

Evaluation of Satellite Soil Moisture Products Against Long-Term In-Situ Observations in Southern Iran

Peyman Afrasiabikia¹, Atefeh Parvaresh Rizi^{1*}, Luca Brocca²

¹Department of Irrigation and Reclamation Engineering, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran

² Director of Research, Research Institute for Geo-Hydrological Protection, National Research Council, Perugia, Italy.

*Corresponding Author, parvarsh@ut.ac.ir

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Abstract

Soil moisture is vital for agricultural water management in semi-arid regions facing water scarcity. This study evaluated four satellite-based soil moisture products—SMAP Enhanced L3 Radiometer (9 km), SMAP 1 km downscaled (NSIDC), ASCAT SWI v3.0 (~11 km), and a custom Random Forest downscaled product (SMAP1km RS)—against long-term in-situ data from Zarghan Agricultural Research Station in southern Iran. Performance was assessed at daily, 10-day, 15-day, and 30-day intervals using R, RMSE, MAE, and NSE metrics. Results showed strong scale dependency: daily retrievals had significant discrepancies, but temporal aggregation greatly improved accuracy. At the 30-day scale, SMAP 1 km performed best ($R=0.95$, $NSE=0.91$), followed closely by SMAP 9 km and SMAP1km RS. ASCAT consistently underperformed. The custom SMAP1km RS showed promise but did not exceed the official SMAP 1 km dataset. SMAP 1 km is the most reliable source in this semi-arid area, and temporal aggregation effectively reduces retrieval noise, supporting irrigation water use monitoring in the region.

1. Introduction

Soil moisture (SM) is a critical parameter in the terrestrial water and energy cycles, providing direct information on soil water availability, evapotranspiration, and plant stress, and thus influencing hydrological processes, agricultural productivity, and climate feedbacks (Brocca et al., 2011; Yee et al., 2017; Kim et al., 2018). Reliable SM estimates are indispensable for applications such as drought monitoring (Mishra et al., 2017), irrigation water use assessment (Zipper et al., 2024), and crop yield forecasting (Rossato et al., 2017). While in situ observations provide the most accurate measurements, they remain sparse and costly to maintain, which limits their applicability for regional-scale monitoring (Lakshmi, 2013; Dorigo et al., 2012). Consequently, satellite-derived soil moisture products have become invaluable for extending SM observations across time and space (Entekhabi et al., 2014). Several microwave-based missions have been launched in the past two decades to provide global soil moisture estimates. The Advanced Scatterometer (ASCAT), distributed as the Soil Water Index (SWI) by the Copernicus Global Land Service (CGLS), is widely used in hydrological modeling due to its long-term temporal coverage and consistency across diverse climates (CGLS, 2018). The Soil Moisture Active Passive (SMAP) mission, launched by NASA in 2015, provides high-quality global soil moisture products, including the Enhanced L3 Radiometer 9 km product (SPL3SMP_E v6) (O'Neill et al., 2021). Downscaling approaches have further enabled the generation of higher-resolution SM products, such as the 1-km SMAP dataset available from NSIDC (Lakshmi & Fang, 2023), which leverages MODIS land surface parameters to refine the 9-km radiometer retrievals. Despite these advances, product performance varies substantially with land cover, topography, and climatic conditions, requiring site-specific validation against in situ data (Bindlish et al., 2017; Zhang et al., 2019). Moreover, high-resolution datasets are particularly needed for agricultural applications, where spatial heterogeneity in soil and vegetation strongly affects water availability. To this end, machine

learning-based downscaling approaches that integrate optical, thermal, radar, and topographic data have emerged as promising solutions for enhancing the spatial fidelity of coarse-resolution soil moisture products (Bai et al., 2019; Maleki et al., 2019).

In this study, we assess the performance of four soil moisture datasets over the Zarghan Agricultural Research station in Fars Province, Iran. The validation was conducted using long-term in situ soil moisture observations from the station. This station provides multi-depth soil moisture records under various agricultural practices, making it a valuable reference dataset for evaluating satellite-derived soil moisture products. The four soil moisture datasets include:

- SMAP Enhanced L3 Radiometer (9 km, SPL3SMP_E v6) (O'Neill et al., 2021),
- SMAP 1-km downscaled product (NSIDC, v1) (Lakshmi & Fang, 2023),
- ASCAT Soil Water Index (SWI, v3.0, CGLS/TU Wien), and
- SMAP1km RS- a custom 1-km downscaled SMAP product generated by the authors using a Random Forest model trained on MODIS (NDVI, LST, LAD), Sentinel-1 backscatter, and DEM-derived slope on Google Earth Engine.

The evaluation was performed using the time series of the pixel containing the station, ensuring spatial consistency with ground observations. To capture agricultural management-relevant timescales, comparisons were conducted for daily data as well as aggregated 10-day, 15-day, and 30-day averages. Three widely used performance metrics were applied: correlation coefficient (R), root mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE). Together, these analyses aim to determine the most reliable product and temporal aggregation for representing soil moisture dynamics in the semi-arid conditions of the study area.

2. Material and Methods

2.1 Study Area and In-situ Data

This research was carried out in Fars Province, southern Iran, as part of a broader project on irrigation monitoring in the Doroodzan agricultural region. The larger study focused on estimating irrigation water use across the Doroodzan irrigation network (~76,000 ha), one of the most important agricultural systems in Iran, using satellite-based soil moisture products. Within that framework, the present work concentrates on the Zarghan Agricultural Research Station, located nearby but outside the network boundaries (Figure 1).

The Zarghan station provides a unique setting for validating satellite-based soil moisture products because it is not subject to irrigation. Soil moisture variations at this site are controlled almost entirely by natural precipitation and climatic conditions, without the confounding effects of irrigation scheduling or water management practices. This makes it particularly suitable for assessing the intrinsic performance of satellite datasets under semi-arid conditions.

The climate of the study area is semi-arid, characterized by hot, dry summers and mild winters. Annual precipitation averages about 500 mm, with the majority falling in the cold season. Summers are typically dry, with negligible rainfall, high temperatures, and strong evaporative demand. These conditions lead to pronounced seasonal fluctuations in soil moisture, which provide a robust natural signal against which satellite retrievals can be evaluated. The Zarghan station has been systematically monitoring soil moisture for multiple years using fixed sensors installed at several depths. These long-term, continuous records capture both seasonal and interannual variability in soil water content driven by natural rainfall events. Because of its consistency and reliability, the station offers a high-quality benchmark for evaluating the accuracy and stability of satellite-derived soil moisture products in semi-arid agricultural regions.

2.2 Satellite Soil Moisture Datasets

2.2.1 SMAP Enhanced L3 Radiometer (9 km, SPL3SMP_E v6): We employed NASA's SMAP Enhanced Level-3 Radiometer soil moisture product (SPL3SMP_E, Version 6), distributed by the National Snow and Ice Data Center (NSIDC). This dataset provides daily global surface soil moisture retrievals (top ~5 cm) on the EASE-Grid 2.0 at a nominal spatial resolution of 9×9 km. The product composites AM (~06:00 LST) and PM (~18:00 LST) overpasses into daily HDF5 granules, spanning from March 31, 2015 to the present (O'Neill et al., 2021). Validation against SMAP core calibration/validation sites has demonstrated high agreement with in-situ measurements, making this product a reliable benchmark for soil moisture monitoring in semi-arid environments.

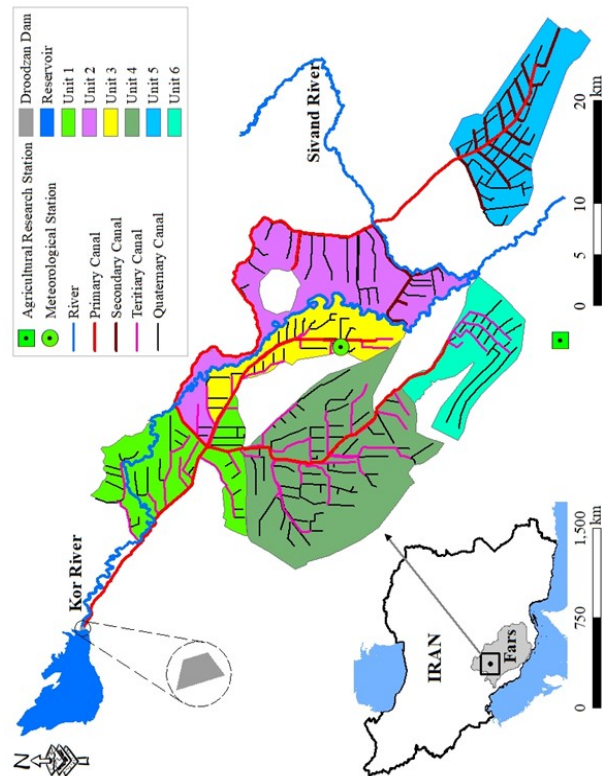


Figure 1. Map of the Doroodzan Irrigation District, Fars Province, Iran and Zarghan Agricultural Research Station.

2.2.2 SMAP 1-km Downscaled Product (NSIDC, v1): To assess the benefits of finer resolution, we included the SMAP 1-km downscaled surface soil moisture dataset (Version 1), released by NSIDC (Lakshmi & Fang, 2023). This product applies an inertia-based downscaling algorithm that incorporates MODIS land surface temperature and vegetation information to spatially disaggregate the 9-km radiometer retrievals onto a 1-km global EASE-Grid 2.0. Data are provided as daily GeoTIFF files covering the period from April 2015 onward. Independent validation has shown that the 1-km product improves representation of spatial heterogeneity, with stronger performance in agricultural and semi-arid regions compared to the native 9-km product.

2.2.3 ASCAT Soil Water Index (SWI v3.0, CGLS/TU Wien): The ASCAT Soil Water Index (SWI, Version 3.0), produced by the Copernicus Global Land Service (CGLS) in collaboration with TU Wien, was also analyzed. The SWI is generated by applying a two-layer infiltration model with multiple characteristic decay times to Metop ASCAT Level-2 surface soil moisture retrievals (nominal resolution ~25 km). The results are interpolated using a Backus-Gilbert method to a regular $0.1^\circ \times 0.1^\circ$ (~11 km) grid and provided as daily CF-compliant NetCDF4 files. The SWI represents a soil water content index rather than volumetric soil moisture, and it has been widely applied in hydrological modeling across diverse climates. However, in semi-arid agricultural environments, its coarser spatial resolution and sensitivity to vegetation and surface roughness may limit local-scale accuracy.

2.2.4 SMAP1km RS (SMAP downscaled to 1 km using Remote Sensing predictors): In addition to the official NSIDC downscaled product, we developed a custom 1-km SMAP dataset tailored for the Zarghan study area. The approach was implemented in Google Earth Engine (GEE) and used daily SMAP 10-km soil moisture retrievals (NASA_USDA/HSL/SMAP10KM_soil_moisture) as the coarse input. To enhance spatial detail, auxiliary predictors included MODIS NDVI (MOD13Q1), MODIS land surface temperature (MOD11A2), MODIS LAI (MOD15A2H), Sentinel-1 VV backscatter (COPERNICUS/S1_GRD), and topographic slope derived from USGS GTOPO30. For each date, these predictors were stacked and used to train a Random Forest model (50 trees) with stratified sampling of 50 points per scene. The trained model was then applied to downscale the 10-km SMAP observations to 1-km resolution, producing daily maps from which the pixel corresponding to the Zarghan station was extracted. This locally optimized product is intended to test whether machine-learning downscaling with region-specific predictors can improve alignment with in-situ soil moisture dynamics compared to global, generalized products.

2.3 Temporal Aggregation

Satellite and in-situ soil moisture time series were analyzed at multiple temporal scales. In addition to the native daily resolution of each dataset, we generated aggregated series at 10-day, 15-day, and 30-day intervals by averaging consecutive daily values over non-overlapping windows. These temporal aggregations were selected to (i) reduce short-term noise and retrieval uncertainties present in daily satellite observations, (ii) align with common agricultural management and reporting periods, and (iii) assess how temporal smoothing affects the agreement between satellite-derived products and in-situ measurements. The inclusion of multiple aggregation windows also allows evaluation of the scale-dependency of product performance, which is relevant for operational monitoring where decision-making often relies on dekadal (10-day) or monthly statistics rather than daily fluctuations.

2.4 Validation Approach

The evaluation of satellite soil moisture datasets was carried out by comparing each product with the in-situ measurements from the Zarghan Agricultural Research Station. For consistency, the satellite value corresponding to the pixel containing the station was extracted, and only coincident observation dates were included in the analysis. For the aggregated datasets (10-, 15-, and 30-day), both in-situ and satellite values were averaged over the same successive time intervals to ensure direct comparability.

Three widely used statistical indicators were employed to assess product performance:

- **Correlation coefficient (R):** measures the strength and direction of the linear relationship between satellite estimates and in-situ observations, indicating how well the two datasets co-vary.
- **Root Mean Square Error (RMSE):** quantifies the average magnitude of differences between satellite-derived and observed soil moisture, reflecting overall accuracy in absolute terms.
- **Nash–Sutcliffe Efficiency (NSE):** evaluates how well the temporal dynamics of the in-situ series are

reproduced by the satellite product, with higher values indicating greater skill.

These three complementary indicators together provide a comprehensive assessment of each dataset: correlation reflects co-variability, RMSE captures the size of errors, and NSE shows the ability to reproduce natural fluctuations.

3. Results

3.1 Time Series Analysis

The temporal comparison between satellite products and in-situ soil moisture at the Zarghan station highlights strong differences in performance across temporal scales (Figure 2). At the daily resolution, all satellite datasets broadly captured the seasonal wetting and drying cycles observed at the station. However, substantial short-term discrepancies were evident. The SMAP 1 km product most closely followed the station dynamics, though with some underestimation during high-moisture periods. SMAP 9 km showed a similar pattern but with larger deviations. The custom SMAP1km RS product reproduced the general seasonal variability but tended to diverge during rainfall-driven peaks. ASCAT, by contrast, consistently overestimated soil moisture and failed to reproduce rapid fluctuations, showing clear disagreement with the in-situ series.

With 10-day and 15-day aggregation, the agreement between satellite and in-situ observations improved markedly. Temporal smoothing reduced high-frequency noise and allowed the seasonal dynamics to emerge more clearly. At these scales, SMAP 1 km tracked both the timing and magnitude of soil moisture variations with high fidelity. SMAP 9 km and SMAP1km RS also performed well, though slightly below SMAP 1 km. ASCAT improved relative to the daily comparison but still maintained a systematic positive bias and weaker temporal correspondence.

At the 30-day scale, all SMAP-based products showed very close alignment with the in-situ data. SMAP 1 km provided the strongest match, capturing the seasonal cycle with minimal deviation. SMAP 9 km and SMAP1km RS also reproduced the observed dynamics but exhibited slightly larger errors, particularly during transition periods between wet and dry seasons. ASCAT's monthly series aligned better with the overall seasonal cycle than at finer scales but still overestimated soil moisture levels compared to the station record.

Overall, the time series analysis confirms that temporal aggregation enhances the consistency of satellite-derived soil moisture estimates with ground observations, with the SMAP 1 km product consistently outperforming the other datasets, followed by SMAP 9 km and SMAP1km RS, while ASCAT remained the least accurate across all temporal scales.

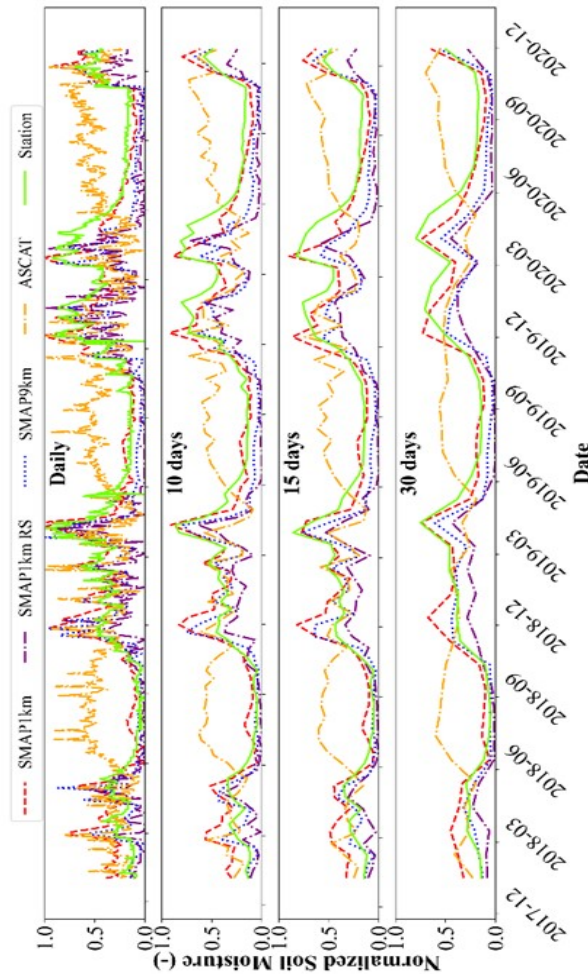


Figure 2. Time series of soil moisture from the Zarghan Agricultural Research Station and four satellite products (SMAP 1 km, SMAP 9 km, SMAP1km RS, and ASCAT) at daily, 10-day, 15-day, and 30-day temporal resolutions.

3.2 Statistical Performance

The statistical evaluation using correlation (R), RMSE, MAE, and NSE provides quantitative confirmation of the trends observed in the time series (Figure 3). At the daily scale, SMAP 1 km achieved the best performance ($R \approx 0.81$, $NSE \approx 0.59$), followed by SMAP 9 km ($R \approx 0.78$, $NSE \approx 0.35$). ASCAT performed very poorly, with negative NSE (-1.27) and weak correlation, highlighting its inability to capture short-term variability in this environment. The SMAP1km RS product yielded moderate results but was weaker than the official SMAP products, mainly due to higher errors.

At the 10-day and 15-day scales, all products showed significant improvement. SMAP 1 km consistently delivered the highest skill ($R \approx 0.94$ – 0.95 , $NSE \approx 0.88$ – 0.89), while SMAP 9 km and SMAP1km RS also performed strongly ($R > 0.91$, positive NSE). ASCAT improved but remained notably weaker ($R \approx 0.71$ – 0.72 , $NSE \approx 0.27$ – 0.30).

At the 30-day scale, performance peaked for all SMAP datasets. The SMAP 1 km product reached the best overall accuracy ($R =$

0.95 , $NSE = 0.91$, lowest $RMSE \approx 0.02$). SMAP 9 km and SMAP1km RS also achieved high correlations (>0.93) and good efficiency, although with slightly larger errors than SMAP 1 km. ASCAT further improved ($R \approx 0.73$, $NSE \approx 0.32$) but still lagged behind the SMAP products.

In summary, the statistical analysis demonstrates that:

- Temporal aggregation greatly enhances product performance, reducing noise and improving reliability.
- The SMAP 1 km product consistently outperformed all others, especially at aggregated scales.
- The SMAP1km RS product, while performing reasonably well, did not surpass the official SMAP datasets.
- ASCAT SWI showed the weakest performance, particularly at the daily scale, limiting its suitability for site-level applications in this semi-arid region.

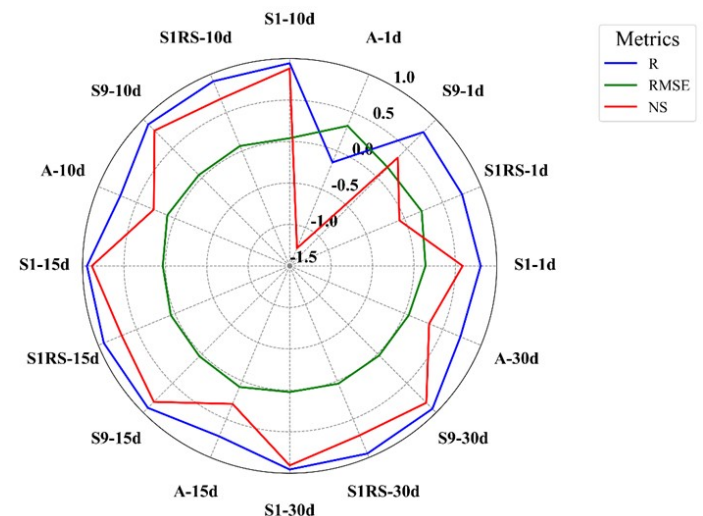


Figure 3. Radar chart summarizing statistical performance of the four satellite soil moisture datasets across temporal scales.

Datasets are abbreviated as S1 = SMAP 1 km (NSIDC downsampled), S9 = SMAP 9 km (Enhanced L3 Radiometer), A = ASCAT SWI v3.0, and SIRS = SMAP downsampled to 1 km using Remote Sensing predictors (this study). Metrics include R, RMSE, and NSE.

4. Discussion

This study assessed the performance of four satellite soil moisture datasets against long-term in-situ measurements at the Zarghan Agricultural Research Station under semi-arid conditions. The results demonstrated substantial variability in product performance across temporal scales, with the SMAP 1 km dataset consistently outperforming the other products, particularly at aggregated timescales.

4.1 Scale Dependency of Performance

A key finding was the strong influence of temporal aggregation on dataset accuracy. At the daily scale, performance was moderate for SMAP products and poor for ASCAT, with high noise and weak efficiency (negative NSE). However, as the temporal resolution was increased to 10, 15, and 30 days, all

satellite datasets showed significant improvements. This trend highlights the role of temporal averaging in reducing random errors associated with satellite retrievals, such as sensor noise, radio-frequency interference, and retrieval uncertainty under variable soil and vegetation conditions (Brocca et al., 2019). The monthly aggregation in particular allowed SMAP 1 km to reach correlations above 0.95 and NSE values above 0.90, in close agreement with the in-situ record. These findings are consistent with earlier global and regional studies that also reported better performance of satellite soil moisture products at coarser temporal scales (Zipper et al., 2024).

4.2 Relative Performance of SMAP, ASCAT, and Custom RS Products

Among the evaluated products, the official SMAP 1 km dataset showed the strongest agreement across all time scales. Its superiority reflects the benefit of NASA's advanced downscaling algorithm, which integrates ancillary data (e.g., MODIS land surface temperature) to refine spatial resolution (O'Neill et al., 2021; Lakshmi & Fang, 2023). The SMAP 9 km product also showed robust performance, albeit with slightly lower accuracy due to its coarser resolution.

The custom SMAP1km RS product, developed in this study through Random Forest downscaling of SMAP 10 km with ancillary remote sensing variables (MODIS NDVI, LST, LAI, Sentinel-1 backscatter, and DEM), demonstrated promising results. Although it did not surpass the official SMAP 1 km product, it achieved correlations exceeding 0.90 and positive NSE values at aggregated time scales, indicating that the machine learning approach was effective. The lower performance compared to the official product is likely related to limited training data density, the heterogeneity of ancillary predictors, and the sensitivity of Random Forest to noise in semi-arid environments. Nonetheless, this product highlights the feasibility of developing region-specific, flexible downscaling frameworks that can be applied in data-scarce areas where global high-resolution products are not available.

In contrast, the ASCAT SWI consistently underperformed. Its weaker performance is consistent with previous studies reporting limitations of scatterometer-based products in semi-arid regions. The coarse native resolution (~25 km), combined with the simplified infiltration model used to derive the SWI, likely limits its ability to capture localized soil moisture dynamics around the Zarghan site. Moreover, the persistent overestimation of soil moisture values observed here is a common issue linked to ASCAT retrieval sensitivity to surface roughness and vegetation effects (Brocca et al., 2017).

4.3 Implications for Irrigation Water Use Studies

Although this analysis focused on validation at the Zarghan station, it was conducted as part of a larger effort to monitor irrigation water use in the Doroodzan irrigation network. The results provide critical insights for selecting appropriate soil moisture datasets for operational water management. Specifically, the superior accuracy of SMAP 1 km supports its use as the primary input for SM-based inversion approaches aimed at quantifying irrigation water use across the Doroodzan network. The custom SMAP1km RS product, while not outperforming the official SMAP dataset, nonetheless demonstrates that localized downscaling frameworks can complement global products and may be particularly valuable in areas outside the coverage or applicability of standard datasets.

4.4 Limitations and Future Directions Placement:

This study was limited by the use of a single in-situ validation site (Zarghan station), which, while valuable for long-term monitoring, may not fully represent the spatial heterogeneity of soil and land management conditions across the Doroodzan region. Expanding the evaluation to additional stations would strengthen the robustness of the conclusions. Another limitation concerns the temporal focus on rain-fed soil moisture dynamics; since the Zarghan station is not directly influenced by irrigation, further assessments in irrigated fields would be needed to fully capture the products' sensitivity to human-driven soil moisture variations.

Future work should also explore the use of advanced machine learning and data fusion approaches for downscaling, including deep learning models and synergistic integration of SMAP with Sentinel-1 radar backscatter. Such methods may reduce biases and improve the spatial fidelity of downscaled products, ultimately enhancing their utility for agricultural water management under semi-arid conditions.

5. Conclusion

This study evaluated the performance of four satellite-derived soil moisture datasets—SMAP 1 km, SMAP 9 km, ASCAT SWI, and a custom downscaled SMAP1km RS product—against long-term in-situ observations from the Zarghan Agricultural Research Station in southern Iran. The results showed a clear dependence of performance on temporal aggregation: while daily estimates exhibited considerable noise and discrepancies, accuracy improved markedly at 10-, 15-, and 30-day scales.

Among the datasets, the SMAP 1 km product consistently achieved the highest accuracy, with correlation coefficients exceeding 0.94 and NSE values above 0.90 at monthly scales. The SMAP 9 km product also performed strongly, though with slightly larger errors. The custom SMAP1km RS dataset, developed in this study through Random Forest downscaling with multiple remote sensing predictors, showed promising results, particularly at aggregated scales, but did not surpass the official SMAP 1 km product. In contrast, ASCAT SWI exhibited the weakest agreement, especially at the daily scale, confirming its limited suitability for site-level monitoring in semi-arid regions.

These findings provide an essential foundation for the larger objective of quantifying irrigation water use in the Doroodzan irrigation network. The superior performance of the SMAP 1 km dataset highlights its value as a reliable input for operational irrigation monitoring and water resource management. Meanwhile, the custom downscaling framework illustrates the potential for developing region-specific products tailored to local conditions, which may be particularly useful in data-scarce or heterogeneous environments.

Future work should focus on expanding validation to multiple sites, incorporating irrigated fields, and testing advanced downscaling or data-fusion methods. Such efforts will enhance the reliability and applicability of satellite-derived soil moisture products for sustainable agricultural water management in semi-arid regions.

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