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How Ångström–Prescott Coefficients Alter the Estimation of Agricultural Water Demand in South Korea

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Abstract: The Food and Agriculture Organization (FAO) Penman–Monteith equation, recognized as the standard method for the estimation of reference crop evapotranspiration (ET_0), requires many meteorological inputs. The Ångström–Prescott (A-P) formula containing parameters (i.e., a and b) is recommended to determine global solar radiation, one of the essential meteorological inputs, but may result in a considerable difference in ET_0 estimation. This study explored the effects of A-P coefficients not only on the estimation of ET_0, but also on the irrigation water requirement (IWR) and design water requirement (DWR) for paddy rice cultivation, which is the largest consumer of agricultural water in South Korea. We compared and analyzed the estimates of ET_0, IWR, and DWR using the recommended (a = 0.25 and b = 0.5) and locally calibrated A-P coefficients in 16 locations of South Korea. The estimation of ET_0 using the recommended A-P coefficients produced significant overestimation. The overestimation ranged from 3.8% to 14.0% across the 16 locations as compared to the estimates using the locally calibrated A-P coefficients, and the average overestimation was 10.0%. The overestimation of ET_0 corresponded to a variation of 1.7% to 7.2% in the overestimation of the mean annual IWR, and the average overestimation of the IWR was 5.1%. On average, the overestimation was slightly reduced to 4.8% in DWR estimation, since the effect of A-P coefficients on the IWR estimation decreased as the IWR increased. This study demonstrates how the use of A-P coefficients can alter the estimation of ET_0, IWR, and DWR in South Korea, which underscores the importance of their proper consideration in agricultural water management.

Keywords: design water requirement; irrigation water requirement; paddy irrigation; Penman–Monteith equation; reference crop evapotranspiration

1. Introduction

The estimation of agricultural water demand is very important in long-term water resources planning, because agricultural water use accounts for the largest portion of total freshwater use. Globally, about 70% of freshwater is consumed by agricultural production [1], and agriculture will use more water in the future [2]. In order to estimate agricultural water demand, the reference crop evapotranspiration (ET_0) needs to be calculated. The Food and Agriculture Organization (FAO) Penman–Monteith (P-M) equation, which combines both energy and mass balances based on physical principles, is recommended as the standard method for estimating ET_0 in a variety of climate types [3].

The equation, however, can be restricted in use, since it requires a number of meteorological inputs which may not be available everywhere [4,5].

Global solar radiation is one of the essential inputs of the P-M equation. The Ångström–Prescott (A-P) formula is recommended for the estimation of the global solar radiation if it is not measured [3]. Parameters in the formula (i.e., a and b) vary depending on atmospheric conditions and solar declination [3]. Accordingly, there have been many studies on their estimation in different regions having different climates [6–11]. For South Korea, Choi et al. [12] calibrated A-P coefficients by using 25 years (1983–2007) of observed daily global solar radiation and sunshine duration data at 18 meteorological stations. The calibrated coefficients were validated by comparing the estimates of daily solar radiation, using the locally extracted coefficients from the spatially interpolated map of the calibrated coefficients, with the observed solar radiation for a one-year period (September 2008 to August 2009) at eight locations. In the case that no measured solar radiation data are available and no calibration has been carried out for the parameters, the values of 0.25 and 0.50 are recommended for a and b, respectively [3].

Despite the many studies on estimating the A-P coefficients for a specific region, only a few studies have evaluated the effects of A-P coefficients on the estimation of ET_0. Moreover, previous studies on the effects have suggested that the recommended A-P coefficients may call into question the accuracy of the P-M equation [7,10]. Sabziparvar et al. [10] showed that daily ET_0 estimates in a humid subtropical climate could be improved up to 72.7% when the calibrated A-P coefficients were used instead of the recommended A-P coefficients. For these reasons, Liu et al. [7] argued that there is a need for further exploration into the variation in ET_0 caused by the A-P coefficients in different climates.

In addition to the ET_0, the estimation of irrigation water requirements (IWRs) and design water requirements (DWRs), which is an essential part of the design and operation of agricultural water resources systems [13], is also affected by the use of A-P coefficients when the estimation uses the P-M equation. The IWR is the net depth of water that is required to be applied to a crop to fully satisfy its specific crop water requirement for achieving full production potential [14]. The estimation of IWR, explained in the following section in detail, generally requires the estimation of ET_0 and crop coefficients for a given crop, but also involves other factors such as effective rainfall and deep percolation, which altogether influence the effects of A-P coefficients on the estimation. When it comes to the DWR for a certain return period in paddy irrigation in South Korea, this is determined from the frequency analysis of IWRs for a given location [13]. Considering the proportion of agricultural water in total water use and the frequent use of the P-M equation in the estimation of agricultural water demand, it is necessary to study whether the use of recommended A-P coefficients overestimates or underestimates the IWRs and DWRs; this question has not been comprehensively explored so far.

The objective of this study, therefore, is to bridge these gaps by exploring how the A-P coefficients alter the estimation of ET_0, IWR, and DWR in South Korea. South Korea provides a good testing ground to further study the effects of A-P coefficients on the estimation, because in South Korea, the P-M equation is used as the standard for calculating evapotranspiration when agricultural water demand is estimated [15] and about 80% of agricultural water is used for the production of one single crop: paddy rice [16]. In this study, therefore, IWRs and DWRs are calculated for paddy rice production.

2. Materials and Methods

This study proceeds as follows. First, we evaluate the accuracy in the estimation of ET_0, calculated by the recommended A-P coefficients in 16 study sites by comparing with the estimates of ET_0 using the locally calibrated A-P coefficients provided by Choi et al. [12]. Second, we explore the difference between the estimates of IWR using the recommended and calibrated coefficients. Third, we analyze and compare the DWRs from the frequency analysis of the estimated IWRs.

2.1. Study Sites

We selected 16 meteorological stations that had their calibrated A-P coefficients and provided complete and reliable weather data for estimating ET_0 as study sites in South Korea (Figure 1). The selected sites are located across South Korea from the coast to inland and they are classified as having humid subtropical and continental climates by the Köppen–Geiger climate classification [17] (Table 1). To estimate ET_0, IWR, and DWR, we collected daily meteorological data including precipitation, maximum and minimum temperatures, wind speed, relative humidity, and sunshine hours from 1983 to 2007 from the Korea Meteorological Administration (https://data.kma.go.kr). This time period is the same one used by Choi et al. [12] to derive the calibrated Ångström–Prescott coefficients. Detailed geographical characteristics of the study sites and the calibrated Ångström–Prescott coefficients are given in Table 1.

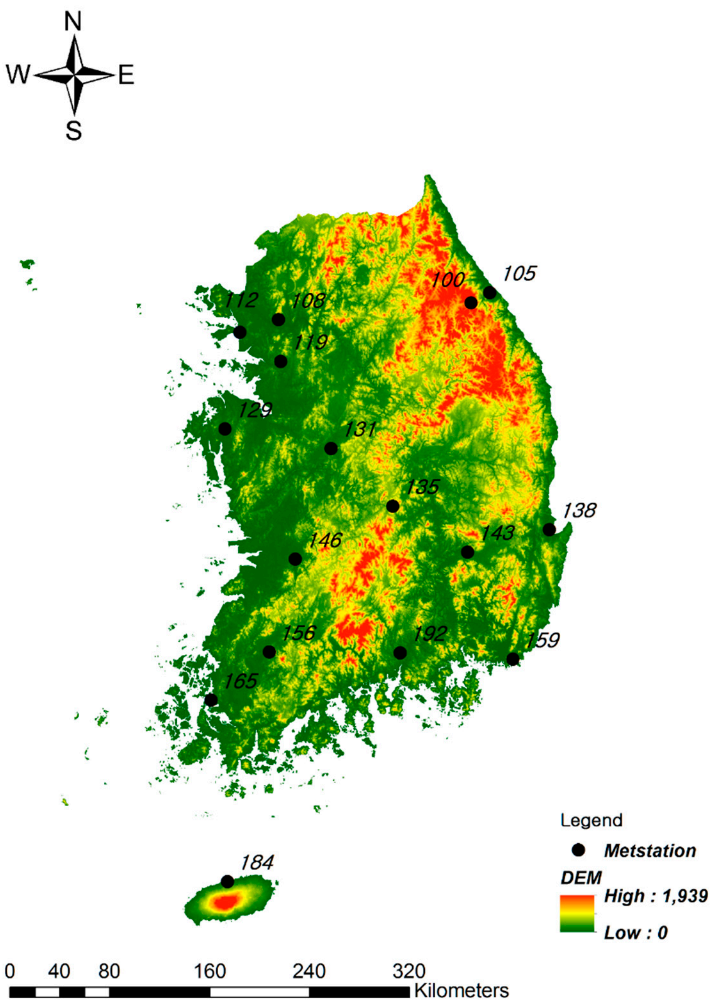

Figure 1. Location of the study sites.

Table 1. Geographic characteristics of the meteorological stations and the Ångström–Prescott coefficients used in this study.

Station ID	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Location	Climate Classification [1]	Ångström–Prescott Coefficients [2]		
							a	b	a + b
100	Daegwallyeong	37.68	128.72	772.6	Inland	Dfb	0.175	0.559	0.734
105	Gangneung	37.75	128.89	26.0	Coast	Cfa	0.217	0.482	0.699
108	Seoul	37.57	126.97	85.7	Inland	Cwa	0.197	0.452	0.648
112	Incheon	37.48	126.62	69.0	Coast	Cwa	0.192	0.476	0.661
119	Suwon	37.27	126.99	34.8	Inland	Cwa	0.199	0.459	0.658
129	Seosan	36.78	126.49	28.9	Inland	Cwa	0.222	0.484	0.706
131	Cheongju	36.64	127.44	58.7	Inland	Cwa	0.198	0.491	0.689
135	Chupungryeong	36.22	127.99	243.7	Inland	Cwa	0.181	0.485	0.666
138	Pohang	36.03	129.38	3.9	Coast	Cfa	0.201	0.493	0.694
143	Daegu	35.88	128.65	53.5	Inland	Cwa	0.204	0.463	0.667
146	Jeonju	35.84	127.12	61.4	Inland	Cfa	0.206	0.470	0.676
156	Gwangju	35.17	126.89	72.4	Inland	Cfa	0.211	0.495	0.706
159	Busan	35.10	129.03	69.6	Coast	Cwa	0.200	0.471	0.671
165	Mokpo	34.82	126.38	38.0	Coast	Cfa	0.230	0.500	0.729
184	Jeju	33.51	126.53	20.5	Coast	Cfa	0.197	0.506	0.703
192	Jinju	35.16	128.04	30.2	Inland	Cwa	0.194	0.477	0.743

[1] Climate classification is determined by the reanalyzed Köppen–Geiger map (retrieved from http://koeppen-geiger.vu-wien.ac.at/present.htm) using 25 years (1986–2010) of recent climate data from Rubel et al. [17]. [2] Coefficients are adopted from the results of Choi et al. [12] and they were derived from 25 years (1983–2007) of observed global solar radiation and sunshine duration data across South Korea.

2.2. FAO Penman–Monteith Equation

The FAO P-M equation used to estimate grass reference crop evapotranspiration (ET_0) is given as follows [3]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 is in mm day^{-1}, R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2-m height (), u_2 is the wind speed at 2-m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope vapor pressure curve (kPa $^{-1}$), and γ is the psychrometric constant (kPa $^{-1}$).

The detailed procedures for calculating all the parameters used in Equation (1) are described in Allen et al. [3].

2.3. Ångström–Prescott Coefficients

The coefficients (i.e., a and b) of the Ångström–Prescott formula given below are required to estimate (global) solar radiation (R_s), which is used for calculating the net radiation (R_n) in Equation (1); the recommended coefficients from Allen et al. [3] and calibrated coefficients from Choi et al. [12] were used in this study.

$$R_s = \left(a + b\frac{n}{N}\right)R_a \quad (2)$$

where R_s is in MJ m^{-2} day^{-1}, n is the actual duration of sunshine (h), N is the maximum possible duration of sunshine or daylight (h), $\frac{n}{N}$ is the relative sunshine duration, R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}), a is the regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days ($n = 0$), and $a + b$ is the fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$).

2.4. Irrigation Water Requirement

IWR is the fraction of crop water requirements that is not satisfied by rainfall, soil water storage, and the groundwater condition [14]. The crop water requirements are defined as the depth of water required by a disease-free crop growing in large fields to compensate for water loss through evapotranspiration and to achieve the full production potential for a given growing environment [14]. The IWR for paddy rice in this study is the net irrigation water requirement, which does not take into account the losses that occur in the irrigation process. The IWR was calculated using a simplified water balance equation modified from Jensen et al. [18] as follows, considering that the irrigation water used for leaching and miscellaneous water requirements in ponding paddy fields in South Korea is negligible [13].

$$\mathrm{IWR} = \mathrm{ET_c} + \mathrm{DP} - \mathrm{EFR} \tag{3}$$

where $\mathrm{ET_c}$ is the actual crop evapotranspiration (mm), DP is the deep percolation (mm), and EFR is the effective rainfall (mm).

The $\mathrm{ET_c}$ of paddy rice is calculated by multiplying the empirical 10-day crop coefficients given by Yoo et al. [19] and 10-day $\mathrm{ET_0}$ values estimated by Equation (1). The deep percolation of paddy fields was assumed to be 5.0 mm $\mathrm{day^{-1}}$, reflecting the monitoring results of previous studies in South Korea [20]. The effective rainfall for paddy fields is calculated using a freeboard model [21] to simulate the ponding water depth as follows:

$$\mathrm{PD_t} = \mathrm{PD_{t-1}} + \mathrm{IR_t} + \mathrm{RF_t} - \mathrm{ET_{ct}} - \mathrm{DP_t} - \mathrm{SR_t} \tag{4}$$

where PD is the ponding depth (mm), IR is the irrigated water (mm), RF is the rainfall (mm), SR is the surface runoff (mm), and t is time (day).

We assumed that the outlet height of the paddy field is 80 mm and that irrigation water is supplied for a controlled ponding water depth of 40 mm, except for the period of midseason drainage (i.e., when the ponding water depth is 0 mm) from 25 June to 15 July. Rainfall of less than 5 mm $\mathrm{day^{-1}}$ is considered ineffective rainfall [22].

In the IWR estimation, the water requirement for transplanting was included and assumed to be 140 mm, as suggested by the Ministry of Agriculture and Forestry in South Korea [23]. The transplanting date and irrigation periods were defined as 26 May and from 27 May to 11 September, respectively.

2.5. Design Water Requirement

DWRs to determine a reference year (i.e., drought reference design year (DRDY)), which is used for designing agricultural water facilities (e.g., irrigation canals and agricultural reservoirs) in South Korea, were calculated by following the guidelines suggested by Yoo et al. [13]. DWRs were determined from the frequency analysis of the calculated time-series of the 25 IWRs at each study site, and the reference return period was 10 years. The generalized logistic (GLO) distribution, which was the probability distribution function recommended by Yoo et al. [13] and verified again through the same procedure used in their study (not presented here), was used as the optimal probability density function to determine the DWR of a 10-year return period through Chow's frequency factor method below [24]. The parameters of the GLO distribution function, which were tested and accepted by goodness-of-fit tests (i.e., Kolmogorov–Smirnov (K-S) and probability plot correlation coefficient (PPCC) methods), were estimated using the probability weighted moments method.

$$x_T = \mu(1 + K_T C_v) \tag{5}$$

where x is a variate, μ is the mean, K is the frequency factor, C_v is the coefficient of variation ($\frac{\sigma}{\mu}$), and T is the return period. For a given return period, the frequency factor can be determined by the K-T relationship for a given probability distribution (GLO distribution in this study).

Once the DWR is determined, the year in which the estimated IWR is closest to the DWR is determined as the DRDY. Detailed information on the IWR of the DRDY (e.g., daily maximum IWR and gross IWR considering irrigation losses) is used to design the agricultural water facilities.

3. Results

3.1. Reference Crop Evapotranspiration

The estimates of ET_0 using the recommended A-P coefficients were larger than the estimates using the calibrated A-P coefficients at all study sites (Table 2). Although there have been limited studies conducted to provide locally calibrated A-P coefficients in South Korea [12,25], the recommended coefficients have normally been used for the ET_0 estimation. This suggests that the ET_0 may have been overestimated so far. The results of this study indicate that the overestimation seems to have reached almost 10%. On a daily and annual basis, the ET_0 estimates using the recommended coefficients showed an average overestimation of 9.2%. In seven of the 16 study sites, the ET_0 estimates showed more than 10% overestimation. Except for one study site, Mokpo, all other sites presented more than 5% overestimation. The largest overestimation was found in Suwon (13.9%), followed by Seoul (13.0%), Chupungryeong (12.4%), and Jinju (12.4%). The smallest overestimation, 2.9%, was found in Mokpo (Table 2). The t statistics suggested that all study sites showed a significant difference ($p < 0.01$) between ET_0 estimations using the different A-P coefficients on a daily basis, while 15 out of 16 sites showed a significant difference ($p < 0.01$) on an annual basis (Table 2).

During the growing seasons (May to September) from 1983 to 2007, in nine of the 16 study sites, overestimation in the ET_0 estimates caused by the use of the recommended A-P coefficients was more than 10% and the average overestimation across all study sites was 10.0% (Figure 2). The overestimation ranged from 3.8% to 14.0%. Chupungryeong showed the largest overestimation of 14.0% during the season, followed by Suwon (13.9%), Jinju (13.1%), and Seoul (12.9%), while the smallest overestimation was found in Mokpo (3.8%) (Figure 2).

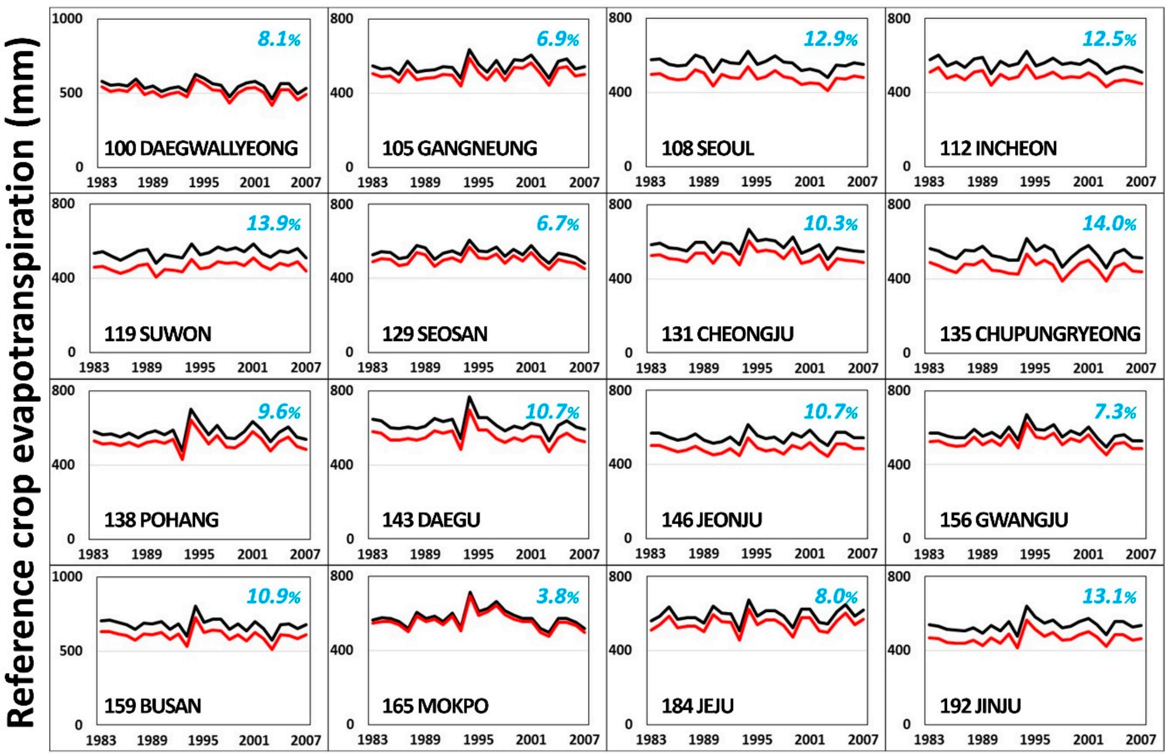

Figure 2. Estimates of the reference crop evapotranspiration (ET_0) during the growing season of paddy rice (May to September) using the recommended (black solid line) and calibrated A-P coefficients (red solid line) for the period 1983–2007. The average difference between the two estimates of ET_0 for the study period is presented as a percentage in sky blue (e.g., 8.1% for Daegwallyeong).

Table 2. Daily, monthly, and annual mean reference crop evapotranspiration (ET_0, mm) at study sites for a 25-year period (1983–2007), and the difference in estimates between using the recommended and calibrated Ångström–Prescott (A-P) coefficients.

Station ID	Station Name	A-P Coefficients	Daily	Monthly												Annual
				1	2	3	4	5	6	7	8	9	10	11	12	
100	Daegwallyeong	Recommended	2.1 (5.8%) [1,**]	24.0 (1.6%)	29.6 (2.6%)	51.7 (3.6%)	91.3 (3.6%)	109.3 (4.8%) *	100.5 (7.6%) *	95.4 (9.8%)	87.6 (9.6%) *	64.0 (7.9%) **	55.1 (4.0%)	38.3 (1.9%)	27.4 (1.2%)	774.3 (5.8%) **
		Calibrated	2.0	23.7	28.8	49.8	88.1	104.0	92.9	86.0	79.2	58.9	52.9	37.6	27.1	729.1
105	Gangneung	Recommended	2.7 (6.5%) **	42.3 (4.0%)	46.4 (4.9%)	70.6 (5.6%)	104.9 (5.8%)	124.4 (6.7%) *	113.6 (7.8%) *	114.9 (8.0%)	107.9 (8.0%) *	83.7 (7.6%) **	73.7 (6.1%) *	54.5 (4.7%)	46.3 (3.8%)	983.3 (6.5%) **
		Calibrated	2.5	40.7	44.2	66.6	98.8	116.1	104.7	105.7	99.2	77.3	69.2	52.0	44.6	919.1
108	Seoul	Recommended	2.5 (13.0%) **	26.5 (11.0%) **	36.3 (11.2%) **	64.0 (11.4%) **	97.3 (11.6%) **	121.0 (12.8%) **	122.5 (13.6%) **	109.5 (14.5%) **	113.6 (14.1%) **	90.0 (14.0%) **	66.4 (13.7%) **	38.7 (12.1%) **	26.8 (11.3%) **	912.6 (13.0%) **
		Calibrated	2.2	23.6	32.2	56.7	86.0	105.6	105.9	93.7	97.6	77.4	57.3	34.1	23.8	793.8
112	Incheon	Recommended	2.5 (11.4%) **	29.2 (8.2%) *	37.7 (8.8%) **	63.4 (9.3%) **	92.4 (10.0%) **	115.1 (11.4%) **	118.6 (12.6%) **	112.6 (13.4%) **	118.2 (12.7%) **	91.5 (12.5%) **	67.2 (11.6%) **	42.7 (9.1%) **	30.9 (7.9%) **	919.5 (11.4%) **
		Calibrated	2.2	26.8	34.3	57.5	83.2	101.9	103.7	97.5	103.2	80.1	59.4	38.8	28.4	815.0
119	Suwon	Recommended	2.3 (13.9%) **	21.3 (14.2%) **	30.6 (13.7%) **	56.4 (13.0%) **	87.2 (12.8%) **	112.5 (13.4%) **	116.4 (13.8%) **	110.4 (14.3%) **	112.6 (13.9%) **	85.6 (14.2%) **	57.9 (15.1%) **	31.5 (14.8%) **	20.9 (14.9%) **	843.3 (13.9%) **
		Calibrated	2.0	18.3	26.4	49.1	76.0	97.4	100.3	94.7	97.0	73.4	49.2	26.9	17.8	726.4
129	Seosan	Recommended	2.3 (6.6%) **	22.9 (6.2%)	31.3 (6.3%)	56.0 (6.0%) **	85.7 (6.0%) **	112.2 (6.4%) **	114.8 (6.8%) **	109.2 (7.1%) *	114.1 (6.9%) *	86.3 (7.0%) *	60.3 (7.0%) **	34.0 (6.4%) *	22.8 (6.3%) *	849.8 (6.6%) **
		Calibrated	2.2	21.5	29.3	52.7	80.6	105.0	107.0	101.4	106.2	80.3	56.1	31.8	21.4	793.3
131	Cheongju	Recommended	2.5 (9.8%) **	22.5 (9.4%) *	33.0 (9.1%) *	61.9 (8.7%) **	97.3 (8.5%) **	123.6 (9.2%) **	124.5 (10.0%) **	121.1 (10.7%) **	119.4 (10.3%) **	87.0 (10.3%) **	60.7 (10.2%) **	33.2 (9.9%) **	21.4 (10.0%) **	905.5 (9.8%) **
		Calibrated	2.2	20.4	30.0	56.5	89.0	112.3	112.0	108.1	107.1	78.0	54.4	29.9	19.3	817.1
135	Chupungryeong	Recommended	2.5 (12.4%) **	33.2 (7.3%) *	40.8 (8.6%) *	68.7 (9.5%) *	102.7 (10.1%) **	121.4 (12.0%) **	115.7 (14.1%) **	111.5 (15.5%) **	107.3 (15.1%) **	81.0 (14.5%) **	64.1 (12.6%) **	41.6 (10.1%) **	32.8 (7.7%)	920.7 (12.4%) **
		Calibrated	2.2	30.7	37.3	62.1	92.3	106.9	99.4	94.2	91.1	69.2	56.0	37.4	30.3	806.9
138	Pohang	Recommended	2.8 (7.9%) **	43.3 (5.1%)	48.6 (6.1%)	73.7 (6.7%)	105.1 (7.2%) **	125.1 (8.0%) **	118.4 (9.2%) **	123.3 (9.5%) *	119.0 (9.2%) *	89.2 (8.8%) **	75.9 (7.4%) *	52.7 (6.4%) *	42.9 (5.3%)	1017.1 (7.9%) **
		Calibrated	2.6	41.1	45.7	68.8	97.5	115.1	107.5	111.6	108.1	81.3	70.3	49.4	40.7	937.1
143	Daegu	Recommended	2.9 (10.0%) **	38.5 (8.1%) **	47.2 (8.6%) **	77.3 (8.9%) **	111.6 (9.2%) **	135.2 (9.9%) **	132.6 (10.4%) **	130.2 (10.9%) **	126.7 (10.8%) **	93.6 (11.0%) **	74.8 (10.7%) **	47.8 (9.8%) **	36.8 (8.9%) **	1052.3 (10.0%) **
		Calibrated	2.6	35.4	43.2	70.4	101.3	121.9	118.8	116.0	113.0	83.3	66.8	43.1	33.6	946.7
146	Jeonju	Recommended	2.4 (11.5%) **	23.2 (12.2%) **	32.4 (11.7%) **	59.2 (10.9%) **	92.1 (10.6%) **	115.6 (11.0%) **	115.7 (11.5%) **	115.8 (11.7%) **	114.9 (11.5%) **	85.9 (11.8%) **	61.4 (12.3%) **	34.6 (12.3%) **	23.0 (12.3%) **	873.9 (11.5%) **
		Calibrated	2.1	20.4	28.7	52.8	82.4	102.9	102.5	102.3	101.7	75.8	53.8	30.3	20.1	773.7

Table 2. *Cont.*

Station ID	Station Name	A-P Coefficients	Daily	Monthly												Annual
				1	2	3	4	5	6	7	8	9	10	11	12	
156	Gwangju	Recommended	2.5 **(7.2%)** **	28.4 **(6.2%)** **	37.0 **(6.5%)** *	64.3 **(6.5%)** **	95.0 **(6.5%)** **	118.7 **(7.0%)** **	117.0 **(7.7%)** **	119.3 **(7.9%)** *	120.2 **(7.6%)** *	91.3 **(7.4%)** *	68.8 **(7.1%)** **	39.6 **(6.9%)** **	27.4 **(6.6%)** *	927.1 **(7.2%)** **
		Calibrated	2.4	26.6	34.6	60.1	88.8	110.5	108.0	109.8	111.2	84.5	63.9	36.8	25.6	860.5
159	Busan	Recommended	2.9 **(9.6%)** **	50.8 **(6.5%)** **	56.6 **(7.2%)** *	80.5 **(8.0%)** **	102.9 **(9.0%)** **	119.4 **(10.2%)** **	111.9 **(11.5%)** **	115.4 **(11.7%)** **	127.9 **(10.8%)** *	100.3 **(10.0%)** **	87.2 **(9.1%)** **	61.5 **(8.1%)** **	51.4 **(6.9%)** **	1065.8 **(9.6%)** **
		Calibrated	2.6	47.4	52.5	74.1	93.7	107.2	99.1	101.9	114.1	90.3	79.3	56.5	47.9	964.0
165	Mokpo	Recommended	2.7 **(2.9%)** **	38.2 **(1.8%)**	43.4 **(2.1%)**	67.9 **(2.4%)**	94.7 **(2.7%)**	115.6 **(3.0%)**	114.3 **(3.5%)**	118.3 **(3.6%)**	129.3 **(3.3%)**	100.6 **(3.0%)**	85.7 **(2.4%)**	55.5 **(2.1%)**	39.4 **(1.8%)**	1002.9 **(2.9%)**
		Calibrated	2.7	37.5	42.5	66.3	92.2	112.0	110.3	114.0	125.1	97.6	83.6	54.3	38.7	974.0
184	Jeju	Recommended	2.9 **(7.0%)** **	45.8 **(3.5%)**	49.1 **(5.0%)**	71.2 **(6.2%)**	94.8 **(7.0%)** **	113.3 **(7.9%)** **	113.7 **(8.7%)** **	135.0 **(8.3%)** *	131.1 **(8.0%)** *	100.4 **(7.6%)** **	84.4 **(6.2%)** **	59.7 **(4.8%)**	47.2 **(3.5%)**	1045.7 **(7.0%)** **
		Calibrated	2.7	44.2	46.6	66.7	88.1	104.4	103.8	123.9	120.6	92.8	79.2	56.8	45.6	972.7
192	Jinju	Recommended	2.5 **(12.4%)** **	30.9 **(10.9%)** **	39.9 **(10.7%)** **	65.8 **(10.7%)** **	92.0 **(11.2%)** **	113.1 **(12.0%)** **	111.3 **(13.0%)** **	115.3 **(13.2%)** **	113.9 **(13.1%)** **	83.7 **(13.2%)** **	63.2 **(13.2%)** **	37.6 **(12.9%)** **	28.2 **(12.4%)** **	895.0 **(12.4%)** **
		Calibrated	2.1	27.5	35.6	58.8	81.7	99.5	96.9	100.1	99.1	72.6	54.8	32.7	24.7	784.1
Average		Recommended	2.6 **(9.2%)**	32.6 **(6.8%)**	40.0 **(7.5%)**	65.8 **(7.9%)**	96.7 **(8.2%)**	118.5 **(9.1%)**	116.3 **(10.1%)**	116.1 **(10.6%)**	116.5 **(10.2%)**	88.4 **(10.0%)**	69.2 **(9.1%)**	44.0 **(7.8%)**	32.9 **(6.9%)**	936.8 **(9.2%)**
		Calibrated	2.3	30.4	37.0	60.6	88.7	107.7	104.5	103.8	104.6	79.6	62.9	40.5	30.6	850.8

[1] The values in parentheses are the overestimated percentages of the ET_0 estimates using the recommended A-P coefficients as compared to the estimates using the calibrated A-P coefficients. * Significant at the 95% confidence level ($t \geq t_{0.05}$). ** Significant at the 99% confidence level ($t \geq t_{0.01}$).

The monthly differences in the ET_0 estimates of the study sites located in the coastal or mountainous regions became larger during the paddy rice growing season (May to September), as shown in Table 2. Changes in the difference in the monthly mean estimates of ET_0 at the sites are indicative of a bell curve throughout the year (Figure 3). Particularly in Daegwallyeong and Chupungryeong, which are located at the relatively high altitudes (in mountainous regions) of 772.6 m and 243.7 m, respectively, the monthly variation of the difference between the ET_0 estimates was much larger than that of the other study sites. On the other hand, in the inland study sites, the monthly changes in the estimation difference showed a relatively flat shape without a large difference during the year, even though the monthly difference from October to January was relatively high as compared to the difference during spring. On average, the differences between the estimates by A-P coefficients of the inland sites were greater than the differences of the study sites located in the coastal regions (Figure 3).

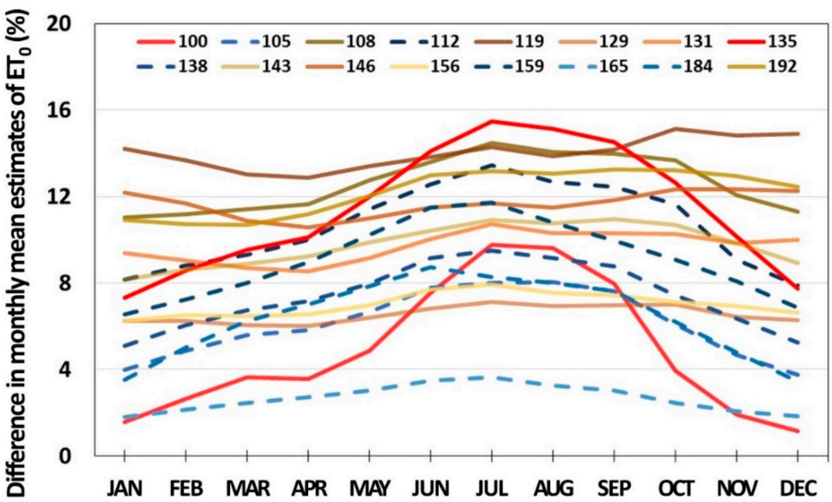

Figure 3. The difference in monthly mean estimates of reference crop evapotranspiration (ET_0). The series of solid brown lines indicate the inland study sites, and the series of blue dotted lines represent the study sites on the coast. The series of solid red lines are the study sites in the mountainous regions.

3.2. Irrigation Water Requirement

The effect of A-P coefficients on the estimation of IWR was smaller than that on the ET_0 estimation. On average, the use of the recommended A-P coefficients overestimated IWR by about 5.1%, which is about half the percentage (10.0%) of the overestimation of ET_0 during the growing season of paddy rice. This is because other important factors such as effective rainfall and deep percolation also influence the estimation of IWR besides the actual evapotranspiration calculated from the ET_0, and they can reduce the impact of ET_0 on the estimation. The percentage of the overestimation of IWR ranged from 1.7% to 7.2%. The largest overestimation was observed in Chupungryeong and Seoul (7.2%), followed by Suwon (7.1%) and Jinju (6.6%), while the smallest overestimation was observed in Mokpo (1.7%) (Figure 4). However, only one site (Suwon) presented a statistically significant difference ($p < 0.05$) (Table 3).

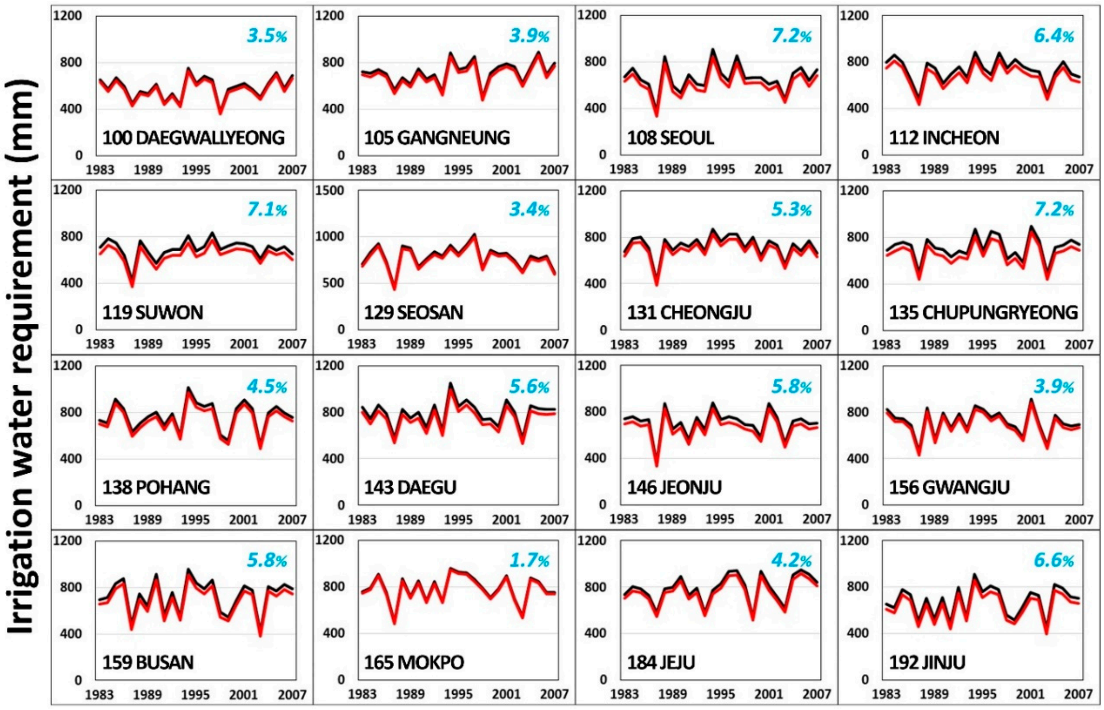

Figure 4. Estimates of the irrigation water requirement (IWR) for paddy rice using the recommended (black solid line) and calibrated A-P coefficients (red solid line) for the period 1983–2007. The average difference between the two estimates of IWR for the study period is presented as a percentage in sky blue (e.g., 3.5% for Daegwallyeong).

The difference between the minimum IWRs of the two estimations using the recommended and calibrated A-P coefficients was larger than that between the maximum IWRs (Table 3). The percentage of the difference between the minimum IWRs ranged from 2.3% to 10.7%, while the percentage of the maximum IWRs ranged from 1.5% to 7.1%. This suggests that the effects of A-P coefficients on the estimation of IWR can be reduced during the drought period. Although agricultural drought can be defined in a different way, it is normally associated with either one or both of evapotranspiration and rainfall [26,27]. A year with a large IWR can be evaluated as an agricultural drought period, since IWR is the required irrigation water considering the amount of evapotranspiration and rainfall for the ideal growth of crops.

Table 3. Basic statistics of the irrigation water requirements (IWRs) for the study sites over a 25-year period (1983–2007).

Station ID	Station Name	Ångström–Prescott Coefficients	Mean (mm)	Max (mm)	Min (mm)	SD [1]	CV [1]	CS [1]	CK [1]
100	Daegwallyeong	Recommended	583.9 (3.5%) [2]	752.4 (3.1%)	370.2 (2.9%)	92.9	0.159	−0.466	3.296
		Calibrated	563.3	729.5	359.4	90.2	0.160	−0.406	3.234
105	Gangneung	Recommended	715.8 (3.9%)	891.1 (3.2%)	497.6 (4.4%)	97.0	0.136	−0.340	3.523
		Calibrated	688.2	862.9	475.6	95.0	0.138	−0.352	3.521
108	Seoul	Recommended	662.8 (7.2%)	908.1 (7.1%)	370.2 (9.8%)	114.0	0.172	−0.157	4.608
		Calibrated	614.8	844.0	334.0	107.9	0.175	−0.181	4.569
112	Incheon	Recommended	729.6 (6.3%)	883.1 (6.1%)	475.7 (9.0%)	98.9	0.136	−0.822	4.335
		Calibrated	683.3	828.9	433.0	95.2	0.139	−0.854	4.402
119	Suwon	Recommended	695.1 (7.1%) *	833.3 (7.1%)	417.6 (10.7%)	82.3	0.118	−1.515	7.720
		Calibrated	645.7	773.8	373.0	79.2	0.123	−1.677	8.219
129	Seosan	Recommended	712.1 (3.4%)	951.7 (3.2%)	377.3 (5.7%)	120.6	0.169	−0.692	4.605
		Calibrated	687.8	921.2	355.8	118.3	0.172	−0.730	4.698
131	Cheongju	Recommended	725.8 (5.3%)	869.1 (5.0%)	420.9 (8.2%)	93.2	0.128	−1.534	6.960
		Calibrated	687.5	825.8	386.3	91.0	0.132	−1.598	7.194
135	Chupungryeong	Recommended	711.7 (7.2%)	898.6 (6.1%)	482.8 (9.0%)	102.5	0.144	−0.473	3.806
		Calibrated	660.3	843.5	439.4	99.3	0.150	−0.504	3.792
138	Pohang	Recommended	770.0 (4.5%)	1012.1 (3.9%)	514.7 (5.1%)	121.2	0.157	−0.385	3.091
		Calibrated	735.4	973.1	488.4	118.2	0.161	−0.372	3.087
143	Daegu	Recommended	792.3 (5.6%)	1051.6 (5.3%)	567.9 (6.4%)	108.4	0.137	−0.231	3.978
		Calibrated	747.7	995.8	531.8	105.1	0.141	−0.273	3.924
146	Jeonju	Recommended	704.4 (5.8%)	880.2 (5.7%)	361.3 (7.7%)	111.3	0.158	−1.148	6.083
		Calibrated	663.2	830.3	333.6	107.0	0.161	−1.124	6.065
156	Gwangju	Recommended	716.9 (3.9%)	910.6 (3.2%)	456.0 (5.0%)	109.1	0.152	−0.613	3.571
		Calibrated	689.1	881.4	433.4	107.0	0.155	−0.608	3.572
159	Busan	Recommended	728.9 (5.8%)	960.8 (5.4%)	415.5 (8.1%)	140.8	0.193	−0.620	2.966
		Calibrated	686.6	909.1	381.7	136.5	0.199	−0.632	2.975
165	Mokpo	Recommended	787.3 (1.7%)	960.9 (1.5%)	495.2 (2.3%)	115.4	0.147	−0.805	3.873
		Calibrated	774.1	946.4	484.0	114.6	0.148	−0.801	3.869
184	Jeju	Recommended	789.6 (4.1%)	950.7 (3.7%)	535.3 (3.8%)	118.0	0.149	−0.620	3.104
		Calibrated	756.9	915.2	514.8	114.9	0.152	−0.591	3.048
192	Jinju	Recommended	678.8 (6.6%)	913.5 (6.1%)	438.2 (8.8%)	125.7	0.185	−0.341	2.478
		Calibrated	633.7	857.6	399.8	121.4	0.192	−0.356	2.494

[1] SD, CV, CS, and CK indicate the standard deviation, coefficient of variation, coefficient of skewness, and coefficient of kurtosis, respectively. [2] The values in parentheses are the overestimated percentages of the IWR estimates using the recommended A-P coefficients as compared to the estimates using the calibrated A-P coefficients. * Significant at the 95% confidence level ($t \geq t_{0.05}$).

3.3. Design Water Requirement

DWRs were determined by using a time-series of IWRs during the growing season of paddy rice from 1983 to 2007. The DWRs determined using the recommended A-P coefficients ranged from 693.5 mm to 927.3 mm, with an average of 846.3 mm. In the case of using the calibrated A-P coefficients, the DWRs ranged from 670.2 mm to 905.8 mm, with an average of 805.8 mm. In both cases, the minimum DWR was found in Daegwallyeong, but the maximum DWR was found in Jeju when the recommended A-P coefficient was used and in Mokpo when the corrected A-P coefficient was used (Table 4).

Table 4. The design water requirement (DWR) and drought reference design year (DRDY) for each the study site.

Station ID	Station Name	Recommended Ångström–Prescott Coefficients		Calibrated Ångström–Prescott Coefficients	
		DWR (mm)	DRDY	DWR (mm)	DRDY
100	Daegwallyeong	693.5 (3.4%) [1]	2007	670.2	2007
105	Gangneung	831.2 (3.6%)	1997	801.2	1997
108	Seoul	799.9 (6.9%)	1988	744.4	2005
112	Incheon	843.2 (6.0%)	1984	792.2	1999
119	Suwon	784.2 (6.9%)	1984	730.2	1984
129	Seosan	852.1 (3.2%)	1985	824.7	1985
131	Cheongju	826.4 (5.0%)	1996	785.3	1996
135	Chupungryeong	832.6 (6.7%)	1997	777.1	1997
138	Pohang	913.8 (4.2%)	1985	875.7	1985
143	Daegu	922.1 (5.3%)	1996	873.3	1996
146	Jeonju	828.7 (5.5%)	2001	782.9	1988
156	Gwangju	844.3 (3.6%)	1988	814.1	1994
159	Busan	893.2 (5.3%)	1986	845.7	1986
165	Mokpo	920.0 (1.5%)	1996	905.8	1996
184	Jeju	927.3 (3.9%)	1996	891.2	1996
192	Jinju	828.3 (6.1%)	2004	778.0	2004
Average		846.3 (4.8%)		805.8	

[1] The values in parentheses are the overestimated percentages of the DWR estimates using the recommended A-P coefficients as compared to the estimates using the calibrated A-P coefficients.

As expected, the effect of A-P coefficients on the estimation of DWR decreased slightly compared to their effects on the estimation of IWR. The DWR, assumed to be for a ten-year return period, should be a value between the maximum and mean IWRs calculated using 25-year IWRs. As discussed above, the effect of the A-P coefficient on the estimation of IWR becomes smaller as the IWR increases. Therefore, the effect of A-P coefficients on the estimation of DWR should be less than that on the IWR estimation. On average, the use of the recommended A-P coefficients resulted in a 4.8% overestimation of DWR. The percentage of overestimation ranged from 1.5% to 6.9%. The largest overestimation was observed in Seoul and Suwon (6.9%), followed by Chupungryeong (6.7%) and Jinju (6.1%), while the smallest overestimation was found in Mokpo (1.5%) (Table 4).

The DRDY, which enables engineers to determine a reference year for designing the size of agricultural facilities and is mainly used in the design of agricultural facilities in South Korea [13], is directly related to the estimate of DWR. The difference in DWR estimates can lead to different results in DRDY estimates, which in turn affect the economics of agricultural facilities. The DRDY was determined differently by the difference in DWR estimates at four (Seoul, Incheon, Jeonju, and Gwangju) out of 16 study sites (Table 4).

4. Discussion and Conclusions

The FAO P-M equation is recognized as the standard method for the estimation of ET_0 and has been widely used in a variety of climates. The A-P formula is recommended to determine (global) solar radiation, one of the essential meteorological inputs of the P-M equation. However, A-P coefficients used in the equation could have a considerable impact on the estimation of ET_0, and thus influence the estimation of IWR and DWR in agricultural water resources planning. In this study, we explored the impact of A-P coefficients on the estimation of ET_0, IWR, and DWR by analyzing and comparing their estimates using the recommended and locally calibrated A-P coefficients in 16 locations of South Korea.

Based on our results, considerable overestimation from using the recommend A-P coefficients (i.e., a = 0.25 and b = 0.50) was verified in the estimation of ET_0 across all 16 study sites in South Korea. The overestimation ranged from 3.8% to 14.0% as compared to the estimates using the locally calibrated A-P coefficients and the average was 10.0%. All study sites were significantly different ($p < 0.01$) on a daily basis, and 15 out of 16 sites showed a significant difference ($p < 0.01$) on an annual basis. In contrast to other studies [7,10], which presented possibilities of both the over- and underestimation of ET_0, the use of the recommended A-P coefficients in this study only resulted in ET_0 overestimation. This is presumably because of the climate region. The study sites included in the current study are located in the humid subtropical and continental climate regions, according to the Köppen–Geiger climate classification [17], while the other studies covered more various climate regions such as tundra and tropical and subtropical desert. Nevertheless, the study sites of Liu et al. [7] and Sabziparvar et al. [10], which are located in the same climate region as this study, also presented overestimated results for ET_0 estimation. The estimation of ET_0 is the basis for predicting the demand for agricultural water use in water resources planning and many other applications, which require water partitioning (e.g., hydrological modeling) or the estimation of crop water consumption (e.g., crop modeling). Given the important role and frequent use of the P-M equation in the ET_0 estimation, the accurate estimation of evapotranspiration using the locally calibrated A-P coefficients should be recommended when available.

The 10% overestimation in the ET_0 estimation during the growing season of paddy rice resulted in a 5.1% overestimation of the IWR, on average. A variation of 3.8% to 14.0% in the overestimation of the mean annual ET_0 estimation during the growing season corresponded to a variation of 1.7% to 7.2% in the overestimation of the mean annual IWR estimation. This suggests that the use of the recommend A-P coefficients can have a level of uncertainty similar to the impact of future climate change in predicting the agricultural water demand for paddy rice production in South Korea. Yoo et al. [28] predicted that climate change could lead to a change of −2.7% to 2.7% in agricultural water demand for paddy rice production in South Korea for this century. Although only one out of 16 study sites presented a significant difference ($p < 0.05$) in the IWR estimation, the possible overestimation for paddy irrigation would reach about 625 million tons (5% of 12.5 billion tons), considering the amount of agricultural water used for paddy rice cultivation [14]. It reaches about 12.5 billion tons a year, which accounts for almost 30% of the industrial water use (2.1 billion tons a year) in South Korea [16]. The effect of the A-P coefficients on the IWR estimation showed a tendency to decrease as the IWR increased. Therefore, the effect of A-P coefficients on the DWR estimation was slightly reduced, and it was about 4.8% on average. The DRDY, which is defined by the DWR, was determined differently by the use of A-P coefficients at four sites out of the 16 study sites. Therefore, it is necessary to examine the impact of the use of A-P coefficients more closely in terms of engineering and economics perspectives, in that the DWR estimates and the resulting DRDY directly affect the design of irrigation facilities.

There can be many uncertainties associated with the use of the P-M equation other than those concerning the A-P coefficients [29–31]. However, as shown in the results of this study, the use of A-P coefficients can cause considerable uncertainty in estimating ET_0 using the P-M equation and its applications. As such, this study underscores the need for the accurate consideration of the A-P coefficients in agricultural water management. As the FAO recommends [3], if the A-P coefficients can be locally calibrated, then the use of the calibrated coefficients should be considered when using the P-M equation. Estimates of other variables (e.g., the crop coefficient) being used in the process of calculating the actual evapotranspiration from ET_0 should be reestablished in order to properly use the calibrated A-P coefficients.

We have also identified some directions for future studies. The effects of climate change and calibration method on the estimation of A-P coefficients need to be explored. Climate change is expected to make a significant difference in the various meteorological factors associated with the estimation of ET_0. Therefore, it is necessary to see how A-P coefficients will affect changes in future ET_0 driven by climate change. In addition, since the A-P coefficients can differ depending on the data and method used in their estimates [7], it is necessary to further examine the effect of the method on ET_0 estimation. Last but not least, as argued by Liu et al. [7], in the estimation of ET_0, a similar argument can be raised. The effects of A-P coefficients on the estimation of agricultural water demand and the design of agricultural water resources system should be explored in a variety of climates.

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