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COMPARATIVE EVALUATION OF THREE PENMAN-MONTEITH VARIANT MODELS FOR GROUNDWATER LEVEL ESTIMATION IN JEJU ISLAND

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*Abstract***:** Accurate estimation of groundwater levels is crucial for effective water resource management, particularly in regions like Jeju Island, where groundwater is the primary water source. This study emphasizes the importance of preprocessing meteorological observations to address the temporal disconnect between rapid meteorological fluctuations and the slower responses of groundwater systems. Key factors such as cumulative effects, delayed reactions, and seasonal variations were considered during preprocessing to improve the reliability of evapotranspiration estimates. Three Penman-Monteith evapotranspiration models (PM, FAO-24, FAO-56) were evaluated using pre-processed data, including accumulated precipitation (100-day), temperature (20-day), and other meteorological parameters. Validation against 2023 groundwater level data demonstrated that the FAO-56 model preprocessing achieved the best performance, with the highest correlation (r = 0.89), lowest mean squared error (MSE = 0.10), and smallest error range (overestimation: +1.1m, underestimation: -1.4m). These results highlight that accurate groundwater level estimation relies on proper preprocessing of observations rather than solely optimizing model operations. The findings provide valuable insights for enhancing groundwater monitoring and sustainable water management in areas with complex geological and hydrological conditions.

Keywords: Groundwater, Jeju Island, Penman-Monteith Model. Evapotranspiration, FAO-24 model, FAO-56 model

I. INTRODUCTION

Jeju Island, located in the monsoon climate zone of Northeast Asia, receives an annual average rainfall exceeding 1,500 mm. Due to the island's porous volcanic geology, most of this rainfall rapidly infiltrates into the subsurface rather than forming surface rivers, resulting in very few streams. Consequently, the island relies almost entirely on groundwater for its domestic water supply.

Despite these abundant water resources, per-capita daily water consumption continues to rise. Increased extraction can lead to groundwater contamination, land subsidence, flooding from rising groundwater levels, and saltwater intrusion. Such challenges highlight the importance of understanding groundwater conditions to mitigate potential disasters. These groundwater shortages and management issues are especially critical for Jeju Island and common concerns for other island regions.[1]

However, groundwater moves through fractures and pores in geological layers, making direct observation difficult. Conventional methods for measuring groundwater levels typically involve long-term monitoring at existing wells or constructing new observation wells.[2] While these approaches provide valuable data, they are limited to monitored locations and do not comprehensively understand groundwater variations.

To address these limitations, this research aims to estimate groundwater levels (GWL) at observed locations using a three-Penman-Monteith evapotranspiration structure model. By considering groundwater as a central component of the hydrological cycle and incorporating it into a physically grounded water balance calculation, this study seeks to improve the accuracy of GWL estimation and enhance the interpretation of groundwater dynamics.

II. RELATED RESEARCH

2.1 Water balance

Estimating groundwater balance is one of the simplest methods to understand groundwater recharge.[3] A water budget is a crucial aspect of any conceptual model. This method must consider inflow, outflow, and changes in storage. A reliable recharge estimate must also consider all the water that cannot recharge the aquifer.

The general expression for the groundwater balance equation (1) is as follows:

$$\Delta S = (P + G_{in}) - (Q + ET + G_{out}) \qquad (1)$$

where P represents precipitation, G_{in} is groundwater inflow, Q is discharge, ET stands for evapotranspiration, G_{out} is groundwater outflow, and ΔS denotes the change in storage.

In a typical unconfined aquifer, the main factors contributing to the inflow and outflow components include recharge from rainfall, canals, irrigation, tanks, influent recharge from rivers, inflow from other basins, groundwater extraction, discharge to waterways, and outflow to other basins, among others.[4]

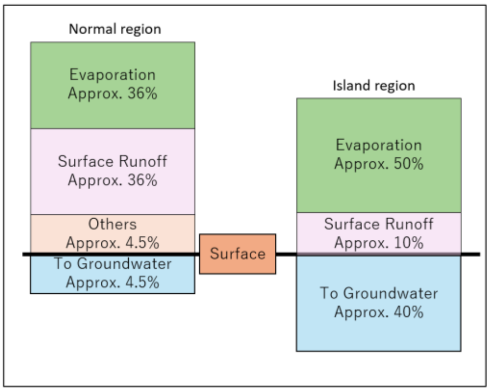

Figure 1. Water balance compared to Normal region and Island region

2.2 Groundwater Level Estimation and the Role of the Penman-Monteith Method

Groundwater level estimation relies on physical models, which require a thorough understanding of the influencing factors within the hydrological cycle. Evapotranspiration is significant among these factors but cannot be directly observed, making accurate estimation crucial.

The Penman-Monteith method [5] has been proposed as a reliable approach for estimating evapotranspiration, and it forms a key component of such models. This study focuses on three selected variants of the Penman-Monteith method that are considered suitable for island regions like Jeju.

These include the original Penman-Monteith FAO-24[6], its adopted improvement Penman-Monteith FAO-56[7], and an additional refined model for enhanced accuracy in island environments. Each model incorporates meteorological and hydrological data to provide a robust framework for estimating evapotranspiration.

The FAO-24 model serves as a foundational method leveraging simplified parameters. At the same time, the FAO-56 version enhances its accuracy by incorporating variables such as canopy resistance and a standardized approach to reference evapotranspiration [8]. These improvements are particularly relevant for island regions like Jeju Island. The third model introduces further refinements to adapt the estimation process to the island region's unique geographical and climatic characteristics.

This study aims to determine which model yields the most accurate evapotranspiration estimation by applying these three Penman-Monteith variants, ultimately improving the overall reliability of groundwater level estimates.

A. Penman-Monteith equation

Several empirical methods have been developed to estimate evapotranspiration from different climatic variables. Some of these derived from the Penman equation to determine evaporation from open water, bare soil and grass, evapotranspiration based on a combination of an energy balance and an aerodynamic formula (2), given as

$$\lambda ET = \frac{[\Delta(R_n - \mathrm{G})] + (\gamma\lambda E_a)}{(\Delta+\lambda)} \tag{2}$$

where R_n =net radiation flux (MJm^{-2}/day), G =sensible heat flux into soil (MJm^{-2}/day), E_a =vapor transport of flux(mm/day), Δ is slope of saturation vapor pressure$(kPa^{\circ}C^{-1})$, γ is psychrometric constant $(kPa^{\circ}C^{-1})$, ET=evapotranspiration rate(mm/day)

B. FAO-24 Penman-Monteith

The FAO-24 methods were developed as more practical alternatives when complete meteorological data sets were unavailable. While simpler, they generally provide less accurate results than the more comprehensive Penman-Monteith method(3).

$$ET = c[0.408\frac{\Delta}{\Delta+\gamma}(R_n - G) + 2.7\frac{\gamma}{\Delta+\gamma}(\mathrm{I} + 0.864U)(e_a - e_d) \tag{3}$$

where, R_n =net radiation flux (MJm^{-2}/day), G =sensible heat flux into soil (MJm^{-2}/day), Δ is slope of saturation vapor pressure $(kPa^{\circ}C^{-1})$, γ is psychrometric constant $(kPa^{\circ}C^{-1})$, e_a is saturation vapor pressure at air temperature (kPa), e_d is actual air vapor pressure (kPa), ET=evapotranspiration rate(mm/day)

C. FAO-56 Penman-Monteith

The FAO-56 Penman (4) simplifying equation (3) takes advantage of a few assumed points constant parameters for cropped grass reference crops. The definition for the reference crop was a hypothetical reference crop with a crop height of $0.12m$, a fixed surface resistance of $70sm^{-1}$ and an albedo value, which means the portion of light reflected by the leaf surface of 0.23.

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

where ET=evapotranspiration rate(mm/day), T =mean air temperature(°C), and u=wind speed(m/s), R_n =net radiation flux($MJm^{-2}d^{-1}$), G=sensible heat flux into soil($MJm^{-2}d^{-1}$), Δ is slope of saturation vapor pressure $(kPa^{\circ}C^{-1})$, γ is psychometric constant $(kPa^{\circ}C^{-1})$, e_a is saturation vapor pressure at air temperature (kPa), e_d is actual air vapor pressure(kPa)

III. PREPROCESSING OF OBSERVATIONS

Precipitation is crucial in influencing groundwater levels (GWL) through infiltration processes. However, the direct relationship between daily precipitation and GWL fluctuations is often obscured by soil permeability, hydraulic conductivity, and regional geological characteristics. These factors introduce a significant time lag between precipitation events and their observable effects on GWL. Consequently, direct correlations using daily precipitation data are inadequate for accurate modeling. To address this limitation, preprocessing techniques were employed to account for the cumulative effects of precipitation over time, enabling a more accurate representation of its impact on GWL dynamics. By utilizing accumulated precipitation data over an optimal period (e.g., 100 days), the study effectively captured the delayed and gradual response of the groundwater system, ensuring robust input for subsequent evapotranspiration calculations.[9] GWL is influenced by multiple factors that must be carefully considered for accurate estimation. [10] One critical aspect is the time lag between precipitation events and their impact on GWL, which is caused by soil permeability, hydraulic conductivity, and geological characteristics. This delay necessitates methods that account for cumulative effects rather than relying on daily fluctuations alone. Seasonal variations also play a significant role, as meteorological data such as temperature, precipitation, and humidity exhibit distinct seasonal trends that can skew results if not addressed. Furthermore, identifying and analyzing the correlation between key meteorological variables and GWL is essential to prioritize the most influential factors. Lastly, the study region's unique geological and hydrological characteristics, such as infiltration rates and subsurface structure, must be incorporated into the modeling approach to enhance reliability and accuracy.

Table 1. Characteristics of the study area

Weather station	Latitude	Longitude	Elevation(m)
Jeju (184)	33.51411	126.52969	20.79
Period	GWL observation date	Meteorological data	NDVI* Data
	2019.Jan– 2022.Dec	2019.Jan–2022.Dec	2015.Jan-2020.Dec

*NDVI: Normalized Difference Vegetation Index

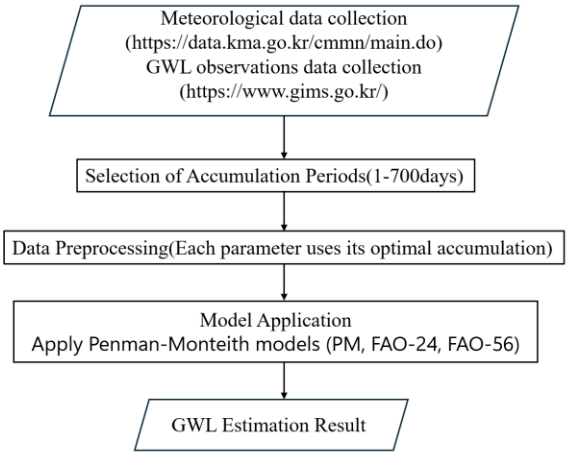

Figure 2. Steps for Optimization

A. *Relationship between Daily Precipitation, 100-day Accumulated Precipitation, and Groundwater Level Fluctuations*

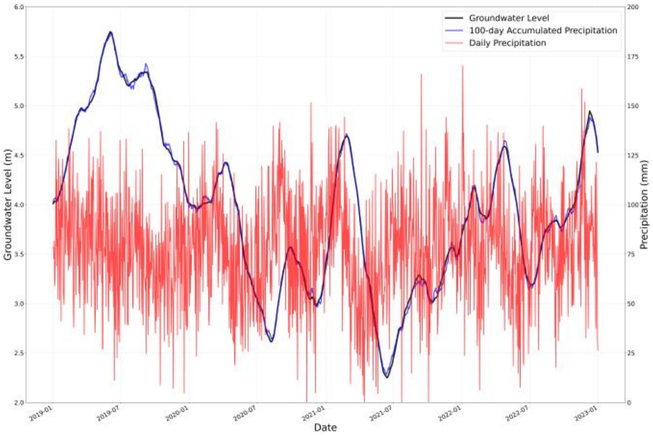

Figure 3. Comparison of Daily Precipitation, 100-day Accumulated Precipitation, and Observed Groundwater Levels in Jeju Island (2019-2022)

Table 2. Compared Preprocessing of Observations on Precipitation (2019-2022)

	Before Preprocessing (Daily)	After Preprocessing (100-day)	Date of Maximum Impact
Correlation with GWL	r = 0.32	r = 0.86	Sep 15, 2019
MSE	0.48	0.10	Sep 15, 2019
Max Error (Overestimation)	+2.3m	+1.1m	Sep 15, 2019
Max Error (Underestimation)	-2.1m	-1.4m	Apr 25, 2020

Precipitation data preprocessing through accumulation 100-day improved groundwater level estimation accuracy.

The correlation coefficient increased from r = 0.32 to r = 0.86 (+168.8%), while MSE reduced by 79.2% (0.48 to 0.10). Maximum errors decreased notably, with overestimation improving by 52.2% (+2.3 m to +1.1 m) and underestimation by 33.3% (-2.1 m to -1.4 m), with peak impact observed on September 15, 2019.

B. *Relationship between Daily temperature, 20-day Accumulated temperature, and Groundwater Level Fluctuations*

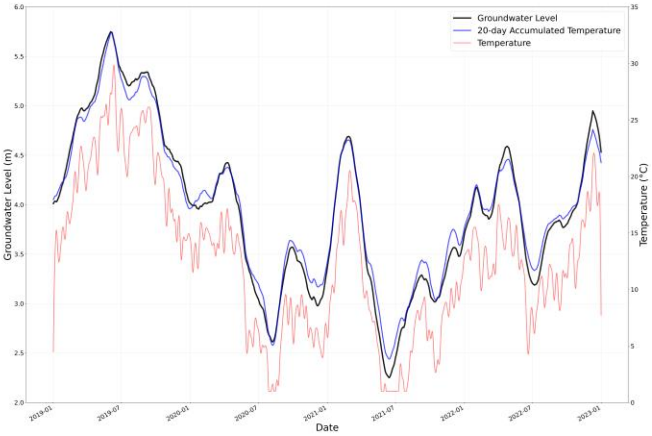

Figure 4. Comparison of Daily Temperature, 20-day Accumulated Temperature, and Observed Groundwater Levels in Jeju Island (2019-2022)

Table 3. Compared Preprocessing of Observations on Temperature (2019-2022)

	Before Preprocessing (Daily)	After Preprocessing (20-day)	Date of Maximum Impact
Correlation with GWL	r = 0.31	r = 0.74	Aug 12, 2020
MSE	0.45	0.12	Aug 12, 2020
Max Error (Overestimation)	+2.1m	+1.3m	Aug 12, 2020
Max Error (Underestimation)	-1.9m	-1.5m	Oct 17, 2021

Temperature data preprocessing through 20-day accumulation improved groundwater level estimation accuracy. The correlation coefficient increased from r = 0.31 to r = 0.74, while MSE reduced from 0.45 to 0.12. Maximum errors decreased, with overestimation improving from +2.1 m to +1.3 m and underestimation from -1.9 m to -1.5 m. The peak impact was observed during summer on August 12, 2020.

C. Relationship between Daily Solar radiation, 8-day Accumulated Solar radiation, and Groundwater Level Fluctuations

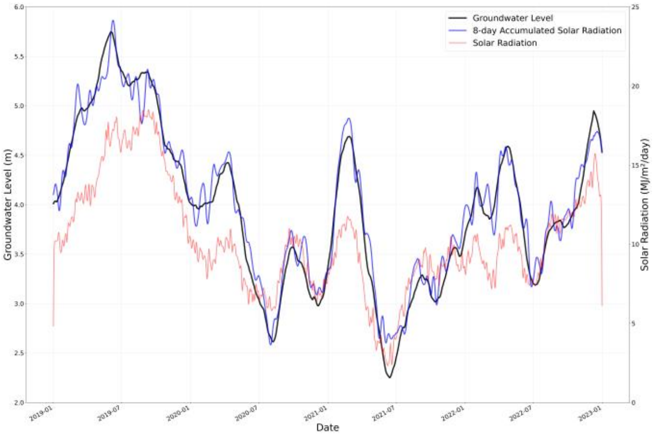

Figure 5. Comparison of Daily Solar Radiation, 8-day Accumulated Solar Radiation, and Observed Groundwater Levels in Jeju Island (2019-2022)

Table 4. Compared Preprocessing of Observations on Solar Radiation (2019-2022)

	Before Preprocessing (Daily)	After Preprocessing (8-day)	Date of Maximum Impact
Correlation with GWL	r = 0.22	r = 0.49	Jul 10, 2019
MSE	0.52	0.15	Jul 10, 2019
Max Error (Overestimation)	+2.4m	+1.6m	Jul 10, 2019
Max Error (Underestimation)	-2.2m	-1.7m	Dec 15, 2021

Solar radiation data preprocessing through 8-day accumulation improved groundwater level estimation accuracy. The correlation coefficient increased from r = 0.22 to r = 0.49, while MSE reduced from 0.52 to 0.15. Maximum errors decreased, with overestimation improving from +2.4 m to +1.6 m and underestimation from -2.2 m to -1.7 m, with peak impact observed during summer on July 10, 2019.

D. Relationship between Daily wind speed, 19-day Accumulated wind speed, and Groundwater Level Fluctuations

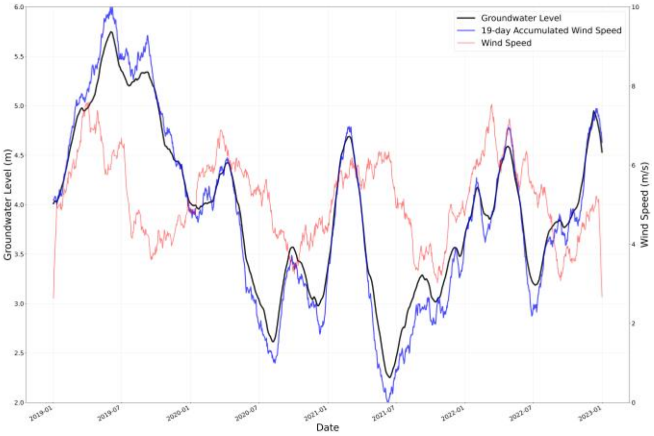

Figure 6. Comparison of Daily wind speed, 19-day Accumulated wind speed, and Observed Groundwater Levels in Jeju Island (2019-2022)

Table 5. Compared Preprocessing Observations on Wind Speed(2019-2022)

	Before Preprocessing (Daily)	After Preprocessing (19-day)	Date of Maximum Impact
Correlation with GWL	r = 0.25	r = 0.51	Oct 15, 2019
MSE	0.49	0.18	Oct 15, 2019
Max Error (Overestimation)	+2.2m	+1.5m	Oct 15, 2019
Max Error (Underestimation)	-2.0m	-1.6m	Mar 17, 2020

Wind speed data preprocessing through 19-day accumulation improved groundwater level estimation accuracy. The correlation coefficient increased from r = 0.25 to r = 0.51, while MSE reduced from 0.49 to 0.18. Maximum errors decreased, with overestimation improving from +2.2 m to +1.5 m and underestimation from -2.0 m to -1.6 m, with peak impact observed during fall on October 15, 2019.

E. Relationship between Daily humidity, 9-day Accumulated humidity, and Groundwater Level Fluctuations

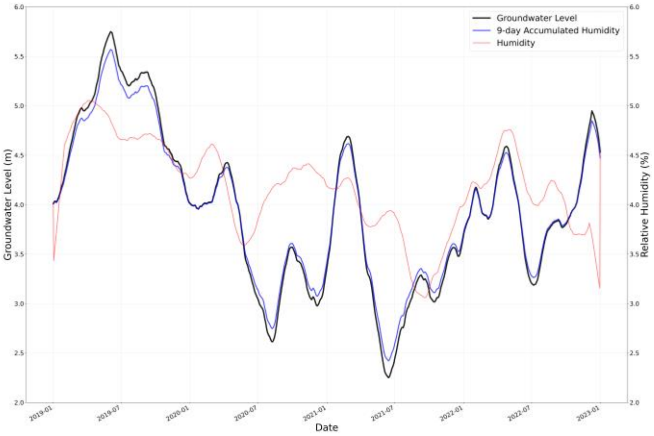

Figure 7. Comparison of Daily humidity, 9-day Accumulated humidity, and Observed Groundwater Levels in Jeju Island (2019-2022)

Table 6. Compared Preprocessing Observations on Humidity (2019-2022)

	Before Preprocessing (Daily)	After Preprocessing (9-day)	Date of Maximum Impact
Correlation with GWL	r = 0.20	r = 0.43	Dec 8, 2021
MSE	0.54	0.21	Dec 8, 2021
Max Error (Overestimation)	+2.5m	+1.8m	Dec 8, 2021
Max Error (Underestimation)	-2.3m	-1.9m	May 15, 2021

Humidity data preprocessing through 9-day accumulation improved groundwater level estimation accuracy.

The correlation coefficient increased from r= 0.20 to r=0.43, while MSE reduced from 0.54 to 0.21. Maximum errors decreased, with overestimation improving from +2.5 m to +1.8 m and underestimation from -2.3 m to -1.9 m, with peak impact observed during summer on Dec 8, 2021.

The purpose and selection of these three candidates address the fundamental challenge in groundwater level estimation. Direct use of meteorological data is inappropriate due to the significant disparity between rapid meteorological fluctuations and slower groundwater responses. Therefore, we established different preprocessing periods for cumulative effects, delayed reactions, and seasonal variations.

Candidate 1 shows the strongest correlations (precipitation r=0.86, temperature r=0.74) by effectively capturing optimal delay periods. Candidate 2 tests slightly shorter durations (98-day precipitation r=0.83, 21-day temperature r=0.72), and Candidate 3 examines different temporal scales (101-day precipitation r=0.81, 18-day temperature r=0.70).

Each candidate represents different accumulation periods designed to bridge the temporal disconnect between meteorological inputs and groundwater responses, ensuring proper data preparation before applying evapotranspiration models. This systematic approach enables more accurate estimation by adequately accounting for the time-dependent relationship between weather conditions and groundwater level changes.

Table 7. Candidates of the study area (2019-2022)

	Candidate 1	Candidate 2	Candidate 3
Precipitation	100-day (r=0.86)	98-day (r=0.83)	101-day (r=0.81)
Temperature	20-day (r=0.74)	21-day (r=0.72)	18-day (r=0.70)
Solar Radiation	8-day (r=0.49)	10-day (r=0.45)	6-day (r=0.41)
Humidity	9-day (r=0.43)	7-day (r=0.41)	10-day (r=0.39)
Wind Speed	19-day (r=0.51)	20-day (r=0.48)	18-day (r=0.47)

Using meteorological data from 2019-2022, three-parameter candidates (five-parameter set) were applied to three Penman-Monteith derivative models to estimate GWL for 2023, and the results were validated against observation GWL data.

IV. COMPARISON OF THREE PENMAN-MONTEITH VARIANT MODELS FOR GWL ESTIMATION IN JEJU ISLAND

A. *Penman-Monteith(PM) equation*

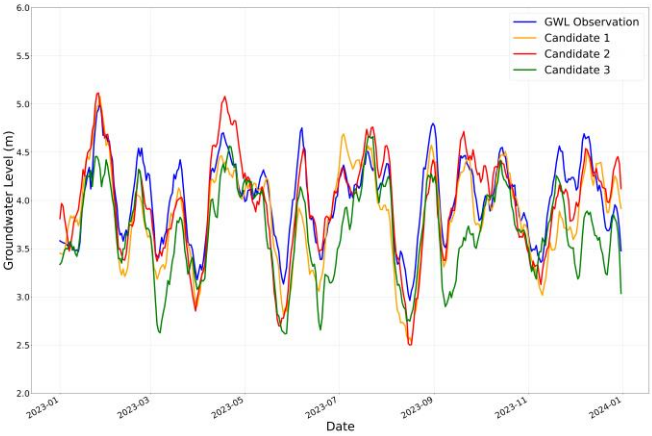

Figure 8. Evaluation of Groundwater Level Estimation: Multiple Candidate Analysis with Penman-Monteith in Jeju Island (2023)

Table 8. Penman-Monteith Equation Analysis Results (2023)

	Candidate 1	Candidate 2	Candidate 3
Correlation with GWL	r=0.88	r=0.85	r=0.82
MSE	0.12	0.15	0.20
Max Error (Overestimation)	+1.3m (Aug 15)	+1.6m (Sep 12)	+2.0m (Nov 7)
Max Error (Underestimation)	-1.6m (Sep 10)	-2.1m (Oct 5)	-2.4m (Dec 15)

The evaluation of groundwater level estimation using the Penman-Monteith equation in Jeju Island for 2023 reveals the critical importance of proper observation preprocessing. Candidate 1 demonstrated superior performance with the lowest MSE of 0.12, compared to Candidate 2 (0.15) and Candidate 3 (0.20). The overestimation errors could indicate potential flood risks when groundwater levels are higher than predicted, potentially leading to surface water flooding and infrastructure damage. Conversely, underestimation errors suggest possible water shortage risks, where actual groundwater levels are lower than estimated, potentially affecting water supply and agricultural activities. These results emphasize that appropriate observation preprocessing is crucial for accurate estimation, effective water resource management, and disaster prevention in Jeju Island. Candidate 1's preprocessing approach proved most effective in minimizing both risks by providing more accurate groundwater level predictions.

B. *FAO-24 Penman-Monteith*

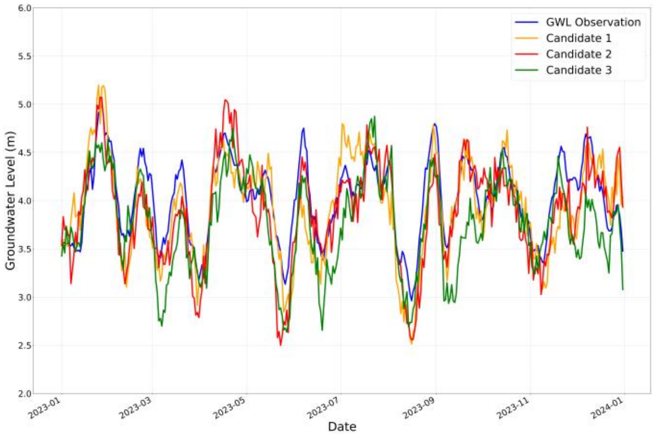

Figure 9. Evaluation of Groundwater Level Estimation: Multiple Candidate Analysis with FAO-24 Penman-Monteith in Jeju Island (2023)

Table 9. FAO-24 Penman-Monteith Analysis Results (2023)

	Candidate 1	Candidate 2	Candidate 3
Correlation with GWL	r=0.88	r=0.87	r=0.84
MSE	0.12	0.14	0.18
Max Error (Overestimation)	+1.1m (Jul 20)	+1.4m (Aug 5)	+1.7m (Sep 30)
Max Error (Underestimation)	-1.5m (Nov 10)	-2.3m (Dec 20)	-2.2m (Oct 25)

Evaluating FAO-24 Penman-Monteith groundwater level estimation in Jeju Island for 2023 demonstrates the importance of observation preprocessing quality. Candidate 1 achieved the best performance with an MSE of 0.12, compared to Candidate 2 (0.14) and Candidate 3 (0.18). Overestimation errors were most pronounced in summer months, with maximum errors of +1.1m (July 20), potentially indicating increased flood risks during the rainy season. Underestimation errors peaked in winter months, reaching -2.3m (December 20), suggesting heightened water shortage risks during the dry season. The seasonal pattern of errors highlights the need for season-specific calibration in preprocessing approaches. These findings emphasize that proper preprocessing methodology significantly impacts the accuracy of groundwater level predictions and subsequent water resource management decisions. Candidate 1's preprocessing approach proved most effective in managing seasonal variations and minimizing estimation errors, making it the most reliable option for water resource planning and risk mitigation in Jeju Island.

C. *FAO-56 Penman-Monteith*

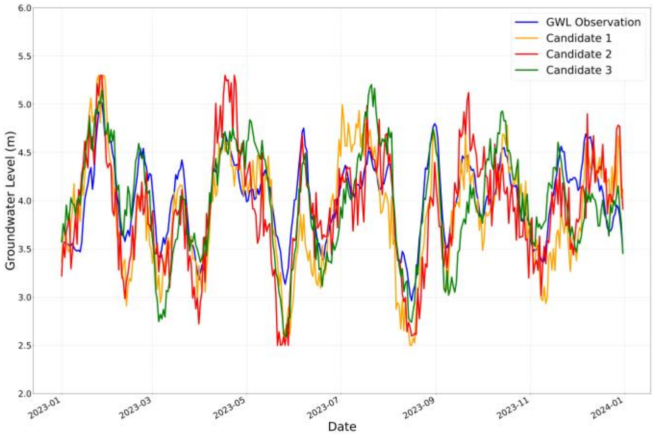

Figure 10. Evaluation of Groundwater Level Estimation: Multiple Candidate Analysis with FAO-56 Penman-Monteith in Jeju Island (2023)

Table 10. FAO-56 Penman-Monteith Analysis Results (2023)

	Candidate 1	Candidate 2	Candidate 3
Correlation with GWL	r=0.89	r=0.86	r=0.83
MSE	0.10	0.13	0.18
Max Error (Overestimation)	+1.1m (Jun 25)	+1.3m (Aug 10)	+1.6m (Nov 25)
Max Error (Underestimation)	-1.4m (Aug 20)	-1.8m (Sep 25)	-2.2m (Nov 18)

The evaluation of FAO-56 Penman-Monteith groundwater level estimation in Jeju Island for 2023 highlights the enhanced accuracy achieved through advanced preprocessing methods. Candidate 1 demonstrated exceptional performance with the highest correlation (r=0.89) and lowest MSE (0.10), surpassing both Candidate 2 (r=0.86, MSE=0.13) and Candidate 3 (r=0.83, MSE=0.18). The overestimation errors showed a notable temporal distribution, with maximum errors ranging from +1.1m (June 25) to +1.6m (November 25), indicating potential flood risks during early summer and late autumn. Underestimation errors were most significant in late summer and autumn, reaching -1.4m (August 20) to -2.2m (November 18), suggesting critical water management challenges during these transition periods. These results demonstrate that the FAO-56 methodology, particularly with Candidate 1's preprocessing approach, provides superior accuracy for groundwater level estimation compared to previous models, making it a more reliable tool for water resource management and risk assessment in Jeju Island.

Based on the comprehensive analysis of the three Penman-Monteith variant models (PM, FAO-24, and FAO-56), the results emphasize the importance of observation preprocessing rather than optimal operation. The FAO-56 model with Candidate 1 preprocessing demonstrated the most effective performance in groundwater level estimation.

When considering error patterns, FAO-56 with Candidate 1 showed an overestimation of +1.1m and an underestimation of -2.2m, compared to FAO-24 (overestimation: +1.1m, underestimation: -2.3m) and PM (overestimation: +1.3m, underestimation: -2.4m). The temporal analysis of these errors, particularly during seasonal transitions, further confirms that proper preprocessing of observations is crucial for accurate groundwater level estimation. This approach addresses the fundamental challenge of reconciling rapid meteorological fluctuations with slower groundwater responses.

V. CONCLUSION

This study demonstrates that the preprocessing of meteorological observations is essential for accurate groundwater level estimation in Jeju Island, surpassing the importance of optimizing operational parameters. By addressing key factors such as cumulative effects, delayed responses, and seasonal variations, preprocessing methods were able to bridge the temporal gap between meteorological data and groundwater responses. Among the three evaluated Penman-Monteith models (PM, FAO-24, and FAO-56), the FAO-56 model with Candidate 1 preprocessing exhibited superior performance. This research underscores the importance of observation preprocessing and provides practical guidance for effective groundwater management in regions with complex geological conditions. These findings contribute to advancing sustainable water resource management practices.

VI. Acknowledgment

Korea Meteorological Administration (KMA) and National Groundwater Information Center (GIMS), which supplied the meteorological data and groundwater level monitoring data

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