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TECHNICAL NOTE

Evaluation of different methods for gap filling of long-term actual evapotranspiration time series measured by lysimeters

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Abstract

Terrestrial evapotranspiration (ET) is the second largest water flux in the global water cycle. It can be measured with different techniques; weighable lysimeters can provide very accurate measurements, and some very long-term time series exist. However, these lysimeter time series are affected by data gaps that must be filled to estimate actual ET totals and long-term trends. In this paper, we explore four different gap-filling methods: the potential ET-method, the ratio method, the FAO-based water balance method, and HYDRUS modeling. These gap-filling methods were evaluated for three time series of actual ET measured by lysimeters and meteorological data of three European sites. Separate evaluations were made for the five driest and five wettest April–October periods to investigate whether the performance of the gap-filling methods was affected by hydrological conditions. Series of random gaps were artificially created for the three time series, including gaps of four different lengths. Actual ET was estimated for these gaps with the gap-filling methods, which were evaluated based on RMSE and mean bias error. The results show that the ratio method outperformed other methods for gap filling of lysimeter data for Basel (Switzerland), whereas the HYDRUS method outperformed other methods for Rheindahlen (Germany). For Rietholzbach (Switzerland), the different methods performed very similarly, except that the FAO method gives slightly larger RMSEs. The gap-filling methods do not perform very differently for dry and wet conditions. The ratio method is recommended for filling smaller gaps, and the HYDRUS method is recommended for longer gaps of 30 d.

1 | INTRODUCTION

Terrestrial evapotranspiration (ET) is the water transferred from the land surface to the atmosphere. This water exchange usually involves a phase change from liquid (or ice) to gas, and the needed energy for this transition is mainly supplied by incoming short-wave radiation (Brutsaert, 2005). If incoming short-wave radiation is used for ET and not for heating the air (sensible heat flux), it has a cooling impact on the land surface (Wang & Dickinson, 2012). In terms of global net water fluxes, ET is the second largest flux of the hydrologic cycle

Abbreviations: EC, eddy covariance; ET, evapotranspiration; MBE, mean bias error.

after precipitation and supposes a major component of water loss from water bodies like rivers, lakes, and reservoirs. In general, roughly 60–65% of the mean precipitation evaporates over the land surface (Brutsaert, 2005). Evapotranspiration determines which part of the precipitation is left to recharge groundwater, which plays an important role in drinking water supply and irrigation.

Actual ET is the transfer rate of water from soil and plants to the atmosphere, whereas potential ET is the theoretical maximum possible transfer rate for conditions without water shortage. Accurate assessment of spatiotemporal variability of actual ET is important for water resources management (Matin & Bourque, 2013), especially with reference to changes in drought frequency and intensity. It is also important for agricultural practice, like irrigation scheduling. Accurate estimation of spatiotemporal variability of actual ET trends can be helpful for understanding the interaction and feedback between atmospheric and land surface hydrologic processes in various natural and human-affected environments (Wu, Hu, Huang, & Zhang, 2017). Better constraining land ET in 21st century climate scenarios is critical for better prediction of heat waves and droughts, evaluating impacts of climate change on ecosystems and water resources, and designing adaptation policies (Douville, Ribes, Decharme, Alkama, & Sheffield, 2013; Seneviratne, Lüthi, Litschi, & Schär, 2006). The temporal variations in actual ET are the result of the interactions among meteorological, hydrological, and other factors, which makes it challenging to predict actual ET. The drivers of change in ET are widely debated, and sparsity of high-quality long-term data contributes to the uncertainty in the long-term ET trend. There have been intensive investigations on the driving mechanisms for changes in actual ET including model and water budget studies (Duethmann & Blöschl, 2018), albeit the sign and size of long-term trends could not yet be confirmed by direct measurements (Hegerl et al., 2018; Huntington, 2006; Ohmura & Wild, 2002). Düthmann and Blöschl (2018) argued that the increase of actual ET observed over a large number of catchments in Austria over the last 40 yr is caused by an increase in potential ET, an increase in precipitation, and also, to a lesser extent, the longer duration of the growing season (Duethmann & Blöschl, 2018). Jung et al. (2010) found that in the period 1998–2008, global terrestrial ET declined in relation to reduced soil moisture supply in this period (Jung et al., 2010). Miralles et al. (2013) pointed out that the reduced soil moisture supply can be explained by the particular strong El Nino event around 1998 (Miralles et al., 2013).

Actual ET can be measured by various techniques like the eddy covariance (EC) method (Williams et al., 2004; Wilson, Hanson, Mulholland, Baldocchi, & Wullschleger, 2001), the Bowen ratio method (Angus & Watts, 1984; Markwitz, Knohl, & Siebicke, 2017), and the lysimeter method (Holmes, 1984; Scanlon, Tyler, & Wierenga, 1997; Xu & Chen, 2005).

Core Ideas

- It is necessary to fill actual ET gaps in order to estimate lysimeter-measured actual ET totals.
- Four methods are compared for gap-filling actual ET time series measured by lysimeters.
- It is recommended to fill smaller gaps with the ratio method and longer ones with the HYDRUS model.

The EC method has become a widespread method to measure ET in the past 25 yr. However, the EC method is generally affected by systematic errors related to the energy balance closure problem (Franssen, Stöckli, Lehner, Rotenberg, & Seneviratne, 2010; Wilson et al., 2001). In addition, EC-based ET measurements are strongly affected by random errors (Foken, 2008; Foken, Wimmer, Mauder, Thomas, & Liebethal, 2006; Franssen et al., 2010; Hollinger & Richardson, 2005; Kessomkiat, Franssen, Graf, & Vereecken, 2013; Post, Hendricks Franssen, Graf, Schmidt, & Vereecken, 2015; Richardson et al., 2006). The Bowen ratio method, in general, is cheaper, and less maintenance is needed compared with the EC method, but it only performs well for short vegetation and does not perform well for very stable or very unstable conditions (Wang & Dickinson, 2012).

Lysimeters give potentially more accurate information on actual ET but have a disadvantage in that they provide only local information and their installation is very costly. Lysimeter time series are, in some cases, longer than EC time series (exceeding 50 yr in the case of the non-weighing lysimeters of Castricum in the Netherlands and St. Arnold in Germany, or exceeding 40 yr for the weighable lysimeter of Rietholzbach, which has been in continuous operation since 1976), which was a main motivation to explore these longer time series with a primary aim to estimate long-term trends in actual ET from the lysimeter data. Most of the existing long-term lysimeter time series have not yet been explored. Therefore, estimating long-term actual ET with lysimeter data is of great interest.

Construction of complete long-term time series consists of several steps, including data acquisition, adequate maintenance, and data storage. If any of those steps is compromised by insufficient data quality, data gaps could result. The most challenging step is data acquisition, which can be affected by animal disturbance, instrument failure, measurement limitations, or adverse meteorological conditions. In order to estimate long-term trends in actual ET with help of lysimeters, it is necessary to develop a suitable method to construct complete ET time series without gaps. A number of gap-filling models for EC-related ET were proposed in publications (Alavi, Warland, & Berg, 2006; Chen, Chu, & Li, 2012; Falge et al., 2001; Moffat et al., 2007). Falge et al. (2001) investigated two gap-filling methods for filling missing EC-related fluxes and they found that look-up tables provide the best strategy. Alavi et al. (2006) and Moffat et al. (2007) evaluated more complex techniques to fill artificial latent and sensible heat fluxes. The Kalman filtering approach resulted in improved ET estimation for both small and large gaps, which is applied to fill gaps in the research of Alavi et al. (2006). Moffat et al. (2007) generated artificial gaps of 50 different lengths and evaluated 15 techniques to estimate missing values. The gap filling will introduce uncertainty to yearly ET values so that the evaluation of different gap-filling methods is important in the context of estimating ET trends. Concerning lysimeter-measured ET, the scientific literature provides no conclusive strategy to fill gaps.

In this paper, different gap-filling methods are proposed and compared for three different lysimeters (Rietholzbach, Switzerland; Rheindahlen, Germany; and Basel-Binningen, Switzerland), with long time series of recorded actual ET. The gap-filling methods which are evaluated are the potential ET method (Allen, Pereira, Raes, & Smith, 1998), a ratio method that uses the ratio of actual ET/potential ET estimated before and after measurement gaps, the FAO-related water balance method (Allen et al., 1998), and one-dimensional HYDRUS modeling (Šimůnek, Šejna, Saito, Sakai, & van Genuchten, 2008; Šimůnek, van Genuchten, & Sejna, 2005; Šimunek, van Genuchten, & Šejna, 2012, 2016; Sutanto, Wenninger, Coenders-Gerrits, & Uhlenbrook, 2012). The performance of the different gap-filling methods is evaluated by creating artificial data gaps of different lengths in the time series and comparing the estimated actual ET for these data gaps with the measured actual ET. It is also analyzed whether gap-filling methods perform better or worse under wet or dry conditions. Therefore, separate analyses are made for the five wettest and the five driest April–October periods. We can expect that the different methods perform differently under those conditions because, for example, the potential ET method is not expected to give accurate results under water-limited conditions.

2 | MATERIALS AND METHODS

2.1 | Lysimeter sites

Gap filling was tested for three different actual ET time series measured by lysimeters. The time series are from Rietholzbach (Switzerland), Rheindahlen (Germany), and Basel-Binningen (Switzerland) (see also Figure 1). At these sites, not only lysimeter but also meteorological data were recorded.

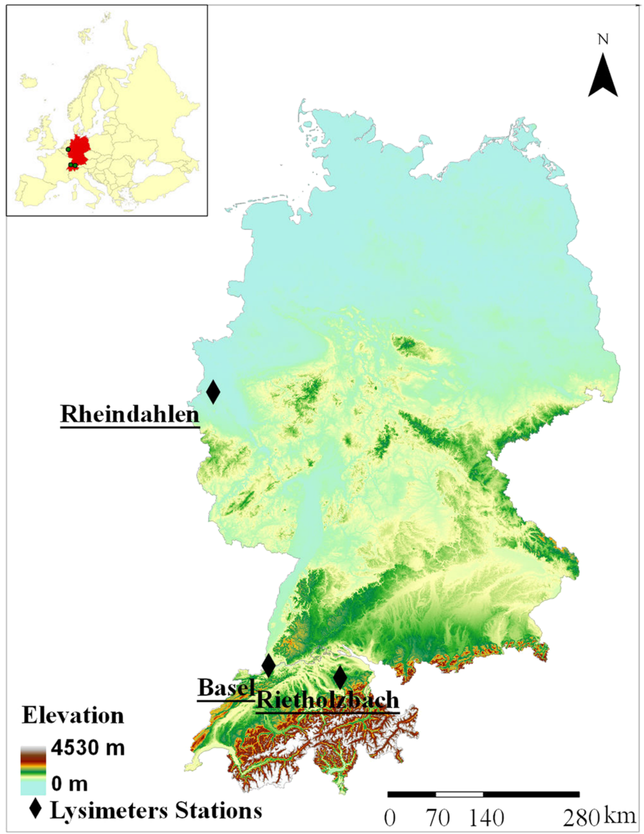

FIGURE 1 Location of the three lysimeter measurement sites (data downloaded from USGS [https://www.usgs.gov/] and the Database of Global Administrative Areas [GADM, https://gadm.org/])

Figure 2 shows time series of average yearly precipitation, temperature, potential ET, and dry index for the three sites. The dry index (Di, mm) is defined as

$$\mathrm{Di} = P - \mathrm{ETa} \tag{1}$$

where P is precipitation (mm) and ETa is actual ET (mm).

All three lysimeter sites are humid, especially Rietholzbach with an average yearly precipitation > 1,400 mm. The temperature shows an upward trend at all three locations, with Rietholzbach obviously colder than the other two locations. Similarly, the atmospheric demand increased over the measurement periods for the three locations, with the strongest increase in potential ET for Basel (see also Figure 2d). The year 2003 appears especially dry for the lysimeters in Basel and Rietholzbach, but this dryness was less pronounced for Rheindahlen.

In order to examine changes of the vegetation cycles, the normalized difference vegetation index (NDVI) based on satellite data has been used in this study. Figure 3 shows the seasonal variations of precipitation, actual ET, potential ET, temperature, and NDVI. Actual ET, potential ET, temperature, and NDVI show similar patterns, with maximum values in summer and minimum values in winter. Potential

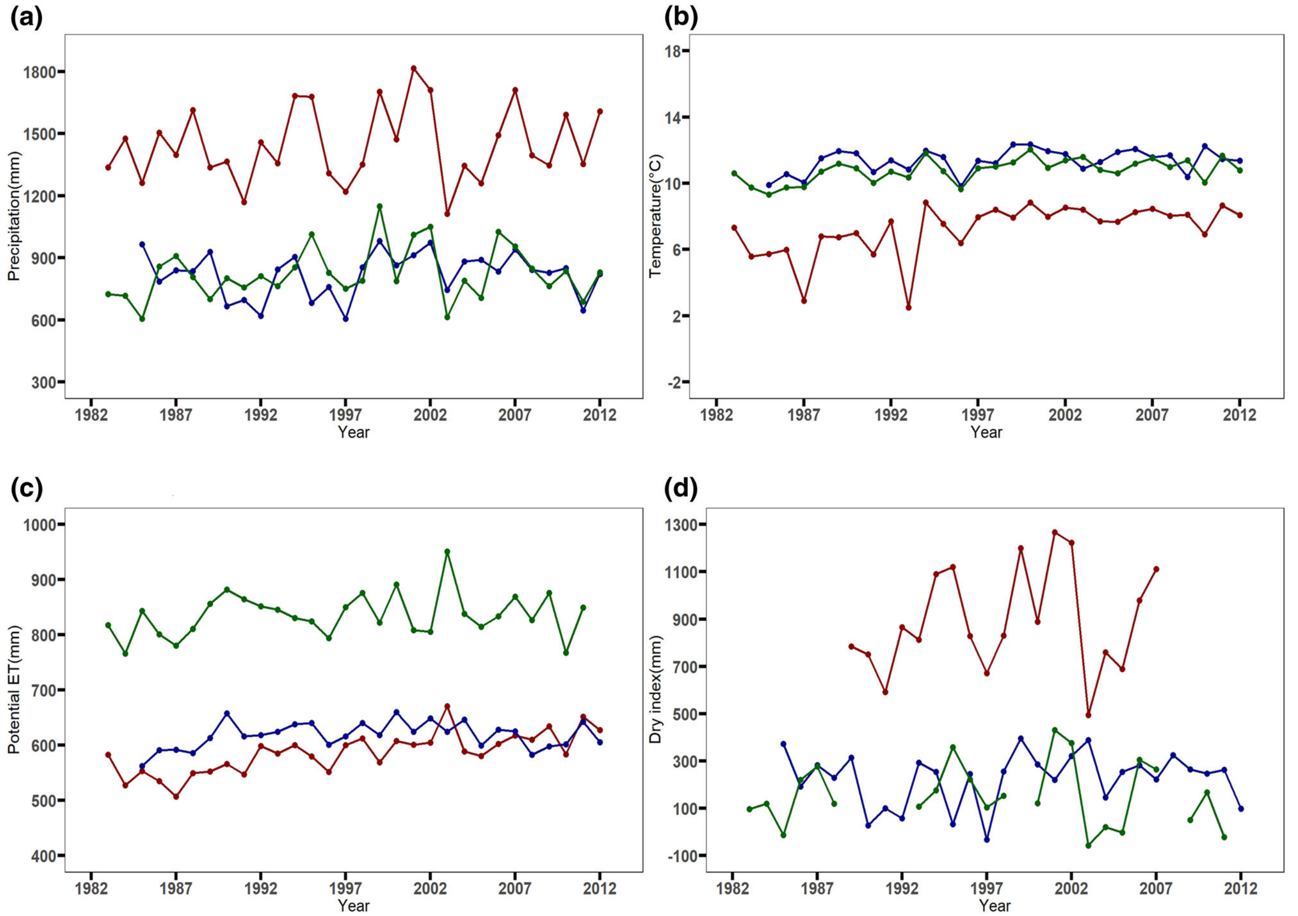

FIGURE 2 Recorded time series of (a) yearly precipitation amount (mm), (b) average temperature (°C), (c) average potential evapotranspiration (ET, mm), and (d) dry index (mm) at the three lysimeter sites in Rietholzbach (red), Rheindahlen (blue), and Basel (green)

ET is higher in Basel than at the other two sites, which is related to higher incoming radiation and air temperature at this site than, for example, at Rietholzbach, which is the coldest site.

For the Rheindalen lysimeters, actual ET was relatively high in winter (compared with Rietholzbach and Basel), which might be related to the higher winter temperatures at this site. On the contrary, summer actual ET was lower at this site than at Rietholzbach and Basel. This can be explained by lower precipitation in summer at Rheindahlen than at Basel and Rietholzbach. We can see that the growing season spans the time period from March or April until October for these lysimeter sites, which means that from spring to autumn the grass on the lysimeters usually grew, whereas in winter there was no or limited grass growth.

2.1.1 | Rietholzbach

The Rietholzbach catchment is a small watershed in northeastern Switzerland (see also Figure 1) and has altitudes ranging between 682 and 950 m asl, covered mainly with grass, but 26% of the land cover is forest. The soil types in the catchment are Cambisol and Gleysol (40.7 and 23.9%, respectively). In 1976, a hydrological and micrometeorological measurement site was installed in the catchment, including a weighing lysimeter.

The Rietholzbach lysimeter, situated at 755 m asl (47.38° N, 8.99° E), has a diameter of 2 m and depth of 2.5 m, which can be classified as a large lysimeter, and is covered by grass (Seneviratne et al., 2012). The lysimeter measures with a resolution of 0.032 mm, which provides highly accurate measurements (Hirschi, Michel, Lehner, & Seneviratne, 2017). The lysimeter is filled with Gleyic Cambisol from surface to 2-m depth and with gravel from 2- to 2.5-m depth, in order to collect seepage water.

Both weight change and drainage are recorded by the weighable lysimeters. Precipitation is obtained from a tipping bucket, and other meteorological variables are recorded by instruments as detailed in Table 1.

Most of the data that are needed for the different gap-filling methods were measured since 1976. However, incoming

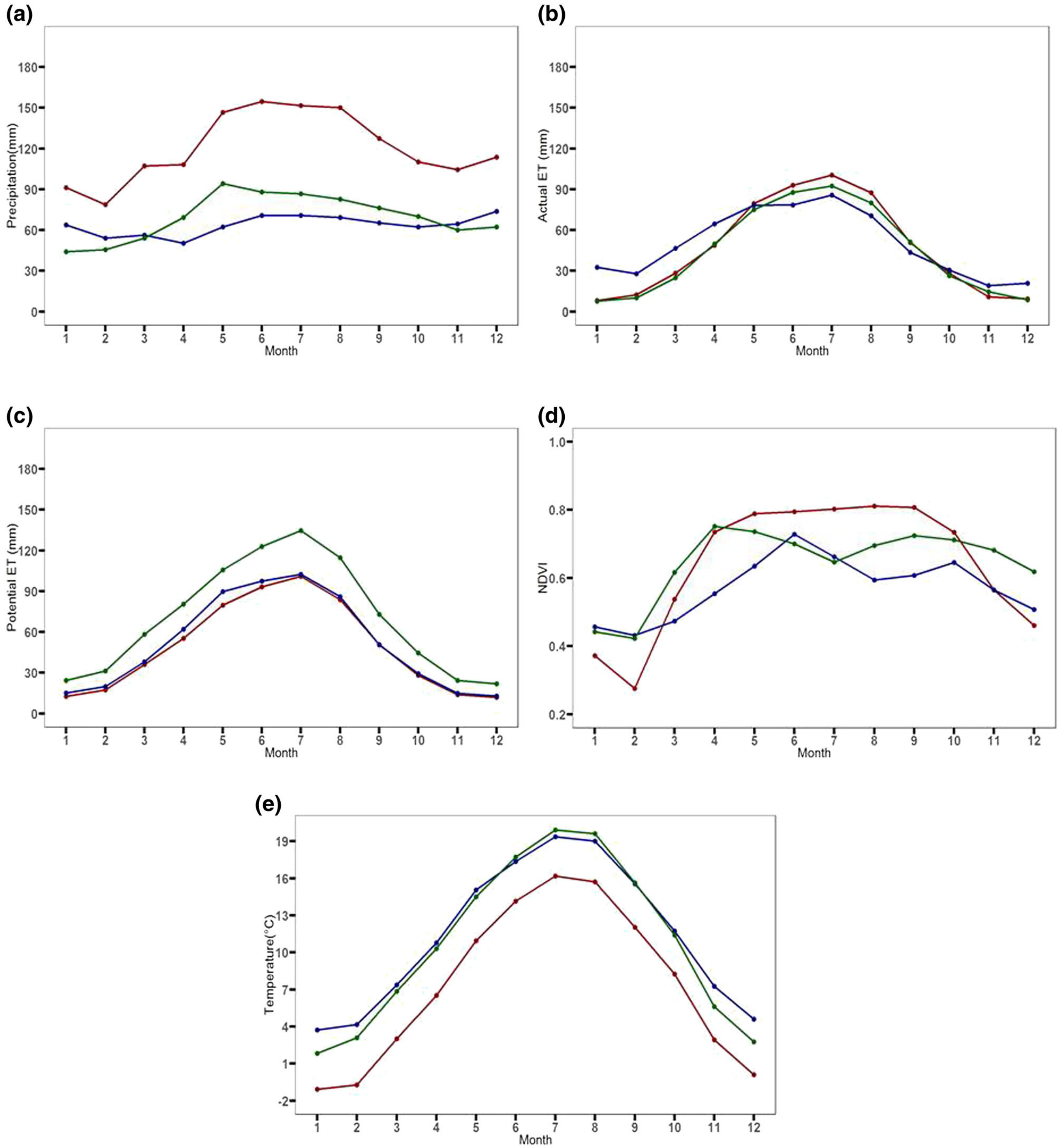

FIGURE 3 Recorded annual cycle of (a) precipitation amount (mm), (b) average actual evapotranspiration (ET, mm), (c) average potential ET (mm), (d) normalized difference vegetation index (NDVI), and (e) temperature (°C) at the three lysimeter sites in Rietholzbach (red), Rheindahlen (blue), and Basel (green)

short-wave radiation was measured only since 1989, and the wind speed was not available after 2007. For the period 1981–1988, incoming short-wave radiation was estimated on the basis of a regression analysis between Rietholzbach and its neighboring station Tänikon (operated by MeteoSwiss). These data were needed for calculating potential ET, which is input for several of the gap-filling methods. Therefore, the time series, which has been used for testing gap-filling methods in Rietholzbach, is 27 yr long (1981–2007). As Table 2 shows, there were only small gaps in the lysimeter time series of Rietholzbach. The maximum gap was 4 d, and most gaps were just 1 d.

TABLE 1 Instruments and soil types in study sites

Parameter	Rietholzbach	Rheindahlen	Basel
Lysimeter	Weighable	Weighable	Weighable
Drainage	Weighing lysimeter	Weighing lysimeter	Tipping bucket
Precipitation	Tipping bucket	Tipping bucket	Tipping bucket
Air temperature	Thygan VTB6	Platinum resistance thermometer	Thygan
Relative humidity	Thygan VTB6	Aspiration psychrometer	Thygan
Wind speed	Cup anemometer	Cup anemometer	Cup anemometer
Solar radiation	Thermopile	Sternpyranometer	Pyranometer
Soil type	Gleyic Cambisol	Luvisol	Luvisol

TABLE 2 Frequency distribution of the gaps for the three lysimeters

Gap size	Rietholzbach	Rheindahlen	Basel
d			
1	111	38	154
2	29	18	51
3	13	11	17
4	4	4	10
5–9	0	6	13
10–29	0	4	9
>29	0	2	7

2.1.2 | Rheindahlen

The measurement site Rheindahlen (51.18° N, 6.43° E) is located in Germany in the state of North Rhine-Westphalia near the city of Mönchengladbach and run by the Stadtwerke Mönchengladbach (see also Figure 1).

A weighable lysimeter station covered with grass and a completely automatic weather station, which registers precipitation, air temperature, relative humidity, wind speed, and air pressure, is installed at the site and has been operational since 1983. The four lysimeters in Rheindalen have a surface of 1 m^2 and depths of 1 or 2 m and are filled with a Luvisol soil. Precipitation is measured by tipping buckets, and seepage water is collected from the drainage of the lysimeters. More details can be found in Table 1.

The period investigated for gap filling was from 1985 to 2011, as the years 1983 and 1984 were not included to calculate ET with one-dimensional HYDRUS modeling, and data after 2011 were not available when this study was carried out. We can see the distribution of the gaps in Table 2; there are only two large gaps, and most gaps are just 1 d.

2.1.3 | Basel

Basel is located in northwestern Switzerland (47.33° N, 7.35° E), and the elevation of the lysimeter station is 316 m asl. The lysimeter is run by the University of Basel and located next to the meteorological station Basel-Binningen, run by the Swiss Meteorological Service.

The lysimeter has a surface of 3.07 m^2 and depth of 2 m, is filled with a Luvisol soil, is grass covered, and has a measurement resolution of 1 kg corresponding to a resolution of 0.326-mm water column. Seepage water is collected and measured with a tipping bucket, and precipitation is measured by a tipping bucket. Table 1 gives additional information about meteorological instruments.

The length of the Basel lysimeter time series is 42 yr (1977–present), with daily data before 1988 and 10-min data afterwards. The time series is affected by data gaps due to mechanic failure or unreliable data. Gap sizes for the Basel lysimeter are given in Table 2. The data gaps have varying lengths, with, for example, gaps of 7 d (22 Mar. 2000–28 Mar. 2000), >2 mo (6 Oct. 1994–15 Dec. 1994), or even as large as 8 mo (29 Apr. 1999–29 Dec. 1999). The proportion of 1-d gaps is the highest, and there are also some large gaps of different sizes sparsely distributed throughout the measurement period. Given the data gaps, the data from 1989–1992, 1999, and 2008 were excluded from the analysis, and data before 1983 and after 2011 were not considered.

2.2 | Methodology

Lysimeter ET is determined on the basis of a water balance computation. This can be done if values for three variables are known: precipitation, discharge at the bottom of the lysimeter, and lysimeter weight change, according the following equation:

$$\mathrm{ET} = P - Q - \frac{\Delta W}{A} \tag{2}$$

where ET (mm) is actual ET, P (mm) is precipitation, Q (mm) is discharge, ΔW (kg) is weight change, and A (m^2) is lysimeter surface. Weight change was determined in this work as the difference in weight between the end of the day and the beginning of the day, which allows estimating daily actual ET amounts.

Artificial gaps were created for all three lysimeter time series. Approximately 1,000 1-d gaps, 500 3-d gaps, 250 7-d gaps, and 100 1-mo gaps were randomly created for each of the three lysimeter time series.

Different methods were compared for gap filling:

1. *Potential ET according Penman–Monteith*. Potential ET was calculated according the FAO Penman–Monteith method that is defined for an extended surface of green grass with an assumed height of 12 cm, a surface resistance of 70 s m^{-1}, an albedo of 0.23, and no shortage of water and nutrients (Allen et al., 1998). According to this approach, the gaps are simply filled by assuming that actual ET is equal to potential ET, which is often true for the three considered sites that only rarely face water-limited conditions. Potential reference ET is given by

$$\mathrm{ET}(0) = \frac{0.408\Delta\left(R_{\mathrm{n}} - G\right) + \gamma\frac{900}{T+273}u_2\left(e_{\mathrm{s}} - e_{\mathrm{a}}\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (3)$$

where ET(0) (mm d^{-1}) is reference ET, Δ (kPa °C^{-1}) is the slope vapor pressure curve, R_n (MJ m^{-2} d^{-1}) is net radiation at the vegetation surface, G (MJ m^{-2} d^{-1}) is the soil heat flux density, T (°C) is air temperature at 2-m height, u_2 (ms^{-1}) is wind speed at 2-m height, e_s (kPa) is saturation vapor pressure, e_a (kPa) is actual vapor pressure, $e_s - e_a$ (kPa) is saturation vapor pressure deficit, and γ (kPa °C^{-1}) is psychrometric constant.
2. *Ratio method.* According to the ratio method, ET was estimated for a certain day t in a gap as follows:

$$\mathrm{ET}(a)_{\mathrm{ratio},t} = \mathrm{ET}(0)_t \left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ET}\,(0)}\right]_t \quad (4)$$

where ET (0) is potential ET (mm d^{-1}) calculated from meteorological data for the considered day t in the gap,

$$\left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ET}\,(0)}\right]_t = \left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ET}\,(0)}\right]_{t_1} + \left(t - t_1\right)\frac{\left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ET}(0)}\right]_{t_2} - \left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ET}(0)}\right]_{t_1}}{\left(t_2 - t_1\right)} \quad (5)$$

where

$$\left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ET}\,(0)}\right]_{t_2}$$

is the ratio at the time point t_2 (after the gap),

$$\left[\frac{\mathrm{ET}_{\mathrm{ly}}}{\mathrm{ER}\,(0)}\right]_{t_1}$$

is the ratio at the time point t_1 (before the gap), and t is the time point between t_1 and t_2 for which the actual ET is estimated. In this work, three different strategies are followed to calculate the ratios at t_2 and t_1. The ratios at these time points are calculated either for 1 d, 3 d (the 3 d preceding the gap [for t_1] and the 3 d after the gap [for t_2]), or 5 d (the 5 d preceding the gap and the 5 d after the gap).
3. *FAO water balance method.* The FAO-based actual ET(Allen et al., 1998) is estimated as

$$\mathrm{ET(a)}_{\mathrm{FAO}} = K_{\mathrm{s}}K_{\mathrm{c}}\,\mathrm{ET}\,(0) \quad (6)$$

where K_c is the crop coefficient and K_s is the water stress coefficient. The actual ET is calculated for each time step by calculating K_s for each time step based on water balance considerations:
For D_r > RAW, K_s is given by:

$$K_{\mathrm{s}} = \frac{\mathrm{TAW} - D_{\mathrm{r}}}{\mathrm{TAW} - \mathrm{RAW}} = \frac{\mathrm{TAW} - D_{\mathrm{r}}}{(1 - p)\,\mathrm{TAW}} \quad (7)$$

where D_r (mm) is root zone depletion, RAW (mm) is readily available soil water in the root zone, TAW (mm) is total available soil water in the root zone, and p is the fraction of TAW that a crop can extract from the root zone without suffering water stress. The TAW is calculated as

$$\mathrm{TAW} = 1{,}000\ \left(\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}}\right)\ Z_{\mathrm{r}} \quad (8)$$

where θ_{FC} (m^3 m^{-3}) is the soil water content at field capacity, θ_{WP} (m^3 m^{-3}) is the soil water content at wilting point, and Z_r (m) is rooting depth. For this method, calculations were made with two variants: a rooting depth of 0.5 m and a rooting depth of 1.0 m. When the root zone depletion is smaller than RAW, $K_s = 1$ (no water stress).
4. *HYDRUS.* The HYDRUS model (Šimůnek et al., 2005, 2008) numerically solves the Richards equation for the modeling of water flow in variably saturated porous media. In this study, HYDRUS-1D version 4.17 was used for modeling unsaturated water flow in the lysimeter soil column for a longer portion of the lysimeter time series. Soil hydraulic parameters (K_s, α, n, Θ_s, and Θ_r) were inversely estimated by the Marquardt–Levenberg algorithm. The measured discharge time series at the bottom of the lysimeter was used as conditioning information. The estimated soil hydraulic parameters were afterwards applied in simulations for the complete time period with lysimeter measurements, in order to estimate actual ET for the gaps without measured actual ET. The precipitation and potential ET (calculated according Equation 2) as input for the HYDRUS model calculations were obtained from measured meteorological data at the lysimeter sites. Table 3 provides further information on the HYDRUS simulations at the different lysimeter sites, including calibration period, the number of soil horizons and their depths, and the estimated soil hydraulic parameter values for each soil horizon. In all cases, a seepage face lower boundary condition was

TABLE 3 Application of HYDRUS at the three lysimeter sites for gap filling: calibration period, soil horizons and depths, and estimated soil hydraulic parameter values

Parameter[a]	Rietholzbach	Rheindahlen	Basel
Calibration period	1981–2007	1985–2011	1983–2011
No. of soil horizons	1	2	2
Depth of soil profile, cm	200	300	210
K_s, Horizon 1, cm d^{-1}	10	18	55.2
α, Horizon 1, cm^{-1}	0.00355	0.02	0.0276
n, Horizon 1	1.45	1.31	1.90
Θ_s, Horizon 1	0.560	0.53	0.4172
Θ_r, Horizon 1	0.083	0.046	0.0201
K_s, Horizon 2, cm d^{-1}	N/A[b]	19	162
α, Horizon 2, cm^{-1}	N/A	0.024	0.0163
n, Horizon 2	N/A	1.576	2.0
Θ_s, Horizon 2	N/A	0.45	0.3588
Θ_r, Horizon 2	N/A	0.067	0.0125
Soil type	Gleyic Cambisol	Luvisol	Luvisol

[a] K_s, saturated hydraulic conductivity; α and n, shape parameters of soil water retention curve; Θ_s, saturated water content; Θ_r, residual water content.
[b] N/A, not applicable.

TABLE 4 Calibration and validation quality of HYDRUS modeling for three locations

	Calibration		Validation	
Location	RMSE of seepage	R^2	RMSE of seepage	R^2
	mm mo^{-1}		mm mo^{-1}	
Rietholzbach	3.20	.68	3.70	.62
Rheindahlen	1.03	.39	1.35	.15
Basel	1.16	.62	1.68	.72

used. A zero-flux boundary condition is given when the pressure head at the bottom node is negative and is automatically switched to zero-pressure head boundary condition at saturation, which allows gravity-driven drainage at the lysimeter bottom.

Seepage data have been used for the calibration, and results for the HYDRUS model calibration are given in Table 4. For Rietholzbach and Basel, a better reproduction of seepage data, in both the calibration and verification phases, is found than for Rheindahlen.

2.3 | Evaluation criteria

Estimated values for the (artificial) data gaps (and for each of the four gap-filling methods) are compared with the measured values based on the RMSE and mean bias error (MBE):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{ET}_\mathrm{a}^\mathrm{pred} - \mathrm{ET}_\mathrm{a}^\mathrm{meas}\right)^2} \tag{9}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{ET}_\mathrm{a}^\mathrm{pred} - \mathrm{ET}_\mathrm{a}^\mathrm{meas}\right) \tag{10}$$

where $\mathrm{ET}_\mathrm{a}^\mathrm{pred}$ is predicted ET (mm), $\mathrm{ET}_\mathrm{a}^\mathrm{meas}$ is measured lysimeter ET (mm), and n is the number of data gaps. The gap-filling method that results in the smallest RMSE and MBE is considered the preferred gap-filling method for estimating missed actual ET data from lysimeter time series. The evaluations presented in this paper are calculated over the complete time period and per season. In addition to this, the five wettest and driest April–October periods from the time series were selected, and separate analyses were conducted for those years. The driest and wettest years were selected based on the dry index (Di).

3 | RESULTS AND DISCUSSION

3.1 | Overall performance of gap-filling techniques

The RMSE results for the comparison of the different gap filling methods at the three lysimeter stations are presented in the Tables 5–7. For the Rietholzbach lysimeter, the different gap-filling methods show a quite similar performance (RMSE ≈ 0.7 mm d^{-1}), with the smallest overall RMSE for the potential ET method. This can be explained by the very wet conditions at the Rietholzbach site, and it is expected that actual ET is usually close to potential ET at this site. Nevertheless, for the smallest gaps of just 1 d, the ratio method outperforms the potential ET method at the Rietholzbach site. For the longest time gaps (week and month), the model-based approaches (FAO_1.0 and HYDRUS) also perform well at this site, with just slightly larger RMSE than calculations based on the potential ET. The MBE values indicate that, in general, the different gap-filling methods show only a limited bias, with a slight overestimation of actual ET by the potential ET method (0.05–0.08 mm d^{-1}, depending on gap size), whereas some other gap-filling methods like FAO_0.5 and the ratio methods underestimate actual ET. The FAO_1.0 gap-filling method is, on average, very close to the actual ET (MBE values between 0.00 and 0.03 mm d^{-1}). Overall, given

TABLE 5 RMSE and mean bias error (MBE) for the different gap-filling methods and different gap sizes for the Rietholzbach time series (1981–2007)

Model	1-d RMSE	1-d MBE	3-d RMSE	3-d MBE	7-d RMSE	7-d MBE	30-d RMSE	30-d MBE
	mm d^{-1}							
Potential_ET[a]	0.68	0.078	0.69	0.052	0.66	0.060	0.67	0.060
FAO_0.5	0.88	−0.073	0.91	−0.106	0.90	−0.099	0.87	−0.089
FAO_1.0	0.71	0.028	0.73	−0.002	0.72	0.003	0.70	0.013
Ratio_1-day	0.69	−0.032	0.79	−0.059	1.02	−0.017	1.23	−0.011
Ratio_3-day	0.64	−0.047	0.75	−0.045	0.83	−0.049	1.04	−0.011
Ratio_5-day	0.65	−0.050	0.71	−0.045	0.74	−0.037	0.88	−0.029
Hydrus	0.75	0.047	0.76	0.022	0.74	0.029	0.74	0.034
Gaps	980		491		252		105	

[a]ET, evapotranspiration.

TABLE 6 RMSE and mean bias error (MBE) for the different gap-filling methods and different gap sizes for the Rheindahlen time series (1985–2011)

Model	1-d RMSE	1-d MBE	3-d RMSE	3-d MBE	7-d RMSE	7-d MBE	30-d RMSE	30-d MBE
	mm d^{-1}							
Potential_ET[a]	1.32	0.638	1.31	0.657	1.35	0.653	1.37	0.687
FAO_0.5	1.54	−1.187	1.56	−1.210	1.57	−1.191	1.60	−1.218
FAO_1.0	1.51	−1.152	1.52	−1.170	1.53	−1.137	1.56	−1.156
Ratio_1-day	0.89	0.124	1.06	0.175	1.19	0.184	1.38	0.248
Ratio_3-day	0.88	0.154	0.98	0.224	1.07	0.232	1.11	0.196
Ratio_5-day	0.88	0.165	0.94	0.236	1.04	0.237	1.11	0.208
Hydrus	0.71	0.054	0.70	0.054	0.71	0.038	0.72	0.090
Gaps	1,000		500		258		102	

[a]ET, evapotranspiration.

TABLE 7 RMSE and mean bias error (MBE) for the different gap-filling methods and different gap sizes for the Basel time series (1983–2011, except 1989–1992, 1999, 2008)

Model	1-day RMSE	1-day MBE	3-day RMSE	3-day MBE	7-day RMSE	7-day MBE	30-day RMSE	30-day MBE
	mm d^{-1}							
Potential_ET[a]	0.98	0.549	1.00	0.568	0.98	0.567	1.01	0.541
FAO_0.5	1.13	0.171	1.12	0.197	1.10	0.206	1.08	0.223
FAO_1.0	0.99	0.247	0.99	0.392	0.98	0.392	0.98	0.376
Ratio_1-day	0.92	0.029	0.97	0.034	0.90	0.016	1.08	0.036
Ratio_3-day	0.80	0.044	0.80	0.042	0.81	0.056	0.87	0.012
Ratio_5-day	0.78	0.051	0.78	0.040	0.76	0.055	0.84	0.011
Hydrus	0.97	0.514	0.99	0.524	0.97	0.529	1.00	0.499
Gaps	1,061		472		262		103	

[a]ET, evapotranspiration.

the small MBE values and the lower RMSE values for the potential ET method, it can be concluded that the potential ET method outperforms the other methods, but differences with other gap-filling methods are small.

For the Rheindahlen lysimeter, the HYDRUS-model gave the smallest RMSE (~0.7 mm d^{-1}), followed by the ratio method (increasing from 0.88 mm d^{-1} for 1-d gaps to 1.11 mm d^{-1} for 30-d gaps). The other methods gave relatively large RMSE values between 1.3 and 1.6 mm d^{-1}. For Rheindahlen, the two different rooting depths in the FAO approach gave very similar RMSE values. All gap-filling methods overestimate actual ET for the Rheindahlen lysimeter except the FAO method, which gives a strong underestimation. The clear overestimation of actual ET by the potential ET method (MBE ≈ 0.6–0.7 mm d^{-1}) is in accordance with our expectations, as the Rheindahlen lysimeter is sometimes affected by drought stress. The other gap-filling methods (the ratio method and HYDRUS) only slightly overestimate actual ET. The strong underestimation of actual ET by the FAO method is related to the assigned wilting point and field capacity on the basis of soil texture information. Apparently, for the Rheindahlen lysimeter, these values resulted in too little available water in the root zone. This strong bias resulted also in the high RMSE values. Both in terms of MBE and RMSE, the HYDRUS approach shows the best performance, and the ratio method only performs slightly worse, whereas the potential ET method and especially the FAO method show clearly worse performance.

Finally, for the Basel lysimeter, the ratio method gave the lowest RMSE values (∼0.8 mm d^{-1}), whereas the other methods gave RMSE values around 1.0 mm d^{-1}, except for the FAO method with a shallower rooting depth, which gave slightly larger errors. Also for Basel, we see that a rooting depth of 1.0 m for the grass results in a smaller RMSE than a rooting depth of 0.5 m. The better results for a deeper rooting depth can be related to conditions of water stress, which mainly occur in summer and early autumn. Under those conditions, the total amount of available water might be restrictive for a rooting depth of 0.5 m but still sufficient for a rooting depth of 1.0 m. As was found at Rheindahlen, the potential ET method results in an overestimation of actual ET with MBE values between 0.5 and 0.6 mm d^{-1}. This is related to the fact that ET is limited by soil moisture for the Basel lysimeter during summer. The other gap-filling methods result in a smaller overestimation of actual ET with the smallest bias for the ratio method, followed by the FAO method. Overall, for the Basel lysimeter, the ratio method clearly provides the best results, in terms of both RMSE and MBE.

Overall, the ratio approach shows the best performance, as it gives the smallest RMSE and bias at the Basel site, the second best results for the Rheindahlen lysimeter (in terms of both RMSE and MBE), and the best or second best results for the Rietholzbach lysimeter if the data gaps are relatively small. The other methods, although sometimes outperforming the ratio method, do not give consistently good results. In addition, it can be expected that the potential ET method only performs well under wet conditions, and this is confirmed by systematic larger MBE values (than other gap-filling methods) at the lysimeter sites. The HYDRUS method has a main disadvantage in that it is labor and computationally intensive. The performance of the ratio method depends on the gap size, which is not the case for the other gap-filling methods. For small gaps, the ratio method performs better than the other methods and is preferred. For long gaps of 30 d, alternative approaches like HYDRUS model calculations might be a better alternative. The optimal time window size to average the ET ratios before and after the gap was also investigated. Time windows between 1 and 9 d were tested. The best results were found for a window of 5 d, slightly better than for 3 d and much better than for 1 d. A longer time window of 7 or 9 d does not further reduce the RMSE but slightly increases it instead. It is concluded that a time window of 5 d before and after the gap is a good choice.

3.2 | Season-dependent performance of gap-filling methods

The different gap-filling methods are also compared for different seasons. Results are displayed in Figure 4. In most cases, results for the different seasons are in accordance with the complete year, but there are some specific findings. In general, related to the yearly cycle of air temperature and vegetation activity, the actual ET is highest in summer, lower in spring and autumn, and lowest in winter. The RMSEs for estimating actual ET of data gaps are therefore also largest in summer and smallest in winter. For the Rietholzbach site, the ratio method (from here onwards only results for the Ratio_5-day method are shown) gives much larger RMSE values than the other gap-filling methods for the winter season, whereas for the other seasons it performs well, especially for spring and small time gaps. For Basel, we find that the ratio method also gives better results in winter than other gap-filling methods, whereas for Rietholzbach, the opposite is the case. It is difficult to explain these differences, which we feel are related to the small ET values in winter, so that results are more strongly affected by random errors. It is also interesting that the RMSE values in winter are relatively large, taking into account that the absolute actual ET values in winter are much lower than in summer (around a factor of three). For example, for Basel, the RMSEs in autumn and winter are half the values in summer. For the Rheindahlen lysimeters, HYDRUS modeling gives the best performance, followed by the potential ET method and FAO method (root depth = 1 m). The very good performance of HYDRUS is surprising, as for the Rheindahlen site the calibration was not as good as for the other two sites. The drier conditions of Rheindahlen, with periodic drought stress in summer, might have contributed to the relatively good performance of HYDRUS for this lysimeter.

3.3 | Performance of gap-filling methods for driest and wettest years

Soil texture might indirectly impact the performance of gap-filling methods as soil texture influences the occurrence of

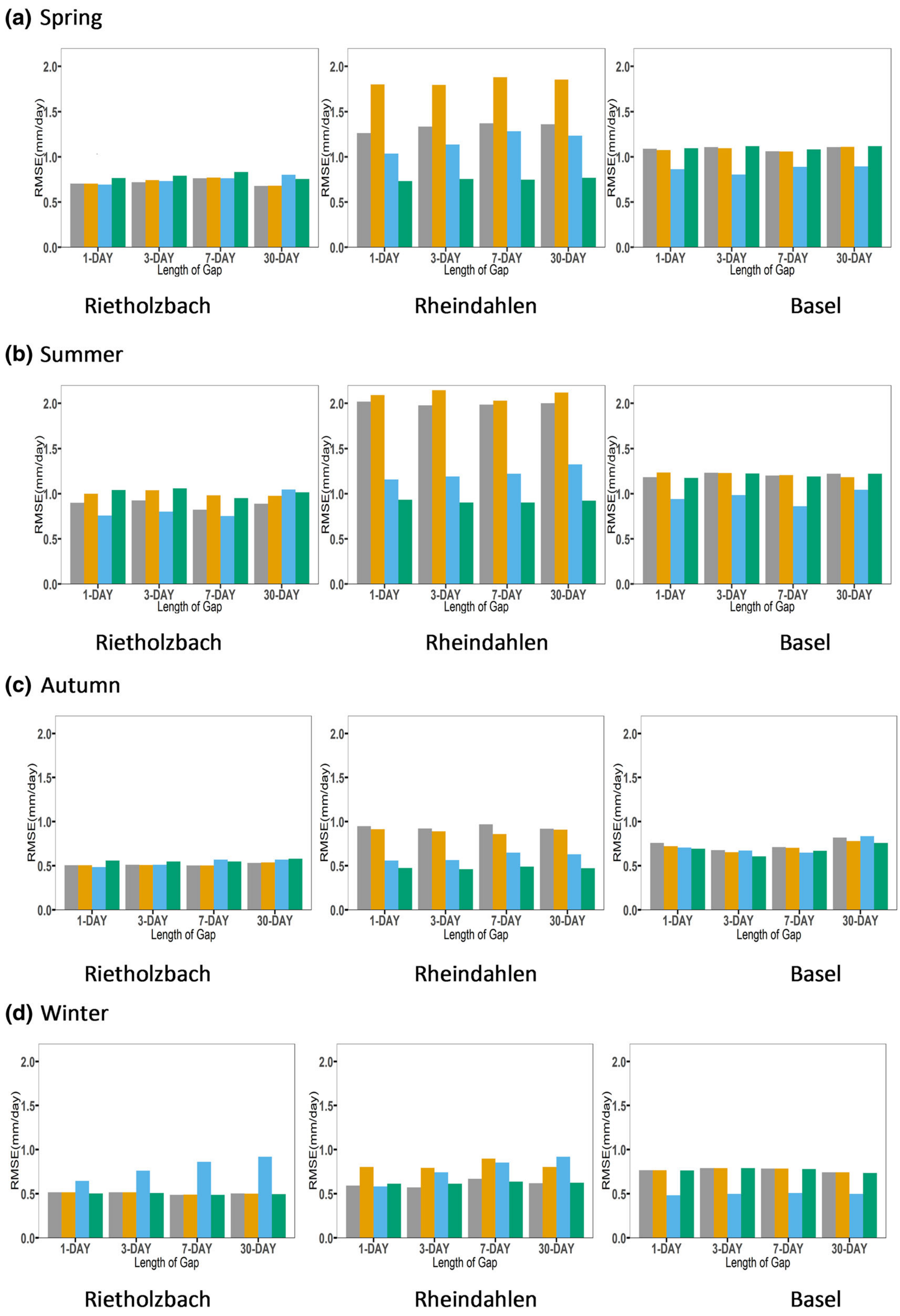

FIGURE 4 The RMSE values for Rietholzbach, Rheindahlen, and Basel for the four different seasons. From the top row to the bottom row: (a) spring, (b) summer, (c) autumn, and (d) winter. The RMSE values for the following methods are displayed: gray = potential evapotranspiration FAO, yellow = FAO, blue = ratio, green = HYDRUS

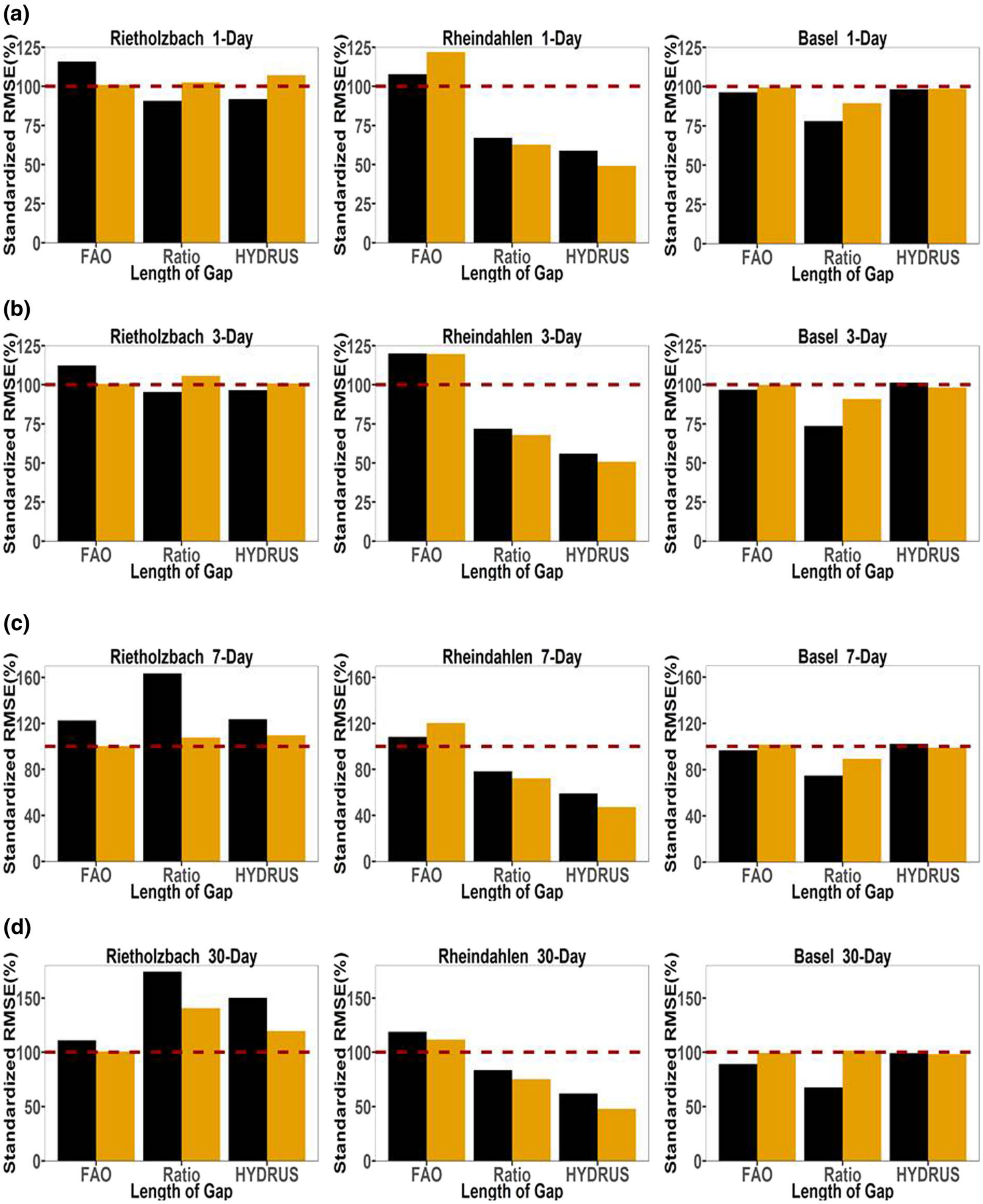

FIGURE 5 The RMSE values for different gap-filling methods and all three lysimeters, evaluated for the five driest and five wettest April–October periods for different gap lengths of (a) 1 d, (b) 3 d, (c) 7 d, and (d) 30 d (black = five driest years, light brown = five wettest years). Results are standardized with respect to potential evapotranspiration (potential ET = 100)

drought stress. The impact of drought stress on the gap-filling methods is analyzed further in this section. Figure 5 displays the RMSE for the different lysimeters and different gap-filling methods separately for the five driest and five wettest April–October periods. In this figure, the results are standardized with respect to the potential ET method, whose results are set to 100. In general, the overall behavior described in Section 3.1 is also found here, and differences between the wettest and driest April–October periods are small. This might be related to the fact that for these sites, even in the driest years, ET is mostly energy limited and not moisture limited. As a consequence, a potential difference of the performance of the gap-filling methods under energy-limited and moisture-limited conditions probably does not show up very clearly. Figure 5 nevertheless shows that the ratio method performs relatively better (in comparison with the other gap-filling methods) for the driest years, whereas for the other methods, this is not the case. This is especially the case for the Basel site, which is more affected by droughts than the other sites. However, there is not a clear indication that one method or another would clearly perform better under dry conditions.

4 | CONCLUSIONS

Long time series of actual ET measured by lysimeters are of high scientific interest given the lack of very long actual ET time series measured by other devices. Also, lysimeter time series are affected by smaller and larger data gaps that need to be filled. Four gap-filling techniques were compared and applied to actual ET data measured by lysimeters at three sites (Basel and Rietholzbach in Switzerland and Rheindahlen in Germany): (a) potential ET, calculated according the Penman–Monteith equation; (b) the ratio method, which is filling the gaps with linear interpolation of the ratio of observed actual ET and calculated potential ET before and after the gap; (c) the FAO water balance approach; and (d) one-dimensional HYDRUS modeling using inversely estimated soil hydraulic parameters. The accuracy of the four gap-filling techniques was assessed based on filling artificially generated data gaps of different lengths. The performance for gap lengths of 1, 3, 7, and 30 d was evaluated. The main conclusions are as follows:

1. The ratio method outperformed other gap-filling methods for the Basel lysimeter station. For the Rheindahlen research site, the HYDRUS method outperformed other gap-filling methods, and for the Rietholzbach research site, the potential ET method slightly outperformed other gap-filling methods. Overall, over the three sites, the ratio method shows the best performance. However, the performance of the ratio method depends on the gap length and is worse for larger gap lengths, whereas the other methods are less or not affected by the gap length. For very large gaps of, for example, 30 d, the HYDRUS modeling approach is preferred over the ratio method.
2. The performance of the gap-filling methods does not depend strongly on the time of the year. However, a weak dependence can be detected, and in winter, the ratio and HYDRUS methods are not superior to other methods, whereas in spring and summer, they show better performance.
3. A separate analysis for the five driest and five wettest April–October periods shows that the performance of the gap-filling methods is not much affected by the wetness condition, probably because even in the driest years, actual ET was mostly energy limited and not moisture limited at the three sites. The analysis shows that the ranking of the gap-filling methods is not much affected by the wetness condition, but the absolute numbers show some small changes: the ratio method performs better under dry conditions.

The application of the ratio method is recommended as the gap-filling approach for actual ET data measured by lysimeters, for gaps smaller than 1 wk. For larger gaps of 30 d, gap filling by the HYDRUS modeling approach is the preferred option.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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