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Measurements of evapotranspiration using a dynamic lysimeter

Mätning av evapotranspiration med en dynamisk lysimeter

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Abstract

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A new dynamic weighing lysimeter is described.

Digital values of evapotranspiration, condensation or wet fog deposition are summed up during 1—2 minutes and are recorded automatically. The evapotranspiration from lichens and heather vegetation measured by means of the lysimeter and that calculated by the Bowen ratio energy balance method are compared. Some errors in evaluation of evapotranspiration by means of both methods are discussed.

Key words: Lysimeter, Evapotranspiration, Bowen ratio energy balance method.

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Contents

1 Briefly about lysimeters

The term lysimeter means differential measuring instrument and may be taken, in general, to apply to all instruments which measure weight changes, especially weight reduction due to evapotranspiration in a particular volume of soil with or without accompanying vegetation.

There are two main types of lysimeter in use: the drainage and the weighing types. In the first case, potential evaporation is obtained as the difference between added and drained water quantity. In the second case, changes in the total weight of the soil sample are measured, whereby the real evapotranspiration during as short a time as ten minutes can be estimated. There are two types i.e. the mechanical and the hydraulic weighing lysimeter.

In the *mechanical weighing* lysimeter the soil sample is placed directly on the balance. The sensitivity will be high, if friction can be reduced using an advanced support construction.

In the *hydraulic weighing* lysimeter the soil sample is placed in a tank floating on a fluid. Changes in level reflect weight changes in the sample. Extremely small weight changes can be detected using this method. A collection of lysimeters of varying design has been published by WMO 1961 [Technical note no 83].

Lysimeters demand large soil volumes in order that heat and water transport within the soil sample be comparable to conditions in undisturbed soil. When the soil supports vegetation, root growth must be able to proceed without obstruction. These conditions result in very extensive and expensive installation work, particularly in the case of lysimeters using hydraulic weighing.

During the years 1971—74 Torbjörn Johnson, at the University of Umeå, constructed a lysimeter according to a modified principle: the *dynamic lysimeter*. Since 1974 the prototype, including the measuring and recording systems, has been developed and adapted to field use. The dynamic lysimeter is described in section 3.

2 The aim of the investigation

The primary purpose of the investigation is to describe the assembly and performance of the lysimeter under field conditions. This can be suitably achieved after reliability and sensitivity have been studied under varying weather conditions.

A small-scale investigation of the heat and water balance in a pine heath is now under way at the College of Forestry in northern Sweden. An important part of this investigation is the measurement and calculation of evapotranspiration from the ground layer vegetation in which the dominating forms are lichens and heather. Lysimeter measurements made possible, at least during short periods, direct measurements of evapotranspiration from and condensation upon the lichens and heather.

It is possible to compare the results of the direct measurements using the lysimeter with the meteorologically estimated evapotranspiration. Differences can arise owing to a number of factors, the most important of which is advection. The effects of advection, i.e. the net horizontal transfer of heat and water vapour by the action of wind, must be ignored when using meteorological methods. It is seldom that an advection-free area can be found in forested regions.

3 Description of the dynamic lysimeter

3.1 Construction

The aim of constructing a new lysimeter was to obtain high sensitivity and precision combined with a low construction cost and simplicity of installation. L. G. Morris (1959) describes a mechanical construction based on a lever balance. The balance was fitted with a counterweight, driven by a motor, which balanced the counterweight to a fixed point of balance. The motor is stationary as long as no changes in weight occur. Like L. G. Morris, T. Johnson chose mechanical weighing as the basic principle, but a dynamic moment was introduced by causing the lever balance to swing back and forth through the equilibrium balance position. In this way the effects of friction are greatly reduced, as, too, is the need to place the balance on a large and stable base. Extensive preparation of the ground can therefore be avoided.

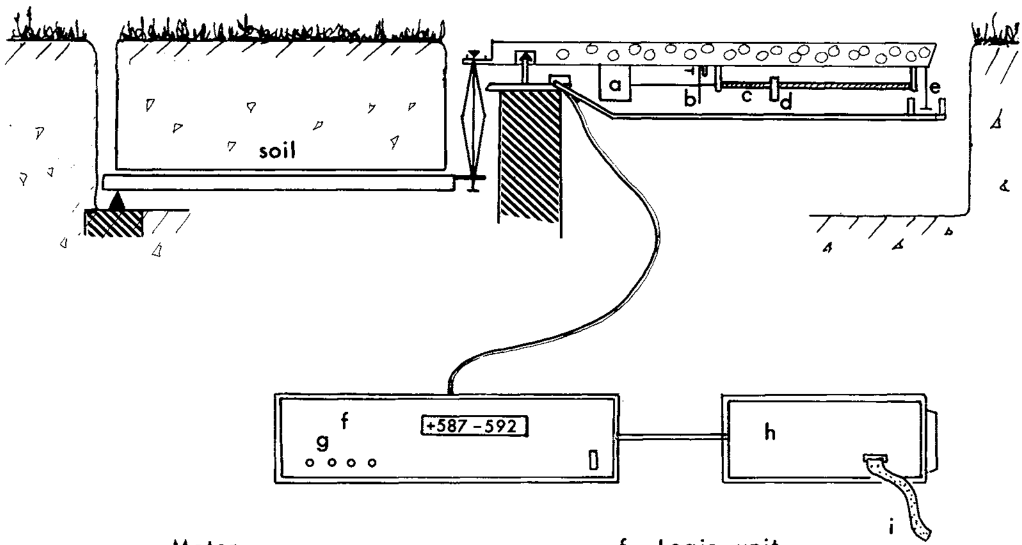
The main component in the lysimeter is a balance arm which rests on a knife edge dividing the arm in the ratio of 10 to 1, Figure 1. The longer section of the arm can be loaded with variable stationary weights. The balance arm and the sample are caused to swing up and down through the position of balance by the continuous action of a moving counterweight along a bar parallel to the balance arm. That is to say, the moving weight balances the arm about an equilibrium position by means of small movements inwards and outwards about a central position. The movements of the balance arm and the moving counterweight are converted to pulses after being registered by photoelectric detectors. The results, in the form of pulses from the lysimeter, are fed into a datalogger, specially designed for the lysimeter. The signals corresponding to the time that the balance arm is above its equilibrium position are stored in one memory and those corresponding to the time that the arm is below the equilibrium position, in another. The signals are read off after a predetermined number of complete swings and the data are punched on tape in ASC II coded form. Since all signals from the lysimeter are in binary conversion form, analogue form is unnecessary. This makes possible a reliable electronic system, which greatly reduces the cost of signal processing.

The datalogger can determine the number of periods which the swinging balance arm makes prior to the punch-out. After a certain number of punch-outs the correct time (date and time) and two control values are also punched out. Signals from sensors, for example, for temperature and humidity, can be received and punched out instead of the two control values.

A digital temperature and humidity detector, which could be connected directly to the datalogger, was developed at the same time as the pulse detector. Temperature is measured by a normal thermometer which is read off by a movable photo-electric cell. Circular instruments with a nominal fixed point on the negative side, eliminating the need for plus and minus terms, were used in the prototype. Pulses are registered beginning at the fixed point and finishing at the movable pointer.

3.2 The function and sensitivity of the dynamic lysimeter

The lysimeter measures the time during which the balance arm is above and below the balance position, expressed as the number of pulses. These intervals are equal when the sample has constant weight. The movable counterweight then moves back



a Motor
b Holedisc
c Rotating bar
d Moving counterweight
e Indicator
f Logic unit
g Preset for clock
h Punch
i Paper ASC II code

Figure 1. Principle of the dynamic weighing lysimeter.

and forth equidistant from the central position. An increase in the weight of the sample causes an immediate increase in the time (number of pulses) that the balance arm is above the balance position as compared to below it. The moving counterweight compensates this change by increasing the length of its movement away from the sample end of the balance arm until the initial state of equilibrium is restored. The time for a complete period of swing (10 up and 10 down) does not differ by more than a few per cent between the new and the previous equilibrium condition. The difference between the time spent in the up and that spent in the down position of the swinging balance arm, and the time taken to reach the new balance condition are a measure of both the sensitivity and readjustment time of the lysimeter. Both these factors are dependent upon the mass and rate of movement of the counterweight. The heavier the counterweight, the greater will be the damping effect on the swing frequency of the balance arm, and thus on its displacement for a given change in weight of the sample. The readjustment time is also reduced. Increasing the rate of movement of the counterweight has the same effect.

A heavy counterweight is used if large weight changes are expected in the sample, and vice versa, if the expected weight changes are small. The lysimeter's working range decreases in the latter case.

It should be noted that the damping of the lysimeter is a function of the whole system's centre of gravity in relation to the position of balance. The degree of damping can be varied by raising and lowering the fixed counterweights in relation to the balance arm. The apparatus should always be calibrated when such large changes in sample weight occur that the fixed counterweight must be moved.

3.3 Calibration

The lysimeter measures the time that the balance arm is above (positive values) and below (negative values) the balance position. The calibration gives the increase or decrease in weight of the sample *corresponding to the difference* between the positive and negative values. The same difference in lysimeter readings can correspond to different weight changes in the sample, depending upon the mass of the moving counterweight. Known weights were either added to, or removed from, the test area in order to alter the weight of the sample during calibration.

Figure 2 shows the lysimeter's behaviour when a 1.65 g weight was placed on and removed from the sample surface. The moving counterweight was 105 g and the time for ten complete swings varied between 1.7 and 1.8 minutes. The 1.65 g weight was placed close to the swinging side of the sample tank, Figure 1. The same weight change results regardless of whether a weight of 3.3 g is placed centrally on the sample or distributed evenly over the whole surface.

Interference and irregularities in the lysimeter's performance during calibration are evident from Figure 2, but it may also be noted that the sample weight slowly decreased up to 8 p.m. It can also be seen that the lysimeter reacted significantly to the calibration weight, regardless of its relatively insignificant mass (approximately one hundred-thousandth of the total mass of the sample). Table 1 illustrates the change in the number of pulses caused by an increase and decrease in the weight of 3.3 g, respectively. It became obvious during the calibration that the position of the sample tank when the calibration weight was placed on, or removed from, the sample was of importance to the reading. If the calibration weight was placed on an upward-moving tank (balance arm moving downward), both the reading and the readjustment time decreased in comparison with the same case where the tank was moving downward. The variations in the lysimeter readings seen in Table 1, from the calibra-

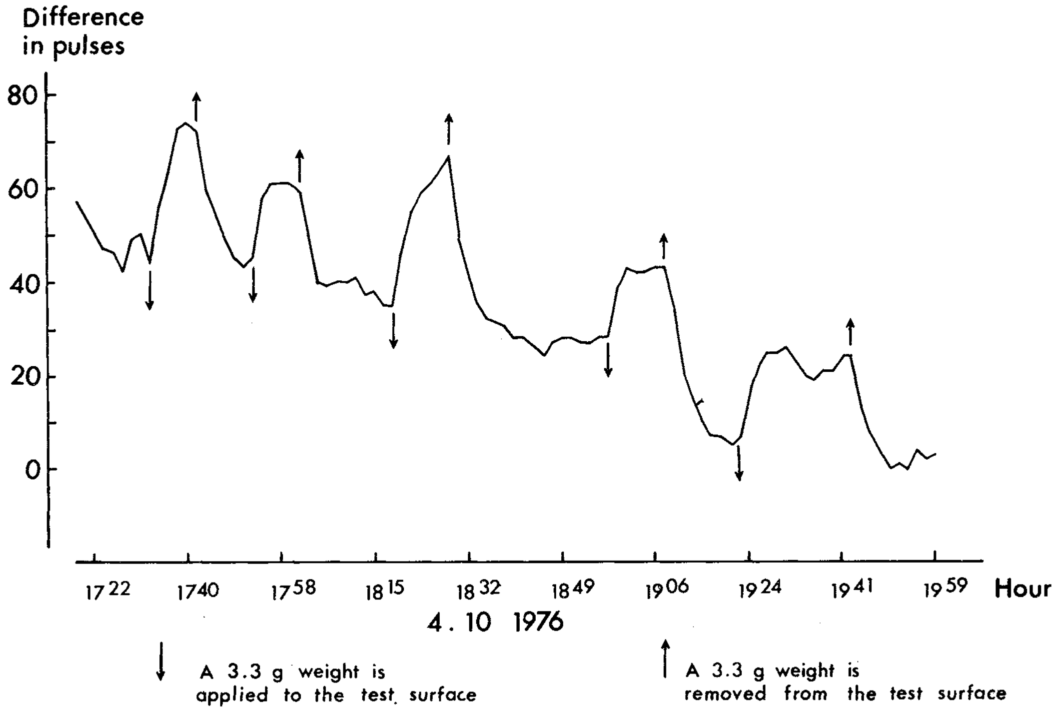


Figure 2. Calibration measurement of the dynamic lysimeter. The 3.3 g calibration weight was applied to and removed from the sample tank. The total weight was about 700 kg.

Table 1. Calibration of the dynamic lysimeter. Calibration weights have been applied to (+) and removed from (−) the sample tank.

Date	Time	Movable weight g	Swing time in minutes (10 swings)	Number of pulses (10 swings)	Changes in pulses exclusive of calibration	Calibration weight g	Number of pulses due to calibration weight	Sensitivity g/puls
740726		60	0.9	625	−100	+10.40	270	0.04
740726		60	0.9	625	−100	−10.40	245	0.04
740906	1640—1647	60	1.5	865	−80	+100.00	980	0.10
	1655—1700	60	1.5	865	−40	+20.08	144	0.14
	1710—1715	60	1.5	865	−30	−20.08	150	0.13
	1733—1742	60	1.5	865	−50	−100.00	950	0.11
	mean	60	1.5	865				0.12
740918	1945—1954	258	0.9	750	−18	+20.08	301	0.07
	2014—2025	258	0.9	750	−18	+19.20	272	0.07
	mean	258	0.9	750				0.07
750716	1529—1532	735	1.7	1100	−33	+100.08	178	0.56
	1603—1608	735	1.7	1100	−50	−100.08	180	0.56
	1953—2000	735	1.7	1100	−35	−100.08	175	0.57
	mean	735	1.7	1100				0.56
761004	1731—1739	105	1.7	711	−1	+3.30	31	0.11
	1740—1748	105	1.7	711	−1	−3.30	28	0.12
	1748—1756	105	1.7	712	−1	+3.30	19	0.17
	1758—1806	105	1.7	711	−1	−3.30	22	0.15
	1817—1826	105	1.7	711	−2	+3.30	34	0.10
	1826—1839	105	1.7	711	−2	−3.30	36	0.09
	1856—1900	105	1.7	712	−1	+3.30	16	0.21
	1908—1918	105	1.8	711	−2	−3.30	38	0.09
	1922—1934	105	1.7	713	−1	+3.30	22	0.15
	1942—1951	105	1.8	712	0	−3.30	24	0.14
	mean	105	1.7	712				0.13

tion in 1976, are partly attributable to the above reason and partly to the sensitivity of wind, among other things. These effects may be regarded as "background noise".

Table 1 shows the results of calibrations performed in 1974 and 1975. The calibration weights and the mass of the moving counterweight, as well as the time of swing, were varied. The different calibration instances are not directly comparable because the rate of movement of the variable counterweight was varied, and certain design modifications were made during this time. The total range, in kilogrammes, is obtained by multiplying the mass of the moving weight, in kg, by a factor of 7.8. In 1975 the lysimeter could register weight changes up to 5.7 kg without the fixed weights having to be moved, as compared with 0.5 kg in 1974, when the counterweight was 60 g.

4 The research area and methods

Measurements were performed periodically in the summers from 1974 to 1976. The research station is located on a flat sediment area which covers the southern part of Svartberget Research Park, latitude 64°20′N, longitude 19°55′E. There is a micrometeorological station in the area, belonging to the College of Forestry's ecological research station.

The lysimeter and accompanying instruments were placed on a 3000 m^2 section of open ground. This glade is surrounded by a sparsely stocked stand of young Scots pines with an average height of 4.7 m. Because of the small size of the glade, the evapotranspiration from it is affected by the surrounding trees.

The soil consists of silt, and the vegetation largely of lichens and heather.

4.1 Installation of the lysimeter

The change in weight of a sample tank was measured. The sample tank was made of aluminium, 0.5 m deep and with a sample area of 1 m^2. The tank was placed in a board-lined, square hole in the ground, the upper rims of the tank being level with the surrounding soil surface. One side of the sample tank swung freely by the lysimeter's balance while the opposite side was mounted in ball-bearings on concrete blocks (see sketch in Figure 1).

The sample tank was filled with 30 cm of mineral soil from the area. The upper 20 cm of soil, with its accompanying vegetation layer, was then placed uppermost in the tank. Lichens and mosses accounted for 70 % of the vegetation up to a height of 5 cm.

The cover, considering greater vegetation height, was as follows (1975):

	%	Height cm
Lichens	35	5
Mosses	15	
Heather	35	30
Scots pine	5	35
Grass	5	
Cowberry	<5	

The sample tank was in motion during the time that measurements were taken. The motion was greatest on the free swinging side. Weight changes must therefore be evenly distributed over the sample tank if measurements are to be of consequence. If the weight change is unevenly distributed, then the results will have different values depending upon where on the surface the weight change is greatest. Hence, the greatest sensitivity is observed when the weight change occurs nearest to the balance arm and least sensitive (zero) on the opposite side (over the support). It is possible to avoid problems caused by uneven weight changes by using a special cradle arrangement for supporting the sample tank. This has, however, yet to be tested in the field.

The support and balance arm were placed in an excavated shaft with a lid, in order to eliminate the effects of wind on the balance arm. The sample had a total weight of about 700 kg.

A glass tube was located in one of the corners of the sample tank, whereby drainage water could be run off and measured. No drainage has been observed during the investigation periods, in spite of periods of heavy rainfall. The vertical transport of water between the sample and the ground was broken and therefore the capillary phenomena were different from those observed in undisturbed ground.

4.2 Meteorological measurements

The main of the meteorological measurements was to be able to estimate evapotranspiration. The energy budget method or, more precisely, the Bowen ratio energy balance method, was chosen for this purpose (see among others Rosenberg 1974). Evapotranspiration (E) can, according to this method, be approcimately represented by:

$$E = \frac{R_n - B}{L\left(1 + v\frac{\Delta\Theta}{\Delta e}\right)}$$

where

R_n = net radiation
B = heat stored or utilized in the soil
L = heat of evaporation (2450 J/g)
v = Psychrometer constant (0.66 mb/°C)
$\Delta\Theta$ = difference in potential air temperature ($\Theta = T - 0.01 \cdot z$, z expressed in meters) between two test levels above the ground
Δe = difference in vapour pressure (in mb) between the two test levels

The term $v\frac{\Delta\Theta}{\Delta e}$ is called the Bowen ratio.

The net radiation (R_n) was measured using a net radiometer (Ersking), which was placed 1.5 m above ground level, and the ground heat transfer, using a heat flow meter (Tech Dienst), which was placed on the mineral soil, i.e. below the lichen-heather cover and the 4 cm thick humus layer. The air temperature (for estimation of $\Delta\Theta$) was measured using resistance wire thermometers (PT 100) placed at heights of 20 and 50 cm above ground level. Humidity meters (Humicap, Vaisala) were placed at the same two heights. The low measuring heights were chosen in order to reduce the marginal effects of the surrounding trees, as well as to keep the error in the measurement of the gradients relatively low in comparison with the periodically high values of these gradients. The accuracy of the temperature measurements was ±0.1°C, in the middle of the day, and the accuracy of the relative humidity measurement ±1 %.

Temperature and humidity sensors were mounted in small electrically ventilated radiation shields, designed and constructed by A. Openshaw of the College of Forestry. He also designed the integrated wind speed meter (cup anemometer) which, together with the above instruments, was connected to a digital data collection system (Solartron). Measurements were recorded at intervals of between 5 and 20 minutes. The readings in mV were transferred to the respective units using suitable functions. The mean hourly values were then calculated. The rainfall was measured and recorded using a raingauge (type Hellman) equipped with a one-month recording unit (Lambrecht).

5 Results

A large volume of data have been collected during several studies. Measurements have been carried out both in the field and in a greenhouse. Only two periods of field measurements are presented in this paper: the periods in which some micrometeorological measurements were made. Measurements from October, 1976, are presented first, followed by those from July 31, 1975. Irrigation experiments were carried out during the latter period.

5.1 October measurements

The measurements were carried out during the period from October 4 to October 7 (Figures 3—8). The weather during these late autumn days was characterized by frequent fog and stratus clouds, particularly at night. When the nights were clear the air temperature was below zero, causing the field and ground vegetation to freeze. The day of October 5 was cloudless after the early morning mist had dispersed. Otherwise the days were cloudy. On the morning of October 7 rain began to fall in the Vindeln area.

The lichens were assumed to be saturated with water. Evaporation from the lichens, and particularly transpiration from the Scots pine seedling and the heather in the sample tank, should have been low because of low insulation, low temperature and the fact that the humus layer was partly frozen at times. However, with a small movable counterweight (105 g) the lysimeter should have been sensitive to small weight changes in the sample. The sensitivity was 0.13 g/pulse (Table 1).

5.1.1 *Measurements made on October 4—5*

The air temperature, humidity and wind speed on the 4th and 5th of October are shown in Figure 3. The air temperature fell briefly below zero on the night of the 4th, but rose and was relatively high in conjunction with a mist during late evening and early morning (9 p.m.—1.30 a.m.). The mist dispersed and was replaced by stratus cloud during the early morning, whereupon the temperature dropped below freezing and remained there until 8 a.m. The weather cleared during the late morning, but the mist appeared again the following night.

Temperature and vapour pressure differences between the 50 and 20 cm levels above ground were negative, i.e. the 50 cm level was both colder and drier than the 20 cm level between 8 a.m. and 3 p.m. on October 5 (Figure 3).

The sample decreased in weight by 9 g from the time that the lysimeter readings were begun until 11 p.m. on October 4 (Figure 4). Thereafter, the sample increased in weight, with the greatest increase occurring in the early morning. The mist was wet at this time and deposited very small (10—50 µm diameter) droplets of water. Deposition due to the mist, together with possible condensation on the vegetation, amounted to 76 g (0.08 mm) of water. The mist precipitation was large enough to influence the raingauge. The sample weight decreased slowly as early as 4 a.m. and continued until 9 a.m. when the warmth of the sun became effective and evapotranspiration increased.

The total decrease in weight due to evapotranspiration was 215 g. Evapotranspiration reached a maximum of 0.03 mm per hour around noon (Table 2).

The energy budget method (Bowen ratio method) gave low condensation during the night and very low evapotranspiration during the morning until about 6 a.m., when evapotranspiration was greater until 3.15 p.m.

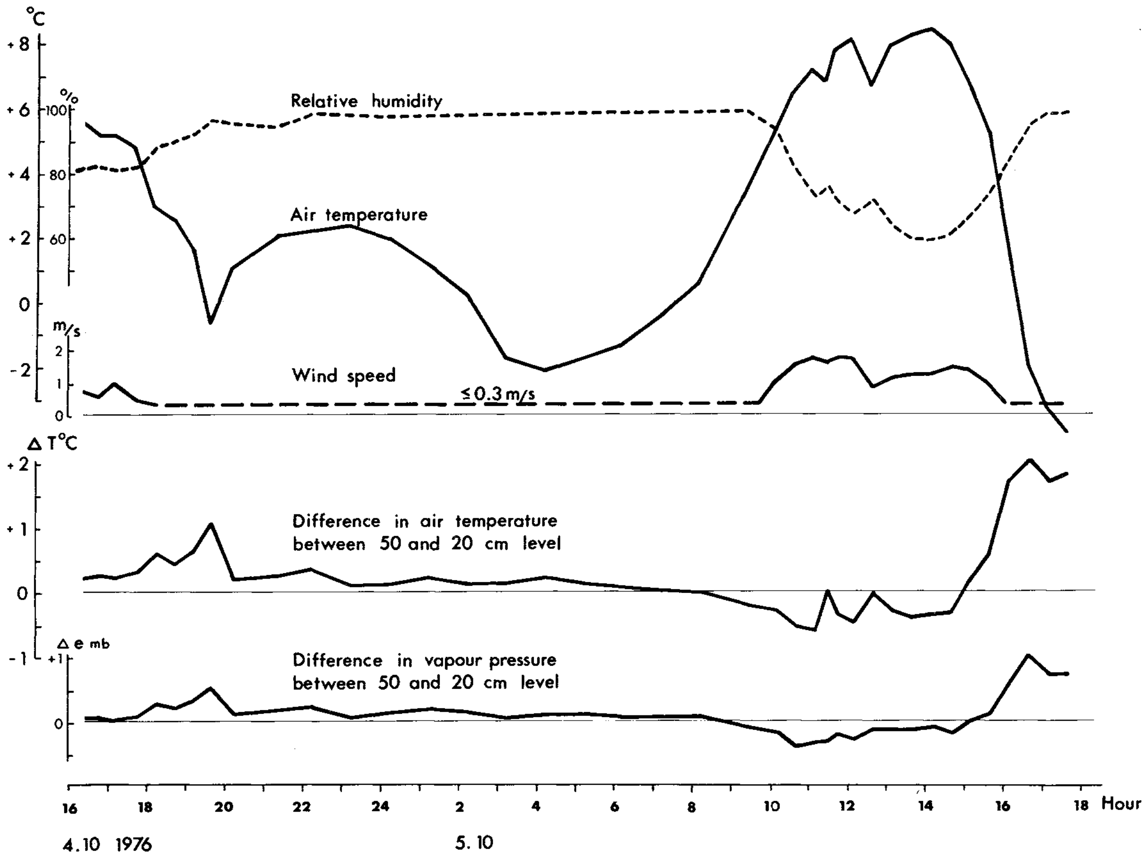


Figure 3. Meteorological elements at the research station at Åheden, October 4—5, 1976.

Table 2. Evapotranspiration (condensation, wet fog precipitation) for a 1 m² area of vegetation. Evapotranspiration is indicated by a minus sign (1 mm = 1 kg/m²).

Day	Time	Bowen ratio method		Lysimeter method	
		mm	mm/h	mm	mm/h
4—5.10	1600—2245	+0.0		−0.01	
1976	2245—0400	+0.0		+0.08	+0.03 max. wet fog
	0400—0730	−0.0		−0.01	
	0730—1500	−0.7	−0.16 max.	−0.16	−0.03 max.
	1500—1800	+0.0		−0.04	
31.7	1013—1133			−0.40	−0.30 mean
1975	1105—1215	−0.3	−0.3		
	1225—1558			−1.50	−0.42 mean
	1435—1505	−0.4	(−0.7)	−0.23	
	1435—1505	−0.3*	(−0.5)*		

* Radiation only.

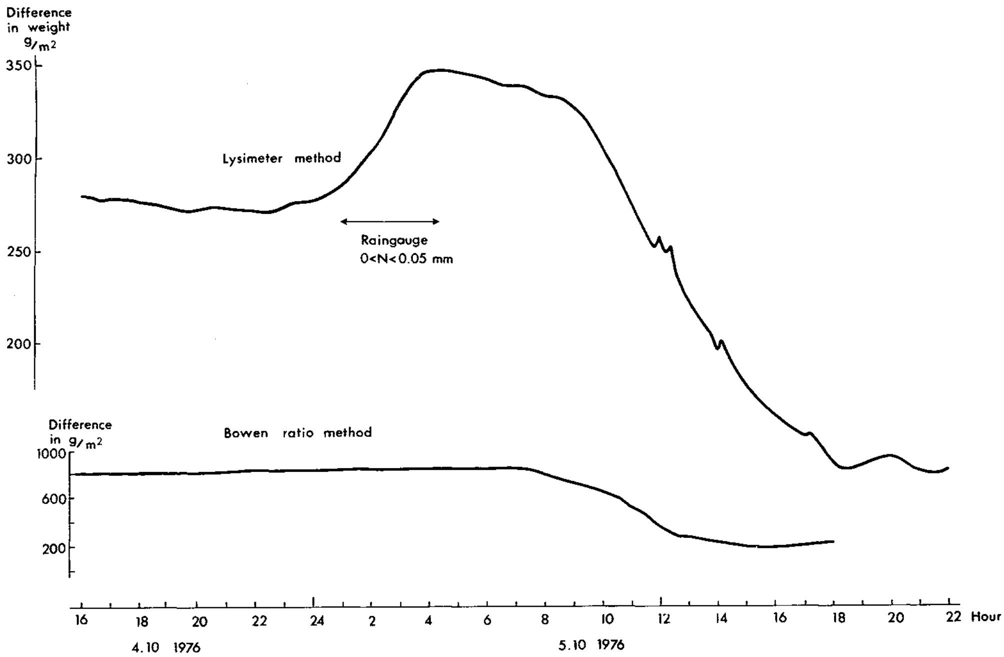


Figure 4. Evapotranspiration and condensation of lichen-heather vegetation measured by the lysimeter and calculated using the Bowen ratio energy balance method. Wet fog droplets were deposited in the late evening of the 4th and in the early morning of the 5th.

(Figure 5, broken curve). Figure 5 illustrates the latent heat flow, LE (W/m^2) (evapotranspiration = E), the net radiation, R_n, of the lichen and heather vegetation and the heat flow through the mineral-soil surface, B.

The calculated cumulative evapotranspiration (condensation), in g/m^2, is shown in Figure 4. A total evapotranspiration of 0.7 mm (maximum 0.16 mm/hour) was reached using the energy budget method (Figure 4 and Table 2). A longer period of evapotranspiration was obtained using the lysimeter as compared with the energy budget method. But the total evapotranspiration was only about a quarter of the value, when measured with the lysimeter. It can be noted that both methods gave the same time for the beginning of evapotranspiration (4 a.m.). The reasons for the large difference in the results obtained from the two methods are discussed in section 6.

5.1.2 *Measurements made October 5—7*

The night of the 5th of October and the evening of the 6th were cold and the temperature at ground level was below zero. The sample weight changed insignificantly during the night up to as late as 10 a.m. on the following day (Figure 6). It was cloudy during the day and the evapotranspiration was insignificant (90 g) until about 4 p.m. During the evening of the 6th of October, the sample weight increased somewhat (condensation), and then decreased (26 g) until 2 a.m. The sample had probably received droplets (98 g) from wet mist until about 6 a.m.

According to the lysimeter, it began to rain between 9.16 and 9.18 during the morning of October 7 (Figure 7). After a weight increase corresponding to 0.3 mm of rain (330 g), the limit of the measuring range was reached at 9.38 a.m. Rainfall had

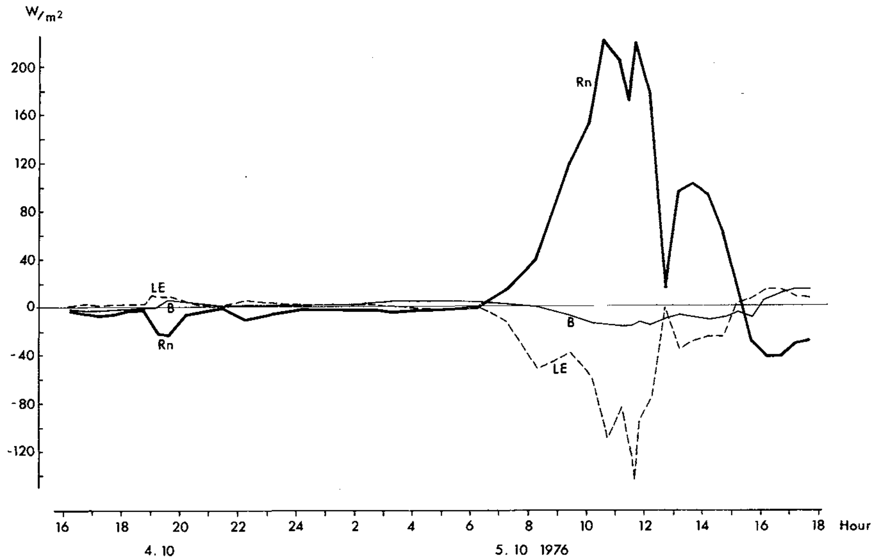


Figure 5. Components of the energy exchange of the lichen-heather vegetation at Åheden, October 4—5, 1976.

R_n = Net radiation.
LE = Latent heat flux.
B = Heat flux in ground.

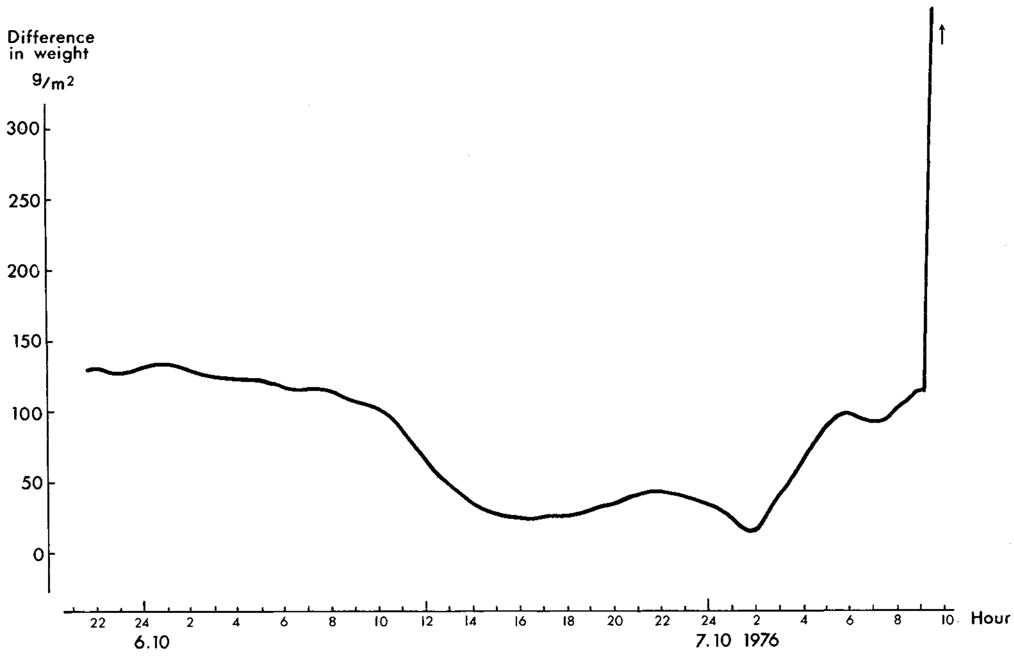


Figure 6. Changes in the weight of the sample tank registered by the lysimeter. Slight evapotranspiration occurred in the middle of the 6th and probably wet fog precipitation early in the morning of the 7th, later followed by rain.

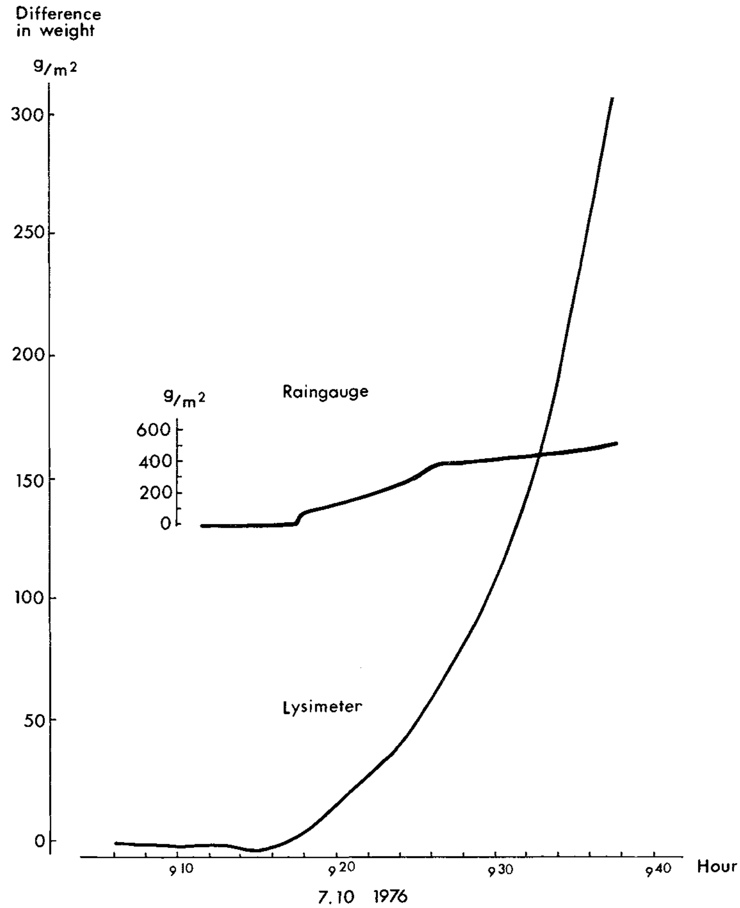


Figure 7. The rain on the 7th of October registered by the lysimeter and the rain-gauge.

then reached 0.5 mm according to the rain-gauge. Thus, the rainfall according to the lysimeter was 0.2 mm lower. A certain slowness can be distinguished in the lysimeter readings when the sample weight undergoes large and rapid changes in weight (see page 20).

The irregularities in the curve in Figure 4 occurring at about 12 noon and 2 p.m. are shown in detail in Figure 8. The average wind speed during periods of 4—5 minutes is also shown on this graph. Measurements were made 1.9 metres above ground level. As may be seen from the graphs, irregularities in the lysimeter readings occurred during those periods when the average wind speed was highest during the day and probably showed the greatest variation. The wind speed was somewhat lower and less variable during the periods just before and just after the irregularities in the lysimeter readings.

5.2 **July measurements**

These measurements were made on the 31st of July 1975. The movable counterweight in the case was 735 g and the sensitivity was 0.56 g per pulse (Table 1). The lower sensitivity resulted in a wider working-range (without the necessity of altering the fixed weights) than in the previous case.

It may also be of interest to study the lysimeter's performance with the larger movable weight. Figure 9 shows measurements made from 10.47 to 11.31 a.m. In the same way as in measurements made during October, irregularities appeared during the day, for example at 11.01 and 11.12 a.m. These were much less noticeable

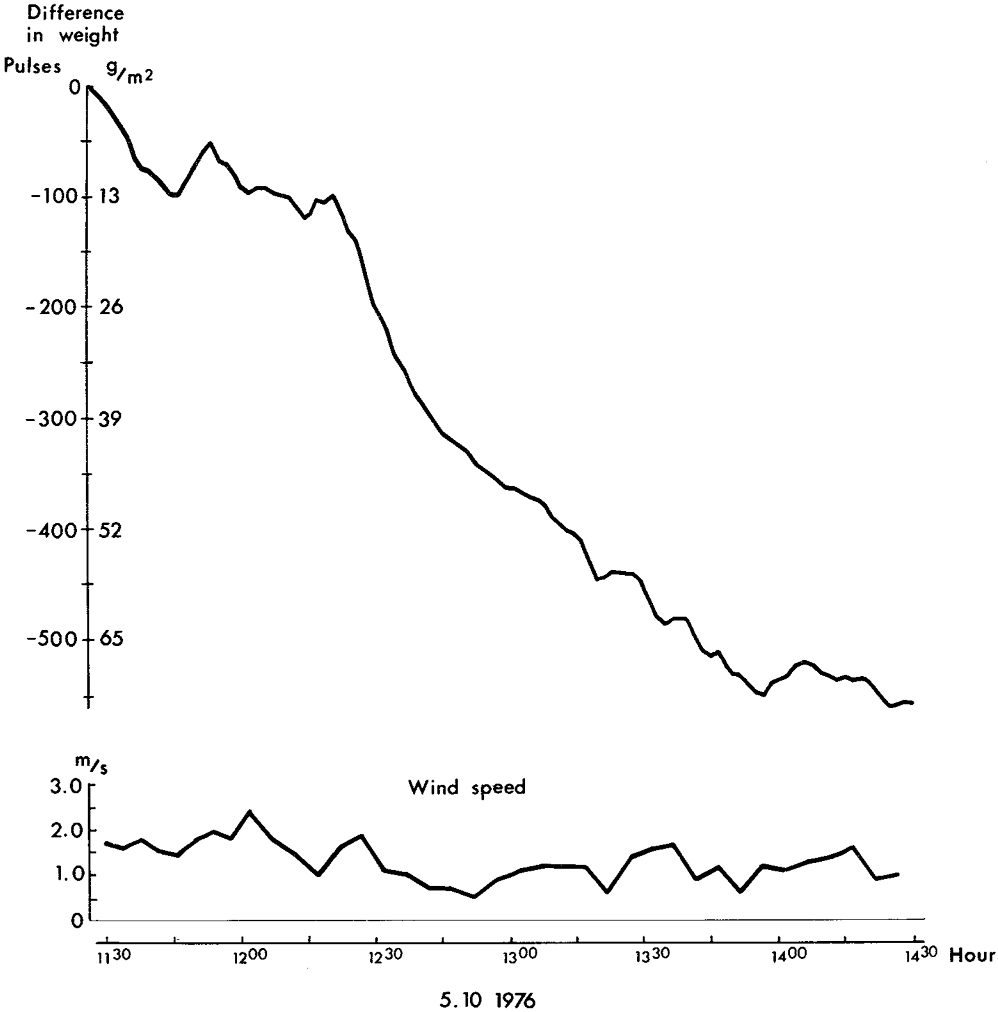


Figure 8. Part of the evapotranspiration during the 5th of October, measured by the lysimeter. Irregularities can possibly be due to variations in the wind speed.

than in the previous case. This can be explained by the fact that the sensitivity was 80 per cent lower in the latter case.

The temperature was very high on the 31st of July, with a maximum of 28.6°C, 50 cm above ground level. The relative humidity was 30—40 per cent during the period in which measurements were taken (see Appendix). A certain amount of cloudiness (cirrus) occurred during the day, which periodically reduced the insulation slightly.

Evapotranspiration from the sample area was mainly accounted for by transpiration from the Scots pine seedling, heather and dwarf shrubs. The lichens and mosses were dehydrated. Fine cracks exposing mineral soil were clearly visible between the dried up lichens.

The measurements were started at 10.13 a.m. and are presented in Figure 10. The sample decreased in weight by 398 g, up until 11.33 a.m., corresponding to an evapotranspiration of 0.30 mm of water per hour. The evapotranspiration between 11.05 a.m. and 12.15 p.m., calculated using the energy

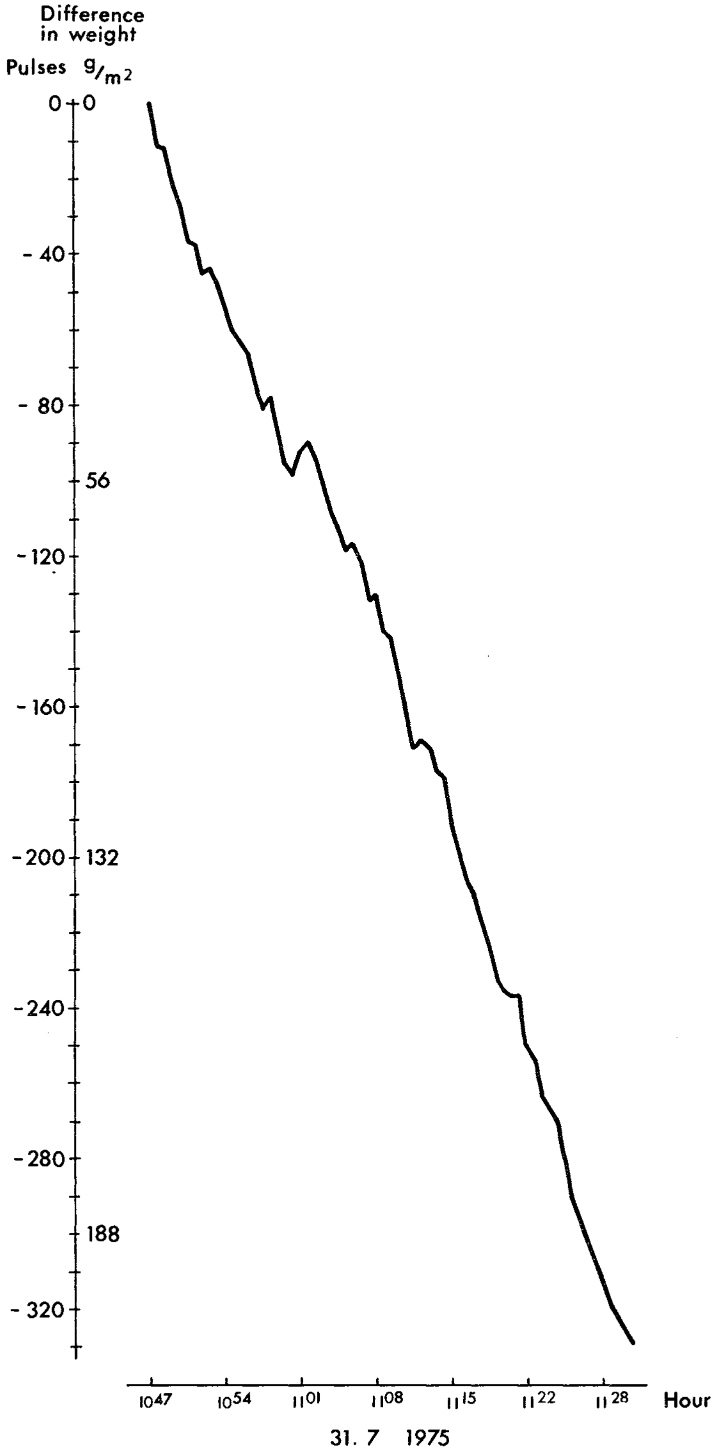


Figure 9. Part of the evapotranspiration on the 31st of July measured by the lysimeter.

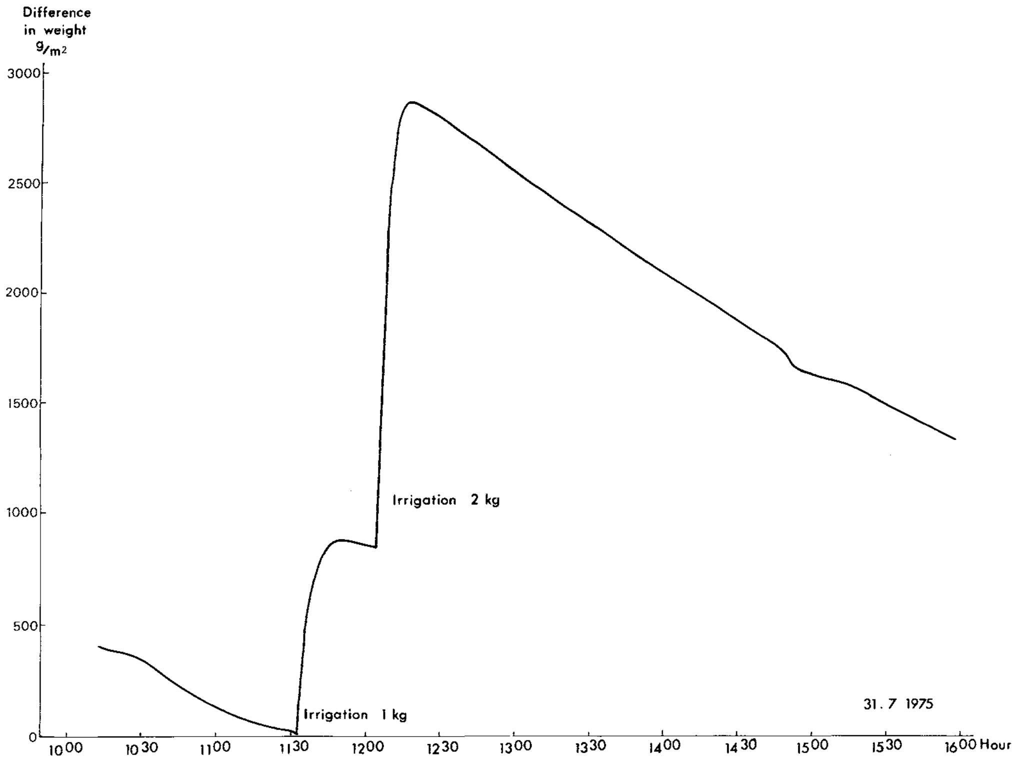


Figure 10. Weight changes due to evapotranspiration and watering of lichen and heather vegetation as registered by the dynamic lysimeter.

budget method, gave the same value (Table 2).

5.2.1 *Irrigation experiments*

The vegetation was watered with one litre of water from 11.33 to 11.38 a.m. According to the lysimeter the sample increased in weight by 880 g, i.e. 120 g less than the added quantity of water. A pump-operated spray-can was used in the experiment. Many of the fine droplets were driven away by the wind before reaching the sample surface or evaporated at once on coming into contact with the warm dry vegetation. The surface temperature of the lichens was about 40°C. The water must also be evenly distributed over the surface of the sample if the lysimeter is to cause the same change in weight as the added water quantity (see page 11). This condition could not be wholly met using the method of watering described above.

It took 17 minutes (until 11.50) for the lysimeter to equilibrate in this first watering experiment.

Irrigation was repeated at 12.05 p.m., this time with two litres of water. The water was quickly sprinkled and splashed over the surface. A weight increase of 2010 g was recorded by the lysimeter. This high value is explained, as above, by uneven distribution of the water over the surface. A slightly larger quantity of water probably landed on the half of the surface nearer to the balance arm's support. The lysimeter equilibrated in 15 minutes after this second watering. It may be noted that, as in the previous watering, the lysimeter recorded increasing weight up to about 10 minutes after watering had ceased. This reflects the fact that the movable counterweight must move through a long distance to equilibrate the lysimeter when a large and rapid change in weight occurs.

A very small amount of water was absorbed by the lichens. The tiny droplets from the spray evaporated very quickly from sunlit surfaces. It was observed during the second watering, where the water was sprinkled and splashed onto the surface, that much of the water ran into the fine cracks between the dried-up lichens. Evapotranspiration after watering need not, therefore, be much greater than before watering; nor was it in this case. The evapotranspiration after watering was 1500 g (12.25—3.58 p.m.) according to the lysimeter, i.e. an average of 0.42 mm/hour (Table 2), which is only 0.1 mm/hour greater than before watering. The rate of decrease in weight was constant, apart from between 2.50—3.00 p.m. The energy budget method gave an evapotranspiration for unwatered vegetation of 0.4 mm between 2.35 and 3.05 p.m. or 0.7 mm/hour (Table 2). The calculated evapotranspiration rate was therefore almost double that obtained by direct measurement. It is surprising that the calculated value was greater than it would have been if the total net radiation energy had been used up exclusively for evapotranspiration. The radiation energy accounted for an evapotranspiration rate of 0.5 mm/hour, i.e. only 0.1 mm/hour greater than the lysimeter values.

6 Discussion and some experiences

The dynamic lysimeter was *reliable* in spite of temporary difficulties, such as in the case when sand and dust were blown and deposited on the movable parts. Since the balance arm was kept swinging constantly the increased friction caused by particles deposited on the knife-edges resulted in no detectable alteration in the readings. However, the balance arm must be kept clean, since the balance will be offset if the fixed weights become coated with dust. Even though the sides of the samples tank were slanted, water droplets adhered to them when it rained. For these reasons, the lysimeter should be checked daily. If measurements are also to be made within a narrow range, i.e. with high sensitivity, the movable counterweight can quickly reach the outer limits of its movement in the case of rain or high rate of evaporation. These positions are equipped with microswitches so that the counterweight, on reaching a switch, is reversed under half a swing. This makes the recorded values characteristic. If this continues and the trend in the change in weight is expected to continue, it will be necessary to alter the position of the fixed weights, so that the movable weight will return to a position at the other end of its working range. In other cases the movable weight ought to be centred. When the position of the fixed weights is changed, the lysimeter must be recalibrated by placing small known weights on the sample surface.

The balance was *mechanically stable,* i.e. with constant weight on the sample tank the displacement was equal on both sides of the equilibrium position. It must be pointed out here that the position of the fixed counterweights determines the stability of the balance condition. The centre of gravity of the system must always be below the level of the balance position. The principle of dynamic weighing even allows for minor packing of the soil, since the only effect is that the position of the movable counterweight will be altered slightly. This appears as a temporary irregularity in the accumulated weight-change curve.

The electronic systems functioned satisfactorily and were not influenced by outside interference. In the case of power-failure, with the timing being reset to zero, recording will begin immediately the power is restored. It has happened that sunlight has interfered with the photoelectric cells. This was eliminated after the cells were covered and the balance arm placed in a covered hole in the ground.

There are other problems common to lysimeters in general. Aslyng & Kristensen (1961) point out the importance of maintaining good thermal contact between the sample tank and the surrounding ground. This they achieves by using two tanks; one floating in a fluid within the other. In our case, with air in the intervening space between the tank and the ground, the space must be kept as small as possible.

Morris (1959) discusses thoroughly several interesting technical sources of error in connection with his "weighing machine". He explains, among other things, the magnitude of the error due to buoyancy forces which vary with the density of the air.

King, Tanner & Suomi (1956) calibrated their lysimeter using the energy budget method. They demonstrated an effect that is often overlooked, namely, that the effective evapotranspiration area of the lysimeter can differ from the actual sample area. They showed that the effective evapotranspiration area was greatly reduced after the grass was cut, probably depending on the fact that the rims were now enfaced instead of being covered by grass.

We consider it important (as did King, Tanner & Suomi (1956)) to compare the lysimeter method with other methods. However, the quality of the research area must be very high if the comparison is to be of any significance. The field must be extensive, flat and covered evenly with homogeneous vegetation.

The energy budget method is less reliable in the case of advection, i.e. when the wind blows over an area with horizontal, temperature and humidity gradients. From time to time there was a certain risk of marginal effects during our experiments, caused by advection due to the comparatively small open area.

This is apparent in the measurements made on the afternoon of July 31, 1975, when the evapotranspiration calculated using the Bowen ratio method was almost double that indicated by the lysimeter. The latter was only 0.1 mm/h lower than if the total net radiation had been used up for evapotranspiration. Both methods gave similar results for the morning.

There was also a large difference between the lysimeter readings and the meteorological method for the 5th of October: the Bowen ratio method gave an evapotranspiration approximately 5 times greater, or 0.7 mm for 7 hours, than that obtained from the lysimeter (0.2 mm for 7 hours). Both methods gave low values for evapotranspiration thus making the absolute difference small. The difference may be partly because of advection and partly because of the frozen humus layer in the morning (5th of October). Energy was used to melt the ice in the vegetation instead of for evapotranspiration. It can also be noted that the Bowen ratio method gives the best results when the insulation is high and the vertical gradients are well developed.

The dynamic lysimeter, like all other lysimeters using a relatively small soil volume, is best fitted for short-term measurements, i.e. short-term studies of the water-balance in ground layer vegetation. The long-term and slow changes in the water content of the whole mass of soil can differ from the changes in the undisturbed surrounding ground. It is worth observing that it is possible, using the dynamic lysimeter, to measure not only very small quantities of evapotranspiration but also the condensation and deposition of fog droplets on the vegetation.

Summary

A new dynamic weighing lysimeter is described. In principle, the dynamic lysimeter consists of a balance arm with a movable counterweight that continuously seeks a point of equilibrium by small movements. The times taken by these movements are read off as pulses and fed automatically into a data logger. The sensitivity of the lysimeter was varied between 0.04 g per pulse to 0.56 g per pulse depending on the mass of the movable counterweight.

Contemporary meteorological measurements and lysimeter measurements are described. These were made at the Ecological Forest Research Station at Vindeln, with lichens and heather dominant in the ground vegetation. These measurements gave a lower evapotranspiration for the lysimeter as compared with the results obtained from the Bowen ratio energy balance method. The differencies probably largely depend on the effect of advection.

During rainfall, the lysimeter showed a certain damping in reading equilibrium owing to the dynamic principle. In the case of small changes, for example, evapotranspiration, condensation and wet fog deposition upon the vegetation, the dynamic lysimeter reached the point of equilibrium in a very short time.

The dynamic lysimeter was mechanically stable, functioned satisfactorily and was easy to set up in the field.

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Sammanfattning

I uppsatsen beskrivs en ny lysimeterkonstruktion, den dynamiska vägande lysimetern.

Lysimetern utgörs i princip av en balansvåg med en rörlig motvikt, som kontinuerligt söker ett jämviktsläge genom små förflyttningar. Tiden i pulser för dessa förflyttningar avläses digitalt och summeras automatiskt i en data-logger. Känsligheten har varierats mellan 0,04 g/puls och 0,56 g/puls beroende på den rörliga motviktens massa. Provytans storlek var 1 m^2 och jordprovets vikt omkring 700 kg.

I uppsatsen redovisas samtidiga lysimeter- och mikrometeorologiska mätningar. Dessa utfördes på Skogshögskolans ekologiska forskningsstation vid Vindeln där vegetationen övervägande utgjordes av lavar och ljung. Evapotranspirationen uppmätt med lysimetern var lägre eller lika stor som avdunstningen beräknad med energibudgetmetoden (Bowen metoden). Avvikelsen mellan metoderna beror till större delen sannolikt på advektion.

För stora viktändringar, dvs. vid regn, visade lysimetern en ökande eftersläpning med viktändringen beroende på den dynamiska principen. Lysimetern reagerade emellertid snabbt vid evapotranspiration, kondensation och då dimdroppar avsattes mot vegetationsytan.

Den dynamiska lysimetern var driftsäker och lätt att installera i fält.

Appendix

Factors used for calculation of evapotranspiration (condensation +) using the Bowen ratio method, and the weight change according to lysimeter measurement.

R_n = net radiation
T = air temperature
U = relative humidity
Δe = difference in vapour pressure
B = heat flow in soil
LE = latent heat flow
E = evapotranspiration in g/m^2 water

			50 cm above ground level		20 cm above ground level							*Lysimeter*
Date	Time	R_n W/m²	T °C	U %	T °C	U %	△T °C	△e mb	B W/m² Mean	LE W/m² Mean	E g/m² Σ	E g/m² Σ
31.7	1105	420	+ 26.6	38	+ 26.7	38	− 0.1	0.0				
1975	1115	410	+ 27.4	41	+ 27.9	38	− 0.5	+ 0.7				
	1130	410	+ 26.8	39	+ 27.1	40	− 0.3	− 0.6	+ 66	− 172	− 320	− 358
	1150	410	+ 28.2	35	+ 28.6	38	− 0.4	− 1.5				(1020—1130)
	1200	400	+ 27.5	39	+ 28.0	35	− 0.5	+ 1.1				
	1215	390	+ 28.2	34	+ 28.1	36	+ 0.1	− 0.7				
	1435	330	+ 28.2	33	+ 28.3	33	− 0.1	− 0.1				
	1445	340	+ 28.4	32	+ 27.9	35	+ 0.5	− 0.8				
	1450	330	+ 28.0	35	+ 27.6	36	+ 0.4	− 0.1				
	1455	340	+ 28.3	34	+ 28.0	36	+ 0.3	− 0.5	+ 20	− 465	− 370	− 226
	1500	330	+ 28.2	32	+ 27.8	35	+ 0.4	− 0.9		(− 330)*	(− 260)*	
	1505	320	+ 27.9	34	+ 27.7	37	+ 0.2	− 1.0				
4.10	1556—1630	− 3	+ 5.8	80.0	+ 5.6	80.6	+ 0.2	+ 0	+ 2	+ 1	≃ + 0	− 1
1976	1630—1700	− 5	+ 5.3	80.5	+ 5.1	81.6	+ 0.2	+ 0.1	+ 3	+ 2	≃ + 0	− 1
	—1730	− 7	+ 5.3	80.1	+ 5.1	81.0	+ 0.2	+ 0	+ 3	+ 1	≃ + 0	0
	—1800	− 6	+ 5.0	80.9	+ 4.7	82.0	+ 0.3	+ 0.1	+ 2	+ 2	≃ + 0	− 1
	—1835	− 3	+ 3.5	88.0	+ 2.9	88.2	+ 0.6	+ 0.3	+ 1	+ 2	≃ + 0	− 1
	—1900	− 3	+ 2.9	90	+ 2.5	90	+ 0.4	+ 0.2	0	+ 2	≃ + 0	− 1
	—1925	− 23	+ 2.2	93	+ 1.6	93	+ 0.6	+ 0.3	− 1	+ 10	≃ + 10	− 2
	—1955	− 24	+ 0.3	92	− 0.7	96	+ 1.0	+ 0.5	− 5	+ 8	≃ + 0	− 1
	—2040	− 6	+ 1.2	97	+ 1.1	96	+ 0.2	+ 0.1	− 4	+ 1	≃ + 0	+ 3
	—2158	− 1	+ 2.2	95	+ 2.0	95	+ 0.2	+ 0.2	0	+ 1	≃ + 0	− 3
	—2240	− 11	+ 2.4	98	+ 2.1	97	+ 0.3	+ 0.2	− 1	+ 5	≃ + 0	− 1
	—2340	− 6	+ 2.3	98	+ 2.3	97	+ 0.1	+ 0.1	− 1	+ 3	≃ + 10	+ 7
5.10	—0040	− 3	+ 2.0	98	+ 1.9	97	+ 0.1	+ 0.1	− 1	+ 2	≃ + 0	+ 5
1976	—0140	− 3	+ 1.3	98	+ 1.1	97	+ 0.2	+ 0.2	− 1	+ 1	≃ + 0	+ 15
	—0240	− 4	+ 0.3	98	+ 0.2	97	+ 0.1	+ 0.1	− 2	+ 1	≃ + 0	+ 23
	—0340	− 5	− 1.6	98	− 1.8	97	+ 0.1	+ 0.1	− 5	0	≃ + 0	+ 24
	—0440	− 4	− 2.1	98	− 2.3	98	+ 0.2	+ 0.1	− 6	− 1	≃ − 0	+ 4
	—0540	− 3	− 1.7	99	− 1.8	98	+ 0.1	+ 0.1	− 5	− 1	≃ − 0	− 3
	—0640	− 2	− 1.4	99	− 1.4	98	+ 0.1	+ 0.1	− 4	− 1	≃ − 0	− 5
	—0740	+ 13	− 0.5	99	− 0.5	98	0	+ 0.1	− 2	− 14	≃ − 20	− 3
	—0840	+ 38	+ 0.5	99	+ 0.5	98	− 0	+ 0.1	0	− 54	− 90	− 4
	—0955	+ 117	+ 3.0	99	+ 3.1	98	− 0.2	− 0.1	+ 7	− 39	− 80	− 25
	—1030	+ 153	+ 4.8	93	+ 5.1	93	− 0.3	− 0.2	+ 13	− 64	− 60	− 16
	—1056	+ 222	+ 5.8	80.0	+ 6.4	81.0	− 0.6	− 0.4	+ 15	− 111	− 80	− 11
	—1126	+ 204	+ 6.6	71.5	+ 7.2	71.8	− 0.6	− 0.3	+ 16	− 85	− 70	− 16
	—1146	+ 170	+ 6.8	71.0	+ 6.8	74.4	− 0	− 0.3	+ 16	− 148	− 80	− 10
	—1156	+ 219	+ 7.4	69.2	+ 7.7	69.9	− 0.4	− 0.2	+ 14	− 99	− 30	− 3
	—1230	+ 174	+ 7.5	65.7	+ 8.0	66.3	− 0.5	− 0.3	+ 16	− 77	− 70	− 1
	—1255	+ 13	+ 6.5	70.2	+ 6.6	71.0	− 0	− 0.1	+ 11	− 2	− 0	− 23
	—1330	+ 95	+ 7.6	62.3	+ 7.9	62.4	− 0.3	− 0.2	+ 8	− 37	− 30	− 15
	—1355	+ 103	+ 7.8	59.8	+ 8.2	59.4	− 0.4	− 0.1	+ 10	− 30	− 20	− 9
	—1430	+ 93	+ 8.0	59.0	+ 8.3	58.8	− 0.4	− 0.1	+ 11	− 26	− 20	− 10
	—1457	+ 61	+ 7.5	60.5	+ 7.9	60.9	− 0.4	− 0.2	+ 10	− 25	− 20	− 12
	—1530	+ 12	+ 6.9	65.3	+ 6.7	66.4	+ 0.1	− 0	+ 5	+ 2	+ 0	− 11
	—1555	− 30	+ 5.7	71.4	+ 5.2	73.2	+ 0.6	+ 0.1	+ 10	+ 6	+ 0	− 6
	—1625	− 42	+ 3.2	81.9	+ 1.5	84.3	+ 1.7	+ 0.6	− 5	+ 13	≃ + 10	− 7
	—1657	− 42	− 0.0	95	− 2.1	94	+ 2.0	+ 1.0	− 11	+ 13	≃ + 10	− 5
	—1730	− 32	− 1.7	97	− 3.4	97	+ 1.7	+ 0.7	− 14	+ 7	≃ + 10	− 3
	—1755	− 30	− 2.3	98	− 4.1	97	+ 1.8	+ 0.7	− 13	+ 6	≃ + 10	− 9

* Net radiation transformed to evaporation.