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Assessment methodologies of groundwater redevelopment considering sustainable utilization: a case study in central Taiwan

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Abstract

Before a groundwater source is redeveloped, many factors determining the groundwater resources should be analysed. As a minimum these should include natural recharge rate, current pumping rate, downstream reserves and reduction factors. Considering the difficulties with actual measurement of groundwater recharge, a method for estimating the rate must be adopted. A complete assessment methodology should be used based on the downstream reserve water of the groundwater area, the rights of users, environmental utilization and the groundwater recharge sources of target area. This approach is necessary in order to help numerical convergence and ensure the sustainability of groundwater resources. This paper uses the groundwater basin of Puli in central Taiwan as an example. It proposes a sound and simple assessment methodology that can be used by the government water resource management teams and development projects to estimate reasonable and sustainable groundwater redevelopment.

Keywords: Groundwater, sustainable development, water resource management

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1. Introduction

In the early 20th century Safe Yield was proposed as the assessment foundation for groundwater availability, while the definition of Safe Yield being: "The limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve" (Lee, 1915) [1]. Though it described Safe Yield as hydrogeological observation, no clarification was made regarding dangerous depletion of the storage reserve and regular withdrawal. Later research indicated that the natural recharge of groundwater can be seen as Safe Yield. Since 1950 US Geological Survey discarded such term due to inexplicit definition of Safe Yield, and adopted Sustainable Yield as the basis for evaluation for groundwater availability. However, the definition of Sustainable Yield is even less clear than Safe Yield, while most definitions generally indicated the negative impact to economy, community and environment when groundwater development is based on Sustainable Yield. Although the definition of Sustainable Yield was lack of clear statement, it mostly indicated that Sustainable Yield must be less than Safe Yield, i.e. recharge on the groundwater zone (Kalf and Woolley, 2005) [2].

This paper adopted the EU's Water Framework Directive [3] and believed that most drain of groundwater is surface water within the area; and if there is no human development or utilization, the groundwater discharge should equal to groundwater recharge in the long term. The base flow of surface water discharged from groundwater is restricted by ecological needs for surface water. Therefore it should not regard the total drain of groundwater as Sustainable Yield. Considering the surface water conservation for ecology needs, the maximum rate of Sustainable Yield of groundwater area should exclude necessary ecological base flow from surface water within catchment area from the natural recharge (CIS, 2009)[3]. Previously mentioned Sustainable Yield should be the maximum availability in a groundwater area, however an Aquifer Sustainability Factor must be given to represent the hydrogeological characteristics, groundwater environment status, economic development and other characteristics of project area, so as to define groundwater availability (Smith et al., 2010; Moltz et al., 2013; Henriksen and Refsgaard, 2013) [4 – 6].

As a result, the availability for groundwater redevelopment can be shown as follows:

$$Q_r = Q_a - P \tag{1}$$

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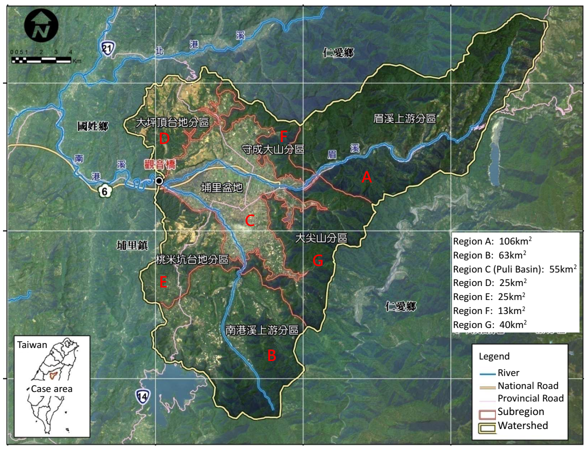


Figure 1: Project area and it's sub region of water budget.

$$Q_a = (R - D) \times F \tag{2}$$

In which: Q_r being the availability for groundwater redevelopment; Q_a being groundwater availability; P being current pumping; R being groundwater recharge; D being downstream reserve, which consists of existing surface water usage of downstream river, scheduled withdrawal for water resource engineering under development, downstream groundwater recharge, and ecological base flow; F being Aquifer Sustainability Factor. As result from Smith et al. (2010) [4], the factor is from 15% to 85%.

In Equation (1) the estimation of actual pumping is required, however in reality it is impossible to conduct investigation on each and every well within the area, therefore here we assessed with officially-declared unit withdrawal and land cover. In Equation (2), complicated groundwater flow simulation is involved. To reflect actual status and provide essential reference for water resource management decision making, relevant research and analysis is critical prior to groundwater simulation. So far the water usage of each objective in Taiwan is not yet fully comprehended; meanwhile, it merely focuses on the research over groundwater flow and the surface water is omitted on groundwater resource studies; parameter setting based on such notion may lead to deviation from reality and cause numerical operation fail to converge, or simulation result inconsistent with reality.

There is a lack of documents recording the relevant details of assessment before numerical simulation of groundwater flow, such as proper method for estimating the groundwater withdrawal, recharge and natural discharge, as well as how to assess proper surface groundwater distribution with simple water budget. To achieve an appropriate estimate of groundwater redevelopment, this paper chose Puli Basin, central Taiwan, to establish estimation equation and its procedure by taking into account of the coverage of surface and groundwater, region from upstream to downstream, the rainfall, evaporation, runoff, recharge, groundwater drain, etc. in the hydrological cycle, as well as withdrawal, pumping, transbasin diversion, irrigation return flows, etc. of water resource. Furthermore, the above total estimates can be adopted in simulation of time and space domain as initial conditions and parameters for numerical operation, so as to minimize speculation and unreasonable input of parameter adjustment while calculating proper groundwater redevelopment amount. The study area shows the differences between empirical and simulation results of water budget are about 5% to 20%, and the reasonable groundwater redevelopment is 39.26 million m^3 per year.

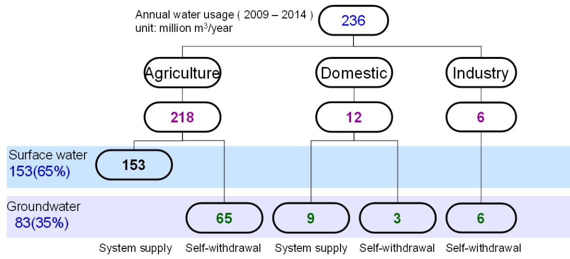


Figure 2: Estimated results of water consumption within case area.

2. Study Area

The genesis of the basin is assumed to be caused by the crustal tension and extrusion. Water accumulated and formed lake, sediment at the bottom of the lake, river eroded towards the source and drained out the lake, alternate deposition and alluvial formed groundwater aquifer. Consolidated formation border on east side of Puli Basin can be seen as zero-flow boundary. On the west side, the high level thick gravel platform recharge groundwater from the side (Fig. 1). Thick at the center and shallow on the rim, the aquifer of Puli Basin is an inverted cone. Pumping wells located mostly at 200 m thick sand-contained gravel zone recharged by surface water, hence is chosen as study target.

In wet season, the groundwater level at the west basin is about 4-6 m and gradually decreases towards the west until meeting the river level as part of surface water; on east side, the depth reaches at least 10 m. Suggest east side irrigation system taking from groundwater, plus no recharge from east consolidated formation, hence leads to deeper groundwater level. The depth during dry season can go 1–4 m deeper than high flow season. While the level of groundwater on the west doesn't change much from wet to dry season, the east varies greater relatively.

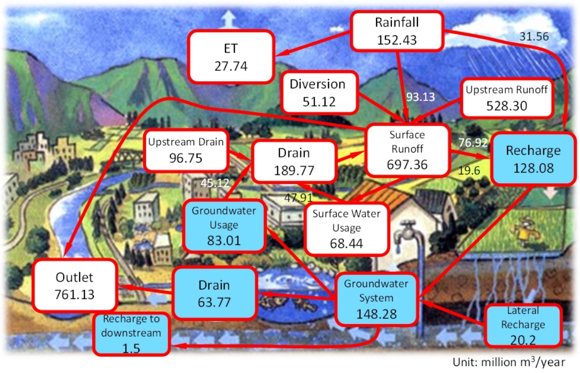
2.1. *Behavior of water consumption*

Case groundwater area located at Puli Basin, central Taiwan, where 75% of 76,000 population depends on Taiwan Water Corporation (TWC)'s water supply

Table 1. Setup of recharge and pumping area for hydrogeological conceptual model.

Land use classification	Recharge from river	Recharge from rainfall	Recharge from irrigation	(Area outside of Irrigation Association) Pumping for irrigation
River	YES	NO	NO	NO
Paddy	NO	NO	YES	YES
dry crop	NO	YES	NO	YES
Impermeable	NO	NO	NO	NO
Non-irrigation permeable	NO	YES	NO	NO

Remark: Recharges from river, rainfall, irrigation recharge and irrigation pumping regions are presumed according to land use classifications to estimate reasonable groundwater recharge and withdrawal.



Remark: Background picture taken from internet and does not reflect actual case area facility or topography.

Figure 3: Estimated results using empirical water budget method on case area.

from groundwater pumping well, while non-supplied (self-withdrawal) area pump groundwater for own utilization.

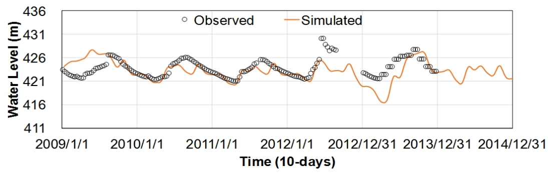
The main supply for industrial use comes from groundwater. Most factories are located on the southeast side of the basin. The estimated water amount is 6.42 million m^3, with 84 companies mostly being beverage and pulp and paper based industry.

Irrigation is the main utilization of agriculture use within the basin. Of which, Irrigation Association's consumption is based on surface water, with groundwater as alternative backup source; outside Irrigation Association's business area of non-system supplied, groundwater well is remain in use as main source.

So far, other than TWC and Irrigation Association's records of actual withdrawal and self-withdrawal outside supply system, there are no actual water usage records.

2.2. Estimation of water consumption

Agriculture water use is based on actual surface water usage provided by Irrigation Association (IA) at 153 million m^3 per year; the usage of groundwater is calculated at the irrigation area outside IA business zone multiplied by irrigation depth by IA (excluded conveyance loss), plus livestock water usage; water for



Remark: No calibration or verification was made to simulation parameters. The values are given based on reference and supplement investigation; due to the difficulty retrieving the actual pumping volume of year 2009-2014, therefore there is difference between simulation and observation value. While partial records are to be confirmed, overall trend is consistent.

Figure 4: Simulation result of groundwater level.

livestock is calculated at the unit usage of Agricultural unit multiplied by the number of livestock. For domestic water supply, the actual groundwater supply provided by TWC is adopted at 9 million m^3 per year. For self-withdrawal, it is calculated by non-TWC-supplied population multiplied by unit quantity of water consumed. Industrial usage is calculated by the amount of authorized water right at 6.42 million m^3 due to TWC does not supply for the use of process. Total annual usage of each purpose is calculated, as shown in Fig. 2, at an average of 236 million m^3.

3. Methodology

From the aspect of groundwater recharge and drain, this paper suggests using groundwater recharge amount for groundwater resource estimation, and empirical water budget method and numerical modeling for analysis. In this paper the empirical water budget method considers the factors of hydrological cycle, groundwater abstraction, irrigation return flows, and possible groundwater recharge. Actual surface water flow amount is recorded at the exit of the basin, cross checked and calculated possible groundwater flow amount. Through the calculation and analysis, feasibility of water quantity in each link is considered, so as to provide groundwater flow numerical simulation's initial input and to compare and verify the two as well as adjust mutual parameters. For empirical water budget method, it is difficult to give precise calculation to groundwater flow and surface water river recharge,

Table 2. Calculation table of water budget on case area by using empirical method.

Source	Direction	Inflow term (million m^3/year)		Outflow term (million m^3/year)	
Surface Water	Top	Rainfall	152.43[C-1]	Evapotranspiration	27.74[C-6]
		Transbasin Diversion	51.14[C-2]	Surface Intake	68.44[C-7]
	bottom	Drain	-[C-3]	Groundwater Recharge	128.08[C-8]
	Lateral	Upstream Runoff	528.3[C-4]	Surface Runoff	697.38[C-9]
		Irrigation Return Flows	189.77[C-5]	(Surface Discharge Observation of Basin Outlet)	761.13[C-10]
Groundwater	Top	Vertical Recharge	128.08[C-11]	Drain of Groundwater	63.75[C-14]
				Pumping	83.03[C-15]
	bottom	Deep Aquifer	0[C-12]	Deep Recharge	0[C-16]
	Lateral	Lateral Recharge	20.2[C-13]	Recharge to Downstream Basin	1.5[C-17]

Remark: estimated from 2009 to 2014, demonstrated on region C (55.06 km^2). Values defined as follows.
C-1: Referred to contour distribution of annual average rainfall. Annual average rainfall (2,768 mm) × the area of Region C;
C-2: Irrigation Association Water Withdrawal Annual Report, average actual withdrawal is adopted;
C-3: Groundwater drain not included in surface runoff to examine surface runoff only from surface source.
C-4: The sum of surface runoff of all regions excluding region C;
C-5: The ratio of return flows is 70% based on Reference [7], the large amount of temperature-controlled water used before discharge in planting white bamboo shoots; irrigation return flows = (surface withdrawal + irrigation pumping) × 70%
C-6: Evapotranspiration is estimated to be 70% of the evaporation from meteorological observation stations, and is calculated as the annual average (720 mm) × the area of this region × 70%;
C-7: Surface withdrawal of this region (canals within Puli Basin) in the Statistical Yearbook of actual withdrawal declared by Irrigation Association;
C-8: The sum of rainfall recharge (31.56 million m^3), irrigation recharge (19.6 million m^3), river recharge (76.92 million m^3); in which river recharge = surface runoff × recharge rate. Recharge rate 10% is based on Reference [8];
C-9: Surface Runoff = Rainfall (C-1) + Transbasin Diversion (C-2) + Upstream runoff (C-4) + Irrigation return flows (C-5) − Evapotranspiration (C-6) − Surface intake (C-7) − Groundwater recharge (C-8). This value is smaller than the record of surface flow existing from watershed outlet. Hence groundwater drain should exist;
C-10: Records of surface flow existing from catchment area for comparison with groundwater drain;
C-11: Come from surface water recharge as C-8;
C-12: Material underneath region C consists of fine aggregate and consolidated bed. Assume no groundwater flowing in from under, therefore zero is adopted;
C-13: Lateral recharge from upstream groundwater;
C-14: Determined by groundwater inflows deducting outflows; groundwater drain = vertical recharge (C-11) + lateral recharge (C-13) − pumping (C-15) − Recharge to Downstream Basin (C-17); Consistency after comparing the result with surface water flow record of basin outlet (C-10) deducting surface runoff (C-9);
C-15: Estimation of water consumption by this paper;
C-16: Material underneath region C consists of fine aggregate and consolidated bed. Assume no groundwater flowing in from under, therefore zero is adopted;
C-17: With Darcy formula, groundwater area (2,665 m^2), hydraulic conductivity (0.0018 m/s) and hydraulic gradient (0.01 m/m) are determined by results of references and geologic map.

Table 3. Results of water budget by using two methods.

Method term	**Empirical water budget (million m^3/year)**	**Numerical simulation (million m^3/year)**	**Remark**
Rainfall and irrigation Recharge (Vertical Recharge)	51.16	48.85	Empirical water budget assessment is based on experience. Numerical simulation takes rainfall, irrigation, river depth and river bed (surface) hydraulic conductivity into consideration and calculates with MODFLOW River Package. Recharge of the latter is related to the change of groundwater level, and it is more able to reflect the actual characteristics.
River recharge	76.92	92.70	
lateral recharge	18.7	16.07	
Pumping (wells)	83.01	83.01	Annual average volume calculated with empirical water budget method and changed into pumping volume by ten-days of each year. The value is then substituted into numerical simulation method.
Drain	63.77	75.48	Groundwater outflow changes due to different recharge assessment method. With empirical method the result is acquired by deducting each volume, and with numerical simulation it is calculated based on groundwater level, elevation, surface hydraulic conductivity, and with MODFLOW Drain Package. With this method it clarifies the time and space distribution of each volume. The latter is suggested to be the principal basis of this paper.

thus empiric value is substituted instead for calculation. MODFLOW (a groundwater modeling simulator) is then adopted for further numerical simulation.

3.1. Assumptions

According to current observation data of groundwater level of Puli Basin, long term groundwater level remains leveled-off. From equilibrium point of view, when there is little change of reserve of groundwater along timeline, the total inflow of groundwater system equals to the outflow of it. Considering the collectability of data sources and the hydrology characteristics of high and low season of recent years, the data of 2009 to 2014 on hydrology and water withdrawal are adopted for analysis basis.

In special characteristics, 7 regions are divided on entire watershed (Fig. 1): Mei River upper stream, Nangang River upper stream, Puli Basin, Dapingding Platform, Taomikeng Platform, Shoucheng Mountain, and Dajian Mountain, marked as A-G. Of which, Mei River upper stream (Region A) and Nangang River upper stream (Region B) have similar characteristics: the surface and groundwater enter from Mei River and Nangang River's pass into Puli Basin; Dapingding Platform (Region D) and Taomikeng Platform (Region E) are non-consolidated formation where surface water recharges groundwater, and recharges from the side of the interface with Puli Basin; Shoucheng Mountain (Region F) and Dajian Mountain (Region G) are consolidated formation, little habitants or agricultural movement. Presume no withdrawal from or exchange between surface or groundwater, and no water recharge to Puli Basin groundwater but surface water into basin as surface runoff.

Estimated by annual average, calculated items include: Rainfall, evapotranspiration, surface runoff, vertical and lateral groundwater recharge, surface water intake, transbasin diversion, irrigation return flows, groundwater withdrawal, and groundwater drain. The total surface runoff are then compared and checked with actual observation at watershed outlet.

3.2. Analysis of water budget

From the previous analysis, when there is very little variation of the storage, inflow equals to outflow according to the empirical water budget analysis, with separated estimation of surface water and groundwater. Each item is estimated as close to reality, however due to the locations of groundwater level measurement station, it is difficult to surmise complete groundwater level from 2009 to 2014 for the estimation of groundwater drain. Therefore, the groundwater drain of Puli Basin, together with the calculated result for each item in equilibrium analyzing chart, is the result of the difference between inflow and outflow. Each region is calculated individually before consolidation. In this paper only Puli Basin (Region C) is demonstrated, as shown in the following calculation:

1. Average rainfall estimate for each region is based on annual average rainfall contour, and is calculated as the annual average rainfall multiplied by the area of surface region;

2. Evapotranspiration is estimated as 70% of the evaporation from meteorological observation stations, and is calculated as the annual average × the area of the surface × 70%;

3. As mentioned previously, most surface withdrawal is for IA's farming purpose, and other target area is supplied by groundwater. Therefore surface withdrawal is calculated based on IA's annual withdrawal report;

4. As mentioned above, the amount of withdrawal takes from each groundwater pumping usage;

5. The estimation for each recharge of Puli Basin and the lateral pathway interfaced with boundaries are based on reference and 2D geologic map. Groundwater section, hydraulic conductivity and hydraulic gradient are determined and calculated using Darcy law.

6. irrigation return flows = (surface withdrawal + irrigation pumping) × 70%; the ratio of return flows 70% is based on Reference [7], the large amount of temperature-controlled water used before discharge in planting white bamboo shoots;

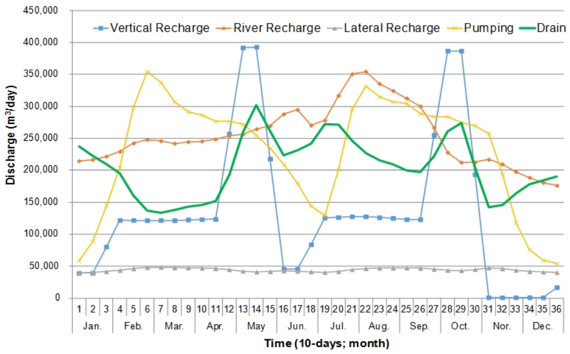
7. Vertical groundwater recharge is the sum of rainfall recharge, irrigation recharge and rive recharge; of which, river recharge = surface water runoff × recharge rate. Recharge rate is adopted as 10% based on reference [8].

8. Rainfall recharge = total rainfall recharge depth × rainfall recharge area; total rainfall recharge depth is determined by the characteristics of non-saturated layer from the result of boring particle size analysis and 15mm/day recharge is adopted based on reference [9]. When rainfall is more than recharge base, 15mm/day recharge depth is adopted, and when less, actual rainfall is adopted and the sum of two equals to total rainfall recharge depth; rainfall recharge area 25.3 km^2 is calculated by excluding impervious area and crop harvest area from Puli Basin;

9. Irrigation recharge = total irrigation recharge depth × irrigation recharge area; total irrigation recharge depth is based on the irrigation time determined by IA report. Irrigation depth 2 mm/day is based on IA report and reference [9]; irrigation recharge area 32.24 km^2 is based on rice field irrigation area.

10. Net surface runoff excluding groundwater drain; Puli Basin surface runoff = rainfall + transbasin diversion volume + upstream runoff + irrigation return water − evapotranspiration − surface withdrawal − vertical groundwater recharge;

11. Puli Basin groundwater drain is estimated by deducting groundwater outflow items from inflow items; groundwater drain = vertical recharge + upstream lateral recharge − pumping − groundwater outlet lateral recharge to downstream basin; watershed outlet record



Remark: average result of 2009 till 2014 based on groundwater numerical simulation.

Figure 5: Quantity of water budget using simulation method on case area.

of surface water flow deducting surface runoff is applied for reasonable checking.

4. Study Result

4.1. Results of empirical estimation

From the water budget output of each divided region of Puli Basin watershed, there exist similarity between Region A & B, Region D & E, Region F & G. Region C, the Puli Basin, bears more calculation item resulting from receiving both upstream surface water and groundwater, as well as the irrigation return flows and transbasin diversion.

From Table 1, the result of calculated groundwater drain (66.05 million m^3) plus surface runoff (695.08 million m^3) under respective calculation items matches the record of surface runoff from the watershed outlet (761.13 million m^3). No obvious infeasible phenomena are observed through the inspection of each estimate. Therefore, the empirical water budget method based vertical recharge, lateral recharge and pumping will be used for initial input for future groundwater numerical modeling to simulate and verify the validity of groundwater drain and each item within the hydrogeological conceptual model.

The water budget analysis based on the result of Puli Basin (Region C) is shown as Fig. 3. Of 148 million m^3 annual Puli Basin groundwater recharge, 31.56 million m^3 rainfall of Puli Basin makes up 21%, irrigation recharge 19.6 million m^3 makes up 13%, river recharge 76.67 million m^3 at 52%, basin lateral recharge 20.2 million m^3 at 14%. Of total Puli Basin groundwater outflow, 54% pumping at 80.48 million m^3, 45% drain from surface at 66.05 million m^3, and recharging downstream groundwater from Basin exit make up 1%, at 1.5 million m^3.

4.2. Numerical simulation & recharge estimation

Due to the difficulty of tracing back the actual pumping of 2009-2014 based on the setting methods described hereinbefore, reasonable hydrogeological parameters and pumping are given. Of which, groundwater pumping and recharge areas are given by land use survey result, as shown in Table 2. Current land use status is sorted and summed through high-resolution Remote Sensing Image, cadastral map, e-map and other reference and field survey, so as to present reasonable land use status.

The groundwater hydrograph resulted from 2009 to 2014 of numerical simulation is shown as Fig. 4. No calibration or verification was made in simulation parameters. The values are given based on reference and supplement investigation; due to the difficulty retrieving the actual pumping volume of year 2009–2014, therefore there is difference between simulation and observation value. While partial records need to be confirmed, overall trend is consistent. From here, the numerical model has reflected the proper Puli Basin groundwater characteristics. More precise numerical modeling results can be achieved when large scale water census could be proceeded in the future. Individual volume analysis result of water budget is shown in Table 3 and Fig. 5.

Groundwater recharge of study area includes: rainfall and irrigation recharge, river recharge, and net lateral recharge. The total annual recharge is 157.62 million m^3. According to Equation (1) & (2), groundwater redevelopment of case area (shown as Table 4) is 39.26 million m^3, based on current annual groundwater pumping 83 million m^3.

5. Conclusion

Pre-processing analysis for numerical simulation of groundwater conceptual model helps clarify surface flow and groundwater usage, examine each volume in the hydrological cycle and clarify the time and space distribution characteristics of groundwater pumping and recharge. It also helps numerical convergence, as well as providing reasonable groundwater redevelopment suggestion. In this case, through empirical estimation and numerical simulation, during 2009 to 2014, each item of water budget of Puli Basin (55.06 km^2) is acquired by cross certification. Total groundwater recharge at 158 million m^3 per year, pumping at 83.01 million m^3 per year, groundwater drain to surface by natural force at 75.48 million m^3. Of which, 48.85 million m^3 rainfall and irrigation recharge takes up 31%, 92.7 million river recharge takes 59%, 16.07 million m^3 lateral recharge to basin periphery takes 10%. Natural flow of groundwater to surface occurs at an average of each ten-days, from 0.13 to 0.3 million m^3 daily. The differences between empirical and simulation results of water budget are about 5% to 20%. The yearly reasonable groundwater redevelopment is 39.26 million m^3.

Table 4. Calculation table of groundwater redevelopment on study area.

Term	Estimated method	Value (million m^3/year)
Groundwater Recharge (R)	Result integrated from empirical method & numerical model method	157.62
Downstream Reserve (D)	Existing downstream surface water usage, water withdrawal amount from water source facility in development, downstream groundwater recharge, ecological base flow	13.77
Aquifer Sustainability Factor (F)	Greatest value applies from literature summarized value 15 to 85%	85%
Groundwater availability (Q_a)	Equation (2)	122.27
Existing pumping (P)	Authority Statistical Yearbook & estimated unit pumping volume	83.01
Groundwater redevelopment (Q_r)	Equation (1)	39.26

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