Estimation of Groundwater Recharge on Various Sites in a Tropical Semiarid Basin using a Water Balance Model in Dry Surface Soil.

Shinichi Onodera

Environmental Science, University of Tsukuba
1-1-1 Tennodai Tsukuba 305 Japan
Fax:+81-298-53-6709
Email:onodera@kankyo.envr.tsukuba.ac.jp

Abstract

In this study, a simple water balance model linking with Green-Ampt model was improved on basis of measured results in a semiarid upland, Tanzania, and it was applied to local areas under different soil or rainfall conditions in a same basin. In spite of only three parameters with regard to the part under the ground in this model, the calculated value simulated well the measured value. In this model, the critical rainfall which groundwater recharge occurs was determined by the soil physical properties, and field observations also indicated this tendency. Furthermore, the effects of the soil and rainfall condition on the groundwater recharge were confirmed.

1. Introduction

Evaluation of groundwater recharge in a regional basin is a basic information for efficient groundwater resource management as well as for forecasting hydrologic process with the change in climate or land use (Allison et al.,1994). It is particularly important in regions where groundwater is a water source for municipal use. In recent years, many studies on groundwater recharge in various semiarid zones have estimated the natural groundwater recharge rate using physical (Gee et al., 1994) and chemical methods (Sukhija et al., 1988; Gee and Hillel,1988; Sharma, 1989 etc.). On the other hand, spatial and temporal informations of plant cover or soil condition can be obtained using remote sensing data. In spite of the accumulation of many case studies, it has been difficult to predict recharge rate in a regional basin where local areas under the various conditions might exist. Because the large errors were included in estimating the actual evapotranspiration and water flux in the vadose zone (Gee and Hillel,1988) , there were few applicable physical models to predict recharge rates in various local areas.

For developing the applicable physical model to groundwater recharge in semiarid zones, it is necessary to confirm the hydrological process in surface soil using direct physical methods, and to improve the classic physical model on the basis of measured processes. In this study, a simple water balance model linking with Green-Ampt model was improved on basis of measured results in a semiarid upland, Tanzania, and it was applied to local areas under different soil or rainfall conditions in a same basin.

2. Water balance model in surface soil

The case considered here is the water balance in surface soil without the absorption by the plant roots in the deep soil under the tropical semiarid. If the transpiration is negligible in deep soil, the evaporation front locates near ground surface. Therefore, the water balance in surface soil is described as:

$$R = P - E - Q + \Delta V \qquad (1)$$

where R, P, E, Q, ΔV are the groundwater recharge, precipitation, evaporation, overland flow, and change in soil water content, respectively. In tropical semiarid regions, the annual potential evapotranspiration exceeds 2000mm, and daily potential evapotranspiration exceed 5mm even during a rainy season. On the other hand, the daily actual evapotranspiration (AE) rapidly decreases with the soil water content after the rainfall event, and it always is extremely lower than the potential evapotranspiration (PE) during the dry season (Hayashi, 1990). In this model, the runoff was used measured values and evaporation rate was calculated by the estimated PE (Onodera et al., 1996) and the measured linear relationship between the PE and AE.

During a rainfall event, the rain water usually fills with pores in surface soil and flows over the ground surface (Onodera, 1996). In addition, it penetrates concentratedly and partially in dry sand (Grass et al., 1989; Onodera, 1993) or through the preferred pathway (Stephens, 1994) . The infiltration process in the dry soil with the overland flow is similar to Green-Ampt Model. Based on the assumption of the model, the infiltration rate (q) is written using Darcy's equation as,

$$q = Ks\,(1 - (\psi b - \psi t) / Ls) \qquad (2)$$

where, Ks is the permeability and it equals the saturated hydraulic conductivity, ψ b shows the pressure head at the wetting front and equals the water entry value (ψ w), ψ t shows the pressure head at the ground surface, and Ls shows the length of the wettiig zone. ψ t is the positive value under the ponded infiltration and equals the ponded depth or overland flow depth. Then ψ t becomes the air entry value (ψ a) under the redistribution process. Based on the equation (2), it is deduced that the hydraulic gradient is negative and the water flux will be upward when Ls is smaller than the difference between ψ w and ψ a. Therefore, the depth of the surface soil layer (Le) where little soil water contribute to groundwater is determined as the difference between ψ w and ψ a. Because ψ t becomes ψ a at the end of the rainfall, the wetting zone is approximately the saturated condition (θ s), and the critical rainfall amount (Pc) is defined as,

$$Pc = Le\,(\theta s - \theta i) \qquad (3)$$

where, θ i is the soil water content before a rainfall event. According to the equation (1), it is determined that groundwater recharge occurs when the difference between P and Q exceed Pc. The excess water rapidly moves downward as partial and concentrated flow without evapotranspiration (Onodera, 1993).

Parameters (ψ a and θ s) of the model used the physical properties measured by the laboratory experiments (Table 1). In other hand, because the experimental method of ψw in the laboratory have not been established, the observed value by Onodera (1996) was applied to ψw. Onodera (1996) observed that the pressure head at the depth of 20cm increased rapidly from the dry condition to -3cm (±3cm) with the arrival of the wetting front. Therefore, it was assumed that ψ w was -3cm in this model.

Table 1 Soil physical properties.

soil type	ψa	θs	Ks	color
sand	-10	35	$5x10^{-3}$	grayish brown
silt	-16	50	$5x10^{-4}$	reddish brown

* ψ a: pressure head at the air entry,
Ks : saturated permeability
θ s: water content at the saturated condition

3. Study area and method

The study area is located in Makutapora Basin, 25km north of Dodoma, the Capital city of Tanzania

(Fig.1). The main hills, Chenene Hills, lie in the northeastern margin of the basin, and Makutapora Swamp is surrounded by pediplain uplands in the center of the basin. The elevations of the hills, swamp and pediplain upland are around 1200 to 2000, 1060, and 1090 to 1150 a.m.s.l., respectively. The basement consists mainly of Precambrian granitic rocks and small block of metasediments. The basement is complexly faulted. A thin sandy soil of the high permeability and reddish silty soil of the low permeability (Table 1) covers the granitic and sedimentary rock on the slope and upland, respectively. On the other hand, a thick silty or clayey soil covers on the swamps and lowlands. The deep groundwater exists in the weathered or fissured rocks under the Swamp. The area has a tropical semiarid climate. Most of the annual rainfall, about 600mm, occurs from December to April. Shindo (1994) measured the distribution of rainfall in the basin, and indicates that the amount at Chenene on the foot of the hills was 1.9 times of that at Makutapora, and that the frequency of rainfall events exceeding 50mm at Chenene was twice that at Makutapora.

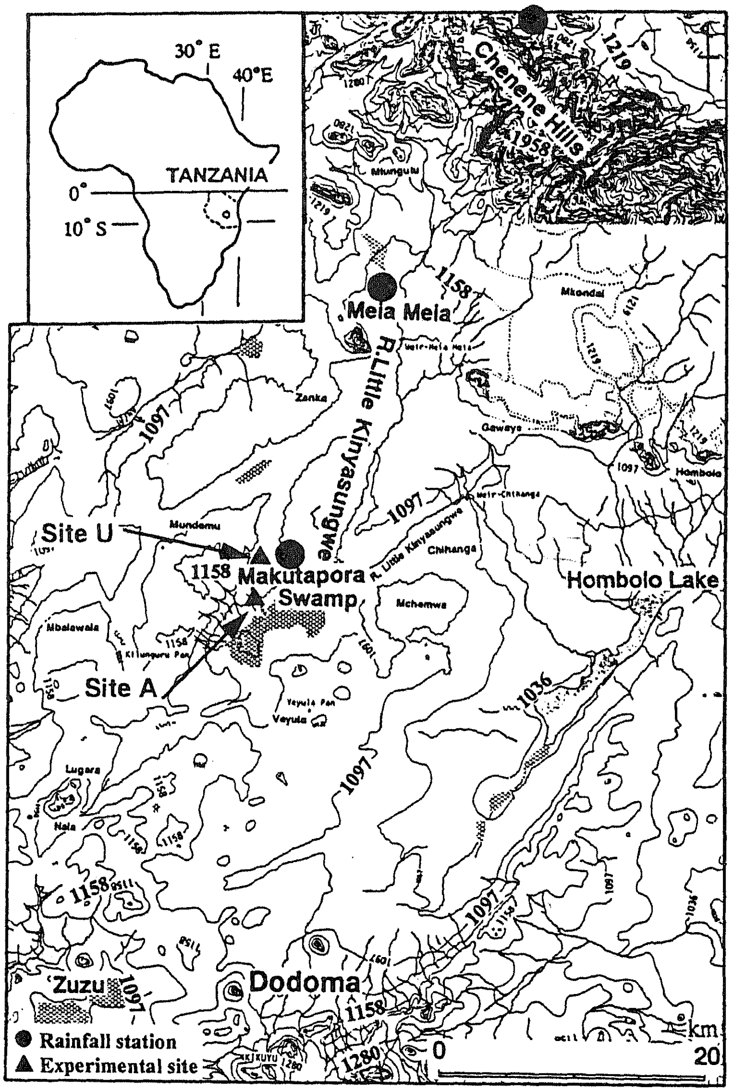

Fig.1 Location of study area.

To evaluate the effects of the rainfall and soil conditions on the groundwater recharge and calibrate the model with observed values, the observations of hydrological processes were carried out at two experimental sites of the western side of Makutapora Swamp, from December in 1989 to March in 1991. One is on the pediplain upland with sandy soil (Site U) and the other is on the gentle slope with reddish soil (Site A). At Site U, the tensiometer observation, soil water sampling and estimation of evaporation were conducted, respectively. The evaporation rate was estimated using the direct physical method. An undisturbed 100cc soil sample was collected on the ground surface every morning using a steel cylinder of the length of 5cm and weighed to measure the water content. The collected sample cylinder was installed on the ground surface every day and weighed after one day to measure the daily actual evaporation rate. As the bottom of the cylinder was sealed by a cover, the evaporation rate was estimated by considering rainfall and overflow amount. However, this method may underestimate the evaporation rate when the evaporation front locates below the 5cm deep such as during the dry season. Therefore, the values observed during the rainy season was used for calibrating the model. On the other hand, the tensiometer observation and measurements of every event runoffs at Site A were conducted, respectively. The runoff was measured at four field plots of 3.2m x 3.2m ($10m^2$) in size.

4. Results and discussions

4.1 Water balance in the sandy soil on the upland

Figure 2 shows the seasonal variation in the water contents and recharge rates estimated using the direct method and calculated using the water balance model from November 1990 to April 1991, respectively. Based on the water balance in the surface soil, the recharge rate was estimated by the difference between the rainfall at one event and the evaporation rate accumulated during the period from that rainfall event to the next one. The recharge rate was obviously high after a rainfall event of more than 40 mm/day, and water content in the surface soil increased. In contrast, the recharge rate was negative after a rainfall of less than 10mm/day except for the wet period. From these results, the recharge rate was related linearly to the rainfall amount (Onodera,1996) . The relationship indicates that the recharge rate is negative at events of less than 15mm and the loss rates with evaporation is relatively constant and around 15mm for the rainfall at events of more than 15mm. On the other hand, the Pc on the upland was calculated to be 21mm under the dry condition and 11mm under the wet condition using the parameters in Table 1, respectively. The observed tendency agreed with the calculated results in the basis of the concept of the model.

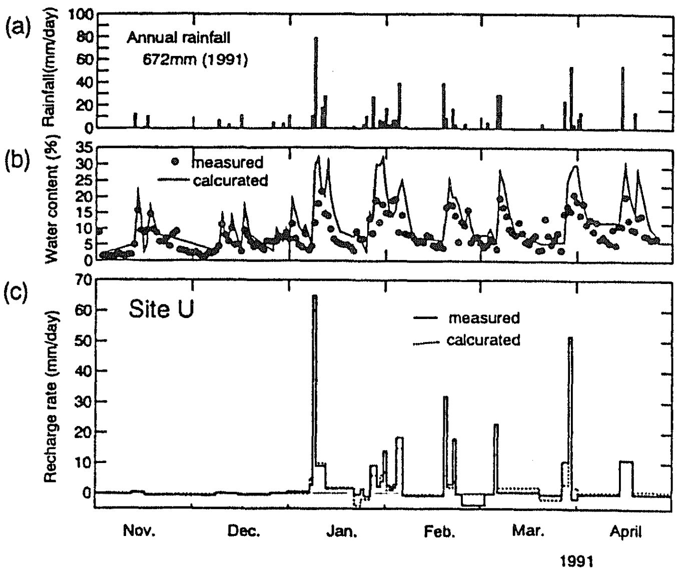

Fig.2 Seasonal variations in the (b)water content and (c)recharge rate at Site U.

Furthermore, the variation in the recharge rate calculated using the model approximately agreed with the observed variation, whereas the variation in the calculated water content was larger than the observed one because the calculated range in the model was narrower than the observed one. The cumulative recharge rate during this rainy season was estimated to be 341mm from the observed data and 328mm from the calculated data, respectively. The recharge rate of shallow groundwater on the same site was also estimated to be 330mm/year by Onodera (1993) using the tracer method. It estimated using the direct method was similar to one using the tracer method. These results support the validity of this model.

4.2 Effects of the soil condition on groundwater recharge

Based on the validity of the model described above, the applications of it to the estimations of recharge rates under the various soil and rainfall conditions were attempted. To evaluate the effect of the soil condition, the groundwater recharge rates were estimated in the adjacent hydrogeomorphological units with the reddish silty soil and sandy soil around Makutapora and Meia Meia, respectively. The Pc in the reddish silty soil was calculated to be 59mm under the dry condition and 20mm under the wet condition, respectively, based on the model parameters. In the gentle slope (Site A) around Makutapora, the annual recharge rate was estimated to be 1mm. The observed variation in pressure heads at Site A supported the results calculated using the model. The pressure head at the depth of 20cm rose up to 0cm H_2O after a rainfall event, whereas it at the depth of 100cm kept very low throughout the rainy season.

The results indicate that the wetting front stops at the surface soil layer.

In addition, the groundwater recharge was evaluated on the pediment slope with the reddish silty and sandy soil in Meia Meia, where the annual rainfall was 1.2 times of that at Makutapora. Figure 3 shows the variation in calculated recharge rates on the pediment slopes with the reddish soil and sandy soil around Meia Meia. The effect of the soil condition on the groundwater recharge is clear. The annual recharge rates were estimated to be 65mm in the reddish soil and 427mm in the sandy soil, respectively. The recharge rate in the reddish soil was less than that in the sandy soil. The grain size of soil affects the ϕ a as well as the permeability. The smaller the grain size is, the lower the ϕ a is and the larger the Le and Pc are, respectively.

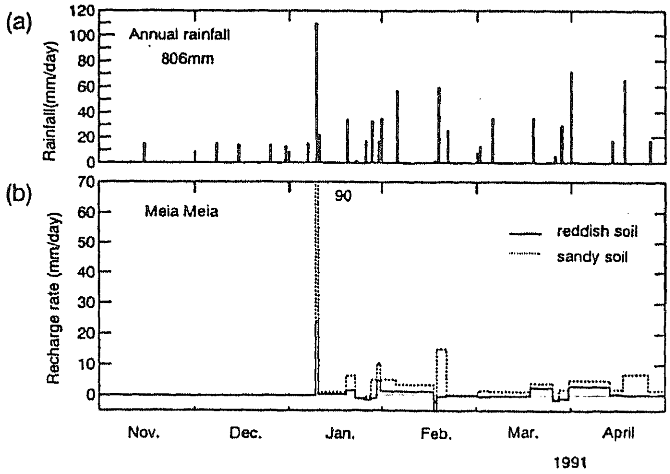

Fig.3 Seasonal variations in recharge rates in the reddish silty soil and sandy soil.

4.3 Effects of the rainfall condition on groundwater recharge

To evaluate the effect of the rainfall condition, the groundwater recharge rates were estimated on the three areas, Makutapora, Meia Meia, and Chenene, where the annual rainfalls in 1991 are 672mm, 806mm, and 1414mm, respectively. The calculated annual recharge rates on the sandy soil were 328mm in Makutapora, 427mm in Meia Meia, and 893mm in Chenene, respectively. The rates were 48.8% of the annual rainfall in Makutapora, 53.0% in Meia Meia, 63.2% in Chenene, respectively. These results indicated that the recharge rate increased with rainfall amount. Particularly, it increased with the frequency of the rainfall event of more than 50mm as well as the event rainfall amount. On the other hand, the calculated recharge rates on the reddish soil were 1mm in Makutapora, and 65mm in Meia Meia, respectively. The rates were 0.1% of the annual rainfall in Makutapora and 8.1% in Meia Meia, respectively. Because the Pc is the distinct value for the soil type, the effect of the rainfall condition was different according to the soil condition.

5. Concluding remarks

In this study, the simple water balance model linking with Green-Ampt Model was applied to the semiarid basin in Tanzania, to evaluate the groundwater recharge in a regional basin using the less parameters under the ground. Thought the parameters under the ground in this model were only three, the calculated value simulated well the measured value. Furthermore, the effects of the soil and rainfall conditions on the groundwater recharge were confirmed. In the future study, the determination of spatial distribution of soil and the estimation of the variation in rainfall and evapotranspiration will be possible using the remote sensing technique. Therefore, it is still more necessary to establish the experimental method of the soil parameters and to evaluate the water absorption by the deep plant root in this model.

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