Estimation of recharge using a revised CRD method

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Abstract

The cumulative rainfall departure (CRD) method, based on the water-balance principle, is often used for mimicking of water level fluctuations. Because of its simplicity and minimal requirement of spatial data, the CRD method has been applied widely for estimating either effective recharge or aquifer storativity, and consequently gained a focus in South Africa. This paper critically reviews this method and proposes expanded algorithm. Validation of the method under typical South African conditions is discussed based on model-generated and known cases. The study is aided with a user-friendly Excel program called Recharge Estimation Model in Excel (REME).

Introduction

Background

Hydrogeologists often compare rainfall and groundwater levels for estimation of groundwater recharge. The reader may refer to Wenzel (1936), Sophocleous (1991) and Wu et al.(1996).

In South Africa Bredenkamp et al. (1995) applied the CRD method in dolomitic aquifers and promoted the method through their publication entitled "*Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity*". Their approach is based on the premise that equilibrium conditions develop in an aquifer over time, i.e. average rate of losses equating to average rate of recharge of the system.

They clearly showed that natural groundwater level fluctuation is related to that of the departure of rainfall from the mean rainfall of the preceding time. If the departure is positive, the water level will rise and vise versa. However, it can be demonstrated that as long as there is a surplus of recharge over discharge of an aquifer, even though the departure is negative, the natural water level may continue to rise.

Purpose

The purpose of this paper is to revisit the existing method and to improve the algorithm to accommodate a wide variety of circumstances. Following improvement of the algorithm a user-friendly tool could be developed for groundwater practitioners. Such a need was identified by the Department of Water Affairs and Forestry, which sponsored a project aimed at promoting the effective use of simple yet powerful methods for recharge estimation. This paper summarises some results of this project.

Theory

Groundwater balance

Assuming an aquifer of area (A) receiving recharge from rainfall (Q_R) with production boreholes (Q_p) tapping the aquifer and with natural outflow (Q_{out}), a simple water balance equation for a given time interval *i* can be written as follows:

$$Q_{Ri} = Q_{pi} + Q_{outi} + \Delta h_i AS \qquad (i = 1, 2, 3 ... N) \tag{1}$$

where Δh_i is water level change and S aquifer storativity (specific yield). If Q_{Ri} is averaged over such a time interval where Δh_i is zero, the system may be treated as in equilibrium. This is, however, seldom the case in reality.

If Q_{pi} is a constant rate, aquifer storage ($\Delta h_i AS$) adjusts to accommodate for net balance between Q_{Ri} and Q_{outi}. This adjustment of the storage would be reflected in piezometric surface or water level change in boreholes. The cause-effect relationship between rainfall oscillation and water-level fluctuation is effectively represented by the correlation between the CRD and water level fluctuation.

Recharge formulae

Bredenkamp formula

Bredenkamp et al. (1995) defined CRD as follows:

$${}_{av}^{1}CRD_i = \sum_{n=1}^{i} R_n - \kappa \sum_{n=1}^{i} R_{av} \quad (i = 0, 1, 2, 3, \ldots N) \tag{2}$$

where R is rainfall amount with subscript "$_i$" indicating the i-th month, "$_{av}$" the average and $\kappa = 1 + (Q_p + Q_{out})/(AR_{av})$. $\kappa = 1$ indicates that pumping does not occur and $\kappa > 1$ if pumping and/or natural outflow takes place.

It is assumed that a CRD has a linear relationship with a monthly water level change. Bredenkamp et al. (1995) derived

$$\Delta h_i = (r / S) \cdot ({}_{av}^{1}CRD_i) \; (i = 0, 1, 2, 3, ...N) \tag{3}$$

where r is a percentage of the CRD which results in recharge from rainfall.

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Eq. (3) may be used to estimate the ratio of recharge to aquifer storativity through simple regression between CRD_i and Δh_i (Bredenkamp et al., 1995).

New formula

It is often the case that an appropriate value of the parameter κ in Eq. (2) must be chosen to mimic adequately the water level fluctuation in boreholes. However, its physical meaning is still unclear. Rainfall time series in general are composed of random and deterministic components, the latter is in the form of trends and periodicities. A short series of data often displays a trend to a certain degree, which cannot be reflected in Eq. (2). A new CRD has therefore been formulated to account for such a trend:

$$ {}^{1}_{t}CRD_i = \sum_{n=1}^{i} R_n - \left(2 - \frac{1}{R_{av}\, i} \sum_{n=1}^{i} R_n \right) \sum_{n=1}^{i} R_t \qquad (i = 1, 2, 3, \ldots N) \qquad (4) $$

where R_t, a threshold value representing aquifer boundary conditions, is determined during the simulation process. It may range from 0 to R_{av} with 0 indicating an aquifer being closed and R_{av} implying that the aquifer system is open, perhaps being regulated by spring flow. Note that Eq. (4) reduces to Eq. (2) if rainfall events R_i do not show a trend ($R_t = R_{av}$). In this case, cumulative rainfall average would conform to R_{av}.

It is assumed that CRD is the driving force behind a monthly water level change if the other stresses are relatively constant. The groundwater level will rise if the cumulative departure is positive and it will decline if the cumulative departure is negative.

Since CRD ∝ ($\Delta h + (Q_p + Q_{out})/(AS)$), then $rCRD = S(\Delta h + (Q_p + Q_{out})/(AS))$. After rearrangement, one obtains the following:

$$ \Delta h_i = (r/S)\cdot\left({}^{1}_{t}CRD_i\right) - \left(Q_{pi} + Q_{outi}\right)/(AS) \qquad (i = 0, 1, 2, 3, \ldots N) \qquad (5) $$

Term $(Q_{pi} + Q_{outi})/(AS)$ in Eq. (5) is necessary only if a pumping hole has influence over the study area where water levels were collected.

Eq. (5) may be used to estimate the ratio of recharge to aquifer storativity through minimising the difference between calculated and measured Δh_i series. This optimisation is implemented in a user-friendly Excel program called REME (available on request).

Discussion

Analysis of Eq. (2) through Eq. (5) reveals the following facts:

- If rainfall R_i is constant over time, $R_i = R_{av}$ and groundwater levels do not fluctuate naturally. Steady state conditions prevail.
- Term $(Q_{pi} + Q_{outi})/(AS)$ of Eq. (5) is necessary only if the influence of pumping and/or outflow on water level changes is evident.

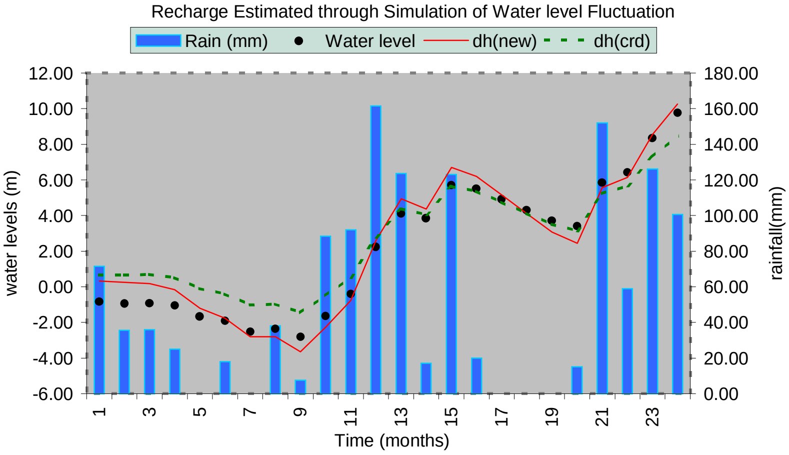

Figure 1
Simulation of groundwater fluctuation using the CRD method based on model generated data

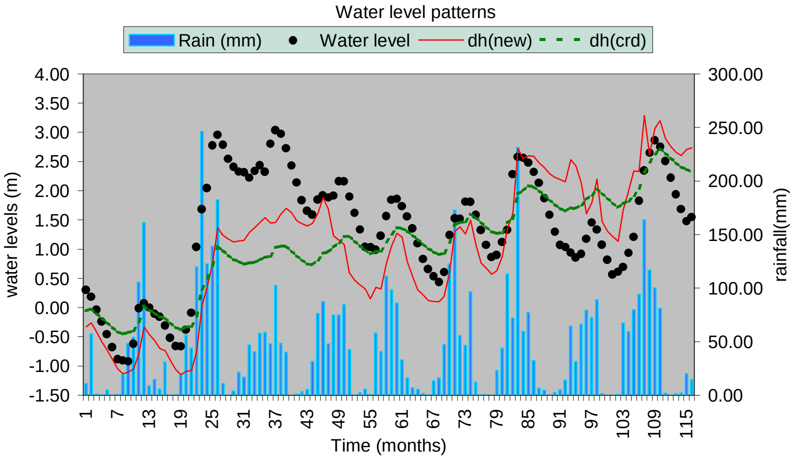

Figure 2
Simulation of groundwater fluctuation using the CRD method based on data from Grootfontein compartment

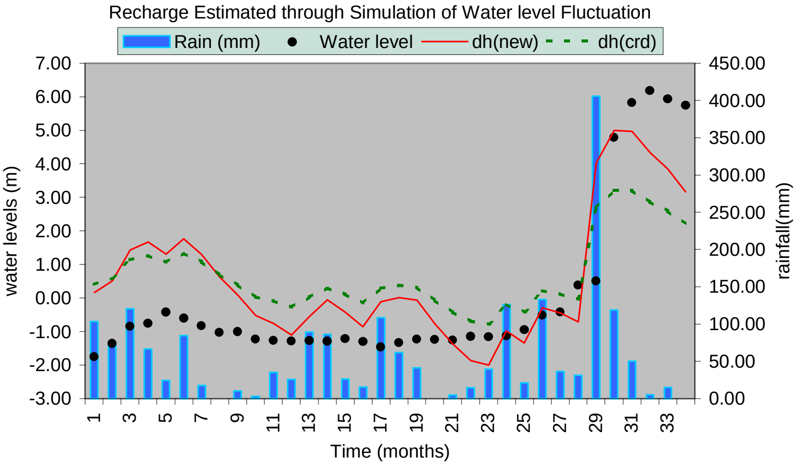

Figure 3
Simulation of groundwater fluctuation using the CRD method based on data from Dewetsdorp aquifer

This may be true in cases of highly fractured dolomitic aquifers where high values of transmisivity are encountered.

- Only the ratio r/S can be determined through water level simulation.
- Since Eq. (3) makes use of Eq. (2), Eq. (3) cannot accommodate for variable pumping rates. Eq. (5) accounts for changing pumping and outflow rates ($Q_{pi} + Q_{outi}$).
- Eq. (3) implicitly assumes that there are no long-term trends in the rainfall.

Water balance based methods are lumped parameter approaches. They do not address parameter variation in space and should be applied with caution.

Case studies

Closed aquifer system

A hypothetical aquifer with recharge of 2% of rainfall over a closed area of 5x5 km^2 has a borehole at the centre pumping at a rate of 15 000 m^3 per month. The aquifer has a storativity of $1x10^{-3}$. Water levels over 24 months are generated using Modflow-based software.

The water level series is simulated using the computer program REME. Comparison of simulated water levels with the generated ones is shown in Fig. 1 where dh(crd) are water levels calculated using Bredenkamp et al. (1995) Eqs. (2) and (3), while dh(new) are water levels calculated using Eq. (5). The average modelled recharge is 1.79% of rainfall.

Dolomite aquifer

The Grootfontein aquifer is compartmented by dolerite dykes. The compartment situated in the recharge zone covers an area of $1.25x10^3$ km^2. Aquifer storativity has been estimated at 2.39% (Bredenkamp et al., 1995). Both methods were applied to this case. Results are shown in Fig. 2. Based on the revised CRD method (Eq. (5)), a recharge value of 5.71% of rainfall was calculated whereas Bredenkamp et al. (1995) formulae yielded a value of 11%.

Karoo aquifer

The Karoo aquifer in Dewetsdorp was investigated by Kirchner et al. (1991). It covers an area of 21 km^2 with aquifer storativity estimated at 0.19%. Both methods were applied to this case and yielded an average recharge of 1.45% of rainfall as shown in Fig. 3. Applying Eq. (5) produces a better fit.

Limitations

Most aquifers in South Africa are of a fractured nature with small storativities. Hence, changes in groundwater levels in these aquifers are very sensitive to recharge from rainfall. For this type of aquifers simulation of water levels based on the CRD is less accurate. Another important factor influencing the accuracy of the CRD is the depth to the groundwater table in these aquifers.

According to Vegter (1995), the depths to water tables in aquifers with secondary porosity (e.g. fractured and weathered rock) is commonly between 10 and 30 m below ground level. This group includes such primary drainage regions as denoted D, F, G, K, P, R and Q (Midgley et al., 1994). The depths to water tables in fractured and karstic aquifers often vary from 10 to 40 m below ground level. This group includes such primary drainage regions as E, M, S, V and W (Midgley et al., 1994). The depths to water levels in weathered fractured aquifers are often ranging from10 to 125 m below ground level. This group includes such primary drainage regions as A, B, C, H, L, I, J, N, O, T and U (Midgley et al., 1994). In general, the depths range from 10 to 125 ms. If depths within 50 m are termed as shallow aquifers, those beyond 50 m are relatively deep aquifers.

If the depth to the groundwater table exceeds 50 m we recommend that consideration of the CRD method be applied with time lags. This is due to the different filtering (delay) effect of rainfall passing through the unsaturated zone (Wu et al., 1996). Fluctuation of water levels in deep aquifers thus may be retarded or smoothened, and consequently fails to correspond to the rainfall signals.

Conclusion

The CRD method is simple but powerful for groundwater recharge estimation. Since $\kappa \geq 1$, Eq. (3) can yield erroneously high recharge values. The revised formula proposed in this paper is able to account for rainfall series with trends and is more accurate. The ratio r/S can be estimated for shallow aquifers using the CRD method, which does not require a large amount of spatial data. The estimation can be optimised through a Solver built in Excel. The applicability of the CRD method for deep aquifers remains to be verified.

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