Comparative Study of a Long-Established Large Weighing Lysimeter and a State-of-the-Art Mini-lysimeter

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Weighing lysimeters are a well-established means of accurately obtaining local-scale estimates of actual evapotranspiration (ET), precipitation, and seepage within soils. At the Rietholzbach research catchment in northeastern Switzerland, two weighing lysimeters are in operation. One is a recently installed state-of-the-art monolithic mini-lysimeter with a tension-controlled lower boundary; the other is a large backfilled free-drainage lysimeter in operation since 1976. For this study, the mini-lysimeter measurements were processed using the Adaptive-Window and Adaptive-Threshold (AWAT) filter. The resulting water-balance estimates were then compared with those of the lower resolution large lysimeter, whose processing has remained unchanged since its installation. A number of additional, retrospectively applicable processing steps for the large lysimeter were then tested to mitigate the main sources of error for this instrument. Those found to be most beneficial were the application of a 10-min moving average to the mass measurements and the setting of ET to zero in hours with liquid precipitation. In spite of the differences in design, a generally close agreement between the two lysimeters was observed, which was further improved with the optimized large-lysimeter processing. A comparison of the lysimeter mass increases associated with liquid precipitation further revealed, however, that the large lysimeter experiences a previously unknown under-catch of about 11.5%, which could also be important for other lysimeter facilities. This under-catch led to a reduction in large-lysimeter seepage during the analyzed period, although the ET flux was not found to be affected.

For many aspects of hydro-meteorological, climatological, ecological, and agronomical research, it can be important to have accurate estimates of the full set of water-balance components. This comprises ET (which we define as an upward flux only), precipitation (which can be either meteorological precipitation [rain, hail, sleet, snow, etc.] or condensation [dewfall, fog deposition, frost formation, etc.]), and seepage through the soil column (which we define as a net downward flux). Weighing lysimeters are well-established instruments for measuring these fluxes (e.g., Maidment, 1992; Rana and Katerji, 2000; Meissner et al., 2007; Seneviratne et al., 2012; Schrader et al., 2013; Nolz et al., 2014; Hoffmann et al., 2016). Weighing-lysimeter data are commonly used for validating hydrological models (e.g., Chapman and Malone, 2002; Soldevilla-Martinez et al., 2014) and investigating the water-use strategies of particular plant types (e.g., Ko et al., 2009; Piccinni et al., 2009; Girona et al., 2011). They can also be used for evaluating other hydro-meteorological instruments and measurement techniques, such as eddy-covariance estimates of ET (e.g., Ding et al., 2010; Hirschi et al., 2017). Recent advances in lysimeter weighing technology, installation procedure, and lower boundary design have greatly improved the precision of the resulting water-balance estimates, with modern devices typically possessing weighing resolutions equivalent to 0.01 mm (Fank and Klammel, 2013).
At the Rietholzbach research catchment in northeastern Switzerland, two weighing lysimeters are in operation. One is a recently installed state-of-the-art monolithic mini-lysimeter with a tension-controlled lower boundary; the other is a large, backfilled, free-drainage lysimeter in operation since 1976. The mini-lysimeter has a very high temporal and absolute weighing resolution and can provide estimates for the full set of water-balance components. On the other hand, the large lysimeter has a relatively low temporal resolution, meaning that external tipping-bucket measurements of precipitation must be considered to allow a residual estimation of ET from the mass record (World Meteorological Organization, 2014). As a result, this instrument can only be used to estimate ET and seepage, with the former susceptible to substantial errors relating to tipping-bucket under-catch (Nolz et al., 2014).

One issue associated with the mass measurements of weighing lysimeters is that a relatively high degree of noise may be present. This primarily results from wind-induced mechanical vibration of the lysimeter vessel resting on the underlying scales (Xiao et al., 2009b; Nolz et al., 2013). Xiao et al. (2009b) further reported that changes in temperature may affect the stability of the mass measurements because the amount of current produced by a load cell at a given load is temperature dependent. This effect, however, is assumed to be minor compared with the influence of wind. For this study, the presence of noise is mainly an issue for the mini-lysimeter because of its high temporal and absolute weighing resolution. Therefore, prior to estimating the water-balance components, it is of great importance to filter the mini-lysimeter mass measurements to minimize this noise. This was done by applying the AWAT filter, introduced by Peters et al. (2014) and later improved by Peters et al. (2016) and Peters et al. (2017).

Because of the aforementioned differences between the state-of-the-art mini-lysimeter and the longer established large lysimeter, it is desirable to compare the measurements from each device to (i) evaluate how these differences impact the resulting water-balance estimates, especially ET, and (ii) determine if and how the current large-lysimeter processing can be improved in a retrospectively applicable manner. Additionally, the high-precision precipitation estimate from the mini-lysimeter can be compared with tipping-bucket records of precipitation from the same site to assess their quality.

**Materials and Methods**

**Measurement Site**

The Rietholzbach catchment is a small pre-alpine watershed located within the Thur River basin in northeastern Switzerland. The catchment has an area of 3.31 km² and covers an altitude range of 682 to 950 m asl. The area is sparsely populated, mainly consisting of pastureland (71.9%) and forest (25.6%). The main soil types present in the catchment are Cambisol (40.7%), Gleysol (23.9%), Gleyic Cambisol (17.7%), and Regosol (17.6%) (Seneviratne et al., 2012). The region is characterized by a temperate humid climate with a mean air temperature of 7.1°C and a mean annual precipitation of 1438 mm during the period 1976 to 2015 (Hirschi et al., 2017). Since 1975, the Rietholzbach catchment has been used by ETH Zürich for conducting a variety of hydro-meteorological research. The main measurement station, from which all of the data for this study were gathered, is located at Büel (47.38° N, 8.99° E). Figure 1 shows a aerial view of the measurement station and the surrounding area, with an inset schematic highlighting the instrumentation relevant to this study.

The study period spanned 13 mo, from 1 Sept. 2015 to 30 Sept. 2016. For most of the analyses, however, the data from 1 Nov. 2015 to 30 Apr. 2016 were omitted because of the presence of snow in these months, as this could distort the lysimeter mass measurements through snow drift and snow bridges (Hirschi et al., 2017). Moreover, the presence of both liquid and solid precipitation would lead to a high temporal variability in the degree of wind-induced tipping-bucket under-catch (World Meteorological Organization, 2008), which we thus avoided.

**Instrumentation**

**Large Lysimeter**

The large weighing lysimeter in Büel has been providing continuous ET and seepage measurements since 1976. The lysimeter has a surface area of 3.14 m² (2-m diameter) and a depth of 2.5 m. The surface is grass covered and is intended to reflect the conditions of the surroundings in terms of soil structure, composition, cutting, and fertilization. The container is synthetic and backfilled with...
Gleyic Cambisol, except for a filter layer of gravel and sand between 2- and 2.5-m depth to prevent damming (Seneviratne et al., 2012). The lysimeter’s three load cells have a combined resolution of 100 g, which corresponds to a water column of approximately 0.032 mm. The drainage, which occurs by gravitation only, is measured with a 50-mL tipping bucket, yielding a resolution of approximately 0.016 mm. The drawbacks of this free-drainage design are that the soil at the lysimeter base must be saturated for seepage to occur (Weller et al., 2014) and that capillary rise from lower depths cannot be represented because it is disconnected from the groundwater table (Rana and Katerji, 2000). On the other hand, the relatively large volume of the lysimeter should provide a high level of representativeness for the site. Originally, the lysimeter mass and seepage were recorded hourly, although the records since 2000 are available at a 5-min resolution. For a schematic of the large lysimeter, see Seneviratne et al. (2012).

Mini-lysimeter

The mini-lysimeter (SFL-600, Meter [formerly UMS]) was installed in Büel in August 2015. It has a surface area of approximately 0.071 m² (0.3-m diameter) and a depth of 0.6 m. The soil column is monolithic and thus represents an undisturbed soil profile. As with the large lysimeter, the surface is grass covered and should well reflect the conditions of the surroundings. In spite of its reduced depth, the mini-lysimeter is sufficient to capture the effective root zone of the overlying grass vegetation. At the lysimeter base, the soil matrix potential is continuously measured using a dielectric water potential sensor (MPS-2, Meter [formerly Decagon]) and compared with a reference measurement from a tensiometer (T8, Meter [formerly UMS]) at the same depth in the undisturbed surroundings. A bidirectional pump connecting a series of suction cups at the lysimeter base to an external drain-water bottle then adds or removes water from the lysimeter to minimize the difference between these two measurements. This tension-controlled design ensures that the lysimeter dynamics conform to those of the field. In doing so, it allows for seepage under unsaturated conditions and for (equivalent) capillary rise from lower depths, which cannot be represented with the large lysimeter. The drawback of the mini-lysimeter’s design is that its small area and depth could lead to errors in properly representing the conditions of the site. Because the lower boundary is tension controlled, however, this issue should be far less pronounced than for similar-sized free-drainage lysimeters.

The masses of the lysimeter vessel and the external drain-water bottle are recorded on a 1-min basis using separate electronic balances and stored separately. The balance for the lysimeter vessel has a resolution of 1 g, equivalent to a water column of approximately 0.014 mm, while the balance for the external drain-water bottle has a resolution of 0.5 g, equivalent to a water column of approximately 0.007 mm. The mass change of the lysimeter vessel within a given time interval represents the (net) change in lysimeter storage ($\Delta S_{1,2}$), while the mass change of the external drain-water bottle represents the (net) seepage ($Q_{1,2}$). For a schematic of the mini-lysimeter, see UMS (2013) or https://www.metergroup.com/environment/products/smart-field-lysimeter/.

Precipitation Sensors

Since 1976, the reference precipitation measurement at Büel has been conducted using a standard tipping-bucket rain gauge installed at 1.5 m. The buckets have a volume of 2 mL, yielding a resolution of 0.1 mm. A second tipping bucket, in operation since 1977 and with an identical resolution, is installed nearby at ground level. Originally, the measurements from each of these instruments were stored hourly, although more recent measurements are available at a 5-min resolution.

In addition to these quantitative sensors, an opto-electric precipitation monitor (Thies) was mounted for this study. This instrument is designed to accurately detect the occurrence of meteorological precipitation without measuring the quantity. This is done at a 30-s resolution by means of a relay, which is triggered in the case of hydrometeors falling through an infrared barrier. It has been programmed to indicate precipitation when it detects at least five hydrometeors within one 30-s period or one hydrometeor each 30 s thereafter. The number of 30-s precipitation counts per 5 min (ranging 0–10) is then calculated and saved. This instrument is useful for identifying precipitation events that are too light to register on the tipping buckets and for distinguishing meteorological precipitation and condensation in the lysimeter mass records. For much of the study period, however, substantial data gaps are present because of issues with the power supply and datalogger storage. During May to October, this amounts to 46.7% of the data.

For a full list of instrumentation and measured variables at Büel, see http://www.iac.ethz.ch/url/rietholzbach. An overview of the main long-term measurement records is also available in Seneviratne et al. (2012).

Mini-lysimeter Processing

Because the temporal resolution of the Rietholzbach mini-lysimeter is very high, we assume that within each recorded time interval ET and precipitation do not co-occur. After the mass change due to seepage has been accounted for, it follows that any remaining decrease of the lysimeter mass must result from ET, while any remaining increase must result from precipitation. To estimate these fluxes reliably, however, it is necessary to first process the mass measurements to minimize any errors. To begin, the data were manually filtered to remove large erroneous jumps. This was done by shifting the entire mass record following these jumps to the level of the preceding measurements. After applying this preprocessing step, $\Delta S_{1,2}$ and $Q_{1,2}$ were calculated from the mass changes of the lysimeter vessel and the external drain-water bottle, respectively. The AWAT filter was then applied to the mini-lysimeter total system mass (lysimeter vessel plus external
drain-water bottle) to minimize noise. For a full description of this filter, see Peters et al. (2014, 2016, 2017). The filter parameters used in this study were 1 and 31 min for the minimum and maximum moving-average width and 1.2 and 15 g (equivalent to 0.017 and 0.212 mm) for the minimum and maximum threshold values. Interpolation between anchor points was performed with a piecewise cubic Hermite spline, with an 85th quantile “snap routine” implemented at inflection points. After applying the AWAT filter, the 1-min fluxes \( E_{L2,AWAT} \) and precipitation were calculated based on the decrease or increase, respectively, in the mini-lysimeter total system mass. As mentioned, an additional step that can be performed is the separation of precipitation into meteorological precipitation and condensation using the precipitation monitor. As such, whenever the period between two adjacent anchor points in the AWAT-filtered mass record ±5 min coincided with a greater-than-zero precipitation monitor recording, that period was flagged as “wet,” and any increase in mass was interpreted as meteorological precipitation \( P_{\text{met},L2,AWAT} \). On the other hand, if the precipitation monitor recorded nothing, the period was flagged as “dry” and we interpreted any increase in mass as condensation \( C_{L2,AWAT} \). Defining wet and dry times in this way ensures that the mass increases associated with meteorological precipitation events are correctly flagged as such, even if they have become temporally diluted as a side effect of the AWAT filter. If a given hour or day contained any wet periods, it was defined as wet overall; otherwise it was defined as dry overall. Because it is very useful to separate \( P_{\text{met},L2,AWAT} \) and \( C_{L2,AWAT} \) times in which the precipitation-monitor data were unavailable were omitted from the analyses. The 1-min fluxes of \( E_{L2,AWAT} \), \( P_{\text{met},L2,AWAT} \), and \( C_{L2,AWAT} \) were then summed to give hourly and daily totals.

Figure 2 shows an example of the mini-lysimeter total system mass record, before and after the AWAT filter was applied. In this example, the pre-AWAT data at times contain a high degree of noise, evident through the high variance of the signal. This appears to be correlated with the indicated 2-m wind speed, which illustrates the negative effect of wind on the stability of the mass measurements. If the water-balance components were estimated directly from the pre-AWAT record, they would surely be overestimated because each increase and decrease of the total system mass would be incorrectly interpreted as valid precipitation and ET, respectively (Schrader et al., 2013). On the other hand, the noise is greatly reduced in the AWAT-filtered record. At the top of the figure, the instantaneous flux type for this record is indicated. From 04:00 to 07:34 and 11:47 to 17:14, the filtered mass decreases, indicating periods of ET. Between 07:34 and 11:47, the mass increases, coinciding with a period of greater-than-zero precipitation monitor counts, indicating meteorological precipitation. From 17:14 to 20:00, the mass again increases while the precipitation counts equal zero, indicating condensation.

Large-Lysimeter Processing

The processing of the large lysimeter in Büel has remained unchanged since measurements began in 1976. As mentioned, the lysimeter mass and seepage were originally recorded only on an hourly basis. At such a coarse temporal resolution, the separation of ET and precipitation within the mass record is not feasible. Instead, external measurements of precipitation must be input to allow a residual calculation of ET from the water balance (World Meteorological Organization, 2014). These are taken with the reference tipping bucket at 1.5 m. A major disadvantage of this approach is that tipping buckets are prone to under-catch, primarily resulting from deformation of the wind field around the gauge orifice (World Meteorological Organization, 2008). Additionally, the tipping-bucket resolution is too coarse to represent condensation, leaving it as an additional unknown. Historically, condensation from the large lysimeter has not been represented in the long-term climatological data series (see Hirschi et al., 2017). The residual calculation of ET based on external measurements can, however, potentially result in negative values, which are corrected in that data series on the basis of their frequency and magnitude within a day. This sign-based approach may be problematic, however, for a number of reasons. First, the coarse temporal resolution of the measurements (especially those prior to 2000) allows a cancelation

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**Fig. 2.** Mini-lysimeter total system mass (lysimeter vessel plus external drain-water bottle) from 04:00 to 20:00 (UTC + 1) on 1 Dec. 2015, before and after applying the Adaptive-Window and Adaptive-Threshold (AWAT) filter. Also plotted are the mean hourly 2-m wind speed and precipitation monitor counts (number of 30-s intervals containing meteorological precipitation per 5 min) during the same period. The determined vertical water flux type for the AWAT-filtered record (evapotranspiration \( E_{L2,AWAT} \), meteorological precipitation \( P_{\text{met},L2,AWAT} \), or condensation \( C_{L2,AWAT} \) throughout the given period is also indicated. Note that the observed evapotranspiration during the morning hours was accompanied by high wind speed and high air temperature (around 8°C throughout the night; not shown).
of ET and condensation within the mass record when both fluxes occur within a given time interval. Additionally, a separation on the basis of sign is ill advised because any random errors affecting true ET or condensation values close to zero will give rise to values with too high magnitudes overall, resulting in an overestimation of both fluxes. Lastly, under-catch of meteorological precipitation with the tipping bucket can cause the associated lysimeter mass increases to be incorrectly interpreted as condensation, often leading to implausibly high values (Nolz et al., 2014). For this study, we therefore reconsidered the large-lysimeter processing by including condensation in the water-balance equation. This is thus given as

$$E_{L1} - C_{L1} = P_{met, TB1.5} \frac{W_{r+1} - W_r}{\rho_w A_{L1}} - Q_{L1} \tag{1}$$

The terms on the right-hand side of the equation represent the measured inputs: $P_{met, TB1.5}$ (mm h$^{-1}$) is the hourly meteorological precipitation from the 1.5-m tipping bucket, $Q_{L1}$ (mm h$^{-1}$) is the hourly seepage from the lysimeter base, and $W_r$ (kg) and $W_{r+1}$ (kg) are the instantaneous lysimeter masses recorded at the beginning and end, respectively, of the hour. The difference between the masses represents the hourly change in lysimeter storage ($\Delta S_{L1}$) (kg h$^{-1}$). This term is divided by the density of water, $\rho_w$ (kg mm$^{-3}$), and by the surface area of the large lysimeter, $A_{L1}$ (mm$^2$), such that all of the terms in Eq. [1] have the units of millimeters per hour. The residual term is thus ET minus condensation ($E_{L1} - C_{L1}$) (mm h$^{-1}$). Again, note that the single terms $E_{L1}$ and $C_{L1}$ cannot be determined individually for the reasons explained above.

There are two main sources of error associated with the inputs to Eq. [1]. First, because the lysimeter mass measurements are instantaneous and not filtered in any way, they may deviate substantially from the true values, e.g., because of wind-induced vibrations (Xiao et al., 2009b; Nolz et al., 2013) or inherent inaccuracy of the electronic scales. It is worth noting that since each hourly mass measurement is input as $W_{r+1}$ in one iteration and as $W_r$ in the next, such deviations will result in a symmetric distribution of overestimations and underestimations of the hourly mass change and thus of $E_{L1} - C_{L1}$. The other large source of error to the input data, as mentioned, is precipitation under-catch with the tipping bucket, giving an underestimation of the term $P_{met, TB1.5}$. When this occurs, it directly results in an equal underestimation of $E_{L1} - C_{L1}$. Using the AWAT-filtered mini-lysimeter data, we investigated a number of additional, retrospectively applicable large-lysimeter processing steps for mitigating these errors.

Results and Discussion

Comparison of Evapotranspiration and Precipitation Measurements

To investigate the agreement between the two lysimeters, the estimate of ET minus condensation from each was first compared (Fig. 3). For the AWAT-filtered mini-lysimeter, this was generated by simply subtracting the record of condensation ($C_{L2, AWAT}$) from the record of ET ($E_{L2, AWAT}$) to give $E_{L2, AWAT} - C_{L2, AWAT}$. A relatively coarse daily resolution was chosen for the comparison, such that random errors in each record would be less pronounced and any systematic differences would stand out. When only dry days are considered, the two records are very strongly correlated, with an $R^2$ of 0.969. The sums of each record also agree closely, with 123.3 mm for the AWAT-filtered mini-lysimeter and 121.8 mm (−1.2%) for the large lysimeter. This agreement indicates that there is very little bias between the two instruments during dry times in spite of the differences in design. When wet days are also included, however, the large-lysimeter total (195.2 mm) is 17.4% lower than that of the mini-lysimeter (236.2 mm), indicating a large bias presumably related to the tipping-bucket under-catch of meteorological precipitation. This is evident as many of the wet data plot substantially below the 1:1 line, with some indicating implausibly high negative daily values. Furthermore, the correlation is reduced when all days are considered, with an $R^2$ of 0.831.

To investigate this bias further, Fig. 4a examines the hourly meteorological precipitation measurements from the 1.5-m tipping bucket ($P_{met, TB1.5}$). The AWAT-filtered mini-lysimeter record of meteorological precipitation ($P_{met, L2, AWAT}$) was taken as the reference for this comparison, as it should be unaffected by under-catch. As can be seen, the correlation between these records is very high, with an $R^2$ of 0.986. The plotted linear regression, however, clearly shows that the tipping-bucket record is substantially underestimated relative to the mini-lysimeter, which we attribute to tipping-bucket under-catch. The totals of each record (593.1 mm for $P_{met, L2, AWAT}$, and 488.7 mm for $P_{met, TB1.5}$)
Additionally, Sevruk (1996) found that tipping buckets record (e.g., related to wetting or evaporation [World Meteorological Organization, 2008]) still give rise to a substantial under-catch. Previously, Hoffmann et al. (2016) found that manual Hellmann gauges installed just above ground level give similar precipitation to precision weighing lysimeters. As with Gebler et al. (2015), however, the lysimeters used in that study had a relatively coarse weighing resolution (equivalent to 0.08 mm) and might have caused them to underestimate the true amount of precipitation, resulting in a smaller observed difference between them and the tipping bucket. The hourly mass differences in the resulting record were then calculated as before, and the resulting record of ET minus condensation ($E_{L1,MA} - C_{L1,MA}$) was obtained. Using this, the RMSE decreases to 0.081 mm h$^{-1}$ and the $R^2$ increases to 0.771. Meanwhile, the large-lysimeter sum for the period examined (229.7 mm originally and 229.8 mm with the moving average) remains close to that of the mini-lysimeter (225.8 mm). On the basis of these results, we deduce that the benefit of noise reduction due to the moving average outweighs any potential artificial optimization of large-lysimeter processing

We next investigated a number of additional, retrospectively applicable processing steps for the large lysimeter, intended to mitigate the main sources of error highlighted above. First, to reduce the amount of noise in the large-lysimeter mass measurements, a retrospectively applicable moving average was tested. This was applied to the 5-min mass measurements and is thus only applicable for the more recent part of the lysimeter record. Historically, a moving average was not applied because even the narrowest possible moving-average width (three data points) spans a relatively long time interval (10 min) and could potentially result in substantial artificial smoothing of valid signals. The effect of such a moving average on the large-lysimeter record of hourly ET minus condensation is assessed in Fig. 5 (for dry times only). In Fig. 5a, the (uncorrected) $E_{L1} - C_{L1}$ is compared with the corresponding AWAT-filtered mini-lysimeter record, producing an RMSE of 0.091 mm h$^{-1}$ and an $R^2$ of 0.727. For Fig. 5b, a three-point (10-min) moving average was first applied to the large-lysimeter mass record. This was done for all times, except when any of the three mass measurements in a given interval came from an hour in which $P_{met,TB1.5}$ was > 0 mm. We thereby prevent any negative effects related to the temporal dilution of precipitation events in the large-lysimeter mass record. The hourly mass differences in the resulting record were then calculated as before, and the resulting record of ET minus condensation ($E_{L1,MA} - C_{L1,MA}$) was obtained. Using this, the RMSE decreases to 0.081 mm h$^{-1}$ and the $R^2$ increases to 0.771. Meanwhile, the large-lysimeter sum for the period examined (229.7 mm originally and 229.8 mm with the moving average) remains close to that of the mini-lysimeter (225.8 mm). On the basis of these results, we deduce that the benefit of noise reduction due to the moving average outweighs any potential artificial optimizability of large-lysimeter processing

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We next examined two corrections to mitigate the effect of 1.5-m tipping-bucket under-catch on the estimation of \( E_{L1} - C_{L1} \). These corrections were applied on the hourly time scale and are based on the recorded tipping-bucket data. They are therefore each applicable back to 1977 at least. Figure 6 compares the resulting records of hourly ET minus condensation with that of the AWAT-filtered mini-lysimeter. The uncorrected large-lysimeter record \( (E_{L1} - C_{L1}) \) is given in Fig. 6a. From this we observe that the two lysimeters agree well during hours with \( P_{\text{met,TB1.5}} = 0 \) mm, with an \( R^2 \) of 0.718 when only these hours are considered. On the other hand, the large lysimeter generally underestimates \( E_{L1} - C_{L1} \) during hours with \( P_{\text{met,TB1.5}} > 0 \) mm because of the under-catch with the 1.5-m tipping bucket. On the basis of the \( E_{L2,\text{AWAT}} - C_{L2,\text{AWAT}} \) record, \( E_{L1} - C_{L1} \) should be close to 0 mm during these times, yet many of the observed values are implausibly low. This is reflected in the overall sums for the given period, as the large-lysimeter total (207.5 mm) is 16.5% lower than that of the mini-lysimeter (248.7 mm). These numbers differ slightly from those given for Fig. 3 because available hours within partially missing days are also included here. When the uncorrected large-lysimeter data for all times are considered, the resulting \( R^2 \) is 0.644 and the RMSE is 0.108 mm h\(^{-1}\).

The first correction approach (Fig. 6b) is to perform the large-lysimeter calculation using the measurements from the ground-level tipping bucket instead of the one at 1.5 m because the former experiences a lower degree of under-catch. Overall, however, the resulting record \( (E_{L1,0} - C_{L1,0}) \) has an even worse agreement with the mini-lysimeter than the uncorrected record, as the \( R^2 \) value is somewhat reduced (0.606) while the RMSE does not change. The spread of \( E_{L1,0} - C_{L1,0} \) during times with \( P_{\text{met,TB1.5}} > 0 \) mm also clearly remains very large. Moreover, the \( E_{L1,0} - C_{L1,0} \) sum for the given period is 267.1 mm, which is 7.4% higher than that of \( E_{L2,\text{AWAT}} - C_{L2,\text{AWAT}} \). The reasons for this unexpected behavior are addressed below.

The second approach to mitigate the effect of tipping-bucket under-catch is simply to set the large-lysimeter ET minus condensation to zero for hours in which \( P_{\text{met,TB1.5}} > 0 \) mm (Fig. 6c). The drawback of this approach is that any valid ET and/or condensation also occurring in these hours will be lost. On the basis of the \( E_{L2,\text{AWAT}} - C_{L2,\text{AWAT}} \) sum during these hours, however, we estimate that this loss should only be about 2.1%. Indeed, the resulting large-lysimeter record \( (E_{L1,Z} - C_{L1,Z}) \) sums to 242.6 mm and is thus only 2.4% lower than that of the mini-lysimeter. Hence, the loss is only minor for the period examined. Because this approach...
also improves the RMSE and $R^2$ between the two lysimeters (0.084 mm h$^{-1}$ and 0.725, respectively), it is therefore the best of those investigated, and on the basis of these findings it would be beneficial if applied to the historical and future large-lysimeter data from the Rietholzbach. It should be noted, however, that Hirschi et al. (2017) found the amount of ET occurring during times of precipitation to vary considerably from year to year at the same site. A longer analysis is therefore advised to guarantee the suitability of this approach.

Comparison of Lysimeter Mass Increases during Precipitation

As seen in Fig. 6b, the large-lysimeter record of ET minus condensation calculated with the ground-level tipping bucket ($E_{L1,0} - C_{L1,0}$) is unexpectedly generally greater than that of the AWAT-filtered mini-lysimeter for times in which $P_{\text{met,TB1.5}} > 0$ mm. This cannot arise from biases related to the tipping bucket because it would imply an over-catch of precipitation rather than the observed under-catch. We deduce, therefore, that this must reflect a difference in precipitation catch between the lysimeters themselves.

To investigate this, the seepage-corrected mass increases of each lysimeter per unit area (expressed in mm h$^{-1}$) were compared with the corresponding ground-level tipping-bucket recordings (Fig. 7). This was done for hours in which the AWAT-filtered mini-lysimeter ET and condensation both equaled zero, such that any overall differences between the records, in theory, must result from differences in meteorological precipitation catch. Because we have already observed that the ground-level tipping-bucket recordings are underestimated, we would expect each set of lysimeter data to plot somewhat above the 1:1 line. This expected relationship is, indeed, observed for the mini-lysimeter, whereas the large-lysimeter data generally plot lower. We therefore deduce that the large lysimeter experiences a substantial under-catch of meteorological precipitation relative to the mini-lysimeter. Assuming the mini-lysimeter data to be correct, the sums of the plotted mass increases (496.5 mm for the mini-lysimeter and 439.9 mm for the large lysimeter) indicate the magnitude of this under-catch to be 11.4% (for liquid precipitation).

Regarding the possible reasons for the under-catch, it should be noted that the surface of the large lysimeter is not perfectly level with its surroundings but rather protrudes by about 10 cm (Supplemental Fig. S1). One implication of this is that wind blowing horizontally into the protruding edge of the lysimeter must accelerate to pass over it and could deflect falling precipitation in the process (as occurs with regular precipitation gauges). Moreover, it is possible that the grass growing on the large lysimeter was not cut as frequently as that of the surroundings during the study period, which could increase the effective protrusion of the instrument and amplify the error. Further study is needed, however, to determine the exact cause(s) of the large-lysimeter under-catch.

Comparison of (Corrected) Lysimeter Water-Balance Estimates

To investigate the overall agreement of the complete set of water-balance estimates of each lysimeter, the sums of the individual components across all available hours from May to October were examined (Fig. 8). The large-lysimeter record of ET minus condensation for this figure ($E_{L1,\text{MA,Z}} - C_{L1,\text{MA,Z}}$) was calculated after applying the two additional processing steps previously identified as beneficial, such that it should agree well with the AWAT-filtered mini-lysimeter record, even when times of precipitation are included. This is, indeed, the case, as the large-lysimeter total (242.3 mm) is only slightly less than that of the mini-lysimeter (248.7 mm). Because the two lysimeters have different depths (0.6 m for the mini-lysimeter and 2.5 m for the large lysimeter), the total seepage and change in storage of each may differ, unrelated to errors or differences in seepage design (free drainage vs. tension controlled). For the analyzed period, seepage from the mini-lysimeter sums to 319.7 mm. On the basis of the hourly mass changes of the external drain-water bottle, this corresponds to 355.7 mm pumped out of the lysimeter vessel minus 15.9 mm pumped back in. On the other hand, there was substantially less seepage from the large lysimeter, with a total of just 230.4 mm. This difference is partially explained by a higher degree of water retention in the large lysimeter, whose storage increased by 51.9 mm, compared with 24.8 mm for the mini-lysimeter. This can potentially be explained by the differences in the depth and seepage design of the lysimeters, leading to a lag in the release of water from the large lysimeter. The difference in water retention alone, however, cannot fully account for the observed difference in seepage. Additionally plotted for each lysimeter is the residu-ially estimated total meteorological precipitation input, which is obtained by summing the ET minus condensation, seepage, and...
change in storage of each. For the mini-lysimeter, this amounts to 593.2 mm, which is very close to the total derived from the AWAT-filtered mass record (593.1 mm), as we would expect. On the other hand, the residual total for the large lysimeter is just 524.6 mm. Assuming the mini-lysimeter data to be correct, this indicates an under-catch of meteorological precipitation, estimated to be about 11.5%. This may arise because of the slight protrusion of this instrument above the surroundings and could be amplified if the grass on the lysimeter is not cut as frequently as the surroundings. Conveniently, setting ET minus condensation to zero for hours in which the 1.5-m tipping bucket records precipitation also corrects for the large-lysimeter under-catch.

A comparison of the full set of available water-balance estimates from each lysimeter revealed a substantially lower amount of seepage from the large lysimeter than from the mini-lysimeter during the period analyzed. This is partially explained by a greater increase in stored water in the large lysimeter, although the majority of the difference seems to arise from the reduced input of water due to the aforementioned large-lysimeter under-catch. On the other hand, the record of ET minus condensation from the large lysimeter was not found to be affected by this issue, as it shows a strong agreement with that of the mini-lysimeter in the absence of tipping-bucket errors (i.e., during dry times or after applying the tipping-bucket-related correction to give $E_{r,1,1,2} - C_{1,1,2}$).

In conclusion, this comparative study allowed us to identify the following main results:

- In general, the records of ET minus condensation from each lysimeter agreed closely, in spite of the differences in the size and design of each. This is an important result because it suggests that the substantial depth of the large lysimeter prevents any notable representativeness issues associated with its free-drainage design. Similarly, it suggests that the mini-lysimeter (which was more practical to install and maintain) does not suffer from its smaller size because the water content and seepage are controlled to match the conditions of the surroundings (with the bidirectional pump) and because it nevertheless captures the effective root zone of the overlying grass vegetation.
Filtering of the raw lysimeter mass measurements to minimize noise and other errors is important for obtaining high-quality estimates of the water-balance components. The comparison of the lysimeter fluxes also allowed us to identify additional, retrospectively applicable processing steps for the large lysimeter that should improve the quality of its estimates.

Unexpectedly, we found that the large lysimeter experiences a substantial under-catch of meteorological precipitation. To our knowledge, precipitation under-catch with lysimeters has not previously been reported. While this may be unique to the investigated instrument, it could also be relevant for other lysimeter facilities and should therefore be taken into consideration when interpreting other lysimeter records and when conducting future lysimeter installations and maintenance.

Because measurements of the water-balance components, in particular ET, are of high importance in many areas of research, these findings provide some promising perspectives for better and more comprehensive monitoring of these fluxes in meteorological and hydro-climatological networks.

Supplemental Material
The supplement contains one figure showing the protrusion of the large lysimeter above its surroundings.

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References


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