6 mm/day of water percolates into paddy soils during irrigation seasons (Lee, 1988). The Rural Research Institute in South Korea has determined through field experiments conducted since 1970 in several basins that the average deep percolation rate ranges from 5.0 to 5.6 mm/day (KWRC, 2002). Since, deep percolation of paddy fields was assumed to be 5.0 mm/day.

2.2.3. *Effective rainfall and ponding water depth*

Effective rainfall is the amount of water available for crop growth from rainfall except surface runoff loss. Effective rainfall during irrigation seasons depends on rainfall amount, rainfall intensity, topography, soil infiltration rate, soil moisture, water management practices and so on. It is difficult to estimate effective rainfall because of infiltration rate change with time and soil conditions, and the spatial and temporal variability of rain (Malano et al., 2004). The effective rainfall for paddy fields is calculated using a freeboard model (IRRI, 1977) to simulate the value of ponding water depth. The freeboard model is formulated as Eq. (5),

$$PD_t = PD_{t-1} + IR_t + RF_t - ETc_t - DP_t - SR_t \qquad (5)$$

where t is the time (day), PD the ponding water depth (mm), SR the surface runoff in the paddy field outlet (mm), IR the irrigated water (mm) and RF is the rainfall (mm). Rainfall below 5 mm/day is considered ineffective rainfall (Dastane, 1978; Chung et al., 2006).

Therefore, effective rainfall (EFR) is expressed as Eq. (6):

$$EFR_t = RF_t \ \text{for} \ SR_t = 0 \qquad (6)$$

$$EFR_t = RF_t - SP_t \ \text{for} \ SR_t > 0$$

Some suggestions were made for the freeboard model as follows: the outlet height in the paddy field is 80 mm, deep percolation is 5 mm and irrigation is supplied for controlled ponding water depth for each growth stage (Table 3).

2.3. *Design water requirement and drought reference design year (DRDY)*

2.3.1. *Drought of a 10-year return period*

It may not be economically feasible to construct a system with enough capacity to meet the expected crop water requirement in 10 out of 10 years. However, it may be feasible to design and construct a system which meets the requirement in 8 out of 10 years. For example, if designers or farmers can accept the related risk, that is, they will have an inadequate water supply causing reduction in yields or crop failure on average in 2 out of 10 years—then the design based on a 70–90% probability of evapotranspiration may be the most cost-effective (Cuenca, 1989). There is an inverse relationship between the capacity of the irrigation system and the degree of farming risk that a

Table 2 – Crop coefficients of transplanted paddy rice in South Korea (Yoo et al., 2006)

Days after transplanting	10	20	30	40	50	60	70	80	90	100	110	120	Avg.
Crop coefficients	0.78	0.97	1.07	1.16	1.28	1.45	1.50	1.58	1.46	1.45	1.25	1.01	1.27

Table 3 – Controlled ponding water depth by rice growth stages in a paddy field (Doorenbos and Kassam, 1986)

Date	5/30	6/1–6/20	6/21–7/31				~8/10	8/11–9/10		
Growth stages	Transplanting	Tillering	Head development				Heading	Grain filling and ripening		
Ponding depth	60	40	0	20	30	30	30	40	40	0

Values are in millimetres.

farmer faces. The most cost-effective system over the long term will generally be a system that requires farmers to accept some level of risk. An optimal design will allow farmers to evaluate the trade-off between the cost of the system and the level of risk. This requires the design engineer to make a great effort to collect sufficient data to develop a statistical distribution function for crop water requirement (Cuenca, 1989).

Historically, irrigation systems in South Korea have been vulnerable to drought for consecutive years. That is, sequence droughts have occurred once in a period of 10 years: 1927–1929, 1937–1939, 1942–1944, 1967–1968, 1976–1977, 1982–1983, 1994–1995 and 2000–2001. Therefore, computing the NIWR of a 10-year return period drought will enable engineers to estimate a reference year, drought reference design year, for the design of agricultural water resource systems in South Korea (MAF, 1999).

2.3.2. *Frequency analysis*

If enough daily data are available, the NIWR can be shown as a specific distribution (Chow, 1951). Different probability distribution functions (PDF) have been examined, such as Normal (NOR), Log-Normal (LN), Gamma (GAM), Log-Pearson Type III (LP3), Generalized Extreme Values (GEV), Gumbel (GUM), Log-Gumbel (LGU), Weibull (WBU) and Generalized Logistic (GLO). In this study, frequency analysis was performed to estimate the 10-year return period drought. The procedure for frequency analysis is as follows:

- Setting up a time-series of the NIWR for each location.
- Estimating the parameters of each PDF (NOR, GAM, GEV, GUM, LGU, LN, LP3, WBU, GLO) by probability weighted moments method recommended by the WMO (Greenwood et al., 1979; Landwehr et al., 1979).
- Selecting and define an optimal PDF using goodness-of-fit tests including Kolmogorov–Smirnov (K–S) and Probability Plot Correlation Coefficient (PPCC) methods.
- Calculating the DWR of 10-year return period drought using the chosen optimal PDF and Chow frequency factor method (Chow, 1951). Chow frequency factor method has the following expression:

$$x_T = \bar{x} + \sigma K_T \quad (7)$$

where x is a variate, $\bar{x}$ a mean, σ a standard deviation, K a frequency factor and T is a return period. For a given return period, the frequency factor can be determined from the K–T relationship for the proposed distribution and the magnitude x for the return period can be computed using Eq. (7), using the corresponding frequency factor and the computed statistical parameter. The K and T can be found in the chart for each PDF (Chow, 1951).

3. Estimation of net irrigation water requirement (NIWR)

The ETc, EFR and NIWR during the growing season were estimated using the NIWR model at the nine study locations. Table 4 shows the statistics of ETc, EFR and NIWR for the nine locations. These values indicate that annual average ETc during the irrigation season had a maximum value of 473.8 mm in Daegu and a minimum value of 413.8 mm in Chuncheon. The average EFR had a maximum value of 420.3 mm in Jinju and a minimum value of 335.8 mm in Daegu. Based on both ETc and EFR, the average NIWR was maximal at 800.4 mm in Daegu and its minimum value was 723.2 mm in Chuncheon.

Table 4 – ETc, EFR and NIWR during the paddy rice growing season over a 30-year period (1976–2005)

Location	ETc			EFR			NIWR			Ratio[a]
	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	
Chuncheon	413.8	467.8	369.0	398.6	658.9	278.0	723.2	838.7	628.9	109.1
Seoul	425.0	506.9	355.7	413.5	634.9	224.6	730.3	886.8	593.2	109.7
Suwon	419.5	491.8	346.6	382.3	571.3	218.1	739.2	849.3	637.5	115.3
Cheongju	446.3	553.6	366.6	392.7	599.1	270.0	757.1	877.3	625.8	119.0
Daejeon	439.7	557.6	357.1	399.5	610.0	200.3	745.2	934.7	625.4	119.9
Daegu	473.8	619.8	376.4	335.8	545.4	137.9	800.4	1009.6	656.5	157.3
Jeonju	430.8	522.1	354.7	388.2	651.8	181.0	737.7	891.1	580.0	121.3
Gwangju	445.9	562.0	362.0	397.1	591.2	214.0	754.2	920.8	570.6	122.8
Jinju	422.0	533.0	353.2	420.3	637.4	144.0	735.3	931.0	595.3	113.0

Values are in millimetres.
[a] Ratio = avg. ETc/avg. EFR.

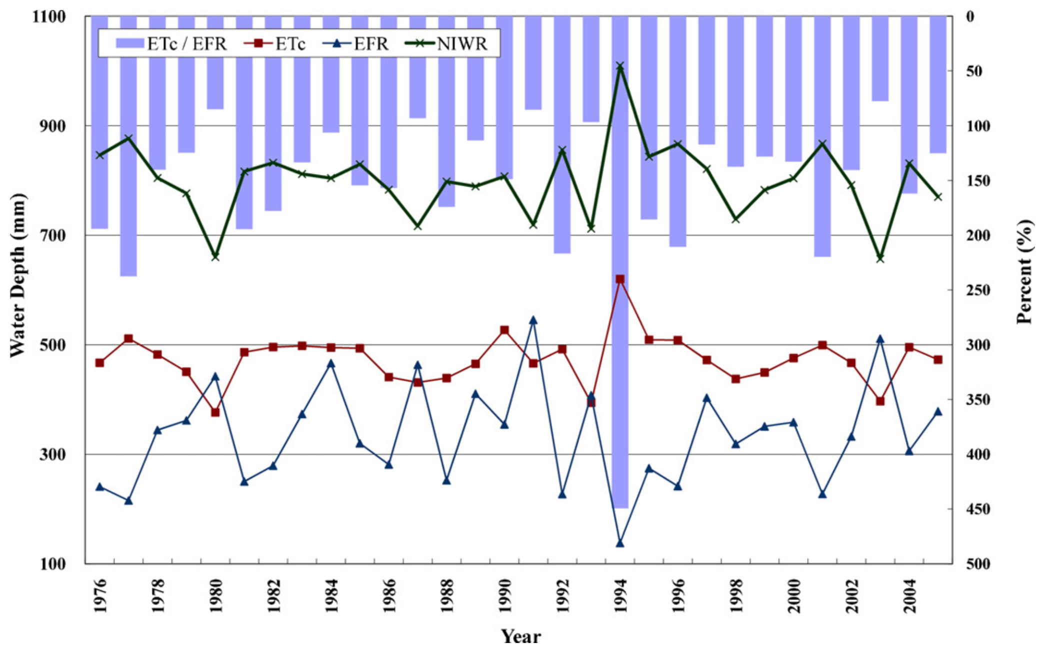

Fig. 3 – ETc, EFR and NIWR during the paddy rice growing season over a 30-year period in Daegu.

Regarding the ratio of average ETc over average EFR, it was relatively low at 109.1–109.7% in the northern regions of Chuncheon and Seoul, 115.3–119.9% in the central regions of Suwon, Cheongju and Daejeon, and 113.0–122.8% in the southern regions of Jeonju, Gwangju and Jinju except for Daegu. The estimated rate increased with more southerly locations with the exception of Jinju, which is near the seaside and had the largest amount of rainfall. The rate was highest in Daegu and lowest in Chuncheon. Daegu had high amount of ETc due to its low amount of rainfall compared with other locations contributed to this high ratio. Located in the north of South Korea with relatively high rainfall, Chuncheon had relatively low ETc compared with other locations.

Figs. 3 and 4 show the annual changes in the estimated ETc, EFR and NIWR from 1976 to 2005 in Daegu and Chuncheon, respectively. Daegu had 1009.6 mm in 1994, 876.9 mm in 1977 and 867.0 mm in 2001, which were the largest in NIWR during this reporting period. In particular, 1994 saw the maximum NIWR during the period because ETc was estimated to be at a maximum of 694.8 mm and EFR at a minimum of 137.9 mm. In fact, a severe drought hit South Korea in 1994 as a result of temperature extremes and little rainfall. In contrast, in 1984

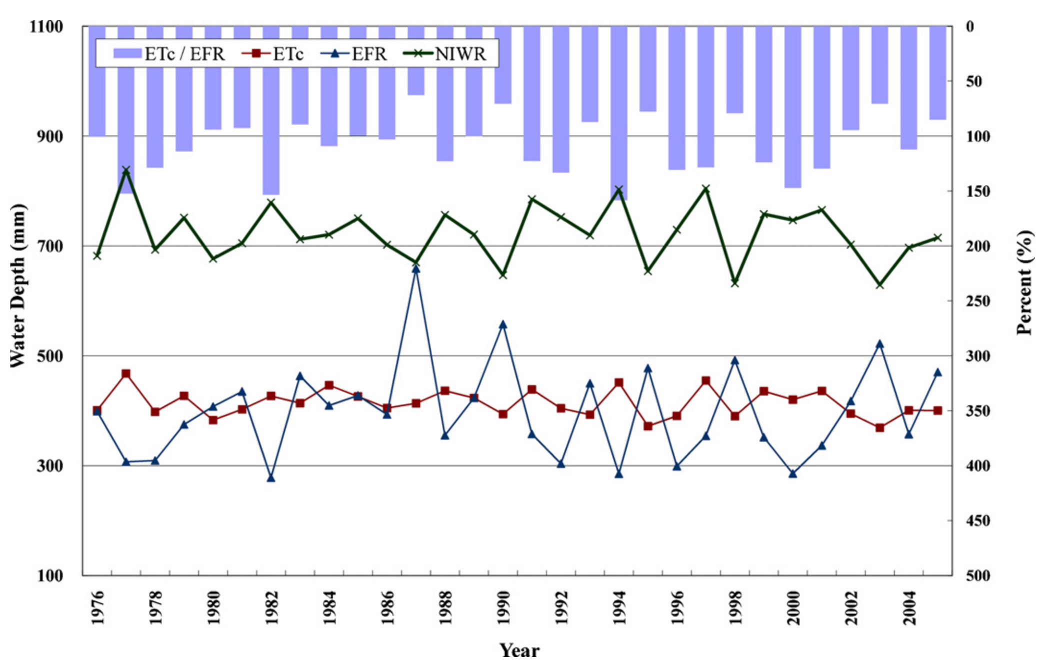

Fig. 4 – ETc, EFR and NIWR during the paddy rice growing season over a 30-year period in Chuncheon.

Table 5 – Basic statistics on unbiased estimates of the NIWR for nine locations over a 30-year period (1976–2005)

Location	Mean	Max.	Min.	S.D.	Coeff. variation	Coeff. skewness	Coeff. kurtosis
Chuncheon	723.5	838.7	628.9	52.7	0.073	0.102	2.863
Seoul	730.3	886.8	593.2	66.2	0.091	0.439	3.967
Suwon	740.4	849.3	637.5	59.2	0.08	0.194	2.721
Cheongju	759.5	877.3	625.8	59.5	0.078	−0.524	3.797
Daejeon	747.7	934.7	625.4	71.4	0.095	0.229	3.679
Daegu	801.5	1009.6	656.5	70.1	0.087	0.249	5.312
Jeonju	738.1	891.1	580.0	64.2	0.087	−0.341	4.014
Gwangju	754.7	920.8	570.6	67.8	0.09	−0.439	4.704
Jinju	734.7	931.0	595.3	74.7	0.102	0.127	3.597

Values are in millimetres.

Table 6 – Results of goodness-of-fit tests for PDFs

Location	NOR	GAM	GEV	GUM	LGU	LN	LP3	WBU	GLO
Chuncheon	O	P	O	O	P	O	K-	O	O
Seoul	O	P	O	O	P	O	K-	O	O
Suwon	O	P	O	O	P	O	K-	O	O
Cheongju	O	P	O	P	P	O	O-	O	O
Daejeon	O	P	O	O	P	O	O-	O	O
Daegu	P	P	O	P	P	P	O-	O	O
Jeonju	O	P	O	P	P	O	K-	O	O
Gwangju	O	P	O	P	P	O	K-	O	O
Jinju	O	P	O	P	P	O	O-	O	O

O, All goodness-of-fit tests can be accepted; K, only Kolmogorov–Smirnov test cannot be accepted; P, only PPCC test cannot be accepted; -, PPCC test cannot be performed.

the NIWR was relatively smaller because EFR was high at 466.3 mm, even though the 494.8 mm value for ETc was relatively large. Daegu is usually considered to have high NIWR when compared with other locations because it has a relatively smaller EFR.

Chuncheon had NIWR of 838.7 mm in 1977, 804.6 mm in 1997 and 802.8 mm in 1994, all of which were posted as the largest NIWR during the entire period. In Fig. 4, relatively large values of NIWR were caused by high ETc and low EFR in those 3 years. By contrast, NIWR was estimated at 628.9 mm in 2003, 631.9 mm in 1998, 646.8 mm in 1990 and 669.9 mm in 1987. In these 4 years, NIWR was low due to low ETc and high EFR. In 1987, the fourth lowest NIWR was estimated despite the highest EFR calculated in the 30-year period. Generally, NIWR decreases as EFR increases. In 1987, however, this was not the case. The reason is that NIWR is determined by composite factors of rainfall, such as time, intensity and amount.

4. Optimal probability distribution function

To estimate NIWR in the 10-year return period, a time-series of NIWR was made during the rice growing period from 1976 to 2005. Table 5 gives basic statistical variables including mean, maximum, minimum, standard deviation, coefficient of variation, skewness and kurtosis for the NIWR time-series estimates about locations. The parameters of nine PDFs are estimated using the probability weighted moments method with basic statistical variables of time-series.

Table 7 – PPCC test statistics for PDFs

Location	NOR	GAM	GEV	GUM	LGU	LN	LP3	WBU	GLO
Chuncheon	0.995	0.934	0.995	0.978	0.970	0.995	–	0.976	0.992
Seoul	0.971	0.937	0.972	0.973	0.968	0.971	–	0.949	0.981
Suwon	0.987	0.935	0.989	0.971	0.962	0.987	–	0.966	0.982
Cheongju	0.978	0.881	0.977	0.939	0.926	0.978	–	0.983	0.986
Daejeon	0.980	0.933	0.978	0.971	0.962	0.980	–	0.963	0.981
Daegu	0.956	0.897	0.947	0.943	0.936	0.956	–	0.949	0.963
Jeonju	0.971	0.871	0.969	0.936	0.923	0.971	–	0.977	0.980
Gwangju	0.969	0.865	0.967	0.931	0.918	0.969	–	0.978	0.983
Jinju	0.974	0.894	0.972	0.951	0.938	0.974	–	0.967	0.971
Mean	0.976	0.905	0.974	0.955	0.945	0.976	–	0.968	0.980
S.D.	0.011	0.030	0.014	0.018	0.021	0.011	–	0.012	0.008

Table 8 – DWR and DRDY for drought of 10-year return period by the PDFs

Location	GLO		WBU		GEV	
	DWR	DRDY	DWR	DRDY	DWR	DRDY
Chuncheon	790.7	1991	787.3	1991	809.9	1997
Seoul	811.7	1982	806.7	1982	831.8	1997
Suwon	816.4	1982	811.9	1982	836.4	1997
Cheongju	829.4	1977	828.9	1977	849.1	1996
Daejeon	836.1	1996	832.5	1996	856.5	2001
Daegu	882.5	1977	880.5	1977	903.7	1977
Jeonju	811.7	2001	812.4	2001	831.0	1988
Gwangju	832.0	1988	832.8	1988	851.7	1988
Jinju	825.3	1977	823.9	1977	845.1	1977
Avg.	826.2	–	824.1	–	846.1	–

Values are in millimetres.

The K–S and PPCC tests were conducted for the nine PDFs at the nine locations. Table 6 shows the results of the K–S test with a 5% significance level for the nine PDFs at each location. Except for LP3, eight out of the nine PDFs met the significance level of 5% in all locations. LP3 was not accepted in Chuncheon, Seoul, Suwon, Jeonju and Gwangju. As for the PPCC test, GEV, WBU and GLO met the significance level of 5% in all locations. NOR and LN passed the PPCC test in all locations with the exception of Daegu. GUM did not pass the PPCC test in five locations, including Cheongju, and GAM and LGU were not acceptable in any location.

As a result, the PDFs determined by goodness-of-fit tests in all locations were GEV, WBU and GLO. In Table 7, the PPCC test statistics are shown in addition to the mean and standard deviation of PDFs at each location to estimate the optimal PDF out of these three PDFs. The PPCC goodness-of-fit test is evaluated by a correlation coefficient between the original and estimated data. Therefore, if the average is largest and the standard deviation is smallest, the PDF can properly recreate the sample data set. Thus, GLO had the maximum average and the minimum standard deviation among the three PDFs of GEV, WBU and GLO. Accordingly, GLO was selected as the optimal PDF for estimating NIWR in the 10-year return period.

5. Design water requirement and drought reference design year

Each local DWR was estimated using frequency analysis with selected optimal PDF. DWR and DRDY calculated are shown in Table 8. Daegu had a maximum DWR of 882.5 mm and Daejeon had the second largest value. While Chuncheon had the smallest value at 790.7 mm, the DWR in Daegu estimated at 46.4–91.8 mm is larger than those in other locations. For Chuncheon, the relatively low ETc and high EFR due to its northerly location gave rise to the smallest estimated DWR. For DRDY, 1982 was selected for Seoul and Suwon; 1977 for Cheongju, Daegu and Jinju; 1991 for Chuncheon; 1996 for Daejeon; 2001 for Jeonju; 1988 for Gwangju.

To analyze the DWR differences among PDFs, the DWR was calculated for the three selected PDFs: GLO, GEV and WBU. Table 8 shows the variations of results by changing the PDFs from GLO to GEV or WBU in the estimation of DWR and DRDY. The DWR differences between WBU and GLO were relatively small ranging from 5.0 to 8.0 mm following the locations, so that DRDY was occurred in the same year for GLO and WBU in all locations. The DWR estimation using GEV differed from GLO by 19.2–21.2 mm. This was actually a large difference compared with what had been seen between GLO and WBU. Unlike WBU, DRDYs were selected differently at six locations with GEV, except for Daegu, Gwangju and Jinju. In other words, when DWR was estimated using frequency analysis, GLO was evaluated as being optimal. Furthermore, WBU is the next best PDF due to its success in the K–S and PPCC tests. GEV is not suitable for estimating DWR because it had a large difference of 20 mm compared with the other two PDFs.

6. Summary and conclusions

This study aims to estimate design water requirement using FAO Penman–Monteith method and to find an optimal probability distribution function (PDF) for determining DWR at the drought reference design year in South Korea.

The DWR of 10-year return period drought were computed using NIWR model and frequency analysis. To select the optimal PDF, nine types of PDFs were tested using the K–S and PPCC goodness-of-fit methods. The Generalized Logistic (GLO) was selected as being optimal from among nine PDFs, and DWRs were estimated using the selected optimal PDF for nine locations. The results of DWRs range from 790.7 mm in Chuncheon to 882.5 mm in Daegu. For DRDY, 1982 was selected for Seoul and Suwon; 1977 for Cheongju, Daegu and Jinju; 1991 for Chuncheon; 1996 for Daejeon; 2001 for Jeonju; 1988 for Gwangju. To demonstrate DWR differences and DRDY among the PDFs, the DWR and DRDY were compared for the three selected PDFs, GLO, GEV and WBU. GEV is not suitable for estimating DWR because it has a large difference in computing water requirement.

The results of this study are expected to be used as a guideline of DWR calculation and RDRY selection in South Korea to design and operation of agricultural water resource structures in terms of capacity and capability enhancement confronting the risk of drought from climate variations caused by climate change.

REFERENCES

Abdelhadi, A.W., Hata, T., Tanakamaru, H., Tada, A., Tariq, M.A., 2000. Estimation of crop water requirements in arid region using Penman–Monteith equation with derived crop coefficients: a case study on Acala cotton in Sudan Gezira irrigated scheme. Agric. Water Manag. 45, 203–214.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop requirements. FAO irrigation and drainage paper no. 56. Food and Agriculture Organization of the United Nations, Rome, Italy.

Azevedo, P.V., de Silva, B.B., da Silva, V.P.R., 2003. Water requirements of irrigated mango orchards in northeast Brazil. Agric. Water Manag. 58, 241–254.

Chow, V.T., 1951. A general formula for hydrologic frequency analysis. Trans. Am. Geophys. Union 32.

Chung, H.W., Kim, S.J., Kim, J.S., Noh, J.K., Park, K.U., Son, J.K., Yoon, K.S., Lee, K.H., Lee, N.H., Chung, S.O., Choi, J.D., Choi, J.Y., 2006. Irrigation and Drainage Engineering, second ed. Dongmyeong Publisher, Seoul, Republic of Korea (in Korean).

Cuenca, R.H., 1989. Irrigation System Design—An Engineering Approach. Prentice Hall, Englewood Cliffs, New Jersey.

Dastane, N.G., 1978. Effective rainfall in irrigated agriculture. FAO irrigation and drainage paper no. 25. Food and Agriculture Organization of the United Nations, Rome, Italy.

Doorenbos, J., Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. FAO irrigation and drainage paper no. 24. Food and Agriculture Organization of the United Nations, Rome, Italy.

Doorenbos, J., Kassam, A.H., 1986. Yield response to water. FAO irrigation and drainage paper no. 33. Food and Agriculture Organization of the United Nations, Rome, Italy.

Greenwood, J.A., Landwehr, J.M., Matalas, N.C., Wallis, J.R., 1979. Probability weighted moments: definition and relation to parameters of several distributions expressible in inverse form. Water Resour. Res. 15, 1049–1054.

Ibrahim, A.A., Stigter, C.J., Adam, H.S., Adeeb, A.M., 2002. Water-use efficiency of sorghum and groundnut under traditional and current irrigation in the Gezira scheme, Sudan. Irrigat. Sci. 21, 115–125.

International Rice Research Institute (IRRI), 1977. Annual report for 1997. Los Banos, Philippines.

Jang, M.-W., Choi, J.-Y., Lee, J.-J., 2007. A spatial reasoning approach to estimating paddy rice water demand in Hwanghaenam-do, North Korea. Agric. Water Manag. 89, 185–198.

Jensen, M.E., Burman, R.D., Allen, R.G. (Eds.), 1990. Evapotranspiration and Irrigation Water Requirements. Committee on Irrigation Water Requirements of the Irrigation and Drainage Division of ASCE (Am. Soc. Civil Engrs.). ASCE Manual No. 70, New York, NY, p. 332.

Koo, J.W., Kwun, S.K., Kim, T.C., Lee, K.H., 1998. Design Criteria of Agricultural Land and Water Development (Irrigation). Ministry of Agriculture and Forestry, (in Korean).

Korea Water Resources Cooperation (KWRC), 2002. Dam Design Manual. Korea Water Resources Cooperation, Daejeon, Republic of Korea (in Korean).

Kuo, S.-F., Ho, S.S., Liu, C.-W., 2006. Estimation irrigation water requirements with derived crop coefficients for upland and paddy crops in ChiaNan Irrigation Association, Taiwan. Agric. Water Manag. 82, 433–451.

Landwehr, J.M., Matalas, N.C., Wallis, J.R., 1979. Probability-weighted moments compared with some traditional techniques in estimating Gumbel parameters and quantiles. Water Resour. Res. 15, 1055–1064.

Lee, N.H., 1988. Simulating daily operation of water management system of irrigation districts. Ph.D. thesis. Seoul National University, Seoul, Republic of Korea (in Korean, with English abstract).

Malano, H.M., George, B.A., Davidson, B., 2004. A framework for improving the management of irrigation schemes in Vietnam. In: Proceedings of a workshop of Australian Centre for International Agricultural Research, vol. 28, Hochiminh, Vietnam.

Ministry of Agricultural and Fisheries (MAF) and Agricultural Development Corporation (ADC), 1987. A Study on Consumptive use of Paddy Field. Ministry of Agricultural and Fisheries, Republic of Korea (in Korean).

Ministry of Agriculture and Forestry (MAF), 1999. Comprehensive Plan for Agricultural and Rural Water. Ministry of Agriculture and Forestry, Republic of Korea (in Korean).

Park, K.W., 2004. Development of a simu-lation model for automatic irrigation mana-gement (SIMA) in paddy land. Ph.D. thesis. Seoul National University, Seoul, Republic of Korea (in Korean, with English abstract).

Wickham, T.H., Singh, V.P., 1978. Water movement through wet soil. In: Soil and Rice, International Rice Research Institute, Los Banos, Philippines.

Yoo, S.-H., Choi, J.-Y., Jang, M.-W., 2006. Estimation of paddy rice crop coefficient for FAO Penman–Monteith and modified Penman method. J. Korean Soc. Agric. Engrs. 48 (1), 13–23 (in Korean, with English abstract).