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Estimating the rate of recharge to the groundwater table using environmental chloride as a tracer

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ABSTRACT

The use of environmental chloride as a tracer in the unsaturated soil zone to estimate groundwater recharge in dry climatic conditions is well documented. An evaluation of this method in estimating groundwater recharge to a sand aquifer in UK under temperate climatic conditions was carried out by comparing the estimates of recharge (from chloride profiling method) with that of a different method and with those by other workers. The results suggest that it is possible to use the unsaturated zone chloride profiling method to estimate recharge for the area studied. This result along with the documented information is analysed and discussed, and this discussion suggests a possibility of using the chloride profiling method to estimate groundwater recharge in the tropics including dry zone of Sri Lanka.

Key words: groundwater, recharge, chloride profiling method.

INTRODUCTION

For the efficient development and utilisation of groundwater resource, a reasonable estimate of groundwater recharge or the rate at which the water table is replenished is essential. There are a number of methods of estimating groundwater recharge (Lerner *et al.* 1990; Gee and Hillel 1988). These methods are more applicable under different climatic, soil and geologic, land use, topography and water table depth situations. Financial conditions, availability of required data (climatic, soil and vegetation), time available and time scale of measurement involved also influence the method to be selected. A comprehensive review of each method is given in de Silva (1996).

The use of environmental chloride to trace the movement of water in the unsaturated soil zone (hereafter called the chloride profiling method) is a simple method of estimating recharge. This method has been used to estimate groundwater recharge in India (Sukhija *et al.* 1996; Sukhija *et al.* 1988), North America (Scanlon 1991); Australia (Allison and Hughes 1978; Sharma and Hughes 1985; Cook *et al.* 1989; Kennet-Smith *et al.*, 1994), Cyprus (Kitching *et al.* 1980; Edmunds and Walton 1980), Sudan (Edmunds *et al.* 1988) and Senegal (Edmunds and Gaye 1994).

The present paper evaluates the use of chloride profiling method to estimate recharge in a sandy aquifer in Bedfordshire in UK, by comparing the estimate of recharge by the chloride profiling method with;

(a) an estimate for recharge by a different method (for the same area) and

(b) recharge estimates by different workers for the sandy aquifer.

The paper also discusses the possibility of use of chloride profiling method to estimate recharge in the dry zone of Sri Lanka.

MATERIALS AND METHODS

The location chosen for the study is a site on the Silsoe College farm in Bedfordshire, UK. The topography of the site is flat and vegetation is mainly grass with plants of *Thistle* interspersed. Top soil is sandy loam up to about 1.0m depth and underlain by Lower Greensand formation (Lower Cretaceous). Thin layers (up to 1.0m) of hardened sandstone known as carstone are found at depths of 4.0m, 7.5m, 9.0m and 12.0m. For Silsoe the 15 year (1961-1976) mean annual precipitation was 559 mm and the mean potential evapotranspiration for the same period was 616 mm. The depth to the water table at this location was about 12 m.

Soil sampling for determination of chloride concentration in soil

A total of 21 holes on randomly chosen sampling points in a 2.5 m square grid were hand augured and details of each hole are given in Table 1.

A Dutch auger (50 mm diameter) was used to

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obtain soil samples. Soil samples of about 100 g at every 250mm depth were collected in polythene bags and sealed immediately. Special care was taken not to contaminate soil samples by human perspiration or any other substances. Labelled sample bags were immediately taken to the soil laboratory for the determination of moisture content and chloride ion concentration. The moisture content by weight was determined gravimetrically according to the British Standards Institution (1990a).

Comparison of elutriation with other extraction methods

To compare the elutriation (extraction of salts in soil by shaking after adding water) process in extracting chloride ions from the soil solution, five sub samples each of a well mixed soil sample was elutriated, centrifuged and extracted under a 0.8 bar suction after adding 50 ml of distilled deionised water. A further five sub samples from the same soil sample were treated with all of above three procedures (i.e., elutriation, centrifuge and extracted under the suction) again after adding 50 ml of distilled deionised water. These samples were then analysed colourimetrically for chloride ion concentrations.

Determination of chloride ion concentration of rainwater samples and soil water extracts

Extraction of soil water in the soil samples were carried out according to British Standards, (1990b) where 50 ml of distilled deionised water was added to a sub-sample of 50 g of soil and shaken for 16 hours. The resulting solution was then filtered using Whatman no 42 (retaining material larger than 2.5 µm) filter paper in to clean plastic bottles. Chloride ion concentrations in rainwater and extracted soil water samples were determined using the mercuric thiocynate method (Zall *et al.* 1956) with a detection limit of 0.05 mg l^{-1}. A Technicon Auto Analyser was used to determine the colour differences created by the release of the ferric thiocynate ion $[Fe(SCN)]^{++}$.

Determination of field capacity and the permanent wilting point

Profile pits were carefully excavated ensuring that the auger hole was always on a side of the profile pit facing the Sun (for better identification of horizons). Depth of root zone and the different horizons were identified by visual inspection. Triplicates of undisturbed soil samples from each soil horizon were obtained using metal rings of 5.5 cm diameter and 2 cm height (by driving them into the pit side slowly) at each horizon up to the root zone depth. The moisture contents at field capacity (0.1 bar suction) and permanent wilting point (15 bar suction) were determined using a standard sand table and pressure membrane apparatus and the results are shown in Table 1.

Table 1. Date augured, depth, mean chloride concentration of soil, root zone depth, field capacity (% by volume) and wilting point (% by volume) at each sampling point.

Sampling point	Date Augured	Depth of auger hole, m	Mean chloride concentration of soil, mg.l^{-1}	Root zone depth, m	Field Capacity, % by vol.	Wilting Point, % by vol.
A	18-May-94	3.5	42	1.19	24.5	10.6
B	18-May-94	3.8	35	1.25	22.4	11.6
C	29-May-94	3.5	16	1.2	23.1	14.2
D	29-May-94	4.3	29	1.2	33.3	18.5
E	29-May-94	3.8	15	1.3	24.2	14.2
F	29-May-94	4.0	30	1.25	21.6	12.5
G	01-Jun-94	4.0	26	1.25	23.4	11.4
H	01-Jun-94	3.8	23	1.25	23.7	13.0
I	07-Jul-94	3.8	26	1.12	20.0	9.5
J	08-Jul-94	4.0	30	1.18	25.1	12.9
K	08-Jul-94	4.0	30	1.2	26.0	13.1
L	08-Jul-94	·4.0	25	1.3	18.5	7.9
M	08-Jul-94	3.0	29	1.2	17.3	8.1
N	20-Jul-94	3.8	27	1.2	19.6	13.7
O	20-Jul-94	3.5	28	1.3	24.7	13.1
P	20-Jul-94	3.8	14	1.2	20.0	8.6
Q	20-Jul-94	4.3	12	1.15	23.4	13.6
R	21-Sep-94	4.0	18	1.25	25.4	15.1
S	12-Oct-94	4.3	27	1.25	21.7	12.1
T	19-Oct-94	4.3	17	1.2	19.7	10.6
U	19-Oct-94	4.0	20	1.2	22.5	12.5

Collection of climatic data

Daily precipitation (to be used in the chloride profiling method and SWB method) and potential evapotranspiration data (to be used in the SWB method) were collected for 30 years from 1962 to 1991 (Jerry Knox, Personal communication).

Unsaturated zone chloride profiling method

The movement of (chemically inactive) solutes in the unsaturated zone primarily consist of two mechanisms, viz., advection (also known as convection or mass flow) and dispersion.

Table 2. Verification of recharge estimates by chloride method with other methodss by different workers.

Country and Location	Rain mm year^{-1}	Ep[1], mm year^{-1}	Soil	Vegetation	Recharge range, mm year^{-1}	Method verified with	Source
Australia, South Australia	750	-	Sands over* heavy clay, sandy clay, and limestone	-	50 - 70 100, 100 - 140, 105, 120	Tritium Profiles	Allison and Hughes (1978)
Australia, South Australia	750	-	Sands loam over limestone Aeolianite, Skeletal soils	-	140 - 155 195, 200, 250, 270	Tritium Profiles	Allison and Hughes (1978)
Australia New South Wales	310	2100	-	Cropping	6 - 9 3 - 6 4 - 32	Soil water balance	Kennet -Smith *et al.* (1994)
Australia New South Wales	225	2200	-	Pasture	0 - 1	Soil water balance	Kennet -Smith *et al.* (1994)
Australia Victoria	430	1700	Clay	Cropping	3	Soil water balance	Kennet -Smith *et al.* (1994)
Australia	530	1500	Clay	Pasture	1 - 6	Soil water balance	Kennet -Smith *et al.* (1994)
India, Pondicherry	1200	-	Sandy Alluvial deposits	-	220 - 260	Tritium Profiles	Sukhija *et al.* (1988)

Note: 1. Pan evaporation
2. A hyphen is shown where the relevant information is not reported.

Considering these two processes, the solute flux (Js) is (Bresler 1973; Peck *et al.* 1981):

$$J_S = -D_h(\theta, v).\frac{\partial C_z}{\partial z} + C_z \cdot q_w \quad\text{.................(1)}$$

where $D_h(\theta, v)$ is the hydrodynamic dispersion coefficient which is a function of volumetric soil moisture content (θ) and average soil moisture velocity (v), C_z is the concentration of solute, q_w is the volumetric soil moisture flux and z is the space co-ordinate (measured positive downwards from the soil surface). Rearranging equation 1, the soil moisture flux q_w is obtained by;

$$q_W = \frac{1}{C_Z}\left[J_S + D_h(\theta, v).\frac{\partial C_z}{\partial z}\right] \quad\text{.................(2)}$$

The process of advection, meaning movement of solutes dissolved in the soil solution due to the mass flow of the solution, is represented by the first term within the outer brackets and the dispersion process is represented by the second term in the outer brackets in equation 2. Dispersion is thought to comprise of mechanical dispersion (which results from tortuous flow paths in pores and also from differential flow velocities in a pore due to higher frictional forces near the pore walls) and molecular diffusion (results from random thermal-kinetic motion caused by concentration gradients).

Olsen and Kemper (1968) report that if flow velocities are less than about 730 mm year^{-1}, the mechanical dispersion is negligible. Usually the soil water velocities are less than this value (Scanlon 1991) and therefore, hydrodynamic dispersion is considered to occur from mass flow only. It must be noted that if the dispersion term is negligibly small [i.e., $D_h(\theta, v)=0$] and the solute input is considered as from precipitation only (i.e., J_s= Cp.P, where P is mean annual precipitation and Cp is mean chloride concentration in precipitation), then equation 2 becomes;

$$q_W = \frac{P.C_p}{C_z} \quad\text{........................(3)}$$

which is the equation used mainly by researchers using the chloride profiling method. Equation 3 can be obtained more easily by considering the chloride mass balance for the root zone [or more precisely for the zone up to the zero flux plane (ZFP) from the soil surface], equating chloride flux input to the soil surface to that of flux leaving the root zone as follows (ignoring any molecular diffusion as above).

$$P.C_p = q_W \cdot C_z$$

$$\therefore q_W = R_e = \frac{P.C_p}{C_z} \quad\text{.................(4)}$$

It must be noted that P in equations 2, 3 and 4 is the actual amount of rainwater infiltrating and therefore, losses of precipitation by runoff and interception needs to be taken into account in applying these equations in estimating recharge.

Table 2 shows instances where estimates from chloride profiling method have been verified with other methods by different workers.

Penman-Grindley soil water balance model

The Penman-Grindley soil water balance (Lerner *et al.* 1990) was used to calculate the deep percolation from the root zone. The soil water balance is explained in detail in de Silva (1996). The root constant [i.e., the soil moisture deficit where actual evapotranspiration (AE) falls below potential evapotranspiration (PE)] used was 76 mm. Beyond root constant, the ratio of AE/PE was taken as 0.1 (Lerner *et al.* 1990). As recommended by Howard and Lloyd (1979), a time interval of one day was used in the soil water balance. Also 15 years of daily climatic data (from 1962 to 1976) was used in the model.

RESULTS

Fig. 1 shows the effect of different treatments (i.e., elutriate, centrifuge and extract under a 0.8 bar suction and a combination of all three) to extract the chloride ions from soil solutions. From Fig. 1 it is evident that there is not much difference between the amounts of chloride ions extracted under different treatments, which is confirmed by a single factor analysis of variance test at 5% significant level as shown in Table 3 (Fcalc is less than Fcrit and therefore the difference between treatments are not significant at 5% significance).

Table 3. Result of single factor analysis of variance test (5% significance level)comparing the effects of different treatments to extract chloride ions in soil.

Source of Variation	Sum of squares	Degrees of freedom	Mean squares	Fcalc	Fcrit
Between Groups	1.04	3	0.53	1.06	3.24
Within Groups	5.24	16	0.33		

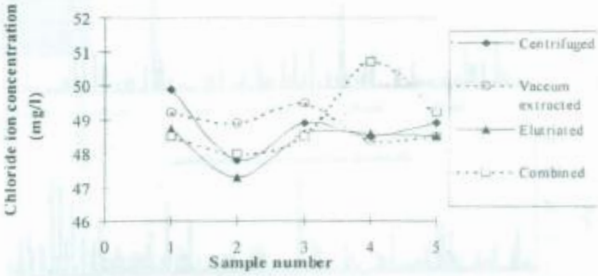

Fig 1. Comparison of treatments (centrifuge, vacuum extract, elutriate, all three combined) to extract chloride ions from the soil solution.

Fig. 2 shows the precipitation and chloride ion concentration in precipitation from March 1994 to May 1996 at the study location. Results indicate that rains of short duration contain rainwater of higher chloride concentrations which agrees with the findings of Edmunds and Gaye (1994). The average chloride concentration in precipitation for the time duration (2 years) was 5.0 mg l^{-1}.

The variation of moisture content and chloride concentration in soil with depth for some selected profiles are shown in Fig. 3. (The same for all the profiles are found in de Silva, 1996). The mean chloride concentration of soil below the depth of root zone for each profile is given in Table 4.

The average chloride concentration below 1.5 m (depth of root zone) was taken as the steady state

Table 4. Comparison of estimates of recharge from the chloride method and from the soil water balance method at all sampling points.

Sampling point	Steady state chloride ion concentration in soil solution (below root zone), mg l^{-1}	Recharge estimated from chloride method using equation 4, mm year^{-1}	Root constant, mm	Root depth, m	Recharge estimated from soil water balance, mm year^{-1}
A	42	67	76	1.19	165
B	35	80	76	1.25	135
C	16	175	76	1.20	135
D	29	96	76	1.20	135
E	15	186	76	1.30	135
F	30	83	76	1.25	135
G	26	108	76	1.25	135
H	23	122	76	1.25	135
I	26	108	76	1.12	165
J	30	93	76	1.18	165
K	30	93	76	1.20	135
L	25	112	76	1.30	135
M	29	102	76	1.20	135
N	27	104	76	1.20	135
O	28	100	76	1.30	135
P	14	200	76	1.20	135
Q	12	233	76	1.15	165
R	18	155	76	1.25	135
S	27	104	76	1.25	135
T	17	164	76	1.20	135
U	20	140	76	1.20	135
Mean		125			140

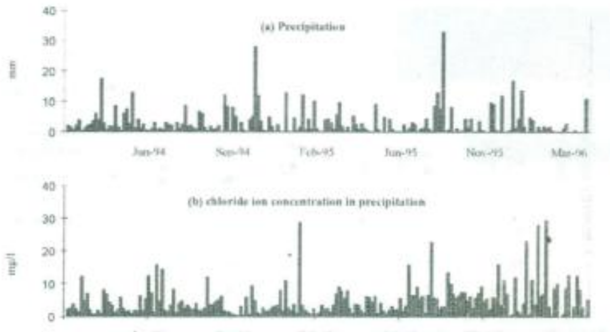

Fig. 2(a). Precipitation and (b) concentration of chloride ions in precipitation at study location from March 1994 to May 1996.

DISCUSSION

As the first part of the objectives, this paper evaluates the suitability of using the unsaturated zone chloride profiling method to estimate recharge in the sandy aquifers of Bedfordshire in UK. As seen from Table 4, the average estimate of recharge for the area from both methods compare well. Also, the average estimate of two methods are comparable with estimates by other workers for the area (Table 5). Further, more than 75% of the recharge estimates by the chloride profiling method are within 94-183 mm year^{-1} (which was estimated as recharge) by Monkhouse (1979) as given in Table 5. Therefore, it

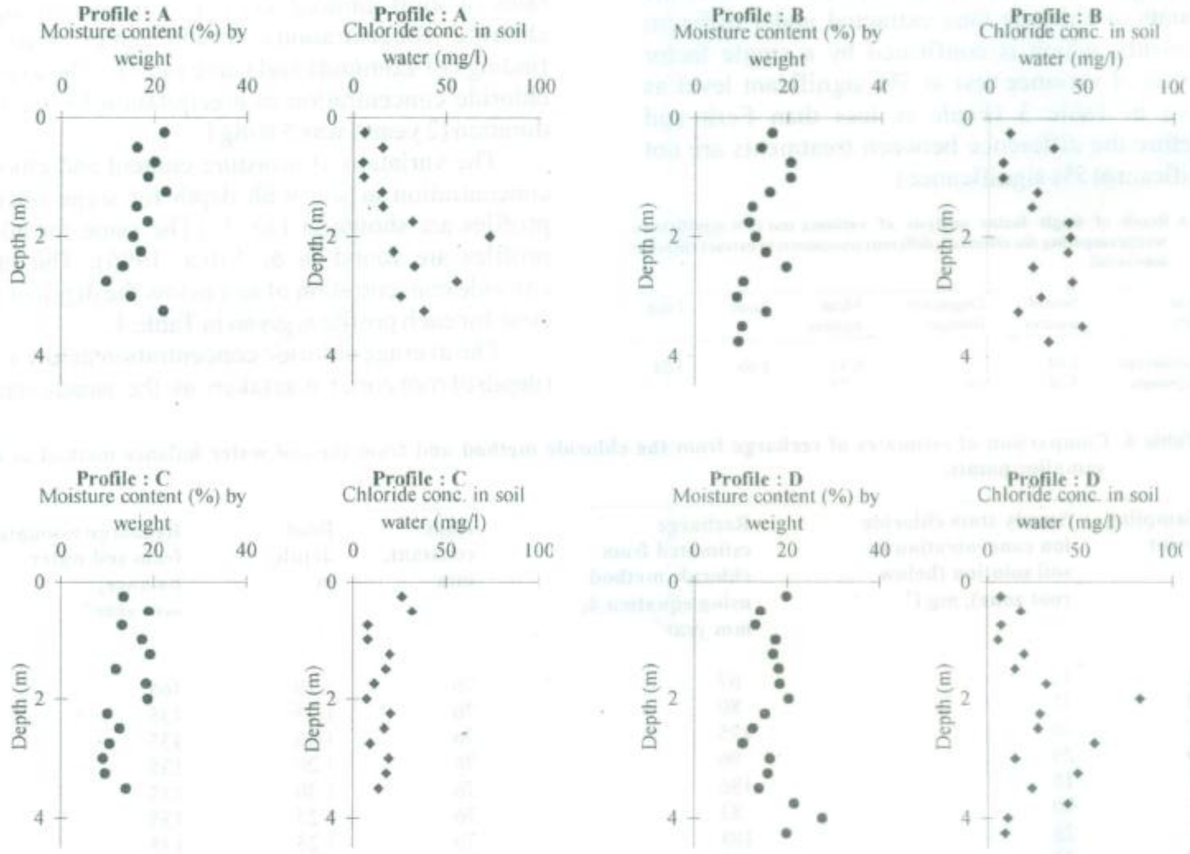

Fig 3. The variation of moisture content and chloride concentration in soil with depth for some selected profiles

chloride concentration for each profile. This value along with recharge rates calculated from equation 4 are given in Table 4. Here P is mean annual precipitation (559 mm year^{-1}) as losses due to interception and runoff are negligible.

is concluded that the chloride profiling method can be used to estimate recharge in the study area.

However, as can be seen from Table 4, the estimates of recharge by the chloride profiling method at close intervals show significant spatial variability (from 67 mm year^{-1} to 233 mm year^{-1}). Also, the estimates from the soil water balance do not

Table 5. Estimates of recharge by different workers for the Sandy aquifer.

Method of Recharge Estimation	Estimated Recharge, mm year^{-1}	Source
Soil water budget	94-183	Monkhouse (1974)
Measuring Chloride concentration in surface streams	168	Irving (1982)

show this variability. This could be due to;

(a) Chloride method estimates actual recharge (i.e. the rate of water reaching the water table or the lower depths of the soil profile) whereas soil water budget method estimates potential recharge (i.e. percolation from the root zone).

(b) Chloride method estimates long term (a number of years) recharge whereas soil water budget method estimates short term (a few years) recharge.

(c) Experimental errors

(d) A combination of all of above.

Fig. 1 shows a comparison of the effectiveness of elutriation process with those of other standard extraction processes. Thus, it is concluded that the elutriation process is as effective as any other process (i.e. centrifuge, vacuum extract and a combination of centrifuge, vacuum extract and elutriate) in extracting chloride ions from the soil solution. This conclusion is in agreement with results from extraction of chloride ions in Senegal by Edmunds and Gaye (1994).

Table 2 shows the successful application of the chloride profiling method in many climates and this study demonstrates the applicability of the chloride profiling method for a temperate climate. Therefore, combining the results of this study with information in Table 2, it is likely that this method can be applied in most climates including the tropical and subtropical Islands and coastal areas of continents. The following points also confirm the suitability of the chloride profiling method to estimate recharge in such climatic zones.

(a) The chloride ions in rainfall originate from the sea and being in close proximity to the sea, there will always be easily measurable quantities of chloride ions in rain (and in soil).

(b) Long term rainfall records are needed for the chloride profiling method and it is very likely that these records are available in many parts of the tropics. Also non availability of daily rainfall records (required in other methods of recharge estimation) is not a problem, since what is required is the long term value.

(c) The chloride profiling method does not require the estimation of actual evapotranspiration (as required by other methods) and this is a definite advantage in using the chloride profiling method.

(d) As demonstrated in this study, the methodology involved in the chloride profiling method is simple and easy to use method. Furthermore, all the laboratory tests involved can be performed easily.

Therefore it is evident that the chloride profiling could be a suitable, easy to use method to estimate the groundwater recharge in the dry zone of Sri Lanka. However, this method will require a knowledge about the chloride ion concentration in rainfall and therefore, it is important that government agencies working in this sector start measuring and recording it at important locations.

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