Sensitivity of potential evapotranspiration to climate factors in forested mountainous watersheds

Fereshteh Ghiami-Shomami¹, Kohzo Kawasaki², Leonardo³, Seirou Shinoda³ and Yanyang Fan³

¹Graduate School of Engineering, Department of Mechanical and Civil Engineering, Gifu University, Japan

²Graduate School of Natural Science and Technology, Department of Civil Engineering, Gifu University, Japan

³Faculty of Engineering, Department of Civil Engineering, Gifu University, Japan

Abstract:

Estimation of reference evapotranspiration (ET_0) is important in hydrological studies. As climate change is predicted to cause changes in water resources and agriculture sectors, the possible implications of changes in different climate variables on ET_0 need to be understood. Sensitivity analysis was employed to illustrate the effects of perturbation in meteorological parameters (maximum and minimum air temperature ($T_{\max}$ and $T_{\min}$), sunshine hours (n), maximum and minimum relative humidity ($RH_{\max}$ and $RH_{\min}$)) and wind speed (u_z) on ET_0 . ET_0 was calculated by The Food and Agriculture Organization of the United Nations (FAO) 56 Penman-Monteith approach using climate data from 1979–2017 for the Enbara and Futatsumori watersheds in forested mountain areas in Japan. We quantified the contributions of climatic factors to ET_0 at daily, monthly, seasonal and annual time scales. Daily results showed large fluctuations. According to the monthly and seasonal analysis, during warm seasons, $T_{\max}$ and n had more influence on ET_0 , especially in May, while for the cold seasons, RH effect was dominant, especially in December. Based on the annual results, the factors most influencing ET_0 were $T_{\max}$ followed by n , u_z , RH and $T_{\min}$. We also found that the response of ET_0 to changes in climatic parameters differs for sites with different topographic and geographic characteristics.

KEYWORDS climate data; Penman–Monteith; reference evapotranspiration; sensitivity analysis; watershed; Gifu

INTRODUCTION

The issue of climate change has received considerable attention in recent years due to its potential to affect the precipitation, runoff and evapotranspiration components of the hydrological cycle (Attarod *et al.*, 2015; Liang *et al.*, 2008). Many natural disasters associated with changes in hydrological processes due to the climate change have led to major problems in Japan (Iizumi *et al.*, 2012; Kawagoe *et al.*, 2010; Mouri *et al.*, 2012; Primark *et al.*, 2009; Shiono *et al.*, 2013). Japan is likely to experience more

annual rainfall as well as increases in rainfall intensity and the number of days with rainfall greater than 50 mm in the future. Beside rainfall, Japan is also getting warmer with a 2–3°C rise is predicted for mean annual temperatures (JMA, 2005; Kato, 1996; Kurihara *et al.*, 2005).

Among all components of the hydrological cycle, actual evapotranspiration (ET_C) is a major element which can be estimated from reference evapotranspiration (ET_0) and crop coefficients (K_C). Values for ET_C are used in water resources planning and management, hydrological catchment models and irrigation. ET_0 is defined as the evapotranspiration of a hypothetical surface of green grass, which is actively growing and is not short of water, with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹, and an albedo of 0.23. In hydrological studies, reliable estimation of ET_0 is of critical importance and is required to analyze the water balance. Since ET_0 is dependent only on meteorological conditions, not the underlying surface, and is readily measurable or calculable, it can be used to reflect regional water-energy balance changes and the effect of climate change (Du *et al.*, 2016; Gu *et al.*, 2018).

Among different methods which have been developed to estimate ET_0 , the Penman-Monteith model simplified by The Food and Agriculture Organization of the United Nations (FAO) Paper No. 56 (henceforward called FAO56-PM) is generally accepted to have high performance in terms of predicting ET_0 (FAO, 1998). This model has been commonly used globally due to its advantage in taking into account both thermodynamic and aerodynamic characteristics (Er-Raki *et al.*, 2007, 2008; Jabloun and Sahli, 2008; Temesgen *et al.*, 2005; Wright *et al.*, 2000).

As the required input variables to apply FAO56-PM are relatively high, any sensor-based errors or bias in measurements can cause tremendous error in the outputs of the estimated ET_0 (DeJonge *et al.*, 2015a). On the other hand, climate change is expected to make dramatic changes in the meteorological variables leading to changes in ET_0 (Irmak *et al.*, 2006). Therefore, it is essential to understand the effect of perturbations in each climatic variable on ET_0 calculations, whether caused by sensor-based measurement errors or climate change. These objectives would be satisfied through sensitivity analysis (SA) which quantifies the dominant meteorological factors in estimating ET_0 . The SA of ET_0 is needed to provide information on the relationship

Correspondence to: Fereshteh Ghiami-Shomami, Graduate School of Engineering, Department of Mechanical and Civil Engineering, Gifu University, Yanagido 1-1, Gifu 501-1193, Japan. E-mail: fereshteh.ghiami.sh@gmail.com

Received 12 April, 2019
Accepted 20 June, 2019
Published online 24 July, 2019

between data availability and estimation accuracy of ET_0 (Hou *et al.*, 2013) as well as determining the required accuracy for measuring climatic data (Irmak *et al.*, 2006). Furthermore, it allows improvements in our understanding of the possible impact of climate change on the hydrological cycle by providing information about the connections between climatic conditions and ET_0 variability.

Several studies have assessed the sensitivity of ET_0 to climate variables (Debnath *et al.*, 2015; DeJonge *et al.*, 2015b; Mosaedi *et al.*, 2017; Ndiaye *et al.*, 2017). Using data from the U.S. Weather Bureau, Coleman and DeCoursey (1976) showed that, for winter months, relative humidity, and during summer, both solar radiation and temperature, control changes in all ET_0 equations. Piper (1989) selected a vast area covering different countries located between latitudes 25°N and 25°S and at altitudes of less than 500 m. He concluded that errors in measurement of mean temperature would have a major effect on ET_0 estimation while the effect of wind speed, sunshine hours and wet bulb temperature measurement errors are similar and less significant. Sensitivity analysis of ET_0 performed in northwest China revealed that, in the mountainous area and during the cool months, vapor pressure has the most effect on ET_0 with the least sensitive factor during the year being mean air temperature (Zhang *et al.*, 2010).

To the best of our knowledge, no study has investigated the sensitivity of ET_0 to the variation in climatic factors in different scenarios in Japan. In addition, available water resources, which are being affected by changes in hydrological processes, would be better managed if supported by information on the sensitivity of ET_0 to meteorological parameters. Considering this, and given that there are interactions between climatic parameters, which could be highly affected by global warming, SA of ET_0 is essential. Thus,

the present study aimed to first determine the response of ET_0 to perturbations (all sorts of data errors, or actual climatic changes) in meteorological factors. Furthermore, the dominant climatic factor associated with seasonal and annual ET_0 changes were identified. Finally, the differences in sensitivity coefficients of each climatic variable at sites with different topographic and geographic characteristics were also clarified.

METHODS

This study was carried out in Enbara and Futatsumori (Kojima *et al.*, 2013; Zainal *et al.*, 2012) watersheds in forested mountainous areas located, respectively, in Yamagata and Nakatsugawa cities of Gifu prefecture, central Japan. We have been investigating the relationship between runoff properties and the characteristics of the forest environment in these watersheds. Enbara watershed was represented by the Japan Meteorological Agency (JMA) weather station at Tarumi (12 km away) and Futatsumori watershed by the Kurokawa station (9.2 km away) of (Figure 1). Considering the data quality and completeness, a 39-year (1979–2017) daily data set of maximum and minimum relative humidity ($RH_{\max}$ and $RH_{\min}$), sunshine duration (n), maximum and minimum temperatures ($T_{\max}$ and $T_{\min}$) and wind speed (u_z) for the selected stations were obtained from the Automated Meteorological Data Acquisition System (AMeDAS). The data of u_z was observed at a height of 9.4 for Kurokawa station while Tarumi u_z data was recorded at heights of 7.5 and 10 before and after 2010, respectively. Since relative humidity data has not been gathered at the above-mentioned stations, a distance-based interpolation approach was applied to use neighboring stations' RH data and esti-

Figure 1. Location of AMeDAS stations and watersheds

mate RH at the selected stations. In this regard, Fukui, Gifu and Takayama data were used to estimate RH at Enbara, and Iida, Gifu and Takayama data used for RH at Futatsumori. Table I shows the geographical characteristics and the annually averaged meteorological variables calculated with these data.

Reference evapotranspiration

FAO suggests that the application of a standardized Penman–Monteith approach is preferred to predict ET_0 when the required data is available and reliable. The performance of FAO56-PM has been confirmed under different climate types and it has the major advantage of considering both meteorological and physiological crop variables in estimating ET_0 (Richard *et al.*, 1998). The FAO56-PM equation to calculate daily ET_0 is given by:

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

where ET_0 is the reference evapotranspiration (mm d^{-1}), T is the mean daily temperature ($^{\circ}\text{C}$), G is the soil heat flux ($\text{MJ m}^{-2} \text{d}^{-1}$), R_n is the net Radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$), e_s is the mean saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of saturation vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$) and u_2 is the mean wind speed at height 2 m (m s^{-1}). The wind speed measured at heights other than 2 m can be adjusted according to the follow equation:

$$u_2 = u_z \frac{4.87}{\ln(67.8h - 5.42)} \quad (2)$$

where h is the height of the measurement above the ground surface (m) and u_z is the measured wind (m s^{-1}). Also for standardization, T for 24-hour periods is defined as the mean of the daily maximum ($T_{\max}$) and minimum temperatures ($T_{\min}$) rather than as the average of hourly temperature measurements (FAO, 1998).

Sensitivity analysis

Sensitivity analysis determines the expected change in the dependent variable (output) in response to changes in the independent variables (input) (McCuen, 1974). Various nondimensional forms of sensitivity coefficients (C_s) have been developed by calculating the partial derivative of the dependent variable (ET_0) to the independent variables (climate factors). To identify the ET_0 -related changes in response to changes in climatic variables, a mathematically-based approach was used to calculate the C_s of ET_0 (McCuen, 1974).

$$C_s(x_i) = \lim_{\Delta x_i \rightarrow 0} \left(\frac{\Delta ET_0 / ET_0}{\Delta x_i / x_i} \right) = \frac{\partial ET_0}{\partial x_i} \times \frac{x_i}{ET_0}, \quad (3)$$

where x_i is the i th meteorological parameter and $C_s(x_i)$ is the C_s of ET_0 with regard to x_i . A negative (positive) C_s for a climatic factor suggests that ET_0 will inversely (similarly) respond to changes in the meteorological variable. The larger the C_s , the more ET_0 is affected by that variable.

To achieve the objectives of our study, first, the variables were changed within a range of -30 to $+30\%$ with an interval of 5% (twelve scenarios) and the percent change in ET_0 was estimated (Goyal, 2004). Next, the percent changes in the meteorological variables were plotted against percent changes in the ET_0 as a sensitivity curve to calculate parameter sensitivity to the estimated ET_0 . Finally, the C_s of each climate variable was calculated at daily, monthly, seasonal and annual scales. The first two scales are important in designing irrigation systems while information at an annual scale is required to manage water resources. On the other hand, any research findings on a seasonal scale would be valuable for designing water reservoirs. In this study, spring, summer, autumn, and winter were defined as March to May, June to August, September to November, and December to February, respectively.

RESULTS AND DISCUSSION

Similar variation pattern of monthly $T_{\max}$, n and ET_0

Figure 2 presents the temporal behavior of climate variables in the two watersheds at a monthly time scale. According to the air temperature (T) pattern, which had a single-peak, the maximum (minimum) values were observed in August (January or February). The largest value of $T_{\max} - T_{\min}$ was recorded in April and May for both stations. This parameter dropped to its lowest value in January, considered one of the coldest months.

The patterns of n and ET_0 were similar to those in $T_{\max}$ which showed an increase and then a reduction from January to December. The peak in ET_0 occurred in May and August, at approximately 3 mm d^{-1} . This coincides with dry conditions characterized by low RH accompanied by high temperature, u_z and n . On the other hand, ET_0 tended to reduce to a minimum value during the rainy season, particularly in June. This decline can be explained by the remarkable decrease in n and increase in RH during this month. The minimum value of ET_0 and n mainly occurred during December and January. The difference between the maximum and minimum ET_0 varied more drastically in summer months than winter months.

Table I. Geographical features of the synoptic stations along with their mean annual climate parameters for the period 1979–2017

Watersheds	Coordinates			Climate type (Köppen-Geiger)	Annually averaged meteorological variables					
	Latitude	Longitude	Height above MSL (m)		$T_{\max}$ ($^{\circ}\text{C}$)	$T_{\min}$ ($^{\circ}\text{C}$)	n (hr)	u_z (m s^{-1})	$RH_{\max}$ (%)	$RH_{\min}$ (%)
Enbara	35° 38'	136° 36'	190	Cfa	17.5	8.7	3.7	0.9	86.1	52.3
Futatsumori	35° 35'	137° 19'	(1979–1998) 460 (1998–present) 517	Cfa	17.6	6.9	5.1	0.7	87.2	49.9

Figure 2. Box-and-whisker plot of temporal variation in monthly ET_0 and its main meteorological variables averaged for the period 1979–2017. a and h) maximum temperature, b and i) minimum temperature, c and j) sunshine hours, d and k) wind speed, e and l) maximum relative humidity, f and m) minimum relative humidity, g and n) evapotranspiration

The pattern of RH was opposite to those of n and T . The highest (lowest) value of RH was recorded in cold and rainy seasons (spring). u_z had quite small variation over the the year. The monthly peak of u_z occurred in spring with a speed range of 0.5–2.0 ($m s^{-1}$). In contrast, the minimum value of u_z occurred in December ($\sim 0.5 m s^{-1}$).

T_{max} and T_{min} driving the most and least changes in ET_0 during the year

Figure S1 shows the daily variation in C_s which helps us to grasp a comprehensive understanding on how ET_0 responds to each meteorological parameter during the year. The annual sensitivity curves of ET_0 are given in Figure S2. Sensitivity curves of ET_0 to weather parameters were typically linear. Large magnitude slopes indicate the most important metrological parameter affecting ET_0 .

As shown in Figure S1, the C_s of all climate factors exhibited a large degree of daily fluctuation throughout the year. Although the temporal patterns in T_{max} and T_{min} were almost the same (Figure 2), the variations of their C_s were different. At both stations, the sensitivity coefficients of T_{min} ranged from zero to 0.14, which are significantly lower than all other variables. The variation in the C_s for T_{max} and n was almost identical during the year with a pronounced temporal cycle. Negative C_s was obtained for RH , suggesting that an increase in ET_0 with a redecution in RH and vice-versa. Daily variation patterns in RH were opposite to those of u_z , but the peak of both variables evident during the same period.

According to Figure S2, at both stations the two factors most influencing ET_0 were T_{max} followed by n , whereas T_{min} did not have such a significant effect. In response to the increase in T_{max} , n and T_{min} by +30%, the percent change in ET_0 was about 11%, 8% and 2.5%, respectively. At the

Enbara site, decreases and increases in u_z by 5% to 30% favored a variation of ET_0 from -0.7% to -4.7% and 0.7% to 4.3% . These results show that ET_0 was more affected by the reduction in u_z than to by its increase. In contrast, increases in the other climate variables led to greater changes in ET_0 relative to their reduction.

Overall based on Figures S1 and S2, T_{max} and n were the dominant factors driving the change in ET_0 during the year; Ambas and Baltas (2013) also concluded that n and T are major controlling factors in ET_0 changes. The increase in T affects ET_0 primarily by increasing the capacity of air to hold water vapor, which is more notable during warm months. In this way the changes in T_{max} or n due to global warming will lead to considerable changes in ET_0 . Furthermore, among the six climate variables, T_{min} had the least effect on ET_0 and its C_s showed small alteration during the year. Similar results were reported by Irmak *et al.* (2006).

ET_0 affected most by T_{max} and n during warm period and RH and u_z in cool period

Monthly C_s for each variable are given in Table II to clarify the effect of changes in each climatic factors on ET_0 as a function of month. Figure 3 also shows seasonal differences in C_s for each climate factor. Since the ET_0 values were generally higher during the warm months as a result of increased n and T (Figure 2), the percentage change in ET_0 was markedly influenced by T_{max} and n from March to November at both stations (Table II). As shown in Figure 3, the minimum and maximum values of C_s for T_{max} and n were found in winter and summer, respectively. While C_s of T_{max} for all seasons ranged between 0.16 and 0.35, which is quite strong, C_s for T_{min} varied between 0.02 to 0.12 (Table II and Figure S1) from winter to summer, suggesting that T_{min} was less influential on ET_0 in all seasons. In con-

Table II. Monthly averaged sensitivity coefficients for individual meteorological factors

Watersheds	Variables	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Enbara	$T_{\max}$	0.13	0.16	0.26	0.36	0.38	0.35	0.34	0.37	0.38	0.38	0.31	0.19
	$T_{\min}$	0.03	0.03	0.02	0.05	0.08	0.10	0.13	0.13	0.11	0.07	0.04	0.02
	n	0.04	0.10	0.16	0.20	0.23	0.21	0.22	0.27	0.20	0.15	0.06	0.01
	u_z	0.20	0.19	0.19	0.16	0.13	0.10	0.08	0.10	0.12	0.18	0.22	0.22
	$RH_{\min}$	-0.28	-0.26	-0.22	-0.17	-0.14	-0.13	-0.12	-0.10	-0.16	-0.20	-0.25	-0.30
	$RH_{\max}$	-0.28	-0.26	-0.22	-0.17	-0.13	-0.13	-0.12	-0.10	-0.15	-0.19	-0.23	-0.28
Futatsumori	$T_{\max}$	0.14	0.17	0.25	0.33	0.36	0.34	0.34	0.38	0.36	0.36	0.31	0.20
	$T_{\min}$	0.06	0.06	0.04	0.04	0.07	0.10	0.13	0.14	0.12	0.08	0.03	0.03
	n	0.06	0.16	0.22	0.26	0.27	0.23	0.27	0.33	0.27	0.22	0.10	0.02
	u_z	0.21	0.17	0.15	0.13	0.11	0.09	0.07	0.09	0.09	0.13	0.19	0.23
	$RH_{\min}$	-0.21	-0.17	-0.14	-0.12	-0.11	-0.12	-0.11	-0.09	-0.12	-0.13	-0.18	-0.21
	$RH_{\max}$	-0.18	-0.15	-0.13	-0.11	-0.09	-0.11	-0.10	-0.08	-0.10	-0.11	-0.15	-0.18

Figure 3. Sensitivity coefficients for the two watersheds for a) Spring, b) Summer, c) Autumn and d) Winter

trast to T , humidity increased in the cold months as well as the rainy season and decreased in the spring (Figure 2). As seen in Table II, the C_s of RH was similarly strongly negative during the cold months, indicating that ET_0 was most affected by RH during the winter time; this is in accordance with the findings of Coleman and DeCoursey (1976). RH was a major limiting factor in ET_0 , due to negative C_s , confirming that climate change might have less impacts if warming is accompanied with higher humidity (Zeng and Heilman, 1997).

The effect of RH and u_z on ET_0 was most dominant from

December to February while insignificant impacts of these variables were evident from June to August (Table II). Wind flows likely exchange the moist air very quickly with dry air, notably during spring and winter in our study area (Figure 2), and makes ET_0 more sensitive to u_z during these periods in comparison with other seasons (Ghafouri-Azar *et al.*, 2018) (Figure 3).

In general, for both sites, the sensitivity of ET_0 to climatic variables was more significant during October and May. Changes in ET_0 during warm months, especially in spring and summer, appeared to be mostly controlled by

Figure 4. Comparison of annual relative influence of climate variables on ET_0 at a) Enbara and b) Futatsumori watersheds

$T_{\max}$ and n whereas in cold months RH and u_z were the primary factors, especially in the winter season. This is because of the reduction in the energetic term, which makes the aerodynamic term more significant, resulting in increases in the C_s for RH and u_z during the cold months. This result suggests that the response of ET_0 to climate change will vary with season.

Dominant effect of aerodynamic term in Enbara and Energy term in Futatsumori

It has already been mentioned that all variables showed the same variation patterns in C_s at both sites (Figure 2). However, the results at Futatsumori were somewhat different from those at Enbara. This is more evident in the comparison of their seasonal C_s (Figure 3) and also the annual relative influence of climate variables on ET_0 at the two stations (Figure 4).

As seen in Figure 4, the energy term, measured by n , seemed to have more influence on ET_0 at Futatsumori (27%) compared to Enbara (20%) similar to the seasonal comparison of C_s (Figure 3). On the other hand, ET_0 at Enbara, which typically experiences wind with higher speed than Futatsumori (Figure 2 and Table I), was more affected by the aerodynamic term measured by u_z ; there RH (13%, 14%) was higher than Futatsumori (12%, 10%) (Figures 3 and 4).

Comparison between the two watersheds suggests that ET_0 is differently sensitive to climatic parameters at sites with different topographic and geographic characteristics. The Enbara watershed is located at the boundary of a plain and mountain area which changes the heat transfer processes, compared to the Futatsumori watershed which has characteristics of a uniform mountainous area. This difference caused non-matching patterns of n and $T_{\max}$ at Enbara (Figure S1). Also owing to the geographic situation in which the Futatsumori watershed is located, clearer skies and more sunshine are usually observed (Figure 3), causing weaker (stronger) RH (n) impacts on ET_0 at this site compared to the Enbara watershed.

CONCLUSIONS

ET_0 , which is one of the most important hydrological and meteorological variables, can be used as an excellent indicator of hydroclimatic change (Du *et al.*, 2016). In light of this to obtain a better understanding of the factors affecting

ET_0 behavior this paper conducted SA using six daily climatic variables from two watersheds in Gifu prefecture of Japan over a 39 year interval. This area was chosen based on prior research on the assessment of climate change impacts on hydrological process, using observed hydrological data sets from two watersheds. For the purpose of this study, C_s for each climate factor were derived to help us evaluate the impact of changes in the measured meteorological variables on the estimated ET_0 . Also, the relative influence of each meteorological parameter on ET_0 in the two watersheds was compared.

The results of SA showed that ET_0 was highly sensitive to both $T_{\max}$ and n , especially in May, such that accurate estimation of these parameters is vital. For the cold seasons, the aerodynamic term measured by RH was the most influential factors for ET_0 , suggesting that ET_0 will respond differently to changes in climate during the warm and cold seasons. Comparison of the two watersheds revealed that the sensitivity of FAO56-PM estimates of evapotranspiration to different input data and parameters is dependent on topographic and geographic characteristics.

Since increases in ET_0 values would affect water budgets, this work may contribute to more appropriate climate change strategies that could be particularly well adapted to vulnerable sectors or areas. Future research could use these findings as a theoretical basis to examine the response of hydrological process to climate change.

ACKNOWLEDGMENTS

We are grateful to the observers of JMA for providing us with the requisite measurements.

SUPPLEMENTS

Figure S1. Mean daily sensitivity coefficient

Figure S2. Percent changes in ET_0 with respect to changes in climatic variables in annual time scale, Enbara (solid) and Futatsumori (dashed)

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