A NEWLY DEVELOPED GROUNDWATER LYSIMETER FOR MEASURING EVAPOTRANSPIRATION FROM DIFFERENT GROUNDWATER LEVELS IN A SMALL CATCHMENT AREA OF THE NORTH GERMAN COASTAL REGION

U. SCHENDEL*

SUMMARY
A groundwater lysimeter is described which allows the measurement of evapotranspiration from the groundwater table and the capillary zone just above the groundwater down to a depth of 180 cm.

Two groundwater lysimeters planted with grass were used to determine the water balance of the river plain in a small catchment area of the north German coastal region bordering the North Sea.

Evapotranspiration from soil moisture and the groundwater was determined separately. The groundwater table in the lysimeters was adjusted to the natural groundwater table in the river plain of the catchment area.

With 799 mm of rainfall at the average of four successive years, total evapotranspiration in the river plain amounted to 520 mm, of which 289 mm (56 percent) accounted for withdrawal from the soil moisture zone and 231 mm (44 percent) from the groundwater and the capillary zone just above the groundwater table.

At the same time water balance of the total catchment area was determined. The ratio of evapotranspiration in the river plain to that of the total catchment area allows for the calculation of evapotranspiration in larger areas of the same climatic region with the same vegetation. This work is at present in progress for a large part of the 70 000 ha catchment area of the river Eider in the western part of Schleswig-Holstein.

UN NOUVEAU LYSIMÈTRE POUR MESURER L'ÉVAPOTRANSPIRATION DE DIFFÉRENTS NIVEAUX DE L'EAU SOUTERRAINE DANS UN PETIT BASSIN DE LA RÉGION CÔTIÈRE D'ALLEMAGNE

RÉSUMÉ
Un lysimètre est décrit qui permet la mesure de l'évapotranspiration de la nappe phréatique et de la zone capillaire au-dessus de celle-ci à une profondeur pouvant atteindre 180 cm.

Deux lysimètres couverts d'herbe ont été utilisés pour déterminer le bilan d'eau de la plaine le long de la rivière dans un petit bassin de la région bordant la mer du Nord en Allemagne septentrionale.

L'évapotranspiration de l'humidité du sol et de la nappe étaient déterminées séparément. Le niveau de la nappe dans les lysimètres était ajusté à celui de la nappe naturelle dans la plaine bordant la rivière dans le bassin.

Avec une précipitation de 799 mm en moyenne sur quatre années successives, l'évapotranspiration, dans la plaine de la rivière, s'élevait à 520 mm, dont 289 mm (56%) enlevés à l'humidité du sol et 231 mm (44%) à la nappe et à la zone capillaire au-dessus d'elle.

En même temps, on déterminait le bilan d'eau dans tout le bassin. Le rapport de l'évapotranspiration dans la plaine bordant la rivière à celle du bassin total permet de calculer l'évapotranspiration dans de plus grandes surfaces de la même région climatique, avec la même végétation. Ce travail est actuellement poursuivi pour une grande partie des 70 000 ha du bassin de la rivière Eider dans la partie ouest du Schleswig-Holstein.

* University of Kiel, Germany.
INTRODUCTION

In 1962 investigations were started to determine the water balance of a small catchment area (6.9 km²) in the north German high-humidity coastal region bordering the North Sea. Since 1965 these investigations have been part of the German contribution to the International Hydrological Decade. The results obtained so far are published elsewhere [1, 2, 3]. The well-vegetated area is covered approximately 15 percent by meadow and pasture in the river plain and 85 percent by crops. Podzolic soils are prevailing in the higher situated areas of the catchment area, whereas peat soils are found in the river plain.

Climatic characteristics: rainfall (longterm average): 799 mm; temperature (annual mean): 8.1 °C; relative humidity (annual mean): 82 percent; potential evaporation (free water surface, longterm average): 610 mm; actual evapotranspiration (six years average): 433 mm. Groundwater appears in the upper layers and fluctuates between 50 cm and 150 cm below surface.

Difficulties were experienced when determining the groundwater balance as a part of the total water balance. For this purpose a groundwater lysimeter was developed which allows the measurement of evapotranspiration from the groundwater and percolation. Evapotranspiration from the soil moisture zone in the lysimeter can be calculated from the difference of precipitation minus percolation.

THE GROUNDWATER LYSIMETER

The groundwater lysimeter is a modification of an evaporimeter previously developed by the writer in South Africa [4]. The lysimeter is shown in figure 1.

A PVC-made cylinder, 180 cm long and 30 cm wide is filled with soil and installed in such a way that the 707 cm² surface of the cylinder is level with the natural surroundings. The cylinder contains either disturbed or undisturbed soil. In the latter case the cylinder is carefully lowered enclosing the soil column prepared in advance. It takes some caution when lifting up the cylinder in order to get the 30 cm high and gravel-filled funnel to be connected to the cylinder. The cylinder is then placed on a concrete pipe in such a way that the funnel part fits properly in the hole of the pipe. Finally, the soil in the cylinder is planted with grass.

The funnel part of the soil cylinder is connected to a plexiglass cylinder by means of a 3/4 in. plastic pipe. The plexiglass cylinder serves as a levelling container in order to obtain a constant water table. The levelling container can be moved up and down by means of a clamp which is fixed to an iron rod. Thus, the water table in the soil cylinder can be adjusted in correspondence with the groundwater table of the natural surroundings. The levelling container has a water outlet for excess water (runoff) to be collected in a percolation container. Evaporation of the water in the plastic container is prevented by a plastic cover.

When groundwater or capillary water just above the groundwater table is attracted by the plant roots or by evaporation, the water table in the soil cylinder—and automatically in the levelling container—is lowered almost simultaneously. This causes a system working by which the original water table in the levelling container and in the soil cylinder is regained, thus keeping the water table always at a constant height. The system consists of a 1000 ccm water-filled measuring cylinder which is closed by a rubber stopper. The cylinder is turned upside down. Two plexiglass pipes of 5 mm inside diameter are drawn through the rubber stopper connecting the measuring cylinder with the levelling container (fig. 1). The pipes serve as air pipe or water inlet pipe respectively. When evapotranspiration in the soil cylinder causes the water meniscus—as indicated on the air pipe in figure 1—to break off, air is
A newly developed groundwater lysimeter for measuring evapotranspiration escaping into the measuring cylinder (see indication of air bubbles in the upper part of the measuring cylinder), while the water in the levelling container is refilled by means of the water inlet pipe. Refilling stops automatically when the air pipe touches the water surface again. Air outlet and water inlet take place almost simultaneously. To get the system working it is necessary that the water inlet pipe penetrates about 1 to 2 mm into the water surface of the levelling container.

Refilling of the measuring cylinder takes place by means of a funnel inserted into one of the two holes at the bottom of the cylinder. When refilling, the taps of the water inlet and air pipes are closed.

![Figure 1. Groundwater lysimeter (not according to scale)](image-url)
Rainwater infiltrating into the soil cylinder either penetrates to the groundwater table or is stored as soil moisture in the zone above the water level. In the latter case the system prevents the groundwater table from rising, because excess water flows through the outlet of the levelling container into the percolation container.

The daily rate of evapotranspiration from the groundwater and the capillary zone just above the groundwater table is read off the scale of the measuring cylinder. Evapotranspiration from the soil moisture zone is calculated from the difference between rainfall and percolation. This is, however, not possible on a daily basis and may be done monthly.

RESULTS

Two groundwater lysimeters were installed in the above mentioned catchment area. The cylinders of the lysimeters were carefully filled with soil in the same order in which it was removed from the natural surroundings. Grass sods were then placed on the top of the soil columns. After a relatively short time the plant cover of the lysimeters was well established and showed no difference to that of the surroundings.

The groundwater table in the lysimeters was adjusted twice a month to that observed in two wells of the river plain. Rainfall and snow were recorded quite close to the lysimeters. Table 1 shows the water balance for the average of the years 1963-1966. These four years give a fairly good average because they represent two or less normal years (1962 and 1965), one dry year (1964) and one wet year (1966). The figures represent mean values of two lysimeters.

Total mean evapotranspiration of the years 1963 to 1966 amounted to 520 mm, with the highest evapotranspiration rate of 96 mm in June and the lowest of 2 mm in December. Forty-four percent (231 mm) of the total amount of evapotranspiration is contributed by the groundwater which fluctuates between 50 cm below soil surface in January, February and March and 130 cm in June and July. The difference between precipitation and percolation is 289 mm. It can be assumed that percolation in the lysimeters equals runoff under natural conditions, probably with some lack of time. Usually the change of soil moisture storage becomes ±zero when calculating the water balance for a number of successive years. The difference between precipitation and percolation, which equals runoff to a fairly great extent, can in this case of four successive years almost be accepted as soil moisture depletion which means evapotranspiration. This means that at the given groundwater tables (see table 1) 56 percent of the total annual evapotranspiration is contributed by soil moisture and 44 percent by the groundwater. It must, however, be kept in mind that the groundwater percentage of evapotranspiration cannot be separated in the strongest sense of the word from the soil moisture percentage, due to capillary rise of water from the groundwater table into the soil moisture zone. The figures can therefore only give an indication of the soil moisture and groundwater part of evapotranspiration.

It is of some interest to follow the figures in column 2 (consumptive use from soil moisture) and column 3 (consumptive use from the groundwater) of table 1, as they give some indication as to what extent the plants are able to compensate for water deficiency in the soil moisture zone by withdrawing higher quantities of groundwater or capillary water just above the groundwater table. During November, when the grass cover is still assimilating and soil moisture is easily available total water consumption amounts to 16 mm, of which 11 mm (69 percent) is withdrawn from the soil moisture zone and 5 mm (31 percent) from the groundwater which is 50 cm below soil surface. From December until February, with about the same groundwater table (approx. 50 cm below soil surface) and with lower rates of total
evapotranspiration (2.4 and 11 mm respectively), the groundwater percentage of
total evapotranspiration amounts to 50 percent in December, 75 percent in January
and 63 percent in February. One can assume that transpiration in these three months
has almost stopped. There is only little evaporation from the soil moisture zone
(1 mm during December and January each, and 4 mm during February).

The relatively high percentage of groundwater loss from December can, however,
only apparently be regarded as due to evapotranspiration. With temperature round
about freezing point and a relative air humidity between 80 and 90 percent in these
three months there is only little probability of evaporation taking place from ground-
water 50 cm below soil surface. The groundwater loss in these three months seems
rather to be the result of upward water movement caused by the condensation of
the warmer groundwater in the cooler soil moisture zone where it is then available
for evaporation.

With rising temperatures during March and April, total evapotranspiration
increases from 11 mm in February to 25 mm in March and 54 mm in April. The
groundwater level is still at 50 cm below surface in March and drops to 70 cm in
April. The groundwater percentage of evapotranspiration is reduced to 36 percent
(9 mm) in March and to 31 percent (17 mm) in April. There is sufficient plant
available water in the soil moisture zone so that only a relatively small amount of
water is required from the groundwater.

However, the situation changes completely during May and June. The grass in
the lysimeters is growing up rapidly, total evapotranspiration increases to 91 mm in
May and 96 mm in June, while rainfall was only 52 mm in May and 68 mm in June.
Soil moisture deficiency causes the plants to meet their main water requirement
from the groundwater (58 mm during May and 66 mm during June, which are
respectively 64 and 69 percent of the total evapotranspiration), although the ground-
water table has dropped to 95 cm below surface in May and 130 cm in June.

The grass was cut by the end of June. Under conditions of reduced transpiration
(after cutting) in July and of higher rainfall during August (98 mm) and September
(83 mm), the plants cover their water need mainly from the soil moisture zone, while
the groundwater percentage of total evapotranspiration decreases from 41 percent in
July over 34 percent in August to 20 percent in September. The groundwater table
is at 130 cm below surface in July and at 110 cm in August and September.

During October, with a groundwater table of 90 cm below soil surface, the
groundwater percentage of total evapotranspiration increases again slightly. This is
probably due to condensation caused by the temperature gradient from the warmer
groundwater to the cooler soil moisture zone. The tendency of an increasing ground-
water percentage of the total water loss, probably due to condensation, continues
until January.

During the 1963-1966 period the sum of the annual mean values of percolation
and total evapotranspiration amounts to 1030 mm, which exceeds precipitation by
231 mm. This responds to the natural conditions in the catchment area, for ground-
water flowing down from the higher situated areas increases runoff and evapo-
transpiration in the lower situated areas, so that the sum of both runoff (in the case
of the lysimeter = percolation) and evapotranspiration is always higher in the river
plain than rainfall.

The water balance as shown in table 1 covers normal, dry and wet years and
can therefore be regarded as almost representative of the lower situated areas of
the river plains in the northern German humid coastal regions. During the same
period the water balance of the total catchment area was determined by measuring
discharge, soil moisture and changes of the groundwater level. Thus it was possible
to calculate actual evapotranspiration for the total catchment area which amounted
to 433 mm—compared with 522 mm in the lower river plain. As the river plain counts
**Table 1. The water balance of groundwater lysimeters in a catchment area of the North-German coastal region (Hennstedt, Kr. Norderdithmarschen)**
(Mean values of the years 1963-1966, figures in mm)

<table>
<thead>
<tr>
<th></th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Mean 1963-1966</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Precipitation</td>
<td>90</td>
<td>100</td>
<td>44</td>
<td>34</td>
<td>32</td>
<td>47</td>
<td>52</td>
<td>68</td>
<td>78</td>
<td>98</td>
<td>83</td>
<td>73</td>
<td>799</td>
</tr>
<tr>
<td>2. Percolation</td>
<td>79</td>
<td>99</td>
<td>43</td>
<td>30</td>
<td>16</td>
<td>10</td>
<td>19</td>
<td>38</td>
<td>44</td>
<td>58</td>
<td>31</td>
<td>43</td>
<td>510</td>
</tr>
<tr>
<td>3. Diff. precipitation minus percolatin (consumptive use from soil moisture)</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>16</td>
<td>37</td>
<td>33</td>
<td>30</td>
<td>34</td>
<td>40</td>
<td>52</td>
<td>30</td>
<td>289</td>
</tr>
<tr>
<td>4. Consumptive use from the groundwater</td>
<td>5</td>
<td>1*</td>
<td>3*</td>
<td>9</td>
<td>17</td>
<td>58</td>
<td>66</td>
<td>24</td>
<td>21</td>
<td>13</td>
<td>7</td>
<td></td>
<td>231</td>
</tr>
<tr>
<td>5. Total evapotranspiration</td>
<td>16</td>
<td>2</td>
<td>4</td>
<td>11</td>
<td>25</td>
<td>54</td>
<td>91</td>
<td>96</td>
<td>58</td>
<td>61</td>
<td>65</td>
<td>37</td>
<td>520</td>
</tr>
<tr>
<td>6. Consumptive use from the groundwater, expressed as percentage of total evapotranspiration</td>
<td>31</td>
<td>50</td>
<td>75</td>
<td>63</td>
<td>36</td>
<td>31</td>
<td>64</td>
<td>69</td>
<td>41</td>
<td>34</td>
<td>20</td>
<td>24</td>
<td>44</td>
</tr>
<tr>
<td>7. Groundwater table below surface in cm</td>
<td>53</td>
<td>53</td>
<td>50</td>
<td>50</td>
<td>70</td>
<td>95</td>
<td>90</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>82</td>
<td></td>
</tr>
</tbody>
</table>

* Due to condensation.
only for 15 percent of the total catchment area, and the higher situated areas for 85 percent, evapotranspiration for the latter can also be calculated from the amount of evapotranspiration of the total area and that of the river plain. This amounts to 420 mm per annum.

By this way, and on the basis of the measurements with the groundwater lysimeters, it is possible to calculate evapotranspiration for larger areas in the same climatic region, as is at present being done for a large part of the catchment area of the river Eider in Schleswig-Holstein, which includes 70000 ha. As discharge in this area was also measured in pumping stations for a number of years, the amount of groundwater recharge can be determined by comparing the discharge calculated from the difference of rainfall minus evapotranspiration, with the measured discharge. A negative value from the difference of measured discharge minus calculated discharge would indicate groundwater recharge.

REFERENCES


STUDIES OF INFILTRATION AND OVERLAND FLOW FOR NATURAL SURFACES

K. J. Langford, R. J. Mayer, and A. K. Turner*

Summary
This paper outlines work in progress on three aspects of agricultural hydrology, namely depression storage, overland flow and infiltration.

Depression storage was measured by placing a plastic sheet over a fallow which had been finely cultivated. The water retained on the sheet is thought to be a good measure of the average depression storage. Values of 1.4 and 1.5 mm were obtained for this particular surface.

Simulated rain was applied to this plastic sheet and run-off hydrographs recorded. The results are plotted in the form of a detention-storage versus discharge graph which shows the effect of rainfall intensity on the flow. The hysteresis effects between the rising and falling stages were of the order of 50%, which indicates that methods using recession curves to determine detention storage characteristics of the rising stage, and ultimately of infiltration could be in error.

* The authors are respectively Graduate Students and Senior Lecturer in Agricultural Engineering, University of Melbourne Parkville, 3052, Victoria, Australia.