Authors Response

Dear Prof. Löw,

today, we have uploaded the revised version of our HESSD manuscript, entitled "Highresolution estimation of the water balance components from high-precision lysimeters". As already mentioned in the response letters to the reviewer's comments, we have considered all the comments and suggestions and adapted the manuscript accordingly.

In particular, we have applied the following main changes:

- We have re-written the abstract and large parts of the first section of the introduction now focusing more on the objectives of the study.
- We have added a short section (3.6) where we discuss the representativeness of the short time interval of measurements for testing the filtering approaches.

With respect to the suggestions of both reviewers to publish the study preferably as a technical note we agree that the content is rather technical. Nevertheless, such kind of comprehensive and well-described filtering scheme for high-precision lysimeter data is highly requested by the lysimeter community. In our paper, we provide this scheme and also take the advantage of having measurements of 18 lysimeters in parallel to evaluate and compare the presented approaches. When submitting the paper, we were inspired by the recent HESS paper by Peters et al. (2014) which is of similar technical nature and was also published as a regular research paper of comparable length. We think that the paper cannot be shortened substantially without losing the required justification and demonstration of the proposed method. In order to inform the reader early about the rather technical content of the paper and not to raise false expectations, we changed the title to "A comprehensive filltering scheme for high-resolution estimation of the water balance components from high-precision lysimeters" and revised the abstract accordingly.

We think that the main scientific input of our manuscript is to provide quantitative tools to generally improve the value of lysimeter data especially for highly dynamic precipitation patterns which are critical for water fluxes accross the soil surface.

We would be very glad, if the revised manuscript can now be considered for publication in HESS.

With kind regards,

Matthias Hannes , Ute Wollschläger, Frederik Schrader, Wolfgang Durner, Sebastian Gebler, Thomas Pütz, Johann Fank, Georg von Unold and Hans-Jörg Vogel

Reply to the comments (Referee 1)

We would like to thank the reviewer for the valuable and constructive comments and suggestions which helped us to improve the paper. We have addressed all the comments and suggestions in our response letter and adapted the revised version of the manuscript accordingly. In the following, we provide detailed answers to all comments and suggestions.

However, I found the paper describing a technical procedure with little advances in terms of science. Therefore, I found the paper more appropriate as technical note instead of scientific paper.

We agree with the reviewer that the paper is of very technical, however, for the large lysimeter community, of very relevant nature. The length of the paper required to explain the filtering procedures exceeds the length of *a few pages* as requested in the HESS guidelines for a Technical Note. When submitting the paper, we were inspired by the recent HESS paper by Peters et al. (2014) which is of similar technical nature and was also published as a regular research paper of comparable length. We think that the paper cannot be shortened substantially without losing the required justification and demonstration of the proposed method. In order to inform the reader early about the rather technical content of the paper and not to raise false expectations, we changed the title to "A comprehensive filtering scheme for high-resolution estimation of the water balance components from high-precision lysimeters" and revised the abstract accordingly.

1) The first question raised in my mind is related to the costs. It is shown in the paper that lysimeters can be very useful for estimating high-quality rainfall, evapotranspiration and drainage fluxes, also with high temporal resolution. However, I was wondering what are the costs of a lysimeter measurement system? I believe that a network of 18 lysimeter sensors is quite expensive, but likely I am wrong. How do they compare with standard raingauge or eddy-covariance sensors? What are the maintenance costs? What is the actual applicability of lysimeter data for hydrological applications? I would like the authors address some of these questions in the paper.

We would like to thank the reviewer for his/her valuable suggestions. We have revised large parts of the introduction and now address some of the points.

The reviewer is correct that lysimeter systems are expensive and require a high maintenance and data processing effort. However, they are currently the only method for directly measuring all components of the terrestrial water balance (see e.g. Seneviratne et al., 2012) and are regarded as standard for evaporation measurements which are used to validate data from other methods (Shuttleworth, 2012, p. 91). In addition, there already exists a large number of lysimeter facilities which provide these data. For example, Lanthaler and Fank (2005) carried out a survey about lysimeter stations in Europe and found more than 2400 lysimeter vessels, of which about 400 were weighable. So, despite the high costs, the value of lysimeter measurements has long been recognized and the number of existing lysimeters for various purposes is quite large. The number of 18 lysimeters from the Bad Lauchstädt site used in our study of course is rather exceptionel but only a small part of the filtering procedure presented in the paper (described in sect. 2.3.3) uses data from all lysimeters running in parallel. The filtering steps described in the preceding sections can be applied to a single lysimeter and do not require data from a whole set of lysimeters. Besides for the synchro filter, we have used the data from the neighboring lysimeters in section 3 to estimate the accuracy of the filtering procedure and to address uncertainties of the filtered flux estimates. We have clarified the manuscript in this respect.

Even if we do not have exact numbers, from our experience we assume the costs and maintenance effort for lysimeter and Eddy covariance systems to be quite comparable. For a detailed comparison of actual evapotranspiration and precipitation estimates from lysimeters with eddy covariance and rain gauge measurements, we would like to refer to the recent study of Gebler et al. (2015).

2) I was wondering what is the impact of using a dataset for a period of only 2 months on the results. I am aware that it is not easy to obtain lysimeter data, but I believe that the analysis with only 2-month might be not enough to really understand the goodness of the filtering scheme proposed in the paper. Very likely, in another season different results will be obtained. Is it possible to extend the analysis period? If this is not the case, I suggest the authors to add some comments on this issue.

We agree with the reviewer that the data set appears to be rather short in length. However, for discussing the effects of the filtering schemes on the data we need to look at them at very high resolution. A longer data set would have hidden the details of the filtering effects. We have discussed at which occasions (that are not included in the analysed time period) our filtering scheme would run into problems and we have not found many of them. Times which are always challenging to handle are dates where agricultural work (e.g. sowing, harvesting of crops, soil management (tillage), ...), which disturbes the weighing data, is conducted on the lysimeter. On these dates, manual filtering/data processing procedures will definitely be required before the automatic filtering routines can be applied. Other periods that might be challenging to handle are periods where the lysimeters are snow covered, since the snow cover on the lysimeter is often connected to the snow cover outside the lysimeters which, in turn, heavily disturbs the weighing data. This, however, is a well known problem in lysimetry which by nature produces unreliable weighing data that also need to be removed manually from the data set. Here, of course additional information about the site conditions (snow cover) during winter is required. All other situations should be well evaluable with the current filtering scheme. We now discuss this issue in the new section 3.6 in the revised manuscript.

3) The first step of the processing scheme is the manual filter. While I fully understand the

importance of the visual inspection of the data, this manual step does not allow applying the filter automatically, and hence may strongly limit the operational use of lysimeter data (e.g., for flood forecasting as reported in the Introduction of the paper). Can the authors add some comments on that? Specifically, what is the impact on the results if the manual filtering step is removed? We can accept a slight deterioration of the results if the processing scheme can be applied automatically.

As described in section 2.2.1, the manual filter is applied to remove defective data periods which induce heavy disturbances in the measured data, e.g. during maintenance or problems during data transfer. These exceptional events can have rather strong effects on the weighing data, are hardly detectable and currently cannot be compensated by the subsequent filters. Strictly speaking, this filtering step could potentially be automized by connecting the filtering procedure to a standardized field protocol of the technical staff and to the data transfer protocols which, however, is not the focus of this study. We will add a comment about this to the paper.

4) Finally, I believe that the authors should add the information about the availability of the filtering code. Do the authors make the code freely available? This would be highly important for the users of lysimeter data and it will be important to increase the relevance of the paper (at least in my opinion).

We would like to thank the reviewer for this valuable suggestion. The filtering code can be made available by the authors upon request. We have added a respective note to the acknowledgement section of the paper.

P572,L20: typo: ocuur corrected

P575,L1: typo: floodforecasting corrected

P575,L5: change to what extend in to what extent done

P579,L2: Can the authors quantify noticeable deviations?

Although such erroneous fluxes are typically in the order of 0.01 mm/h (depending on the smoothing time length), such errors can accumulate to an overestimation of about 22 mm in the cumulative water balance of a one year period, as the following simple estimation shows. As this is a systematic error that leads to overestimated values of precipitation and evapotranspiration, this effect should be considered in the data processing. (erroneous flux) \cdot (average night time) $\cdot \frac{1}{2}$ (half of the oscillation is positive) \cdot (days of the year))

 $0.01 \, mm/h \cdot 12 \, h \cdot \frac{1}{2} \cdot 365 \, y^{-1} = 21.9 \, mm/y.$ We have added this information to the manuscript.

P580,L13: Is ET the potential or the actual evapotranspiration? Please specify. Lysimeters always provide actual evapotranspiration. We now explain this in detail in the introduction and in the following simplify it as "evapotranspiration"

P590,L15: on the detailed control of the pumps at the lower boundary. Can the authors specify better this sentence? done

References

- Gebler, S., Hendricks-Franssen, H.-J., Pütz, T., Post, H., Schmidt, M. and Vereecken, H.: Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket. Hydrol. Earth Syst. Sci., 19, 2145-2161, doi:10.5194/hess-19-2145-2015, 2015.
- [2] Lanthaler, Ch and Fank, J.: Lysimeter stations and soil hydrology measuring sites in Europe - Results of a 2004 survey, Proceedings 11. Gumpensteiner Lysimetertagung, 5. and 6. April, 2005, http://www.raumberggumpenstein.at/cm4/de/forschung/publikationen/downloadsveranstaltungen/viewdownload/69lysimetertagung-2005/772-lysimeter-stations-and-soil-hydrology-measuring-sites.html.
- [3] Peters, A., Nehls, T., Schonsky, H., and Wessolek, G.: Separating precipitation and evapotranspiration from noise - a new filter routine for high-resolution lysimeter data. Hydrol. Earth Syst. Sci., 18, 1189-1198, doi:10.5194/hess-18-1189-2014, 2014.
- [4] Seneviratne, S.I., Lehner, I., Gurtz, J., Teuling, A.J., Lang, H., Moser, U., Grebner, D., Menzel, L., Schroff, K., Vitvar, T., and Zappa, M.: Swiss prealpine Rietholzbach research catchment and lysimeter: 32 year time series and 2003 drought event. Water Resour. Res., 48, W06526, doi:10.1029/2011WR0011749, 2012.
- [5] Shuttleworth, W.J.: Terrestrial Hydrometeorology, Wiley-Blackwell, 448 pp., 2012.

Reply to the comments (Referee 2)

We would like to thank the reviewer for the valuable and constructive comments and suggestions which helped us to improve the paper. We have addressed all the comments and suggestions in our response letter and adapted the revised version of the manuscript accordingly. In the following, we provide detailed answers to all comments and suggestions.

The paper does not represent a substantial contribution to scientific progress, being poor in new concepts, ideas and methods. In this form, the paper shows a simple signal-processing application rather than a lysimeter-based experiment.

However, I suggest a strong reorganization of the paper as technical note.

We agree with the reviewer that the paper is of very technical nature and does not describe a lysimeter-based experiment. However, for the large lysimeter community, filtering schemes for the new generation of high-precision lysimeters are highly important and build the basis for reliable scientific analyses of the terrestrial water balance components from lysimeter measurements which are used in many studies in agriculture, hydrology and climate sciences. The length of the paper required to explain the filtering procedures exceeds the length of *a few pages* as requested in the HESS guidelines for a Technical Note. When submitting the paper, we were inspired by the recent HESS paper by Peters et al. (2014) which is of similar technical nature and was also published as a regular research paper of comparable length. Hence, we would prefer keeping the study a research paper. In order to inform the reader early about the rather technical content of the paper and not to raise false expectations, we have changed the title to "A comprehensive filtering scheme for high-resolution estimation of the water balance components from high-precision lysimeters" and revised the abstract accordingly.

Experimental dataset is short in time extension (only 2 months) and poor in natural "water balance terms" variability. Results focus on little time windows, without interview longtime effect on water balance and emphasizing on the performance of the adopted filtering scheme.

We agree with the reviewer that the data set appears to be rather short in length. However, for discussing the effects of the filtering schemes on the data we need to look at them at very high resolution. A longer data set would have hidden the details of the filtering effects. We have discussed at which occasions (that are not included in the analysed time period) our filtering scheme would run into problems and we have not found many of them. Times which are always challenging to handle are dates where agricultural work (e.g. sowing, harvesting of crops, soil management (tillage), ...), which disturbes the weighing data, is conducted on the lysimeter. On these dates, manual filtering/data processing procedures will definitely be required before the automatic filtering routines can be applied. Other periods that might be challenging to handle are periods where the lysimeters are snow covered, since the snow cover on the lysimeter is often connected to the snow cover outside the lysimeters which, in turn, heavily disturbs the weighing data. This, however, is a well known problem in lysimetry which by nature produces unreliable weighing data that also need to be removed manually from the data set. Here, of course additional information about the site conditions (snow cover) during winter is required. All other situations should be well evaluable with the current filtering scheme. We now discuss this issue in the new section 3.6 in the revised manuscript.

Abstract requires a strong rearrangement. Objects of the paper are poor and emphasize a simple mathematical application rather a lysimeter-based experiment P571-L1: precipitation or net precipitation? did you considered the intercepted precipitation? P571-L4: I do not agree that Eddy flux system is a direct method for ET measurement. ET value is an indirect estimation obtained from atmospheric measurements and "eddy flux", computed as a covariance between instantaneous deviation of wind speed and air water concentration. We have revised the abstract and now focus more on the objectives of the new filtering scheme. We agree that Eddy flux is not a direct method and have removed this statement from the abstract. In fact, lysimeters are the only direct field method for estimating evaportranspiration this is why a careful analysis of the obtained data is so important.

The first period of the introduction is confused. The boundary term is improperly allocated. The bibliography on lysimeter study is poor. Moreover, the paper of Robinson et al. (2004) regards a study over the lysimeter water collection efficiency (geometrical aspect) and on the knowledge of radionuclides transport (soil physical aspects).

We have revised large parts of the first part of the introduction and now focus on the value of lysimeter measuements as they are the only method that is able to provide direct estimates of all components of the terrestrial water balance, most importantly evapotranspiration. We also added futher references from climate and hydrological sciences (also large-scale studies) which have successfully used lysimeter data estimate evaportanspiration and to analyse hydrological trends or events (e.g. Seneviratne et al., 2012; Teuling et al., 2009). Nevertheless we would like to point out that the intention of the paper is not to develop a complete review about lysimeter studies but to provide a comprehensive filtering scheme for providing high-quality data for subsequent analyses. A review of several existing papers dealing with the filtering of lysimeter data is provided in the second part of the introduction.

I suggest an overview on the error types and on their propagation theory. The period in P572-L16-29 is not clear. Is known that, when we obtain a water balance term from a difference operation, the errors are hidden in the computation.

This paragraph highlights the principal issue of measurement errors on the calculation of the separate components of the water balance. The reduction of these errors prior to this calculation is the objective of the paper and we now state this more clearly in the introduction. In the following paragraphs different kinds of error types and filtering examples are summarized and reviewed. The propagated error of a difference operation would simply be the sum of the error ranges of the two measurements but this is not the type of problem we are dealing with. We aim to reduce errors that are highly variable in time and depend on highly varying influences. The strategy followed in this paper is to minimize such errors prior to the mass balance calculations and to estimate the residual uncertainty by varying the filter parameters as described in the text.

P573-L25.However, for integrating evapotranspiration data from lysimeters into larger-scale hydrologic or climate models, adequate filtering algorithms are essential to provide the required data accuracy. Relatively to the above sentence, question raised in my mind is related to the costs, especially when lysimeter method are used for regional scale study. Moreover, your data quality, obtained with sophisticate filtering procedure, is scientifically and economically justified when up-scaling errors are considered? I doubt on the applicability of lysimeter data for hydrological forecasting!!

This statement indeed was somewhat unfortunate and we have clarified these formulations in the introduction. Nevertheless, there exist a number of studies evaluating catchmentor even regional- or continental-scale hydroclimatic processes with the help of lysimeter data such as the 2003 drought event in Europe (Seneviratne et al., 2012) or the evaluation of main drivers of evapotranspiration at continental scale by Teuling et al. (2009). In these studies, the lysimeter measurements are used as very valuable reference data as they provide estimates of all terrestrial water balance components, most importantly evapotranspiration. We do not advocate to use lysimeters as representative for the water balance at much larger scales. However there is a lot to learn from lysimeters on the separation of precipitation into the various flow components and on processes of plant-soil interactions. It is this knowledge that has the potential to be transferred to larger scales.

As explained in the abstract, objects emphasize a simple mathematical application rather a lysimeter-based experiment.

Please refer to our response to the first comment.

Relatively to the Smoothing filter (2.2.4), seem that SavitzkyGolay filter and moving average have the same performance to reduce the errors. Only when will set a 1st degree polynomial, SG filter has comparable performance with moving average. Moreover, SG has the capability of detects particular events (dew and rime) included into data series. The performance is linked to the choice of polynomials degree and windows length.

Of course, the SG-Filter has different characteristics compared to the moving average depending on the used polynomial degree and the window length. For the filtering of lysimeter weighing data, the filtering with a SG filter (of a polynomial degree of 2 or larger) compared to the moving average has the adavantage of a lower tendency of blurring but the disadvantage of a tendency of overshooting which also leads to an additional error source. These advantages and disadvantages were discussed by Schrader et al. (2013). For low smoothing times as used in this study, the influence of blurring is highly reduced. Therefore we prefered the MA filter. The remaining influence of the effect of smoothing was discussed in detail. However, the difference of the various smoothing filter types will at least vanish for the limit of averaging times $t \rightarrow 0$, so that in the case of very low averaging times, the differences will be minor. In the lysimeter community different preferences to smoothing filters exist, and it is possible to use the suggested filtering scheme with other smoothing filter types.

References

- Peters, A., Nehls, T., Schonsky, H., and Wessolek, G.: Separating precipitation and evapotranspiration from noise - a new filter routine for high-resolution lysimeter data. Hydrol. Earth Syst. Sci., 18, 1189-1198, doi:10.5194/hess-18-1189-2014, 2014.
- [2] Schrader, F., Durner, W., Fank, J., Gebler, S., Pütz, T., Hannes, M., Wollschläger, U..: Estimating precipitation and evaportanspiration from precision lysimeter experiments. Procedia Environmental Sciences, 9, 543-552, doi:10.1016/j.proenv.2013.06.061, 2013.
- [3] Seneviratne, S.I., Lehner, I., Gurtz, J., Teuling, A.J., Lang, H., Moser, U., Grebner, D., Menzel, L., Schroff, K., Vitvar, T., and Zappa, M.: Swiss prealpine Rietholzbach research catchment and lysimeter: 32 year time series and 2003 drought event. Water Resour. Res., 48, W06526, doi:10.1029/2011WR0011749, 2012.
- [4] Teuling, A.J., Hirschi, M., Ohmura, A., Wild, M., Reichstein, M., Ciais, P., Buchmann, N., Ammann, C., Montagnani, L., Richardson, A.D., Wohlfahrt, G., and Seneviratne, S.I.: A regional perspective on trends in continental evaporation. Geophys. Res. Let., 36, L02404, doi:10.1029/2008GL036584, 2009.

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High-resolution A comprehensive filtering scheme for high-resolution estimation of the water balance components from high-precision lysimeters

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Discussion Paper

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Abstract
Lysimeters offer the opportunity to determine precipitation, evapotranspiration and groundwater-re with high accuracy. In contrast to other techniques, like Eddy-flux systems or evaporation pans, lysimeters provide a direct measurement of evapotranspiration from a clearly defined surface area at the scale of a soil profile

Large weighing lysimeters are currently the most precise method to directly measure all components of the terrestrial water balance in parallel via the built-in weighing system. In particular the estimation of precipitation can benefit from the much higher surface area compared to typical raingauge systems. Nevertheless, As lysimeters are exposed to sev-

- eral external influences that could falsify the calculated fluxes. Therefore, the estimation of 10 the relevant fluxes requires an appropriate data processing with respect to various error sources. Most lysimeter studies account for noise in the data by averaging. However, the effects of smoothing by averaging on the accuracy of the estimated water balance is rarely investigated forces such as management practices or wind influencing the weighing data,
- the calculated fluxes of precipitation and evapotranspiration can be altered considerably 15 without having applied appropriate corrections to the raw data. Hence, adequate filtering schemes for obtaining most accurate estimates of the water balance components are required. In this study, we present a filtering scheme use data from the TERENO SoilCan research site Bad Lauchstädt to develop a comprehensive filtering procedure for high-precision lysimeter
- data, which is designed to deal with the various kinds of possible errors . We starting 20 from the elimination of large disturbances in the raw data resulting e.g. from management practices all the way to the reduction of noise caused e.g. by moderate wind. Furthermore, we analyze the influence of averaging times and thresholds required by some of the filtering steps on the calculated water balance . We further and investigate the ability of two adaptive
- filtering methods (the Adaptive Window and Adaptive Threshold filter (AWAT-filter) and the 25 consecutively described (Peters et al., 2014) and a new synchro-filter) in further reducing applicable to the data from a set of several lysimeters) to further reduce the filtering error. On the basis Finally, we take advantage of the data sets of all 18 simultanously running

lysimeters of the TERENO SoilCan research site in lysimeters running in parallel at the Bad Lauchstädt site to evaluate the performance and accuracy of the proposed filtering scheme. For the tested time interval of two months, we show that the estimation of the water balance with high temporal resolution and good accuracy is possible.

Introduction 1 5

The determination of water fluxes across the boundary layer between soils, plants and ne determination of water fluxes across the boundary layer between soils, plants and mosphere and their temporal dynamics is of fundamental importance for the understanding the Large weighing lysimeters are currently the only method for directly measuring all components atmosphere and their temporal dynamics is of fundamental importance for the understanding of the

- ,Paper of the terrestrial water balance (Goss and Ehlers, 2009; Seneviratne et al., 2012) including 10 precipitation, actual evapotranspiration (in the following referred to as evapotranspiration), soil water storage and deep drainage (e.g., van Bavel, 1961; Howell et al., 1991; Yang et al., 2000; Peters et al., 2014). Particularly for determining actual evapo(transpi)ration, weighing lysimeters are the most accurate and reliable field method and the data are
- regarded as standard for evaporation measurements which are used to validate data from 15 other measurement techniques (Shuttleworth, 2012, p. 91). Despite the rather high costs for installation and maintenance, and the considerable effort for data processing, this is also a reason why numerous lysimeter facilities exist worlwide. For example, Lanthaler and Fank (2005) carried out a survey about lysimeter stations in Europe and found more
- than 2400 lysimeter vessels, of which about 400 were weighable. Estimates of water and 20 energy balance. While it is challenging to obtain direct measurements of these fluxes in the field, lab measurements are restricted to small systems and artificial boundary conditions. Modern lysimeters offer the possibility of measuring the relevant fluxes of natural soils under atmospheric boundary conditions and are therefore often seen as tools for bridging the
- gap between lab and field measurements. Lysimeters have a long tradition of measuring 25 groundwater recharge. Their ability of measuring also water fluxes at the soil-atmosphere interface was soon recognized. Today balance components from this type of lysimeters

Discussion Paper

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have been used in numerous studies in agriculture, hydrology and climate sciences, e.g. for estimating crop water use efficiency (e.g., Young et al., 1996), ground water recharge (e.g., Yang et al., 2000), or for modelling water and/or solute dynamics in soils (e.g., Loos et al., 2007). In recent years, even catchment- or regional- to continental-scale hydroclimatic

- processes have been analysed with the help of lysimeter data such as the 2003 drought 5 event in Europe (Seneviratne et al., 2012) or the evaluation of main drivers of evapotranspiration at continental scale (Teuling et al., 2009). In these studies, the lysimeter measurements are used as valuable reference data for evapotranspiration. Furthermore, data from weighable
- 10

Used as valuable reference data for evapotranspiration. Furthermore, data from weighable lysimeters have been used for comparing evapotranspiration and precipitation estimates with other measurement techniques such as Eddy covariance data and rain gauges (e.g., Evett et al., 2012; Gebler et al., 2015). Technically, high-precision weighing systems make modern lysimeters an ideal and very precise measurement tool for both demands determining the different water balance components (Fank and von Lineid, 2007). The and the high temporal resolution of modern lysimeters (Fank and von Unold, 2007) . The and the high temporal resolution of modern lysimeter

measurements allows investigations of detailed processes at the data allows a detailed 15 separation of precipitation and evapotranspiration fluxes across the soil-plant-atmosphere interface -

However(e.g., Fank, 2013; Schrader et al., 2013; Peters et al., 2014). Nevertheless, the derivation of accurate fluxes with high precision from lysimeter-measurements requires an adequate data processing due to multiple sources of errors affecting the measurement

20 systems. Besides weighing system errors, measurements of field lysimeters are exposed to several external influences. External errors are, for example, vibrations induced by wind or field work, mass changes due to animals like mice or birds, influences due to sampling from the seepage water reservoir. Therefore, a preceding filtering procedure for the measured data is mandatory to evaluate the fluxes with high accuracy.

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Although processing of the raw data prior to the water balance calculations. This is because, although the determination of fluxes from the weighing data is straightforward, precipitation (P) and evapotranspiration (ET) have to be separated in an indirect way. Positive fluxes at the soil-atmosphere-interface are interpreted as $\frac{P}{P}$ and $\frac{P}{P}$ and negative fluxes as ET, assuming that these processes do not ocuur simultanously<u>occur simultaneously</u>. This algorithmic separation can lead to large errors in the calculated individual fluxes, if <u>external</u> <u>alterations of the mass data and</u> noise-induced oscillations are not filtered from the data and therefore are interpreted as P or ET fluxes. Even though, for some applications (e.g., for modeling bare soils) it may be sufficient to know only the net flux at the soil-atmosphere

- for modeling bare soils) it may be sufficient to know only the net flux at the soil-atmosphere interface. The differentiation between P and ET is essential, when transpiration processes come into play. This is due to the fact, that for soils covered by vegetation, Besides internal weighing system errors, external errors are, for example, vibrations induced by wind (e.g., Howell et al., 1995), mass changes due to soil management, animals like mice or birds
- stepping on the lysimeter, or influences due to sampling from the major part of ET is lost by transpiration, and this water is removed via root water uptake from deeper regions of the soil. A mixing of surface and subsurface fluxes would lead to errors when modelling these processes. seepage water reservoir.

There already exist a number of studies dealing with filtering procedures for lysimeter
 mass data. A common method to remove the noise is a smoothing of the data with a static or a moving mean. Although widely applied in the literature, the effects of smoothing and averaging on the accuracy of the estimated fluxes are rarely discussed. For example, Meissner et al. (2007) investigated the ability of lysimeters measuring to measure small changes in water storage considered as dew and rime with a temporal resolution of one hour. In contrast, Nolz et al. (2013a) report wind influences on the weighing signal and suggest an averaging time of 30 minutes. In their recent studies (Nolz et al., 2013b, 2014), smoothing is done with a natural cubic spline and manually adjusted smoothing factors. While an enlargement of the smoothing time window leads to a reduction of noise effects (noise error), the temporal resolution is reduced and an increasing part of the precipitation is lost due to a mixing with eventuation (mixing error). Canaidering this isource, Veughan et al.

to a mixing with evapotranspiration (mixing error). Considering this issue, Vaughan et al. (2007) present a filtering method that is based on the fitting of the mass curve. However, their investigation is based on a data set with a time temporal resolution of 1 h and the process details are further reduced by the fitting algorithm. In their study from 2009 Vaughan

and Ayars (2009), data smoothing is done with a Savitzky-Golay-filter operating over a time period of a minimum of one hour.

First steps in investigating filtering schemes for evaluating temporally highly resolved components of the water balance on the basis of synthetic and field data were presented by Schrader et al. (2013) discussing the issue of falsifying fluxes by large averaging times. Fank

- (2013) used a one-year high-resolution time series of field data from the hydro-lysimeter at the Wagna research station to estimate precipitation and evapotranspiration. He showed the influence of different averaging times on the resulting water balance estimates and was the first to recommend temporally adaptive thresholds for the filtering of measurement noise from the data. Recently, Peters et al. (2014) proposed a filtering algorithm, the so-called
- Adaptive Window and Adaptive Threshold filter "AWAT") for lysimeter weighing data to obtain temporally higher resolved data by adapting the used filtering parameters according to the signal strength . Despite these efforts of developing adequate strategies for retrieving the water balance with high accuracy and high temporal resolution, the influence of these filtering approaches on the accuracy and resolution on a basis of real data sets is still
- hardly investigated. However, for integrating evapotranspiration data from lysimeters into larger-scale hydrologic or climate models, adequate filtering algorithms are essential to provide the required data accuracy. Furthermore, the relevance of short-term rain events with a duration below one hour but high precipitation rates is well known. This is relevant not only for floodforcasting but also for the wetting behaviour of the soil and successfully applied

this filter to a 4.5 months time series of field data from the lysimeter station Marienfelde. This study is motivated by the following two questions: i) What accuracy of the water balance can be achieved at a temporal resolution in the subhour regime (15min), and ii) to what extend do the choice of the filtering parameters or the use of more elaborate adaptive methods influence this accuracy? We first present a comprehensive processing scheme, which accounts for the different error types on the lysimeter weighing data . We then analyze the effects The objective of this study is to first develop a comprehensive filtering procedure for high-precision lysimeter data, which is designed to deal with various kinds of possible errors starting from the elimination of large disturbances in the raw data resulting e.g. from management practices all the way to the reduction of noise caused e.g. by moderate wind. Second, we analyze the influence of averaging times and thresholds required by some of the filtering parameters for noise reduction steps on the calculated fluxes. We further water balance and investigate the ability of two adaptive filtering methods (the Adaptive Window and Adaptive Threshold (AWAT) filter and the consecutively described AWAT-filter (Peters et

- al., 2014) and a new synchro-filter) in further reducing applicable to the data from a set of several lysimeters) to further reduce the filtering error. To differentiate between the effects of the noise error and the mixing error, we split our data into subsets, where only one of both effects is relevant. For our investigations, we use data sets from 18 high-precision lysimeters covering a period of two months. All lysimeters are located at the experimental station Bad
- ¹⁰ Finally, we take advantage of the data sets of all 18 lysimeters running in parallel at the TERENO SoilCan Site in Bad Lauchstädt , which is part of the TERENO SoilCan network in Germany . This set of parallel lysimeters can be considered as real replicates, as they are exposed to the same atmospheric boundary condition. Thus, they provide information on the (Pütz et al., 2011) to evaluate the accuracy and robustness of the filtering approach and,
- ¹⁵ moreover, errors that are difficult to distinguish from real events can be identified proposed filtering scheme.

2 Material and Methods

2.1 Data AquistionLysimeter measurements

The lysimeters used for this study are part of the TERENO SoilCan project (Pütz et al., 2011). In the framework of the TERestrial ENvironmental Obervatories (TERENO), a network of observatories has been set up to explore long-term impacts of climate and land use change on a regional level (Bogena et al., 2006; Zacharias et al., 2011). Following this idea, the TERENO SoilCan project comprises a total of 126 lysimeters that are distributed over 13 sites throughout Germany (Pütz et al., 2011).

- The lysimeters of the SoilCan network are arranged in hexagons of six lysimeters (consecutively indicated by L1, L2, ...) at one plot. Figure 1 shows a schematic drawing of the lysimeter configuration. Each of the lysimeters has a circular surface of 1 m² area and a depth of 1.5 m. The lysimeters are equipped with different sensors for measuring matric potential at 10 cm, 30 cm, 50 cm and 140 cm below the ground surface. The volumetric soil water content is measured with TDR sensors at three different depths (10 cm, 30 cm, 50 cm). Further measurements of CO₂ concentration, soil heat flux and net radiation are
- conducted continuously. The matric potential at the lower boundary is controlled by a set of suction cups, such that water can be pumped into and out of the lysimeter. An automatic pumping system is used to adjust the pressure head at the lower boundary to the value of three reference tensiometers installed in the field. The lysimeters are equipped with a
- weighing system that allows a resolution of 10 g (respectively 0.01 mm) for measuring the mass of the lysimeter, and 1 g for recording the mass of the seepage water reservoir. The mass data we refer to as raw data or signal was internally aquired at a frequency of 0.2 Hz (5 sec), averaged with a moving mean over 6 of these 5 sec values and logged with a frequency of 1 per minute.
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At the research site in Bad Lauchstädt, three hexagons (here indicated by BL1, BL2, BL3) with a total of 18 lysimeters were set up. Two hexagons (12 lysimeters) are cultivated with crops (BL1 and BL2). In the period of the presented data set (01. March to 31. May 2013), the grown crop was winter rape. The other 6 lysimeters are covered with grass. For each hexagon, the soils originate from two different locations in Germany. Therefore,

in Bad Lauchstädt, we can investigate <u>data from</u> six different soil textures from six different locations, each location represented with a total of three lysimeters. For the evaluation of the filtering algorithms, we used the data sets of all the 18 lysimeters for a period of two month in spring 2013.

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2.2 Basic Comprehensive processing scheme for high-precision lysimeter data basic procedure

Lysimeters are always directly exposed to environmental conditions and therefore prone to multiple error sources. The determination of an accurate time-resolved water balance requires an adequate data processing to eliminate these influences. From our experience, a proper processing scheme We propose a processing scheme that should include five major steps , which are listed in figure 2.

(figure 2): The threshold filter and the smoothing filter are described in detail by Schrader et al. (2013) and will therefore only be shortly addressed. To this basic scheme we added a manual filter, a median filter and an oscillation threshold filter as further components, which we consider as to be essential for the determination of temporally highly resolved fluxes using lysimeter data. It is important to conduct the filtering in the suggested sequence. In particular the filtering of discrete events (filter steps 1-3) has to be done prior to the filtering of noise (4-5). Otherwise, distinct events will be blurred by smoothing and cannot be filtered effectively afterwards.

Apart from the first filter step (manual filter), all the filter steps are applied to the mass data of the seepage water tank, corresponding to the seepage water flux, as well as to the summarized mass data of lysimeter and seepage water tank, corresponding to the flux at the soil-atmosphere interface (*P* and *ET*). Only the manual filter is applied to the mass data sets of the seepage water tank and the lysimeter (before summarizing it). The threshold filter is first applied to the seepage mass data (especially due to automatic emptying of the seepage water tank) before calculating the sum of lysimeter and seepage mass. In the following subsections, we will describe and discuss each of the individual filtering steps in detail.

20 2.2.1 Manual filter

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After a step of pre-processing, which may include interpolation or filling of missing data points if necessary, a manual filter should be the first step in data processing. It is used

to remove defective data periods. The most common error sources in this respect are heavy external influences affecting the weighing data, which are e.g. caused by harvesting, maintenance or measurements on the lysimeters. The influence of such forces on the

- ²⁵ Ing, maintenance or measurements on the lysimeters. The influence of such forces on the weighing data can be very strong (or hard to recognize in other manners), so that the subsequent filtering algorithm will not succeed in removing these errors. It may also be feasible, to automize this filtering step by connecting the processing code to standardized field protocols of the technicians and the data transfer logs of the lysimeters but this refers to other than mass data and is not within the scope of this study. Another option could be to determine heavily affected time periods by checking the automatically processed results. In
- the presented data set, we exposed a manual filtering for some hours at three different days with known maintenance and at two further periods, where one single lysimeter showed distinct outliers in the data. During these periods, there was no precipitation <u>detected by the</u> <u>nearby raingauge</u> and the weighing data was interpolated to fill the measurement gaps. The effect of the manual filter is illustrated in figure 3b compared to raw data (figure 3a).

10 2.2.2 Threshold filter

The threshold filter has the capability of removing strong and short external influences from the data set. Typical error sources are mass changes during automatic emptying of the seepage water storage tanks, humans or (heavy) animals stepping on the lysimeter or malfunctions in data transfer. By defining thresholds for the maximum possible precipitation, evapotranspiration and the maximum mass change in the seepage water reservoir, the filter can detect physical physically unrealistic fluxes. These data points are removed and substituted by linear interpolations. Small errors, caused by wind effects or, for instance, by small animals, cannot properly be removed from the data at this stage because the filter threshold should not undershoot high, but still reasonable water fluxes. The description of

the parameter selection is given in section 2.3.1. An example for the benefit of the threshold filter is illustrated in figure 3c.

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2.2.3 Median filter

While the threshold filter is a suitable tool to eliminate large errors, influences, that lead to only small mass changes (like small animals, wind, temperature-effects, signal noise ...) are
²⁵ not removed. The first step for a reduction of these errors is the application of a median filter that eliminates short-term spikes from the data set that are below the limits of the threshold filter. The effect of the median filter is illustrated in figure 3d. This filter is a very effective amendment to the threshold filter for eliminating discrete errors. As described in section 2.3.1 we use a time window of 15 minutes for the calculation of the median.

5 2.2.4 Smoothing filter

While the previous filter steps are designed to eliminate discrete errors, the last two filter steps are designed to deal with remaining diffuse noise. The primary step in removing noise is a smoothing filter, where different smoothing algorithms can be used. Schrader et al. (2013) discussed the application of a second degree Savitzky-Golay filter (which is based on a polynomial approximation) as well as the simple moving average which both show different advantages and disadvantages for the application of lysimeter data. The overall issue of such smoothing filters is the blurring of short-time effects and the mixing of *ET* and *P*. To avoid temporal distortion or even elimination of short-term events, it is advisable to restrict smoothing to a short time period. In our calculations, we used the simple moving average with a time window of n = 15 minutes, to restore a high temporal resolution and to avoid distinct blurring effects (see section 2.3.1). The moving average calculates the arithmetic mean of the data points in the time window $t_{i-(n-1)/2}$ to $t_{i+(n-1)/2}$ for each data point at time t_i . Figure 3e gives an illustration of the effect of the smoothing filter.

2.2.5 Oscillation threshold filter

Smoothing filters are not able to eliminate all fluctations, especially when they are limited to short time windows to retain a high temporal resolution and to preserve short term effects. In situations where the external forcing (precipitation or evapotranspiration) is low or van-

ishing, remaining noise will falsify alter the calculated fluxes. Figure 3f illustrates the issue of remaining noise components in the calculated fluxes before and after the use of the oscillation threshold filter. Although the oscillatory fluxes are small, they may lead to noticeable deviations in the cumulative values of precipitation and evapotranspiration.

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One way of filtering these oscillations would be a simple threshold algorithm, where only fluxes, that exceed a certain threshold are considered as real fluxes. This technique has the disadvantage, that slow changes (during evapotranspiration, light rain, dew or snowfall) will not be registered. To avoid this problem, our algorithm ensures that also slow processes will be recognized as long as their contribution in a sum exceeds the defined threshold. Starting from an initial data point, this algorithm determines the next point in time where the cumulative mass change exceeds a predefined threshold. When this threshold is reached, the intermediate data points are linerally interpolated:

$$M_k = M_i + \frac{M_l - M_i}{t_l - t_i} \cdot (t_k - t_i) \text{, for } i < k < l - 1$$
(1)

In this formula, M is the sum of the masses of the lysimeter and the seepage water tank at time t, k indicates the starting point, and l the first point, where the threshold has been exceeded. Small fluctuations that are not due to real fluxes are eliminated. The oscillation threshold filter enables the registration of slow processes such as light rain events, snowfall or evapotranspiration, if they are lasting long enough to exceed the threshold as a sum. The functioning of this algorithm is illustrated in figure 3f. Nevertheless, processes with a low flux rate and a short duration – such that the threshold is not reached – are still not registered and they fall out of the precision range defined by the oscillation threshold. Thus, the threshold value defines the limit of processes that cannot further be resolved because they cannot be distinguished from the remaining noise. The choice of the oscillation threshold value is discussed in section 2.3.1.

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20 2.2.6 Calculation of fluxes

After the execution of the presented filtering steps, the fluxes can be calculated from the processed data set. The seepage flux S is simply calculated from the increase in the mass m_S of the seepage water reservoir.

$$S(t_i) = \frac{m_{\mathsf{S}}(t_{i+1}) - m_{\mathsf{S}}(t_i)}{t_{i+1} - t_i}$$
(2)

⁵ The calculation of precipitation and evapotranspiration requires a distinction of these cases. This separation implies the assumption that no evapotranspiration is occuring during rainfall events or that evapotranspiration is at least negligible.

$$J(t_i) = \frac{M_{i+1} - M_i}{t_{i+1} - t_i}$$
(3)

$$P(t_{i}) = \begin{cases} J(t_{i}) & \text{, if } J(t_{i}) >= 0\\ 0 & \text{, if } J(t_{i}) < 0 \end{cases}$$

$$e T(t) = \begin{cases} 0 & \text{, if } J(t_{i}) >= 0\\ -J(t_{i}) & \text{, if } J(t_{i}) < 0 \end{cases}$$
(4)
(5)

Here, *J* indicates the mass flux at the soil-atmosphere interface, *P* is precipitation and *ET* is evapotranspiration. Additionally to the mass changes due to these water fluxes, the biomass accumulation due to plant growth also leads to a continuous continuous mass change. Using the described separation procedure, this mass change is registered as pre-15 cipitation. The mass reduction due to harvesting is counted as *ET*. For a correct determination of the cumulative fluxes in the water balance, these fluxes have to be corrected with regarding regard to this effect. We In this study, we refrain from a detailed discussion of this long-term aspect and focus on the filtering of short-term fluctuations in the lysimeter data.

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20 2.3.1 Parameter Filter parameter selection

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The basic processing scheme provides all the necessary components to tackle the different error sources on the lysimeter weighing data and to obtain a time-resolved water balance. However, the operator has to define some parameters, which influence the quality of the filtering and the precision of the resulting fluxes. The choice of the threshold values in filtering step 2 (threshold filter) is rather simple and can be determined by the maximal pumping rate at the lower boundary of the lysimeter, the maximal precipitation rate and the maximal ET rate including a safety factor (see also Schrader et al. (2013)). The parameters that were used as standard in our calculations are listed in table 1.

The selection of the time window for the median and the smoothing filter (filter steps 3 and 4) is much more critical. While large time windows ensure an effective reduction of noise (noise error), such large averaging times also reduce the temporal resolution of processes 10 and lead to a progressive mixing of P and ET (mixing error), which also is an error source in the calculation of an accurate water balance. The influence of the smoothing filter and the oscillation threshold filter on the noise error and the mixing error is displayed in figure 4. By using the subsequent oscillation threshold filter, it is possible to shorten time periods for averaging and to retain a higher resolution of processes. Considering the high dynamics of 15 observed precipitation events of less than 20 minutes in periods of high evapotranspiration (i.e. short summer rain, see also examples in figure 7) we recommend a time window of 15 minutes at maximum, which is used in our calculations. This ensures keeping a high temporal resolution of our processed data set. This window length of 15 minutes is also sufficient for the purposes of the median filter, which is designed to eliminate local errors of 20 only some data points in the data and is also used for our calculations.

Finally, the only remaining parameter to choose , is the oscillation threshold value (filter step 5), which is used to remove remaining noise components from the data, while maintaining a high temporal resolution in the calculated fluxes. Figures 4a and b illustrate that a very effective elimination of noise is possible, using the oscillation threshold filter. Figure 4c shows further, that the combination of the short time short-time smoothing together with the oscillation threshold filter leads to a better temporal reflection of the precipitation process compared to the removal of oscillations by the use of a longer averaging time. However, it can be seen, that the oscillation threshold filter also leads to an underestimation of precipitation events, comparable to the described mixing error.

Higher oscillation thresholds increase the risk of filtering oscillations that represent real processes (e.g. dew formation). The threshold has to be chosen as large as necessary (to filter noise) and as small as possible (to retain slow processes and to prevent the underes-

- timation during rain events). This idea is reflected by the subsequently described adaptive methods, attempting to optimize this parameter with respect to signal. Beside the use of these techniques, we applied the oscillation threshold filter to derive a possible range for the cumulative water balance by selecting a maximum and a minimum value for the possible threshold. As minimum value, we used a threshold of 0 g, implying that every remaining
- oscillation is interpreted as real effects. To determine a maximum threshold, we investigated the fluxes of the different lysimeters during night time nighttime conditions and selected the threshold at a height, where nearly all of these night-time-oscillations nighttime oscillations vanished. For our data set, we ended with a maximum value of 50 g. This implies, that for the maximum threshold, only processes, which contribute with a minimum of 0.05 mm
- to the cumulative flux are considered in the water balance. While the use of the minimum threshold will lead to an overestimation of the cumulative fluxes of P and ET, the use of the maximum threshold will cause an underestimation of these values. We therefore assume to find the true values in between these limits.

2.3.2 Parameter adaptation using an estimate of the signal strength

²⁰ Peters et al. (2014) suggest to adapt the parameters for the smoothing window length and the oscillation threshold to the signal strength in the data. The idea behind this method is to increase the smoothing time window and the oscillation threshold in periods where the signal strength is low and the noise is becoming more dominant and to reduce them in situations where noise is less relevant. In their Adaptive Window and Adaptive Thresh-

- old (AWAT) filter algorithm, Peters et al. (2014) estimate the signal strength by applying a polynomial fit to the data within a predefined time window. The deviation of the data to the polynomial fit leads to a measure of the signal strength. This estimate is used to adapt the time window for smoothing as well as the oscillation threshold to the signal strength. The parameters are varied in a range between a minimum and a maximum value, predefined by the operator. For the oscillation threshold, Peters et al. (2014) suggested to choose the
- maximal resolution of the weighing system as minimum value. For our data set, we chose a minimum value of 10 g (respectively 0.01 mm). The further values applied for the AWATfilter are listed in table 2 together with the parameters applied in the filtering approach using parallel lysimeters as described in section 2.3.3.

2.3.3 Parameter adaptation using parallel lysimeters

- This-While all filtering steps described in the previous sections are applicable to data from single lysimeters, this method uses the combined information derived from a set of parallel lysimeters located at the same site for the adaptation of the oscillation threshold to the measuring situation. Such data are e.g. available at the TERENO SoilCan sites or at other larger lysimeter research stations with more than just one lysimeter. While external forcing by precipitation or evapotranspiration should lead to synchronous reactions of the different lysimeters, the erroneous oscillations are randomly distributed. To eliminate these fluctuations, the fluxes of the different lysimeters are compared at each data point. The adaptation of the threshold is done in a recursive procedure, starting with a minimum threshold value for the whole data period. After the calculation of the fluxes with the actual threshold value
- ²⁰ ues, the fluxes between the parallel lysimeters are compared. At each data point, where the individual lysimeters of the set show different signs in the calculated fluxes, the threshold is raised by one step. After the comparison at each data point, the recursion starts again with calculating the fluxes with the updated (now time dependend) threshold values. The recursion ends when the signs of the calculated fluxes are equal or a maximum threshold set walke is gained. This leads to a good reduction of poise in periods of fluctuations while
- value is gained. This leads to a good reduction of noise in periods of fluctuations while maintaining the detailed dynamics of processes , where the lysimeter masses show a dis-

tinct trend without random oscillations. In our study, we use an algorithmic comparison of six lysimeters , according to one hexagon of a SoilCan SoilCan hexagon of our test site. To prohibit that one single lysimeter that may not react optimally, which would prevent the registration of small fluxes, we implemented the algorithm such that only an agreement of five lysimeters in the sign of the calculated fluxes is necessary, to prevent a lifting of the threshold in the recursion process. For our calculations we used a step width of 0.01 mm for the recursion, starting with a minimum threshold value of 0.01 mm to a maximum of 0.20 mm (see also table 2). We refer to this method as synchro-filter.

3 Results and Discussion

10 3.1 Flux dynamics

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The influence of the different processing steps on the calculated fluxes <u>on for</u> one example lysimeter is illustrated in figure 5. While the manual filter and the threshold filter succeed in eliminating large erroneous fluxes (figure 5b and c), the subsequent processing steps (figures 5d-f) lead to a pronounced reduction of small errors and noise. Because the filtering steps work on different scales, we zoom into the data for a good illustration of the effects.

To examine the remaining variability between the lysimeters after the data processing, we compared the calculated precipitation fluxes for the different lysimeters at our research site. As a first part of that comparison, the mean and the range of the calculated fluxes at across the soil-atmosphere interface of all 12 crop lysimeters have been calculated (we omitted the grass lysimeters in this consideration because of the different transpiration). The good accordance is illustrated in figure 6. The highest variation with a range of 4 mm/h corresponds to the event with the maximum precipitation rate of 20.2 mm/h.

3.2 Temporal resolution

The ability of preserving detailed dynamics and a good temporal resolution by using the basic filtering scheme becomes obvious when looking at the calculated fluxes. Figure 7a

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shows a heavy rainfall event on 9 Mai 2013 with a duration of only about 20 minutes, which would be smeared out to a moderate rainfall by applying larger averaging times. A light and short rainfall on 4 Mai 2013 in between situations of evapotranspiration is displayed in figure 7b. Larger averaging times would lead to a merging of ET fluxes and precipitation fluxes. Finally, figures 7c and d illustrate the intense dynamics of precipitation events in the examples of a medium rainfall event in the period from 26 April 2013 to 28 April 2013 and a light rainfall from 12 April 2013. A large part of this dynamics would be blurred with an averaging time of more than one hour.

3.3 Cumulative precipitation

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- For investigating the accuracy of the determined fluxes, the cumulative precipitation for 10 all 18 lysimeters at the Bad Lauchstädt site was calculated for the minimal and the maximal oscillation threshold. The range between the mean values for these two cases was plotted together with the measurement of the nearby raingauge (figure 8). The indicated filter uncertainty is representing the range of uncertainty, which results from the contrary influences of noise error and mixing error, and was calculated by using the minimal and 15
- maximal threshold as described in section 2.3.1. This consideration leaves us at the end of the data time series with a cumulative precipitation of (158.2±3.2)mm, indicating a remaining uncertainty of only 2%. Besides the filtering uncertainty, the variety in the calculated precipitation between the different lysimeters gives us a more integrated picture of the in-
- formative value of the estimated precipitation for field purposes. This variety can be caused 20 by systematic deviations between the systems, unfiltered influences on the different lysimeters or the natural heterogeneity in the precipitation. The standard deviation between the different lysimeters for the cumulative precipitation was about 2.7% of the total value (independent of the choice of the threshold value). If lysimeter measurements will be used as
- basis to estimate precipitation for a larger area, these two uncertainties have to be added, 25 which results in an uncertainty of approx. 5%. The comparison of the lysimeter results with the raingauge measurements shows a good accordance, with slightly lower values for the raingauge during the largest part of the time series. These lower values can be caused by

the known errors of the Hellmann-raingauge system (e.g., Richter, 1995) or by the heterogeneity of the rainfalls and the distance between the measurement devices. Figure 8b shows a comparison of the precipitation on a daily basis.

- Figure 9 shows the filter uncertainty together with the results for the adaptive and the
 basic approach using different parameter selections. In all the approaches, the data was processed with the first three filtering steps (manual filter, threshold filter, median filter) before doing further filtering steps. In the case of an averaging time of 5 min, we also reduced the time window for the median filter to 5 min. Only the approaches with a more extreme choice of the filtering parameters (5 min and 120 min smoothing window, 100 g threshold)
 lead to results that are outside the determined uncertainty range. For all the other parameters
- eter selections as well as the adaptive methods, the cumulative precipitation is inside the uncertainty range. The difference of the basic approach to the adaptive methods is therefore quite low and does not exceed the 2 % uncertainty. However, this may be due to the fact that the positive effect of remaining noise is compensated partly by a negative effect of the mixing error. If this would be the reason, an underestimation of precipitation during events
- would go in hand with an overestimation of precipitation during situations of low external forcing. Such a behaviour would lead to deviations in the time-resolved fluxes, even if these errors would cancel out in the cumulative balance.

To furher further examine if the more sophisticated filtering approaches (the AWAT-filter, and the synchro-filter) lead to a reduction of both these error components and therefore to a better accuracy of the calculated water balance over the whole time series, a partitioning of the data set into periods with and without precipitation was done. Figure 10 shows the different periods. Rainfalls with a minimum flux rate of 1 mm/h (blue boxes) were chosen such that the selected period starts and ends between 200 and 250 min before and after the registration of positive fluxes. This is to ensure that even the temporal blurring of high averaging times of 180 min will not lead to a smearing of the fluxes out of the selected time window. In these periods of distinct rain, the noise error plays a minor role (because the

fluxes are mainly positive and do not oscillate from positive to negative values) and so they can be used to estimate the size of the mixing error. The green boxes indicate very small

rainfalls. These periods were excluded from the examination, because in such cases, the mixing error as well as the noise error are relevant. The rest of the data set represents periods of <u>dominat dominant</u> noise and minor error. The only contributions to precipitation are very small processes like dew formation.

- ⁵ For estimating the contribution of the investigated errors we compared the calculated precipitation to a reference value. For the rain periods, where noise is playing a minor role, we used the basic approach with an oscillation threshold of 10g (corresponding to the weighing accuracy) as reference. This low value prevents distinct influences of the mixing errors, while the noise effect is assumed to be minor. For the no-rain periods, where the
- mixing of ET and P is less important, we used the basic approach with the maximum oscillation threshold value of 50 g as reference, where nearly all oscillation during night time vanished. Figure 11a shows the deviations to these reference values for different averaging times, without applying an oscillation threshold filter. The deviation during the rain-periods, indicated by the blue line, is an estimate for the mixing error, the deviation during the no-rain
- ¹⁵ periods (red line) is an estimate for the noise error. The noise error is clearly decreasing with increasing averaging time, while the contribution of the mixing error is increasing. For an averaging time of about 50 min, the two errors are compensating each other. For higher averaging times, the mixing error is increasing and leads to a deviation of about 5 mm for an averaging time of 120 min. Averaging time below 20 min (without the use of an oscillation threshold) leads to a strong increase of the noise error.

In figure 11b the influence of the chosen threshold on the error estimates is illustrated. For this examination, we used the basic processing scheme with a fixed time window of 15 min for smoothing together with a variable value for the oscillation threshold. The principle effect of an increasing mixing error with higher threshold values and an increasing noise error ²⁵ for lower threshold values is comparable to the effect indicated in figure 11a – but with a much better reduction of noise especially for low thresholds, which is due to the preceding filtering with a fixed averaging time of 15 min. Although a good choice of the smoothing time and the following oscillation threshold filter further reduces the risk of large error influences.

However, the main advantages of using the oscillation threshold filter are the maintenance of a higher temporal resolution (for a better reflection of the process dynamics) and the possibility to get an estimation of the filtering uncertainty in the previously described way. Recapitulating these results, the overall error occuring from the described filtering errors, excluding averaging times below half an hour without using an oscillation threshold filter, 5 contribute to the total water balance with a maximum of about 3% (for AWAT-filter and the synchro-filter). The resulting error estimates are both indicated in figure 11a. Both methods further reduce the errors compared to the range of errors given by the accuracy range and, hence, provide a better estimate. While the estimate for the noise error is less for the synchro-filter (1.1 mm) than for the AWAT-filter (2.2 mm), the AWAT-filter is more effective in 10 avoiding the mixing error during rain periods (0.2 mm AWAT, -1.0 mm synchro). Here it has to be stated, that our reference value is only an estimator for the real value, and the real value for the cumulative precipitation is not known exactly. This is especially important when interpreting the results for the noise error, where some real effects might be misinterpreted as errors. In summary, the adaptive methods seem to achieve a good reduction of the 15 filtering errors for our test data set, but the advantage in comparison to the basic methods seems to be minor. This is especially the case, if we compare the errors to the higher variability between the different lysimeter measurements, which is not dependent on the filter method. Nevertheless, the filtering errors in other data sets may be higher because of a greater influence of noise on the data. We therefore recommend to always make an 20 estimation of estimate the uncertainty in the described way by choosing a minimum and a maximum threshold for getting an idea of the possible filtering uncertainty. If this uncertainty range is relatively high, it may be worth to use more sophisticated methods like the AWATfilter or - provided several parallel lysimeters are available - the synchro-filter to further reduce the uncertainty. 25

3.4 Cumulative evapotranspiration

The influence of the filtering error that was discussed in the previous chapter for the cumulative precipitation is similar to for the cumulative evapotranspiration. An overestimation of P (positive flux) comes along with an overestimation of ET (negative flux), because the total flux at the upper boundary is determined by the absolute mass change of the lysimeter and the seepage water reservoir. Thus, an absolute uncertainty of 3 mm for the cumulative value of P due to filtering uncertainty is implied in place.

⁵ value of *P* due to filtering uncertainty is implying implies the same uncertainty for *ET*. The relative uncertainty is dependent depends on the absolute value of *ET*. For the used data sets, the absolute value of *ET* exceeded the value of *P*, so that the described filtering uncertainty is even below the value of 2%.

However, the variance between the different lysimeter measurements is much higher for ET than for precipitation. In figure 12 this variance it is illustrated as mean and standard 10 deviation for the basic processing approach with an oscillation threshold of 50 g. For this calculation, only the 12 crop lysimeters of the Bad Lauchstädt test site were taken into account, the 6 grassland lysimeters were excluded because of the different transpiration. The resulting standard deviation at the end of the time series is only about 6.5% of the total. The higher variance may be caused by differences in plant growth as well as by 15 differences in soil properties. This uncertainty (together with the filter uncertainty about 8.5%) can serve as a first estimate for the uncertainty when using lysimeter measurements for estimating ET for a surrounding field of the same soil and vegetation. This implies the assumption, that the plant development on the lysimeters reflects the plant development in the field at least in the mean, without systematic deviations. To investigate the influence 20 of the soil type, the small figures show the cumulative ET separated by the soil origin. Two soils (Sauerbach and Bad Lauchstädt) exhibit considerable differences in the mean evapotranspiration and a reduced variability. Because of the small data basis with only three replicates per soil we refrain from a statistical examination of the influence of the soil type. 25

3.5 Seepage flux

Strong fluctuations on the seepage mass data are rare. The signal is typically much smoother and mass changes occur slowly. Furthermore, no algorithmic separation in positive and negative fluxes have has to be processed, so that the choice of the smoothing and threshold

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parameters on the seepage flux is negligible and small unfiltered peaks remain uncritical. The filtering of the seepage mass data has mainly to cope with the steps caused by emptying and filling of the seepage water tank, which is processed by the threshold filter (filter step 2). The result of the data processing is shown for one examplary lysimeter seepage tank in figure 13. A comparison between the different lysimeters is relinquished because the seepage flux is strongly dependend on the soil type as well as on the detailed control of the pumps at the lower boundary which add or remove water to or from the lysimeter to adjust the matric potential at the lower boundary of the lysimeter in accordance with the

10 field measurements.

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3.6 Representativeness of evaluated time interval

For the evaluation of the proposed filtering scheme we used data from a rather short time interval of only two months in length and one may question about its representativeness. For discussing the effects of the various filtering steps on the data we need to look at them at very high temporal resolution. A longer data set would have hidden the details of the filtering effects. Occasions where our filtering scheme could run into problems are dates where extensive soil management (e.g. sowing, harvesting of crops, tillage, ...), which disturbes the weighing data, is conducted on the lysimeters. On these dates, the manual filtering would have to be done very properly before the automatic filtering routines could be applied.

- Other periods that might be challenging to handle are periods where the lysimeters are snow covered, since the snow cover on the lysimeter is often connected to the snow cover outside the lysimeters which, in turn, heavily disturbs the weighing data. This, however, is a well known problem in lysimetry which by nature produces unreliable weighing data that also need to be corrected manually in the data set. Here, of course additional information about the site conditions (snow cover) during winter is required. All other situations should
 - be well evaluable with the current filtering scheme.

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4 Summary and conclusions

In this study, we presented a basic filtering scheme to remove the various kinds of errors on the lysimeter weighing data, leading to a falsification of the calculated water balance components. We showed the effectivity of these filter components and investigated the influence of the parameter selection on the accuracy of the calculated water balance components. Furthermore, we used the data set of 18 parallel parallelly running lysimeters to determine the variability between these measurements and compared it with the filtering uncertainty. For our test data set, we found, that the uncertainty in the cumulative precipitation and evapotranspiration due to the choice of the filtering parameters for noise reduction is only about 2%. This uncertainty is less than the uncertainty that is given by the heterogeneity of the precipitation measurements between the different lysimeters, that is 2.7%. For the use of lysimeter measurements to estimate precipitation in the surrounding field, both uncertainties have to be summed up, which makes a total uncertainty of approx. 5%. This accuracy can be achieved while maintaining a high temporal resolution of 15 min. Exam-

- ples were shown, where good temporal resolution is necessary to retain the correct process dynamics. Despite the higher variability in the resulting ET (6.5%), which may be due to differences in plant growth, this moderate uncertainty below 10% (after adding both errors) show the potential of using lysimeter measurements as a suitable estimate of field ET with a tolerable uncertainty (what should be investigated in further studies). We further tested
- two filtering approaches, where the filtering parameters are adapted to additional data information. Both adaptive methods, the AWAT-filter ((Peters et al., 2014)) and the synchro-filter, showed a good reduction of noise within the uncertainty limits. By using subsets of the data, we further investigated the dependency of the filtering errors on averaging time and oscillation threshold. We showed that the use of averaging times between approx. 30 min and
- 1 h lead to lowest filtering errors. However, using a combination of a short smoothing time (15 min) together with the oscillation threshold filter, the filtering error could even be further reduced. The AWAT-filter and the synchro-filter both showed a good reduction of both error

components. However, the improvement of these methods compared to the basic approach with adequate filtering parameters was only minor.

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10 authors upon request.

References

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Bogena, H., Schulz, K., and Vereecken, H.: Towards a network of observatories in terrestrial environmental research, Advances in Geosciences, 9, 109–114, 2006.

Evett, S., Schwartz, R., Howell, T., Baumhardt, R., and Copeland, K.: Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-

daily ET?, Adv. Water Resour., 50, 79–90, doi:10.1016/j.advwatres.2012.07.023, 2012.

Fank, J.: Wasserbilanzauswertung aus Präzisionslysimeterdaten, in: Proceedings 15. Gumpensteiner Lysimetertagung, pp. 85–92, 2013.

Fank, J. and von Unold, G.: High-precision weighable field Lysimeter-a tool to measure water and solute balance parameters, International Water and Irrigation, 27, 28–32, 2007.

- Gebler, S., Hendricks-Franssen, H.-J., Pütz, T., Post, H., Schmidt, M., and Vereecken, H.: Actual evapotranspiration and precipitation mmeasure by lysimiters: a comparison with eddy covariance and tipping bucket, Hydrol. Earth Syst. Sci., 19, 2145–2161, doi:10.1594/hess-19-2145-2015, 2015.
- Goss, M. and Ehlers, W.: The role of lysimeters in the development of our understanding of soil water and nutrient dynamics in ecosystems, Soil Use and Management, 25, 213–223, doi:10.1111/j.1475-2743.2009.00230.x, 2009.

Howell, T., Schneider, A., and Jensen, M.: History of lysimeter design and use for evapotranspiration measurements, in: Lysimeters for Evapotranspiration and Environmental Measurements, edited

- ³⁰ by Allen, R., Howell, T., Pruitt, W., Walter, I., and Jensen, M., Proc. Intl. Symp. Lysimetry, Reston, VA, pp. 1–9, ASCE, 1991.
 - Howell, T., Schneider, A., Dusek, D., Marek, T., and Steiner, J.: Calibration and scale performance of bushland weighing lysimeters, Trans. ASAE, 38, 1019–1024, 1995.
 - Lanthaler, C. and Fank, J.: Lysimeter stations and soil hydrology measuring sites in Europe Results
- of a 2004 survey, in: Proceedings 11. Gumpensteiner Lysimetertagung, 5. and 6. April 2005, pp. 19–24, 2005.
 - Loos, C., Gayler, S., and Priesack, E.: Assessment of water balance simulations for large-scale weighing lysimters, J. Hydrol., 335, 259–270, doi:10.106/j.jhydrol.2006.11.017, 2007.
- Meissner, R., Seeger, J., Rupp, H., Seyfarth, M., and Borg, H.: Measurement of dew, fog, and rime with a high-precision gravitation lysimeter, Journal of Plant Nutrition and Soil Science, 170, 335– 344, 2007.
 - Nolz, R., Kammerer, G., and Cepuder, P.: Interpretation of lysimeter weighing data affected by wind, Journal of Plant Nutrition and Soil Science, 176, 200–208, 2013a.
 - Nolz, R., Kammerer, G., and Cepuder, P.: Verbesserung der Auswertung von Lysimeter-Wiegedaten,
- Die Bodenkultur Journal for Land Management, Food and Environment, 64, 27–35, 2013b. Nolz, R., Cepuder, P., and Kammerer, G.: Determining soil water-balance components using an irrigated grass lysimeter in NE Austria, Journal of Plant Nutrition and Soil Science, 2014.

Peters, A., Nehls, T., Schonsky, H., and Wessolek, G.: Separating precipitation and evapotranspiration from noise–a new filter routine for high-resolution lysimeter data, Hydrology and Earth System Sciences, 18, 1189–1198, 2014.

Pütz, T., Kiese, R., Zacharias, S., Bogena, H., Priesack, E., Wollschläger, U., Schwank, M., Papen,
H., von Unold, G., and Vereecken, H.: TERENO-SOILCan - Ein Lysimeter Netzwerk in Deutschland, in: 14. Gumpensteiner Lysimetertagung 2011, pp. 5–10, 2011.

20

25

Richter, D.: Ergebnisse methodischer Untersuchungen zur Korrektur des systematischen Messfehlers des Hellmann-Niederschlagsmessers, vol. 94, Deutscher Wetterdienst, 1995.

Schrader, F., Durner, W., Fank, J., Gebler, S., Pütz, T., Hannes, M., and Wollschläger, U.: Estimating precipitation and actual evapotranspiration from precision lysimeter measurements, Procedia Environmental Sciences, 19, 543–552, 2013.

Seneviratne, S., Lehner, I., Gurtz, J., Teuling, A., Lang, H., Moser, U., Grebner, D., Menzel, L., Schroff, K., Vitvar, T., and Zappa, M.: Swiss prealpine Rietholzbach research catch-

- Shuttleworth, W.: Terrestrial Hydrometeorology, Wiley-Blackwell, 2012.
- Teuling, A., Hirschi, M., Ohmura, A., Wild, M., Reichstein, M., Ciais, P., Buchmann, N., Ammann, C., Montagnani, L., Richardson, A., Wohlfahrt, G., and Seneviratne, S.: A regional perspective on trends in continental evaporation, Geophys. Res. Let., 36, doi:10.1029/2008GL036584, 2009.
 van Bavel, C.: Lysimetric measurements of evapotranspiration rates in the eastern United States,
- Soil Sci. Soc. Am. Proc., 25, 138–141, 1961.

5

10

- Vaughan, P., Trout, T., and Ayars, J.: A processing method for weighing lysimeter data and comparison to micrometeorological ETo predictions, Agricultural water management, 88, 141–146, 2007.
- Vaughan, P. J. and Ayars, J. E.: Noise reduction methods for weighing lysimeters, Journal of irrigation and drainage engineering, 135, 235–240, 2009.
- Yang, J., Li, B., and Liu, S.: A large weighing lysimeter for evapotranspiration and soilwater-groundwater exchange studies, Hydrol. Process., 14, 1887–1897, 2000.
- ⁶⁹⁵ Young, M., Wierenga, P., and Mancino, C.: Large weighing lysimeters for water use and deep percolation studies, Soil Sci., 161, 491–501, 1996.
 - Zacharias, S., Bogena, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., Frenzel, M., Schwank,
 M., Baessler, C., Butterbach-Bahl, K., Bens, O., Borg, E., Brauer, A., Dietrich, P., Hajnsek, I.,
 Helle, G., Kiese, R., Kunstmann, H., Klotz, S., Munch, J. C., Papen, H., Priesack, E., Schmid,
- H. P., Steinbrecher, R., Rosenbaum, U., Teutsch, G., and Vereecken, H.: A network of terrestrial environmental observatories in Germany, Vadose Zone Journal, 10, 955–973, 2011.

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Table 1. Parameters for the different filters in the basic processing approach that were used as standard. If no other information is given, the calculations refer to these parameters.

| Standard parameters for the basic processing approach | | |
|---|-------------|--|
| threshold for lysimeter mass changes | +/- 60 mm/h | |
| threshold for seepage mass changes | +/- 9 mm/h | |
| median filter window | 15 min | |
| smoothing filter window | 15 min | |
| oscillation threshold | 50 g | |

Table 2. Used parameters for the adaptive methods.

| | AWAT-filter | synchro-filter |
|----------------|-------------|----------------|
| min. threshold | 0.0081 mm | 0.010 mm |
| max. threshold | 0.240 mm | 0.200 mm |
| averaging time | 1-31 min | 15 min (fixed) |



Figure 1. Schematic drawing of a lysimeter (left) as used in SoilCan attached to the central service pit (right).



Figure 2. Flowchart of the basic processing scheme.



Figure 3. Examples for the effect of the different filtering steps on the mass data (here: summarized mass of lysimeter and seepage water tank of lysimeter BL1-L1). Please note the different scaling of the y-axes. a) raw data, b) manual filter, c) threshold filter, d) median filter, e) smoothing filter, f) oscillation threshold filter.



Figure 4. Effects of different averaging time windows n and the oscillation threshold d on the data oscillations (noise error) during night time situations (a,b) and the underestimation of precipitation due to the mixing of ET and P (mixing error) during a precipitation event (c). While (a) and (b) show the calculated fluxes, (c) shows the summarized mass of lysimeter and seepage water representing the cumulative flux at the upper boundary. The underestimation of the precipitation induced mass change in (c) due to the 60 min smoothing is indicated in the figure.



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Figure 5. Effect of the different processing steps on the calculated fluxes at the soil-atmosphereinterface for one examplary lysimeter (BL1-L1). After presenting the unfiltered data (a), the effect of the manual filter (b), the threshold filter (c), the median filter (d), the smoothing filter (e) and the oscillation threshold filter (f) is shown. For (d), (e) and (f) zoom levels were increased to illustrate the different scales affected by the filtering steps. Please note the different scaling of the axes.

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Figure 6. Variations in the calculated fluxes between the different crop lysimeters. The area in red shows the range of minimal and maximal calculations.



Figure 7. Short time dynamics of precipitation events for selected rain events of 09 May 2013 (a), 04 May 2013 (b), 26 April 2013 - 28 April 2013 (c) and 12 April 2013 (d).



Figure 8. The calculated precipitation with its uncertainties as cumulative precipitation (a) and daily precipitation (b). The total uncertainty is the sum of the estimated filtering uncertainty and the standard deviation of the different measurements on the 18 lysimeters.



Figure 9. The values for cumulative precipitation together with the standard deviation regarding the measurements of the 18 different lysimeters for different parameter selections and the two adaptive methods.



Figure 10. Selection of periods for the investigation of the noise and the mixing error. The purple periods were selected for the estimation of the mixing error, the blue periods of light rain were excluded because of the contribution to both errors and the rest of the data set was used for the estimation of the noise error.



Figure 11. Effects of averaging time (a) and oscillation threshold value (b) on the estimates for the mixing error and the noise error. The error estimates of the AWAT-filter and the synchro-filter are indicated in figure (a) with green stars for the AWAT-filter and purple stars for the synchro-filter.



Figure 12. Cumulative Evapotranspiration (mean+-standard deviation) for the 12 crop lysimeters of the Bad Lauchstädt testsite. The small picture shows the results seperated in soil type groups.



Figure 13. Comparison of processed and raw seepage mass data for the lysimeter BL2-L1.