The Use of Environmental Chloride as a Tracer in the Unsaturated Soil Zone to Estimate Groundwater Recharge to the Dry Zone Aquifers of Sri Lanka

by

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Abstract

Estimating the rate of recharge to the groundwater table is very crucial in developing the groundwater resource especially in the dry zone of Sri Lanka. The unsaturated zone chloride profiling technique is a relatively new, but a widely used method of estimating recharge. The application of this method to 3 locations in the dry zone suggest that the method is a promising method of estimating recharge. Work needed to use the method effectively are also identified.

1.0 Introduction

In the recent past, there have been a significant development of the groundwater resource in the dry zone of Sri Lanka as evident from the construction of a large number (>12,000) of small diameter (about 100 mm) tube wells and large diameter (>5 m) agro wells throughout the dry zone. However, this development has not been preceded or accompanied by systematic studies to evaluate the groundwater resource potential (Senerath, 1990). To assess this potential, a key parameter necessary is the rate of replenishment of the water table or recharge.

A number of methods are available for the estimation of recharge to an aquifer. They are the soil water balance method, lysimeter method, using tritium as a tracer, measuring groundwater level fluctuation and numerical modelling of the movement of water through the root zone using the Darcy equation (Allison et al, 1994; Hendricks and Walker, 1995). A relatively new and a simple method is the use of environmental chloride (mainly in rainwater) to trace the movement of soil water in the unsaturated (soil) zone and hence make an estimate of the rate of recharge to the groundwater table.

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). From the available literature it is evident that Allison and Hughes (1978) in Australia, are the first to report using this technique to estimate recharge, although Peck and Hurle (1973) have considered a chloride balance of farmed and forested catchments in a study of land salinisation due to deforestation. However, Gardner (1967) has developed the theory of the method, which involves movement of solutes below the root zone.

Although the chloride method has been in existence only for about 20 - 25 years, it has been quite popular with the estimators of recharge in many parts of the world. This is possibly due to;

(a) The (apparent) simplicity of the chloride method, as often, the only parameters required to estimate recharge with this method are rainfall (usually available), chloride concentrations in rainfall (available some times) and depth profiles of chloride concentrations in soil (obtained by auguring and analysing for chloride can be done with basic analytical techniques).

(b) The chloride method estimates recharge averaged over a long period (a few years in wet tropical areas to hundreds or thousands of years in semi-arid and arid areas). From other methods, to get such an estimate would be impossible or monitoring over long periods are required. This is especially true in semi-arid and arid areas where the rainfall usually varies significantly with time.

(c) The relatively low costs involved in the process (especially if drilling is inexpensive) also contribute to its popularity. To analyse chloride in soil water, only very basic equipment is needed, which is available in most countries.

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(d) The non requirement of estimating unknown parameters like the actual evapotranspiration and unsaturated hydraulic conductivity (which pose difficult problems).

Table 1 shows instances where estimates from unsaturated zone chloride profiling method have been verified from a different method by different researchers.

Table 1

Verification of recharge estimates by chloride profiling method with other methods by different workers

Country and Site	Rain mm/y	Epan mm/y	Soil	Vegetation	Recharge range (mm/y)	Method verified with	Source
Australia, SA	750	-	Sands over heavy clay, sandy clay, and limestone	-	50 - 70, 100, 100 - 140, 105, 120	Tritium Profiles	Allison and Hughes (1978)
Australia, SA	750	-	Sandy loam over limestone, Aeolianite, Skeletal soils	-	140-155, 195-200, 250-270	Tritium Profiles	Allison and Hughes (1978)
Australia NSW	310	2100	-	Cropping	6 - 9, 3 - 6, 4 - 32	Soil water balance	Kennet-Smith et al., (1994)
Australia NSW	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 - 260 100 - 140	Tritium Profiles	Sukhija et al., (1988)

Note :

A hyphen is shown where the relevant information is not reported.

2.0 Theory of solute (chloride) flow in the unsaturated zone

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. Considering these two processes, the solute flux (Js with units of g/m2/y) under conditions which are described later is (Bresler, 1973; Peck et al., 1981):

$$J_s = -D_h(\theta, v), \frac{\partial Cz}{\partial_z} + C_z . q_w \quad \text{.................. (1)}$$

where $D_h(\theta, v)$ is the hydrodynamic dispersion coefficient (m^2/y) which is a function of volumetric soil moisture content (θ) and average soil moisture velocity (v with units of m/y), Cz is the concentration of solute (mg/l), q_w is the volumetric soil moisture flux (i.e., the rate of recharge at a particular depth or the amount of water moving per unit area in a unit time with units of m^3/y per unit area = m/y) and z is the space co-ordinate (measured positive downwards from the soil surface in m). Rearranging equation 1, the soil moisture flux q_w is obtained by;

$$J_s = \frac{1}{Cz}\left[j_s + Dh\ (\theta\ v), \frac{\partial Cz}{\partial_z} \right] \quad \text{............ (2)}$$

The assumptions made in deriving the above equations are; (a) steady state flow, (b) one dimensional, vertical and downward flow in the unsaturated zone, (c) no flow of rainwater through preferred pathways, (d) negligible anion exclusion effects, (e) no adsorption or release of chloride ions by clay particles, organic matter or soil weathering process (f) no absorption/release of chloride ions by plants (g) no consumption or release of chloride ions by soil fauna, (h) no removal of chloride ions by soil erosion and (i) no sources of chloride from atmosphere other than rainfall.

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).

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 rainfall only [i.e., J_s= Cp.P, where P is the mean annual rainfall (m/y) and Cp is the mean annual chloride ion concentration in rainfall (mg/l)], then equation 2 becomes;

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

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.

$$P.C_p = q_w.C_z$$

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

Therefore, knowing the rainfall, concentration of chloride ions in rainfall and that of the unsaturated soil zone, it is possible to estimate recharge provided it can be shown that convection is the main mode of solute transport (or diffusion and dispersion can be ignored).

2.1 Application of environmental chloride method in the unsaturated zone in the dry zone of Sri Lanka

The chloride method was applied to 3 soil profiles each at 3 different locations in the dry zone of Sri Lanka; i.e., at Angunakolapellessa, Middeniya and Maha Illuppallama (Fig. 1).

Conventional 'Dutch' type auger (which is usually used in soil science to obtain soil samples at different depths) was not successful in auguring holes to get soil samples in the dry zone of Sri Lanka. This was because of the very hard nature of the top and sub soils encountered. Therefore, a method adapted from the method used to drill tube wells manually were used. A steel cylinder of 75 mm diameter and about 100 mm tall was sharpened (to form a 45(cutting edge) at one end and the other end was welded to a screw socket which could be fitted with 20 mm diameter galvanised iron steel rods. This 'auger' was then found to be successful in auguring the top soil until a very hard layer or the bed rock was found. The auguring action was obtained by applying weight on the auger while slowly rotating it. Since no water could be used, the process was very slow, but, under the prevailing circumstances, this was the best and most practical method available.

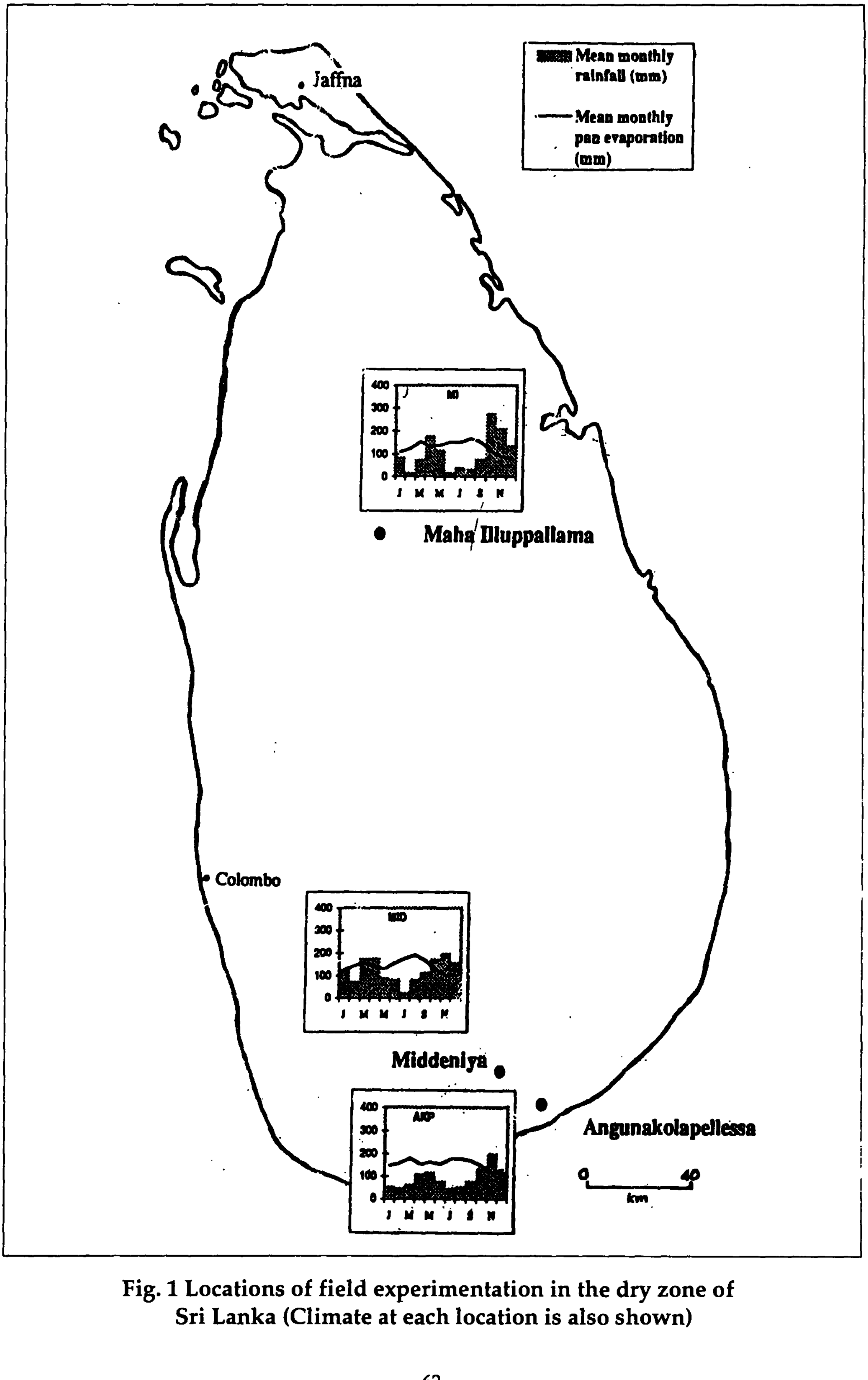

Fig. 1 Locations of field experimentation in the dry zone of Sri Lanka (Climate at each location is also shown)

Soil samples of about 100 g at every 300 mm depth (from a depth of 2 m downwards) were collected in polythene bags and sealed immediately. Special care was taken not to contaminate the soil sample by human perspiration or any other substance. Labelled sample bags were quickly removed to the soil laboratory for the determination of moisture content and chloride ion concentration in soil.

The moisture content by weight was determined by placing 50 g of soil sample in an oven maintained at a temperature of 105(C for 48 hours, drying to a constant mass (British Standards Institution, 1990a) and by knowing the wet and oven dry mass. 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 (m) 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. A Technicon Auto Analyser was used to determine the colour differences created by the release of the [Fe(SCN)]++.

Collection of rainwater to obtain the chloride ion concentration in rainfall was done on all days of measurable rain from 1 February 1995 to 27 December 1995. Details of all these experimental work and results are given in de Silva (1996).

Figs. 2 (a), (b) and (c) show the moisture content (by weight), chloride ion concentrations in soil water and the soil water flux calculated from equation 2 at different depths for the 3 profiles at the 3 locations in the dry zone of Sri Lanka.

To determine if the dispersion component of equation 2 is important, coefficients of hydrodynamic dispersion by Porter et al., (1960), given in Table 2 are used in the absence of exact information for dispersion coefficients of the soils in Sri Lanka.

The dotted line on graphs on the right hand side of Figs. 2 (a), (b) and (c) shows the estimated total soil water flux (i.e., convective flux + diffusive flux) from equation 2 and the continuous line shows the convective flux. From these graphs it is evident that diffusive flux is negligible compared to the convective flux at all depths in all profiles. Therefore, it is concluded that in the unsaturated zone of the dry zone of Sri Lanka, the movement of chloride ions in water is caused by convection and the movement of ions by diffusion and dispersion is negligible.

2.2 Estimates of recharge with the chloride method in the dry zone

Table 3 shows the calculations involved in estimating recharge with equation 4 (as dispersion and diffusion is negligible) and results of recharge estimates for all the profiles in the dry zone.

Table 2

Dispersion coefficient for chloride ions in clayey soils

Moisture content (θ, by volume)	Dispersion coefficient (m^2/yr)	Source
$\theta > 0.24$	$5.1 \times 10^{-2} (1.08\theta - 0.16)$	Porter et al., (1960)
$\theta < 0.24$	$5.1 \times 10^{-2} (2.94\theta^2 - 0.332\theta + 0.00925)$	
$\theta = 0.5$	0.031	Scanlon (1991)
$\theta = 0.1$	0.0031	
Not specified	.031	Kutilek and Nielsen, (1994)

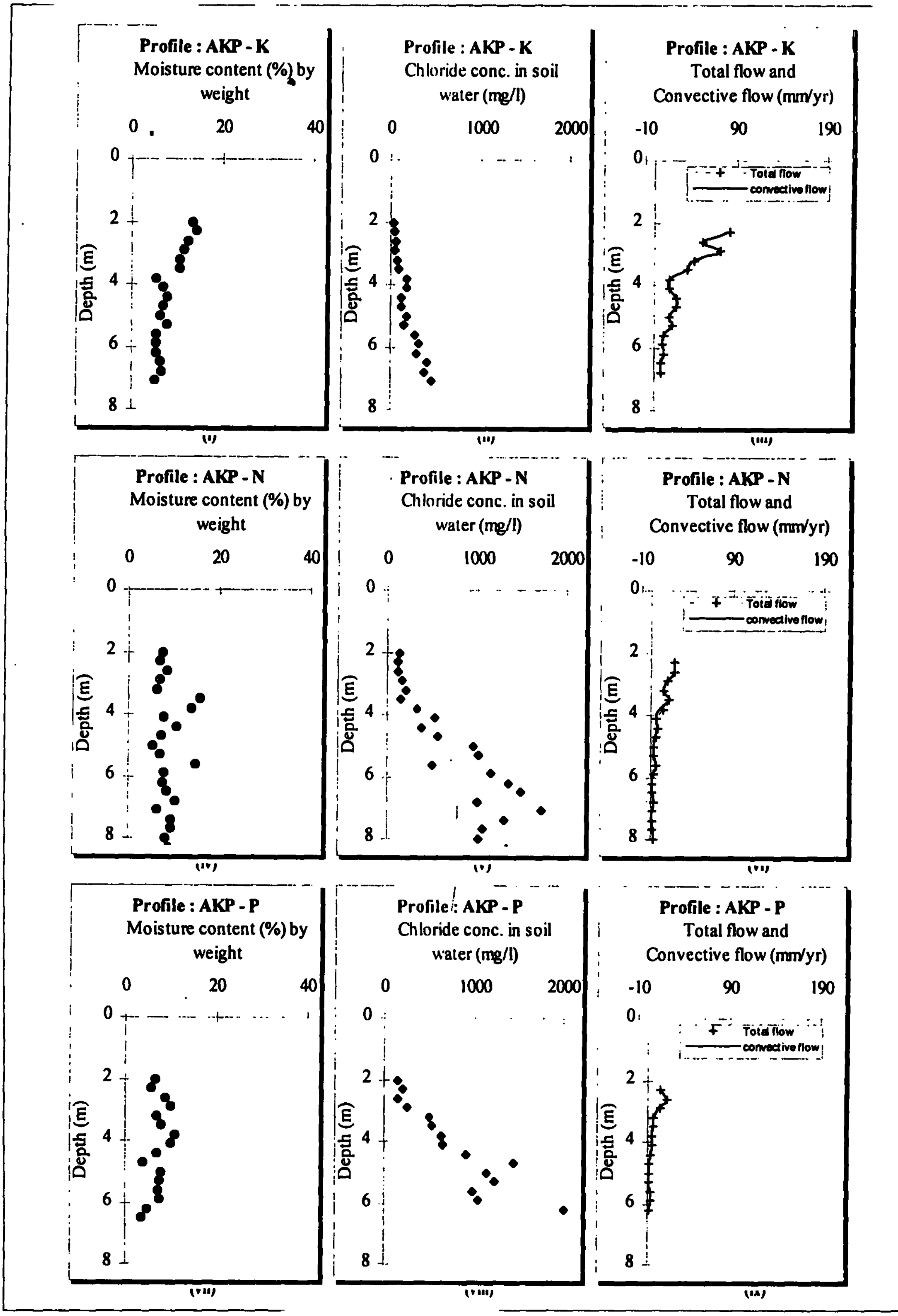

Fig. 2 (a) Moisture content, Chloride conc. and Soil water flux with depth for 3 profiles at Angunakolapellessa

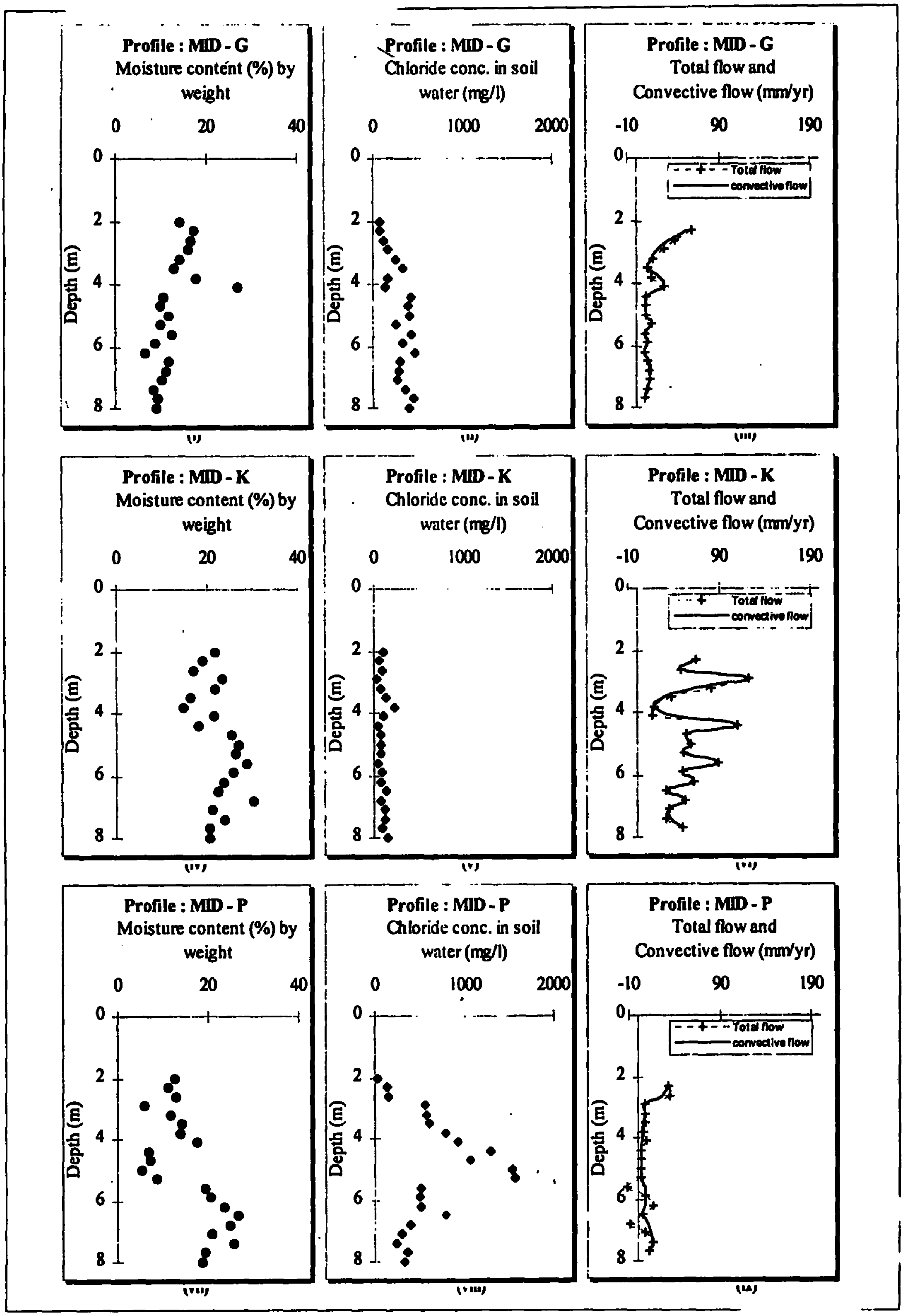

Fig. 2 (b) Moisture content, Chloride conc. and Soil water flux with depth for 3 profiles at Middeniya

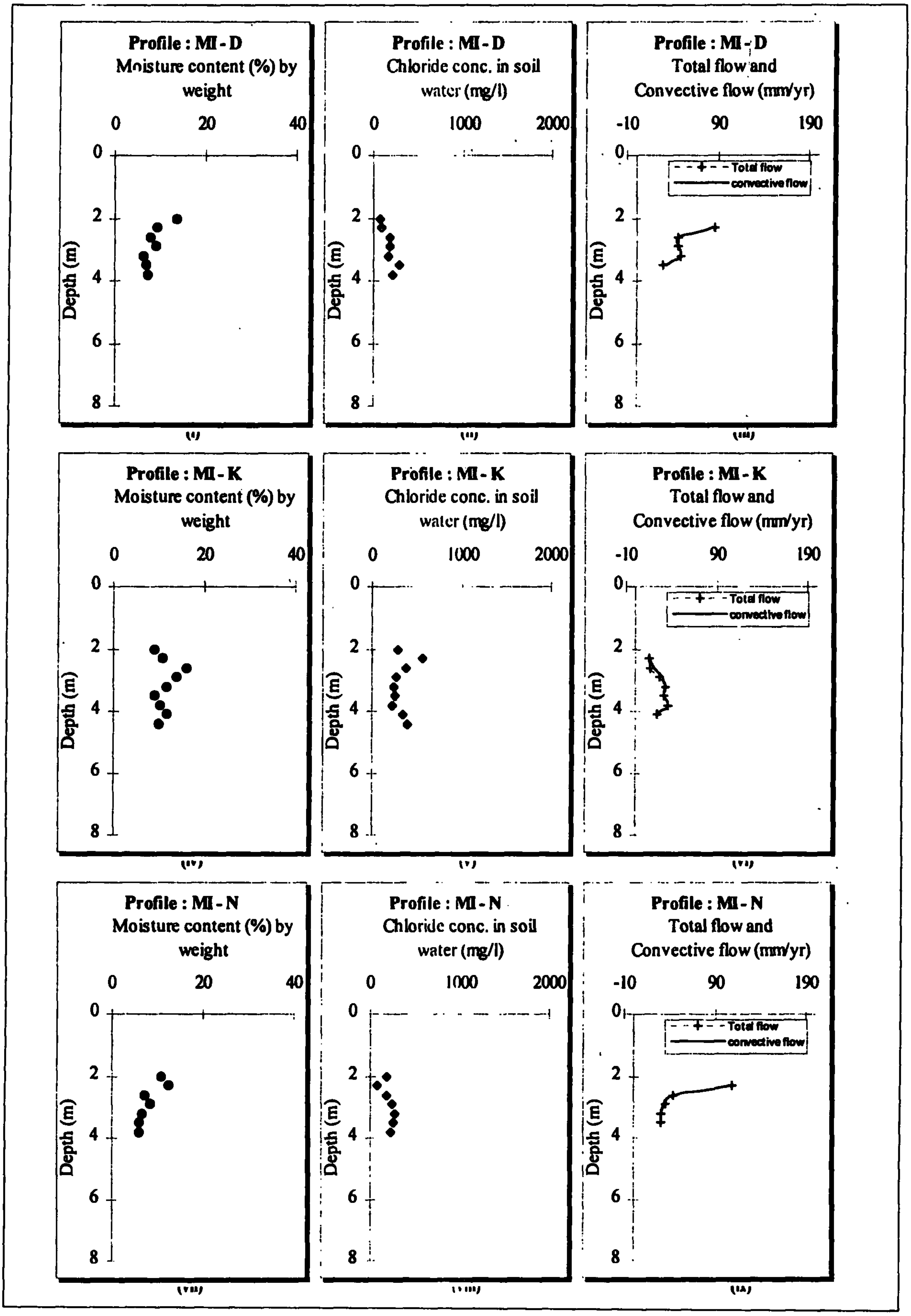

Fig. 2 (c) Moisture content, Chloride conc. and Soil water flux with depth for 3 profiles at Mahallluppallama

Average recharge estimates from the chloride method for each profile are shown in Col. 14 of Table 3. Cols. 15 and 16 show the range of recharge estimates likely if 95% confidence limits for all parameter values in equation 4 are used instead of the average values [e.g., if 95% confidence limits of chloride concentration in rain (in Cols. 9 and 10) are used instead of the average chloride concentration in rain (Col. 8)]. Col. 17 of Table 3 shows the average soil water velocity (obtained by dividing the soil water flux by the volumetric soil moisture content) of each24 profile at all the sites. Cols. 18 and 19 show the range of estimates of recharge possible by a soil water budgeting method (de Silva, 1996).

2.3 Are the recharge estimates in the dry zone from the chloride method reasonable?

Estimating recharge to the groundwater table is one of the most difficult parameters to be determined ìaccuratelyî. However, as discussed, this is one parameter which is essential in the development of the groundwater resource, which we are forced to do in the dry zone of Sri Lanka. Therefore, estimates of recharge by any method needs to be checked with all available evidence before confidence can be placed upon it.

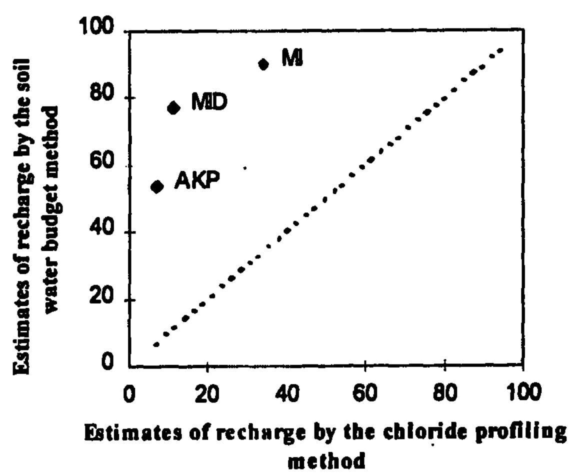

Fig. 3 Comparison of estimates of recharge by the chloride profiling method & SWB method

As seen from Fig. 3, the agreement between the two methods is poor (though it is not necessary for them to agree as the soil water budget method estimates the potential recharge and chloride method estimates are nearer the actual recharge value). There could be a number of reasons for this apparent difference in actual and potential recharge which are described and discussed below.

(a) The possibility of long term average chloride ion concentration in rain being higher than the values obtained experimentally for a period of about 8 months for the locations in the dry zone. (If the chloride concentrations in rain are higher, the recharge estimates will also be higher from equation 3). Edmunds and Gaye (1994) report of a study in Senegal where the mean chloride concentration of rain in 1990 (9.3 mg/l) was about 6 times that in 1989 (1.6 mg/l). Therefore, it is possible that the chloride method has under estimated the recharge in the dry zone due to the non availability of long term chloride data in rainfall.

(b) The possibility of having a high amount of interflow (or horizontal flow of water in the shallow layers of the soil) suggesting that estimates by both methods are correct. (It must be noted that the soil water budget estimates the potential recharge and the chloride method estimates deep percolation into the deeper unsaturated zone). Ward and Robinson (1990) cites a similar case where 80% of the infiltrating water is carried to the streams as interflow in a soil with uniform texture.

(c) Another possibility is that the actual available water capacity is higher than the values used in this study (obtained by assuming that water is absorbed by roots in the root zone only and the zero flux plane is never deeper than the root zone). Wellings and Bell (1980) have reported that the zero flux plane can be 5-6 m deep with grass (about 80 cm deep roots) in UK. It is easily shown that if the available water capacity is higher than used in the soil water budget for the present study, the resulting recharge estimates are reduced.

Reasons (a) and (b) discussed above are the likely reasons for the two methods estimating recharge differently. More research work is therefore necessary to identify the exact causes for the difference in actual and potential recharge.

It is also noted that Howard and Karundu (1992) report a recharge estimate of 30 mm/y for an area in Uganda where climate, soils and vegetation appear to

Table 3 Results of recharge estimates by chloride method and by SWB method for the 3 locations in Sri Lanka (calculations of each column are explained in Appendix)

col. (1)	col. (2)	col. (3)	col. (4)	col. (5)	col. (6)	col. (7)	col. (8)	col. (9)	col. (10)	col. (11)	col. (12)	col. (13)	col. (14)	col. (15)	col. (16)	col. (17)	col. (18)	col. (19)
Sampling point no	Sampling point name	Mean Annual Rain[1] (mm/y)	95% c.l. of rain Min (mm/y)	95% c.l. of rain Max (mm/y)	50% infil rain (mm/y)	80% infil rain (mm/y)	Avg [Cl] rain (mg/l)	95% c.l of [Cl] rain Min (mg/l)	95% c.l of [Cl rain Max (mg/l)	Avg. [Cl] soil in each profile (mg/l)	95% c.l. of [Cl] soil water Min (mg/l)	95% c.l. of [Cl] soil water Max (mg/l)	Avg. rech. from chloride method (mm/y)	Min rech. from chloride method (mm/y)	Max rech. from chloride method (mm/y)	Avg. soil water velocity (mm/y)	Minimum recharge from SWB (mm/y)	Maximum recharge from SWB (mm/y)
1	AKP-K	1091	949	1233	475	986	4.4	3.58	5.22	209	104.2	237.4	15	7	49	219	5	104
2	AKP-N	1091	949	1233	475	986	4.4	3.58	5.22	830	398.1	900.6	4	2	13	71	6	106
3	AKP-P	1091	949	1233	475	986	4.4	3.58	5.22	958	452.3	1132.4	3	2	11	61	4	100
Average for Angunakolapellessa													7	4	24		5	103
4	MID-G	1484	1291	1677	646	1342	4.5	3.7	5.3	321	237.9	349.0	14	7	30	100	6	149
5	MID-K	1484	1291	1677	646	1342	4.5	3.7	5.3	106	255.9	365.0	13	7	28	179	6	149
6	MID-P	1484	1291	1677	646	1342	4.5	3.7	5.3	692	341.8	807.7	6	3	21	49	6	149
Average for Middeniya													11	6	26		6	149
7	MI-D	1271	1106	1436	553	1149	10	7.4	12.6	187	112.6	263.4	44	16	129	446	41	158
8	MI-K	1271	1106	1436	553	1149	10	7.4	12.6	362	279.5	433.6	23	9	52	197	29	140
9	MI-N	1271	1106	1436	553	1149	10	7.4	12.6	227	141.2	317.7	36	13	102	402	29	140
Average for Maha Illuppallama													34	13	94		33	146

be similar to some of these sites in the dry zone. This result suggest that recharge estimates by the chloride method in the dry zone are reasonable.

3.0 Conclusions

This paper attempts to determine the suitability of using environmental chloride as a tracer in the unsaturated soil zone to estimate recharge. From the forgone discussion, it is possible to conclude that

(1). Using environmental chloride as a tracer method to estimate recharge appears to be a promising method of estimating recharge in the dry zone. Also considering that Sri Lanka is a small island with no place in the dry zone more than about 50 km from the sea, this technique could be used in estimating recharge successfully as the rainfall will carry easily measurable amounts of chloride ions because of the proximity to the sea.

(2). Diffusion and dispersion of chloride ions are negligible in the dry zone and the primary mode of chloride transport is by convection (mass flow). Therefore, in future use of this method, equation 4 is likely to yield reasonable estimates of recharge (though it is always better to check if diffusion and dispersion is negligibly small).

(3). There is a strong possibility of a significant difference between actual and potential recharge in the dry zone.

(4). From the chloride method, a recharge estimate close to the actual recharge is likely to be estimated if soil samples from depth can be obtained. Since auguring is not difficult in the dry zone, this method is a promising tool for estimating actual recharge which is the recharge value needed in groundwater resource development (rather than the potential recharge).

However, if the chloride profiling method is to be used effectively, records of long term chloride ion concentrations in rainfall is required. Therefore, responsible government agencies should measure and record this information at important locations especially in the dry zone. More work are also needed to ascertain if dispersion and diffusion of chloride ions are actually negligible. Further, verification of recharge estimates in the dry zone by the chloride method needs more work.

4.0 Acknowledgement

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6.0 Appendix

Details of calculations:

Consider the case of profile AKP-K (Sampling point no: 1).

Cols. 1 and 2 - Self explanatory.

Col. 3 - Average annual rainfall [e.g., 1091 mm/y for Angunakolapelessa, see de Silva (1996)].

Cols. 4 and 5 - Col 3 ± confidence interval ± experimental error

For Site Angunakolapellessa standard deviation of mean annual rainfall = 217.8 mm/yr. for n = 23. Therefore 95% con. interval (CI) is 1.96*217/(23 = 89 mm/y. This is out of a mean rainfall of 1105 mm/y. Therefore the CI is 89/1105 = 8%. This figure of ± 8% is used as 95% CI for other sites as well, as annual rainfall data for longer periods are not available. However, the error caused with this approach is thought to be small. The experimental error in measuring rainfall is about ± 5% (Gee and Hillel, 1988).

ThereforeCol. 4 and 5 = Col. 3 ± 8% ± 5%.

Cols. 6 and 7 - The range of amounts of rain infiltrating (i.e., considering the interception and runoff) at all the sites in the dry zone was obtained as between 50-80% of average annual rain in de Silva (1996).

Therefore,

Col 6 = Col 4 * 50%

Col 7 = Col 5 * 80%

Col. 8 - Average chloride conc. in rainfall at the site (obtained by averaging all the measured values).

Cols. 9 and 10 - 95% confidence limit obtained as mean ± 1.96*Stdev/(no of samples for the chloride concentration in rainfall at each site.

Col. 11 - Average chloride concentration below 2 m for the profile.

Cols. 12 and 13 - 95% Confidence limit values for the chloride concentration in soil. Obtained as before, except because of small sample sizes Student t distribution values are used to compute confidence intervals rather than values from the Normal distribution.

Col. 14 - The average recharge from the chloride method at each sampling point (by the customary way).

Col. 15 - Minimum Value of recharge estimate by Minimum value of effective rainfall, minimum value of Cl conc. in rainfall * maximum value of Cl conc. in soil from equation below (which results from equation 4).

$$\text{Recharge (min)} = \frac{\text{Rain (min). Rain Cl (min)}}{\text{SoliCi (max)}}$$

Col. 16 - As in Col. 15, but yielding the maximum value of recharge.

Col. 17 - The average soil water velocity for each profile obtained by dividing the soil water flux by the volumetric moisture content at each depth.

Cols. 18 and 19 - Minimum and maximum estimates of recharge by the soil water budget [de Silva (1996)] resulting from different model parameter combinations.