Spatial Variability of Groundwater Recharge - II. Factors Affecting Variability and Taking Account of it in Estimating Recharge.

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Abstract

The accompanying paper provided evidence to suggest that spatial variability of groundwater recharge is ‘true’ variability. This paper attempts to determine the major causes of such variability even at small distances, if there appear to be a frequency distribution to this spatial variability and lastly if it is possible take this variability into account in estimating recharge in an area. The clay content of the top soil appear to have a significant effect on recharge. The spatial variability of recharge appear to be log normally distributed and a way is shown where simple statistics can be used to take account of the spatial variability in estimating recharge.

1.0 INTRODUCTION

Having concluded that spatial variability of recharge is true in the accompanying paper (de Silva, xxxx), this paper attempts to determine;

(i) Are there any patterns in the variation of the spatial variability and what are the factors have a major bearing on the spatial variability?

(ii) Does the spatial variability at a location follow a known frequency distribution (such as the normal distribution)?

(iii) Is it possible to decide on the number of sampling points needed at a location to arrive at an estimate of recharge with a given confidence level?

2.0 MATERIALS & METHODS

Materials and methods are as described in de Silva (xxxx).

3.0 RESULTS & DISCUSSION

3.1 The possible causes of spatial variability of recharge at a location

Since all the spatial variability is over small distances, evapotranspireation (ETa) and other climatological variables are likely to be constant for a location. Although the rainfall reaching the ground surface is likely to vary at different points because of the effects of the vegetation, the rainfall available for infiltration can be considered as uniform for the locations as in most rains the ground surface is slightly ponded because of the low infiltration capacities of the soils. The vegetation type in each location looked uniform (on location scale) from physical appearance. Therefore, it is possible that the spatial variability of soil water flux related soil properties could be the reason for this spatial variability of groundwater recharge estimated by chloride profiles.

As such, to see if easily measured soil properties like the clay content in top soil (1 m depth), infiltration capacity of the soil surface and available water capacity (AWC) of the root zone (considered to be a soil property as the depths of roots in each location are similar) can explain the spatial variability, these properties were experimentally obtained as described in de Silva (xxxx) for all locations (except AWC values for Kalpitiya). In determining the clay content, a depth of 1m was selected as the likely depth of the B horizon of soils in the dry zone is about 1 m (which usually contains higher clay contents washed down from the A horizon in the soil profile).

Fig. 1 (a), (b) and (c) show the variation of recharge (estimated by the chloride method in the customary way) with the 3 soil properties mentioned. Though in general the correlation coefficient is not satisfactory, it is evident that in the dry

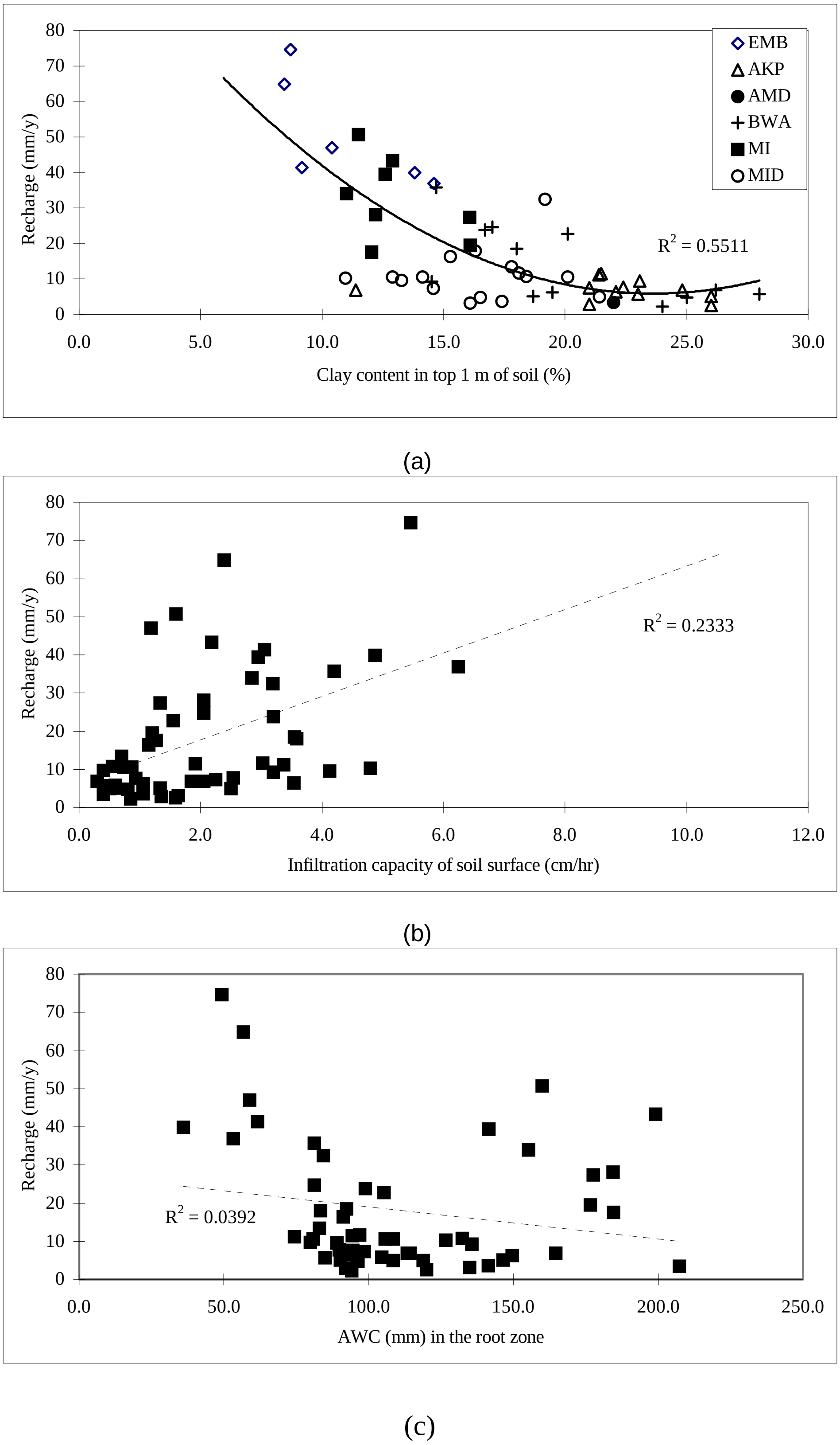


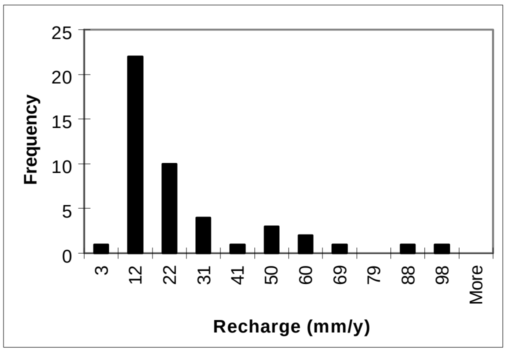
Fig. 1 Variation of recharge with the variation of (a) clay content in top 1m of soil (b) infiltration capacity of soil surface and (c) AWC of the root zone for the locations in the dry zone of Sri Lanka.

zone of Sri Lanka, the soil property with highest correlation with recharge is clay content in the top 1m of soil from Fig. 1. This is in line with the findings of Kennet-Smith et al., (1994) who concluded that recharge correlates with the clay content in the top 2 m of soil in south western Australia.

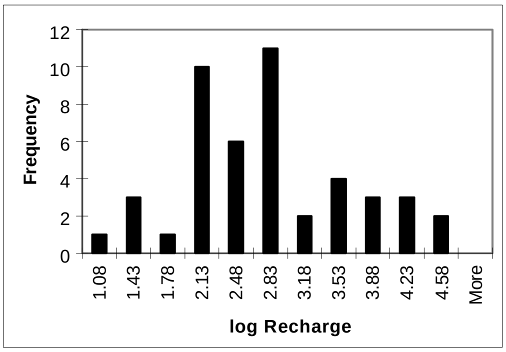
The low correlation coefficients suggest the variability of recharge is not only caused by soil properties. Therefore, it is likely that the spatial variability of recharge at a location (1 ha) is caused by the effect of both soil properties and vegetation on recharge.

3.2 Frequency distribution of the spatial variability of recharge

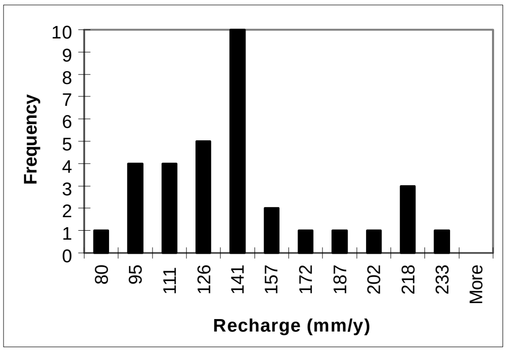
Cook et al., (1989) found from 346 point estimates that recharge follows a log normal distribution over the area concerned. The histograms for the 46 estimates of recharge from the 4 locations in the southern province in Sri Lanka and for the 33 estimates from Silsoe in UK and for their natural logarithm are shown in Fig. 2. It is seen from Fig. 2 that the histograms of recharge are skewed to the left and those of log recharge appear approximately to follow the normal distribution.



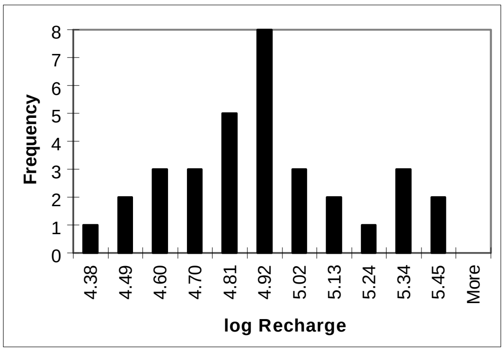
(a)



(b)



(c)



(d)

Fig. 2 (a) Frequency distribution of recharge (obtained by chloride method) and (b) of log recharge for locations in south of Sri Lanka, (c) frequency distribution of recharge and (d) of log recharge for Silsoe [12 out of 33 of recharge estimates are from Smith (1995)]

In Fig. 2 the 46 estimates for Sri Lanka were from 4 different locations, but, they were grouped together, as a larger sample size is required to see if it follow a log normal distribution by plotting the frequency distribution as in Fig. 2.

The Shapiro-Wilk test (Rees, 1995) can be used to test if the sample follows a normal distribution when the sample size is small. Therefore, for the locations where only a small data set is available this test was used and the result is shown in Table 1.

Table 1 Shapiro-Wilk test to determine if distributions are log normally distributed from small samples sizes

Country	Location	Cal W	Tab W
Sri Lanka	Embilipitiya	0.883	0.788
Sri Lanka	Middeniya	0.958	0.887
Sri Lanka	Buweliara	0.963	0.859
Sri Lanka	Angunakolapellessa	0.922	0.859
Sri Lanka	Maha Illuppallama	0.954	0.818
Sri Lanka	Kalpitiya	0.942	0.762
Senegal	North West	0.906	0.788
Senegal	North West	0.826	0.748
Australia	WA	0.870	0.762
Australia	NSW	0.858	0.788
Australia	NSW	0.832	0.788
Australia	NSW	0.865	0.788
Australia	SA	0.884	0.788
Australia	SA	0.946	0.788
Australia	SA	0.914	0.788
Australia	SA	0.841	0.762

In all the cases, Tab W < Calc W and therefore, even in instances where a small data set is available, recharge is approximately log normally distributed.

Researchers have found soil properties closely related to groundwater recharge to be log normally distributed in space. Sisson and Wierenga (1981) found the steady state infiltration rate and Nielsen et al., (1973) found the saturated hydraulic conductivity and soil water diffusivity to be log normally distributed. The latter also found the soil water content to be normally distributed with depth and with horizontal distance. Dahiya et al., (1984) in his review of soil spatial variability cites a number of studies where researchers have found such parameters like air permeability, pore water velocity, hydraulic conductivity and soil water diffusivity, infiltration rate and related parameters, groundwater salinity in arid and semi arid areas and crop yield to be log normally distributed. Broadly he generalises that flux related properties like hydraulic conductivity, pore water velocity and infiltration parameters are more likely to be log normally distributed and variables like bulk density, water content, soil texture and soil pH are more likely to be normally distributed.

Therefore, it is concluded that from the above tests, groundwater recharge over small areas (when estimated by chloride method in the customary way) is approximately log normally distributed.

3.3 Determination of the number of sampling points necessary to estimate recharge with a given confidence in an area

If the spatial variability of groundwater recharge is significant (even over small distances in areas of uniform soil, vegetation and climatic properties), the question of determining the number of sampling points required to estimate recharge for a given accuracy arises.

Using the fact that recharge is approximately log normally distributed, it is possible to come up with a set of curves [using equation 3 in de Silva (xxxx)] which will give the confidence interval for a given sample standard deviation and for a given size of the sample. Fig. 3 shows such a set of curves which gives the 95% confidence interval for a given sample size and sample standard deviation. Alternatively these curves give the size of sample needed for a given confidence interval and given sample standard deviation.

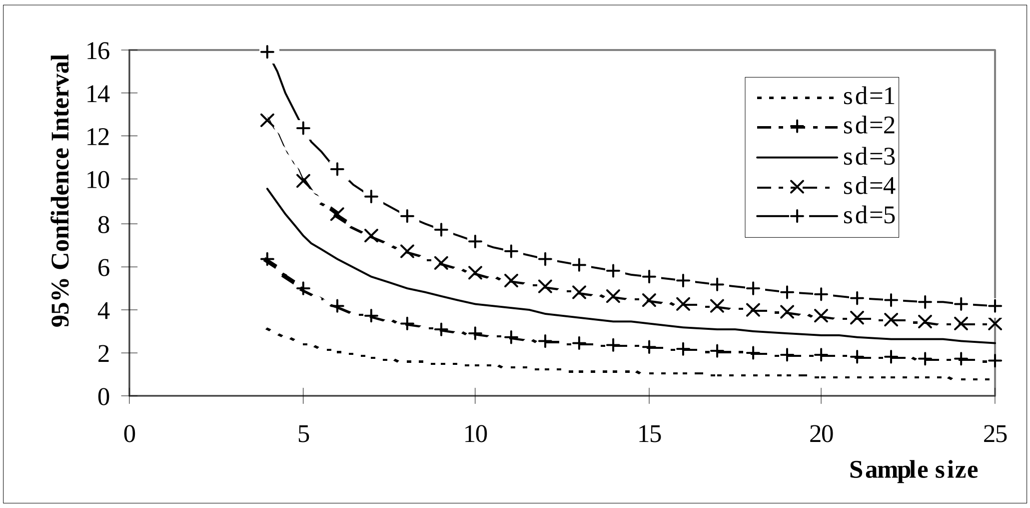


Fig. 3 Variation of 95% confidence interval with sample size for a given standard deviation (sd) [Note: The units of 95% confidence interval values in Fig. 3 are the same units as that of recharge.]

To test the validity of the curves in Fig. 3, recharge data by Cook et al., (1989) were analysed as follows. 10,000 samples each of size from 4 up to 50 (increasing by 2) were chosen randomly and the mean for each sample was calculated. The minimum and maximum value of the mean for each sample size was then obtained. Now these minimum and maximum values represent the likely minimum and maximum recharge with a corresponding sample size that can be obtained from the population (which was considered as the 346 values by Cook et al., 1989). Now if the curves in Fig. 3 are correct, these minimum and maximum values for mean should compare well with the values predicted by the corresponding curve in Fig. 3. The results of the comparison are shown in Fig. 4.

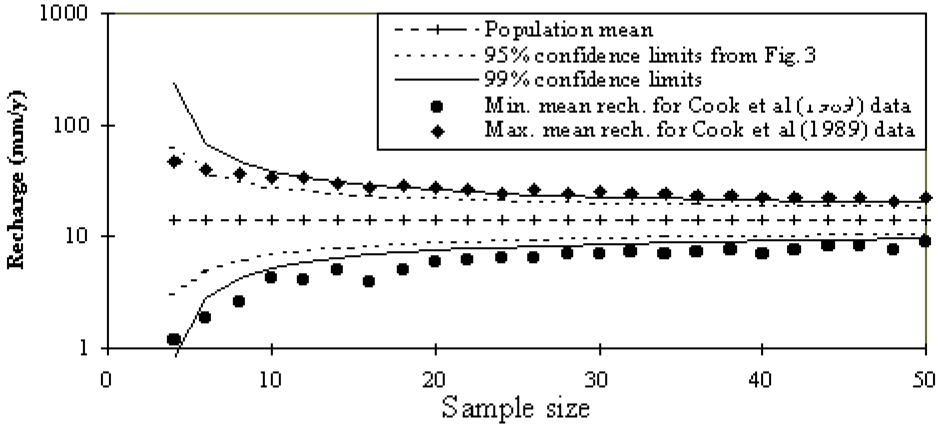


Fig. 4 Theoretical and experimental values for 95% confidence intervals from samples of different size [calculated and plotted from experimental data by Cook et al., (1989)].

From Fig. 4, it is seen that experimental values by Cook et al., (1989) compare well with the theoretical values (from Fig. 4). Therefore, the curves in Fig. 4 may be used to estimate the sample size needed for a given confidence interval and a given standard deviation.

Unfortunately, this approach requires a knowledge of the variability of recharge in the area to be investigated in order to determine the number of sampling points necessary. Therefore, practically, it is necessary to go to the field and estimate at a few random points initially. The graph in Fig. 4 can then be used to determine if more estimates of recharge are needed at different sampling points to achieve an acceptable confidence level.

As an example from the 12 sampling points at Buweliara, (where standard deviation of recharge estimates for that particular location is 0.8 when converted to natural logarithms), the 95% confidence interval is about 1.4 (i.e., ± 0.7 from Fig. 6.10). Since the mean recharge estimate for this location is 2.6 (in natural logarithms), one can be 95% confident that recharge estimates are likely to be 2.6 ± 0.7 = 1.9 or 3.3. These are in natural logarithms and when converted to normal (base 10) values become 7 mm/y and 27 mm/y. Therefore the 95% confidence limits for average recharge estimate by the chloride method for location Buweliara is 7mm/y and 27 mm/y.

4.0 CONCLUSIONS

(i) The degree of spatial variability of groundwater recharge (obtained with the chloride method) is itself variable at different places, both in the dry zone of Sri Lanka and in the other parts of the world.

(ii) The degree of spatial variability of groundwater recharge (obtained with the chloride method) appear to decrease with increasing rainfall/ETp (considered as an indication of aridity) and with increasing clay content, both in the dry zone of Sri Lanka and in other parts of the world.

(iii). Spatial variability of recharge at a location (1 ha) approximately follows a log normal distribution in the dry zone of Sri Lanka, which is in line with the finding of Cook et al., (1989).

(iv). Since ‘point’ estimates of recharge in small areas approximately follows the log normal distribution, to decide the number of sampling points necessary to estimate recharge with a known confidence, the curves in Fig. 4 can be used, provided that an initial estimate of the spatial variability of recharge in the area is available.

5.0 References

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