A comparison of water flux measurements: passive wick-samplers versus drainage lysimeters

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Summary
Quantification of soil water flow is a prerequisite to accurate prediction of solute transfer within the unsaturated zone. The monitoring of these fluxes is challenging because the results are required to answer both scientific and practical questions regarding protection of groundwater, sustainable management of agricultural, forestry, mining or set-aside industrial areas, reducing leachate loss from landfills or explaining the fate of environmentally harmful substances. Both indirect and direct methods exist for estimating water-flux rates and have been used with varying success. In Europe, the use of direct lysimetry methods for measuring water and solute fluxes in soils has increased in recent years. This technique ensures reliable drainage data, but requires relatively large investment and maintenance expenses. Other research groups, especially in the USA, have developed alternative techniques. In this paper we compare the functioning of a passive-wick sampler, especially the deep-drainage meter type (DDM), with two different types of drainage lysimeters (weighing and non-weighing) under field conditions in Germany for the measurement period from May 2004 until April 2009. The study showed that under sandy soil conditions no significant differences occurred between the measurements from DDM and both drainage lysimeter types. Only in periods with increased precipitation was there a tendency of drainage over-estimation by the DDM in comparison with the lysimeters tested. For longer periods, no significant differences in the amount of drainage or the pattern of drainage formation were found between weighing and non-weighing gravitation lysimeters. The practical use of DDMs is restricted because the groundwater level must be >2 m from the soil surface. Suggestions are made for the technical improvement of the DDM as well as the testing of the device with more cohesive soils.

Introduction
A suite of methods for measuring water and solute flux in and below the root zone has been developed over the years. However, there is no standard method available for measuring soil-water flux (Gee et al., 2009). Specific vadose-zone methods to estimate percolation and recharge rates have been critically reviewed (Gee & Hillel, 1988; Allison et al., 1994; Hendrickx & Walker, 1997; Tyler et al., 1999). A state-of-the-art overview and evaluation about in situ soil water extraction methods is given by Weihermüller et al. (2007). They clearly explain advantages and disadvantages of the different methods and show that the decision on the appropriate system depends on the scientific objective, potential limitation in terms of installation effort, maintenance time and financial budget. Gee et al. (2002) suggest the need to differentiate between indirect methods, which involve measurement of specific soil characteristics and calculating water flux rate using data from tensiometers, time domain reflectometry (TDR), frequency domain reflectometry (FD) or heat-pulse probes, and direct methods measuring drainage water using a buried device such as drainage lysimeters or wick-based water samplers.

In Europe the use of direct drainage lysimetry methods for measuring water and solute fluxes in soils has increased in recent years (Lanthaler & Fank, 2005). A wide range of lysimeters has been used in the past, ranging from small, free-draining pan lysimeters or tension-controlled lysimeters that often only capture a small portion of the drainage waters, to large, drainage lysimeters that limit divergence and capture most or all of the drainage water within a prescribed area (Aboukhaled et al., 1982; Meissner et al., 2000, 2008). Allen et al. (1991) postulated that estimates of drainage fluxes are best derived from direct measurements. However, the construction and maintenance of large drainage
lysimeters (especially the weighing type) is expensive (Meissner et al., 2008).

For this reason various research groups have initiated the development of alternative techniques that can directly measure water and solute fluxes more economically. Capillary wick samplers (fluxmeter) are passive devices (Gee et al., 2002) that sample soil water by removing water from the soil with an inert wicking material, such as fibreglass or rock wool (Ben-Gal & Shani, 2002). The applied suction to the soil is maintained by a hanging water-column (Gee et al., 2004). The degree to which this can be applied depends upon the length of the wick, the flux rate and the soil type (Holder et al., 1991; Boll et al., 1992; Knutson & Selker, 1994; Rimmer et al., 1995; Zhu et al., 2002; Mertens et al., 2007): the maximum applied suction is about 50–60 cm (Brandi-Dohrn et al., 1996). According to Boll et al. (1992), Knutson & Selker (1994), Rimmer et al. (1995), Louie et al. (2000), Zhu et al. (2002), Gee et al. (2003) and Siemens & Kaupenjohann (2004), wick samplers allow a quantitative, direct analysis of the water flow if the properties of the sampler are adjusted to the soil properties. Wick samplers are characterized by a comparatively large specific sampling area that results in small differences in cumulative drainage over extended periods of time, especially for coarse, sandy soils.

Large drainage lysimeters and fluxmeters are both appropriate tools to measure water and solute fluxes directly (Gee et al., 2009). They differ considerably in cost and complexity. The wick fluxmeter is smaller and simpler in design. By contrast, drainage lysimeters can be simple or quite sophisticated in design and because of size and placement costs, they are much more expensive.

The objectives of this paper are (i) to compare the function of a passive-wick water sampler with a sophisticated weighing lysimeter and a simple non-weighing lysimeter, with regard to the accuracy of measuring the amount of drainage water under field conditions and (ii) to give recommendations for the practical application of each method.

Materials and methods

Site and soil description

Because different types of passive-wick water samplers exist, a deep-drainage meter (DDM) was used for the comparison (Gee et al., 2004). We tested two water fluxmeters (DDM 1 and 2), two weighing, gravity-flow lysimeters (WLYS 211 and 212) and two simple non-weighing gravity-flow lysimeters (NWLYS 3 and 4). The test sites were located in the Federal State of Saxony-Anhalt, Germany (Figure 1). WLYS 211 and 212, DDM 2 and NWLYS 3 and 4 were located at the Helmholtz-UFZ lysimeter station at Falkenberg (52° 51’N, 11° 48’E). DDM 1 was located at the small experimental catchment area ‘Schaugraben’ (52° 46’N; 11° 46’E). The Schaugraben is a tributary of the Elbe River in northeast Germany. The catchment covers an area of about 2400 ha; it is about 10 km away in a southwest direction from the Helmholtz-UFZ lysimeter station and has similar meteorological conditions and soil characteristics (Chambers et al., 2006). The test sites are climatically assigned to the temperate zone of Central Europe within the transition zone from maritime to continental climate. Precipitation averages 536 mm per year (1986–2001; Falkenberg, Germany), with maximum precipitation occurring during June and July. Long-term mean potential evapotranspiration was 495 mm (1986–2001), and mean annual temperatures ranged from 7.3 to 10°C (1986–2001). The Helmholtz-UFZ lysimeter station at Falkenberg is equipped with a meteorological station. The daily amount of precipitation was measured with a standard rain gauge (1 m above ground level) at the lysimeter station.

We used an identical soil (Dystric Cambisol according to FAO Soil Classification; FAO, 1990) from the Schaugraben catchment for filling DDM 1 and 2 as well as the monoliths of WLYS 211 and 212. NWLYS 3 and 4 were filled with disturbed soil substrates in two layers (topsoil, texture sandy loam 0–30 cm, and subsoil, texture also a modified sandy loam 31–100 cm) from the local region at Bretsch (52° 50’N, 11° 39’E), approximately 12 km away from the lysimeter station at Falkenberg (Figure 1). Some essential soil characteristic data are listed in Table 1.

The lysimeter station at Falkenberg and the site at Schaugraben were equipped with an additional groundwater monitoring pipe, which was installed to a depth of about 3 m below ground level. The monitoring pipe is slit over the whole length to provide near zero resistance to flow and a straightforward way to measure groundwater level. Groundwater level was measured manually at weekly intervals.

Passive-wick water sampler design and installation

The DDM consisted of two connected plastic pipes (Figure 2). The whole system was approximately 1.4 m in length. The pipes contained a series of three funnels. The upper pipe of the DDM contained the soil column and had a diameter of 0.2 m, which corresponds to a surface area of 0.031 m². The lower end of the pipe was in contact with a funnel filled with soil and fibreglass wicks. The total wick length was 0.6 cm, which results in an applied suction at the bottom of the soil column of approximately 50–60 cm (but this varied with soil wetness). Below the wick, a second funnel channelled the drainage water into a tipping bucket that has a resolution of 5 ml. Below the tipping bucket the water was stored in a tank of approximately 1.5-litre capacity that was vented by small-diameter tubing to the atmosphere, which was used to pump water to the soil surface to measure drainage and
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Berlin
GERMANY
Falkenberg
Seehausen
Bretsch
\[ N \]
Position of DDM1 and extraction site of WLYS 211 & 212 as well as DDM 2
Helmholtz- UFZ
lysimeter station, position of DDM 2, NWLYS 3 & 4 and WLYS 211&212
Osterburg
Site of soil extraction for NWLYS 3 & 4

**Figure 1** Diagram of the experimental area and geographical position of the deep-drainage meters (DDM 1 and 2), the weighing lysimeters (WLYS 211 and 212), the non-weighing lysimeters (NWLYS 3 and 4) and the soil extraction sites for the different measuring systems.

for chemical analysis. All excess water that was not sampled in the storage tank seeped from the bottom of the DDM via a gravel layer into the subsoil. The only moving part was the tipping bucket. The unit is compact and durable (Sledge Sales, Dayton, Oregon, USA).

In June 2003 we initiated the installation of DDM 1 at the Schaugraben field site (Figure 1). Figure 2 presents a diagram of the installed equipment. The installation was started by digging a hole of approximately 0.5 m² and 0.6 m depth. The plough horizon (0–0.25 m) and the first subsoil horizon (0.26–0.6 m) were collected separately. Subsequently, the first part of the fluxmeter tube (0.6 m) was manually filled from the depth of 0.6–1.2 m below ground level and then compacted. A second hole was drilled to a depth of 2.1 m below ground level by using a hand auger to accommodate the assembled fluxmeter. The floor of the drilling was levelled and 0.1 m of gravel filling inserted and then the lower part of the fluxmeter unit was prepared. The

**Table 1** Selected soil physical properties at the extraction site of the DDM, the lysimeter monolith (WLYS), Dystric Cambisol (FAO, 1990) and the manually filled lysimeter (NWLYS)

<table>
<thead>
<tr>
<th>Properties</th>
<th>WLYS 211 and 212 and DDM 1 and 2</th>
<th>NWLYS 3 and 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil depth / cm</td>
<td>0–35  36–53  54–108  109–180</td>
<td>0–30  31–100</td>
</tr>
<tr>
<td>Substrate</td>
<td>89.8   97.0   99.0   99.0</td>
<td>73.6</td>
</tr>
<tr>
<td>Sand (2.0–0.06 mm) / %</td>
<td>5.0    1.4    0.5    0.5</td>
<td>14.3</td>
</tr>
<tr>
<td>Silt (0.06–0.002mm) / %</td>
<td>5.2    1.6    0.5    0.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Clay (&lt;0.002 mm) / %</td>
<td>1.88   0.27   0.00   0.52</td>
<td>1.9</td>
</tr>
<tr>
<td>Loss on ignition / %</td>
<td>5.6    4.9    5.0    5.0</td>
<td>5.8</td>
</tr>
<tr>
<td>pH</td>
<td>36.8   34.8   31.6   29.8</td>
<td>31.9</td>
</tr>
<tr>
<td>Total pore volume / %</td>
<td>1.56   1.58   1.60   1.61</td>
<td>1.48</td>
</tr>
<tr>
<td>Bulk density, $\rho_d$ / g cm$^{-3}$</td>
<td>434    853    1000   641</td>
<td>75</td>
</tr>
<tr>
<td>Hydraulic conductivity, $K_s$ / cm day$^{-1}$</td>
<td>343    853    1000   641</td>
<td>75</td>
</tr>
</tbody>
</table>

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capillary wick inside the first funnel was separated into strands and evenly arranged around the inside of the funnel. The funnel with the wick was filled with siliceous sand. Subsequently, the completed instrument was inserted into the hole. The head-space between drilling and fluxmeter was filled completely with material removed during drilling. The connection wire and the tubes for sampling and calibration were separately arranged. Finally, the hole was refilled. During the reassembly, the soil material was manually compacted in layers to restore the natural density.

In 2003, we also installed the second fluxmeter (DDM 2) at Falkenberg within 20–30 m of the drainage lysimeters. At the extraction site in the Schaugraben catchment we removed and collected the upper part of the top soil and the first subsoil horizon to a depth of 0.6 m (Figure 1). The soil of the two horizons was separately transported to the lysimeter station at Falkenberg. A pit with an area of 1 m² and 0.6 m depth was excavated at the lysimeter station. The first fluxmeter pipe was manually filled with subsoil from Schaugraben and re-compacted. The whole assembly was installed as described before for DDM 1. Afterwards, we refilled the pit horizontally with soil from Schaugraben.

It is a precondition for using the DDM that the groundwater table remains at least 2 m below the soil surface. Otherwise, ascending groundwater can enter the storage vessel, leading to incorrect assessment of amounts of seepage water. We equipped the sites with additional groundwater monitoring pipes. For the comparative tests between fluxometers and both types of drainage lysimeters (WLYS, NWLYS), we used water from the storage tank of the DDM in order to directly measure the amount of seepage water and to take samples for chemical analysis.

The groundwater level at the Schaugraben site (DDM 1) as well as at the Helmholtz-UFZ lysimeter station is influenced by adjacent ditch systems. Therefore, a groundwater level of ≤2 m could not be always excluded, especially during wet periods. For this reason we only used periods with a groundwater level >2 m for the comparison of the three different seepage measuring systems.

Weighing-lysimeter design and installation

Figure 3(a) shows a diagram of a WLYS equipped to measure water and solute flux. This type of lysimeter has a surface area of 1.0 m² and a total depth of 2.0 m. The soil column in the stainless steel lysimeter vessel was extracted as a monolith (Meissner et al., 2007). The lower boundary was segmented into eight sections (Figure 3b) to obtain information on the spatial heterogeneity of the water fluxes (Schoen et al., 1999). Every segment was connected with a single tipping bucket to measure the amount of seepage water and to take samples for chemical analysis.

The WLYS was equipped with three shear stress cells, which were placed on top of stainless steel pedestals. Even with a total lysimeter mass of 4000–4500 kg, this drainage system registers mass (weight) changes with a 30-g resolution (Meissner et al., 2007). Tensiometers, TDR probes, thermometers and suction cups were installed at depths of 0.30, 0.90 and 1.50 m. All measured data were stored in a data-logger.

The WLYS (211 and 212) vessels were filled with the monoliths in September 2001 at a grassland site in the Schaugraben catchment (52°46′N, 11°46′E; Figure 1). The cylindrical lysimeter monoliths (1.13 m diameter by 2.0 m deep) were collected by a newly developed method, which cuts the outline of the soil monolith with a rotary milling tool (Meissner et al., 2007). During the cutting procedure, the contour of the soil monolith was pre-cut by a rotating tool, which was connected to the lysimeter vessel. The new procedure avoids structural damages and substantially reduces cutting time during monolith extraction. The extraction site was only minimally disturbed, because the forces needed for cutting the soil monolith are small, because there is reduced coat friction. After the cutting was completed, a metal plate was placed under the lysimeter vessel and a crane was used to lift the whole...
A comparison of water flux measurements

assembly. After a lid was fixed on the top of the vessel, it was turned upside down and the lower 20 cm of soil in the monolith was removed. The internal portion of the lysimeter base was filled in with a graded filter layer made of quartz sand and gravel (0.1–0.5, 0.71–1.25 and 3.15–5.6 mm in grain size diameter; Figure 3a). The composition of the filter allowed water to drain from the monolith into the sand-gravel and to discharge via the tipping buckets into the storage tanks.

The bottom of the WLYS was subdivided into eight equal sections of an area of 0.125 m² (Figure 3b). For subdivision, a stainless steel frame 20 cm high was inserted into the filter layers at the lysimeter bottom. Each section was equipped with its own drainage system. The amount of seepage water is automatically registered by separate tipping bucket modules. After extraction and preparation of the lysimeter base the lysimeter vessels were transported and installed in a recessed polyethylene (PE-HD) container at Falkenberg (Meissner et al., 2007).

**Non-weighing lysimeter design and installation**

Figure 4 shows the principal design of a simple NWLYS, which is often used in Germany for applied research on land management and its impact on drainage water quantity and quality (Leinweber et al., 1999). The NWLYS used consisted of a sheet steel vessel with a quadratic surface area of 1 m² and a total depth of 1.25 m. After the installation at the lysimeter station (which had a total of 120 vessels) a 25-cm thick filter layer (sand over gravel over stone gravel) was placed at the bottom of the lysimeter. A drainage pipe was installed inside the filter layer to collect the seepage and to discharge it into a storage tank in the lysimeter cellar. The vessel

![Diagram of the weighing lysimeter (WLYS) (a) with segmented lysimeter base (b).](image1)

![Diagram of a non-weighing lysimeter (NWLYS).](image2)
was filled manually in 1981 with disturbed soil material (two layers 0–30 and 31–100 cm) from a former agricultural field plot (at Bretsch; 52°50'N, 11°39'E; Figure 1). The soil was removed in two layers (top soil, 0–30 cm, and subsoil, 31–100 cm) and stored separately (see Table 1). The soil was transported to the Helmholtz-UFZ lysimeter station and filled manually in layers in the lysimeter vessel. The layers were compacted by hand to secure a similar bulk density as in the field. After filling, the vessel was irrigated at a rate that simulated normal conditions for the site to accelerate the settling process. The initial field trial was started in 1983. Management

The vegetation cover of both types of lysimeter (WLYS, NWLYS) as well as the fluxmeters (DDM) was similar to the grassland vegetation at the Schaugraben extraction site. The recent agricultural management regimes of the lysimeters and the fluxmeters have been similar but not identical (Table 2). The lysimeters were managed as typical regional grassland with mineral fertilizer added and the sward cut three times per year. Since 2001 they have received an annual fertilizer application of 20 g m⁻² nitrogen (N), 2.5 g m⁻² phosphorus (P) and 11 g m⁻² potassium (K). DDM 1 and 2 were not fertilized after their construction and the grass was mown once per year. The amount of seepage water was continuously measured at the WLYS. The seepage from the NWLYS was collected in a storage tank and the amount measured once per month. The amount of seepage from both fluxmeters was measured once per week.

The conditions (sampling depths and intervals, sites, soils, management, etc.) for comparisons between the three different water flux measurement systems are not identical because the different lysimeter types were selected from different trials with different scientific goals. However, each type of lysimeter has been used successfully to solve specific scientific and practical problems, so it was instructive to compare the performance of each system with respect to both short- and long-term measurements under similar conditions with respect to climate, crop and soil.

Statistical evaluation

The statistical evaluation of the results was carried out using SPSS and SYSTAT 8.0 (SPSS Inc., Chicago, Illinois, USA). The nonparametric Kruskal–Wallis test statistic was applied to identify identically distributed populations among the lysimeter replicates. Data were also compared by using density plots for different types of lysimeters for the whole investigation period and for two sub-periods. Furthermore, the results were analysed using one-way analyses of variance (ANOVA) with lysimeter types (NWLYS, WLYS), fluxmeters (DDM) and sampling year as main factors (including interactions between the factors).

Results and Discussion

Precipitation

Figure 5 presents monthly sums of precipitation measured at Falkenberg. On the basis of previous studies we assumed that the amount of precipitation in the ‘Schaugraben’ catchment was comparable to that in Falkenberg (Chambers et al., 2006). The precipitation showed different patterns during the period of investigation from May 2004 until April 2009, with distinctly increased amounts from April 2007 until October 2008. Therefore, we decided to subdivide the total investigation period into two. The first comprised the period from May 2004 until April 2007, and the second from May 2007 until April 2009. Both periods were compared on the basis of the monthly totals of precipitation (Figure 6). In comparison to the first sub-period the second period was characterized by a significantly increased precipitation ($P = 0.048$), which justified the division into two periods.

Groundwater level

The groundwater level shows a distinct seasonally-affected response, with the lowest readings in summer and autumn (Figure 5) and the highest in winter and spring. As a result of the increased precipitation during sub-period 2, the limit of 2 m for DDM usage was exceeded in July 2007 and from September 2007 until April 2008. These data sets were excluded from further evaluation because of the possibility of groundwater entering the storage tank of the DDM and invalidating the seepage measurements. Furthermore, to provide a good comparison between different measuring systems we have also omitted the data sets for these critical periods for NWLYS 3 and 4 as well as WLYS 211 and 212.

Table 2 Agro-technical and hydrological management of the different water flux measuring systems

<table>
<thead>
<tr>
<th>Factor</th>
<th>Fluximeters DDM 1 and 2</th>
<th>Weighing lysimeters WLYS 211 and 212</th>
<th>Non-weighing lysimeters NWLYS 3 and 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural use</td>
<td>Grassland</td>
<td>Grassland</td>
<td>Grassland</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>No fertilizer</td>
<td>Mineral fertilizer</td>
<td>Mineral fertilizer</td>
</tr>
<tr>
<td></td>
<td>20.0 g m⁻² year⁻¹N</td>
<td>2.5 g m⁻² year⁻¹P</td>
<td>2.5 g m⁻² year⁻¹P</td>
</tr>
<tr>
<td></td>
<td>11.0 g m⁻² year⁻¹K</td>
<td></td>
<td>11.0 g m⁻² year⁻¹K</td>
</tr>
<tr>
<td>Harvest</td>
<td>One cut per year</td>
<td>Three cuts per year</td>
<td>Three cuts per year</td>
</tr>
<tr>
<td>Seepage measurement</td>
<td>Once per week</td>
<td>Continuously</td>
<td>Once per month</td>
</tr>
</tbody>
</table>

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Seepage measured by DDM and lysimeter

The amount of seepage water measured by DDM and both drainage lysimeter types is presented in Figure 7. Additionally, Table 3 gives a detailed overview of the monthly measured amounts of seepage water during May 2004 until April 2009. The seepage in both DDMs was, during the whole period, not significantly different (ANOVA, data not shown). The starting point of seepage formation was comparable for both DDMs. At the beginning of the experiment in May 2004 seepage occurred in both DDMs but the amounts were different. In 2005 the seepage began at DDM 1 two weeks earlier than at DDM 2, and that in DDM 2 started approximately 4 weeks before DDM 1 in the seepage periods for 2006 and 2007. Seepage at DDM 1 lasted 4 weeks longer than at DDM 2 in 2005. In 2006, the discharge period of DDM 1 was comparable with DDM 2 and completed 4 weeks earlier. The seepage formation of both DDMs was temporarily disrupted in March 2007. The observed difference in time for the seepage formation of the DDMs can presumably be ascribed to variation in site conditions at Schaugraben and the Helmholtz-UFZ lysimeter station. The surface of the DDMs is small (0.031 m²). Therefore, the development of only a few macropores may alter the drainage rates and make the results from the DDM more variable than those from lysimeters with larger surface areas. At the end of sub-period 1, the measured total amount of seepage

Figure 5 Precipitation (mm month⁻¹) and groundwater level in the experimental area.

Figure 6 Statistical comparison of precipitation in sub-period 1 (May 2004 to April 2007) and sub-period 2 (May 2007 to April 2009).
Figure 7 Seepage from DDM 1 and DDM 2, NWLYS 3 and 4, and WLYS 211 and 212 during the whole investigation period (May 2004 to April 2009).

Table 3 Statistical characteristics for the amount of drainage measured with different systems between May 2004 and April 2009 (all in mm month\(^{-1}\))

<table>
<thead>
<tr>
<th></th>
<th>Precipitation</th>
<th>DDM1</th>
<th>DDM2</th>
<th>NWLYS3</th>
<th>NMLYS4</th>
<th>WLYS 211</th>
<th>WLYS 212</th>
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<tr>
<td><strong>Sub-period 1</strong> (May 2004 to April 2007)</td>
<td></td>
<td></td>
<td></td>
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<td>No of cases</td>
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<td>51</td>
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<tr>
<td>Minimum</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>126.7</td>
<td>78</td>
<td>69</td>
<td>49.4</td>
<td>49.1</td>
<td>41.4</td>
<td>42.8</td>
</tr>
<tr>
<td>Sum</td>
<td>2877.9</td>
<td>597.5</td>
<td>439.8</td>
<td>358.8</td>
<td>398.6</td>
<td>459.0</td>
<td>362.6</td>
</tr>
<tr>
<td>Mean</td>
<td>47.965</td>
<td>11.363</td>
<td>8.624</td>
<td>7.035</td>
<td>7.816</td>
<td>9.0</td>
<td>7.11</td>
</tr>
<tr>
<td>Upper 95% CI(^a) of mean</td>
<td>55.15</td>
<td>17.145</td>
<td>13.197</td>
<td>10.871</td>
<td>11.624</td>
<td>12.569</td>
<td>10.421</td>
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<tr>
<td>Lower 95% CI of mean</td>
<td>40.78</td>
<td>5.581</td>
<td>4.4</td>
<td>3.2</td>
<td>4.007</td>
<td>5.431</td>
<td>3.798</td>
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<td><strong>Sub-period 2</strong> (May 2007 to April 2009)</td>
<td></td>
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<tr>
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<tr>
<td>Minimum</td>
<td>2.9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Maximum</td>
<td>126.7</td>
<td>53.2</td>
<td>54.4</td>
<td>35.8</td>
<td>34.9</td>
<td>34.4</td>
<td>25.2</td>
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<tr>
<td>Sum</td>
<td>1359.2</td>
<td>299.5</td>
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<td>124.2</td>
<td>97.9</td>
<td>162.8</td>
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<tr>
<td>Mean</td>
<td>56.633</td>
<td>19.967</td>
<td>12.4</td>
<td>8.28</td>
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<td>10.853</td>
<td>5.58</td>
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<tr>
<td>Upper 95% CI of mean</td>
<td>70.825</td>
<td>32.47</td>
<td>21.883</td>
<td>15.305</td>
<td>12.482</td>
<td>17.66</td>
<td>10.083</td>
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<tr>
<td>Lower 95% CI of mean</td>
<td>42.442</td>
<td>7.463</td>
<td>2.917</td>
<td>1.255</td>
<td>0.571</td>
<td>4.047</td>
<td>1.077</td>
</tr>
</tbody>
</table>

\(^a\)CI = confidence interval.
Drainage from both NWLYS 3 and 4 was similar. Drainage started at NWLYS 4 in January 2005 with an amount of 35.4 mm and exceeded that of NWLYS 3 by 30 mm (85%). Another differentiation was observed in December 2005 and January 2006. NWLYS 4 had drainage of 2.1 and 17.1 mm, respectively. In contrast, there was no drainage at NWLYS 3 in this period. However, a difference of 66 mm (22%) between both NWLYS arose at the end of sub-period 1. Drainage started at NWLYS 3 in December 2008 1 month earlier than at NWLYS 4. The drainage of NWLYS 3 exceeded that of NWLYS 4 by 26 mm (21%) at the end of sub-period 2. Over the whole period from May 2004 until April 2009, the drainage of NWLYS 4 exceeded that of NWLYS 3 by approximately 40 mm (10%, Figure 7).

The temporal pattern and rate of drainage at both WLYS 211 and WLYS 212 were similar during the first period. At the end of sub-period 1, the seepage of WLYS 211 was comparable to WLYS 212, but was approximately 6% (17 mm) greater. The drainage behaviour of both lysimeters varied in sub-period 2 whereas drainage started 4 weeks earlier at WLYS 211 than at WLYS 212. For WLYS 211 an increased monthly drainage compared with WLYS 212 was characteristic, which resulted in a difference in drainage of approximately 79 mm (49%) at the end of sub-period 2. There were no technical or management reasons for these differences between the replicates. Based on information from the segmented base, it seems that in lysimeter WLYS 211 a greater amount of preferential flow took place than in WLYS 212. Differences in drainage between technically equivalent and similarly managed lysimeters have been observed elsewhere (Haferkorn, 2000; Knoblauch, 2009).

When the months of unacceptably high groundwater levels (July 2007 and September 2007 to April 2008) are excluded, the greatest total amount of drainage was measured at DDM 1, with 598 mm, followed by WLYS 211 (459 mm) and DDM 2 (440 mm). The smallest amount was at NWLYS 3, with 359 mm, followed by WLYS 212 (363 mm). For sub-period 1 the total amount of drainage ranged between 235 mm (NWLYS 3) and 301 mm (NWLYS 4). The sum of drainage measured in sub-period 2 at DDM 1 exceeded that of sub-period 1 by 298 mm in spite of the longer period (36 and 24 months in sub-periods 1 and 2, respectively, because 9 months were excluded because of the higher groundwater level). All other systems (DDM 2, NWLYS 3 and 4, WLYS 211 and 212) were characterized by decreased drainage in sub-period 2 compared with sub-period 1.

It appears (Table 3) that there was a large variation in the cumulative drainage measured by each of the methods, especially in sub-period 2. Each measuring system had two replicates and the means (Weihermüller et al., 2007) of these provided better agreement between the three measuring systems. Over the whole period, there was an 8% difference in drainage between the WLYS units and the NWLYS units and a 26% difference between the WLYS and the DDM units. For sub-period 1, the differences between the mentioned systems were only 7% for both the DDM and the NWLYS. Because of the greater amount of precipitation during sub-period 2, the difference between WLYS and NWLYS units was 10% and between WLYS and DDM units it was 97%.

A nonparametric Kruskal–Wallis test was applied to identify significant differences in the data for the paired lysimeters. Although the total amount of drainage and timing when drainage occurred were different, no significant differences were identified among the pairs DDM 1 and 2, WLYS 211 and 212 and NWLYS 3 and 4 (Table 4). Data for the paired lysimeters were therefore merged to increase the number of cases and to improve the data base for further statistical analysis.

An ANOVA was carried out to compare both lysimeter types (WLYS and NWLYS) and DDM. The ANOVA for the total period revealed non-significant ($P = 0.447$) differences in drainage between the DDM and the lysimeters (Figure 8a). For sub-period 1, the mean values for DDM and NWLYS were comparable (Figure 8b) and that for WLYS was slightly increased. In contrast, for sub-period 2 there was a significantly increased amount of seepage in the DDM compared with NWLYS and WLYS (Figure 8c). For sub-period 1, it can be concluded that the DDM delivers reasonable results for seepage in periods with regular precipitation. In contrast, the seepage measured by DDM was significantly over-estimated in wet periods. When precipitation was large, the fluxmeters drained excessively. This is probably because of the fixed suction control on the wicks, which under very wet conditions tend to exceed the smaller suction values of the wetted field soil and cause convergence. Similar results have been found in structured clay soils after heavy rainstorms in Tonga (Van der Velde et al., 2005).

When comparing the monthly values of drainage discharge of the three measuring systems as a box-whisker plot the different behaviours of DDM in both sub-periodes became visible (Figure 9a,b). Comparatively small drainage rates were characteristic for the first sub-period (Figure 7). However, several
monthly values are outside the normal range. There is no evidence for increased drainage activity in specific months in the NWLY and WLYS systems. In contrast, statistically significant drainage rates were characteristic for sub-period 2 (May 2007 to April 2009; Figure 9b). The different behavior of the two sub-periods was presumably the result of increased monthly precipitation in sub-period 2 (Figure 5). For both lysimeter types (NWLYS and WLYS) these effects of significantly increased drainage were not observed.

Depth of measurement can be important in determining actual timing and quantity of drainage using different water flux measuring systems. DDM as well as NWLYS (measuring depths 1.2 and 1.25 m, respectively) showed a different temporal pattern of drainage than the WLYS with a measuring depth of 2.0 m. There was a time lag of approximately 4–8 weeks between the recharge periods in WLYS and DDM/NWLYS (Figure 7). Figure 10(a,b) clarifies this by showing the plotted measured values from DDM against NWLYS and WLYS for both measurement periods. While for DDM in a number of months no drainage was recorded, the drainage rate was as large as 45 mm month$^{-1}$ for WLYS. However, for the NWLYS this situation occurred only in a few cases. Thus, drainage re-started earlier at the 2-m depth WLYS than with DDM and NWLYS. This effect was probably caused by the different construction design and sampling the drainage at different depths.

The effective root zone may extend in the sandy soils to a depth of 1.1 m and thus may affect drainage in the shallower lysimeters through root water uptake in periods with a large evaporation demand. Marek et al. (1988) recommend a lysimeter depth of more than 2 m to permit normal crop growth. Haferkorn (2000) suggests the need for an ‘adequate’ lysimeter depth that depends on the climatic conditions, the depth of root penetration by plants and the soil physical characteristics. Klaghofer (1991) considers that a depth of 2 m is sufficient for sandy soils. Therefore, the soil water storage limit of shallow lysimeters such as the NWLYS units and perhaps the DDMs could have been exceeded during some periods of our measurements. As a consequence, the re-starting of seepage may have been delayed for DDM and NWLYS. For WLYS, the soil column was deeper than the depth of the natural

Figure 8 ANOVA analysis for the amounts of seepage measured with different sampling systems: (a) total period May 2004 to April 2009, (b) sub-period 1 May 2004 to April 2007 and (c) sub-period 2 May 2007 to April 2009.

Figure 9 Comparison of sub-period 1 (a, May 2004 to April 2007) and sub-period 2 (b, May 2007 to April 2009) with regard to drainage from DDM, NWLYS and WLYS systems (central bar = median; box edges = 25 and 75%; open circles = 3× interquartile range; asterisks = values outside normal range).
zero-flux plane, which at the extraction site was between 0.9 and 1.3 m below the surface. Hence, it can be assumed that seepage flow in this lysimeter type was not affected by evapotranspiration. During periods without drainage, the soil water content at the lower depths in the WLYS lysimeter may be greater in comparison to that which might be found in the shallower DDM and the NWLYS units. This is a possible result of water extraction by plants at depth. These findings are in agreement with Knappe et al. (2002), who carried out long-term water and solute balance studies with weighing lysimeters that were monoliths with a surface area of 1.0 m$^2$, total depth of 3.0 m, and free drainage.

There were differences in vegetation growing on the lysimeters and on the DDMs. Deeper roots would exploit the lysimeter storage capacity and may be one reason for the observed differences between lysimeter and DDM drainage values. All the experimental systems had a grass vegetation cover (Table 2), but only the NWLYS and WLYS lysimeters were fertilized. This may have resulted in a greater water uptake and reduced drainage compared with the DDM and may be an additional explanation for the increased drainage with the DDMs. A comparison between the periods displayed in Figure 10 shows that the data for the second period of measurement with greater monthly precipitation rates (see Figure 5) is less scattered compared with the first period. The related greater soil moisture and frequent occurrence of saturation or near-saturation may also cause more homogeneous water flux during the wetter period in all the measuring systems than in the drier period from May 2004 until April 2007. However, the overall performance of the three drainage measuring systems showed no clear differences over the long term, which suggests that for these sandy soils, a variety of lysimeters or fluxmeters may be acceptable in documenting effects on drainage.

**Conclusion**

No statistically significant differences were observed in long-term measurement of drainage between DDM, NWLYS and the WLYS systems. This indicates that the three methods of measurement do not allow a distinction to be made between the measurements made with them. Usually, the more sophisticated WLYS provides the best measurement of drainage rates in time and space. During periods of increased precipitation (2007–852 mm, 2008–680 mm) there was a tendency to overestimate drainage with DDM compared with both lysimeter types. On the other hand, in periods with more normal precipitation (i.e. under the conditions of northeast Germany with an average of 536 mm year$^{-1}$) there were no statistically significant differences between the systems. This was somewhat surprising when considering the smaller surface area of the DDM (0.031 m$^2$) compared with the lysimeter (1.0 m$^2$), but suggests relative uniformity in the hydraulic properties and drainage characteristics of the sandy soils tested. While field suction values were not directly measured, the data suggest that under normal annual precipitation cycles, the wick suction values approximated to a reasonable degree the field values for these sandy soils. The DDM is by comparison with a conventional drainage lysimeter, a cost-effective measuring system. During storm events or periods with an increased amount of precipitation, the results from DDM should be critically reviewed if they are to be used as reliable estimators for actual field drainage. Wetter soil conditions under elevated precipitation may give rise to a mismatch between wick and field suctions and cause a discrepancy that will result in over-estimation of drainage. Furthermore, it is advisable to use replicates for all drainage measuring systems in order to improve the reliability of the data.

Important in the practical use of these results is the observation that, for longer periods, no significant differences in amounts or patterns of drainage were observed between NWLYS and WLYS units. This suggests that simple non-weighing lysimeters, with disturbed soil cores, may be used for reliable estimations of drainage. The requirement that a distance of >2 m exist between soil surface and groundwater level for proper operation
of DDM restricts the use of this type of fluxmeter to sites with sufficiently deep water tables. For the sandy soils tested, under the climate conditions of northeast Germany, an installation depth of 1.2 m was not adequate over the whole testing period. Technical improvements in the DDM would include (i) the use of a one-way check valve system to prevent back-flow from temporary high water tables and (ii) possible reduction of the construction depth of the lower part of the DDM to improve the applicability of DDM in regions with a higher groundwater level. Further research is also necessary to test the DDM with less freely draining soils as well as the usefulness of the DDM to measure drainage water quality.

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