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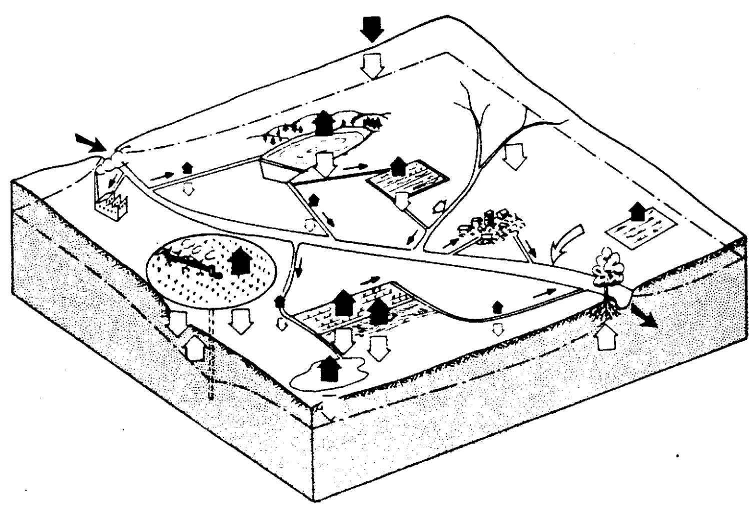

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Analysis of Rainfall-Infiltration Recharge to Groundwater

Jinquan Wu and Renduo Zhang[1]

ABSTRACT

Understanding the recharge process and its relationship with rainfall is of critical importance to the management of groundwater systems. In this research, in-situ lysimeter experiments, statistical methods, and numerical simulations were used to study the process of rainfall-infiltration recharge to the groundwater. With a shallow groundwater table, each recharge process corresponds to an individual rainfall event. Therefore, the infiltration-recharge can be predicted directly from rainfall events through a statistical correlation. The advantage to use the statistical correlation for estimating the recharge is a minimal requirement of input data and computation effort, compared with numerical simulations. As the depth to groundwater increases, the degree of correspondence between rainfall and recharge processes decreases. Below a certain depth, only the correspondence between relatively large rainfall events and peaks in the recharge processes may be observed. A technique was developed to separate the recharge process corresponding to rainfall events, and a concept of effective rainfall events was introduced to analyze the rainfall-recharge relationship. If the water table is further deep, there will be only one peak in the annual recharge process, and the processes of different years may overlap. Only a correlation between the annual precipitation and infiltration-recharge can be obtained. For a very deep water table, the variation of the infiltration-recharge rate becomes quite small, which can be approximated as a constant. The recharge rate may be determined using an annual or multi-year water balance.

INTRODUCTION

Rainfall infiltration-recharge is one of the most essential groundwater resources. On the other hand, recharge from waste storage soils may cause serious groundwater contamination. Therefore, better understanding the physical process of rainfall-recharge through the vadose zone is of fundamental importance for the management of water quantity and quality of groundwater systems. However, quantifying groundwater recharge still remains a challenging task.

Vadose-zone techniques, including physical and chemical methods (*Allison et al.*, 1994), have been used to estimate recharge in soils. Nevertheless, some techniques become problematic because of measured conditions, and some are too expensive to be applied in field situations.

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In a shallow groundwater region, the correspondence between an individual rainfall event and a groundwater recharge process may be observed. Relationships between rainfall and infiltration-recharge have been studied using groundwater regime data (*Viswanthan*,1983, 1984; *Rennolls et al.*, 1980; *Venetis*, 1971).

With deep groundwater, deserts are often considered ideal radioactive and hazardous waste landfills (*Reith and Thomson*, 1992). It is usually assumed that recharge to groundwater is negligible under desert conditions. However, recent studies indicate that significant recharge may occur in arid and semiarid regions, even where annual potential evapotranspiration exceeds precipitation (*Gee et al.*, 1994; *Stephens*, 1994). Unfortunately, measurements of groundwater recharge in dry climates are extremely difficult.

In this paper, groundwater systems are classified into three categories, i.e., with shallow, mediate deep and deep water tables. Relationships of rainfall and infiltration recharge are investigated based on the classification. Groundwater recharge will be quantified using experimental data, numerical simulations and statistical analyses.

METHODS

1. Shallow Water Table

In a region with a shallow water table, infiltrated water reaches the groundwater relatively fast through the vadose zone, and an individual rainfall event produces a quick response of infiltration-recharge. In the groundwater regime, a close relationship between rainfalls and water table rises can be obtained. Most of discrete rainfall events generate isolated recharge processes, and the water table rises caused by different rainfalls are distinguishable from one another. Therefore, at a shallow groundwater depth, the total recharge R_e from a single rainfall event is calculated by multiplying the water table rise with the specific yield (*Zhang*, 1983; *Viswanthan*, 1984). If a recharge process, instead of groundwater regime data, is available, the total recharge is determined by directly integrating the process. The relationship between individual rainfall and its recharge is established through a regression analysis of precipitation (P) and recharge (R_e).

2. Mediate Deep Water Table

If groundwater is of mediate depth, the recharge processes produced by discrete rainfall events merge into one single annual process. A few peaks of recharge rates, and a correspondence between the peaks and large rainfall events may be observed. A peak in the annual recharge process actually represents a recharge process produced by a group of discrete rainfalls clustering around a large rainfall corresponding to this peak. In this paper, the recharge process represented by a peak in an annual recharge process is called a sub-recharge-process (SRP), and the group of individual rainfalls producing a SRP is treated as one unit, termed an effective rainfall event (ERE).

A. Separation of SRP

Sub-recharge-processes (SRPs) can be separated from one another using an extrapolation method similar to that employed in the separation of hydrograph (*Linsley et al.*, 1949) and snowmelt runoff (*Martinec*, 1982). The unknown part in a SRP is estimated using the known data of a recharge process in the recession period, i.e., the recharge rates in the declining part of a peak. The following exponential attenuation is assumed for the recession of the recharge process

$$q = q_{infl}\exp[-\lambda(t - t_{infl})] \tag{1}$$

where q (mm/day) is the recharge rate at time t (day), q_{infl} and t_{infl} are the recharge rate and time at the inflection point of the recharge process, respectively, λ is a coefficient. In practice, it is difficult to find the exact location of the inflection point in a measured recharge process. To avoid this, the above equation is simplified as follows

$$q = q_0\exp(-\lambda t) \tag{2}$$

where q_0 is a lumped coefficient reflecting the influence of q_{infl} and t_{infl}. A least-square regression can be used to determine the coefficients in the equation.

The separation of SRPs begins from the first peak. After the first SRP is subtracted, separating the second SRP is carried out. Following this procedure, all SRPs can be divided. After being separated from each other, the SRPs are used to compute the total recharge R_e through an integration.

B. Determination of ERE

Effective rainfall events (EREs) are grouped together based on the intervals of adjacent rainfalls. A concept of a critical interval is introduced, which is defined as the minimum time interval required for two adjacent rainfalls to generate two distinct recharge peaks. The critical interval is determined by the time needed for a recharge process corresponding to an isolated rainfall event to climb to its top. It is estimated using the following equation

$$T_c = T_1 - T_0 \tag{3}$$

where T_0 is the time lag of the first isolated rainfall in an ERE, from the beginning of the rainfall to the beginning of the recharge, and T_1 is the time lag of the last individual rainfall in an ERE, from the beginning of the rainfall to the peak of the recharge.

A concept of effective precipitation is also introduced to account for the effect of soil surface evaporation between rainfalls in an ERE.

The effective precipitation of an effective rainfall event, P_e, is calculated by

$$P_e = \sum_{i=1}^{n} P_i - \sum_{i=1}^{n-1}\sum_{j=1}^{T_i} \epsilon_{ij} K_j \tag{4}$$

where P_i, i = 1, 2, ..., n, are the individual rainfalls within an ERE, T_i is the length of the ith rainfall interval (day), ε_{ij} is the daily water surface evaporation on jth day from the beginning of the ith rainfall interval, K_j is the ratio of evaporation from soil surface to that from water surface. A functional relationship between the evaporation ratio K and the evaporation time t after a rainfall may be expressed in the form of

$$K = \alpha\exp(-\beta t^{1/m}) \tag{5}$$

where α, β and m are coefficients. Again a least-square regression or an optimizing procedure may be applied to determine α, β and m. In the field, K may be estimated by measuring soil surface evaporation using the zero-flux-plane method (*Cooper*, 1981), and some other methods (*Allison et al.*, 1994).

C. Establishing Relationship of R_e vs. P_e

Employing the methods discussed above, the total recharge R_e of a SRP and the effective precipitation P_e of an ERE can be estimated. Through a regression analysis of the R_e and P_e results, their relationship is established. Then the total recharge at mediate deep groundwater table can be computed using the relationship and available rainfall data.

An extreme case of the mediate water table is with a uni-peak annual recharge process where only one peak appears in a whole year. In such a case, all the rainfalls in one year may be treated as one effective rainfall event, and the annual recharge process is treated as a sub-process in a multi-year continuous process. The relationship between annual rainfall and recharge can be obtained using the same method discussed above.

3. Deep Water Table

If the groundwater table is deep, the variations of the recharge rate are pretty small. Therefore, the annual recharge rate may be treated as a constant. Under the condition with a deep groundwater table, the process of rainfall-recharge is reduced to one average value of the annual recharge rate. The average value may be determined by analyzing the annual or multi-year water balance of the groundwater system, or by measuring the deep percolation of soil water using tensiometer or other methods (*Barnes et al.*, 1994; *Nimmo et al.*, 1994). As advanced computation methods are being developed, computer (numerical) models are increasingly becoming efficient and economical tools for studying the rainfall-recharge processes in the groundwater system.

RESULTS

Figure 1 shows the annual rainfall process of 1988 at an irrigation experiment station in Hebei province of the northern China. Figure 2 to 4 are the annual rainfall-infiltration recharge processes with groundwater depths at 1.5, 3, and 5 m, respectively. The recharge data were collected from lysimeters installed in the field. For the soil profile with a shallow water table, for example 1.5 m, a close correspondence between infiltration-recharge to a rainfall event was manifest. Comparing Figs. 1 and 2, we can see that almost every individual rainfall event greater than about 5 mm corresponds with a recharge. A linear relation of the rainfall data (P) in Fig. 1 and the recharge data (R_e) in Fig. 2 was formulated as follows

$$R_e = 0.87(P - 5.25) \qquad (6)$$

The value of 5.25 mm in Eq. (6) is called the threshold rainfall, below which no recharge will be generated.

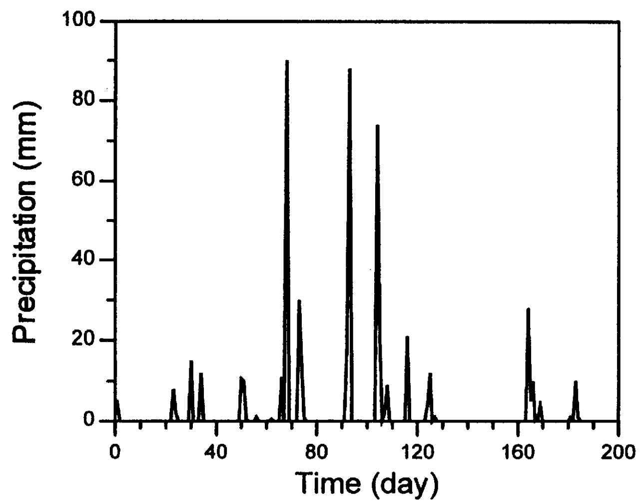

Fig. 1. Rainfall process during 1988.

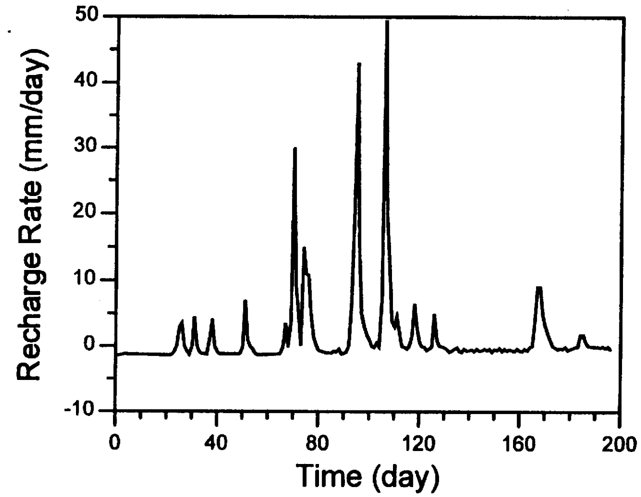

Fig. 2. Annual infiltration-recharge process measured using a lysimeter in the field with a water table at 1.5 m.

Numerically simulated recharge processes were also presented in Figs. 3 and 4. The good comparison between the observed and simulated results indicates that the numerical model is reliable to generate the rainfall-recharge processes. Figure 5 shows computer-simulated rainfall-recharge processes for soil profiles with groundwater depths at 6, 20 and 40 m. The variations of the recharge rate are very small for the groundwater table at 20 or 40 m, and the annual recharge rate is close to a constant. The results were in consistence with the observed phenomena on the loess plateau in the north-western China (*Yan*,1986; *Li*, 1986), where the groundwater table was about 40 m deep. A constant hydraulic gradients near the deep gullies were observed, which suggested that a constant infiltration rate be recharging the deep groundwater.

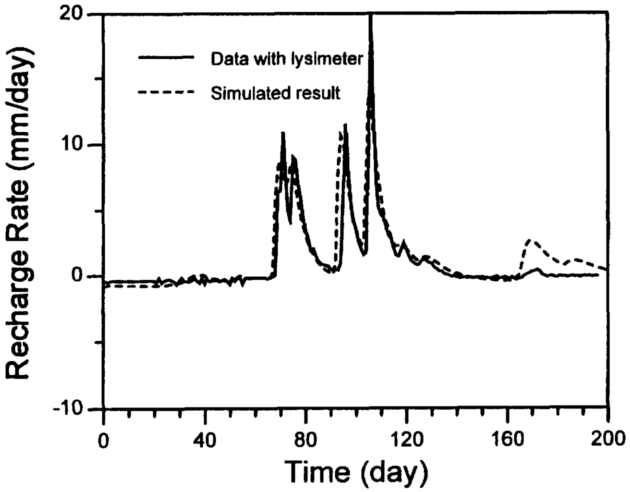

Fig. 3. Annual infiltration-recharge process measured using a lysimeter in the field with a water table at 3 m (solid line) and simulated process using a numerical model (dash line).

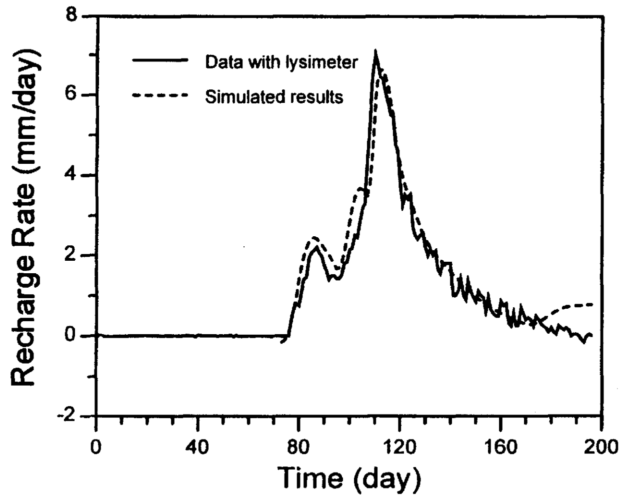

Fig. 4. Annual infiltration-recharge process measured using a lysimeter in the field with a water table at 5 m (solid line) and simulated process using a numerical model (dash line).

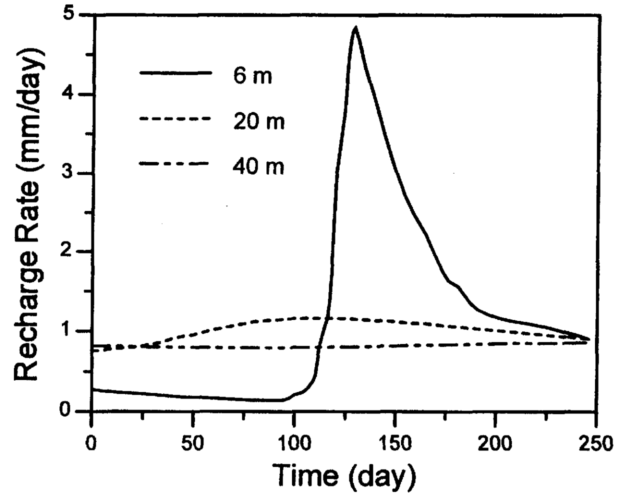

Fig. 5. Recharge processes generated with a numerical model for groundwater depths at 6, 20 and 40 m.

For soil profiles with a mediate deep water table, the relationship between rainfall and recharge becomes more complicated. Numerical simulated annual recharges under different annual rainfall processes were used to establish the correlation between effective rainfalls and their infiltration recharges, using the techniques described above. The procedure of analyzing this correlation is summarized as follows:

a). Divide the annual recharge process into sub-processes corresponding to peaks in the process, and separate the sub-processes through the extrapolation method using known recharge rates in the recession period.

b). Divide the annual rainfall process into effective rainfall events based on the correspondence between large rainfalls/concentrated rainfall groups and the peaks in the recharge process.

c). Calculate the effective precipitation P_e and the total amount of recharge R_e produced by P_e. By performing a regression analysis on the P_e and R_e data, a functional relationship between them was obtained. Figure 6 presents an example of the relationship obtained from computer-simulated data at a groundwater depth of 4 m. The linear relationship between P_e and R_e is in the form of

$$R_e = 0.87(P_e - 27.4) \quad (7)$$

with a coefficient of determination (r^2) 0.980. Again the value of 27.4 mm is the threshold rainfall. Notice that it is much larger than the threshold value for groundwater depth 1.5 m.

While establishing the P_e and R_e relationship, soil surface evaporation between rainfall events was taken into account, and the evaporation ratio of soil surface to water surface was introduced to calculate the amount of effective rainfalls. The variation of evaporation ratio with evaporation time was analyzed using computer-simulated data. Equation 5 was employed, and the evaporation ratio and evaporation time were highly correlated with r^2 = 0.997.

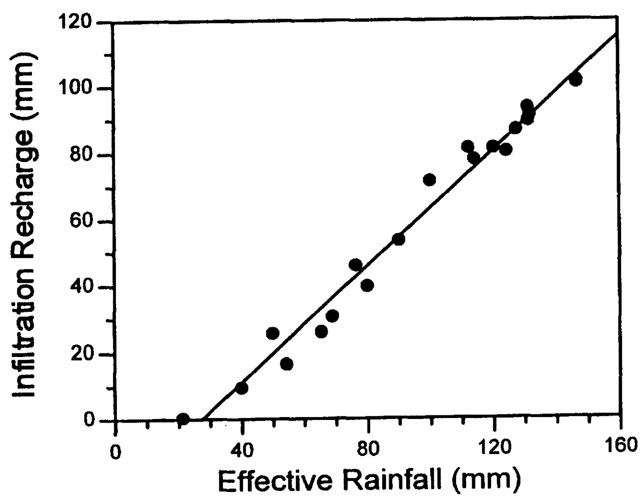

Fig. 6. The relationship between the effective precipitation P_e and the total amount of recharge R_e produced by P_e.

CONCLUSIONS

The relationships of annual recharge processes with respect to groundwater depths were investigated using lysimeter-observed data and computer simulations. For the purpose of estimating infiltration-recharge from rainfall data, groundwater systems were classified into three categories, such as with shallow, mediate deep and deep water tables, according to groundwater depths, and based on the correspondence between rainfalls and the infiltration-recharge. Methods were developed to estimate infiltration-recharge at different groundwater depths.

For a shallow groundwater depth, lysimeter-observed groundwater data were used for establishing the correlation between individual rainfalls and their infiltration-recharge.

For a groundwater system of mediate depth, concepts of effective rainfall events and a critical time interval between adjacent rainfalls were introduced to analyze the rainfall-recharge processes. The soil surface evaporation between individual rainfalls was taken into consideration, and the evaporation ratio of soil surface to water surface was introduced to calculate the amount of effective rainfalls. An extrapolation method was used to separate sub-processes in the annual recharge process. The simulated and extrapolated recharge rates exhibited an excellent agreement.

Computer-simulated data were used to study the relationship between effective rainfalls and the infiltration recharge. The high correlation between them indicates that the methods developed in this paper are feasible for practical application.

For the deep groundwater table, the variations of the recharge rate is pretty small, the annual recharge rate may be treated as a constant. Numerical simulations demonstrated these results and may be used as an efficient tool to compute infiltration-recharge at deep groundwater.

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