Nordic Hydrology, 15, 1984, 235-242

Seasonal Variations of Oxygen-18 in Soil Moisture and Estimation of Recharge in Esker and Moraine Formations

Paper presented at the Nordic Hydrological Conference (Nyborg, Denmark, August - 1984)

R.K. Saxena
Div. of Hydrology, Uppsala University, Sweden

The use of Oxygen-18 as a natural tracer of soil moisture and estimation of recharge in different types of soils is presented and discussed. The δ values of ^{18}O in summer and winter precipitation in southern Sweden differ by about 6-8‰ SMOW, giving the soil moisture a distinct isotopic profile. For instance, meltwater having low $\delta^{18}O$ labels the upper soil horizon with isotopically light water and pushes down the isotopically heavy old moisture contributed by the preceding summer precipitation. The soil moisture thus exhibits a cyclic pattern having low and high ^{18}O contents. The temporal displacements of soil moisture layers depleted or enriched in ^{18}O have been used to calculate seasonal and annual recharge in esker and moraine formations. In Uppsala region the annual recharge varies from 230-300 mm. These estimates are reliable since ^{18}O depleted soil moisture layers contributed by two years consecutive meltperiods have been observed in the soil profile.

Introduction

Soil moisture movement in the unsaturated zone has been widely studied in the past with the help of tracer tagging technique. The labelled molecules of water namely HTO and HDO have been used (Zimmermann et al. 1967a) of which the former has found a wider application. The principle of the method is that soil moisture is tagged or labelled artificially with an isotopic tracer in a horizontal plane below the root zone. During the course of infiltration, the tracer is carried along with the moving soil moisture. Field studies have shown: a) that soil moisture cannot bypass the tagged layer in either direction in the vertical, and b) that the downward displacement of the tagged layer is like a moving piston (Zimmermann et al. 1967b). The rate of soil moisture movement is determined from the temporal displacements of the tagged layer. In some of the studies the displacements of the tagged layer have been monitored throughout the year which give estimates of yearly vertical recharge (Datta et al. 1973).

Apart from artificial tracers, bomb released tritium in precipitation has also been used as an environmental tracer for groundwater recharge estimates. However, the use of environmental stable isotopes of the water molecule (^{18}O and D) especially to study moisture movement in the unsaturated zone has not been seriously attempted. Recently, deuterium profiles probably due to seasonal variation of deuterium in precipitation have been used to estimate annual recharge in sand dunes, see Thomas et al. (1979).

In the present study, the seasonal variations of ^{18}O in precipitation have been traced in the soil moisture with the aim to estimate vertical groundwater recharge and moisture movement in Swedish eskers and moraines.

The winter and summer precipitation in Uppsala differ in their ^{18}O content roughly by 6-8‰. During snowmelt, the meltwater which is of relatively light isotopic composition, acts as a source of ^{18}O depleted water and during infiltration in the soil, labels or tags the soil moisture with low ^{18}O content. After the meltperiod, early summer rains having high ^{18}O content push down the ^{18}O depleted meltwater which in turn further pushes down the older moisture (having high ^{18}O content) contributed by the previous year's summer rains. Thus the meltwater forms a ^{18}O depleted tagged layer which is sandwiched between the older and the younger waters both having relatively high ^{18}O content. The rate of the downward displacement of this tagged layer gives direct information about the rate of soil moisture movement. Under some field conditions in Uppsala where water table is quite deep, infiltrated meltwater from at least two consecutive meltperiods has been traced in the unsaturated zone providing estimates of annual recharge.

Initially ^{18}O profiles of soil moisture were obtained from the sandy formations in Uppsala and Skediga, but later on as the technique proved to be successful, moraine soils in Kloten were also included in the studies.

Some Theoretical Considerations

If A and B are two hypothetical ^{18}O profiles in the soil at times t_A and t_B and the ^{18}O depleted layers are found at average depths Z_A and Z_B (Fig. 1a), then

$$V = \frac{Z_B - Z_A}{t_B - t_A} \tag{1}$$

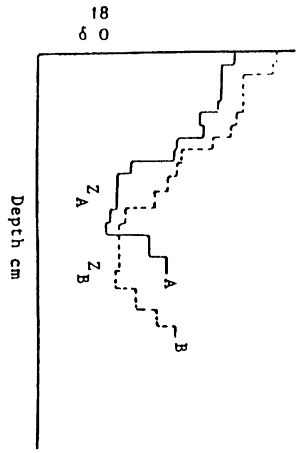

Fig. 1 a.

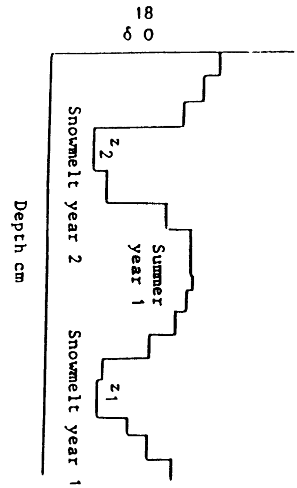

Fig. 1 b.

where V is the rate of soil moisture movement during the period t_A to t_B. If θ is average volumetric moisture content of the soil between the depths Z_A and Z_B, and $(Z_B - Z_A) = Z$ is the corresponding displacement, then

$$R = \theta . Z \tag{2}$$

where R is the groundwater recharge during the period t_A to t_B, provided that the depleted layers have already crossed the root zone and moisture between Z_A and Z_B can not be lost by evaporation. When the groundwater table is quite deep (> 4 m), ^{18}O depleted moisture from two or more successive years' meltperiods is found in the unsaturated zone. Such a situation is hypothetically depicted in (Fig. 1b). Say Z_2 is the average position of meltwater of year 2, while Z_1 is the average position of meltwater of year 1, then the total moisture between Z_1 and Z_2 is the moisture recharging the soil profile between the two meltperiods. In between the depleted layers Z_1 and Z_2, the heavy or enriched moisture contributed by summer rains of year 1 is also present.

Site Description

Uppsala

This sampling station is situated on the western flank of Uppsala Esker. The area is covered by a shallow deposit of post glacial fine sand. The homogeneity of the soil profile is disturbed by the occurrence of thin clay lenses at certain depths. Water table in the area is below 3.5 m.

Skediga

Skediga is situated 10 km north of Uppsala, on a discontinuous and spread esker which is a part of the Uppsala esker. The soil profile is layered: coarse sand and gravel down to 150 cm depth followed by a thick clay lens extending down to 190 cm depth, and fine sand below. Water table in the area varies between 9 and 11 m.

Kloten

Kloten is about 140 km west of Uppsala. The Kloten moraine consists of unsorted material varying in grain-size from big boulders to material crushed down to the size of clay. The soil material is coarser near the surface than farther down.

Experimental Procedure

Field studies were initiated in February 1982 in Uppsala and Skediga. In order to obtain ^{18}O profiles of the soil moisture, 10 cm long cores down to 3 m depth were taken in the sandy material. The moraines cannot be sampled by the coring method because of a large assortment of pebbles and small boulders. Hence for moraines, a pit (190 × 80 cm) is dug and soil samples are colleced in stainless steel cans, by pressing the cans against the walls of the pit. Soil moisture is extracted by vacuum distillation of the soil samples, details of which have been reported earlier (Saxena and Dressie 1984). ^{18}O content of the extracted water samples is measured on a ratio type mass-spectrometer and is expressed as $\delta^{18}O$; i.e. the per mille deviation from the reference standard (SMOW). The accuracy of measurement is ± 0.1‰.

Results and Discussions

The temporal displacements of the ^{18}O depleted layers, the rates of soil moisture movement and recharge estimates are given in Tabel 1. The meltperiods of 1981 and 1982 can be clearly distinguished in the soil moisture profiles observed in May 1982 (Fig. 2). The first ^{18}O depleted layer (average depth 65 cm) represents snowmelt 1982, and the second layer with high ^{18}O content is derived from summer rains 1981. The third layer which is also depleted in ^{18}O (average depth 235 cm) is due to the contribution from 1981 meltperiod. The total water (280 mm) present in between these two ^{18}O depleted layers is that water which entered the soil after the 1981 snowmelt and is the recharge or storage between the meltperiods 1981 and 1982. The ^{18}O depleted layer which was at average depth 65 cm in May 1982 was found at 190 cm depth in May 1983 (Fig. 3), showing 125 cm displacement in one year. The average moisture between 65 to 190 cm depth was 18.5 vol. %, thus the recharge during 1982-83 was 231 mm (using Eq. (2)). Heavy

Table 1 – Rate of moisture movement and recharge estimates.

Location	Time period	Displacement of ^{18}O depleted layers (cm): Av peak positions (cm)	Displacement of ^{18}O depleted layers (cm): Shifts (cm)	Av. moist. cont. vol.%	Rate of moisture movement (d^{-1})	Storage/ recharge (mm)	Precipitation (mm)
U-1	820312-0504	40-65	25	16.8	4.7	42	193
U-1	820504-0722	65-110	45	17.3	5.8	77	74
U-1	820722-0924	110-125	15	10.8	2.4	16	94
U-1	820504-0924	65-125	60	14.1	4.3	85	168
U-2	820722-0923	115-155	40	11.2	6.5	45	93
U-2	820924-1212	155-170	15	22.2	1.9	33	104
U-2	820722-1212	115-170	55	23.6	3.8	130	198
Skediga	820328-0723	40-120	80	11.0	6.9	88	144
U-1	May 81-May 82	70-235	165	17.0		280	691
U-2	May 82-June 83	65-190	125	18.5		231	520
U-2	Sum. 81-Sum. 82	80-240	160	21.0		336	600
Kloten	Spring 82-Sept 83	50-150	100	17.0		170	

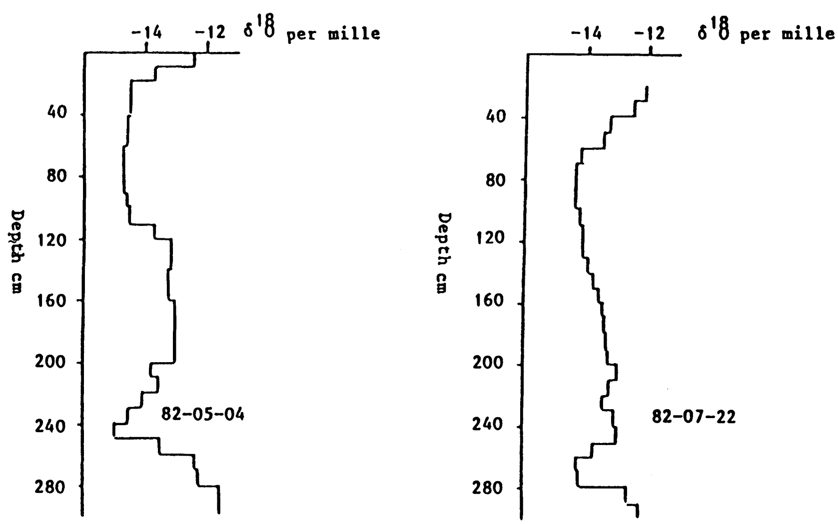

Fig. 2. O-18 profiles in Uppsala esker (plot U1).

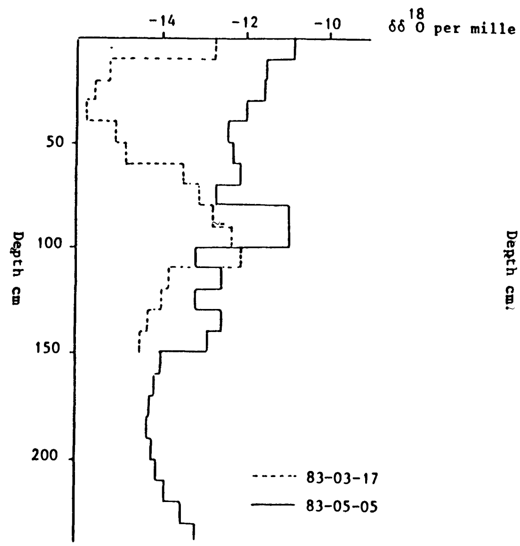

Fig. 3. O-18 profiles in Uppsala esker (plot U2).

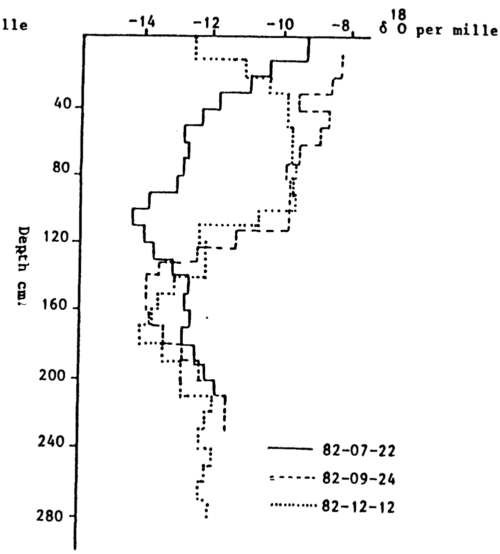

Fig. 4. O-18 profiles in Uppsala esker (plot U2).

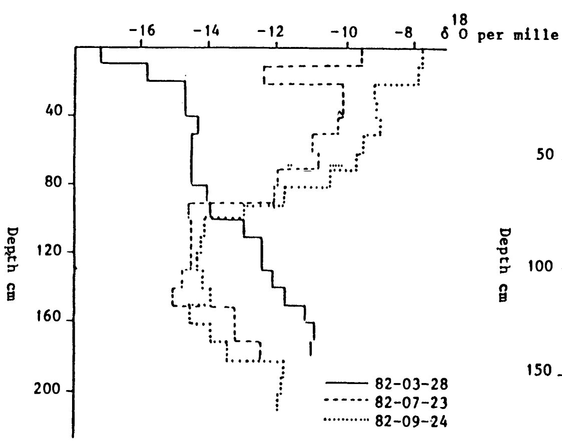

Fig. 5. O-18 profiles at Skediga.

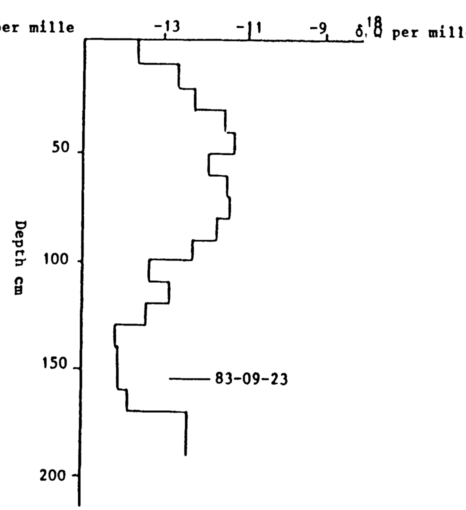

Fig. 6. O-18 profiles at Kloten.

isotopic inputs from summer rains can also be traced. For example, the moisture contributed by 1982 summer rains was found at 80 cm depth in December 1982 (Fig. 4), and the input from summer 1981 was found at 240 cm. The total amount of water between these layers was 336 mm, which is a measure of recharge from summer 1981 to summer 1982.

In February 1983 the snow cover was only 7-9 cm deep in Uppsala and spring was relatively poor in precipitation. Consequently, the depleted soil moisture down to 60 cm depth observed in March 1983 (Fig. 3) lost its isotopic identity, i.e. showed increased δ values in May 1983. This implies that the depleted moisture was partly lost by evapotranspiration and was partly mixed with infiltrating water from summer rains having relatively high δ values. The combined effect of these two processes resulted in increased δ values of soil moisture in shallow depths as observed in May 1983. This indicates that the tracing of moisture contributed by snowmelt is useful when the amount of meltwater is large.

In Skediga the movement of the depleted layer was faster (Table 1) than that in Uppsala on account of coarser material at the former. The ^{18}O depleted moisture was displaced by 80 cm between March and July 1982 (Fig. 5), but it hardly moved between July and September. It appears that the thick clay lens extending from 150 to 190 cm impeded the vertical flow of moisture and a lateral flow developed. This observation is also confirmed by previous studies (Saxena and Dressie 1984) where injected tritium was also used as a tracer.

The ^{18}O profile of soil moisture in moraine material at Kloten is shown in Fig. 6. The ^{18}O depleted moisture between 130-170 cm depth can be attributed to 1982 meltwater infiltration. As a matter of principle, the contribution from 1983 melt-period should have also been present in the upper soil layers (say 60-70 cm). A parallel situation was observed in Uppsala esker, and can be explained in a similar manner, i.e. partial loss of soil moisture by evapotranspiration and partial mixing with water from summer rains having high δ values. Together, these two processes bring about an increase in the ^{18}O content of the soil moisture in shallow depths.

However, assuming that the ^{18}O depleted moisture present at (average depth) 150 cm (Fig. 6) is due to 1982 meltwater infiltration and further that its average depth was about 50 cm in spring 1982 (in analogy to Uppsala profile 1982), then the average recharge from spring 1982 to early autumn 1983 in Kloten moraine (Table 1) is about 170 mm.

Conclusions

Isotopically depleted meltwater that infiltrates in the soil matrix, can be used as a natural tracer for studies of soil moisture movement and groundwater recharge.

The main advantage of the technique is that by a single sampling of soil moisture, it is possible to determine annual recharge for those regions where infiltrated meltwater from at least two consecutive meltperiods can be traced in the soil.

References

Datta, P.S., et al. (1973) Groundwater recharge in Western Uttar Pradesh, Proc. Indian Acad. Sci., 78A, 1.

Saxena, R.K., and Dressie, Z. (1984) Estimation of groundwater recharge and moisture movement in sandy formations by tracing natural oxygen-18 and injected tritium profiles in the unsaturated zone, Isotope Hydrology in Water Resources Development, Proc. Symp. Vienna, IAEA, Vienna, 139.

Thomas, G., et al. (1978) New technique of in-situ soil moisture sampling for environmental isotope analysis applied at Pilat Dune near Bordeaux, Isotope Hydrology, Proc. Symp. Neuherberg, IAEA, Vienna, 753.

Zimmermann, U., Ehhalt, D., and Münnich, K.O. (1967 a) Soil water movement and Evapotranspiration: changes in the isotopic composition of water, Isotopes in Hydrology, Proc. Symp Vienna, IAEA, Vienna, 567.

Zimmermann, U., Münnich, K.O., and Roether, W. (1967 b) Downward movement of soil moisture traced by means of hydrogen isotopes, American Geophysical Union, Geophysical Monograph Series 11, 28.

Received: 1 October, 1984

Address:
Division of Hydrology,
Department of Physical Geography,
Uppsala University,
Box 554,
S-751 22 Uppsala,
Sweden.