ON USING GROUND WATER TABLE FLUCTUATIONS FOR MEASURING EVAPOTRANSPIRATION

LEO HEIKURAINEN

SELOSTE:

POHJAVESIPINNAN VAIHTELUISTA HAIHDUNNAN MITTAAMISESSA

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Preface

During the course of several years, I have carried on measurements of the ground water table in peat lands drained for forestry. These studies have taken place at the Forest Training Station of the University of Helsinki at Hyytiälä. The aim of these studies has been the clarification of evapotranspiration. The first step has been to evolve methods. More extensive studies of evapotranspiration were started in the spring of 1962. In this paper, however, only some results of these studies are examined, the main attention being focussed on the methods of measuring evapotranspiration.

In this connection I express my best thanks to the State Committee of Agriculture and Forestry, whose grants have made this work possible. In addition, I want to thank my many pupils and assistants who have taken part in different phases of the project.

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Leo Heikurainen

Contents

Introduction

To measure the transpiration of trees and forests, many methods have been worked out by plant physiologists and ecologists, forest scientists and hydrologists. Plant physiological methods, which also foresters have developed and used, are based on 1) pot experiments, 2) measurings of changes in the moisture of air conducted through some part of a plant or a small plant, or 3) the decrease of weight in a severed part of a plant observed directly by weighing. A more detailed description of the methods is unnecessary in this connection. A reference to textbooks in this field and especially to studies of evapotranspiration will suffice (for instance Kramer 1949, Kramer and Kozlowski 1960, Stålfelt 1960, Polster 1950 and in Finland e.g. Sirén 1955).

These methods are generally suitable for measuring the water consumption of very small plants. When it comes to measuring the water consumption of large plants such as trees and whole tree stands, a difficult problem keeps cropping up: how to convert a result obtained from a small part of a plant to apply to a whole tree or tree stand? The conversion ratio is usually difficult to determine and always so large that errors in measurements also become large.

In a method used in hydrological studies the total evaporation is determined through rainfall, runoff and changes in water reserves in the ground (cf. e.g. Barner 1961, p. 10—11 and e.g. Niinivaara 1954). This method generally is applicable only to studying the water balance in areas of the size of watershed areas; therefore it is seldom practicable in forest research, for instance.

When this same method is used in smaller areas, the runoff has frequently to be prevented with expensive constructions, in other words, a big lysimeter has to be set up. Such a method has been used by Rich (1959), for instance. Another way to apply this method is to measure rainfall and runoff in an experimental drainage area, which is separated from its environment as far as the water economy is concerned. This arrangement, however, involves many inaccuracies, as the total evaporation is determined as the difference between rainfall and runoff during long periods of time and it is hard to determine accurately the runoff area of the whole district and that of individual ditches. The method, however, has been successfully applied in clarifying roughly the relationships between runoff and total evaporation (e.g. Huikari 1959).

The method to be described here resembles the last mentioned ones in many respects. But it endeavors to measure transpiration also in short periods, a day and a night, for instance, and it deals directly with evaporation.

Terms used and principle of method

Although literature pertaining to this subject contains many thorough clarifications of hydrological terms (e.g. KRAMER 1949 and SONN 1960), a short review of the terminology used seems justifiable.

The amount of rain on a tree canopy or on an open place is called *total rainfall*. Part of this total rainfall remains on the canopy and evaporates; this part is in this work called *interception*. The rest of the rainfall comes to the ground, directly or by flowing along tree stems. The former is here called *stand rainfall*, the latter *stemflow*. This rainfall on the ground joins the *water amount in the ground;* part of the rainfall on the ground may flow away along the surface or into the ground. This part is called *runoff*. Of course, the amount of water in an area may also increase through runoff. *Ground water table* is used as one of the criterions of the water amount in the ground. The water amount in the ground may decrease, apart from runoff, in three different ways: *stand transpiration*, *ground vegetation transpiration* and *evaporation*. All these are collectively denoted by the term *evapotranspiration*. Sometimes this includes also interception, but in this work the last mentioned is treated separately.

Lowering of the ground water table is caused by decrease in the amount of water because of evapotranspiration. The evapotranspiration of a forest is determined by converting a lowering of the ground water table into a decrease in the amount of water. This method works on the condition that runoff is either prevented, or that it can be measured. If the evapotranspiration is to be measured during rainy periods, total rainfall and the part of this coming to the ground must also be determined.

Thus the method is applicable to the clarification of evapotranspiration both in short periods, such as 24 hours, and in longer periods. In its simplest form the method gives total evaporation (evapotranspiration), in other words, transpiration of trees and lesser vegetation together with evaporation. The method can also be applied in such a way as to obtain separately all three components of evapotranspiration. For the sake of simplicity we are only going to examine the transpiration of growing stock, ground vegetation, and evaporation, together. Later in the text also separation of the components and measuring rainfall, interception and stemflow — indispensable in measuring evapotranspiration for longer periods — will be touched on.

Structure of evapotranspiration sample areas

In spring 1962, the following kinds of sample areas were set up to develop the method. On a drained peatland, where the depth of peat was over 1 m, a forest sample plot (e.g. 20 × 20 m) was staked out. The sample plots were separated from the environment to the depth of 50 cm with sheets of galvanized plate which were joined watertight. The upper edge of plate was left about 5 cm above the peat surface to prevent any surface runoff. Four ground water holes, connected with each other with plastic pipes, were dug in the sample area. A runoff pipe, which could be closed and opened, was directed from this system of ground water holes to a ditch. A meter recording the ground water table was installed in a ground water hole situated in the middle of the sample area.

The effectiveness of isolating runoff is based on the fact that humified peat is almost impermeable to water and as the ground water in the sample area and in the peatland surrounding it is kept by the runoff control at the same leved all the time, hardly any forces can arise to move water to or from the sample area.

Falling of ground water table

The recording meters of the ground water table show that on days when rain does not interfere with the movements of the ground water table, this clearly falls daily. Falling begins usually in the forenoon between 7 and 10 o'clock and goes on to 4—10 p.m. During the night the ground water table does not move much. Weather conditions seem to have a clear influence on the amount and duration of falling.

Fig. 1 shows, in the nature of an example, the ground water table curves of three sample areas of the period July 26—30. The following table shows the daily fall of the ground water table.

Sample area	26.7.	28.7.	28.7.	29.7.
	fall, mm			
1	6	5	9	9
2	19	5	9	7
3	15	6	7	10

There is a relationship between the fall of the ground water table and the transpiration by vegetation, mainly trees. Photosynthesis and stomatic transpiration during the day are parallel phenomena, as many investigations on the metabolism of plants have shown (e.g. POLSTER 1950, GAASTRA 1959 and WEIDE 1962). Furthermore, studies of the water uptake of trees have revealed a direct and rapid correlation between transpiration and water uptake (e.g. POLSTER 1961). It is obvious, however, that the water uptake caused by transpiration lags behind transpiration (e.g. KRAMER and KOZLOWSKI 1960, p, 328). This opinion is supported also by my own studies. The correlation, however, is so direct, that the two peaks in the daily course of photosynthesis and transpira-

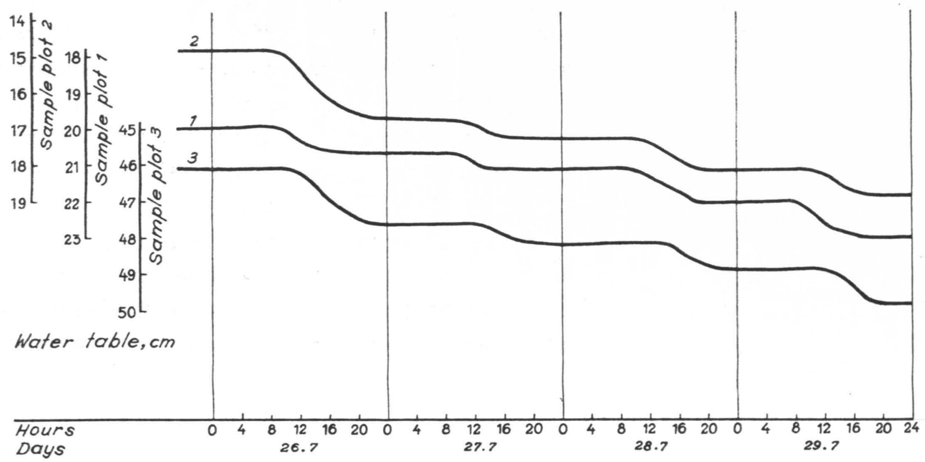

Fig. 1. Daily fall of the ground water table in sample areas 1, 2 and 3 during the period of July 26—29.

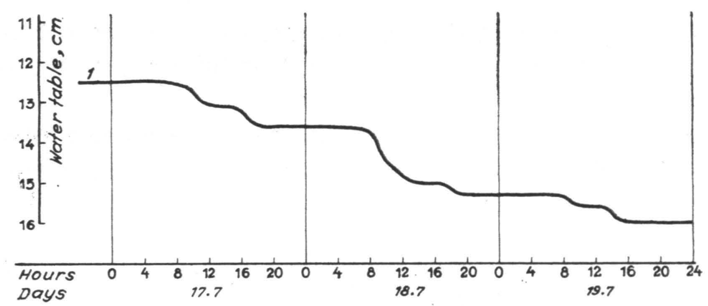

Fig. 2. Daily fall of the ground water table in sample area 1 during the period of July 17—19.

tion frequently observed (e.g. Polster 1961 and Weide 1962) are, under certain conditions, shown by the fall of the ground water table (cf. Fig. 2).

It has been observed before that evapotranspiration is reflected by a falling of a ground water table. These observations have been used to compare the transpiration of different tree species (e.g. Horton 1959 and Kulik, according to Kübler 1961).

In this connection no attention is paid to variations in the amount and time the ground water table falls according to observations. It will suffice to say that the greatest daily falls of the ground water table have exceeded 20 mm, and that the amount of fall seems to depend on the species of tree, the phase of the development of the stand, temperature, cloudiness etc. Thus, in a birch

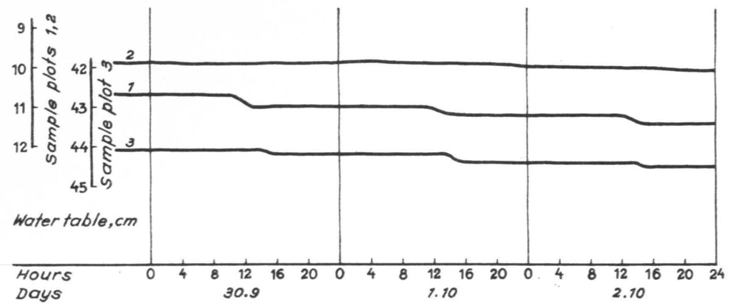

Fig. 3. Daily fall of the ground water table in sample areas 1, 2 and 3 during the period of September 30 — October 2.

stand, for instance, the daily fall stopped completely, at the same time birches lost their leaves, but in a pine stand the daily fall continued clearly although weakly in early October (cf. Fig. 3).

Effect of rainfall and runoff on ground water table

Also the effect of rain on the ground water table was followed by recording ground water meters. In Fig. 4 and 5 examples are shown, one of the period June 20—21, the other August 8—9. Change in the ground water table (WT), rainfall (R) and stand rainfall (SR) are marked in the diagrams. The rainfall curves have been converted into a form better comparable with the ground water curve by multiplying the value of rainfall by four. The diagrams reveal that the rise in the ground water table has closely followed the amount of rainfall. On June 20 and 21 rain occurred after a relatively long period of fine weather, on August 8 and 9 after a moderate rainfall one day earlier. In the former case

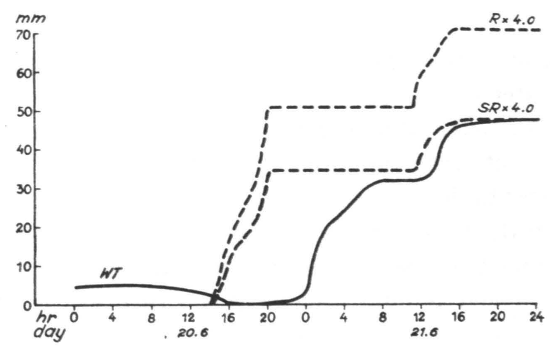

Fig. 4. Effect of rain on the ground water table after a dry spell. R = rainfall, SR = stand rainfall, WT = water table.

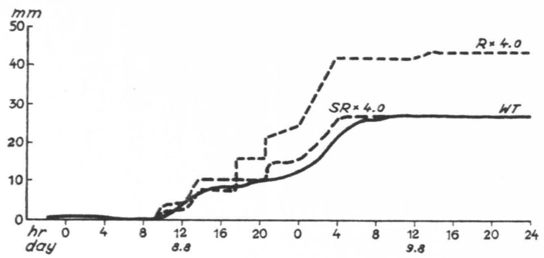

Fig. 5. Effect of rain on the ground water table after a rainy period. R = rainfall, SR = stand rainfall, WT = water table.

the rise in the ground water table has started about 6 hours after the commencement of rain, in the latter case at the same time the rain has begun. The same is the case on June 21, when rain has started again after a rainfall on the previous day; the rise in the ground water table has started almost at the same time the rain has begun.

We can conclude on the basis of the examples above and others not published here that the rise of the ground water table follows closely the amount of rain, but the rise depends, at least as far as time is concerned, on many factors, and consequently the correlation between rain and the rise of the ground water table is difficult to calculate.

Moreover, we should not suppose too readily that the correlation between the fall of the ground water table and evapotranspiration is the same as the correlation between rain and the rise of the ground water table. These questions were studied by laboratory experiments. A quantity which expressess this correlation will be called coefficient of ground water table. Let us mark it by C. When the fall (or rise) of the ground water table is G and the removal (or increase) of the amount of water which has caused it is W, we have a formula:

$$G = C \times W$$

The magnitude of C depends above all on the water saturation deficiency of the peat. If the water saturation deficiency near the ground water table is large the coefficient C is small and vice versa. A saturation deficiency — which here means the amount of water required for a moisture content high enough to form a ground water table — depends on many factors, such as the composition of peat, its humification and amount of water it contains. The water content in one and the same peat is, however, under normal conditions dependent mainly on the composition and humification of peat. In other words, if the ground water table remains on the same level, the water content of the peat layer above it is practically independent of time and weather conditions. The water economy of this layer reaches a definite equilibrium characteristic of each type of peat,

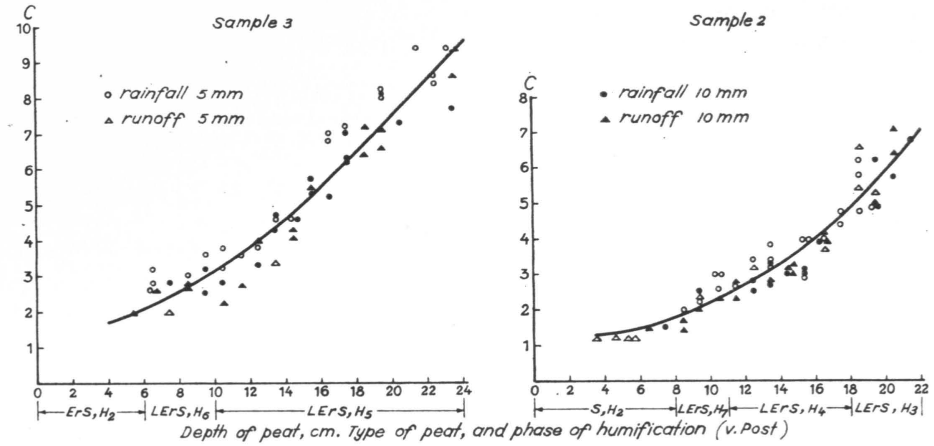

Fig. 6. Dependence of the coefficient of the ground water table (c) on the layer of peat when rainfall or runoff of different magnitudes are used in studies.

field capacity, which is regulated by the relatively easy downward flow of water on the one hand and on the other hand its capillary movements upward, which compensate the loss of water through evapotranspiration. The theory is not new. Richards (1941), for instance observes, that the soil moisture tension depends mainly on the height of the ground water table and only relatively strong forces can change this field capacity. Studies by Sarasto, not published yet, prove the power of capillaric water movement and, on the other hand, Segeberg (1958), for instance, has shown that water sinks into peat relatively fast.

To determine the coefficient of ground water table, laboratory experiments were carried out with peat samples measuring 95 by 75 by 50 cm. These were placed on a gravel layer 10 cm deep in a water-tight box with a runoff pipe. A plastic ground water hole was installed in each peat sample to make it possible to measure the height of the ground water table and its changes with an accuracy of 1 mm.

In the experiments the peat samples received alternately a rainfall of 5 or 10 mm, and between these, water was run off the samples in amounts corresponding to a rainfall of 5 or 10 mm. After each rainfall or runoff the change in the ground water table was measured.

Fig. 6 shows two examples of the series of experiments carried out. The layer of peat where a change has occurred is marked on the horizontal axis; this layer is computed as the average of ground water tables measured before and after a rainfall or a runoff. The coefficient C — the ratio of a change in the ground water table and a rainfall or a runoff — is marked on the vertical axis. Rainfall and runoff have been marked separately on the axes, similarly the rainfall or runoff of 5 mm and of 10 mm has been marked separately.

As a general observation we can see that the ground water coefficient is dependent on the depth of peat or rather on the composition and humification of peat. On the other hand, the ground water coefficient seems to be almost independent whether rainfall or runoff is in question. The amount of rainfall or runoff does not seem to have any essential effect on the value of the coefficient. These points will be clarified in more detail by the following regression analyses.

The functions of the ground water coefficient have been, computed from the whole material, of the following form.

$$\text{Sample 2} \quad y = 1.319 - 0.051\,x + 0.015\,x^2$$
$$\text{» 3} \quad y = 1.112 + 0.131\,x + 0.010\,x^2$$

In the formulae y = ground water coefficient (C) and x = depth of peat layer.

When the form of the function was studied on the basis of the material — separately with the material of rainfall and runoff and separately with the material of 5 mm and 10 mm — the following results were arrived at.

	Sample 2	Sample 3
Rainfall	$y = 2.577 - 0.200\,x + 0.019\,x^2$	$y = 1.014 + 0.177\,x + 0.008\,x^2$
Runoff	$y = 1.392 - 0.103\,x + 0.018\,x^2$	$y = 1.623 - 0.010\,x + 0.015\,x^2$
5 mm	$y = 0.852 + 0.064\,x + 0.010\,x^2$	$y = 1.100 + 0.159\,x + 0.009\,x^2$
10 mm	$y = 2.421 - 0.257\,x + 0.022\,x^2$	$y = 0.166 + 0.258\,x + 0.005\,x^2$

The coefficients of second power in the formulae are generally very significant. Differences of coefficients in formulae from different materials of both samples, compared in pares (rainfall — runoff, 5 mm — 10 mm) were not generally significant. True, parts of curves near the origo are very different, but beginning from the layer of 6 cm they are very similar.

Thus, it seems that the coefficient of ground water table can be determined by experiments, both through rainfall and runoff. Results do not seem to be influenced essentially whether the smaller or the larger rainfall or runoff is used; of course this applies only within certain limits. From a very small rainfall a considerable part remains above the ground water table, and if a large amount of water is used, the large area of change of the ground water table involves so great a variation in the coefficient of ground water table that the result is uncertain. All these differences caused by different ways of determination, however, are of minor importance in comparison with differences owing to different peat profiles. The experiments carried out so far have proved that the coefficient of ground water table has to be determined separately in each sample plot as an argument in accordance with the peat profile. It remains to be checked by

further studies, whether the dependence of the coefficient on the peat profile has to be determined by using rainfall or runoff and how large rainfall or runoff should be used. Samples in further studies should be smaller than those used in these experiments; in this way the method could be modified for field use.

Examples of the use of the method

Since the coefficient of ground water table has not been studied experimentally in the water economic sample areas constructed, the coefficient will be here determined on the basis of observations made in studying the effect of rain on the movements of the ground water table. Experience indicates, though, that such »experiments arranged by nature» do not give results as reliable as those obtained with peat samples in the laboratory, as was seen above (cf. also Huikari 1959, p. 24—25).

The following table consists of a few examples of the fall of the ground water table and its conversion into evapotranspiration.

Sample area	Date	Fall of ground water table, mm	Coefficient C	Evaportanspiration mm per 24 hours
1	July 17	11	2.5	4.4
2	»	15	3.6	4.2
3	»	9	3.1	2.9
1	July 28	9	3.2	2.8
2	»	9	4.9	1.8
3	»	8	3.8	2.1

Since on July 28 the ground water table was lower than on July 17, the coefficient of ground water table in the former case is greater than in the latter.

The following table shows the proportional distribution of tree species in the sample areas.

Sample area	Species of tree	Age, years	Volume, cu m per ha	increment, cu m per ha per year
1	Pine	40	115	4.9
2	Birch	50	90	4.5
3	Spruce	80	160	3.8

Although the results are not yet accurate enough — for reasons mentioned above — and they have been presented mainly to demonstrate the idea of the method, we can draw the following conclusions from the figures showing evapotranspiration. A birch stand seems to transpire as much as coniferous trees, although the birch stand in question has had the lowest volume and also its growth has been considerably weaker than that of pine. Thus the results correspondent to many other studies, in which the evapotranspiration of birch stands has been compared with that of conifers (e.g. THURMANN-MOE 1941).

It is not justifiable as yet, of course, to compare seriously the evapotranspiration values obtained, but let it be mentioned that POLSTER (1950) in Central European conditions observed values of evapotranspiration which are somewhat greater. STÅLFELT (1944) in Sweden has published quite similar results. Hydrological studies in Finland have yielded results of evapotranspiration of the same order (e.g. NIINIVAARA 1953). Also figures of evapotranspiration by HUIKARI (1959) are practically of the same magnitude.

Some possible applications

On the previous pages a method has been introduced to determine the transpiration of tree stands and ground vegetation as well as total evaporation, all together. It has been mentioned above, however, that the method can be applied also to measure these evapotranspirational (part)-factors quantitatively. Stand transpiration can be separated by setting up a relatively large lysimetric experiment in a sample area, with only ground vegetation and evaporation included, trees and even tree roots excluded. Otherwise conditions are the same as in a sample area for evapotranspiration, also the ground water table is kept at the same level. There are lystimeters of different structures, of course, and since no lysimeters have been used in the experiments of this study so far, there is no point going to details in this respect; it will suffice to refer to lysimeters used in Finland, for instance (e.g. VIRTA 1962).

If we want to separate also evaporation and the transpiration of ground vegetation, we shall encounter more difficult problems, which however, can be solved by lysimetric experiments. In forest research, however, it will generally suffice to separate stand transpiration from evapotranspiration.

When the method is to be applied to measuring the total evaporation of longer periods of time, also rainfall, interception, stand rainfall and stemflow must be measured. Such studies have been made in connection with this work, but because they have no direct bearing on the method itself, publication of the results have been thought unnecessary at this stage. LUKKALA (1942), for instance, has dealt with methods of studying interception and SIRÉN (1955) of stemflow.

As a matter of fact, this method, when applied to longer periods of time, resembles another one, which is based on measuring rainfall, runoff and changes in the amount of water in the ground, and which is frequently used in hydrological studies (in Finland e.g. NIINIVAARA 1953, HUIKARI 1959). There is, however, a difference of principle in that in this method evapotranspiration is measured directly, although by means of the ground water table indicating the decrease

in the amount of water in the ground. In addition, in this so-called rainfall — runoff method used by hydrologists, different components of evapotranspiration have not been separated from one another, and a determination of the amount of water in the ground has been thought to be reliable only when the height of the ground water table has been the same at the beginning and at the end of a period. The method now introduced will offer, when fully developed, a means to separate different components of evapotranspiration, and, in carefully confined areas, also to determine quantitatively the transpiration of different tree stands.

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SELOSTE:

POHJAVESIPINNAN VAIHTELUISTA HAIHDUNNAN MITTAAMISESSA

Metsänkasvatusta varten ojitetuilla soilla, joissa pohjavesipinta on suhteellisen korkealla, on voitu osoittaa, että pohjavesipinta laskee päivällä noin 9—18 välisenä aikana ja on muun ajan vuorokaudesta lähes paikallaan. Pohjavesipinnan päivittäinen lasku, joka saattaa olla jopa yli 20 mm, aiheutuu puuston ja aluskasvillisuuden haihdunnasta. Päivittäistä pohjavesipinnan laskua voidaan täten käyttää puuston haihdunnan mittaamiseen. Laboratoriokokein on selvitelty pohjavesipinnan muutoksen ja sen aiheuttaneen vesimäärän muutoksen suhde. Selvittämällä tämän pohjavesikertoimen suuruus kullakin haihduntakoealalla, voidaan pohjavesipinnan päivittäinen lasku muuntaa puuston haihdunnan määräksi.

Kehitetty menetelmä on uusi ja sillä on mahdollista entistä luotettavammin selvittää erilaisten metsiköiden haihdunta. Menetelmä on tietysti käyttökelpoinen vain sellaisilla kasvupaikoilla, joissa pohjavesipinta on suhteellisen korkealla.