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High resolution rainfall – runoff measurement setup for green roof experiments in a tropical environment

T. Vergroesen[1,2], **U. Man Joshi**[3], **N. C. van de Giesen**[2], **and F. H. M. van de Ven**[2,4]

[1]Deltares, Hydraulic Engineering, P.O. Box 177, 2600 MH Delft, The Netherlands
[2]Delft University of Technology, Department of Water Management, P.O. Box 5048, 2600 GA Delft, The Netherlands
[3]Singapore Delft Water Alliance, National University of Singapore, 1 Engineering Drive 2, 117576, Singapore, Republic of Singapore
[4]Deltares, Subsurface and Groundwater, P.O. Box 85467, 3508 AL Utrecht, The Netherlands

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Correspondence to: T. Vergroesen (toine.vergroesen@deltares.nl)

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Abstract

This article describes the measurement setup that is used for green roof experiments in a tropical environment, the required data treatment to obtain reliable values of rainfall, runoff and evapotranspiration, and how to deal with external disturbances that can influence the experiment results. High resolution rainfall runoff measurements to identify, understand and properly model the relevant runoff processes in a green roof require both tailored equipment and data treatment. A tipping bucket rain gauge is calibrated for and installed to measure minute based rain intensities. A runoff measuring setup is developed that can accurately quantify the runoff up to 6 l/min, and has a high resolution in both time and volume. Two different measuring setups are used to verify the evapotranspiration that is derived from the rainfall and runoff measurements.

1 Introduction

Since July 2009 we conduct research on the effect of green roofs on urban runoff in Singapore. The aim of our research is to identify and understand the relevant runoff processes on a very detailed scale. This understanding is required to describe, and to upscale these processes so they can be applied in a correct way in urban runoff modeling tools. Therefore we measure both rainfall on, and runoff from experimental roofs with an area of 1 m^2. The goal of our research requires a highly detailed way of measuring that covers the entire Singapore rainfall spectrum, varying from a light drizzle to a tropical rain storm with intensities up to more than 3 mm/min.

Most practical way to measure the runoff is to use self emptying contraptions like tipping buckets, and record the number of tips per time interval like it is done in tipping bucket rain gauges. Rainfall in Singapore can generate runoff up to 3 l/min from our experiment roofs on a regular base. Using a rain gauge tipping bucket (±10 ml/tip) to measure this runoff can result in a tipping frequency up to 5 tips/s. That is way beyond its accuracy. So measuring flows like that requires much larger tipping buckets.

Disadvantage of large tipping buckets however is that runoff from low intensive rainfall can not be monitored accurately. In this paper we elaborate on the measuring method we apply to obtain accurate high resolution runoff data for the entire Singapore rainfall spectrum.

- We explain precisely how we measure both rainfall and runoff accurately with a high resolution (Sect. 2). For measuring rainfall we only use a smaller time interval than normally is done, and we have calibrated the rain gauge before using it. We have developed the runoff measuring method ourselves.
- We prove that our measuring method is sound, and explain how the raw data have to be treated to generate the required output (Sect. 3).
- We explain how to deal with external influences that can disturb the measurements (Sect. 4). The range of possible external influences is always wider than you can imagine when you start an experiment.
- We compare our way of measuring to methods that were used elsewhere, and discuss the pros and cons (Sect. 5).
- Finally we summarize the main conclusions, and give some recommendations to further improve this method (Sect. 6).

The measurements are divided into rainfall measurements and runoff measurements. In addition we use weather parameters like air pressure and temperature, wind speed and direction, humidity and incoming radiation to determine the evaporation. These data are recorded at a 5 min time interval by a weather station of the National University of Singapore that is located at approximately 100 m from our experiment site. The NUS weather station also records rainfall at a 5 min time interval. During the testing phase of the experiments we used the rainfall data from the NUS weather station as well, and compared them to the measured runoff. Several times during the testing phase the measured runoff did not correspond well with the measured rainfall. The relatively short distance between both locations is obviously too much. Therefore, we decided to use a rain gauge at the experiment site. We assume that the spatial distribution of the environmental parameters that determine the evaporation is much smaller. Because we use the data of the NUS weather station to determine the evaporation, this paper mainly elaborates on the rainfall and runoff measurements.

2 Measurement setup

For rainfall measurements we use an 8 inch tipping bucket rain gauge that is designed to tip at every 0.2 mm of rainfall (Global water, 2007). For runoff measurements we used a tipping bucket flow gauge that is designed to tip every 1 l (Hydrological Services, 2007). The tipping bucket flow gauge is put on top of a high accuracy weighing scale that has a resolution of 1 g. The scale is based on a load cell (Goldbell, 2008) and custom made to fit the size of our tipping bucket.

2.1 Rainfall measurement setup

Before installing the rain gauge (Fig. 1, left) we calibrated it in our laboratory (Fig. 1, right), because tipping bucket rain gauges always have an accuracy that is decreasing with increasing tip frequency (Marsalek, 1981). Main reason for this decreasing accuracy is that it takes some time for the bucket to tip (Devine, 2009). During half of the tipping time rainwater is flowing into the filled bucket, but actually belongs to the next tip. The faster the flow rate the larger this error is. Besides that these tipping buckets often have a small deviation from the value provided by the manufacturer.

The rain gauge is adjusted to record the number of tips per minute (NRT). The calibration of the rain gauge tipping bucket (Sect. 3), resulted in the following conversion rule:

$$\text{Rainfall}\,(\text{mm/min}) = \text{NRT}\cdot(0.2049 + 0.0019\cdot\text{NRT})$$

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A minute with a recorded number of 18 tips (the highest recorded rate so far) implies a rainfall of 18·(0.2049+0.0019·18)=4.3038 mm, during this minute.

2.2 Runoff measurement setup

The experimental roofs, boxes of 1 by 1 m each, are put on tables with adjustable leg heights (Fig. 2). That way the runoff can easily flow into the tipping bucket flow gauge (Fig. 2, right). The setup of the experiment tables is such that the runoff measurement equipment can be situated below the opposite table. A cover around the open sides below the table helps to minimize wind and other possible influences as much as possible.

The tipping bucket flow gauge is situated on top of a weighing scale. During runoff, the scale records the total weight of the flow gauge and the growing weight of the water volume in the bucket continuously. When the volume in the bucket reaches approximately 1 l it empties itself by tipping, thus lowering the weight almost instantly to that of the empty flow gauge again. Contrary to the rain gauge the tipping bucket flow gauge requires no further calibration. The continuous weight recording makes the actual tipping volume less important. The weighing scales have been calibrated by adding and removing exact weights between 100 g and 1 kg on the tipping bucket. The error in the recorded weight differences is less than 1 g.

The measured weights (Fig. 3, left) are transformed into measured runoff (Fig. 3, right) by removing the weight drops, and using the common knowledge that 1 l water weighs 1000 g (Sect. 3).

For example during 1 min of runoff the recorded weight rises from 8100 g to 9100 g, drops back to 8150 g, rises to 9130 g, drops back to 8120 g and rises again to 8650 g, the runoff during that minute was (9100−8100+9130−8150+8650−8120)/1000=2.51 l.

Because the catchment area of the experimental setup equals 1 m^2, 2.51 l runoff equals 2.51 mm/m^2. The thickness of the sides of the experiment boxes requires a slight correction of the catchment area (Sect. 3). Transforming the runoff to mm per catchment area makes it easier to compare the runoff to the rainfall, which is often measured in mm.

2.3 Evapotranspiration measurement setup

Evaporation and transpiration (together called evapotranspiration) from the experiment setup are much more gradual occurring processes than rainfall and runoff. Therefore we decided to determine the evapotranspiration from the experiment setups by means of a water balance (rainfall minus runoff). Over a long period with many runoff events difference in storage (in soil and vegetation) are negligible. We assume that the storage at the end of every runoff period is at equilibrium, and therefore always approximately the same. That way we can use a water balance to determine the average evapotranspiration over a period between the ends of two runoff events (Sect. 3).

To verify this water balance approach we use two different weighing setups, a global one for an entire experiment table (Fig. 4) and a detailed one for a small setup of 28.5 by 28.5 cm (Fig. 5). The latter one is also for verifying the detailed modeling of evaporation processes.

Four bathroom scales measure the weight of the experiment table (Fig. 4). The weight is recorded twice a day by visual inspection of the displays, and adding the four readings. Meta data regarding the state of rainfall and runoff at the moment of recording are added as well. The measured weight difference between two measurements is caused by changes in soil water content (storage). Together with the recorded rainfall and runoff data the observed weight changes can be transferred to evapotranspiration and storage changes (Sect. 3).

Weight loss indicates evapotranspiration. The example in the right side of Fig. 4 shows a weight loss of 9.7 kg over a two day period without rain and runoff, which for an area of 1 m^2 indicates an evapotranspiration depth of 9.7 mm.

The small setup is light enough to use one of the high accuracy weighing scales that record the weight every two seconds. The inner area of the small setup is 28.5 by 28.5 cm. In the setup no relevant vegetation is present, so transpiration can be neglected. Together with the recorded rainfall data the recorded weight changes can be transferred to evaporation (Sect. 3).

The example in the right side of Fig. 5 shows that the recorded weight at the beginning of 24 March 2010 is 13 131 g. The recorded weight at the end of that same day is 12 592 g. That results in a calculated evaporation for that day of 6.6 mm.

3 Data treatment

The raw data generated by the applied measuring instruments are transferred into rainfall and runoff volumes over a certain period of time. Based on these data the evapotranspiration is calculated.

3.1 Rainfall data

The tipping bucket rain gauge counts the number of tips over a predefined time interval, and sends this number to a data logger. Each time interval a number is recorded, and stored into the data logger. Considerations that led to the time interval we have chosen are:

- A time interval of 5 min, used during the testing phase, does not provide the required information detail;
- The capacity of the data logger is approximately 81 000 readings;
- The discrete tipping volume corresponds to a rain depth of 0.2 mm per tip;
- The time interval of the recorded runoff is 1 or 2 s.

The recorded tipping time only indicates the moment the bucket is filled completely. During heavy rainfall with several tips per minute that is good enough. During a light drizzle it can take over 10 min to fill a single bucket. In the latter case the exact time of tipping does not correspond exactly to the time of rainfall. Weighing the discrete tipping volume and the data logger capacity versus the recorded detail of the runoff and the information detail from a 5 min time interval, we decided to use a time interval of 1 min.

The rain gauge is calibrated in a lab, by emptying exactly 100 ml of water through a syringe into the rain gauge funnel at different speeds. For 20 tests the total number of tips and the time of the last tip are recorded, and the rest volume in the tipping bucket is measured. The tipping bucket is properly leveled before the calibration starts. Each calibration run starts with a wet tipping bucket. The pouring is done manually, so the pouring speed is not exactly constant during the entire pouring time, as will be when real rainfall is recorded. The average tipping frequency of the 20 tests varies from 2.01 to 27.69 tips/min. During an additional extreme test 100 ml of water is emptied from a measuring jar within a few seconds into the funnel of the rain gauge, resulting in an average tipping frequency of 67.50 tips/min. Figure 6 gives a graphical overview the calibration results.

The clear linear trend results in the following conversion rule from recorded tips to rainfall depth:

$$\text{Rainfall}\,(\text{mm/min}) = \text{NRT}\cdot(0.2049 + 0.0019\cdot\text{NRT})$$

In which NRT is the number of recorded tips in a single minute

The calibration assumes an equal tipping volume for both buckets. However despite proper leveling some additional tests directly on the single buckets showed that one of the two buckets tips at a structural higher volume than the other. The cause of this difference is not clear. The difference between the two tipping volumes is a little over 10%. That implies that the calibrated conversion rule results in an error of a little over 5% for a single tip. However, the higher the number of tips the smaller this error gets. In the long run the error caused by this difference becomes negligible.

Before the calibration in the lab started the tipping bucket was properly leveled. In order to get the most reliable results, during the installation at the experiment site the tipping bucket was properly leveled once again.

However, even proper calibration and installation can not prevent inaccurate rainfall measurement results caused by wind, wetting, evaporation and splashing effects. This can lead to relatively large errors (up to rainfall losses of 15%) in the measured values. We discuss the influence of these aspects on the rainfall measurements in Sect. 5 of this paper.

3.2 Runoff data

As mentioned earlier the runoff measuring setup consists of a tipping bucket flow gauge on top of a weighing scale. The sole function of the tipping bucket flow gauge is to collect runoff water, and discharge it once a certain volume is collected. The flow gauge is not connected to a data logger. The weighing scale is the actual runoff gauge. The recorded weight of tipping bucket and runoff water together is send to a data logger. The time interval between two data transmissions can be reduced to a single second.

Considerations that led to the time interval we have chosen are:

- A time interval of 1 s, used during the testing phase, is more than sufficient to provide the required information details.
- The discrete tipping volume is approximately 1 l. This corresponds to a rain depth of 1 mm per tip.
- Wind can influence the tipping volume to some extend.
- The rainfall intensity in Singapore was found to go up to more than 3 mm/min.
- Proper data treatment requires 8 records between two tips.

In our setup a rainfall intensity of 3 mm/min can lead to a runoff of 3 mm/min. This implies 1 tip every 20 s, i.e. 10 records between 2 tips. A recording interval of 3 s and a runoff of 3 mm/min results in 6 to 7 records between 2 tips. Based on this and consideration that wind influences can bring down the discrete tipping volume to a little less than 1 mm/tip, we decided to use a time interval of 2 s. During a period of more than a year, only in one event during two consecutive minutes the rainfall exceeded an intensity of 3 mm/min (3.5 and 4.3 mm/min). Runoff intensities larger than 3 mm/min require a minor adjustment to the data treatment as given below.

For the rainfall runoff experiments the recorded weights have be transformed into calculated runoff. Figure 7 shows the basic principle of this transformation. The pink dots in the upper part of this figure represent the actual recorded weights. The recorded weights go up when the runoff is gradually filling the bucket. When the bucket is filled up to its tipping level, it tips and the recorded weight goes down almost instantly. This constantly repeating process results in a saw tooth shaped diagram. Both the tipping time and the tipping action itself disturb the recorded weight. During the time it takes for the bucket to tip, runoff water is still flowing down from the funnel above. When the tipping bucket hits the frame it rests on during the filling phase of the other bucket, additional pressure is exerted on the weighing scale. Depending on the time between the hit and the moment of weight recording the additional recorded weight can go up to more than half a kg. Point 3A in Fig. 7 shows an example of this additional recorded weight gain. As a reaction to the temporary additional pressure the total setup springs back, resulting in an additional weight loss. Point 2B in Fig. 7 shows an example of this recorded weight loss. The additional recorded weight loss is in the same order as the additional recorded weight gain. Therefore the weight recordings around the tipping moment can not be used. However during this time the inflowing runoff continues.

We use the following stepwise approach to handle these problems while minimizing the inaccuracy:

1. From the raw data we determine the time of the maximum recorded weight before the tip (the vertical yellow lines in Fig. 7).
2. We select the last 6 recorded times and weights before the tip minus the last 2 (leaving the brown dots in Fig. 7), as well as the first 6 recorded times and weights minus the first 2 (leaving the blue dots in Fig. 7).
3. We determine the average weight rise (AWR) of the 8 selected records (the brown-blue lines in Fig. 7).

4. We calculate the maximum weight before the tip (horizontal red lines in Fig. 7) by:

   $$W_{\max} = W_1 + \mathrm{AWR} \cdot (T_{\max} - T_1)$$

   where $W_{\max}$=maximum weight before tip; W_1=weight of first selected record, record 1; AWR=average weight rise; $T_{\max}$=time of maximum record before tip; T_1=time of first selected record

5. We calculate the minimum weight after the tip (horizontal blue lines in Fig. 7) by:

   $$W_{\min} = W_{12} - \mathrm{AWR} \cdot (T_{12} - T_{\max})$$

   where $W_{\min}$=minimum weight after tip; W_{12}=weight of last selected record, record 12; AWR=average weight rise $T_{\max}$=time of maximum record before tip; T_{12}=time of last selected record

6. We calculate the weight drop due to the tip: $W_{\max}-W_{\min}$ (the orange numbers in Fig. 7).

7. We add the weight drop to all the recorded weights after the tip (bottom picture in Fig. 7).

The result of this approach is a cumulative weight function in time. The last step to transform this cumulative weight function (g) to a cumulative runoff function (mm/m^2) is to divide the weights by the density of water and by the recharge area. For the density of water we assume 1000 g/l. The inner area of the box is 1 m^2. The thickness of the sides of the box is 1 cm, leading to a total area of approximately 0.04 m^2 for all four sides. We assume that half of the rain that falls on the sides of the box flows into the box. The other half will flow out of the box. The actual rainfall recharge area therefore is approximately 1.02 m^2. To transform the cumulative recorded weights to cumulative recorded runoff the weights are divided by 1020.

Only at the end of a rain event a small amount of water will remain on the sides of the box to evaporate. Therefore the error in measured runoff caused by the assumptions we made is very small, generally much less than 1% of the measured runoff. Furthermore since all setups are similar, these errors will be similar for all setups.

3.3 Evapotranspiration deduction

During a rain event on a green roof first the available storage volume in the soil is filled. Runoff starts when the equilibrium storage capacity is exceeded. The runoff stops when all the excess water is flown out, thus leaving the soil with the equilibrium storage capacity. Therefore we assume that at the end of each runoff event the soil water content is approximately the same. Based on this assumption we can deduct the average evapotranspiration between the ends of two runoff events (Fig. 8):

$$\mathrm{ET}_i = (\Sigma P_i - R_i)/L_i$$

Where ET_i=average evapotranspiration in runoff period i (mm/d); ΣP_i=total rainfall in runoff period i (mm); R_i=total runoff in runoff period i (mm); L_i=length of period between the ends of two consecutive runoff events (d).

Figure 8 shows the basic principle of this approach. The upper part of this figure shows the actual recorded rainfall and runoff, the lower part shows how the evapotranspiration can be calculated for certain periods.

The first period starts at the end of the previous runoff period (point 0), and stops at the end of the next runoff period (point 1), where the second calculation period starts. The points on the top dashed line (lower part of Fig. 8) represent the total rainfall since the start of the first period. The negative values before point 0 indicate the previous rainfall. The vertical difference between the points on the top dashed line and the points on the lower dashed line represent the total runoff since the start of the first period (point 0). The points on the lower dashed line represent the calculated total evapotranspiration since the start of the first period. The lines are dashed because they do not represent the actual rainfall and runoff between the points (compare to upper part of Fig. 8), they just connect the points.

At the start of the 4th calculation period (point 3) the total rainfall is 88.6 mm, and the total runoff is 66.6 mm. At the end of the 4th period they are increased to 128.3 mm and 72.3 mm, respectively. Assuming similar soil water content at the beginning and the end of the 4th period, the average evapotranspiration during this period is:

$$\mathrm{ET}_4 = (\Sigma P_4 - R_4)/L_4 = ((128.3-88.6)-(72.3-66.6))/11.7 = 2.9\,\mathrm{mm/d}\,.$$

For long term averages the accuracy of this approach is of the same order as the accuracy in the treated rainfall and runoff data. For single events the accuracy will be less. This is mainly caused by:

1. Small differences in soil water content at the end of the runoff events.
2. Small runoff events. Some runoff (due to preferential flow) can occur before the soil water storage is completely filled, thus leading to a wrongly defined runoff event.

The error caused by differences in soil water content is relatively small (order 1 mm). For the first calculation period in Fig. 8 the calculated evapotranspiration is almost 11 mm in 18 h, while based on the recorded very poor evaporation conditions during that period evaporation in the order of less than 3 mm could be expected. Most likely the previous rainfall did not exceed the equilibrium soil water content, but the runoff was caused by preferential flow.

3.4 Evapotranspiration data

The evapotranspiration measurements of the experiment table are just to verify the water balance that is derived from rainfall and runoff measurements. Considering the goal of these measurements we use a cost effective and simple method that can be applied and removed easily (Fig. 4). The total weight of the experiment table is recorded by visual inspection of the four bathroom scales. Combination of the weight data with the data on rainfall and runoff (Fig. 9) will give insight in both the evapotranspiration and the changes in soil water content, i.e. changes in storage.

$$W_i - W_{i-1} = \Sigma P_{\Delta t} - \Sigma R_{\Delta t} - \Sigma \mathrm{ET}_{\Delta t} = \Delta S$$

Where i, $i-1$=times of weight recording; Δt=length of the period between i and $i-1$ (d); W_i=recorded weight at time i (kg); W_{i-1}=recorded weight at time $i-1$ (kg); $\Sigma P_{\Delta t}$=total rainfall in period Δt (mm); $\Sigma R_{\Delta t}$=total runoff in period Δt (mm); $\Sigma \mathrm{ET}_{\Delta t}$=total evapotranspiration in period Δt (mm); ΔS=change in storage in period Δt (mm).

Figure 9 (upper part) shows the recorded weight changes during a nine day period. The total rainfall in this period is 90.5 mm, the recorded runoff 66.9 mm (Fig. 9, lower part). The recorded weight at the start of this period is 214.2 kg; the recorded weight at the end of this period is 196.8 kg. During the first weight recording it was dry, but runoff was still flowing a little. So at the start of this period the storage exceeded the equilibrium soil water content.

The storage reduction during this period is 17.4 kg, i.e. 17.4 mm for the 1 m^2 area of the experiment table. The total evapotranspiration during this nine day period is:

$$\Sigma \mathrm{ET}_9 = \Sigma P_9 - \Sigma R_9 - \Delta S = 90.5 - 66.9 + 17.4 = 41.0\,\mathrm{mm}$$

The average evapotranspiration of this nine day period is 4.6 mm/d. Next to the accumulated values of the evapotranspiration Fig. 9 (lower part) also shows the storage change during this period. The storage values in this figure are not absolute, but related to the minimum recorded value, which in this case is at the end of the recorded period.

The accuracy of this approach depends mainly on the accuracy of the weight readings, which is in the order of 0.2 kg per scale. Since we use 4 scales, and we always compare 2 readings the inaccuracy of the differences in total weights is maximal 1.6 kg. Occasional wind effects can enlarge the error a little, so we assume that the accuracy is in the order of 2 kg. That corresponds to 2 mm. The longer the time between two readings the less relevant the recorded error becomes.

To determine the evaporation we use data on solar radiation, air temperature, wind velocity and humidity that are recorded at 5 a minute interval by the NUS weather station. Together with the soil characteristics we determine the evaporation from the soil. Since we want to be able to verify the derived soil evaporation, the most practical way to proceed is to use one of the already available high accuracy weighing scales that are used for the detailed runoff measurements. Considering the weight limits of these scales we use a small setup (Fig. 5). To minimize edge effects we cover the sides with aluminum foil. The runoff from the small setup is not recorded, therefore evaporation can only be determined during dry periods (Fig. 10).

To determine the evaporation from the recorded weights, we use a stepwise approach:

1. The recorded weights are transferred to 5 min averages. This is done to avoid outliers caused by wind effects, and because the evaporation data are also recorded at 5 min interval.

2. The recorded weight changes are transferred to water depths by:

   $$\Delta D = \Delta W/(1000 \cdot 0.285^2)$$

   where ΔD=change in water depth (mm); ΔW=change in weight (g).

3. For periods without rainfall and runoff the evaporation in that period equals the change in waterdepth. Rainfall that will not result into runoff, like on the 26 March 2010 (Fig. 10), has to be added to the water depth to determine the evaporation.

Figure 10 shows that the calculated change in water depth at the 24 March is 6.6 mm. Since no rain occurred the evaporation that day equals the change in water depth. For the 26 March the calculated water depth is 4.8 mm. However that day 0.2 mm of rain is recorded. Since no runoff occurred the calculated evaporation that day is 5.0 mm.

This way the evaporation during any given period of time without runoff can be determined.

The accuracy of this approach depends mainly on the accuracy of the weight readings, which is in the order of a few grams. That corresponds to 0.05 mm. However the determined evaporation may be overestimated a little due to possible edge effects of the small setup.

4 Dealing with disturbances in runoff measurements

It is inevitable that the results of our outdoor experiments are disturbed by external influences. The major external influences are caused by weather effects like wind, solar radiation, etc. and evaporation of water directly from the tipping buckets. Other experienced external influences like clogging of tipping bucket funnels, tipping buckets falling of the weighing scale to things as banal as changing the lock of the access door and interference caused by tying power and data cables together, are dealt with in a non scientific way and will not be discussed here.

4.1 Weather influences

The exact recorded weight is influenced by changes in the weather condition. Fig. 11 shows for two consecutive days the recorded weights of 5 dry tipping buckets during a seven day period without any rainfall or runoff. The setup of box 2 and 4 are open, which means no windshields whatsoever. The other three setups are more or less shielded against the wind. The weighing scales for boxes 4 and 5 (Goldbell, 2008) are slightly different than scales for boxes 1, 2 and 3 (PT Chroma international, 2009).

Wind shields (box 1, 3 and 5) clearly contribute to a more consistent data recording. The (more expensive) weighing scales of boxes 4 and 5 are less influenced by the weather conditions than the other three scales. The recorded weights of all five setups increase slightly at the beginning of the day time, and go down again at the beginning of the night time. These weight variations can go up to almost 50 g or even more (box 2) when the setup is open. These effects seem to coincide with the day–night rhythm.

However they also occur at day time during weather changes.

For both days the correlation between the recorded weights and the weather data recorded by the NUS weather station is determined (Tables 1 and 2). Therefore we transferred the weights to 5 min average values.

The correlation values higher than 0.5 are highlighted in these tables (positive green and negative red). The incoming radiation shows a high correlation with the recorded weights (Fig. 12), higher than the air temperature (Fig. 13). Shielding (box 2 and 4) seems to have no influence on this. The relative humidity also is (reverse) correlated with the recorded weights (Fig. 14). No clear correlation can be found with the air pressure, the wind speed and the wind direction.

The correlation of the recorded weights with the radiation implies also a correlation with temperature and humidity, because of the correlation between these parameters (Tables 3 and 4).

The error caused by these weather influences is normally very small, and that too only temporarily. When runoff starts before a weight rise, and ends before the weight drops again, the total runoff (order 5–50 mm) is overestimated a little (order 0.05 mm). When runoff starts before a weight drop, and ends before the weight rises again, the total runoff is underestimated a little (again order 0.05 mm). Since runoff is caused by rainfall, and rainfall implies clouds, and therefore a drop in solar radiation, it is most likely that runoff overestimation occurs more often than runoff underestimation. The error in runoff intensity (mm/min) will be negligible, because the time it takes for the weight to rise or drop is much longer than a single minute. The peak runoff will probably not be affected at all, since the peak runoff occurs normally when it is still raining.

Errors close to 0.05 mm can only occur when the end of the runoff period coincides with a rise or drop period, or when no or only little runoff is produced. However this considers only relative errors due to the small runoff volume. These errors can only be omitted by looking closely at the data, because writing a weather related algorithm to deal with these errors automatically will introduce new errors that are of the same order as the errors we try to omit in the first place.

4.2 Evaporation from the tipping bucket

Another aspect that influences the measurements is the evaporation of water in the tipping bucket. This will result in weight loss, and consequently an underestimation of the runoff. Figure 15 shows a two day period where this influence is clearly visible.

The example starts with an empty tipping bucket. During the second half of the first morning a severe rainstorm occurred that ended in a light drizzle. The runoff from the concrete roof stopped at a quarter past one in the afternoon, leaving approximately 600 ml in the tipping bucket. From that moment on only evaporation takes place: 37 ml in the remainder of the first day, 27 ml during the first night, 128 ml during the second day, and 8 ml during the first half of the second night, thus leading to a total evaporation of 200 ml. Assuming that evaporation of water directly from the tipping bucket also occurs when runoff water is still flowing in, the runoff is underestimated a little. The magnitude of this underestimation depends on the length of the runoff event. For an average runoff event (4 to 5 h) the underestimation of the total runoff is in the order of 0.05 mm. The error in runoff intensity (mm/min) will only be somewhat relevant at the end of the runoff event when water is dripping in very slowly. The peak runoff will not be affected at all.

5 Discussion

5.1 Rainfall measuring

USGS (1999) conclude that tipping bucket rain gauges have a long record of proven ability, commercial availability, and are the most widely used. Most of these rain gauges, however, have a tendency to under record when rain is greater than 3.0 inches (i.e. 7.62 mm) per hour. Furthermore they consider that at least one recording gauge is necessary to provide the detailed precipitation information needed at each study site. Mentens (2003), Moran et al. (2004), VanWoert et al. (2005), Stovin et al. (2007), Uhl and Schiedt (2008) and EPA (2009) all use tipping bucket rain gauges with a recording interval of 5 min for their green roof experiments. EPA used a single tipping bucket rain gauge on the edge of one of the buildings. In line with the recommendations of USGS they mention that another rain gauge or triangulation of rain gauges around the buildings would have provided more insight to rainfall totals. Only Van Woert et al. mention that the accuracy of the rain gauge decreases with increasing intensity, but like the others they don't mention any kind of rain gauge calibration.

The rain gauge we use, the RG600M, is calibrated by the manufacturer to tip every 0.2 mm (Global water, 2007). Recalibrating this gauge proved that assuming this 0.2 mm per tip for true results in an underestimation varying from a little over 3% for 1 tip/min to over 16% for 18 tips/min.

Using a 5 min monitoring interval will not provide the necessary detail we require for our rainfall runoff process description, because it will take away a large part of the temporal variability of the rainfall. It will also result in a further underestimation of the actual rainfall, because the rain gauge calibration is minute based.

Regarding rain gauge calibration, Devine (2009) measured for a similar tipping bucket rain gauge a half tip time of 0.43 s. When we assume that the entire error of our rain gauge is caused by the amount of lost rain during half of the time it takes for the bucket to tip, and we replace our calibrated relation by a half tip time error relation, we derive (for 2 or more tips per minute):

$$\mathrm{Rainfall\,(mm/min)} = \mathrm{NRT}\cdot 0.2068\cdot(60/\mathrm{NRT})/(60/\mathrm{NRT}-t)$$

Where NRT=number of tips per minute (1/min); 60/NRT=time between tips (s); t=half tip time (s).

Applied on our calibration runs it results in a half tip time of 0.41 s. That is in line with the 0.43 s that was found by Devine for a similar tipping bucket rain gauge. Devine however indicates that this rate correction can be applied from rain intensities of 90 mm/h (=1.5 mm/min) upward. Our calibration result indicates that the rate correction should be applied from 2 tips/min (=25 mm/h) upward. That is in line with the recommendations regarding calibration in the manual of our rain gauge (Global Water, 2007).

So far we recorded 10 889 tips in 5707 min. For the rest of the 510 239 recorded minutes, i.e. 354.3 days, the number of tips is zero. Considering that almost 99% of the available data space (approximately 81 000 records) is filled with zeros, it seems more practical to just record the exact time of every single tip. That way data can be stored at the highest possible detail of information for a much longer time period (Van de Ven, 1990). However when using longer download intervals imply that data recording errors will be discovered later and consequently data gaps will be larger. Next to that exact tipping time creates bogus accuracy, because the tipping time does not necessarily correspond to the exact rain time.

Proper calibration and installation can not prevent inaccurate measurement results caused by wind, wetting, evaporation and splashing effects. Of these effects wind induced rainfall errors are largest. Generally they can cause underestimation of the rainfall up to 15% (Sevruk, 1996). Second in the order of magnitude is the loss due to the wetting of the inner walls of the gauge. Errors caused by evaporation and splashing are relatively low compared to wetting loss and wind induced errors. The magnitude of all these errors depends on rainfall intensity and wind speed as well as rain gauge and site specific factors. Although several numerical solutions are applied to correct for these losses (Habib et al., 1999; Hsu and Guo, 2005) the result will always be a set of derived measurement values with a relatively large inaccuracy.

That implies that comparing the green roof runoff measurements to the reference roof runoff measurements will result in much more accurate results than comparing them to rainfall measurements. Probably the best way to obtain comparable rainfall measurement results is to install a rain gauge at surface level in the centre of a setup similar to the runoff setups, like the subsurface rain gauge at the Hupsel-Assink experimental site (Van den Eertwegh, 2002). Since the project is ongoing, we consider changing to this way of rainfall measuring.

5.2 Runoff measuring

Various methods have been used to measure green roof runoff. Moran et al. (2004) collected the runoff data with a V-notch weir box with a level sensor. Data were recorded in 5-min intervals. Mentens (2003) and VanWoert et al. (2005) used rain gauge tipping buckets with a 5-min interval for runoff. Stovin et al. (2007) recorded the runoff data by means of a collection tank with a high resolution pressure transducer. Though stated to use 5-s intervals, data in the paper were presented at 5-min intervals. Uhl and Schiedt (2008) used collection tanks with a swimmer system for water level measurements to measure the runoff. EPA (2009) used 55 gallon plastic barrels with a pressure transducer which allowed continuous measurement of the water level in the barrel. Pressure data was recorded every 5 min. The pressure transducer systems have a sensitivity which allows determination of approximately 0.02 in. (0.5 mm) of water runoff from the roof area. This sensitivity was more than adequate for assessing the total volume of the storms, but did introduce some uncertainty and variation in time series analysis or instantaneous results, as the transducer might toggle between values or experience drift.

The research projects mentioned above focused on long term effectiveness of green roofs and the measuring equipment that was used generally fits this purpose. Our research focuses on adequately describing the relevant green roof runoff processes. That requires more detailed information on both rainfall and runoff. The runoff measuring system we use is more suited for this, and is also tailored to the size of our experiment table. Beside the adjustment to the way of monitoring the size and shape of our experiment tables was determined by considering the maximum expected runoff intensity versus minimizing the effect of side influences. In addition practical aspects such as the load capacity of the roof our experiments are carried out on, the roof access and the costs per setup were taken into account.

Reducing the data recording time to every second our measuring method can also be used for any combination of test area and rain intensity that lead to a runoff up to a little over 6 l/min. For measuring relevantly larger discharges at a somewhat similar detail Stomph et al. (2002) developed a flow meter for measuring discharges from 1 l/s to as low as 0.03 l/s.

5.3 Evapotranspiration deduction

In most researches so far, like Moran et al. (2004), VanWoert et al. (2005), Stovin et al. (2007) and Uhl and Schiedt (2008) evapotranspiration has been mentioned in a qualitative way only, i.e. the difference between rainfall and runoff. Evapotranspiration in these research projects could have been deducted in a similar way we describe in this paper.

EPA (2009) used 0.5 m^2 weighing lysimeters in a greenhouse that were monitored during drying cycles that lasted 21 days. The weight change was monitored. This method is somewhat similar to our small scale evaporation setup, however our setup is 6 times smaller, and our monitoring frequency is much higher. A smaller setup causes higher side effects, i.e. an overestimation of the evaporation. In stead of using a larger setup that would exceed the weighing capacity of our scale, we tried to reduce the extra evaporation by covering the sides of the setup with aluminum foil.

Mentens (2003) used a water balance approach that is somewhat similar to our large evapotranspiration setup. Weighing lysimeters of 1 m^2 were used, and rainfall and runoff was recorded every 5 min together with air temperature, relative humidity, wind speed and direction, solar radiation and soil temperature. The soil was brought to saturation each morning. Both the amount of added water and the runoff were recorded. The rest of the weight difference is attributed to evapotranspiration. Major differences to our large evapotranspiration setup are the higher weight measuring frequency and the lower flow measuring frequency. Next to that the measured evapotranspiration is limited to relatively wet soil conditions and the roofs are all sloped, which due to gravity will probably result in non homogeneous soil moisture conditions.

6 Conclusions and recommendations

The green roof runoff measuring setup presented in this paper will result in detailed high resolution rainfall-runoff data with a relative high accuracy. The runoff volume resolution is 0.001 mm, with an accuracy of 0.05 mm. The runoff time resolution can be set to 1 s.

The runoff measuring setup is suited for a discharge range between 0 and 6 l/min. Relevant higher discharges will decrease the accuracy, and require a setup with a larger capacity. The principle of a self emptying water collector on a high accuracy weighing scale however, can remain the same.

A tipping bucket rain gauge will only result in reliable measured data when it is properly calibrated for the entire rain intensity range. Only by using something like a self emptying rain collector on a frequently recording weighing scale the resolution and accuracy of the measured data can be increased a little. Rainfall data that are obtained by a rain gauge above floor level have to be adjusted for wind influences. The accuracy of such adjusted rainfall data is at least one order lower than the accuracy of the runoff data. To retrieve the effect of the green roof measured green roof runoff should be compared to measured runoff from a reference roof rather than to measured rainfall. Comparing green roof runoff to rainfall can only achieve a similar accuracy when the rainfall is measured in a similar setup as the runoff.

Evapotranspiration from a green roof can be derived from the rainfall and runoff data as an average value over any period between the ends of two runoff events. By weighing the entire setup the average evapotranspiration as well as the change in stored water volume between any two weight recordings can be derived, provided rainfall and runoff measurements are available. A continuous recording weighing scale together with continuous rainfall and runoff measurements can describe the progress of evapotranspiration and stored water volume over time.

Acknowledgements. The authors gratefully acknowledge the support and contributions of the Singapore-Delft Water Alliance (SDWA). The study was financially supported by the SDWA project number R-264–001-002-272, and by the Delft Cluster II project number CT 06.20.

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Table 1. Correlation between recorded weight and weather conditions for 15 February 2010.

Weight	Pressure	Air temp	Relative humidity	Wind speed	Wind direction	Incoming radiation
box1	0.346	0.615	–0.481	–0.078	0.143	0.863
box2	0.234	0.867	–0.748	–0.066	0.282	0.824
box3	0.255	0.689	–0.506	–0.190	0.273	0.854
box4	0.161	0.533	–0.396	–0.129	0.173	0.840
box5	0.338	0.675	–0.526	–0.149	0.245	0.903

Table 2. Correlation between recorded weight and weather conditions for 16 February 2010.

Weight	Pressure	Air temp	Relative humidity	Wind speed	Wind direction	Incoming radiation
box1	0.219	0.469	–0.501	0.141	0.219	0.853
box2	–0.227	0.861	–0.882	0.174	0.203	0.870
box3	0.049	0.552	–0.604	0.174	0.207	0.866
box4	–0.126	0.744	–0.770	0.191	0.202	0.884
box5	0.094	0.711	–0.714	0.125	0.256	0.867

Table 3. Correlation between weather conditions for 15 February 2010.

Corr. 15 Feb	Pressure	Air temp	Relative humidity	Wind speed	Wind direction	Incoming radiation
Pressure		0.061	–0.137	0.019	–0.094	0.356
Air temp	0.061		–0.931	–0.074	0.238	0.547
Relative humidity	–0.137	–0.931		–0.102	–0.035	–0.392
Wind speed	0.019	–0.074	–0.102		–0.370	–0.045
Wind direction	–0.094	0.238	–0.035	–0.370		0.227
Incoming radiation	0.356	0.547	–0.392	–0.045	0.227	

Table 4. Correlation between weather conditions for 16 February 2010.

Corr. 16 Feb	Pressure	Air temp	Relative humidity	Wind speed	Wind direction	Incoming radiation
Pressure		–0.415	0.483	–0.266	0.056	–0.020
Air temp	–0.415		–0.982	0.096	0.184	0.650
Relative humidity	0.483	–0.982		–0.166	–0.184	–0.669
Wind speed	–0.266	0.096	–0.166		–0.134	0.168
Wind direction	0.056	0.184	–0.184	–0.134		0.151
Incoming radiation	–0.020	0.650	–0.669	0.168	0.151	

Fig. 1. Rainfall measurement setup.

Fig. 2. Runoff measurement setup.

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Runoff measurement setup for green roof experiments in a tropical environment

T. Vergroesen et al.

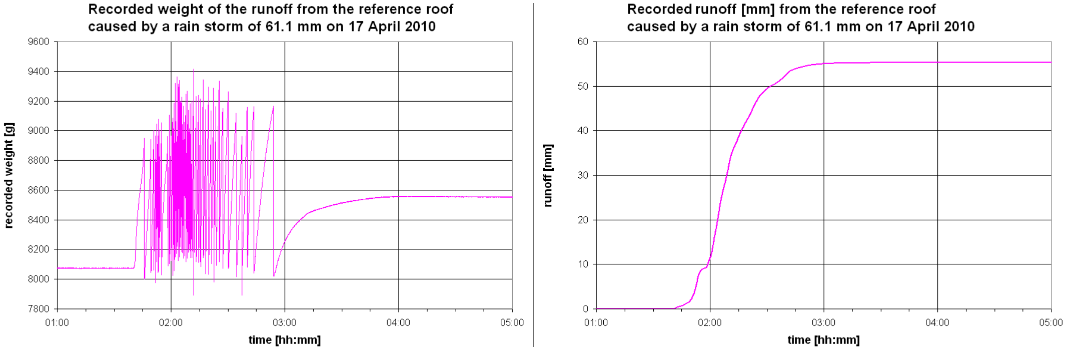

Fig. 3. Transformation of recorded weights to runoff volumes.

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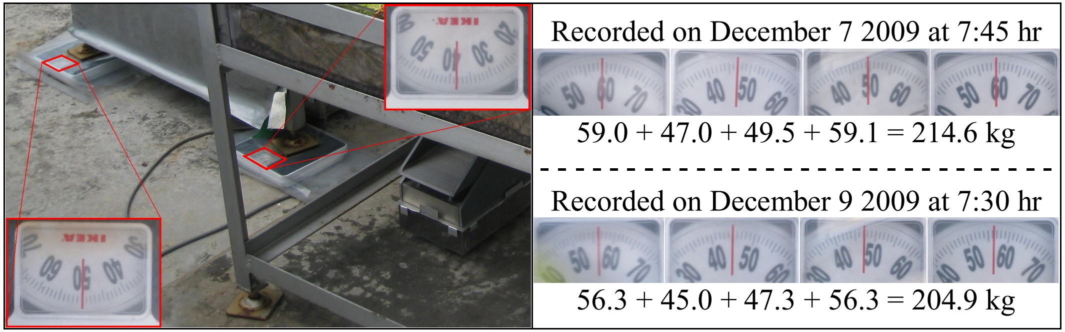

Fig. 4. Evapotranspiration weighing setup: left: bathroom scales under the four legs of the experiment table right: average evapotranspiration during two consecutive days is 9.7 mm.

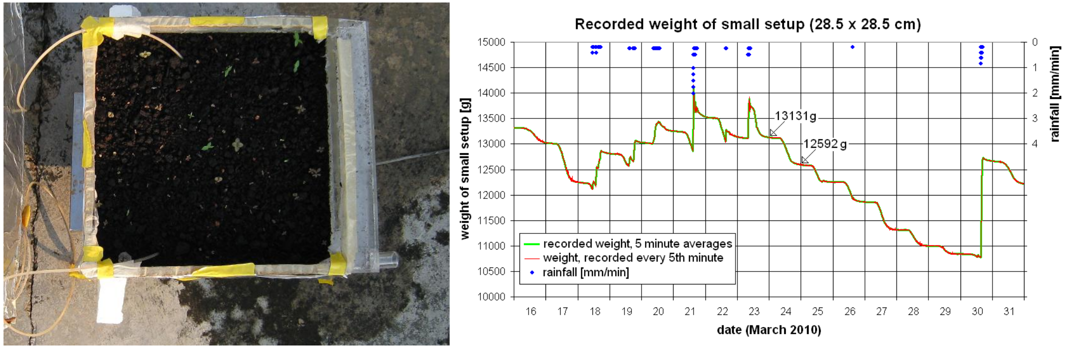

Fig. 5. High accuracy evaporation measurement setup.

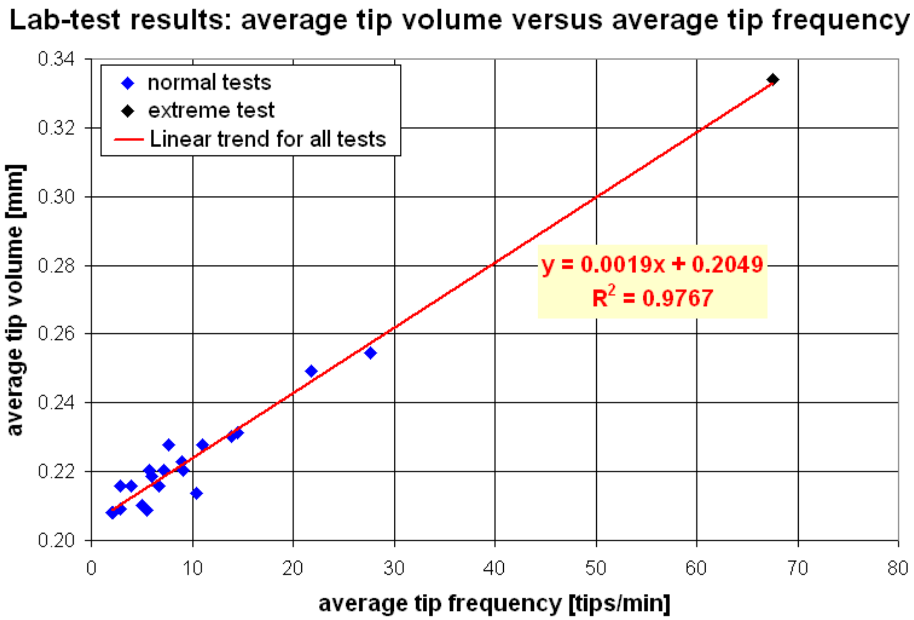

Fig. 6. Result of the rain gauge calibration.

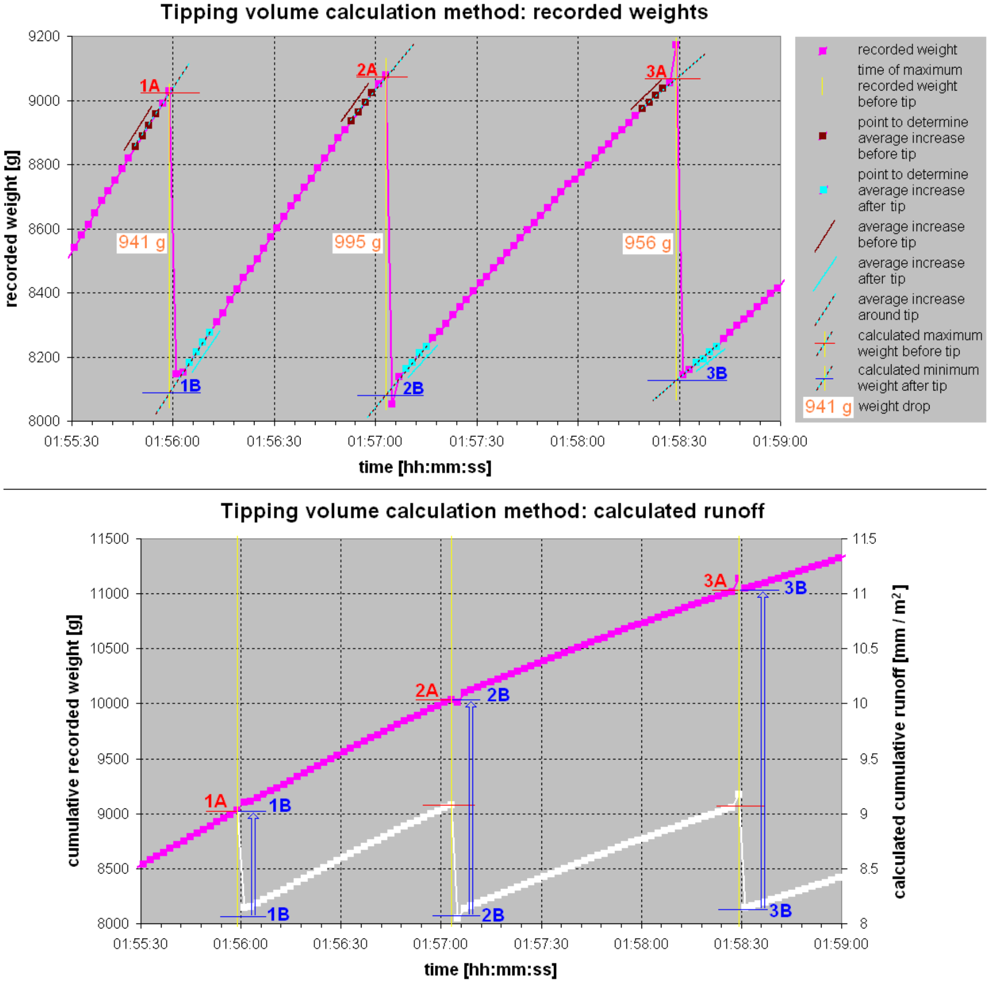

Fig. 7. Transforming the recorded weights into runoff.

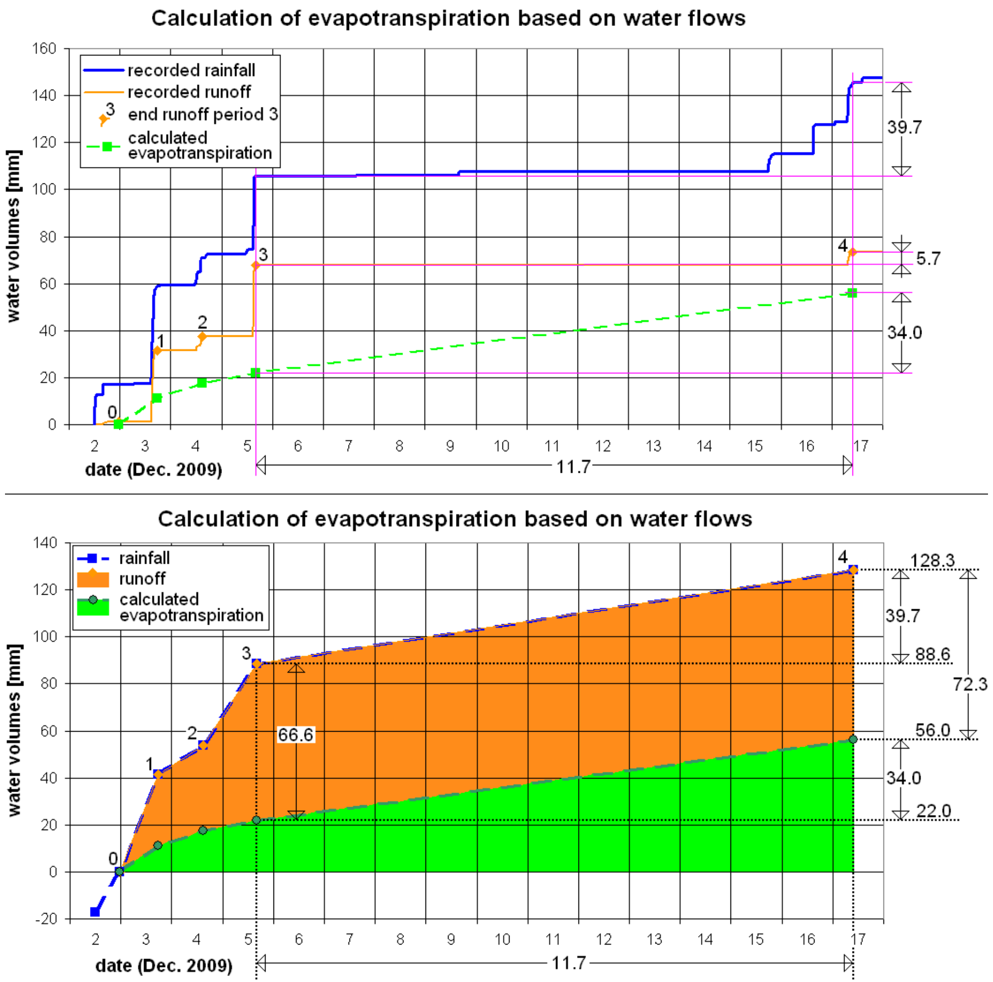

Fig. 8. Calculation of evapotranspiration based on measured rainfall and runoff.

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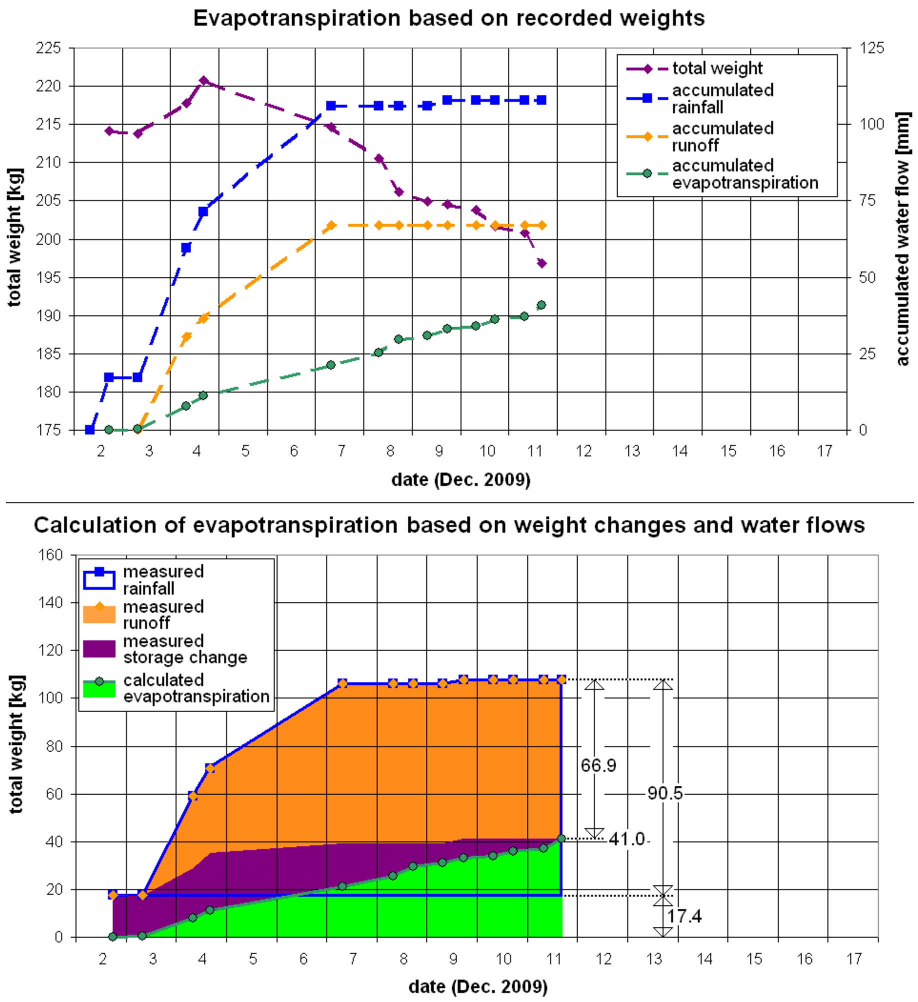

Fig. 9. Calculation of evapotranspiration based on measured water flows and weights.

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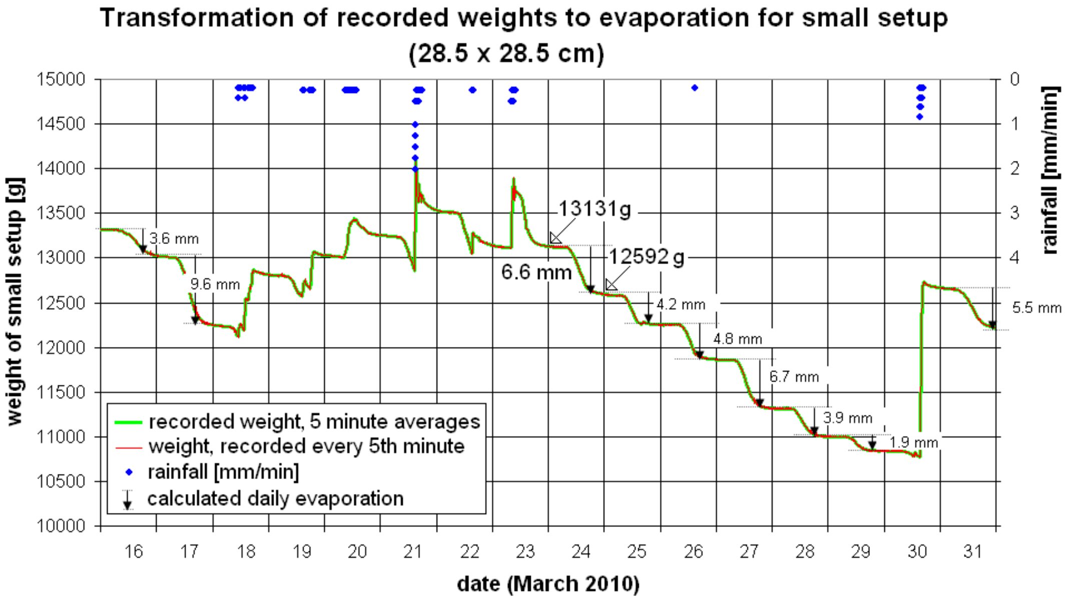

Fig. 10. Calculation of evaporation based on weights of small setup.

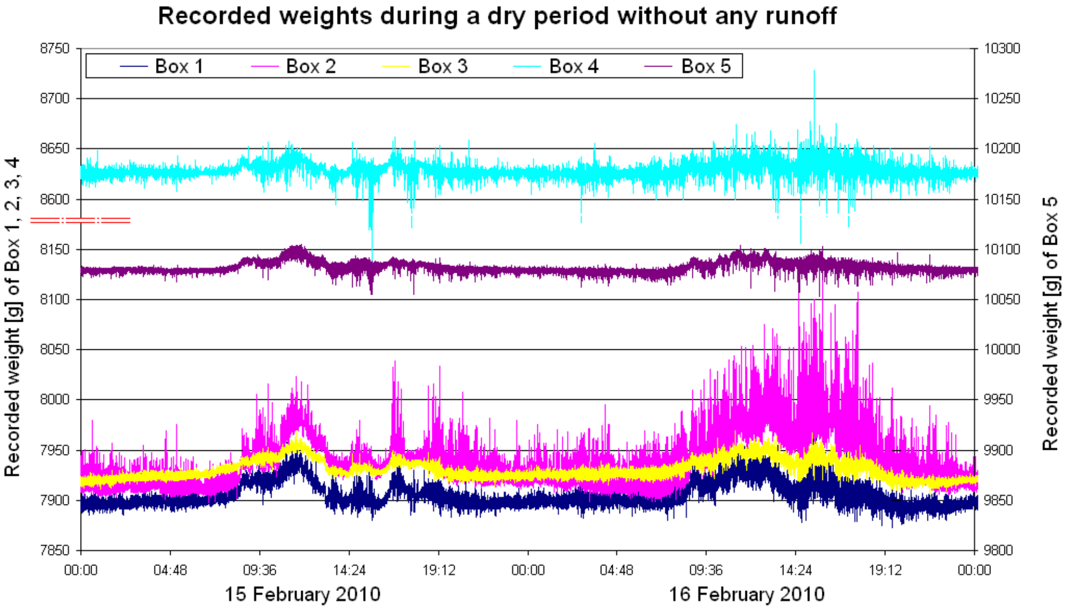

Fig. 11. Recorded weights during a dry day without any runoff.

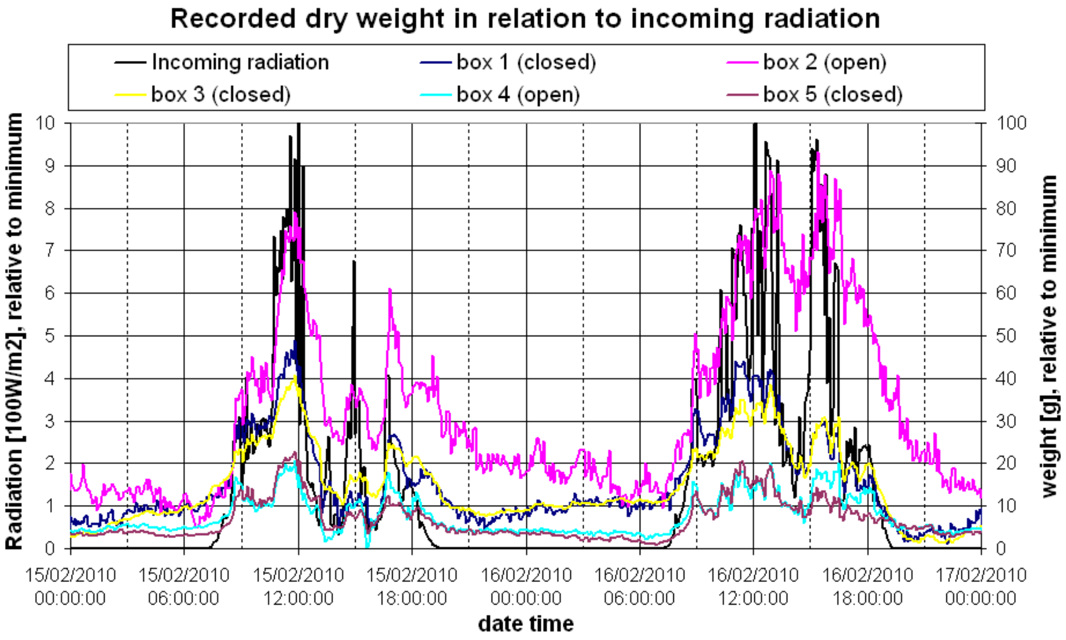

Fig. 12. Correlation between incoming radiation and recorded dry weight (5 min averages).

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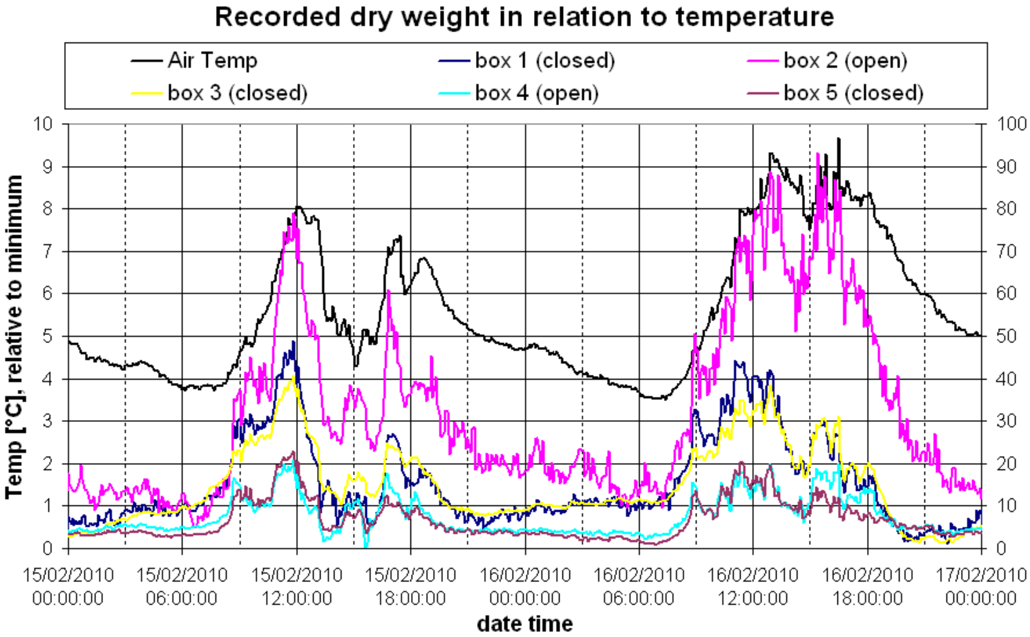

Fig. 13. Correlation between air temperature and recorded dry weight (5 min averages).

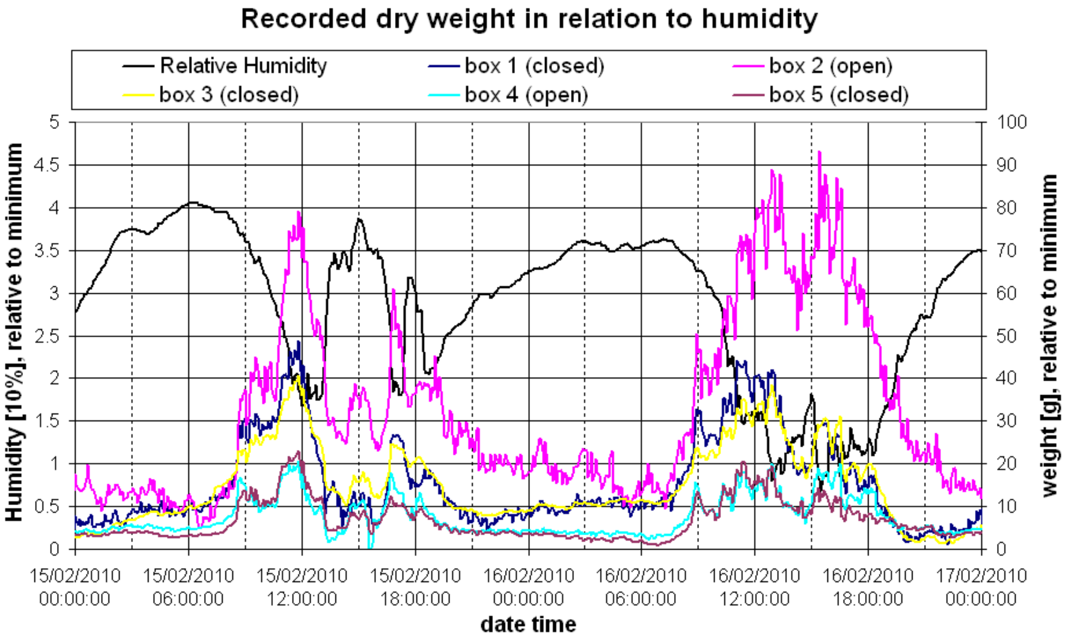

Fig. 14. Correlation between humidity and recorded dry weight (5 min averages).

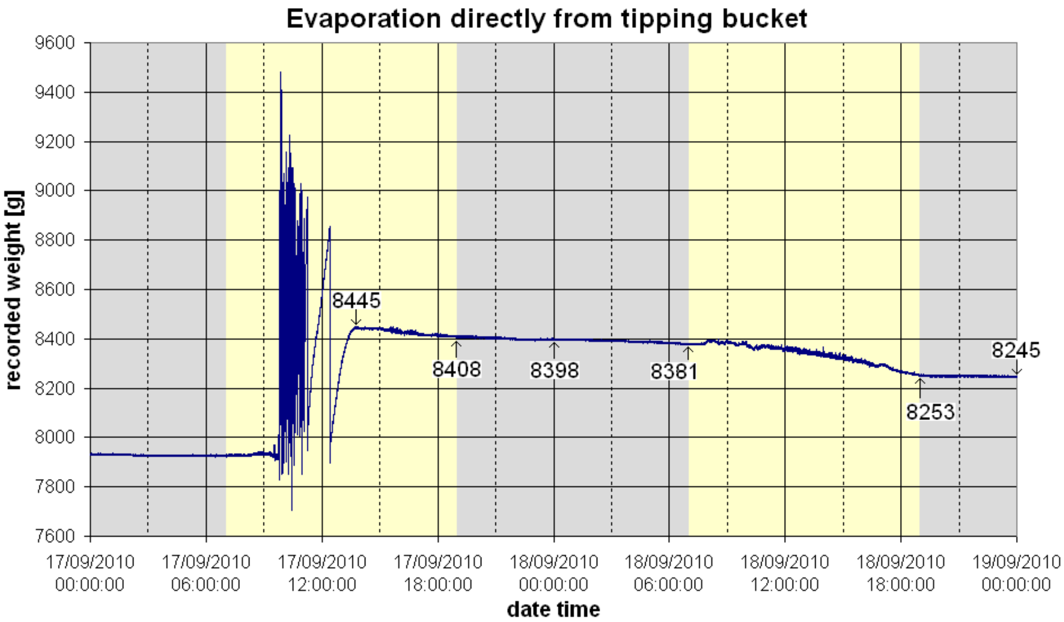

Fig. 15. Weight loss due to evaporation directly from the tipping bucket.