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Research Article

Estimation of Groundwater Resources using Groundwater-Hydrograph Analysis, a Case of Linbian and Donggang basins

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Abstract: This study applied groundwater fluctuation method (GFM) and considered the natural groundwater recession rate to analyze the groundwater storage levels of the Donggang River and Linbian River basins. Subsequently, the safe yield was calculated, providing the basis for future discharge volume. The results of this study indicated that the average total recharge volume between 2009 and 2014 was 1.31m. The annual average discharge volume amounted to 1.03m, and the annual average water loss equaled 0.30m, translating to a safe yield of 0.85–1.17m, averaged at 1.01m. To determine the accuracy of groundwater recharge estimate using the GFM, the estimates obtained in this study were analyzed using MODFLOW, the results of which indicated that the slope of the regression line representing the actual values and estimated values measured 45±3.2°. Finally, according to the fluctuations in storage water volume, the discharge volume in the study area was higher than the recharge volume. If this problem persists, the groundwater level will continue to drop, causing sea water intrusion and land subsidence. Therefore, the groundwater discharge volume in Donggang River and Linbian River basins should be controlled to not exceed 1m/year.

Keywords: Groundwater fluctuation method (GFM), Water balance, groundwater recharge, groundwater safe yield, MODFLOW Model.

INTRODUCTION

Recent economic developments in Taiwan have caused drastic increase in demand for usable water, prompting the use of groundwater rather than surface water. Prolonged extraction of groundwater engenders land subsidence, seawater intrusion, soil salinization, and other land-related problems along the coastal regions. Subsidence-induced problems and disasters also severely impact the safety of the nation's land. Taiwan boasts an abundance of rainwater resources; however, rainfalls typically run off quickly into the sea because of the country's special physiographic conditions and steep mountainous slope. Consequently, rainfalls do not linger long on land, making it difficult to use and manage water resources. To facilitate effective and sustainable use of water resources, the Taiwan government proposed a strategy of using surface water in combination with groundwater. Specifically, surface river water is used during flood periods when possible, while engineering techniques are employed to recharge groundwater, subsequently storing excess water in surface and groundwater reservoirs. Therefore, water stored in the surface water reservoir is used during periods of water shortage, and if more water is needed, the groundwater reservoir can be used. Thus, a balance between water recharge and discharge can be maintained in an effort to mitigate and control the extent of land subsidence.

Regarding studies on groundwater recharge and discharge estimations, Arnold adopted water balance analysis and groundwater hydrograph displacement techniques to estimate the groundwater recharge volume and baseflow volume of the Mississippi River in the United States. Arnold's results showed general agreement in baseflow and recharge estimates from both methods [1]. Chiang *et al.* applied GFM and groundwater storage coefficient, showing their direct application to discharge, recharge, storage variation, and water loss evaluations [2]. Moon *et al.*

classified groundwater hydrographs into five typical groups according to groundwater level fluctuations and corresponding precipitation records to estimate the recharge volume of Korean rivers in 1999 [3]. Hsu *et al.* adopted GFM and isotope analysis to evaluate a groundwater system, including its water balance conditions between 1999 and 2008 as well as the volume of recharge from sources such as rainfall, river, and external groundwater [4]. Finally,Martínez-Santos and Martínez-Alfaroa applied groundwater level fluctuations and groundwater balance equations to reverse-derive the groundwater discharge volume in the Mancha Occidental Aquifer in Spain. Their results indicated agreement between the estimation results and actual discharge records, and showed that specific yield is the key factor influencing the estimation result [5].

RESEARCH METHODS

The aforementioned literature review shows that ground fluctuation method (GFM) can quickly provide an overview of the groundwater resources of a study area and estimate the volumes of discharge and recharge based on actual groundwater fluctuations. Therefore, the present study applied GFM and water balance analysis to estimate the groundwater storage volume of Donggang and Linbian river basins. Subsequently, recharge, discharge, and water loss volumes in each area were analyzed to calculate safe yield, which was used to evaluate groundwater overdraft. The results can serve as reference for the spatial distribution of water recharge and discharge and for the parameter calibration of groundwater numerical models.

Storage Calculation

Daily water level difference measured by each groundwater station was multiplied by control area and corresponding storage coefficient or specific yield to calculate the amount of water stored ΔQ_s.

$$\Delta Q_s = (H_{n+1} - H_n) \times S \times A_r$$

Where

ΔQ_s = Volume (L^3) of water stored on Day n+1 and Day n

Hn+1, Hn = Water level on Day n+1 and Day n (L)

Ar = Control area (L^2)

S = Specific yield S_y or storage coefficient S_s (dimensionless)

Additionally, the volume of storage water at the end of every year minus the volume of storage water on the first day of the same year determines the annual storage water fluctuation Q_{sy}.

$$Q_{sy} = Q_{365} - Q_0$$

Where

Q_0 = Volume of groundwater stored on the first day of a year (L^3)

Q_{365} = Volume of groundwater stored on the last day of the year (L^3)

Discharge Volume Estimation

According to the characteristic of the Pingtung Plain, the groundwater flow recession hydrograph reflected constant decline in slope during the drought period (November 1 of the previous year to April 30). Although some hydrographs were incomprehensible for several regions, identical trends were observed [6]. Hsu *et al.* reported that the annual average discharge rate based on the recession slope during the drought period did not vary over time, indicating stable discharge in the Pingtung Plain irrespective of the weather or climate [7]. This study therefore adopted the recession hydrograph illustrating the groundwater level during the drought period. Specifically, there were minor amounts of sporadic precipitation during this period, which caused the groundwater level to rise, influencing the reasonable estimation of discharge volume. Therefore, this volume of elevation must be filtered in order to obtain the average discharge rate (L/day), which is then multiplied by the necessary time segment and each control area to calculate the discharge volume Q_p.

$$Q_p = L \times D_y \times A_r$$

Where

Q_p = Discharge volume (L^3)

L = Average discharge rate (L/day)

D_y = Number of days (Day)

Recharge Volume Calculation

Based on the daily storage water volume of each groundwater station, the recharge situation for the entire year was determined, and the daily water fluctuation and average discharge volume were compared to obtain the difference. A positive difference denotes water recharge, whereas negative difference indicates water loss and no recharge. The cumulative recharge in a year was considered the annual recharge volume Q_r.

Water Loss Calculation

The groundwater balance equation reveals that loss of groundwater equals the recharge volume minus discharge volume and storage water fluctuation. The water balance method is defined as follows:

$$Q_r = Q_p + Q_\ell + Q_{sy}$$

$$\Rightarrow \quad Q_\ell = Q_r - Q_p - Q_{sy}$$

Where

Q_ℓ = denotes annual water loss volume(L^3)

Safe Yield Assessment

Let annual storage water fluctuation be zero discharge volume, which is used as the safe yield, then the safe yield is substituted using water balance equation:

$$Q_r = Q_p + Q_\ell + \overset{\nearrow\ 0}{Q_{sy}}$$

$$\Rightarrow \quad Q_p = Q_r - Q_\ell$$

$$\Rightarrow \quad Q_p = Q_{r,net}$$

OVERVIEW OF STUDY AREA

The study area was located within the perimeter of the Pingtung Plain encompassing the Donggang River and Linbian River basins with an altitude of ≤100 m. The area was approximately 430 m2 in total, as shown in Figure1 , roughly 33 km from north to south and 20 km from east to west, and the main terrain reclines from northeast toward southwest. The river within the entire region originates from the Central Mountain Range, through which the main rivers including Donggang River and Linbian River basins meander toward the Taiwan Strait.

In addition, according to the recharge volumes of Pingtung Plain presented by Chiang *et al.* the first aquifer layer (F1) accounts for 99.16% of the total recharge volume, whereas the second and third aquifer layers (i.e., F2 and F3, respectively) account for 0.42% of the total recharge volume. Therefore, this study selected the groundwater station of the first aquifer layer (F1) as the basis for calculating the groundwater storage of the study area. There are 11 groundwater stations within the perimeter of the study area, all of which are affiliated with the Water Resource Agency of the Ministry of Economic Affairs. The locations of these stations are shown in Figure 1 and Table 1.

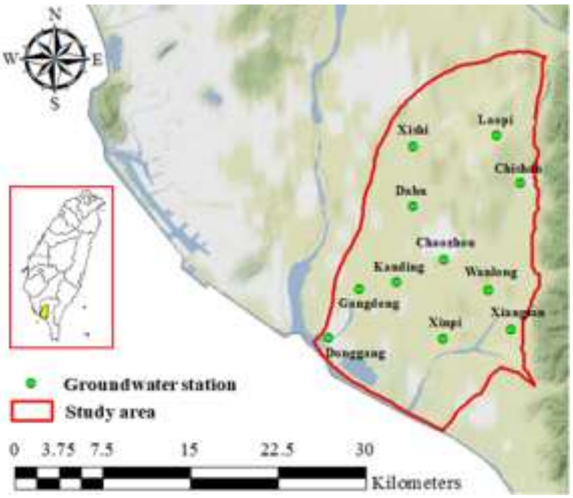

Fig-1: Study area

Table 1: Hydrological information of each groundwater station

Station	TM2 X-coordinate	TM2 Y-coordinate	S_y / S_s	Area
Laopi	207504	2503670	0.173	67656185
Chishan	209521	2499542	0.00047	35361481
Wanlong	206802	2490112	0.173	34537320
Xiangtan	208707	2486714	0.173	22900157
Xishi	200397	2502704	0.00054	44428103
Dahu	200368	2497500	0.173	43453030
Chaozhou	203002	2492830	0.00052	31717972
Kanding	198929	2490845	0.00059	26747442
Xinpi	202895	2485957	0.00051	70178466
Gangdong	195798	2490241	0.0006	24915429
Donggang	193156	2485971	0.173	28434411

Note：Unconfined(S_y): 0.173, Confined(S_s): 0.00047 ~ 0.00060

RESULTS AND DISCUSSION

Analysis of Recharge, Discharge, and Water loss Volume in the Study Area

By using groundwater data collected between 2009 and 2014 as the basis, this study adopted GFM and groundwater balance method to estimate the groundwater recharge, discharge, and water loss in each region, and the results are summarized in Table 2.

Table 2: Water balance analysis between 2009 and 2014

Year	Q_r		Q_p		Q_ℓ		Q_{sy}	
	$10^8 m^3$	m	$10^8 m^3$	m	$10^8 m^3$	m	$10^8 m^3$	m
2009	6.37	1.48	5.55	1.29	1.14	0.26	-0.32	-0.07
2010	6.45	1.50	4.59	1.07	1.59	0.37	0.26	0.06
2011	5.83	1.35	5.07	1.18	0.93	0.22	-0.17	-0.04
2012	6.60	1.53	4.72	1.10	2.08	0.48	-0.20	-0.05
2013	5.61	1.30	4.29	1.00	1.17	0.27	0.15	0.04
2014	5.26	1.22	4.51	1.05	1.01	0.23	-0.26	-0.06
Average	6.02	1.40	4.79	1.12	1.32	0.31	-0.09	-0.02

However, the GFM makes estimations based on water level, storage coefficient (specific yield), and control area of each station, and the control areas measured for each station were inconsistent. Therefore, this study expressed the groundwater storage volume as unit depth for comparison,as shown in Tables 3–5.

Table 3: Water recharge (by depth) (m)

Station	Average (2009~2014)	Percentage
Laopi	2.38	13.7%
Chishan	0.01	0.1%
Wanlong	4.50	26.0%
Xiangtan	6.76	39.0%
Xishi	0.01	0.1%
Dahu	1.61	9.3%
Chaozhou	0.05	0.3%
Kanding	0.02	0.1%
Xinpi	0.02	0.1%
Gangdong	0.02	0.1%
Donggang	1.96	11.3%

Table 4: Water discharge (by depth) (m)

Station	Average (2009~2014)	Percentage
Laopi	2.10	15.4%
Chishan	0.01	0.1%
Wanlong	3.95	28.9%
Xiangtan	5.25	38.4%
Xishi	0.01	0.1%
Dahu	0.73	5.3%
Chaozhou	0.04	0.3%
Kanding	0.02	0.1%
Xinpi	0.02	0.1%
Gangdong	0.01	0.1%
Donggang	1.54	11.3%

Table 5: Storage water fluctuation (by depth) (m)

Station	Average (2009~2014)
Laopi	-0.067362
Chishan	-0.000056
Wanlong	-0.057069
Xiangtan	-0.058664
Xishi	-0.000052
Dahu	-0.022033
Chaozhou	0.00002
Kanding	0.000007
Xinpi	-0.000003
Gangdong	0.000033
Donggang	-0.000457

Unit Depth Analysis of Groundwater Storage in Study Area

Statistical analysis of each groundwater station revealed that the primary areas of recharge within the perimeter of the study area were Wanlong, Laopi, and Xiangtan, accounting for 78.7% of the total recharge volume, followed by Dahu and Donggang, which accounted for 20.6% of the total recharge volume. Because groundwater stations with confined aquifer registered lower coefficient of storage, the recharge volume estimated for Chishan, Xishi, Chaozhou, Xinpi, Kanding, and Gangdong was minimal, accounting for approximately 0.7% of the total recharge,as shown in Table 3.A comparison with the distribution of geologically sensitive groundwater-recharge areas provided by the Central Geological Survey shows that it accorded with the main sources of recharge. Concerning discharge, the locations were almost identical to the relative locations of recharge, suggesting that the frequency of water discharge is high in areas where recharge is frequent, as shown in Tables 3 and 4. Figure 2 presents the locations.

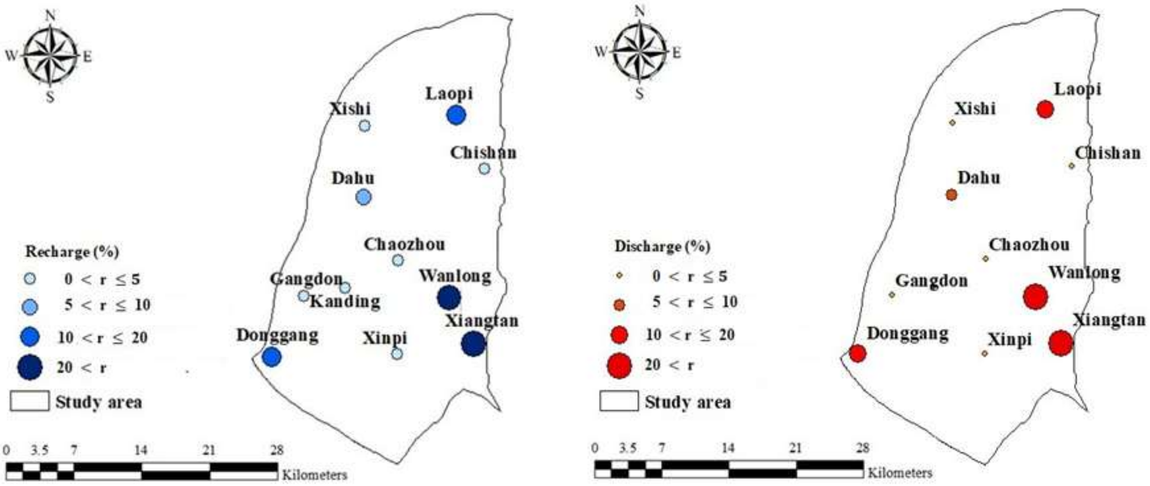

Fig-2: Distribution of recharge and discharge in each groundwater station during study period

Additionally, analysis of annual storage water volume at each station revealed that in Laopi, Chishan,Wanlong, Xiangtan,Xishi,Dahu,Xinpi and Donggang, water was discharged more frequently, as opposed to it being recharged in recent years, thus causing continual decrease in groundwater levels, as shown in Table5. The distribution is depicted in Figure 3.In addition, this study conducted comparative analysis of annual daily average water levels and the annual daily average water levels during the study period. The results indicated a declining trend in water levels in recent years, which accorded with the estimates of this study (Tables 6).

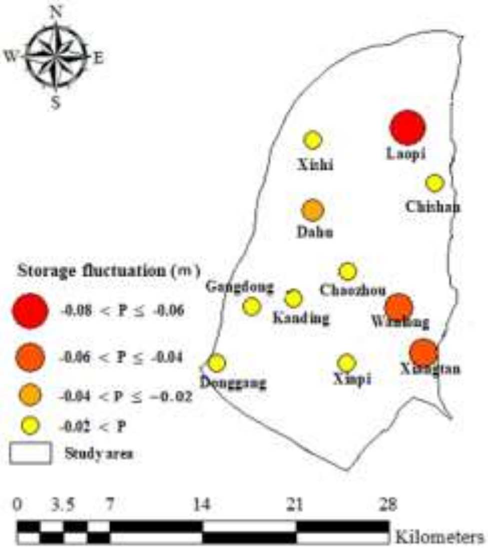

Fig-3: Distribution of annual storage water fluctuation in each groundwater station during study period

Table 6: Analysis of annual daily average water levels over time and during study period

Year / Station	Max. annual daily average water levels		Difference	Min. annual daily average water levels		Difference
	(2008 ago)	(2009~2014)		(2008 ago)	(2009~2014)	
Laopi	29.91	28.92	0.99	28.17	27.49	0.68
Chishan	22.81	22.87	-0.06	21.47	21.81	-0.34
Wanlong	25.47	23.14	2.33	22.37	20.41	1.96
Xiangtan	27.25	25.69	1.56	24.33	22.32	2.01
Xishi	14.41	14.18	0.23	14.10	13.90	0.20
Dahu	7.02	6.85	0.17	6.64	6.15	0.49
Kanding	7.03	7.81	-0.78	4.01	6.51	-2.50
Xinpi	8.74	8.87	-0.13	7.19	8.41	-1.22
Gangdong	0.81	0.51	0.30	0.43	0.29	0.14
Donggang	0.37	0.49	-0.12	-0.26	0.16	-0.42

Unit: (m)

For this study, let annual storage water fluctuation be zero discharge volume, which is used as the safe yield, then the safe yield is the sum of the annual discharge volume and annual storage water fluctuation. The results indicated that the estimates of safe yield ranged between 0.99 and 1.09 m, averaged at 1.09m, as shown in Tables7 If water fluctuation reflects a negative value, it denotes that the total discharge volume of the study area exceeded the recharge volume of the year, whereas a positive value indicates that there are still water available for discharge. In recent years, the annual storage water volume was reduced by 0.02m on average,, which suggests that the demand for discharge volume in the study area was higher than the demand for recharge volume. If this problem persists, the groundwater level will continue to drop, causing sea water intrusion and land subsidence. Therefore, the development of the study area should avoid exceeding 1 m in order to prevent aggravating the problems of sea water intrusion and land subsidence.

Table 7: Safe yield (By depth)

Year	Q_p	Q_{sy}	Safe Yield
2009	1.29	-0.07	1.22
2010	1.07	0.06	1.13
2011	1.18	-0.04	1.14
2012	1.10	-0.05	1.05
2013	1.00	0.04	1.04
2014	1.05	-0.06	0.99
Average	1.12	-0.02	1.09

Analysis of Water Usage and Discharge in Pingtung County

For this study, the water usage situations in Pingtung County reported by the Water Resource Agency under the Ministry of Economic Affairs were compared with the volume of discharge. First, the area of each township was adopted to calculate the population density for deriving the number of populations in the study area. Second, the total volume of water used in Pingtung County minus the irrigation, industrial use, and public use water provided by the Mudan Dam yields the amount of groundwater used in Pingtung County. Finally, the average amount of water used in Pingtung County and the study area was estimated.

Table 8 show that the actual volume of water usage each year and discharge volume calculated in this study differed by approximately 3–12%, with the usage in 2009 exhibiting substantial difference of 28%. This study infers that this is possibly related to the discrepancy between the quantities of public wells according to statistics and the actual situations.

Table 8: Analysis of per capita water usage in pingtung county

Year	Pingtung County (water usage /number of people)	Study area (water usage/number of people)	Difference in percentage
2009	1134	1578	28%
2010	1277	1318	3%
2011	1338	1471	9%
2012	1308	1383	5%
2013	1440	1269	13%
2014	1277	1343	5%

The volume of discharge and actual volume of water used differed by 3 to 13% according to the GFM result. This difference is possibly because this study did not consider groundwater recession rate when estimating discharge volume. Therefore, the differences in percentage for each year were corrected, as shown in Table 9. Table 9 shows that the recharge volume calculated using GFM and after correction differed by roughly 1 to 6% (the result for 2009 was excluded for discussion).

Table 9: Results of GFM and water balance analysis after correction

Year	Q_r			Q_p		Q_ℓ		Safe Yield	
	Estimated value	Correction value	difference in percentage	Estimated value	Correction value	Estimated value	Correction value	Estimated value	Correction value
2009	1.48	1.05	29%	1.29	0.93	0.26	0.20	1.22	0.86
2010	1.50	1.48	1%	1.07	1.03	0.37	0.38	1.13	1.09
2011	1.35	1.28	5%	1.18	1.07	0.22	0.25	1.14	1.03
2012	1.53	1.50	2%	1.10	1.04	0.48	0.51	1.05	0.99
2013	1.30	1.38	6%	1.00	1.13	0.27	0.21	1.04	1.17
2014	1.22	1.19	2%	1.05	1.00	0.23	0.25	0.99	0.94
Average	1.40	1.31	3%	1.11	1.03	0.31	0.30	1.09	1.01

Unit: (m)

MODFLOW Model Verification

The volumes of recharge, discharge, and water loss derived using GFM were employed for simulation. To determine the actual amount of groundwater recharge, recharge by irrigation infiltration, precipitation, and evaporation, as well as surface runoff must be taken into consideration. However, the recharge volume estimated in this study was considered the actual recharge, suggesting that the recharge volume can be inputted directly. If the simulation and observation values in the verification results are favorable, the regression analysis will fall in proximity of the slope line at 45°. Conversely, if the values are unfavorable, resulting in major discrepancy, then convergence cannot be achieved. The results of which indicated that the slope of the regression line representing the actual values and estimated values measured 45±3.2° in this study.

CONCLUSION

This study performed GFM on Donggang and Linbian river basins to estimate the volumes of recharge, discharge, and water loss between 2009 and 2014. Subsequently, the safe yield was evaluated to elucidate the effect of discharge in the study area on groundwater recharge. Because the control areas of each groundwater station differed, this study converted storage volume into unit depth to facilitate comparison with previous studies. Furthermore, the water usage situations in Pingtung County reported by the Water

Resource Agency of the Ministry of Economic Affairs (Table 26) were compared with the volume of discharge. The results revealed that the actual water usage in each year and the discharge volume reported in this study reflected approximately 3–13% difference. Therefore, corrections according to the percentage difference were made. The average annual discharge volume was 1.12m when the natural groundwater recession rate was not considered, and was 1.03m when the natural groundwater recession rate was considered. The average annual recharge volume was 1.40m when the natural groundwater recession rate was not considered, and was 1.31m when the natural groundwater recession rate was considered. The average annual water loss volume was 0.31m when the natural groundwater recession rate was not considered, and was 0.30m when the natural groundwater recession rate was considered. The safe yield ranged between 0.99m and 1.22m, averaged at 1.10m, when the natural groundwater recession rate was not considered, and the safe yield considering natural groundwater recession rate ranged between 0.85m and 1.17m, averaged at 1.01m. The results indicated an approximate of 1 to 6% difference in the recharge volumes obtained using the GFM when natural recession rate was and was not considered.

According to the study results, the annual discharge volume of this study corresponded to the estimation results. The main sources of recharge were Wanlong, Laopi, and Xiangtan, accounting for 78.7% of the total recharge. The overall water loss of the study area reflected the same trend as recharge volume, exhibiting normal physical phenomenon. According to the fluctuations in stored water volume between 2009 and 2014, the annual average reduction was 0.02m, which suggests that the demand for discharge volume in the study area was higher than the demand for recharge volume. If this problem persists, the groundwater level will continue to drop, causing sea water intrusion and land subsidence. Therefore, the development of the Donggang River and Linbian River basins should avoid exceeding 1 m in order to prevent aggravating the problems of sea water intrusion and land subsidence.

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