Estimation of Groundwater Recharge by the Water Balance Analysis using DAWAST Model

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ABSTRACT

Groundwater recharge mostly depends on the precipitation and the estimation of the recharge is important to yield the optimal safe discharge of groundwater that should not exceed the recharge, since the over-extraction can cause to draw down the groundwater level, to pollute the surrounding area, and to damage the eco-systems.

Among the conventional methods to estimate groundwater recharge including methods of groundwater regime analysis, numerical analysis, water balance analysis, and base runoff separation analysis, this research developed a method for the estimation of groundwater recharge by yielding daily soil moisture content and watershed evapotranspiration from the water balance concept of the unsaturated and saturated layers in rainfall-runoff model called DAWAST.

The goal of the research is to estimate the groundwater recharge fulfilling conditions of the safe discharge for any season. To meet this goal, the data of groundwater level and stream flow rate have been monitored in a study area and used to validate the model.

1. INTRODUCTION

Development of substitutable water resources became an impending assignment in efficient utilization plan of water resources, since surface water development reaches the limit.

Various researches had been continued over artificial rain, seawater desalination, and groundwater development for the development of substitutable water resources. When economical efficiency is taken into account, groundwater development can be considered as a principal plan of substitutable water resources.

Groundwater development preferably as substitutable water resources, however, can cause natural disaster without solving the following prerequisites or problems.

First, groundwater is difficult to perceive the shortage and its utilization plan should be established under the annual groundwater recharge rate in order to prevent natural disaster.

Second, long-term utilization policy of groundwater is established on the basis of the groundwater recharge rate. However, the groundwater recharge rate is produced by the surface water hydrological analysis based upon weather data and/or foreign statistical techniques. Therefore, the authoritativeness of national water resources plan is insufficient.

Third, at present, the groundwater recharge rate in Korea is estimated by unverified methods.

Fourth, from the analysis result of future water supply-demand, Korea is classified as the 21th century water resources insufficiency country and thereafter, the government is promoting the water resources plan. Therefore, groundwater is to be preserved and managed as one of the main pure water resources.

At present, there are several researches related to infiltration rate for soil layers, however, there is no reliable research about groundwater recharge. Therefore, there should be some cornerstones of estimation for groundwater recharge.

This research theoretically establishes the water balance equation for groundwater recharge from the basic equation of DAWAST model (1992, Tai-cheol Kim), and experimentally observes the values of model parameters from an experiment site, and then physically verifies between the experimented and observed results to develop a reliable technique for groundwater recharge. Furthermore, the research wishes to present suitable estimation technique for groundwater recharge indirectly by verifying the groundwater recharge of DAWAST model with observed groundwater recharge.

2. SELECTION OF EXPERIMENT WATERSHED

The experiment watershed was selected at Chojeong-ri in Korea. The watershed map is shown as Fig.1. The watershed area is 28.3 km^2, the watershed slope 8% and the length of main river 6.75 km. Water gauge was installed on Seodang bridge and soil moisture measurement instrument and automatic weather station were set near Biheung reservoir. These three data have been collected since March 2001. The water level of stream was measured in every hour by automatic water gauge (WL-14). A set of soil moisture equipments (DIK-321A) was installed to measure the soil moisture at the depths of 30cm, 50cm and 80cm in every hour. The stream flow was measured with propeller-type flow meter (BFM-001) twice a month in normal period and at each water level in flood period.

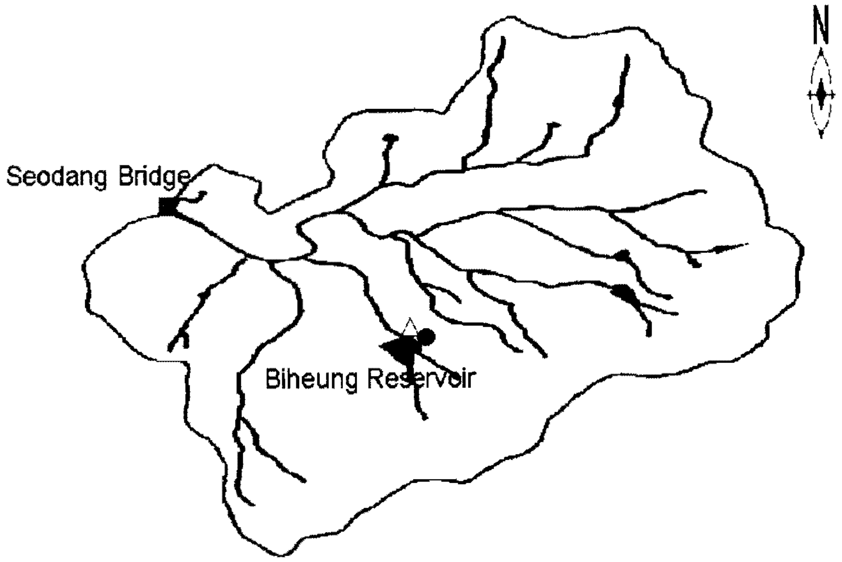

Fig.1. Watershed Map of Experiment Site

3. ESTIMATION OF GROUNDWATER RECHARGE BY DAWAST MODEL

3.1 DAWAST Model

Since phenomena of rainfall and runoff are very complicated according to watershed characteristics, forecasting natural phenomenon is accomplished by simplifying hydrologic reaction to various kinds mathematical expression in order to apply them to actual watershed. Specially, in practical manners, simplifying weather properties and input data of watershed characteristics and also simplifying the structures and parameters of model can make it possible to develop a lumped, conceptualized hydrological model.

This model is based on the conceptualized model and is consisted of 3 sub-models: the optimized model, the generalized model and the regionalized watershed model..

The optimized model is applied to the watershed that has an observed runoff data by compensating the model parameters. The generalized model can be applied to the watershed without the observed runoff data by forecasting parameters from watershed characteristics. The regionalized watershed model can estimate daily runoff for the watershed that has no investigation about the watershed characteristics or has difficulty to derive them by converting the parameters from the optimized model.

3.2 Conceptualization of DAWAST Model

As shown in Fig.2, under the supposition of a closed system that is constant with time, the DAWAST model simplifies the system of the watershed in 3 water layers such as ground surface, unsaturated layer and saturated layers in order to conceptualize hydrological reactions of rainfall-runoff in the watershed and executes hydrological water-balance analysis in daily basis.

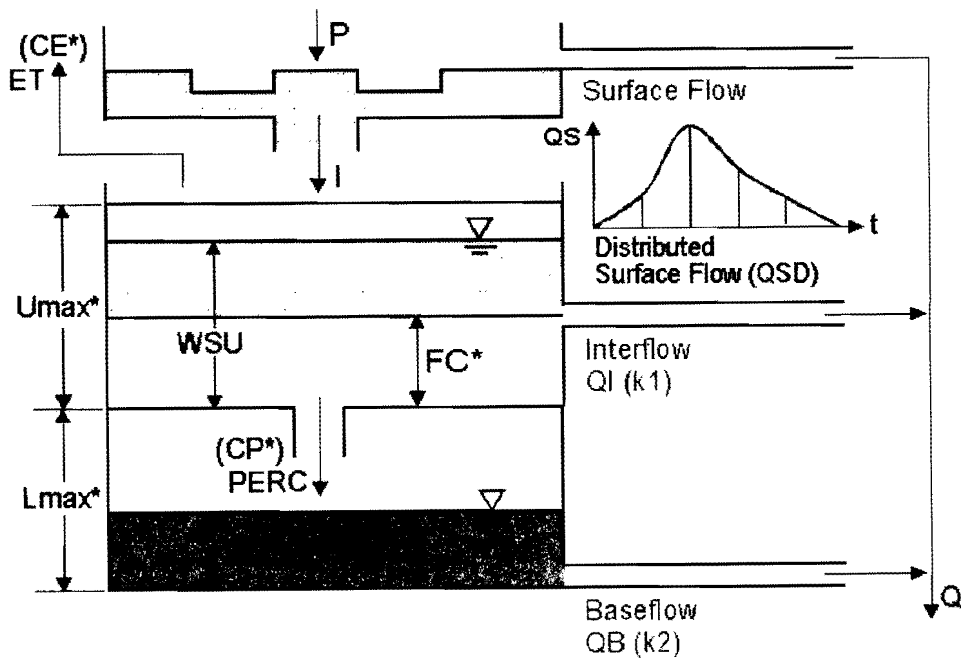

Fig. 2. Schematic Representation of DAWAST Model

Component of runoff is divided into surface runoff, interflow and base runoff represented by 3 water layers, and each runoff considered with watershed soil moisture is analyzed by the method mentioned above and then the daily runoff is estimated by summing up the each component.

This model calculates surface runoff, interflow and base runoff in rainy season and base runoff only in non-rainy season, respectively, and hence calculates total runoff consecutively from the beginning day to the closing day of the simulation.

The model is consisted of 5 water balance parameters that are UMAX, LMAX, FC, CP, and CE shown on the above figure and 3 tracing parameters that are daily runoff distribution rate (Ui), interflow and base runoff recession curve coefficients (k1 and k2), respectively. These parameters are corrected by optimization technique and inputted. Input data for the model are watershed area, daily rainfall, and daily evaporation and output data is daily runoff at the site.

3.3 Water Balance Analysis of Watershed Soil Moisture

3.3.1 Water Balance in Unsaturated layer

Soil moisture in unsaturated layer is increased by infiltration through rainfall and is decreased by the watershed evapotranspiration and percolation. Water balance equation in unsaturated layer is expressed as :

$$WSU_{i+1} = WSU_i + I_i - ET_i - PERC_i \qquad (1)$$

where, WSU_i : Soil moisture content (mm) in unsaturated layer on i^{th} day,

I_i : Percolation (mm) on i^{th} day, ET_i : Watershed evapotranspiration (mm) on i^{th} day.

$PERC_i$: Percolation (mm) on i^{th} day.

3.3.2 Water Balance in Saturated layer

Soil moisture content in saturated layer is increased by percolation at precipitation and is decreased by base runoff. This relationship is expressed in equation (2) and (3)

$$WSS_{i+1} = WSS_i + PERC_i - QB_i \qquad if\ P_i > 0 \qquad (2)$$

$$WSS_{i+1} = WSS_i - QB_i \qquad if\ P_i = 0 \qquad (3)$$

where, QB_i : Base runoff (mm) in saturated layer on i^{th} day.

WSS_i : Soil water content (mm) in saturated layer on i^{th} day.

3.4 Revision of Inner Parameters

3.4.1 Retention Parameter

Surface runoff is very important, since it is biggest quantitatively amongst the components of runoff. In this model, surface runoff is estimated by transforming SCS effective rainfall method (United States Department of Agriculture, 1972).

SCS method has been widely used in runoff analysis because of the simplicity of input data, basic structure and assumption of the model, and of easy application of Curve number (CN) representing the watershed characteristics such as soil type, land utilization, watershed wetness conditions, etc. In SCS method, the curve number is basically median value that roughly represents soil and cover condition of the watershed, and is the value of the average soil moisture condition ignoring rainfall intensity and the value changing with infiltration, evapotranspiration, soil moisture, lag time, etc.

In this model, SCS retention parameter S has been changed the concept and newly defined from maximum storage capacity to available storage capacity of unsaturated layer (Sa) so that the parameter may be suitable for continuous processing of watershed soil moisture and continuous simulation of the model. Hence, in equation (4), parameter S is replaced into from equation (5) to equation (6)

$$QS = (P - 0.2S)^2/(P + 0.8S) \qquad (4)$$

$$S = 25{,}400/CN - 254 \qquad \textbf{(SCS)} \qquad (5)$$

$$S_a = UMAX - WSU, \quad UMAX > WSU \quad \textbf{(DAWAST)} \qquad (6)$$

where, QS : Surface runoff (mm), P : Daily rainfall (mm)
S : Maximum potential storage capacity (mm), CN : Curve number

3.4.2 Watershed Evapotranspiration

Watershed evapotranspiration is estimated by using the following equations which is revised form of Beken's formula:

$$ET_i = Eo_i(1 - e^{-CE \times WSU_i}) \qquad (7)$$

$$Eo_i = C \times EP_i \qquad (8)$$

where, Eo_i : Potential evapotranspiration (mm) on i^{th} day
EP_i : Pan evaporation (mm) on i^{th} day CE : Watershed evapotranspiration coefficient
C : Monthly coefficient of watershed coverage
WSU_i : Present soil moisture content (mm) of unsaturated layer

In watershed water balance,

$$ET = P - Q - \Delta G - \Delta S \qquad (9)$$

where, ET : Watershed evapotranspiration, P : Precipitation, Q : Runoff
ΔG : Variation of soil moisture, ΔS : Variation of groundwater level

Then, watershed evapotranspiration coefficient (CE) can be derived from the above equations (7),(8) and (9).

3.5 Estimation of Groundwater Recharge Rate by DAWAST Model

Groundwater recharge consists of unconfined and confined groundwater recharge, and it depends on topographical factor, meteorological factor, land utilization factor, geological factor of the watershed, and characteristics of aquifer.

However, most geological structure in Korea including Chojeong watershed can not be clearly distinguished between unconfined and confined groundwater. Therefore, there used to no classification of groundwater type for groundwater recharge estimation. On the other hand, for the case of no observed data, watershed hydrological model such as DAWAST can estimate the variation and recharge amount of groundwater indirectly from water balance analysis.

Where, groundwater recharge (RG) is to say in 2 aspects: the groundwater recharge in narrow sense that is groundwater storage (ΔS_g) stored by deep percolation and the groundwater recharge in broad sense that includes base runoff (QB) returning to rivers from infiltration. This relation is shown in equation (10)

$$RG = QB + \Delta S_g \tag{10}$$

Therefore, the water balance including groundwater in a watershed is defined in equation (11) and represented in Fig. 3.

$$\Delta S_g = P - Q - ET + Q_g - \Delta S_s \tag{11}$$

where, ΔS_g : variation of groundwater storage, P : Precipitation,
ET : watershed evapotranspiration, Q : runoff (direct runoff + base runoff),
ΔS_s : soil moisture change in watershed,
Q_g : groundwater inflow (or outflow) from (to) other watersheds.

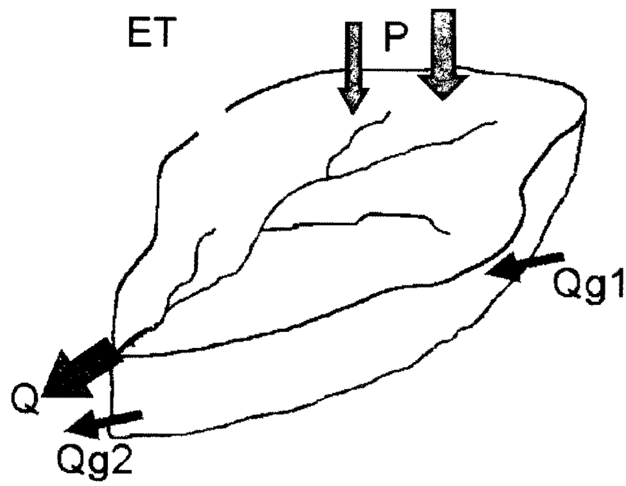

Fig. 3 Watershed Map of Water Balance

Supposing that the groundwater inflow and outflow are the same, then $Q_g = 0$. If soil moisture change in watershed (ΔS_s) and variation of groundwater storage (ΔS_g) are replaced with ΔWSU and ΔWSS in DAWAST model, the groundwater recharge in narrow sense (ΔS_g) can be defined as:

$$\Delta WSS = P - QD - QB - ET - \Delta WSU \tag{12}$$

where, ΔWSS : variation of groundwater storage, QD : direct runoff,
ΔWSU : soil moisture change in watershed, QB : Base runoff.

Finally, the groundwater recharge in broad sense is estimated by adding base runoff to ΔWSS.

$$RG = \Delta WSS + QB = P - QB - ET - \Delta WSU \tag{13}$$

In the research, daily precipitation, runoff, soil moisture content and the variation of groundwater level in Chojeong station have been observed and measured to estimate groundwater recharge using DAWAST, one of the watershed hydrological models.

4. RESULTS AND DISCUSSION

4.1 Data Measurements

4.1.1 Soil Moisture Measurement

To measure soil moisture content (WSU) of unsaturated layer, soil moisture contents in 30 ㎝, 50 ㎝, 80 ㎝ from soil surface were measured by TDR method. The soil moisture values measured by each hour were converted to daily average values for the model.

Also, since the measured data were given for soil moisture content (%v) and they should be converted to WSU values in mm unit in order to apply to the modified Beken's equation (7), the model could find the correlation between soil moisture content and SMC. The correlated equation is shown in equation (14) with r=0.984. From the equation of $SMC(\%v) = 0.448 + 0.086 \times WSU(mm)$,

$$WSU = (SMC - 0.448)/0.086 \qquad (14)$$

The transformed soil moisture content, WSU, is shown in Fig. 4.

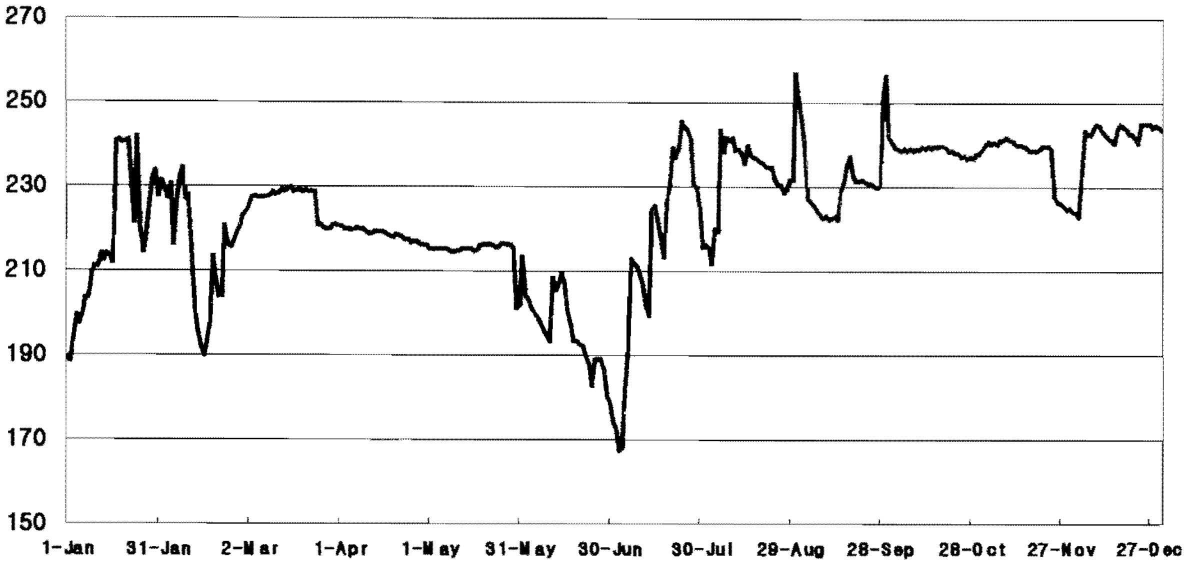

Fig. 4 Transformation of SMC into WSU in 2002

4.1.2 Runoff Measurement

The stream runoff for Chojeong station was measured twice a month during the experiment period, regularly and the rating curve was yielded from the result.

4.1.3 Estimation of Watershed Evapotranspiration Coefficient

Considering the soil moisture content transformed to WSU by equation (14) and groundwater level, the model calculated the coefficient of watershed evapotranspiration with the water balance analysis. The calculated water balance is shown in Table1.

When evapotranspiration is calculated by the day, the result for 2002 was shown as Fig.5. From the calculation result, some part showed negative values of evapotranspiration and for this case, the daily coefficients of watershed evapotranspiration (CE) were also given in negative values. This is caused by very big precipitation and this case is difficult to explain with a short period of water balance analysis. For stable results, the calculation for CE is recommended with 15-day, 20-day and monthly data. Therefore, only for the estimation of CE, the model applied monthly water balance analysis that was used in most common.

Table 1. Water Balance Analysis with Observed Data. (unit:mm)

Classification		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2001	Precip.	-	-	12.7	8.0	8.9	233.5	122.8	70.8	7.0	46.6	6.8	8.4	525.5
	Runoff	-	-	5.3	6.0	6.2	120.0	67.0	24.6	6.2	25.6	6.0	7.3	274.2
	Δ WSU	-	-	7.35	-5.93	-16.86	25.93	27.79	-32.79	-49.93	0.65	-3.61	-3.80	-51.20
	G.L.	-	-	0	0	-0.13	-2.41	0.73	-0.17	0.36	0.09	0.08	0.16	-1.29
	E.T.	-	-	0.05	7.93	19.69	89.95	27.27	79.18	50.37	20.26	4.33	4.74	303.77
2002	Precip.	52.0	6.0	36.0	144.0	102.5	57.5	175.0	596.0	96.5	59.0	17.5	58.5	1,400.5
	Runoff	15.0	5.6	9.7	82.5	45.0	8.2	94.5	436.4	27.6	23.4	6.2	31.2	785.3
	Δ WSU	34.39	-4.84	-1.95	-4.94	-14.04	-23.37	36.98	41.16	-0.47	-18.49	-12.98	18.8	50.25
	G.L.	-0.15	0.06	-0.01	-0.24	0.8	0.35	-0.22	-0.59	0.12	0.57	-0.7	-0.25	-0.26
	E.T.	2.76	5.18	28.26	66.68	70.74	72.32	43.74	119.03	69.25	53.52	24.98	8.75	565.21
2003	Precip.	15.5	18.5	48.5	205.5	131.0	145.5	361.5	371.0	-	-	-	-	1297.0
	Runoff	13.1	6.1	9.1	140.0	72.0	65.1	238.3	249.0	-	-	-	-	792.7
	Δ WSU	-30.31	0.34	18.63	41.05	-20.47	12.67	5.7	2.67	-	-	-	-	30.28
	G.L.	2.82	0.54	1.12	-0.22	1.00	0.01	1.07	0.39	-	-	-	-	6.73
	E.T.	29.89	11.52	19.65	24.67	78.47	67.72	116.43	118.94	-	-	-	-	47.29

※ Precip. : Precipitation, G.L. : Groundwater Level in depth, E.T. : Evapotranspiration

The monthly CE was estimated from the calculated ET by using the modified Beken's equation (7) and is shown in Table 2 and Fig.6.

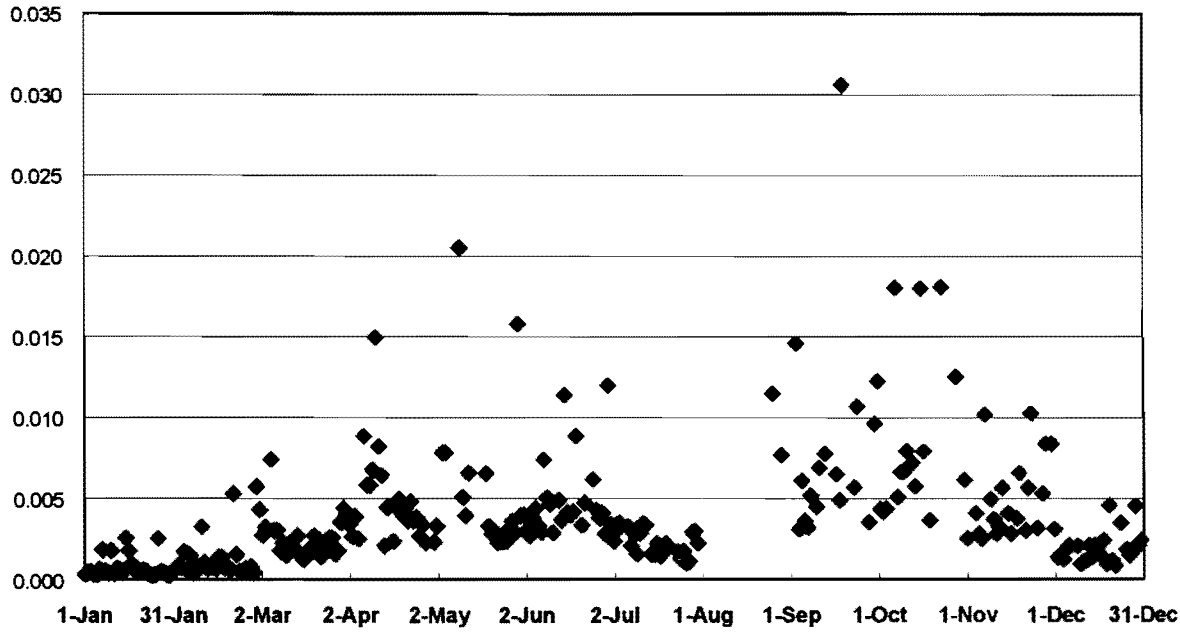

Fig. 5. Daily CE calculated from the water balance analysis in 2002

Table 2. Monthly Coefficient of Watershed Evapotranspiration (CE)

Mon. / Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	-	-	0.000007	0.000473	0.001426	0.010755	0.001789	0.005000	0.003999	0.003483	0.001220	0.001368
2002	0.000763	0.001104	0.002660	0.005000	0.005333	0.004881	0.002336	0.009600	0.007925	0.008767	0.004970	0.002014
2003	0.010831	0.003963	0.002578	0.002589	0.005643	0.005309	0.007334	0.008119	-	-	-	-
Mean	0.005797	0.002534	0.001748	0.002687	0.004134	0.006982	0.003820	0.007573	0.005962	0.006125	0.003095	0.001691

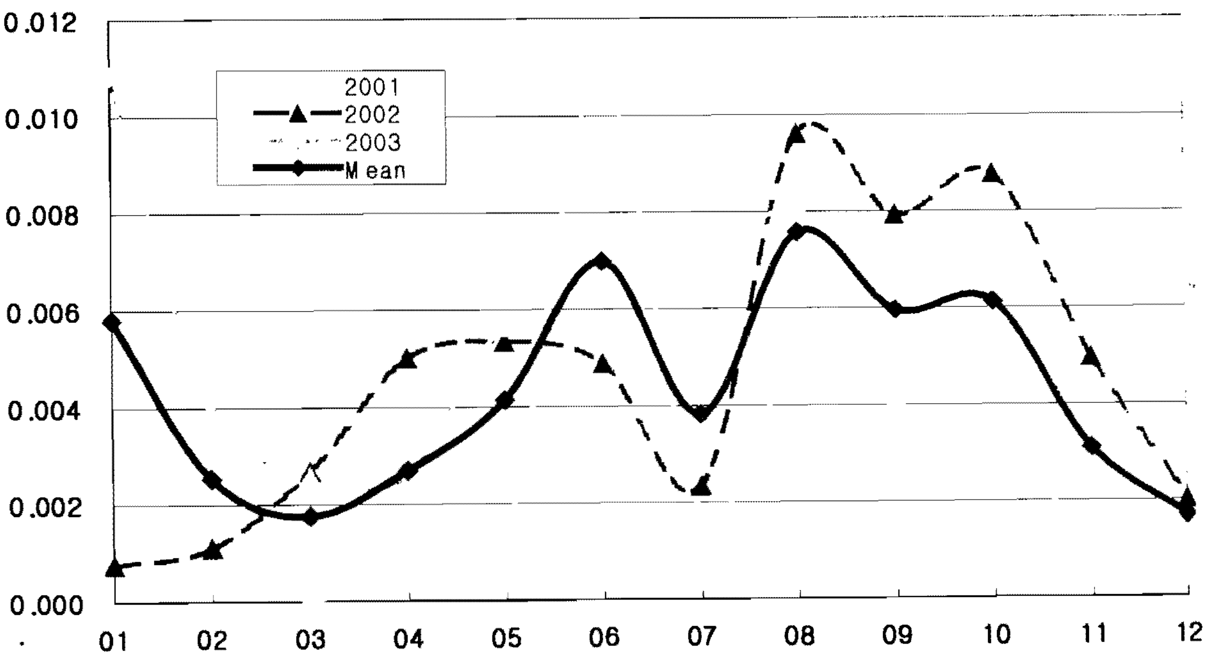

Fig. 6. Monthly CE calculated from the water balance analysis

Whereas the existing model used the only CE value of 0.006, this study applied the monthly CE calculated in Table 2 to the model and the result is shown in Table 3. Compared with the observed runoff, the estimated runoff with mean monthly CE's presented the improved result than that with single CE.

Table 3. Result Comparison of Single CE value and Mean Monthly CE's applied to the Model

Year	Precipitation (mm)	Observed Runoff (mm)	Estimated Runoff (mm)	
			Single CE	Mean Monthly CE
2001	525.5	274.2	208.3 (0.760)	248.2 (0.905)
2002	1400.5	785.3	733.1 (0.934)	815.2 (1.038)
2003	1297.0	792.7	778.2 (0.983)	800.6 (1.010)

The monthly CE value was relatively bigger in the period of June to October that was rainy season than drought season. It can be inferred that precipitation is worked as a potential to generate evapotranspiration.

4.2 Water Balance Analysis using DAWAST model

DAWAST model, as stated earlier, can estimate the groundwater recharge of any basin in Korea indirectly through the water balance even in the situation of no observed data. To confirm the possibility of the estimation, this study performed the water balance analysis with the observed data of Chojeong watershed including precipitation, runoff, evaporation and soil moisture content, and compared the result with the simulated one from DAWAST model.

The simulated result is shown in Fig. 7 and Table 4. The data in Table 4 was calculated in the year.

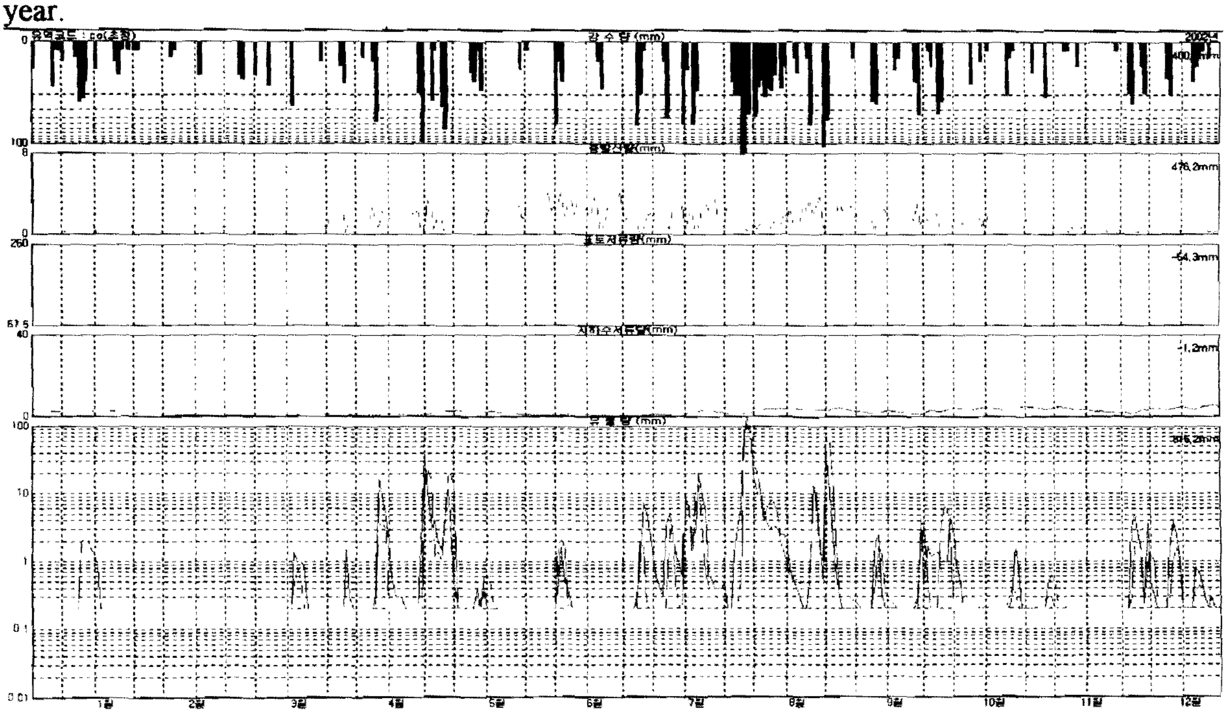

Fig. 7 Daily Runoff and Hydrologic Response with Measured and Calculated Data in 2002

Table 4. Simulated Results of DAWAST Model for Chojeong Station (unit : mm)

Year	Precipi-tation (P)	Observed runoff (Q)	Estimated runoff (EQ)			Evapo-trans-piration (ET)	Δ WSU (ΔS_s)	Δ WSS (ΔS_g)	RG		
			Direct runoff (QD)	Base runoff (QB)	Sum				Narrow sense	Broad sense	RG Rate
2001	525.5	274.2	175.5	72.7	248.2	303.6	-51.30	-3.4	-3.4	59.3	0.138
2002	1,400.5	785.3	594.6	220.6	815.2	476.2	50.26	4.6	4.6	225.2	0.161
2003	1,297.0	792.7	604.5	196.1	800.6	396.3	30.28	-4.6	-4.6	189.6	0.151

※ Observation period : 2001.3.08~2003.8.31

The estimated rates of runoff for the test period were about 47.2% in 2001, 58.2% in 2002, and 61.7% in 2003, respectively. The errors between observed and simulated runoffs were 9.5%, 3.8%, and 1.0% in order. The negative values in Δ *WSU* and Δ *WSS* were resulted from the subtraction between the first and last days of each year.

The groundwater recharge in narrow sense can be represented as Δ *WSS*. The amount of Δ *WSS* was –3.4mm in 2001, 4.6mm in 2002, and –4.6mm in 2003, respectively. The groundwater recharge in narrow sense showed near zero percent to the annual precipitation. With the result of water balance analysis, it is inferred that the deep percolation mostly depleted as the form of base runoff and therefore the groundwater recharge in narrow sense (Δ *WSS*) can be negligible.

The soil moisture content expressed by Δ *WSU* is about 50mm in a year. This amount is almost 4% of the mean annual precipitation and can not be ignored as compared to the groundwater recharge rate.

The groundwater recharges in broad sense were 59.3mm in 2001, 225.2 mm in 2002, and 189.6 mm in 2003, respectively. These values are converted to 13.8%, 16.1%, and 15.1% as the ratio of groundwater recharge to the annual precipitation respectively. It also indicated that the recharge is about 24%~28% of total runoff.

5. SUMMARY AND CONCLUTION

This research suggested a method of estimating groundwater recharge by yielding soil moisture and watershed evapotranspiration in DAWAST model that uses water balance concept of unsaturated and saturated layers in the model.

The model presented the improved result that applied monthly coefficient of evapotranspiration obtained by water balance equation from the model than that with the existing model applying single coefficient of evapotranspiration.

1. The groundwater recharge in narrow sense showed near the value of zero, and with the result of water balance analysis, the deep infiltration mostly depleted as the form of base runoff.

2. The groundwater recharge in broad sense was 59.3 mm/year in 2001 and the quantity was appeared by 1.7×10^6 ㎥/year, the recharge in 2002 was 225.2 mm/year and the quantity 6.4×10^6 ㎥/year and in 2003, the recharge was 189.6 mm/year and the quantity 5.4×10^6 ㎥ /year for 6 months, respectively. The ratio of the groundwater recharge in broad sense to the total runoff was about 24%~28% level.

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