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Selection and assessment of bread wheat lines improved for dough strength and rust resistance

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ABSTRACT

The *GluDl-d* encoded subunits 5+10 are known to be associated with higher dough strength of wheat. Aim of this study was to assess selections made in Indian bread wheat background using subunits 5+10 and rust resistance as selection criteria, for quality parameters including dough rheology. From backcrossing experiments involving bread wheats, selections were obtained with subunits 5+10 and moderate rust resistance conferred by *Sr24Lr24*, in the backgrounds of cvs. Kalyansona or Sonalika. Three selections and recurrent parents Kalyansona and Sonalika were assessed for their dough characteristics using Brabender Farinograph. There was improvement in the mixing time, dough stability and mechanical tolerance index in the selections compared to the parents. In the Kalyansona derivatives three selections showed better yield potential.

Key words: *Triticum aestivum*, Glutenin, HMW subunits, dough strength, rust resistance.

INTRODUCTION

Since the first observation that the presence of subunits 5+10 correlates significantly with bread making quality as judged by SDS-sedimentation volume (SDS-SV) test (Payne *et al.* 1981), there have been many reports on intervarietal comparisons confirming association of subunits 5+10 and bread making quality (Moonen *et al.* 1982,1983; Branlard and Dardevet 1985). The intervarietal comparisons, however, have limitation due to other genetic effects. Although, use of near-isogenic lines is the most convincing way to demonstrate the effect of HMW subunits of glutenin as a primary determinant of dough strength and elasticity (Lawrence *et al.* 1988; Payne and Seeking 1996) use of backcross lines and recombinant inbred lines are also useful material to assess the effect of particular subunit in a comparable genetic background (Moonen and Zeven 1985; Payne *et al.* 1987; Odenbach and Mahgoub 1988; Carrillo *et al.* 1990). Using inbred backcross lines derived from two winter wheat crosses Odenbach and Mahgoub (1988) reported that subunits 2*, 7+9, 7+8, and 5+10 were associated with higher sedimentation values. In closely related lines, loss of subunits 5+10 resulted in poor bread making quality (Payne *et al.* 1988). Positive effect of subunits 5+10 on the SDS-SV was also observed in selections obtained in backcrossing experiments (Bhagwat and Bhatia 1993). In comparable backgrounds, these selections made only on the basis of presence of subunits 5+10, showed higher SDS-SV than those carrying subunits 2+12. Statistical analysis of data on Canadian cultivars (Ng and Bushuk 1988) indicated that selection on the basis of HMW subunits composition should be useful in breeding programme for screening genotypes for bread-making quality.

Although, selection on the basis of HMW subunits of glutenin is in practice in some countries, in the Indian subcontinent which is a major producer of wheat, it is not yet widely used. There is a need for simultaneous quality improvement along with important criteria like rust resistance. Assessment of quality at every step will ensure that the expected gain is realised. Earlier, we had tested some of the selections for quality parameters like protein content and SDS-SV (Das and Bhagwat 1997). In this paper we report results of experiments using backcross lines of Indian bread wheats, to find out whether the effect of better subunits 5+10 can be combined with rust resistance conferred by *Sr24Lr24* and the improvement due to subunits 5+10 was reflected in gluten properties and in dough properties, measured by using Brabender Farinograph.

Abbreviations: BC - backcross, B.U. - Brabender Units, E.R. - elastic recovery, HMW - high molecular weight, KS - Kalyansona, SDS-PAGE - SDS polyacrylamide gel electrophoresis, SK - Sonalika, TGW - thousand grain weight, UKS - Unnath Kalyansona , USK - Unnath Sonalika.

MATERIALS AND METHODS

Biological materials

Earlier, cv. Kalyansona (KS) with subunits 2*, 17+18, 2+12 was crossed with an early and short culm genetic stock TW-1 having subunits 1, 17+18, 5+10. In a backcrossing programme using KS as recurrent parent and subunits 5+10 as selection criterion, selections were obtained (Bhagwat and Bhatia 1993). One selection true breeding for subunits 5+10 derived after two backcrosses and subsequent selfing was crossed with Unnath Kalyansona (UKS) which was the donor of rust resistance gene *Sr24Lr24* (Kochumadhavan *et al.* 1988). The other cross was between cv. Sonalika (SK) and the genetic stock TW-1. From the F_2 population of this cross, plants were crossed with Unnath Sonalika (USK) which was the donor for rust resistance gene *Sr24Lr24*. The backcross F_2 was grown in field and at one month stage the seedlings were injected with stem rust spore suspension. Sori developed initially on newly emerging leaves. After about ten days rust development on leaves was adequate to compare the reaction. Plants showing smaller round and discrete sori between ten to fifteen days after injection were identified as moderately resistant. Susceptible plants and KS showed larger and longer sori which later fused to form a mat on the leaf surface. Individual plant harvests from resistant plants were analysed on SDS-PAGE to observe the presence or absence of subunits 5+10. Plants with subunits 5+10 were carried forward. The subsequent generations were grown as plant to row progeny. Ten plants from each row were injected with stem rust to identify the rows which were true breeding for resistance. Seedlings in F_4 generation were tested under laboratory conditions for their rust reaction. Individual plant harvests from these rows were analysed on SDS-PAGE to select those true breeding for subunits 5+10. Among F_4 plant harvests, those with poor grain weight per plant were rejected. In the later generations the rows were bulk harvested. The UKS and USK carrying *Sr24Lr24* from *Agropyron elongatum* were obtained after five to seven backcrosses followed by three selfings (Menon and Tomar 2001). As UKS and USK are near-isogenic with KS and SK respectively, the selections used in these experiments may be treated as eqivalent of BC_3 and BC_1 selections respectively. In the F_7 generation, selections were grown as three metre rows, and in two subsequent years (1997-98, 1998-99) the selections were grown in a station trial format. There were 5.0m x 1.84m plots of individual entries in randomised block design with three replications. The spacing between rows was 23cm. Seed rate was 100 kg ha^{-1}. Nitrogen was applied at the rate of 120 kg ha^{-1}. All experiments were conducted at the Trombay Field Research Station of Bhabha Atomic Research Centre, Mumbai. Only one generation per year was raised. The average grain yield (g/m^2) was calculated on the basis of three metre line sowing in one year and station trials for two years. The seeds used for the following studies were from station trial experiments done in 1997-98.

Chemical analysis

Grain protein: Determinations of grain protein were made on wholemeal using micro-Kjeldahl procedure using Lab Con Co_2 or KjelPlus apparatus (Pelican Industries Ltd).

SDS-SV: Wholemeal obtained from Udy cyclone mill was used. One gram method described by Dick and Quick (1983) was used.

Gluten extraction and E.R. ratio: One gram wholemeal was mixed with 0.6 ml distilled water for five minutes using a glass rod. Five samples were processed sequentially. The dough balls were washed under a gentle flow of tap water for five minutes to obtain water washed gluten. The gluten ball was pressed between two glass plates under constant weight (4.6 kg) and ten seconds later radii in four places were recorded. The weight was removed and gluten was allowed to contract for about 30 sec. Radii in four places of the contracted gluten were recorded. The ratio of the average expanded radius to average contracted radius gave the Elastic Recovery ratio. Higher ratio indicated higher elasticity. Dry gluten weight was obtained by drying gluten to constant weight at 80°C.

SDS-PAGE: SDS-PAGE was done as described in Bhagwat and Bhatia (1993). Five grain bulks from each replication of the station trial of 1997-98 were used as a sample to check purity and the HMW subunit pattern. Five grain bulks were also used in the previous as well as later year for electrophoresis. The gel measured 17.7 cm x 13.8 cm x 0.7 mm. The running gel contained 0.13% bisacrylamide and 10% acrylamide; the stacking gel contained 0.04% bisacrylamide and 3% acrylamide.

Farinograph studies: For rheological properties, two selections in KS background with best grain yield were used. Selection in SK background although not high yielding was included for comparison. The entries for rheological study were limited by the requirement of large quantity of seed material. The bulked seeds from station trial experiment conducted in 1997-98 were milled and sieved to obtain 60 mesh flour. Brabender Farinograph with 300g mixing bowl was used to determine water absorption capacity (%). Mixing time (min.), dough stability (min.) and mechanical tolerance index (B.U.) were determined by adding, at a stretch, the amount of water required to obtain optimum (500 Brabender Units) dough consistency. Each sample was analysed in duplicate.

Field observations

Natural leaf rust was observed in some years, usually after flowering. Observations on leaf rust susceptibility (in the recurrent parents) or moderate resistance conferred by *Lr24* were made in years when leaf rust appeared.

RESULTS

Rust reaction

The selections showed true breeding behaviour for moderate stem rust resistance when tested by artificial inoculation in each generation. Plants showing smaller round and discrete sori (Fig-1 A) between ten to fifteen days after injection were identified as moderately resistant. Susceptible plants and KS showed larger and longer sori (Fig-ID) which later fused to form a mat on the leaf surface. Seedlings in the F_4 generation, tested under laboratory conditions also showed differences in the resistant (Fig.-IB) and susceptible (Fig.-IE) reactions, and true breeding plants could be confirmed. Figures 1C and IF show the enhanced images of resistant and susceptible reactions respectively. Leaf rust resistance was also observed when there was natural leaf rust incidence.

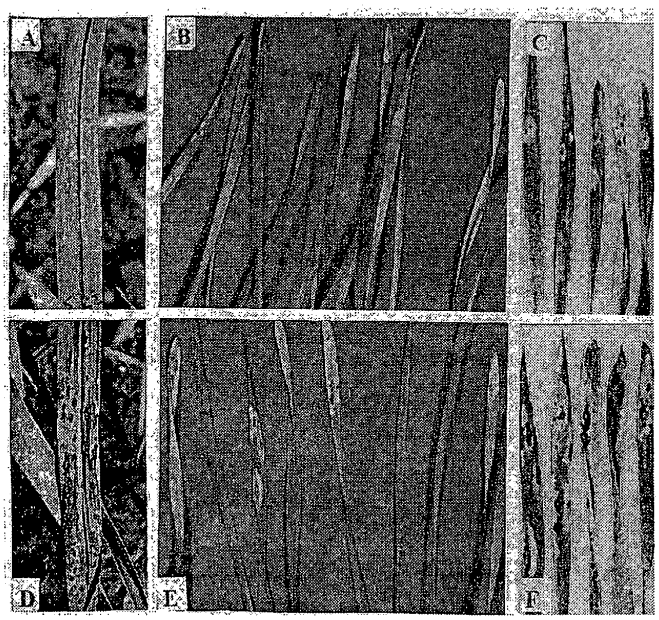

Fig. 1.The rust reaction of moderately resistant selection in Kalyansona background (A) and susceptible Kalyansona (D) in field conditions and progeny of moderately resistant (B) and susceptible (E) plants from segregating population in Sonalika background in laboratory screening. (C) and (F) show enhanced images of moderately resistant and susceptible reaction respectively.

Chemical and dough properties

SDS-PAGE: The selections showed true breeding patterns for subunits 5+10 (Fig.-2A and 2B).

Grain protein: Grain protein ranged from 12.84 in KS control to 15% in two of the selections (Table-1). Four of the six selections were significantly higher than KS. In the second set, SK control was lower than USK and the selection with subunits 5+10. The differences in protein content were found to be variable between years perhaps because they

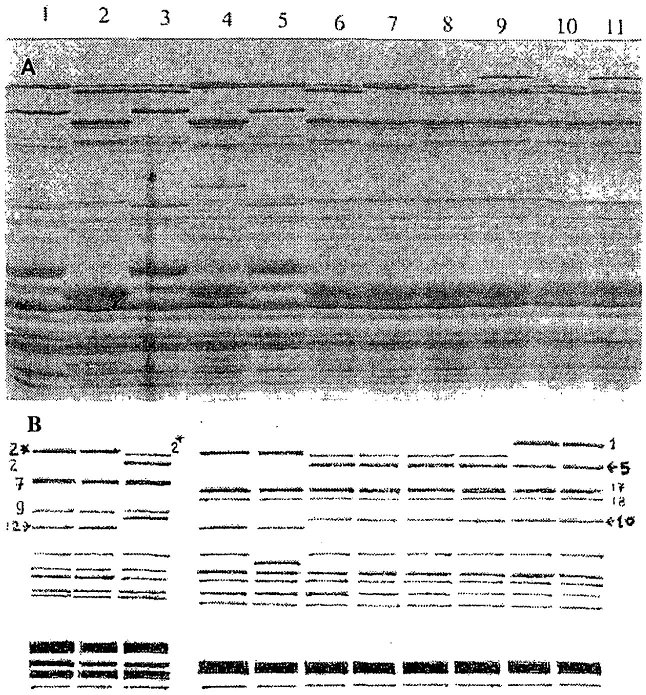

Fig.2 A. Electrophoregram of recurrent parents Kalyansona and Sonalika and their selection with subunits 5+10 resolved on SDS-PAGE. From left to right: SK, 13-7-10, 14-12-16, UKS, USK, 13-27-30, KS, 15-23-24, 13-19-22, 13-11-14, 15-3.

B.Electrophoregram of the recurrent parents Kalyansona, Sonalika and selection with subunits 5+10. From left to right :Sonalika, Unnath Sonalika, Sonalika derivative with subunits 5+10, Kalyansona, Unnath Kalyansona, derivatives of Kalyansona with subunits 2*,17+18,5+10, and 1, 17+18, 5+10. (Line diagram of fig 2A with lanes rearranged).

Table 1.Rust reaction and some quality related characteristics of parents and selections.

Parent/ Selection	HMW subunits	Rust reaction	Grain protein, %	SDS-SV mm	Dry gluten, %	E.R. ratio
KS	2 + 12	S	12.84	78.8	13.43	1.6675
UKS	2 + 12	MR	13.10	75.0	13.87	1.5886
13-7-10	5 + 10	MR	13.06	80.3	14.18	1.7687
13-27-30	5 + 10	MR	14.20	78.2	14.13	1.7356
15-23-24	5 + 10	MR	13.48	77.5	13.88	1.8633
13-11-14	5 + 10	MR	14.95	78.0	13.95	1.7428
13-19-22	5 + 10	MR	15.00	78.5	13.86	1.7837
15-3	5 + 10	MR	15.00	82.0	14.90	1.8594
SK	2 + 12	S	12.32	56.8	14.76	1.4588
UKS	2 + 12	MR	13.81	62.0	14.98	1.5157
14-12-16	5 + 10	MR	14.05	80.0	15.68	1.6013
LSD (5%)			1.17	3.7	1.05	0.184

were due to developmental and environmental factors rather than due to genetic factors.

SDS-SV: The selections 13-7-10 and 15-3 showed significantly higher SDS-SV than UKS and numerically higher than KS control in this experiment. The KS control was higher than expected. Other selections were numerically higher than UKS but not higher than KS control. In the other set, selection 14-12-16 with subunits 5+10 was significantly higher than both SK and USK.

Gluten and E.R. ratios: The association between dry gluten % and protein % was positive but not significant in case of KS and its derivatives. For SK and its derivatives, grain protein % and dry gluten % were in agreement. KS and UKS did not differ significantly in the E.R. ratios. All selections were numerically higher and selections 15-3 and 15-23-24 were significantly higher than KS or UKS. The selection in Sonalika background with subunits 5+10 was numerically higher than SK and USK (Table-1). The selections showed influence of recurrent parent background.

Dough properties: Based on the SDS-SV data and HMW subunit composition and yield data, two selections in KS background and one in SK background were included in the study of dough properties using Farinograph (Table-2). Water absorption of KS (82.2%) was higher than SK (77.5%). Selection 15-23-24 (80.5%) was lower than KS control and the other selection 13-7-10 (82.2%). Selection 14-12-16 in SK background was higher than SK control.

Table 2. HMW subunits composition, water absorption capacity and dough characteristics of parents and selections

Sample	HMW Subunits	Water absorptions, %	Mixing time min♦	Dough stability min♦	Mechenical tolerance index B.U.♦
KS	2*,17+18,2+12	82.2	7.0	4.0	70
13-7-10	2*,17+18,5+10	82.2	10.75	10.25	40
15-23-24	2*,17+18,5+10	80.5	10.5	5.0	55
SK	2*,7+9,2+12	77.5	4.75	0.5	120
14-12-16	2*,7+9,5+10	79.0	8.25	2.5	55

◊ values are means of two determinations on 1997-98 harvest.

Selections in KS background had (1) higher mixing time than KS (Fig.-3 A, B, C), (2) higher dough stability and (3) lesser deterioration after 12 minutes of mechanical abuse. The two selections in KS background themselves showed some difference for dough stability and mechanical tolerance index.

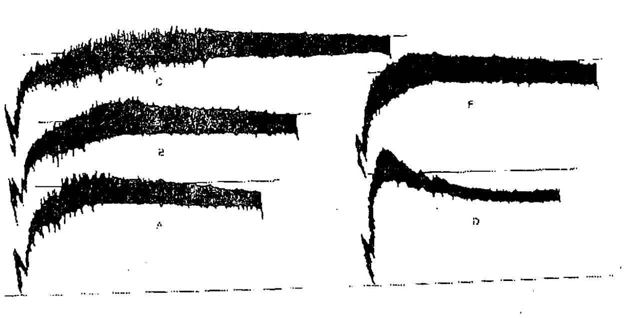

Fig.3.Farinograph tracings of the parents A)Kalyansona, its derivatives B) 15-23-24, C) 13-7-10 and D) Sonalika and its derivatives E) 14-12-16 with subunits 5+10.

The selection in SK background (Fig.-3E) was superior than SK control (Fig.-3D) for all the above mentioned three criteria. The selection in SK background was lower for the three criteria than the selections in the KS background.

Grain yield

The grain weight and grain yield of parents and selections are shown in Table-3. Although the selections were result of backcrossing experiments, differences existed due to less number of backcrosses (equivalent of three and one). The mean thousand grain weights (TGW) for three years given in Table-3 shows that three out of six selections were higher than KS control for TGW. Selection 13-7-10 was significantly higher than KS for grain yield in both years station trials (1997-98 and 1998-99). Selection 15-23-24 and 13-11-14 were significantly higher for grain yield than KS in one year (1997-98). The selection 14-12-16 in the background of SK was lower than SK in all the years. The selections resembled their respective recurrent parents in appearance, flowering and maturity time (data not given).

Table 3. Grain yield and thousand grain weight (TGW) of parents and selections.

Parent/Selection	Grain yield*, g m^{-2}	TGW*, g
KS	235.26	31.31
UKS	220.13	32.49
13-7-10	295.53♦	33.11
13-27-30	273.26	29.23
15-23-24	315.15•∇	33.67
13-11-14	270.36∇	34.77
13-19-22	211.73	26.99
15-3	187.73	29.91
SK	223.7	42.25
USK	210.33	42.22
14-12-16	168.33	34.25

* mean of three years, • mean of two years, ∇ significantly higher than KS in the year 1997-98, ♦ significantly higher than KS in 1997-98 & 98-99.

DISCUSSION

The subunits 5+10 are common in the hexaploid wheats available in India. Among cultivars and experimental stocks, 66% had these subunits (Bhagwat and Bhatia 1988). Analysis of thirty and fifty bread wheat cultivars showed that high Glu-1 scores were frequent and 19 and 12% respectively had subunits 5+10 (Harinder and Payne 1995, Das and Bhagwat 1999). In the entries being tested in the All India Coordinated trial, 41% in the irrigated timely sown category and 37% in the rainfed or late sown category showed the presence of subunits 5+10 (DWR Progress report, 1997-98). The association between subunits 5+10 and better dough strength is well documented. There is, however, need for work on the feasibility and effectiveness of subunits 5+10 as a selection criterion to improve quality in the Indian context. Conscientious selection for factors contributing to dough strength is needed in the programmes rather than their inclusion by chance. Previously, subunits 5+10 from two sources were transferred in a common background using KS as a recurrent parent and improvement associated with subunits 5+10 was observed in terms of better SDS-SV (Bhagwat and Bhatia 1993). Our previous and current results are in agreement with a large number of previous reports that the subunits 5+10 are associated with higher dough strength.

In these experiments, subunits 5+10 derived from one source (TW-1) were transferred into two different backgrounds KS and SK and a numerical or significant increase in SDS-SV was observed. The enhanced dough strength was also reflected in improvement of mixing time, dough stability and mechanical tolerance index. The presence or absence of subunits 5+10 and some variation in the grain protein % would largely explain the variation in the flour and dough properties. The marked difference in SK and its derivative with subunits 5+10 can also be explained on the basis of presence of subunits 5+10 and higher protein %. Some differences, particularly among the selections can be attributed to differences in the genetic background. Rheological properties are also known to improve with protein content (MacRitchie 1988). The improvement in dough properties was observed in the presence of moderate rust resistance conferred by *Sr24Lr24* indicating that the advantages of these characters could be combined effectively. The segment from *Agropyron elongatum* apart from *Sr24Lr24,* also carries genetic material influencing other traits, such as improvement of resistance to Barley Yellow Dwarf Virus and terminal clubbiness of spikes (Menon and Tomar 2001). Quality can be affected by the genetic manipulation, an extreme example of this is the stickey dough problem associated with the 1B/1R translocation (Dhaliwal *et al.* 1987, Bullrich *et al.* 1998), which also confers disease resistance. The quality traits in presence of subunits 5+10 in this study were unaffected by the incorporation of the segment carrying *Sr24Lr24.* Although, the grain yield and grain weight were not the primary criteria, selections with higher grain yield potential than KS could be observed, which is in contrast to studies by Carillo *et al.* (1990), who reported that in a particular cross high yield potential was strongly associated with the HMW glutenin alleles that are attributed to low bread making quality. Combining grain yield in the selection procedure may result in selection with better yield, better dough strength and rust resistance at least in certain crosses.

SDS-SV was determined using Dick and Quick (1983) method originally recommended for durum wheats. Although less sensitive, it has an advantage of using 1g sample. It may be used in *T. aestivum* samples where large differences are likely to exist and other confirmatory tests are also being used. SDS-SV of KS control was higher than expected in the year 1997-98. The only difference in KS control and other entries in the year 1997-98 was that KS control was most susceptible to leaf rust which occurred naturally in that year. SK control, which is also susceptible to leaf rust, showed lesser development of leaf rust perhaps due to its different genetic background and earlier maturity. The heavy rust infection may have affected grain properties of KS control. Higher dough mixing strength for leaf rust infected lines compared to rust resistant lines has been reported previously (Dyck and Lukow 1988).

Higher dough mixing time and dough stability in the selections used in this study showed that subunits 5+10 could be used as a selection criterion. However the differences among the selections showed that the extent of improvement will depend upon genetic background. Similar results are reported by Hussain *et al.* (1998) using isolated gluten. The mixing time of subunit combinations 2*, 17+18, 5+10 was longer than that of 2* 7+9, 5+10. This is similar to the result of Lindahl *et al.* (1996) where longest mixing time is reported to be associated with strongest HMW subunit combination. Similar trend is also seen in the case of E.R. ratio values.

In conclusion, the results in this study showed that subunits 5+10 can be effectively combined with moderate rust resistance conferred by *Sr24Lr24* and simultaneous improvement in rust resistance and dough strength as measured by Brabender Farinograph can be obtained. This improvement can also be combined with better yield potential. This approach of purposefully selecting specific subunits and appropriate resistance genes may be helpful in developing selections with higher dough strength specially suitable for specific end use such as bread making.

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A comparison of actual and potential recharge of water table in the dry zone of Sri Lanka

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ABSTRACT

The actual rate of replenishment of water table (actual recharge) was compared with the rate of deep percolation leaving the root zone (potential recharge) in six study locations in the dry zone of Sri Lanka. There was a significant difference between the two rates suggesting significant amounts of interflow in the upper soil layers as the most likely reason for this difference. This finding is in agreement with the available evidence.

Key words: Actual recharge, Potential recharge, Estimating recharge, Dry zone of Sri Lanka

INTRODUCTION

As the population increases, the demand for water increases and there is a felt need to develop the groundwater resource, especially in the dry zone of Sri Lanka. In developing this groundwater resource, the most important, yet the most difficult parameter to estimate is the rate of recharge or the rate at which the water table in the aquifers is replenished.

There are a number of methods of estimating recharge (Lerner *et al.* 1990; de Silva, 1996). Details of these methods have been described by Lerner *et al.* (1990). Of these, the soil water budget method and tracer techniques have been used widely in different parts of the world.

More often than not, the rate of water reaching the water table (actual recharge) is less than the rate at which water leaving the root zone (potential recharge). The main reasons for this difference are significant amounts of horizontal interflow (i.e., horizontal flow through the upper layers of the soil profile), upward movement of water during severe dry weather periods and in some cases the extraction of moisture by the deep penetrating roots of some species of trees.

The objective of this study is to determine whether actual recharge is significantly different to potential recharge in the dry zone of Sri Lanka.

MATERIALS AND METHODS

Suitable locations were chosen, depending on the availability of facilities to conduct the study, ease of accessibility and most of all the suitability of using the recharge estimation methods to be adopted. The methods of estimation of actual recharge and potential recharge were chosen. Climatic, soil and vegetation data required to estimate recharge with the chosen methods were either collected or experimentally determined (de Silva, 1996). Then estimates of actual and potential recharge were obtained for each study location. These actual and potential recharge estimates were then compared and finally the reasons for the difference in two types of estimates at each location were identified.

Study locations

Study locations are shown in Fig. 1 and Fig. 2 shows the mean monthly rainfall and mean monthly evapotranspiration for study locations. The locations were selected by considering the availability of data and availability of facilities to experimentally obtain soil and vegetation parameters. Table 1 and Table 2 summarise the climatic, vegetation and soil data for each study location [details of experimental determination of soil parameters are given in de Silva (1996)].

Estimating Recharge to the Dry Zone Aquifers in Sri Lanka

De Silva (1998a) compared the most commonly used methods of estimating recharge for the conditions in the dry zone of Sri Lanka.(Table 3). From Table 3 it is evident that for dry zone conditions (including the special equipment requirement, data requirement, time required and cost), the soil water budgeting method was the most appropriate method of estimating the potential recharge and the chloride profiling method was the most appropriate method for estimating the actual recharge.

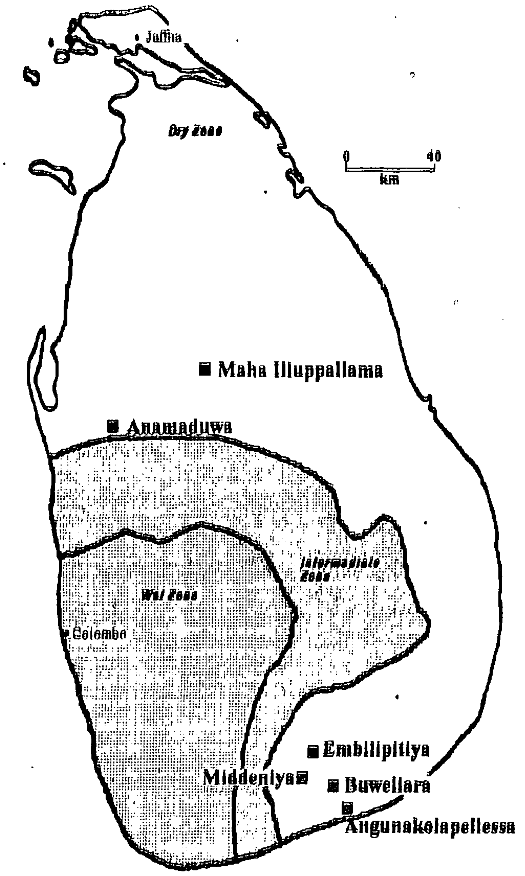

Fig. 1. Study locations in the dry zone of Sri Lanka (Study locations are shown as dark squares)

INTRODUCTION

As the population increases, the demand for water increases and there is a felt need to develop the groundwater resource, especially in the dry zone of Sri Lanka. In developing this groundwater resource, the most important, yet the most difficult parameter to estimate is the rate of recharge or the rate at which the water table in the aquifers is replenished.

There are a number of methods of estimating recharge (Lerner *et al.* 1990; de Silva, 1996). Details of these methods have been described by Lerner *et al.* (1990). Of these, the soil water budget method and tracer techniques have been used widely in different parts of the world.

More often than not, the rate of water reaching the water table (actual recharge) is less than the rate at which water leaving the root zone (potential recharge). The main reasons for this difference are

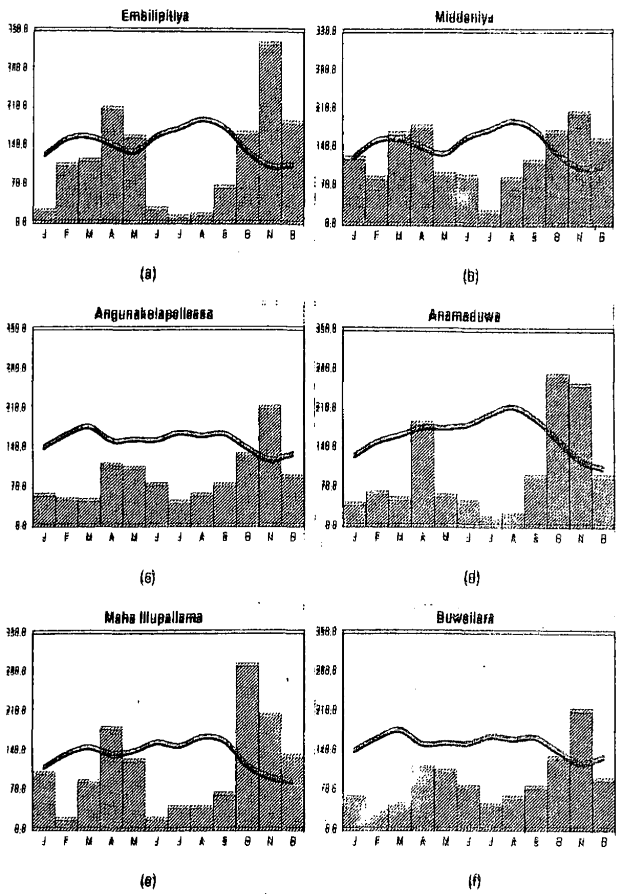

Fig. 2. Mean monthly rainfall (shown as hatched bars) and mean monthly pan evaporation (shown as the dark continuous line) for all study locations (the number on the Y axis are in mm)

Table 2. Soil properties, root zone depth and depth to water table at each study location

Study location	Field Capacity (%)	Permanent Wilting Point (%)	Depth to water table (m)	Root zone depth (m)
Embilipitiya	21.4	15.7	≥2.9	0.69
Middeniya	21.48	13.27	≥18	1.09
Buwellara	26.00	15.56	≥4.0	0.84
Angunakolapellessa	20.2	12.0	≥4.1	0.95
Maha Illuppallama	20.9	11.0	≥3.2	1.17
Anamaduwa	18.12	9.66	≥3.8	1.52

Table 1. Soil, climatic and vegetation details of study locations in Sri Lanka

Study Location	Mean Annual Rain[1] (mm/y)	Mean Annual pan Evaporation[1] (mm/y)	Vegetation	Major Plant Type	Top Soil
Embilipitiya	1397	1729[2]	Shrub jungle	*Maana* (Grass about 30 cm tall)	Loamy Sand
Middeniya	1484	1729[2]	Mango and Teak Plantation	*Eluk* (Grass about 30 cm tall)	Sandy loam
Buwellara[3]	1041	1868	Shrub jungle	-	Sandy Clay Loam
Angunakolapellessa	1041	1868	Shrub jungle	*Eraminiya* (Bush about 1.5m tall)	Sandy Clay Loam
Maha Illuppallama	1305	1579	Jungle	-	Loamy Sand
Anamaduwa	1117	1958[4]	Jungle	-	Sandy Loam

[1] 6 year mean value except for Angunakolapellessa and Buwellara where the mean value are 17 year ones.
[2] Pan evaporation values are from the climate station at Sevenagala (i.e., the nearest agro-climatic station).
[3] Since no rainfall or pan evaporation data are available for Buwellara, data from the nearest climatic station (Angunakolapellessa is used for Buwellara)

Table 3.Comparison of recharge estimation methods in relation to the dry zone conditions of Sri Lanka (Source: De Silva, 1998a)

Recharge Estimation Method	Data required	Special equipment required	Approximate time required to estimate annual recharges	Suitability of dry zone climate of Sri Lanka	Approximate cost for 20 point estimates(SL Rs.)	Type of estimate of recharge	Remarks
Lysimeters	None as direct measurement	None	High (>2 years) as time required for naturalization	More suitable for wet zone as root depths will be shallow and more likely to have measurable drainage	High (100,000 - 500,000)	Actual/ potential	
Soil water budget	Rain, ETp, Runoff, interception, and soil data and calibration data	Low (pressure plate to determine water holding capacity)	Low (about 4 weeks) as recharge is determined from available climatic data	More suitable for wet zone as ETa = ETp most of the time	Low (2,000 - 6,000)	Potential	
Water table fluctuation method	Water table data, specific yield, abstractions from aquifer, area of aquifer	None	1 year (if water table data is not available which is likely to be the case)	Suitable	Low (5,000- 10,000)	Actual	
Catchment water balance method	Rain, Et and stream flow data	None	Low (4 weeks) if data available, 1 yr otherwise	More suitable in wet zone as some data likely to be available	No point est Low cost if data available	Actual	
Numerical modelling of unsat zone flow equation	K(ϕ)-ϕ-θ relationship, Rainfall, ETp, boundary condition, calibration data	High (Neutron probe, Tensiometers, Gypsum blocks, Flow cells)	Moderate (6 months). However, low if data available, but the type of data required is likely to be not available	Suitable	High(>80,000)	Actual/ potential	Availability of resources limited
Zero Flux Plane (ZFP) method	Moisture content and soil water potential data at frequent intervals	High (Neutron probe, Tensiometers, Gypsum blocks)	High (1 year) as data unlikely to be available	Not suitable as periods of no ZFP likely	High(>80,000)	Potential	Availability of resources limited
Darcian flux [K(ϕ)-ϕ] method	K(ϕ)-ϕ-θ relationship, soil water potential data	High (Neutron probe, Tensiometers, Gypsum blocks, Flow cells)	High (1 year) as data unlikely to be available	Suitable	High(>80,000)	Actual/ potential	Availability of resources limited
Tritium profiling	Tritium input, diffusion coefficients	High (Liquid scintillation, coincidence counting machine)	High (1 year)	More suitable in wet zone as less evaporation	moderate (>50,000)	Actual	Availability of resources limited to analyze for Tritium
Chloride profiling	Chloride input, diffusion coefficient, rain, soil chloride data	Low (spectrophotometer)	High (1 year) but 3 months if work is done between Oct-Jan (rainy period). However, if annual variability of chloride level in rainfall are high, a number of years of chloride data in rain are required	Suitable	Low (10,000- 30,000)	Actual	

Note: Costs involved in each method are very approximate and are based on the information from various sources and also from the experience gained during field work in Sri Lanka.

storage. If the balance is carried out annually (especially from the end of rainy season to the same time the following year), the change in soil moisture storage is negligible.

Therefore equation 1 reduces to;

$$Re = P - I - RO - ETa \quad \text{..................(2)}$$

In equation 2, the importance of preferential flow is not immediately clear as there is no such term in it. However, the same equation can be written as in equation 3, where the first term within brackets is the matrix flow (MF) and the second term within brackets is the preferential flow (PF).

$$Re = (P - I - RO - PF - ETa) + (PF) \quad \text{...(3)}$$

Now, the estimation of actual evapotranspiration is affected by matrix flow, which in turn is affected by the amount of preferential flow. Therefore, estimates of recharge (which are affected by estimates of actual evapotranspiration), are affected as a result of preferential flow (i.e., for estimates of recharge to be affected by preferential flow, it is not necessary for preferential flow paths to be effective for deeper depths, but depths just around root zone are sufficient).

The basis for most soil water budgeting models is shown in equation 3. The differences in these models result from the way other variables (I, RO, PF and ETa) are estimated. Therefore, to obtain an estimate for recharge with this method, the parameters required are P, I, Ro, PF and ETa. P (rainfall) measured daily by the Department of Meteorology is available for many locations. Simple, yet sufficiently accurate methods were used to estimate I, RO, PF and ETa. Details of these methods are found in de Silva (1996). The simple soil water budget thus formed is shown in Fig. 3 below.

Since the averaging effect of rainfall & actual evapotranspiration over long time intervals tends to underestimate recharge, the time step used in soil water budget calculations must be one day (certainly less than 10 days) in humid areas (Howard and Lloyd, 1979) while in arid and semiarid areas this should be even lower if this method can be applied at all (Lerner *et al.* 1990).

The soil moisture budgeting models usually

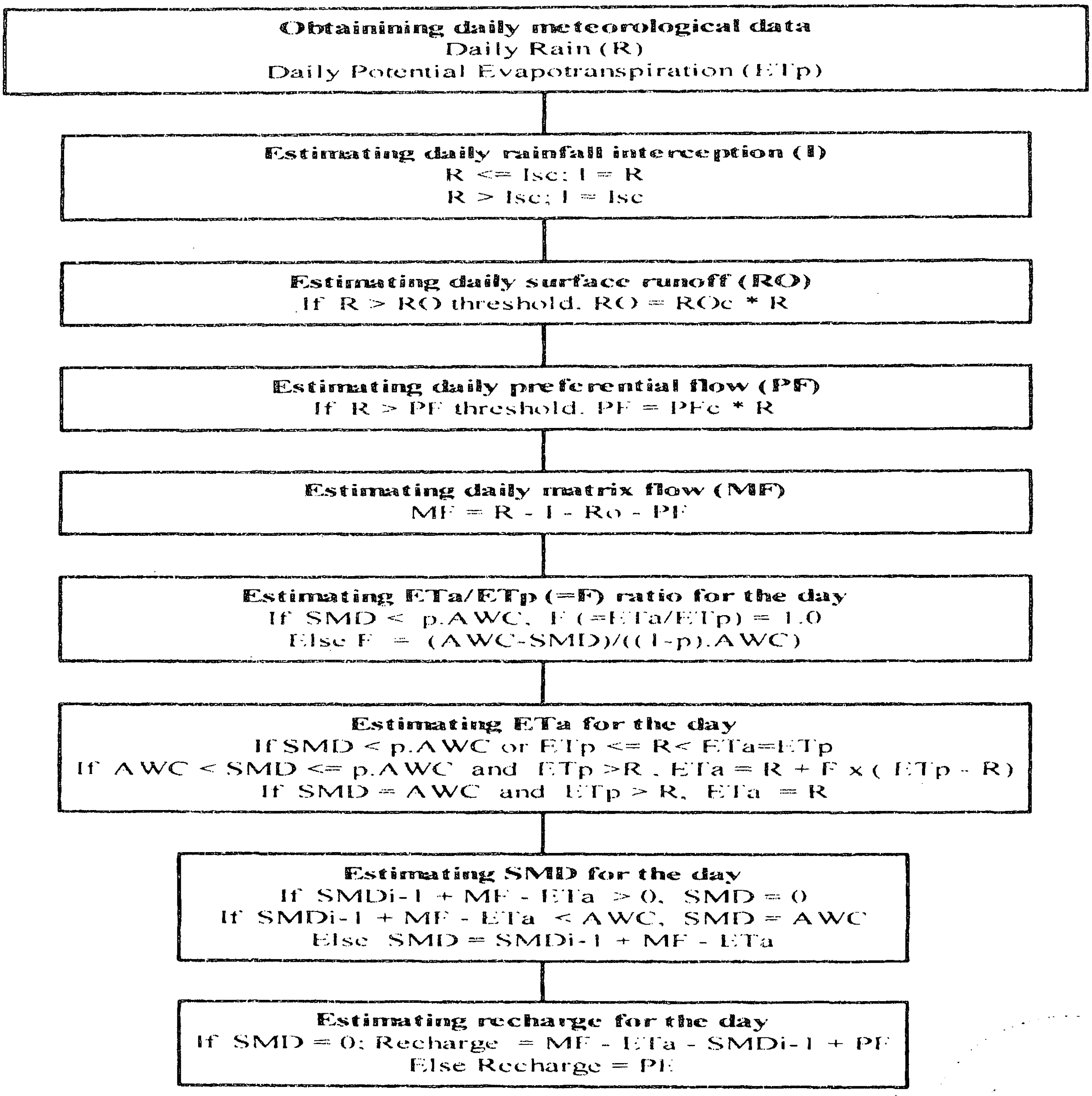

Fig. 3. Flow chart of the soil water budget model suitable for the dry zone

need to be calibrated with results from a lysimeter, from soils moisture measurements or any other estimate of recharge. Rushton and Ward (1979) and Senerath (1990) reported instances of using soil water budgeting methods. The advantages of these methods are that they use readily available data, rapid to apply and account for all water entering the system.

Major disadvantages of a soil water budget include the fact that recharge is estimated as the residual of large numbers of parameters which could produce large errors if actual evapotranspiration is numerically close to rainfall. With errors in other fluxes accumulating the error in the residual can be high. Also the difficulties of measuring the other fluxes especially where the number of fluxes is high (as in tropical countries) is a limitation (Lerner *et al.* 1990).

Estimating actual recharge with the chloride profiling method

Environmental chloride is deposited on land by atmospheric deposition processes (rainfall + dry fallout). If the chloride present in the unsaturated zone has atmospheric deposition as its source and there exists no other source or sink in the unsaturated zone for the chloride ions, then under steady state conditions assuming piston flow, it is possible to obtain a chloride mass balance for the chloride flux entering and leaving the root zone as given below (de Silva, 1998b).

$$R_e = \frac{C_p}{C_z} . P \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where Re = recharge rate leaving the root zone (mm/yr)

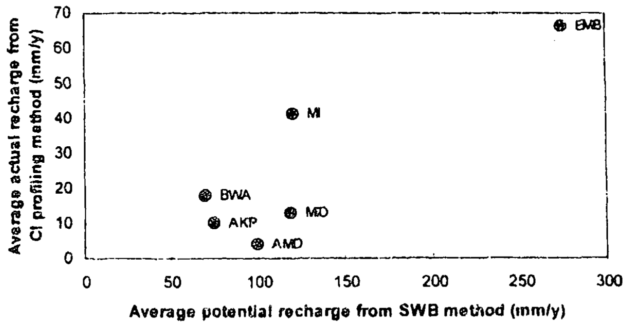

Fig. 4. Comparison of recharge estimates by SWB method and chloride method at the 6 locations in the dry zone.

C_z = mean chloride ion concentration in soil water (mg/l)

P = precipitation (mm/yr)

C_p = chloride ion concentration in rainfall (mg/l)

Therefore the method involves the measurement of rainfall, concentration of chloride ions in rainfall and in soil water only. This is a great advantage, as estimation of actual evapotranspiration or other parameters like water holding capacity and specific yield are not required in this method.

Nutrient cycling by plants may affect solute movement (including that of chloride) on an annual basis, but, in stable landscapes, the amounts removed annually by plant uptake are balanced by the amounts released by plant decomposition, i.e., a steady state should have been achieved (Edmunds *et al.* 1988).

Since the concentration of chloride in soil is inversely proportional to the recharge rates (assuming steady state) the precision of the estimate of recharge will increase with the decrease in recharge rate. Therefore this method could provide good results in areas with conditions approaching aridity.

Table 4. Estimates of potential recharge by the soil water budget method for the study locations in Sri Lanka

Study Location	Mean Annual Rain[1] (mm/y)	Mean Annual pan Eveporation[1] (mm/y)	Interception (% of rainfall)	Runoff (% of rainfall)	Preferential flow (% of rainfall)	Root constant (% of available water capacity)	Recharge (mm/y)
Embilipitiya	1397	1729	12.5	20.0	5	65	275
Middeniya	1484	1729	12.5	22.5	5	65	119
Buweliara[3]	1041	1868	17.5	22.5	5	65	70
Angunakolapellessa	1041	1868	17.5	22.5	5	65	75
Maha Illuppallama	1305	1579	17.5	20..0	5	65	120
Anamaduwa	1117	1958	17.5	25.0	5	65	100

Table 5. Estimates of potential recharge by the chloride profilling method for the study location on Sri Lanka

Study location	Mean Annual Rain (mm/y)	Mean chloride ion concentration in rainfall (mg/l)	Mean chloride ion concentration in soil (mg/l)	Recharge (from equation 2) mm/y
Embilipitiya	1397	3.2	67.7	66
Middeniya	1484	4.5	513.7	13
Buweliara	1041	7.0	404.8	18
Angunakolapellessa	1041	4.4	61.1	10
Maha Illuppallama	1305	10.0	318.3	41
Anamaduwa	1117	5.4	1508.0	04

The method requires a knowledge of historical input of the chloride for a number of years. Also the method is unlikely to work in areas with a shallow water table and in areas where an artificial application of chloride has taken place.

RESULTS AND DISCUSSION

Tables 4 and 5 summerise the calculations for estimating potential recharge with the soil water budget method and for estimating actual recharge by the chloride profiling method respectively.

Fig. 3 shows the comparison of the average recharge estimate for the 6 locations by the chloride profiling method and the SWB method.

As seen from Fig. 3, the agreement between the two methods is poor in all locations (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 study locations in the dry zone. (If the chloride concentrations in rain are higher, the recharge estimates will also be higher from equation 4. Edmunds and Gaye (1994) reported from a study in Senegal that 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 actual 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. This theory is shown in Fig. 4 taking the study location Embilipitiya as an example.

(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 SWB for the present study, the resulting recharge estimates are reduced. However, from the SWB results reported by de Silva (1996) for Ngwazi in

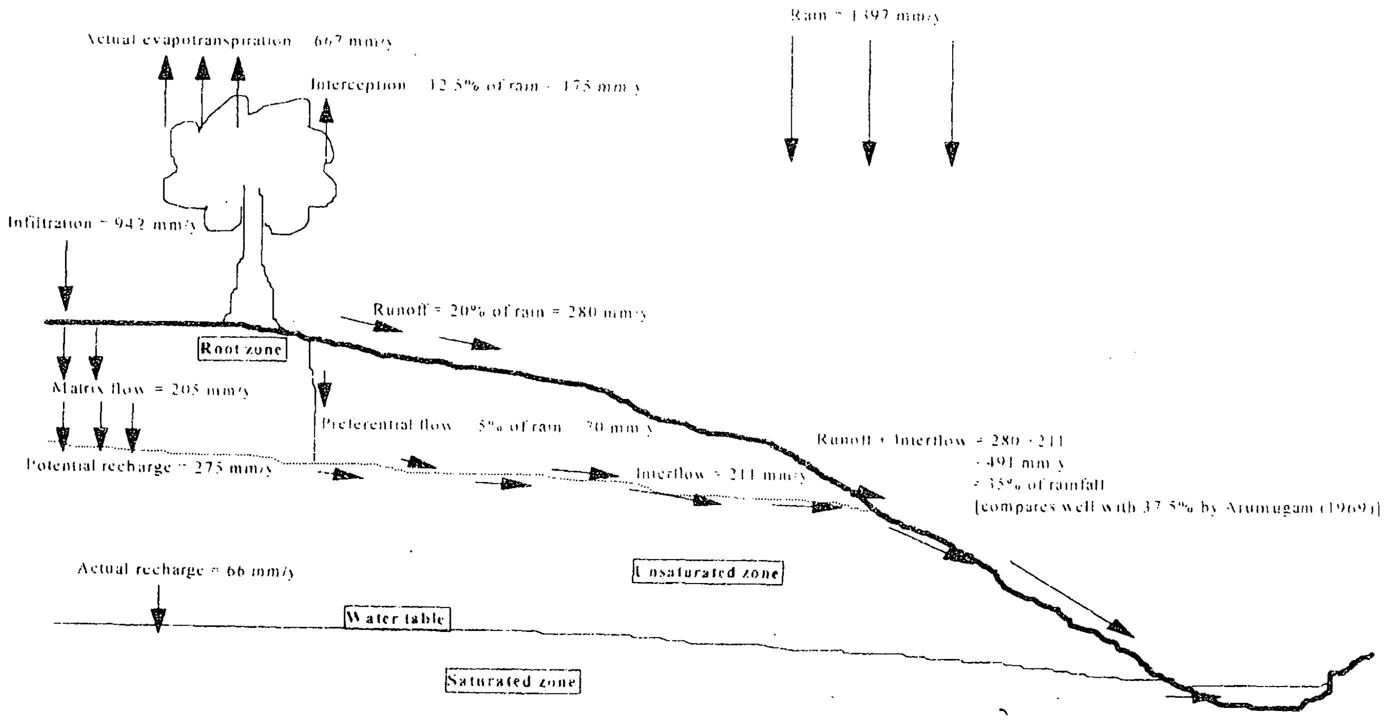

Fig. 5. A possible explanation for the difference of recharge estimates by the chloride method and the SWB method taking Embilipitiya as an example

Tanzania and Nguru in Nigeria, the SWB yielded reasonable results which agreed with estimates of recharge by chloride method and groundwater flow modelling. Also in Silsoe, UK the soil moisture deficit predicted by the SWB method agreed well with those obtained experimentally by the neutron probe. Therefore, it is unlikely to be the reason for the disagreement of recharge estimates by the chloride method and the SWB method. However, more research work on the effect of the zero flux plane being significantly deeper than the root zone on estimating recharge with the SWB is certainly necessary, which will enable a better understanding of the hydro-geology of the dry zone. The absorption of water by deeper tree roots is also a possible reason for the estimates by the two methods to differ, but since the effect is similar to a deeper zero flux plane (as discussed above), it will not be separately treated here.

The fact that the streams and rivers flow immediately after rains also support the theory of significant runoff or runoff and interflow. The non availability of significant amounts of underground water (as evident by the dropping of water tables with even small abstractions) and insignificant baseflow (i.e., the contribution of groundwater from the aquifers to the streams and rivers) also support the theory of less actual recharge.

Therefore, considering the evidence, it is very likely that the actual recharge is significantly different to potential recharge in the dry zone of Sri Lanka. Since, this hypothesis have far reaching consequences, more research work is urgently required to verify and identify causes for the difference in actual and potential recharge.

CONCLUSIONS

The conclusions that can be drawn from this study are as follows. First, the study clearly demonstrated that there is a strong possibility of actual recharge being significantly small compared to the potential recharge in the dry zone aquifers of Sri Lanka. As pointed out elsewhere in the paper, the reason is likely to be the significance of the interflow component in the hydrological cycle. The study also demonstrated that since the chloride profiling method is a simple, easy to use method of estimating actual recharge, the chemistry of rainfall must be determined and recorded along with rainfall records. This probably has to be done by the state agencies involved in this subject such as the Department of Meterology.

Finally it is concluded that since the economic implications of the different actual and potential recharge rates are significant, more research work (spanning possibly over a number of years) is necessary to confirm the preliminary findings of this study.

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