# Improving interpretation of lysimeter weighing data

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## Verbesserung der Auswertung von Lysimeter-Wiegedaten

## 1 Introduction

Understanding of the water cycle and its components is crucial for various environmental issues such as drinking water supply, water resource management, groundwater protection, or agricultural water management. The latter, for instance, is concerned with drainage and irrigation with respect to optimal crop production. In this regard, it would be helpful to observe processes in the soil-plant-atmosphere system. Furthermore, long-term monitoring of water balance components may provide a database for climate change studies.

Lysimeters proved to be valuable instruments for various water balance studies (FELTRIN et al., 2011; LOOS et al., 2007; MEISSNER et al., 2007; VON UNOLD & FANK, 2008). Two large weighing lysimeters were established in Groß-Enzersdorf, Austria (48°12'N, 16°34'E; 157 m) in 1983. The purpose was to determine evapotranspiration and seepage water at a location that was assumed to be representative for the nearby agricultural area "Marchfeld" (NEUWIRTH & MOTTL, 1983). According to the state of the art at that time (ABOUKHALED et al., 1982), each lysimeter was equipped with a lever-arm-counterbalance weighing system. While the structural facilities of the lysimeter station in Groß-Enzersdorf remained substantially unchanged since initial operation, data management was adapted to contemporary standards over the years (NOLZ et al., 2011). The main focus was set on assessment of soil water balance components with high accuracy and high temporal resolution. Improvements concerned data acquisition (measurement, conversion, averaging, and storage), transmission, backup, and processing (calibration, filtering, and plausi-

### Zusammenfassung

Wägbare Lysimeter sind nützliche Geräte zur Messung von Bodenwasserhaushaltskomponenten. Ältere Lysimeteranlagen sind üblicherweise mit Hebelarm-Gegengewicht-Wiegesystemen ausgestattet. Ein Nachteil solcher Systeme ist ihre Anfälligkeit gegenüber äußeren Störungen, vor allem durch Wind ausgeübten Kräften, welche die Messgenauigkeit erheblich verringern können. Zwei Glättungsfunktionen wurden an verrauschten Lysimeter-Wiegedaten in Hinblick auf verbesserte Dateninterpretation getestet. Eine stückweise Sigmoidfunktion konnte problemlos angepasst werden und lieferte brauchbare Ergebnisse von typischen Tagesverläufen der Verdunstung an einzelnen Tagen ohne Niederschlag. Andererseits lieferte eine polynomische Splinefunktion eine bessere Glättung für längere Zeitspannen mit Niederschlagsereignissen.

**Schlagworte:** Datenmanagement, Messauflösung, Genauigkeit, Sigmoid, Spline, Glättung.

### Summary

Weighing lysimeters are valuable devices for measuring soil water balance components. Older lysimeter facilities are usually equipped with lever-arm-counterbalance weighing systems. A disadvantage of such systems is their sensitivity to external disturbances, mainly forces exerted by wind, which can significantly decrease measuring accuracy. Two types of smoothing functions were tested on a set of noisy lysimeter weighing data with respect to improved data interpretation. A basic piecewise sigmoid function was easy to adapt and gave proper results of typical diurnal variation of evapotranspiration on single days without rainfall. However, on a longer time period with rainfall events, a polynomial spline function performed better.

**Key words:** Data management, resolution, accuracy, sigmoid, spline, smoothing.

bility check). Consequently, also data interpretation had to be adapted. A particular problem was a reduced measuring accuracy induced by wind forces (NOLZ et al., 2009). This oversensitivity to external disturbances is a general disadvantage of lever-arm-counterbalance systems (HOWELL et al., 1995; MALONE et al., 1999). Experiments at the lysimeter station in Groß-Enzersdorf have shown that the weighing system itself is subject to mechanical oscillations, and that disturbances such as wind gusts significantly decrease measuring accuracy (NOLZ et al., 2013). The measuring accuracy for a wind velocity < 5 $m{\cdot}s^{-1}$ (measured in 10 m height) was approximately ± 0.4 kg (equivalent to ± 0.14 mm water ponding), at higher wind velocities the accuracy was about three times lower. Severely noisy weighing data make it almost impossible to determine water balance components in certain (short) time intervals. According to VAUGHAN and AYARS (2009), well-adjusted averaging procedures provide an option for noise reduction arising from mechanical oscillation of the weighing system. A straightforward method is to compute a moving average; however, this procedure is limited by the temporal resolution (storage interval), and may not work properly with severely noisy data (NOLZ et al., 2013).

The main objective of this study was to enhance data interpretation of noisy lysimeter weighing data by means of smoothing functions.

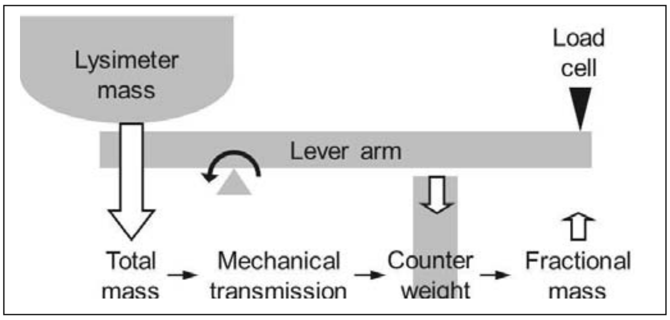


Figure 1: Lysimeter weighing facility: via a lever-arm mechanism with a counterweight, a proportional fraction of the total mass is transmitted to an electronic load cell

Abbildung 1: Lysimeter-Wiegeeinrichtung: über eine Hebelarm-Mechanik mit Gegengewicht wird ein proportionaler Teil der Gesamtmasse auf eine elektronische Wiegezelle übertragen

## 2 Materials and methods

### 2.1 Data acquisition and water balance

The basic parts of the lysimeters in Groß-Enzersdorf are cylindrical vessels with an inner diameter of 1.9 m (surface area 2.85 $m^2$) and a hemispherical bottom made of glass fiber-reinforced plastic with a maximum depth of 2.5 m. At the time of construction the vessels were packed with sandy loam soil (0–140 cm) over gravel (140–250 cm). Each vessel rests on a base frame that transmits the weight through a lever system with a counterweight to an electronic load cell. This mechanical system reduces the total mass of about 11–13 tons (the total mass of the lysimeters is not known exactly) to a fractional mass of some hundreds of kilograms, which is measured by the load cell with an accuracy of ± 0.2 kg. The weighing system registers mass changes in a certain time interval that equal changes of soil water $\varnothing W$, because the mass of the lysimeter vessel and the solid soil remain the same.

Outlets for seepage water $SW$ are situated at the deepest point of each vessel where outflow is measured by means of tipping buckets. A concrete basement with two shafts for the lysimeter vessels accommodates the weighing and seepage water facilities, and devices for data acquisition.

Precipitation $P_{ZAMG}$ is measured in a few meters distance with a standard pluviograph from the Central Institute for Meteorology and Geodynamics, Austria (ZAMG). Alternatively, precipitation $P_{LYS}$ is determined directly from the lysimeter weighing data, based on the approach that either $P$ (positive mass change) or $ET$ (negative mass change) occurs during a certain (short) time interval (VON UNOLD & FANK, 2008). On one hand, this method can provide only an estimation of $P$, because during rainfall events evaporation and transpiration are often not negligible; on the other hand, measurements from standardized pluviographs often show deviations to the increase of soil water $\varnothing W$ in the lysimeter, and the solution of the water balance equation (Eq. 1) gives more plausible results for evapotranspiration $ET$ when using $P_{LYS}$.

Eq.1 symbolizes a basic water balance with the components measured at the lysimeter station: precipitation $P$, irrigation $I$, seepage water $SW$, and change of soil water $\varnothing W$. Hence, it can be used to calculate evapotranspiration $ET$.

$$P + I - ET - SW \pm \varnothing W = 0 \qquad (1)$$

### 2.2 Data management

Figure 2 shows the scheme of data transmission and storage. The output signal of the load cell is transmitted via an analog carrier frequency-measuring amplifier (AMP) (0–10 V) to an analog-to-digital converter (A/D Converter) that converts the analog signal to digital units (digits). Lysimeter weighing data ($W_{raw}$) are measured every few seconds. A moving average is computed from 64 values and stored every 10 minutes on a data logger and on a local server (LYS server) together with the cumulated raw counts (digits) from the tipping bucket ($SW_{raw}$).

Meteorological data (MET) in 1-minute intervals are transmitted directly from the near ZAMG station, and stored on the LYS server with a common time stamp. Some of the available quantities are air temperature, relative humidity, air pressure, solar radiation, precipitation and wind velocity in 10 m height.

Stored data are frequently transmitted to a server at the Institute of Hydraulics and Rural Water Management (IHLW) that operates the lysimeters.

Additional information on cultivation actions (tillage operations, sowing, irrigation, fertilization, and harvest) is necessary for proper data interpretation. Such metadata are recorded in a protocol that is sent via e-mail on demand. In this regard, also pictures from a webcam that monitors activity on the lysimeters are used to facilitate data interpretation. The pictures are taken every minute and stored at IHLW server, where they are available for data processing and interpretation.

First step of data processing is the conversion of stored weighing data and seepage water data into physical quantities by means of calibration factors.

The actual conversion factor for the weighing data $c_{lys}$ = 0.068 kg·digit$^{-1}$ was determined subsequently to a general overhaul of the lysimeter facilities in 2007. Several loads ($m_G$) with a total mass of 106 kg were added to both lysimeters. Referring to this, Figure 3 illustrates data from the grass reference lysimeter. The amount of seepage water during the measuring period was taken into account. Evapotranspiration was determined from the difference between the lysimeter mass without additional load at the beginning and at the end of the calibration procedure, and distributed to the respective intervals. The calibration factor was verified and confirmed by simplified calibration procedures in 2009 and 2011.

Multiplication of raw weighing data $W_{raw}$ (digits) with the calibration factor $c_{lys}$ (kg·digit$^{-1}$) gives the relative lysimeter mass $m_{lys}$ (kg), which is defined as current mass minus a reference mass. The current mass depends on the soil water content, whereas the reference mass approximates the lysimeter mass with dry soil. As mentioned above, the real mass is not known exactly – only mass changes are determined. Dividing $m_{lys} = W_{raw} \cdot c_{lys}$ by the lysimeter surface area ($A_{lys}$ = 2.85 m$^2$) and the density of water $\rho_w$ delivers water equivalent of $W$ with the dimension of a length (Eq. 2).

$$W = W_{raw} \cdot c_{lys} \cdot \rho_w^{-1} \cdot A_{lys}^{-1} \qquad (2)$$

One overturn of a tipping bucket for seepage water acquisition gives an impulse (one digit) that represents the volumetric content of a bucket. The factor $c_{tip}$ = 4.878 ml·digit$^{-1}$ for converting raw seepage water $SW_{raw}$ (digits) into outflow data $SW$ was validated in 2010. Dividing by the lysimeter surface area ($A_{lys}$) gives water equivalent of $SW$ with the dimension of a length (Eq. 3).

$$SW = SW_{raw} \cdot c_{tip} \cdot A_{lys}^{-1} \qquad (3)$$

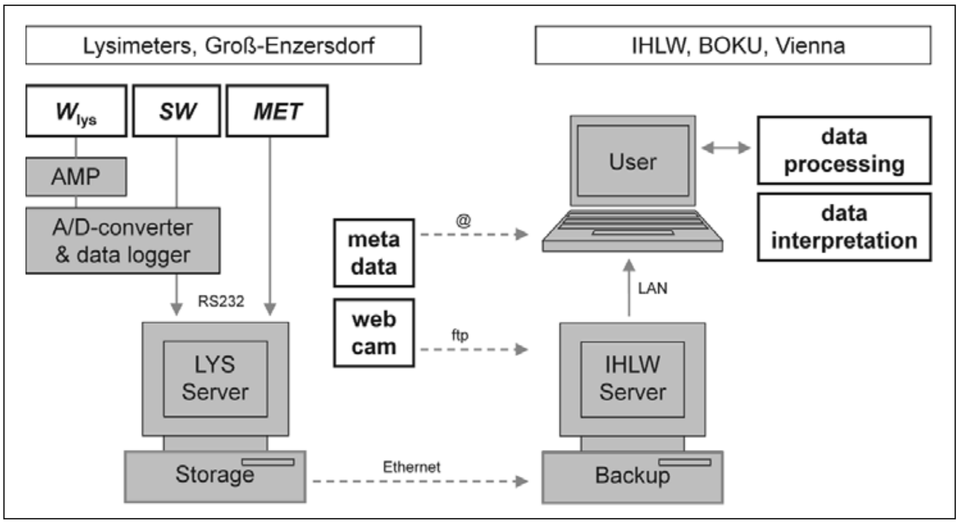


Figure 2: Scheme of data transmission and storage
Abbildung 2: Schematische Darstellung von Datenübertragung und -speicherung

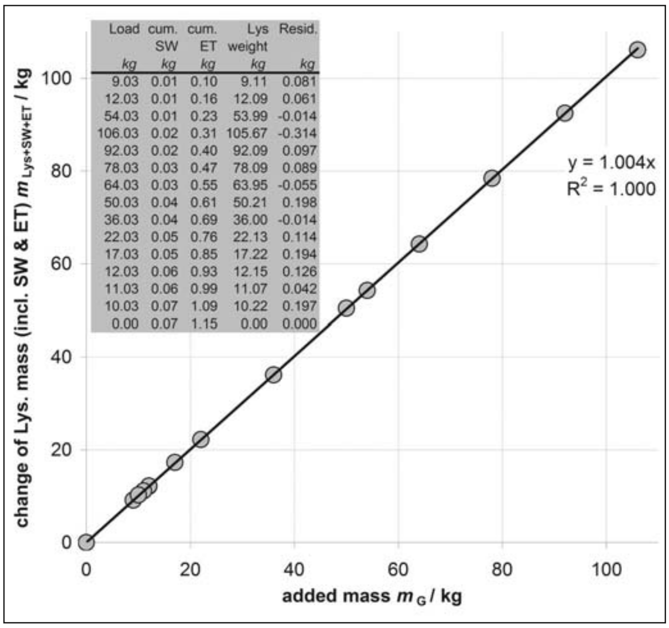


Figure 3: Calibration of the weighing system
Abbildung 3: Kalibrierung des Wiegesystems

## 2.3 Fitting smoothing functions

Weighing data from the grass reference lysimeter and weather data (wind and rain) from September 23rd to October 21st, 2009 were utilized for detailed interpretation. This period was selected mainly because of its wide range of wind velocity – 10-minute wind velocity in 10 m height ($u_{10}$) ranged from zero to 13 m·s$^{-1}$. Hence, rather smooth as well as severely noisy weighing data were found within the selected period. Furthermore, no drainage water and several days without rainfall occurred in the selected period, which reduced sources of possible inaccuracies.

Two types of smoothing functions were tested: a natural cubic approximation spline with discontinuities (for considering rainfall an irrigation), and a basic piecewise (daily) sigmoid function of the form

$$y(x) = a + b \,/\, (1 + \exp\,(-\,(x - c) \,/\, d)). \qquad (4)$$

In contrast to the sigmoid function, spline smoothing could be applied to longer than daily datasets. However, a sound smoothing factor was determined manually for the respective dataset depending on wind velocity and precipitation. The standard factor was 0.001, a higher smoothing factor (0.01) giving less curvature had to be chosen for days with highly wind-affected data (Table 1).

Evaluation criteria were applicability and quality of fitting between observed ($W_i$) and predicted data ($W_{i,p}$) expressed as root mean squared error (*RMSE*) (Eq. 5).

$$RMSE\,\left(W_{i,p}, W_i\right) = \sqrt{\frac{\sum_{i=1}^{n}(W_{i,p} - W_i)^2}{n}} \qquad (5)$$

An example demonstrates the advantage of smoothing when evapotranspiration is determined on a shorter than daily time interval (e.g. hourly).

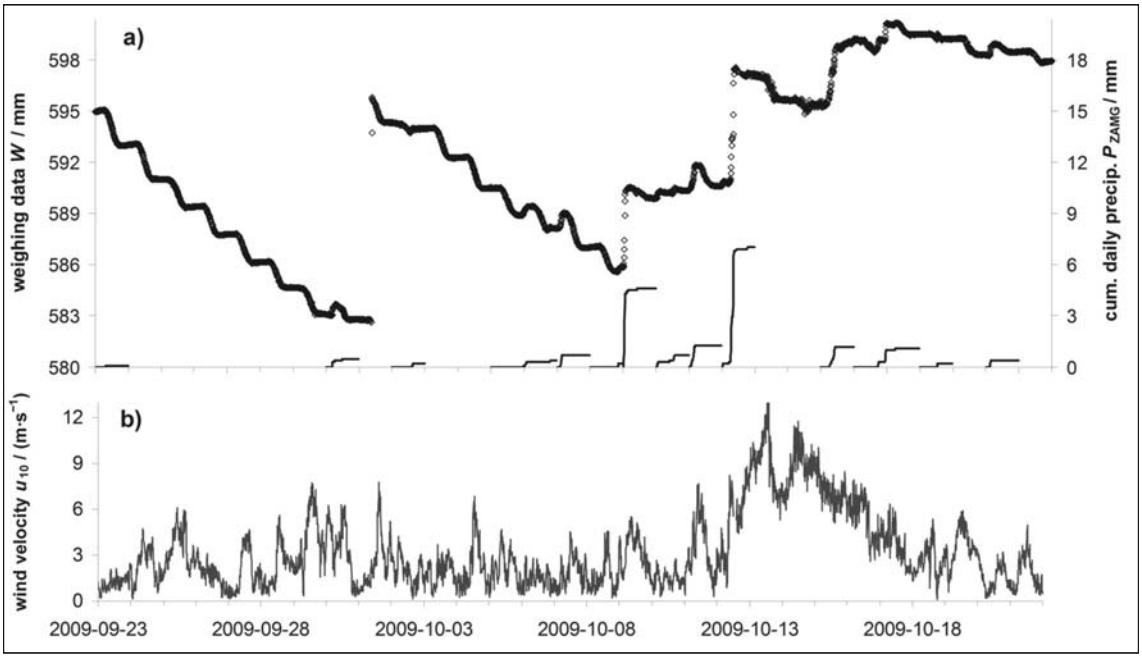


Figure 4:
(a) Lysimeter weighing data, cumulated daily precipitation, and (b) wind velocity during the entire investigated period
Abbildung 4:
(a) Lysimeter-Wiegedaten, kumulierter täglicher Niederschlag und (b) Windgeschwindigkeit während der Untersuchungszeitspanne

## 3 Results and discussion

As mentioned in section 2.3, no drainage water occurred during the studied period. Figure 1 illustrates (a) weighing data in equivalent water head (mm) and cumulated daily precipitation (mm), and (b) wind velocity in 10 m height. Raw data intervals were 10 minutes. Weighing data increased due to irrigation (on 2009-10-01) and precipitation, and decreased due to evapotranspiration from the grass surface.

Irrigation and daily precipitation (from 0:00 to 24:00) from ZAMG-weather data ($P_{ZAMG}$) and from changes in

Table 1: Daily data of precipitation (irrigation), wind velocity, and performance of smoothing functions for the entire investigated period
Tabelle 1: Tagesdaten von Niederschlag (Bewässerung), Windgeschwindigkeit und Anpassungsgüte der Glättungsfunktionen für die gesamte Untersuchungsperiode

| | $P_{ZAMG}$ (mm) | $P_{LYS}$ (mm) | Mean wind vel. $u_{10,mean}$ ($m \cdot s^{-1}$) | Max. wind vel. $u_{10,max}$ ($m \cdot s^{-1}$) | Sigmoid smoothing *RMSE* (mm) | Spline smoothing *RMSE* (mm) | Spline smoothing factor | Example |
|---|---|---|---|---|---|---|---|---|
| 2009-09-23 | 0.1 | 0.0 | 1.2 | 2.4 | no fitting | 0.025 | 0.001 | |
| 2009-09-24 | none | none | 2.3 | 4.7 | 0.040 | 0.028 | 0.001 | |
| 2009-09-25 | none | none | 3.5 | 6.1 | 0.035 | 0.024 | 0.001 | |
| 2009-09-26 | none | none | 1.7 | 3.5 | 0.033 | 0.021 | 0.001 | |
| 2009-09-27 | none | none | 1.9 | 4.7 | 0.033 | 0.021 | 0.001 | |
| 2009-09-28 | none | none | 2.2 | 5.6 | 0.028 | 0.022 | 0.001 | |
| 2009-09-29 | none | none | 4.0 | 7.7 | 0.033 | 0.033 | 0.001 | Figure 6 |
| 2009-09-30 | 0.6 | 0.6 | 3.4 | 6.3 | no fitting | 0.061 | 0.001 | |
| 2009-10-01 | 13.4 (irrigation) | | 2.5 | 7.8 | no fitting | 0.026 | 0.001 | |
| 2009-10-02 | 0.2 | 0.2 | 2.0 | 4.2 | no fitting | 0.019 | 0.001 | Figure 9 |
| 2009-10-03 | none | none | 1.9 | 3.7 | 0.027 | 0.012 | 0.001 | Figure 5 |
| 2009-10-04 | none | none | 2.3 | 6.8 | 0.032 | 0.015 | 0.001 | |
| 2009-10-05 | 0.2 | 0.2 | 2.2 | 4.7 | no fitting | 0.021 | 0.001 | |
| 2009-10-06 | 0.4 | 0.4 | 1.4 | 2.9 | no fitting | 0.021 | 0.001 | |
| 2009-10-07 | 0.8 | 0.8 | 2.0 | 4.5 | no fitting | 0.029 | 0.001 | |
| 2009-10-08 | 0.2 | 0.2 | 1.6 | 4.6 | no fitting | 0.024 | 0.001 | |
| 2009-10-09 | 4.8 | 4.7 | 3.2 | 5.5 | no fitting | 0.074 | 0.001 | |
| 2009-10-10 | 0.9 | 0.9 | 1.4 | 2.8 | no fitting | 0.017 | 0.001 | |
| 2009-10-11 | 1.3 | 1.3 | 3.4 | 7.7 | no fitting | 0.015 | 0.001 | Figure 10 |
| 2009-10-12 | 7.0 | 6.9 | 5.0 | 8.8 | no fitting | 0.049 | 0.001 | |
| 2009-10-13 | none | none | 9.1 | 13.0 | **0.111** | **0.115** | **0.01** | Figure 7 |
| 2009-10-14 | none | **0.3** | 8.7 | 11.8 | no fitting | 0.085 | 0.005 | |
| 2009-10-15 | 1.2 | **4.0** | 7.2 | 10.0 | no fitting | 0.086 | 0.005 | |
| 2009-10-16 | 1.3 | **1.7** | 5.5 | 7.9 | no fitting | 0.055 | 0.005 / 0.001 | Figure 11 |
| 2009-10-17 | 0.1 | 0.1 | 3.6 | 6.3 | no fitting | 0.017 | 0.005 | |
| 2009-10-18 | 0.4 | 0.4 | 2.6 | 5.4 | no fitting | 0.025 | 0.001 | |
| 2009-10-19 | none | none | 3.6 | 5.9 | 0.043 | 0.035 | 0.001 | |
| 2009-10-20 | 0.7 | 0.6 | 1.6 | 3.2 | no fitting | 0.028 | 0.005 | |
| 2009-10-21 | none | none | 1.8 | 5.0 | 0.029 | 0.020 | 0.001 | |

weighing data ($P_{LYS}$) are summarized in Table 1. Noticeable differences were identified only between October 14th and 16th due to snowfall that was detected by the lysimeter, but not by the pluviograph. Both smoothing functions worked well on data of days without precipitation. Individual factors for spline smoothing are also given in Table 1. *RMSE* was generally lower for spline smoothing, except for the drastically noisy data on October 13th. Since sigmoid functions are limited by their shape, sigmoid smoothing could not be applied on days with precipitation.

Six days with different weather conditions concerning precipitation and wind velocity were selected to illustrate exemplarily the performance of the smoothing functions (Figure 5 to Figure 11). Each figure shows (a) lysimeter weighing data with smoothing functions, and (b) wind velocity and eventually rainfall for a certain day.

Figure 5 to Figure 7 represent days without precipitation. In this case both smoothing functions were applicable. *RMSE* was low when weighing data were rather smooth. Figure 2 provides a characteristic illustration of decreasing profile water content due to plant water uptake and evaporation. In this example smoothing would not have been necessary; the original data allow a proper determination of *ET* (1.7 mm).

Figure 6 shows a day with changing wind conditions. *RMSE* between weighing data and smoothed data was equally low for both functions. Outliers were properly

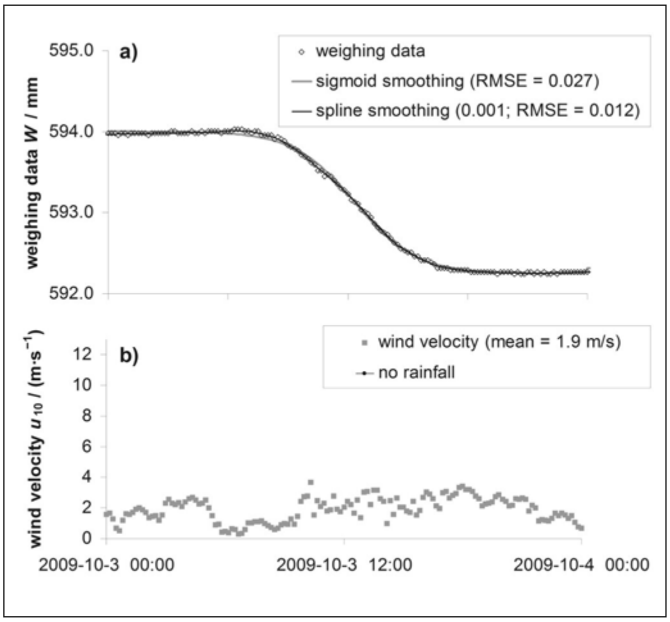


Figure 5: Sigmoid and spline smoothing on a day without rainfall and low wind velocity

Abbildung 5: Sigmoid- und Spline-Glättung an einem Tag ohne Niederschlag und mit niedriger Windgeschwindigkeit

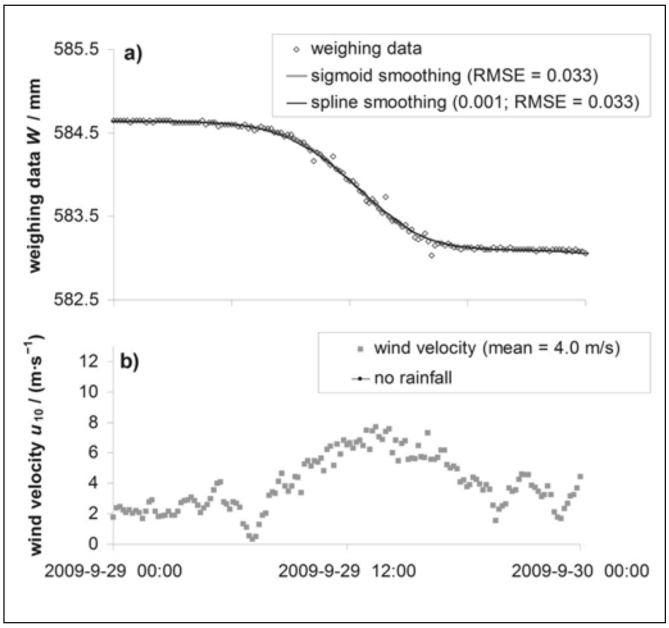


Figure 6: Sigmoid and spline smoothing on a day without rainfall and varying wind conditions that caused outliers in weighing data

Abbildung 6: Sigmoid- und Spline-Glättung an einem Tag ohne Niederschlag und mit wechselnden Windverhältnissen, welche Ausreißer in den Wiegedaten verursachten

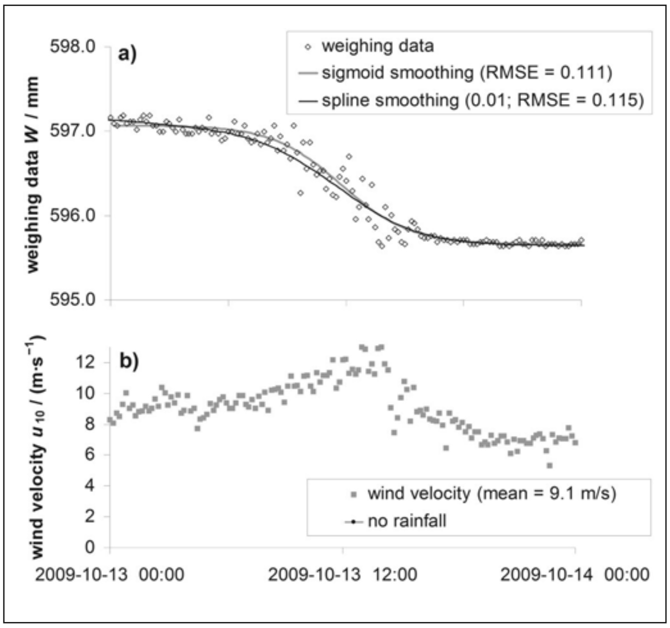


Figure 7: Sigmoid and spline smoothing of significantly noisy weighing data

Abbildung 7: Sigmoid- und Spline-Glättung von stark verrauschten Wiegedaten smoothed. Such outliers in the weighing data may complicate determination of mass changes in shorter time intervals.

High wind velocity on October 13th significantly affected weighing accuracy (Figure 7). In that case both smoothing functions offered a major improvement with respect to data interpretation, especially for short time intervals. Figure 8 illustrates evidently the advantage of smoothing functions when evapotranspiration is determined, for example, on hourly base (see Eq. 1: $SW = 0$, $P = 0$, so $ET = -\varnothing W$).

Spline smoothing behavior and data interpretation for days with precipitation is illustrated in Figure 9 to Figure 11. Smoothing with distinct factors delivered proper results applied on a day with low wind velocity (Figure 9) as well as on a day with changing wind conditions (Figure 10). *RMSE* was low in both cases, but smoothing factor had to be adjusted manually in order to avoid the flattening of slight variations. $P_{LYS}$ determined from weighing data corresponded well with $P_{ZAMG}$ at these days (Table 1).
Unintended flattening of small changes in weighing data is a general disadvantage of smoothing and filtering procedures, respectively. For weighing data from October 16th, for example (Figure 11), it was necessary to adjust the smoothing factor within the daily dataset to get a proper compensation of the noisy data (0:00–15:00) on the one hand, but still indicate changes due to precipitation (snowfall) on the other hand. This example illustrates challenges with respect to automatic data processing. The latter is recommended only if a final personal check is executed.

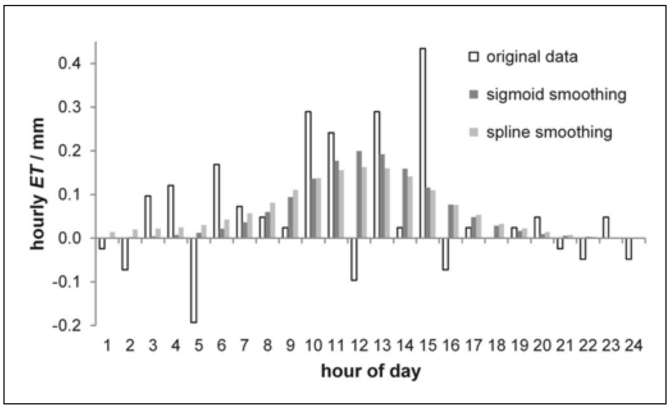


Figure 8: Hourly evapotranspiration (ET) on day 2009-10-13, determined based on original data and both smoothing functions
Abbildung 8: Stündliche Verdunstung (ET) am 13. Okt. 2009, ermittelt aus den Originaldaten sowie mithilfe beider Glättungsfunktionen

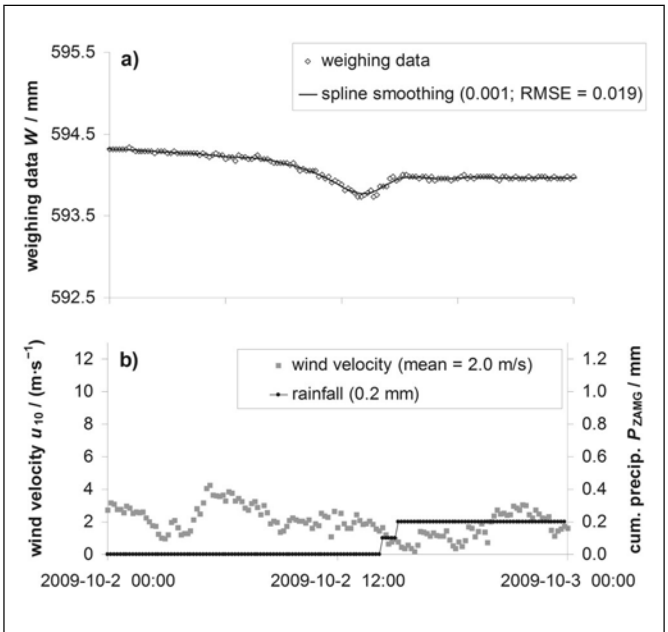


Figure 9: Spline smoothing on a day with low rainfall and low wind velocity
Abbildung 9: Spline-Glättung an einem Tag mit geringem Niederschlag und mit niedriger Windgeschwindigkeit

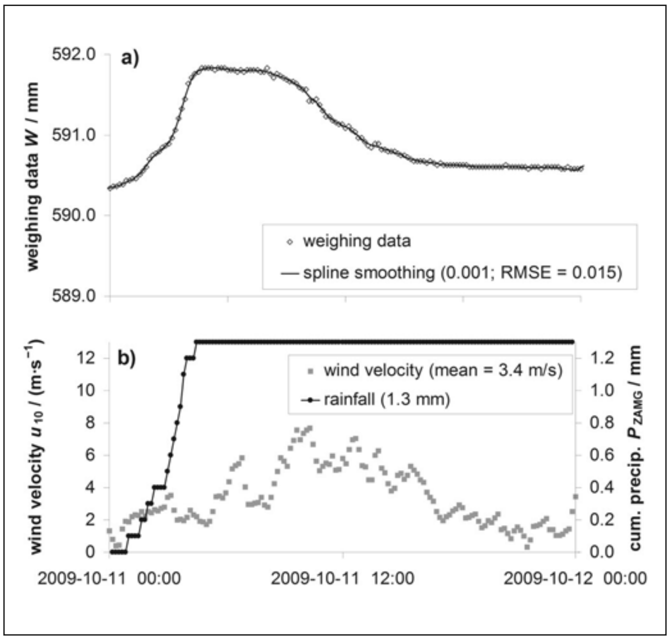


Figure 10: Spline smoothing on a day with rainfall and varying wind conditions
Abbildung 10: Spline-Glättung an einem Tag mit Niederschlag und wechselnden Windverhältnissen.

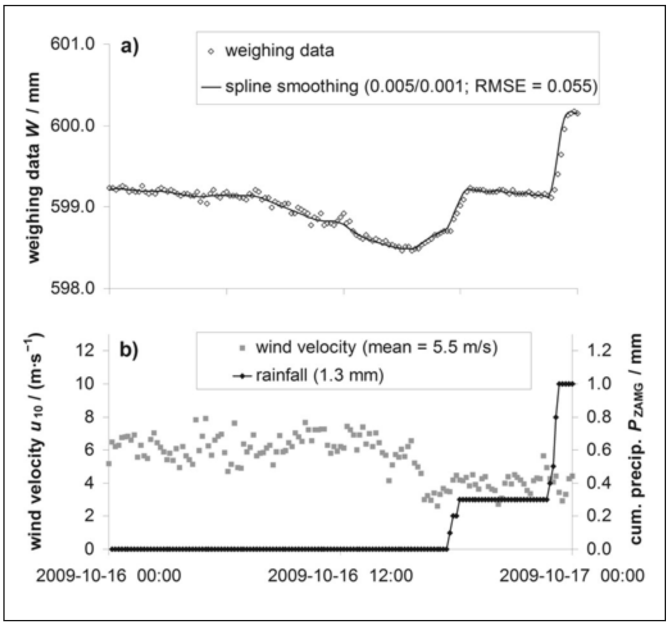


Figure 11: Spline smoothing on a day with high wind velocity and snowfall

Abbildung 11: Spline-Glättung an einem Tag mit hoher Windgeschwindigkeit und Schneefall

## 4 Conclusions

A natural cubic approximation spline and a basic piecewise sigmoid function were tested on a dataset of partly noisy data from a weighing lysimeter with respect to simplified data interpretation. The sigmoid function was straightforward to fit, and it gave sound results of the typical diurnal variation of evapotranspiration. However, its applicability was restricted to datasets of single days without rainfall. The spline function performed generally better, except for one day (out of 28) with severely noisy data. Application was user-friendly, as it was calculated for the whole dataset in one work process. On the other hand, in several cases it was necessary to adjust the smoothing factor, which was rather time-consuming.

Generally, both smoothing methods provided an option for enhancing interpretation of noisy lysimeter weighing data. A main advantage was seen in investigations focusing on shorter than daily time intervals.

## Acknowledgements

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