Evaluation of remote sensing-based evapotranspiration estimates using a water transfer numerical simulation under different vegetation conditions in an arid area

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Abstract
Daily actual evapotranspiration (AET) and seasonal AET values are of great practical importance in the management of regional water resources and hydrological modelling. Remotely sensed AET models and Landsat satellite images have been used widely in producing AET estimates at the field scale. However, the lack of validation at a high spatial frequency under different soil water conditions and vegetation coverages limits their operational applications. To assess the accuracies of remote sensing-based AET in an oasis-desert region, a total of 59 local-scale daily AET time series, simulated using HYDRUS-1D calibrated with soil moisture profiles, were used as ground truth values. Of 59 sampling sites, 31 sites were located in the oasis subarea and 28 sites were located in the desert subarea. Additionally, the locally validated mapping evapotranspiration at high resolution with internalized calibration surface energy balance model was employed to estimate instantaneous AET values in the area containing all 59 of the sampling sites using seven Landsat subimages acquired from June 5 to August 24 in 2011. Daily AET was obtained using extrapolation and interpolation methods with the instantaneous AET maps. Compared against HYDRUS-1D, the remote sensing-based method produced reasonably similar daily AET values for the oasis sites, while no correlation was observed for daily AET estimated using these two methods for the desert sites. Nevertheless, a reasonable monthly AET could be estimated. The correlation analysis between HYDRUS-1D-simulated and remote sensing-estimated monthly AET values showed relative root-mean-square error values of 15.1%, 12.1%, and 12.3% for June, July, and August, respectively. The root mean square error of the summer AET was 10.0%. Overall, remotely sensed models can provide reasonable monthly and seasonal AET estimates based on periodic snapshots from Landsat images in this arid oasis-desert region.

KEYWORDS
daily actual evapotranspiration, desert area, HYDRUS-1D, model evaluation, thermal remote sensing

1 | INTRODUCTION

Understanding the seasonal water consumption of different land cover types is crucial for the management and allocation of river basin water resources, especially for the arid Heihe Inland River Basin of China, where conflicts over limited water resources are primarily between agricultural irrigation and other ecological water uses (Zhou, Cheng, Li, Hu, & Wang, 2012). Land surface evapotranspiration (ET), the largest water loss in this region, has great spatial variation among oasis and desert subareas (Lian & Huang, 2015). Currently, remote
sensing techniques make the spatially continuous quantitative evaluation of actual ET (AET) over heterogeneous ecosystems possible (Chang, Ding, Zhao, & Zhang, 2017; Huang & Choi, 2013; Nouri, Beecham, Kazemi, Hassanli, & Anderson, 2013), and Landsat satellite images have been commonly employed in producing AET estimates at the field scale (Kjaersgaard, Allen, & Irmak, 2011).

Satellite images provide snapshots of land surface conditions at the moment of overpass, and therefore, only instantaneous AET maps can be estimated directly (Xu et al., 2015). In addition, the low temporal resolution of the Landsat satellite, with a 16-day revisit cycle, has limited the ability to produce continuous daily AET time series. Two steps are needed to upscale the instantaneous AET to daily values. First, the daily AET on the satellite overpass days is extrapolated using instantaneous AET maps. For the extrapolation, many studies have compared the performances of two commonly used methods, the constant evaporative fraction (EF; Brutsaert & Sugita, 1992; Shuttleworth, Gurney, Hsu, & Ormsby, 1989) and the constant referenced ET fraction (ET,F; Allen, Tasumi, Morse, et al., 2007). In terms of different land cover types, EF and ET,F are recommended for bare land and cropped surfaces, respectively (Colaizzi, Evett, Howell, & Tolk, 2006; Gonzalez-Dugo et al., 2009; Liu & Huang, 2016). Second, daily AET estimations between image dates are made by interpolating the AET values between the satellite overpass days. For the interpolation, ET,F values are temporally reconstructed based on the ET,F values observed on satellite overpass days at the pixel scale and, then, are used to produce daily and seasonal AET maps by multiplying daily and accumulated alfalfa reference ET (ET,; Allen, Tasumi, Morse, et al., 2007; Kjaersgaard et al., 2011). Recent studies found that the accuracies of the remotely sensed AET estimations are different depending on the land cover types (Velpuri, Senay, Singh, Bohms, & Verdin, 2013). However, the lack of validation data at a high spatial frequency under different soil water conditions and vegetation coverages leads to low confidence in operational AET estimation using remote sensing methods (Tang, Li, & Tang, 2010).

The validation of remote sensing-based AET is usually conducted at a field scale using tower flux observations, sap flow measurements, soil moisture, and field water models or at a regional scale with aircraft fluxes and water mass balance models (Bastiaanssen et al., 1998). A suitable validation procedure could be selected according to spatial coverages and the duration of study periods. Currently, eddy covariance towers (EC) have been used widely for field AET validation because they produce area-averaged ET measurements with source areas of hundreds of square meters, matching well with the resolution of Landsat images (Li et al., 2013). Nevertheless, validation is usually conducted with a small number of samples and in several vegetation types and soil moisture conditions, because of limits imposed by the high cost and strict installation conditions of EC, which constrain validation efforts (Czajkowski, Goward, Studler, & Walz, 2000).

Alternatively, daily AET can be simulated using numerical models of integrated water flow transport and plant water uptake with root-zone soil moisture and other parameters (e.g., meteorological, irrigation, and plant growth data). As the structural differences, AET estimates produced by the numerical models are statistically independent from those estimated using remote sensing-based models (Crow, Kustas, & Prueger, 2008) and are used to validate remote sensing-based AET estimates (Galleguillos, Jacob, Prevoit, French, & Lagacherie, 2011; Galleguillos, Jacob, Prevoit, Lagacherie, & Liang, 2011; Galleguillos et al., 2017). The spatial patterns and temporal variability of soil moisture measurements were found to have distinct characteristics between desert and oasis subareas, which were influenced by soil physical properties (soil texture, soil organic carbon content, bulk density, etc.), hydraulic conductivity values, and vegetation type and coverage (Li & Shao, 2015). This study seeks to compare the daily AET series estimated and simulated based on remote sensing and numerical methods using 59 sampling sites. The METRIC (mapping evapotranspiration at high resolution with internalized calibration) surface energy balance model was employed to produce daily AET estimates. This model has been widely used around the world (Allen, Tasumi, Morse, et al., 2007; Allen, Tasumi, & Trezza, 2007; French, Hunsaker, & Thorp, 2015; Khand, Numata, Kjaersgaard, & Vourliitis, 2017) and has been improved and validated in the middle reach of the Heihe River Basin, where this study was conducted (Lian & Huang, 2015, 2016). The mean absolute errors between METRIC-estimated and EC-measured AET values were 0.60, 1.05, and 0.55 mm d−1 at the farmland, wetland, and desert sites, respectively (Lian & Huang, 2016). The HYDRUS-1D model was adopted to simulate one-dimensional water flow processes in the unsaturated zone (Šimůnek, Van Genuchten, & Šejna, 2016) using water flow and plant water uptake models with soil properties (clay, silt and sand contents, and bulk density), soil water measurements, groundwater depth data, plant growth data, and meteorological parameters.

The objective of this study was to compare the spatial and temporal trends of daily AET values estimated using a remote sensing method and HYDRUS-1D model using a large number of samples under different soil water conditions and vegetation coverages.

2 MATERIALS AND METHODS

2.1 Study area

The cross-comparisons of METRIC-estimated AET with HYDRUS-1D AET estimates were conducted for 59 sampling sites in an oasis-desert area (7 km × 15 km; Figure 1). The study area was divided into two subareas, an oasis subarea with irrigation and a desert subarea without irrigation (Table 1). Of the 59 sampling sites, 31 sites were located in the oasis subarea and 28 sites were located in the desert subarea. For the oasis sites, 26 sites were planted with maize (Zea mays L.), and 5 sites were classified as forestland, with poplar (Populus gansuensis C. Wang and HL Yang) and Mongolian pine (Pinus sylvestris var. mongolica) as the main tree species. In the desert subarea, the main vegetation types were shrubs and annual herbs, including Haloxylon ammodendron (C. A. Mey.) Bunge, Calligonum mongolicum Turcz., Tamarix chinensis Lour., Nitraria sphaerocarpa Maxim, and Reaumuria soongorica (Pall.) Maxim (Li & Shao, 2013). The study area has a temperate dry climate with a mean annual temperature of 7.6 °C. The mean annual precipitation varies from 100 to 250 mm, and 60% of the rainfall occurs between July and September.
2.2 Data collection

2.2.1 Landsat-5 TM data/images

Seven cloud-free Landsat-5 TM subset images were acquired from the United States Geological Survey Earth Resources Observation and Science Center (http://glovis.usgs.gov/) during June to August 2011. All acquired images are the Level 1 Terrain Corrected (L1T) product with processing that includes radiometric correction, systematic geometric correction, and precision correction using ground control (Roy et al., 2016). The study area is located in the overlap area of two adjacent paths. Among these seven images, four originated from Path 134 and Row 33 (June 5, July 7, August 8, and August 24) and three from Path 133 and Row 33 (June 14, July 16, and August 1). During the METRIC model process, surface parameters, including albedo, the Normalized Difference Vegetation Index (NDVI), and momentum roughness length, were resampled to the 120-m spatial resolution of the thermal data-derived parameters (surface emissivity and temperature).

2.2.2 Ground-based data

Hourly meteorological data, including solar irradiance, air temperature, relative humidity, wind speed, and precipitation, were collected at the

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### Table 1: Main characteristics of the study area and the number of sampling sites

<table>
<thead>
<tr>
<th>Subareas</th>
<th>Land cover types</th>
<th>Area (km²)</th>
<th>Proportion (%)</th>
<th>Number of sampling sites</th>
<th>RS-estimated AETa (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oasis</td>
<td>Farmland</td>
<td>55.58</td>
<td>50.62</td>
<td>26</td>
<td>429 ± 89</td>
</tr>
<tr>
<td></td>
<td>Forest</td>
<td>0.97</td>
<td>0.88</td>
<td>5</td>
<td>381 ± 96</td>
</tr>
<tr>
<td></td>
<td>Shrub land</td>
<td>3.04</td>
<td>2.77</td>
<td>0</td>
<td>239 ± 98</td>
</tr>
<tr>
<td></td>
<td>Medium-coverage grassland</td>
<td>0.08</td>
<td>0.07</td>
<td>0</td>
<td>246 ± 60</td>
</tr>
<tr>
<td></td>
<td>River</td>
<td>1.28</td>
<td>1.17</td>
<td>0</td>
<td>520 ± 40</td>
</tr>
<tr>
<td></td>
<td>Reservoir</td>
<td>1.02</td>
<td>0.93</td>
<td>0</td>
<td>526 ± 23</td>
</tr>
<tr>
<td></td>
<td>Marsh</td>
<td>0.3</td>
<td>0.27</td>
<td>0</td>
<td>350 ± 77</td>
</tr>
<tr>
<td></td>
<td>Residential</td>
<td>2.71</td>
<td>2.47</td>
<td>0</td>
<td>366 ± 72</td>
</tr>
<tr>
<td>Desert</td>
<td>Sparse forest</td>
<td>8.43</td>
<td>7.68</td>
<td>9</td>
<td>196 ± 65</td>
</tr>
<tr>
<td></td>
<td>Low-coverage grassland</td>
<td>9.66</td>
<td>8.80</td>
<td>0</td>
<td>169 ± 89</td>
</tr>
<tr>
<td></td>
<td>Sandy desert</td>
<td>21.32</td>
<td>19.42</td>
<td>17</td>
<td>102 ± 57</td>
</tr>
<tr>
<td></td>
<td>Gobi desert</td>
<td>2.78</td>
<td>2.53</td>
<td>0</td>
<td>93 ± 41</td>
</tr>
<tr>
<td></td>
<td>Salt meadow</td>
<td>2.28</td>
<td>2.08</td>
<td>2</td>
<td>73 ± 31</td>
</tr>
<tr>
<td></td>
<td>Bare rock</td>
<td>0.35</td>
<td>0.32</td>
<td>0</td>
<td>88 ± 15</td>
</tr>
</tbody>
</table>

| Subareas |             | All         |              |                          |
|----------|-------------|-------------|--------------|
|          | Subareas    | 109.8       | 100          |
|          | Number of   | 59          |              |

Note. AET = actual evapotranspiration.
aValues are means ± std. dev. of pixel-wise AET values for different land cover types.
Linze Inland River Basin Comprehensive Research Station, located in the study area.

Neutron probe soil water content measurements were applied at each sampling site once a month from May to October 2011. The measurements were conducted in the third week of each month and were completed within 3 days for each occasion (Li & Shao, 2014). The aluminium neutron probe access tubes were set at 3 m, and the measurement intervals were 0.1 m for the 0–1 m soil layer and 0.2 m for the 1–3 m soil layer. Neutron counts were recorded and, then, were converted to volumetric soil moisture contents using depth-specific calibration curves. The calibrations were conducted at 18 sampling sites with different soil water conditions in May. During the neutron counting measurement period, disturbed and undisturbed soil samples were taken to measure gravimetric soil water contents and soil bulk densities, respectively, 0.5 m away from the access tubes (Hu, Shao, Wang, & Reichardt, 2009).

The soil particle size distribution of each sampling site was measured using a Malvern Laser particle size analyser. Samples were collected using a 5-cm-diameter hand auger, and the sampling intervals were 0.1 and 0.2 m for the 0–1 m profile and the 1–3 m profile, respectively (Li & Shao, 2013). In this study, the soil profile of each site was categorized into one to three horizons according to in situ observations. In accordance with the soil horizon texture, the bulk density was estimated using expert knowledge and the results of earlier studies conducted within our study area (Shen, Gao, Hu, & Fu, 2016; Yi et al., 2015). Generally, the variation coefficients of bulk density were less than 10% for all land cover types (Li & Shao, 2014). Desert sites had higher soil bulk density values, with an average of 1.59 g cm$^{-3}$, than the oasis sites, with an average of 1.55 g cm$^{-3}$, and farmland sites had the lowest soil bulk density, with an average of 1.32 g cm$^{-3}$.

Vegetation types were investigated, and various characteristics, including the vegetation height, the leaf area index (LAI), and the root depth, were determined on satellite overpass days and then interpolated at the daily time scale for each site. LAI was calculated based on pixel NDVI values derived from the seven acquired images using the empirical function proposed by Jia, Ma, and Yu (2014). The vegetation heights and root depths were estimated based on prior knowledge on phenology and in situ observation data for typical vegetation and crops provided by the Linze Inland River Basin Comprehensive Research Station (Bai et al., 2008; Hu & Lu, 2009; Huang & Guo, 2009; Jiang & Yan, 2008; Li, Mao, & Liu, 2014; Shen, Gao, Fu, & Lu, 2015; Xiao & Huang, 2016; Yin et al., 2012).

Groundwater levels (GWL) and irrigation data were determined based on in situ monitoring. Generally, a GWL gradient existed, with a shallower GWL for an old oasis distributed along a river channel and a deeper GWL in the desert subarea (Li, Mao, & Li, 2017). Flood irrigation was implemented in the oasis subarea with different water amounts for different land cover types and different soil textures. Maize planted along the river channel was irrigated four times with 150 mm of water each time (once a month), whereas the maize planted near the desert subarea was irrigated seven times with 120 mm of water each time (at 15- to 17-day intervals; Li & Shao, 2014). The first irrigation after sowing was conducted during day of year (DOY) 142–148 for all farmland sampling sites. Forest in the oasis margin was irrigated once during May to June with 200–300 mm of water (Shen et al., 2016; Zhang, Shao, & Li, 2017).

Land cover classification was provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn).

### 2.3 Model description
#### 2.3.1 METRIC model

AET was calculated at a daily time step using the METRIC model in two steps. First, the instantaneous AET during a satellite overpass was calculated using the residual surface energy balance method (Allen, Tasumi, & Trezza, 2007) based on pixel-wise estimations of net radiation, soil heat flux, and sensible heat flux:

$$ R_n = G + \lambda E T + H, \quad (1) $$

where $R_n$ is the net radiation flux ($W m^{-2}$); $G$ is the soil heat flux ($W m^{-2}$); and $\lambda E T$ is the latent heat flux ($W m^{-2}$).

Surface parameters, including albedo ($a$), NDVI, surface emissivity ($\varepsilon_0$), and temperature ($T_s$, K), were calculated as follows:

$$ a = \frac{\alpha_{toa} - \alpha_{path\_radiance}}{\tau_{sw}^2}, \quad (2) $$

$$ NDVI = \frac{\rho_4 - \rho_3}{\rho_4 + \rho_3} \quad (3) $$

$$ \varepsilon_0 = \begin{cases} 1.009 + 0.047 \ln(NDVI) & \text{NDVI} > 0 \\ 1 & \text{NDVI} = 0 \end{cases} \quad (4) $$

$$ T_6 = \frac{K_2}{\ln \left( \frac{K_1}{T_s} + 1 \right)}, \quad (5) $$

$$ T_s = \frac{T_6}{\varepsilon_0^{0.25}} \quad (6) $$

where $\alpha_{toa}$ is the albedo at the top of the atmosphere (unadjusted for atmospheric transmissivity) and was computed using the reflectivity values for Bands 1, 2, 3, 4, 5, and 7; $\alpha_{path\_radiance}$ and $\tau_{sw}$ are parameters used for adjusting the albedo value based on transmittance; $\rho_3$ and $\rho_4$ are the reflectivity values of Bands 3 and 4, respectively; $L_6$ is the spectral radiance for Band 6; $T_s$ is surface temperature of a black body (K); and $K_1$ and $K_2$ are constants for Landsat images ($W m^{-2} sr^{-1} \mu m^{-1}$).

The momentum roughness length ($z_{om}$, m) for each image was then calculated using the $\ln(z_{om})$ versus NDVI/a relationship derived from sample pixels representing specific vegetation types.

"Extreme" pixel selection, the key step of the METRIC model, was conducted separately in the oasis subarea and desert subarea. Two different "hot" pixels were used, that is, the pixel with the highest
surface temperature in the oasis and desert subarea, respectively, whereas a common "cold" pixel selected from the well-watered and fully covered farmland was used. The selection method of "extreme" pixels has been proven to be practical for an oasis-desert landscape by Lian and Huang (2015).

Second, instantaneous AET values were scaled up to daily AET. Daily AET on satellite overpass days ($ET_{daily}$) was estimated by extrapolation of instantaneous ET, using the recommended EF method (Equation (7)) for the desert subarea and the ET,F method (Equation (8)) for the oasis subarea (Lian & Huang, 2016). To estimate daily AET on days between satellite overpass intervals ($ET_{daily,p}$), the study period was divided into seven subperiods, in accordance with the acquired image numbers, and then daily AET values were estimated by multiplying daily ET,F calculated using the Penman–Monteith equation (Allen, Pereira, Raes, & Smith, 1998), by the pixel-wise ET,F for that subperiod (Equation (9); Allen et al., 2011).

\[
ET_{daily} = ET_F \times ET_r \times \frac{\lambda ET_{inst}}{ET_{inst} - G_{inst}},
\]

\[
ET_{daily} = ET_F \times ET_r \times \frac{ET_{inst}}{ET_{r,inst}} \times \frac{ET_{inst}}{ET_{r,inst}},
\]

\[
ET_{daily,p} = ET_F \times ET_r \times \frac{ET_{inst}}{ET_{r,inst}},
\]

where the subscripts daily and inst mean parameter values at daily and instantaneous time scales, respectively, and ET,F is the interpolated ET,F value for days between satellite overpass intervals. Three ET,F reconstruction methods, that is, fixed, linear, and cubic spline interpolation methods, were used in this study. The fixed ET,F assumed that the ET,F remained constant in each subperiod, during which one image was acquired. The linear and cubic spline interpolation methods hypothesized that the daily ET,F value was interpolated between two adjacent image acquisition dates. The difference between these two methods was that the slope was discontinuous at the image dates for the former but was continuous for the latter (Singh, Liu, Tieszen, Suyker, & Verma, 2012).

### 2.3.2 HYDRUS-1D simulation

Local-scale daily AET was simulated at all 59 sampling sites in May to October in 2011 by the HYDRUS-1D model (Šimůnek et al., 2016). Water flow and root water uptake processes were taken into account. The water flow in the vadose zone followed the revised Richards equation (Hillel, 1998):

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ \frac{K(h)}{z} \left( \frac{\partial h}{\partial z} + 1 \right) \right] - S,
\]

where $\theta$ is the volumetric water content (L$^3$ L$^{-3}$); $t$ is time (T); $z$ is the vertical coordinate (L, positive downward); $h$ is the pressure head (L); $K(h)$ is the unsaturated hydraulic conductivity (L T$^{-1}$); and $S$ is the root water uptake rate (T$^{-1}$).

Unsaturated hydraulic properties for each soil horizon were characterized by the van Genuchten–Mualem equations, in which five independent parameters of $\theta_0$ (the residual volumetric water content), $\theta_s$ (the saturated volumetric water contents), $\alpha$, $n$, and $K_s$ (the saturated hydraulic conductivity) were first estimated from the measured soil particle size distribution and bulk density using the Rosetta module in HYDRUS-1D. Values of $\theta_0$, $K_s$, $\alpha$, and $n$ were then optimized using the inverse approach (Šimůnek, van Genuchten, & Šejna, 2012). Measured soil water content profiles were used to optimize soil hydraulic parameters, where the deviations between the simulated and measured soil water content were at a minimum.

A root water uptake model (Feddes, Bresler, & Neuman, 1974) was used to simulate actual root uptake rate, which was limited by the potential transpiration rate ($T_p$), by the rate at which soil can supply water to roots, $\alpha(h)$, and by the root distribution function, $\beta(z)$:

\[
S(h) = \alpha(h) \beta(z) T_p.
\]

The parameters of the Feddes function were determined for different vegetation types (Table 2) based on the HYDRUS-1D internal database, the parameters provided by Grinevskii (2011) and the results of a response study of transpiration to water potential for *Haloxylon ammodendron*, *Hedysarum scoparium*, *Populus euphratica*, and *Populus kansuensis* under drying stress (Bai et al., 2008; Li et al., 2015). Root distribution was estimated based on field investigation and the outcomes of previous studies undertaken in this study area (Shen et al., 2015; Yi et al., 2015). The roots of maize were mainly distributed within the depth range of 0–120 cm in the soil. The roots of forest trees and desert shrubs, such as *Haloxylon ammodendron* and *Caragana korshinskii*, reached depths of 400 cm or deeper in the soil, whereas the roots of seasonal herbs in the desert subarea were usually concentrated within the depth range of 0–50 cm in the soil.

Soil water content profiles measured on May 20 (DOY 140), 4 days before the first irrigation after maize sowing, were used as the initial conditions, with a 2-cm space discretization step. Because of the high $K_s$ values, no surface run-off was produced. Atmosphere boundary conditions with the surface layer, considering precipitation, irrigation, and ET, were employed. Rainfall and irrigation data were monitored and recorded at the Linze research station. In HYDRUS-1D, ET, was split into reference transpiration ($T_p$) and reference evaporation ($E_p$) using Beer's Law and LAI (Ritchie, 1972):

\[
E_p = ET_r \times \exp(-\mu LAI),
\]

\[
T_p = ET_r - E_p.
\]

### Table 2 Parameters of the Feddes function for typical types of vegetation

<table>
<thead>
<tr>
<th>Type of vegetation</th>
<th>$h_1$</th>
<th>$h_2$</th>
<th>$h_3$</th>
<th>$h_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>-15</td>
<td>-30</td>
<td>-325</td>
<td>-600</td>
</tr>
<tr>
<td>Polar</td>
<td>-10</td>
<td>-25</td>
<td>-240</td>
<td>-400</td>
</tr>
<tr>
<td>Chinese tamarisk$^b$</td>
<td>-0.1</td>
<td>-2</td>
<td>-80</td>
<td>-250</td>
</tr>
</tbody>
</table>

$^a$ $h_1$, $h_2$, $h_3$, and $h_4$ are threshold parameters in centimetre. The uptake is at the potential rate when the pressure head is between $h_2$ and $h_3$. The uptake rate becomes zero when $h < h_4$ or $h > h_1$.

$^b$ Other desert grassy vegetation use the same set of parameters as Chinese tamarisk.
where \( \mu \) is an empirical parameter related to the vegetation canopy. At the bottom, free drainage was specified for most cases, while a variable pressure head was applied when the GWL was shallow and the interactions between the vadose and aquifer zones were considered.

AET at each sampling site was the sum of soil evaporation and plant transpiration. Soil evaporation was simulated by the given soil moisture conditions, and plant transpiration was the integration of Equation (11) over the root domain.

### 2.4 Assessment strategy

The coefficient of determination \((R^2)\), root mean square error (RMSE), and relative root mean square error (RRMSE) were used to assess the performance of the METRIC-estimated and the HYDRUS-1D-simulated AET values. The statistics RMSE and RRMSE are defined as follows:

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (ET_{RS,i} - ET_{Hyd,i})^2}
\]

\[
RRMSE = \frac{RMSE}{\frac{1}{N} \sum_{i=1}^{N} ET_{Hyd,i}}
\]

where \( ET_{RS,i} \) is the AET estimated using METRIC for the \( i \)th day, and \( ET_{Hyd,i} \) is the HYDRUS-1D AET estimate for the \( i \)th day.

### 3 RESULTS

#### 3.1 Calibration of the hydrological models

To calibrate the HYDRUS-1D models, soil moisture content profiles measured on DOY 141 were set as the initial condition, whereas measured soil moisture profiles on DOY 171, 201, 232, 263, and 293 were used to optimize the van Genuchten–Mualem parameters for each sampling site. Because maize roots are mainly distributed in the 0–1.2 m zone, the HYDRUS-1D model was implemented in the 0–2 m soil profile for farmland sites, with 0–3 m soil water profiles simulated for the other sampling sites due to deep root distribution. Results of the inverse solutions indicated good agreement between simulated and measured soil moisture contents. For the 59 sampling sites, \( R^2 \) values ranged from 0.45 to 0.98, with a mean value of 0.75. RMSE values varied from 0.008 cm\(^3\) cm\(^{-3}\) to 0.076 cm\(^3\) cm\(^{-3}\), corresponding to RRMSE values varying from 7.3% to 33.7% (Figure 2). High \( R^2 \) values and low RMSE (RRMSE) values suggested HYDRUS-1D models could reasonably simulate vertical water flow and AET for the 59 sampling sites. In addition, there was no significant difference among the \( R^2 \) values for sites located in the oasis subarea and the desert subarea, with mean values of 0.73 and 0.76, respectively. The oasis sampling sites had larger RMSE values (a mean value of 0.040 cm\(^3\) cm\(^{-3}\)) than the desert sampling sites (a mean value of 0.021 cm\(^3\) cm\(^{-3}\)), whereas the RRMSE had the opposite trend, with mean values of 16.6% and 23.2%, respectively.

Dynamics of the soil moisture profiles varied for different land cover types (Figure 3), which were primarily related to precipitation, irrigation, ET, and exchange with groundwater. The highest soil moisture content variability occurred at the farmland sampling site, and the
variation decreased with depth. Soil moisture content ranged from 0.068 to 0.331 cm³ cm⁻³ in the 0–100 cm layer and from 0.314 to 0.441 cm³ cm⁻³ in the 100–200 cm layer (Figure 3a). For forest, both the soil moisture content and its variability were quite low for the 0–150 cm layer (Figure 3b), with high water moisture contents for the 150–300 cm layer attributed to groundwater recharge. Soil moisture content varied from 0.013 to 0.149 cm³ cm⁻³ for the desert sampling site. High soil moisture variability was present in the 0–30 cm layer on DOY 232, which was attributable to the continuous rainy days during DOY 222–229.

3.2 | Assessment of AET temporal dynamics estimated using HYDRUS-1D and METRIC models

Daily AET values from June to August simulated using the HYDRUS-1D models were used to assess the effectiveness of the METRIC model in different soil water conditions and vegetation coverages. The METRIC AET values were extracted from pixels corresponding to the sampling sites, with 120-m resolution in accordance with the thermal infrared band of the Landsat TM. On satellite overpass days, comparisons of the METRIC AET and HYDRUS-1D AET showed good correlations for farmland and forest sampling sites, with $R^2$ values of 0.55 and 0.50, respectively (Figure 4a,b). Low correlation ($R^2 = 0.14$) was obtained in desert sampling sites, where HYDRUS-1D produced a larger range of AET values than the METRIC energy balance model (Figure 4c).

Comparisons of daily AET temporal dynamics during June to August were conducted in both the oasis subarea and desert subarea. For the oasis subarea, METRIC daily AET correlated well with values simulated using the HYDRUS-1D model. Mean $R^2$ values were 0.77, 0.80, and 0.80 for the fixed, linear, and cubic spline interpolation methods, respectively (Table 3). There was no statistical difference

![Figure 3](image1.png)

**FIGURE 3** Simulated and measured soil moisture profiles at three sampling sites for different land covers types on DOY 171, 201, 232, 263, and 293. The HYDRUS-1D simulated soil water profiles are shown with line graph, and the neutron probe measured soil water profiles are shown with scatter graph

![Figure 4](image2.png)

**FIGURE 4** Comparisons of HYDRUS-1D simulated AET and METRIC estimated AET on satellite overpassing days for (a) farmland sampling sites, (b) forest sampling sites, and (c) desert sampling sites. AET = actual evapotranspiration; METRIC = mapping evapotranspiration at high resolution with internalized calibration

<table>
<thead>
<tr>
<th>Land cover Items</th>
<th>Fixed ETrF</th>
<th>Linear Interpolated ETrF</th>
<th>Cubic spline ETrF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmland (N = 26)</td>
<td>Minimum 0.542, Maximum 0.945, Mean 0.832</td>
<td>Minimum 0.581, Maximum 0.960, Mean 0.865</td>
<td>Minimum 0.567, Maximum 0.955, Mean 0.854</td>
</tr>
<tr>
<td>Forest (N = 5)</td>
<td>Minimum 0.265, Maximum 0.769, Mean 0.483</td>
<td>Minimum 0.303, Maximum 0.814, Mean 0.514</td>
<td>Minimum 0.325, Maximum 0.778, Mean 0.526</td>
</tr>
<tr>
<td>All (N = 31)</td>
<td>Minimum 0.265, Maximum 0.945, Mean 0.769</td>
<td>Minimum 0.303, Maximum 0.960, Mean 0.801</td>
<td>Minimum 0.325, Maximum 0.955, Mean 0.796</td>
</tr>
</tbody>
</table>

Note. AET = actual evapotranspiration; ETrF = referenced ET fraction.

![Table 3](image3.png)

**TABLE 3** Statistics of coefficient of determination values ($R^2$) between HYDRUS-1D simulated AET and remote sensing-based AET using three ETrF reconstruction methods (fixed, linear, and cubic spline interpolations) in the oasis subarea
among the outputs of these three ET$_F$ reconstruction methods, although the $R^2$ values for the latter two methods were slightly higher than that for the former method. Furthermore, relatively high $R^2$ values ranging from 0.54 to 0.96 were obtained for the farmland sampling sites (26 of the 31 sites), with mean $R^2$ values of 0.83, 0.86, and 0.85 for the three ET$_F$ reconstruction methods; and relatively low $R^2$ values were obtained for the forest sampling sites (5 of the 31 sites), with mean $R^2$ values ranging from 0.48 to 0.53. In the desert subarea, no correlation was obtained between the daily AET values from the METRIC and HYDRUS-1D models, with all $R^2$ values less than 0.1 for all 28 desert sampling sites using the three ET$_F$ reconstruction methods (not illustrated in tables).

To analyse the temporal dynamics of daily AET values for different land cover types, the comparison results for three typical sampling sites where relatively good correlations between METRIC AET and HYDRUS-1D AET were obtained are illustrated in Figure 5. For the farmland sampling site, the METRIC daily AET ranged from 0.90 mm on DOY 226 to 7.03 mm on DOY 196, and the HYDRUS-1D AET varied from 0.68 mm on DOY 226 to 7.41 mm on DOY 199. Good correlation was obtained during this period (June to August), with $R^2$ and RMSE values of 0.89 and 0.51 mm $d^{-1}$, respectively (Figure 5a).

For the forest sampling site, the HYDRUS-1D daily AET was larger than the METRIC daily AET overall, with mean values of 4.98 mm and 4.57 mm, respectively. The HYDRUS-1D daily AET increased markedly the day after rain or on days when weak precipitation (2 mm or less) was observed (Figure 5b). Specifically, the HYDRUS-1D AET values remained high (above 6.0 mm) during DOY 168–180, except for DOY 171 and 174. These high values were caused by flood irrigation of approximately 250 mm of water on DOY 168 following continuous rainfall events during this period, which totalled 17.6 mm of precipitation (precipitation total of 86.4 mm in June to August). Furthermore, the METRIC daily AET values on DOY 168–180 were estimated based on the calculated ET$_F$ maps on DOY 165, when forest irrigation had not been implemented and the relative extractable water was low before irrigation (Shen, Gao, Fu, & Lu, 2014).

When comparing simulated and estimated daily AET values for the desert sampling sites, no correlation was found. HYDRUS-1D AET increased when rainfall events occurred, with a maximum AET of 4.29 mm, or remained low at less than 1.50 mm, with a mean value of 1.28 mm. METRIC AET varied from 0.22 to 2.29 mm and averaged 1.48 mm.

### 3.3 Comparison of monthly AET values estimated using HYDRUS-1D and METRIC

Pixel-wise comparison of HYDRUS-1D and METRIC monthly AET from June to August and summer AET for the 59 sampling sites are shown in Figure 6. Good correlations were obtained for each month, with $R^2$ values from 0.92 to 0.95 (Figure 6a–c), for summer AET, with an $R^2$ of 0.96 (Figure 6d). RMSE (RRMSE) values were 11.60 (15.1%), 17.50 (12.1%), and 10.36 mm (12.3) for June, July, and August, respectively. Better agreements were found for the summer AET comparison, with RMSE and RRMSE values of 31.18 mm and 10.0%.

In-depth analysis demonstrated that more scatter occurred in the low AET range than in the high. Comparisons of the summer AET estimated by METRIC with those simulated by HYDRUS-1D and the associated statistics are illustrated in Figure 7 and Table 4. For the desert subarea, the METRIC summer AET ranged from 90.1 to 371.4 mm, with

- **FIGURE 5** Daily AET trends from June to August for (a) the farmland sampling site, (b) the forest sampling site, and (c) the desert sampling site. The vertical dot lines show the satellite overpass days. DOY = day of year; METRIC = mapping evapotranspiration at high resolution with internalized calibration.
FIGURE 6  Comparisons of monthly AET estimated by METRIC with those simulated by HYDRUS-1D in (a) June, (b) July, and (c) August; and (d) from June to August. AET = actual evapotranspiration; METRIC = mapping evapotranspiration at high resolution with internalized calibration; RMSE = root mean square error

FIGURE 7  Summer AET estimated by METRIC and their absolute errors (a) and relative errors (b) compared to those simulated by HYDRUS-1D. AET = actual evapotranspiration
a mean of 178.9 mm and a standard deviation of 66.7 mm, whereas the HYDRUS-1D summer AET varied from 102.1 to 356.9 mm, with a mean and standard deviation of 162.4 and 58.3 mm, respectively. The correlation analysis showed a RMSE of 40.83 mm and a RRMSE of 25.1%. For the oasis subarea, good correlation was obtained for the METRIC AET and HYDRUS-1D AET, with a RMSE of 23.70 mm and a RRMSE of 5.3%, although the AET values of the former were slightly larger than those of the latter, with mean values of 476.6 and 447.5 mm, respectively.

These results indicate that despite the low capability of describing daily AET temporal patterns for forest and desert sites, reasonable monthly AET estimates could be obtained using METRIC and a limited number of images.

4 | DISCUSSION

4.1 | HYDRUS-1D AET estimates for different land cover types

The HYDRUS-1D model has commonly been used to simulate vadose zone water transfer in the arid Heihe River Basin, to guide irrigation decisions for maize and wheat fields (Li, Kinzelbach, Zhou, Cheng, & Li, 2012; Zhou et al., 2012), and to assess *Populus euphratica* and Chinese *tamarisk* water consumptions (Li et al., 2015; Zhu et al., 2009). Good agreement was obtained between simulated soil moisture and respective field neutron probe measurements, which indicated that the HYDRUS-1D model can be used. No significant differences were reported between the oasis subarea and the desert subarea, with average $R^2$ values of 0.73 and 0.76, respectively.

Additionally, Galleguillos, Jacob, Prevot, French et al. (2011), Galleguillos, Jacob, Prevot, Lagacherie, et al. (2011) claimed HYDRUS-1D could provide continuous daily AET simulations calibrated with weekly, biweekly, or monthly soil profiles. The spatial-temporal variability of soil moisture in an oasis-desert transition area in the Heihe River Basin showed that the spatial pattern of soil moisture was temporally stable and that different observation frequencies (5-day and 30-day intervals) showed similar characteristics of temporal stability for soil moisture (Shen et al., 2016). In addition, soil moisture products derived from different methods (in situ measurements, passive microwave remote sensing, MODIS (Moderate Resolution Imaging Spectroradiometer) soil moisture estimates, and soil water balance models) were highly correlated with each other (Gan & Gao, 2015). Therefore, spatially intensive in situ soil moisture measurements make it possible to calibrate site-specific HYDRUS-1D models, which could be used to validate the remotely sensed daily AET at a large number of sites with various soil water conditions and vegetation types.

Because vegetation distribution in the region is heterogeneous, especially in the desert subarea, where shrubs are found on fixed and semifixed dunes with some annual herb species (Zhao & Liu, 2010), site-specific LAI measurements are labour intensive and rarely conducted. In this study, LAI values were calculated using the NDVI of the corresponding pixel in acquired images, and then daily LAI series were interpolated. As Landsat-derived NDVI values describe the effective pixel-average surface vegetation cover (Van de Griend & Owe, 1993) and are strongly dependent on the spatial scale (Jiang et al., 2006), other vegetation properties, such as root depth and parameters for the root water uptake function, were determined according to the integrated information of vegetation types contained in a pixel, rather than the species-specific parameters. As a result, the HYDRUS-1D models produced pixel-average AET estimates in this study.

4.2 | Remotely sensed estimation of daily AET

Although no synchronous AET observations were available in the region, we considered that METRIC-provided accurate AET estimates in this region, where the outputs of METRIC had been validated at instantaneous and daily time scales using the satellite overpass time in our former studies (Lian & Huang, 2015, 2016). In addition, the relatively high $R^2$ and low RMSE and RRMSE values of monthly AET derived using METRIC and HYDRUS-1D in Section 3.3 also suggested that reasonable AET estimates were achieved.

For the daily AET series, three ET,F reconstruction methods (fixed, linear, and cubic spline interpolation) were used, and the results demonstrated there were no statistical differences among the outputs of the three methods (Table 3). Singh et al. (2012) also claimed that similar seasonal AET estimates were obtained using the three interpolation methods. As for different land cover types, the remotely sensed daily AET estimates showed different performances. For farmland, estimated daily AET matched well with the HYDRUS-1D daily AET for both trends and magnitudes (Figure 5a), demonstrating that the remotely sensed ET,F interpolation method could be used to provide daily AET series during the summer period in irrigated farmlands, even though precipitation and irrigation were not considered directly in the METRIC model process. For the forests distributed in the oasis subarea, moderate agreement was obtained for the daily AET series estimated using remote sensing methods and HYDRUS-1D, because remotely sensed AET estimates did not capture the increasing trends of AET, especially the increased evaporation, resulting from precipitation and irrigation events occurring between Landsat image dates (Allen et al., 2011; Shen et al., 2014). For the desert subarea, remotely sensed daily AET series were considered to be speculative, even for the AET estimates on satellite overpass days (Figure 4c). Yang and Zhou (2011) investigated the seasonal dynamic of AET over a temperate desert steppe using the EC devices, and their results showed that crop coefficients (calculated as

### TABLE 4

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Method</th>
<th>HYDRUS-1D AET (mm)</th>
<th>METRIC AET (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oasis (N = 31)</td>
<td>Minimum</td>
<td>376.73</td>
<td>408.63</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>520.28</td>
<td>533.53</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>447.51</td>
<td>476.55</td>
</tr>
<tr>
<td></td>
<td>Std.</td>
<td>32.54</td>
<td>37.53</td>
</tr>
<tr>
<td>Desert (N = 28)</td>
<td>Minimum</td>
<td>102.10</td>
<td>90.05</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>356.89</td>
<td>371.39</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>162.44</td>
<td>178.89</td>
</tr>
<tr>
<td></td>
<td>Std.</td>
<td>58.27</td>
<td>66.66</td>
</tr>
</tbody>
</table>

Note. AET = actual evapotranspiration; ET = evapotranspiration; METRIC = mapping evapotranspiration at high resolution with internalized calibration.
the ratio of AET to ET, had obvious day-to-day variabilities, which were strongly correlated to precipitation and soil moisture. Therefore, the accuracies of remote sensing-based AET estimates for desert areas cannot be increased by just improving the temporal resolution of the satellite images, and the integrated use of remotely sensed data and in situ soil moisture measurements with AET estimation models is recommended to obtain daily AET series (Campos, Gonzalez-Piqueras, Carrara, Villodre, & Calera, 2016; Crow et al., 2008; Di et al., 2015).

5 | CONCLUSIONS

The HYDRUS-1D model and measurements of soil moisture profiles provided the opportunity to assess the temporal dynamics of remotely sensed daily AET under different soil water conditions and vegetation coversages. Reasonable daily AET estimates could be achieved based on periodic snapshots from Landsat images for areas where soil moisture remained at a relatively high level (the irrigated farmlands in this study). For areas where the soil moisture was low (the desert subarea in this study), the ET,F values show high day-to-day variability, and the remotely sensed ET,F products from Landsat images could not capture the sharp increase in evaporation after rainfall. In the future, the assimilation of in situ soil moisture measurements and remote sensing-based surface parameters into AET estimation models would be helpful for producing reasonable daily AET estimates for various soil water conditions and vegetation coversages.

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