ESTIMATION OF GROUND WATER RECHARGE USING SOIL MOISTURE BALANCE APPROACH

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ABSTRACT

The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the ground water recharge. Thus, a quantitative evaluation of spatial and temporal distribution of ground water recharge is a pre-requisite for operating ground water resources system in an optimal manner. This paper presents a methodology with step-by-step procedure to determine the ground water recharge by soil moisture balance in the unsaturated zone.

INTRODUCTION

Quantification of the rate of natural ground water recharge is a basic pre-requisite for efficient ground water resource management. It is particularly important in regions with large demands for ground water supplies, where such resources are the key to economic development. However, the rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of ground water resources. The main techniques used to estimate ground water recharge rates are the Darcian approach, the soil water balance approach and the ground water level fluctuation approach. Estimation of recharge, by whatever method, are normally subject to large uncertainties and errors.

Rainfall is the principal means for replenishment of moisture in the soil water system and recharge to ground water. Moisture movement in the unsaturated zone is controlled by capillary pressure and hydraulic conductivity. The amount of moisture that will eventually reach the water table is defined as natural ground water recharge. The amount of this recharge depends upon the rate and duration of rainfall, the subsequent conditions at the upper boundary, the antecedent soil moisture conditions, the water table depth and the soil type.

In many arid and semi-arid regions, surface water resources are limited and ground water is the major source for agricultural, industrial and domestic water supplies. Because of lowering of water tables and the consequently increased energy costs for pumping, it is recognised that ground water extraction should balance ground water recharge in areas with scarce fresh water supplies. This objective can be achieved either by restricting ground water use to the water volume which becomes available through the process of natural recharge or by recharging the aquifer artificially with surface water. Both options require knowledge of the ground water recharge process through the unsaturated zone from the land surface to the regional water table.

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When water is supplied to the soil surface, whether by precipitation or irrigation, some of the arriving water penetrates the surface and is absorbed into the soil, while some may fail to penetrate but instead accrue at the surface or flow over it. The water which does penetrate is itself later partitioned between that amount which returns to the atmosphere by evapotranspiration and that which seeps downward, with some of the latter re-emerging as stream flow while the remainder recharges the ground water reservoir.

Quantification of ground water recharge is a major problem in many water-resource investigations. It is a complex function of meteorological conditions, soil, vegetation, physiographic characteristics and properties of the geologic material within the paths of flow. Soil layering in the unsaturated zone plays an important role in facilitating or restricting downward water movement to the water table. Also, the depth to the water table is important in ground water recharge estimations. Of all the factors controlling ground water recharge, the antecedent soil moisture regime probably is the most important.

Estimating the rate of aquifer replenishment is probably the most difficult of all measures in the evaluation of ground water resources. Estimates are normally and almost inevitably subject to large errors. No single comprehensive estimation technique can yet be identified from the spectrum of those available, which does not give suspect results.

Recharge estimation can be based on a wide variety of models which are designed to represent the actual physical processes. Methods which are currently in use include (i) soil water balance method (soil moisture budget); (ii) zero flux plane method; (iii) one-dimensional soil water flow model; (iv) inverse modelling for estimation of recharge (two-dimensional ground water flow model); (v) saturated volume fluctuation method (ground water balance); and (vi) isotope techniques and solute profile techniques. The two-dimensional ground water flow model and the saturated volume fluctuation method are regarded as indirect methods, because ground water levels are used to determine the recharge.

Water balance models were developed in the 1940s by Thornthwaite (1948) and revised by Thornthwaite and Mather (1955). The method is essentially a book-keeping procedure which estimates the balance between the inflow and outflow of water. In a standard soil water balance calculation, the volume of water required to saturate the soil is expressed as an equivalent depth of water and is called the soil water deficit. The soil water balance can be represented by:

$$G_r = P - E_a + \Delta S - R_o \qquad \ldots(1)$$

where,
G_r = recharge;
P = precipitation;
E_a = actual evapotranspiration;
ΔS = change in soil water storage; and
R_o = run-off.

One condition that is enforced, is that if the soil water deficit is greater than a critical value (called the root constant), evapotranspiration will occur at a rate less than the potential rate.

The magnitude of the root constant depends on the vegetation, the stage of plant growth and the nature of the soil. A range of techniques for estimating E_a, usually based on Penman-type equations, can be used. The data requirement of the soil water balance method is large. When applying this method to estimate the recharge for a catchment area, the calculation should be repeated for areas with different precipitation, evapotranspiration, crop type and soil type.

The purpose of this study is to present a methodology (step-by-step procedure) for estimation of ground water recharge based upon modified soil moisture balance approach. The methodology incorporates the theory of SCS method for finding the storage index.

SCS RAINFALL - RUNOFF RELATION

The runoff curve number method for the estimation of direct runoff from storm rainfall is well established in hydrologic engineering. Its popularity is rooted in its convenience, its simplicity, and its responsiveness to four readily grasped catchment properties: soil type, land use/treatment, surface condition, and antecedent condition. The method was developed in 1954 by the USDA Soil Conservation Service (SCS, 1985).

In developing the SCS rainfall-runoff relationship, the total rainfall was separated into three components: direct runoff (Q), actual retention (F), and the initial abstraction (I_a). Conceptually, the following relationship between P, Q, I_a, and F was assumed:

$$\frac{F}{S} = \frac{Q}{P - I_a} \qquad \ldots(2)$$

in which S is the potential maximum retention. The actual retention is

$$F = (P - I_a) - Q \qquad \ldots(3)$$

Substituting equation (3) into equation (2) yields the following:

$$\frac{(P - I_a) - Q}{S} = \frac{Q}{P - I_a} \qquad \ldots(4)$$

Rearranging equation (4) to solve for Q yields

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \ldots(5)$$

Equation (5) contains one known, P, and two unknowns, I_a and S. Before putting equation

(5) in a form that can be used to solve for Q, it may be worthwhile examining the rationality of the underlying model of equation (2). The initial abstraction is the amount of rainfall at the beginning of a storm that is not available for runoff; therefore, ($P-I_a$) is the rainfall that is available after the initial abstraction has been satisfied. Letting K_1 equal the ratio of Q to ($P-I_a$), K_1 represents the proportion of water available that directly runs off. If S is the amount of storage (e.g., depression, interception, subsurface) available to hold rainfall, $K_2 = F/S$ is the proportion of available storage that is filled with rainwater. Equation (2) indicates that $K_1 = K_2$; in other words, the proportion of available storage that is filled up equals the proportion of available water that appears as runoff.

Given equation (5), there are two unknowns to be estimated, S and I_a. The retention S should be a function of the following five factors: land use, interception, infiltration, depression storage, and antecedent moisture. Empirical evidence resulted in the following equation:

$$I_a = 0.2\,S \qquad \ldots(6)$$

If the five factors above affect S, they also affect I_a. Substituting equation (6) into equation (5) yields the following equation, which contains the single unknown, S:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \ldots(7)$$

Equation (7) represents the basic equation for computing the runoff depth, Q, for a given rainfall depth, P. It is worthwhile noting that while Q and P have units of depth (e.g., mm), Q and P reflect volumes and are often referred to as volumes because we usually assume that the same depths occurred over the entire watershed.

In order to use equation (7) to compute the runoff for a given P, it is necessary to provide a means for estimating the one unknown, S. For this purpose, the SCS runoff curve number (CN) was developed. A curve number is an index that represents the combination of a hydrologic soil group and a land use and treatment class. Empirical analyses suggested that the CN was a function of three factors: soil group, the cover complex, and antecedent moisture conditions.

SCS developed a soil classification system that consists of four groups, which are identified by the letters A, B, C, and D. The SCS cover complex classification consists of three factors: land use, treatment or practice, and hydrologic condition. There are approximately 21 different land uses that are identified in the tables for estimating runoff curve numbers. Agricultural land uses are often subdivided by treatment or practices, such as contoured or straight row; this separation reflects the different hydrologic runoff potential that is associated with variation in land treatment. The hydrologic condition reflects the level of land management; it is separated with three classes: poor, fair, and good. Not all of the land uses are separated by treatment or condition. Antecedent soil moisture is known to have a significant effect on both the volume and rate of runoff. Recognising that it is a significant factor, SCS developed three antecedent soil moisture conditions, which were labelled I, II and III.

As indicated previously, the CN was developed for use with equation (7). Thus, there was a need to relate S, which was unknown of equation (7), and the runoff CN. An empirical analysis led to the following relationship:

$$S = \frac{25400}{CN} - 254 \qquad \ldots(8)$$

Equations (7) and (8) can be used to estimate Q when the values of P and CN are available. It is important to note the following constraint on equation (7):

$$P \geq 0.2\,S \qquad \ldots(9)$$

When $P < 0.2$ S, it is necessary to assume that $Q = 0$.

DATA REQUIREMENT

For estimation of ground water recharge using soil moisture balance approach incorporating the theory of SCS method, the following data are needed.

1. Hourly rainfall (P)
2. Hourly potential evaporation (E_p)
3. Infiltration capacity at a number of places in the watershed
4. 5-day antecedent rainfall
5. Land use map and treatment/practice
6. Initial root zone soil moisture (θ_i)
7. Saturated moisture content (θ_s)
8. Saturated hydraulic conductivity (K_s)
9. Relative permeability of water ($K(\theta)/K_s$)
10. Maximum root zone depth (D_o)
11. Field capacity (θ_f) and wilting point (θ_w)
12. Crop coefficients (K_c)

METHODOLOGY

The following step-by-step procedure can be followed to find ground water recharge in the watershed.

1. Find hydrologic soil groups in the watershed, as per the following criteria:

Soil Group	Infiltration Capacity (cm/hour)

A	7.5 - 11.5
B	4.0 - 7.5
C	0.13 - 4.0
D	0 - 0.13

2. Find antecedent moisture condition (AMC) from 5-day antecedent rainfall.

AMC Group	Dormant Season (cm)	Growing Season (cm)
I	< 1.3	< 3.6
II	1.3 to 2.8	3.6 to 5.4
III	> 2.8	> 5.4

3. Plot Thiessen polygon areas of hydrologic soil groups determined in step (1) and superimpose on the land use map showing fallow land, row crops, small grain, pasture, meadow, roads etc.

4. For each of the demarcated area (A1, A2, ..., B1, B2, ..., C1, C2, ..., D1, D2, ...) obtained in step (3), find the runoff curve number, CN^o from SCS method tables depending upon the land use, treatment or practice, hydrologic soil group and antecedent moisture condition group.

5. Initialize the cumulative recharge, $Q_{rc}(t-\Delta t) = 0$. Assume the time step (Δt) as one hour and repeat the following steps for each subarea. All quantities are to be taken in mm.

6. Find the storage index

$$S(t-\Delta t) = (25400/CN^o) - 254$$

7. Compare the total rainfall P(t) during the time ($t-\Delta t$) to t (i.e. during the time step t) with $0.2*S(t-\Delta t)$ and estimate the initial abstraction, I_a as follows.

$$I_a(t) = 0.2*S(t-\Delta t) \qquad \text{if } P(t) > 0.2*S(t-\Delta t)$$

$$I_a(t) = P(t) \qquad \text{if } P(t) < 0.2*S(t-\Delta t)$$

If total rainfall in the next time step i.e. $P(t+\Delta t)$ is greater than $0.2*S(t-\Delta t)-P(t)$, then

$I_a(t+\Delta t) = 0.2*S(t-\Delta t)-P(t)$ for the next time step.

8. Find the initial water content of the soil, θ_i or $\theta(t-\Delta t)$ and the water content at natural saturation, θ_s deduced from laboratory determination of porosity.

9. Find the Bouwer's estimate of the effective capillary drive, H_b, defined by the equation

$$H_b = \int_0^{h_{ci}} k_{rw} \; dh_c$$

where, $h_{ci} = h_c(\theta_i)$, the initial capillary suction head;
k_{rw} = relative permeability of water = $K(\theta)/K_s$;
K_s = saturated hydraulic conductivity.

10. Estimate the ponding time, t_p as

$$t_p = \frac{(\theta_s - \theta_i) H_b}{r\,(r/K_s - 1)}$$

where, r is the rainfall rate.

11. Estimate the infiltrated water (Q_i) during the current time step, as given below:

$$Q_i(t) = \int_0^{t_p} r(\tau)d\tau - I_a(t) + \int_{t_p}^{\Delta t} i(\tau)d\tau \qquad \text{if } t_p < \Delta t$$

$$Q_i(t) = P(t) - I_a(t) \qquad \text{if } t_p \geq \Delta t$$

where, $i(\tau)$ is the infiltration capacity.

12. Estimate the root zone soil moisture, $\theta(t)$ and ground water recharge, $Q_r(t)$ in the time step t, as follows.

D_o can be taken as 1.5 m for areas without vegetation.

If $[\theta_f - \theta(t-\Delta t)]D_o < Q_i(t)$,
$\theta(t) = \theta_f$
and $Q_r(t) = Q_i(t) - [\theta_f - \theta(t-\Delta t)]D_o$

If $[\theta_f - \theta(t-\Delta t)]D_o > Q_i(t)$,

$$\theta(t) = \frac{\frac{Q_i(t)}{D_o} + [1 - \frac{K_c E_p(t)}{2 D_o(\theta_f - \theta_w)}\theta(t-\Delta t) + \frac{K_c E_p(t)\theta_w}{D_o(\theta_f - \theta_w)}}{[1 + \frac{K_c E_p(t)}{2 D_o(\theta_f - \theta_w)}]}$$

and $Q_r(t) = 0$

The following values of θ_w may be assumed for different soils.

Loams	:	8 - 10 %
Clay-silty soils	:	15 %
Peaty soils	:	35 %
Peats	:	50 %

For uncropped area, the values of K_c and θ_w may be taken as 1 and 0 respectively in the above expression.

13. Find the cumulative ground water recharge, $Q_{rc}(t)$ till the end of time step t, as given below :

$$Q_{rc}(t) = Q_{rc}(t-\Delta t) + Q_r(t)$$

14. Estimate the evaporation losses from upper reservoir, $E_u(t)$ and lower reservoir, $E_l(t)$ as given below :

$E_u(t) = E_p(t)$ if $P(t)>0$ and $E_p(t)<I_a(t)$
$E_u(t) = I_a(t)$ if $P(t)>0$ and $E_p(t)>I_a(t)$
$E_u(t) = E_p(t)$ if $P(t)=0$ and $E_p(t)<[I_a(t-\Delta t)-E_u(t-\Delta t)]$
$E_u(t) = I_a(t-\Delta t)-E_u(t-\Delta t)$
if $P(t)=0$ and $E_p(t)>[I_a(t-\Delta t)-E_u(t-\Delta t)]$

$$E_l(t) = K_c\ E_p(t)[\frac{\theta(t) - \theta_w}{\theta_f - \theta_w}] \qquad \text{if } \theta(t) > \theta_w$$

$E_l(t) = 0$ if $\theta(t) \le \theta_w$

For uncropped area, the values of K_c and θ_w may be taken as 1 and 0 respectively in the above expression.

15. Update the storage index as follows:

$$S(t) = S(t-\Delta t) + E_u(t) + E_l(t) - [Q_i(t)-Q_r(t)]$$

16. Go to step 7 for the next time step.

17. Repeat the steps from 6 to 16 for each of the subarea.

18. Find the total ground water recharge for the whole watershed by adding the cumulative ground water recharge, $Q_{rc}(t)$ values for each subarea.

The above step-by-step procedure can be automated by utilizing a computer program.

CONCLUSION

The conventional method of estimating recharge as precipitation minus evapotranspiration minus runoff, with allowance for changes in soil moisture storage, is very sensitive to measurement errors and to the time scale of analysis. The customary method of calculating ground water recharge by multiplying a constant specific yield value by the water table rise over a certain time interval may be erroneous, especially in shallow aquifers. The hydraulic approach, based on Darcy's equation, offers the most direct measurement of seepage rates and hence recharge. However, it is highly site specific and most laborious and expensive, requiring specialized field equipment and personnel.

A methodology has been presented with step-by-step procedure to estimate the ground water recharge based upon modified soil moisture balance approach. The methodology incorporates the theory of SCS method for finding the storage index. This methodology is expected to give better estimates of ground water recharge. However, to improve the reliability of ground water recharge estimates, we must monitor aquifer behaviour on a continuous or periodic basis to ensure that adequate data are available. The application of several independent or different ground water recharge estimation methods can complement one another and is likely to improve our knowledge of aquifer recharge, provided that an adequate hydrogeologic database and soil characteristics exist.

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