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Estimation of Agricultural Groundwater Usage by Well Pumping Efficiency and Electric Consumption

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ABSTRACT

For estimating groundwater usage, this study chose 1,043 sampling wells from 81,000 wells of database in Changhua and Yunlin county, located at central Taiwan. Well characters including horsepower, pipe diameter, well diameter and dynamic head parameter were surveyed. Besides, well flow and well pumping efficiency were measured at the same time. Empirical formula both for estimating well flow and well pumping efficiency were discussed and verified with six testing wells. It showed that estimation by regression formula had more reasonable values for well flow than well pumping efficiency. Moreover, the verification of empirical formulas showed that the mean error were less than 3% for well flows, but greater than 30% for well pumping efficiency. The empirical formula for well flow was used to estimate annual groundwater usage in Changhua and Yunlin county from 2017 to 2014.The results showed the water demand of irrigation existed gap during drought, and those gaps was approximated 69 million m^3 for Changhua and 94 million m^3 for Yunlin.

KEY WORDS: Groundwater Usage; Electric Consumption; Well Pumping Efficiency

INTRODUCTION

Water resource management and regulation is still a great challenge in land subsidence area of western Taiwan. The temporal and spatial distribution of water demand plays an import role of water resource policy for land subsidence prevention. According to statistics data of Water Resources Agency (WRA), 60~65% of water used for agriculture irrigation in Changhua and Yunlin county where is the most serious subsidence areas in Taiwan. For mitigating land subsidence, regulation of groundwater pumping is adopted as the water resource policy in Choshuichi alluvial fan. However, according to monitoring results, serious draw down of groundwater head and significant subsidence still occurred during the draught. It shows that water resource management is deep affected by groundwater pumping, and there are about 310,000 wells in Choshuichi alluvial fan with 90% of wells using for irrigation.

In the past 20 years, groundwater usage were obtained by different estimation under WRA sponsor. In general, estimated method of groundwater usage could be classified in to field investigation, numerical inverse method, water budget method and electric consumption method. WRA(1992) obtained an annual groundwater usage of 2.1 billion m^3 in Choshuichi alluvial fan by field investigation. Yeh(1998), Chang and Liu (2002), WRA(2012) used numerical model combined with inverse problem to get the annual groundwater usage of 1.0, 2.31 and 1.93 billion m^3 respectively. Water budget method based on groundwater level variations were applied by WRA(1997,1998,2013) and Chiang(2006), and annual groundwater usages were estimated between 0.74 to 2.48 billion m^3. Electric consumption records of pumping well probably provided a feasible method for estimating groundwater usage, but the electric consumption record of each well was necessary for this approaching.

WRA started to establish well database since 2007, including location, pump type, well depth, application, diameter and electric meter number etc. Although the well electric consumption records could be got, but the relationship between pumpage and electric consumption with different well characters stills unknown. In this study, an approaching method based on algorithm well pumping efficiency (WPE) was proposed. Here, well pumping efficiency (WPE) was defined as flow rate per electric consumption. Therefore, the groundwater usage could be estimated by combining well pumping efficiency and electric consumption records.

SAMPLING WELLS AND FIELD INVESTIGATION

It will be an enormous work to establish the relation between electric consumption and well flow for each 310,000 wells. Moreover, well flow is affected by not only well characters but also groundwater heads. The strategy adopted by this study was taken advantage of sampling well to find the relation among well characters, groundwater heads and electric consumption, and tried to build an empirical formula so that the pumpage could be estimated for each well by combination of well electric consumption records.

Sampling wells for build empirical formula

Although there are about 310,000 wells in Choshuichi alluvial fan, but only 81,000 wells distributed in eight townships were already inspected in 2014. Total 1,043 wells were picked by sampling theory under 95% confidence level and the maximum sampling error of 3%. Fig.1 showed the locations of sampling wells, and Tab.1 showed that there was no significant difference between expected and observed sampling number by chi-squared test.

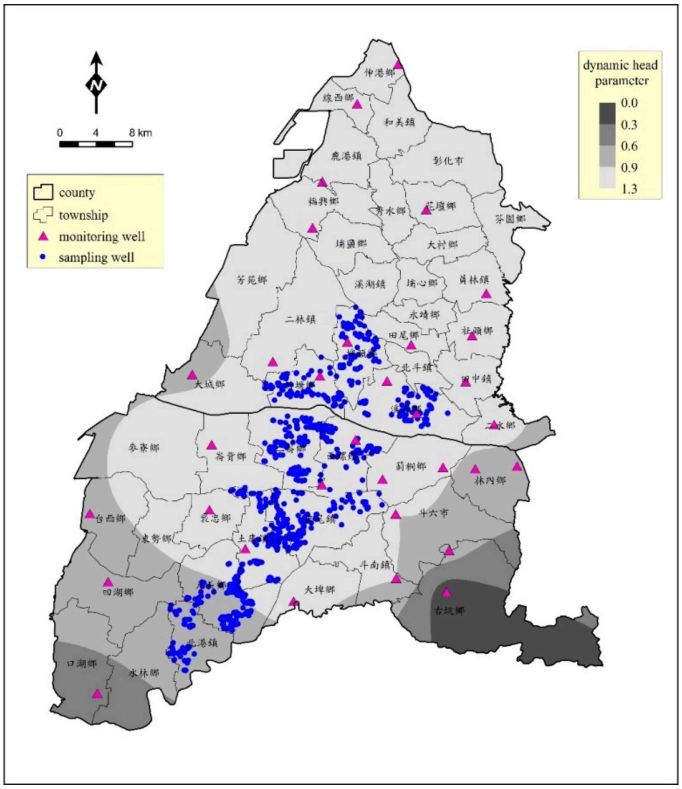

Fig. 1 Locations of monitoring wells, sampling wells and geological classification

Table. 1 Well sampling number of each area for build empirical formula

county	township	total well number	expected sampling number	observed sampling number	χ^2
Changhua	Xizhou	7,383	95	96	0.01
	Pitou	8,255	106	111	0.24
	Zhutang	5,440	70	90	5.71
yunlin	Huwei	10,441	134	136	0.03
	Tuku	10,906	140	124	1.83
	Yuanchang	12,815	165	156	0.49
	Erlun	12,234	158	170	0.91
	Beigang	5,294	68	67	0.01
	Xiluo	8,232	106	93	1.59
total		81,000	1,043	1,043	10.83 < 15.51

Field investigation of sampling wells

According to pump power theory, $P_w = e_p \gamma H Q$, here P_w is the shaft horsepower of pump, e_p the pumping efficiency, γ density of water, H total dynamic head, and Q flow rate. That is, flow rate is function of horsepower, pumping efficiency and total dynamic head, and we assumed that pumping efficiency and head could be estimated by well characters and groundwater head. Well characters including well depth, well diameter, pipe diameter, pump type and pump horsepower were already recorded in well database, thus both well flows and electric consumption rate were measured in this study. Tab.2 showed the measured well flow of 1,043 sampling wells, and Tab.3 showed the measured well pumping efficiency calculated by well flow and electric consumption rate.

Table. 2 Investigation results of sampling well flow (m^3/hour)

township	sampling number	variation	mean	first quartile	mode	third quartile
Xizhou	96	25.4 ~ 113	57.23	44.45	54.43	68.79
Pitou	111	3.8 ~ 95.3	54.54	44.93	53.40	62.38
Zhutang	90	34.9 ~ 78.7	50.63	44.95	49.10	55.14
Huwei	136	2.4 ~ 76.4	35.91	24.65	36.59	47.58
Tuku	124	4.1 ~ 97.8	36.58	25.53	35.33	46.16
Yuanchang	156	2.0 ~ 73.8	35.39	26.74	36.32	44.51
Erlun	170	4.4 ~ 131	58.17	44.99	55.25	75.30
Beigang	67	8.1 ~ 51.3	30.90	20.42	31.81	40.38
Xiluo	93	4.1 ~ 93.1	54.34	42.38	51.71	71.60

Table. 3 Investigation results of sampling well pumping efficiency (m3/kwh)

township	sampling number	variation	mean	first quartile	mode	third quartile
Xizhou	96	5.3 ~ 27.1	11.27	8.10	9.60	13.38
Pitou	111	5.3 ~ 56.3	15.59	9.64	14.62	19.16
Zhutang	90	3.6 ~ 30.2	10.54	8.46	9.66	11.56
Huwei	136	0.7 ~ 36.6	9.41	6.05	8.62	12.73
Tuku	124	1.9 ~ 31.3	11.45	7.16	11.38	14.62
Yuanchang	156	0.8 ~ 23.7	8.25	5.70	7.63	10.20
Erlun	170	2.6 ~ 30.4	12.38	8.27	11.41	16.39
Beigang	67	2.2 ~ 14.8	6.84	5.24	6.59	8.35
Xiluo	93	3.2 ~ 24.3	9.42	7.65	8.65	10.42

ESTIMATION OF DYNAMIC HEAD EFFECT

Well dynamic head is the summation of static groundwater head and drawdown. The static groundwater heads of pumping wells were calculated by kriging interpolation with monitoring wells which locations pointed in Fig.1. Theoretically, the drawdown of pumping well could be computed by way of well specific yield S_y surveyed during well pumping test. Here, well specific yield is defined as well flow under unit drawdown. Therefore, well drawdown could be estimated if pumping flow was given. Unfortunately, pumping flow were unknown and this research would like to propose an empirical formula for estimating pumping flow. The results of pumping test of monitoring wells in Choshuichi alluvial fan vary from 50 cmh/m to 200 cmh/m, and this value decreases from central higher area of alluvial fan to coastal lower region.

For considering dynamic head influence on pumping flow, the parameter of geological normalization was introduced. After static groundwater heads calculated by kriging interpolation, the distance D_S between static groundwater head and surface was computed. Because the most well depths of sampling wells are less than 50 m (see Tab.3), only the static groundwater heads of the upper layer were used. Therefore, the value of D_S were normalized by $\lambda_D = (D_S - D_{S_{min}})/(D_{S_{max}} - D_{S_{min}})$. The larger value of λ_D means the more difficult to get same well flow. Besides, normalization of well specific yield S_y also computed with the same process. That is, $\lambda_S = (S_y -$

$S_{y_{min}})/(S_{y_{max}} - S_{y_{min}})$, and the larger value of λ_S also means the more difficult to get same well flow. Let dynamic head parameter $\lambda_H = \lambda_D + \lambda_S$, and the pumping flow influence caused both by static groundwater head and drawdown could be assessed. The dimensionless value of dynamic head parameters varied from 0.1~1.3, and Fig.1 showed the spatial distribution.

Table. 3 Distribution of sampling well depth and the variation of measured well flow and WPE

Well depth(m)	Sampling number	Well flow (cmh)		WPE (m3/kwh)	
		variation	mean	variation	mean
0~30	718	2.4~131	43	0.7~56	11.6
31~50	276	2~104	53	0.8~31	8.9
51~100	40	14~95	53	2~18	7.6
> 100	9	13~60	44	3.4~19	11.7

RESULTS AND DISCUSSIONS

Correlation analysis among measured variables

Empirical formula both for well flow and well pumping efficiency (WPE) were studied in this research. The measured variables of well characters include horse power, pipe diameter, well diameter, well depth and dynamic head parameter. The similarities between estimated items, well flow and WPE, and measured variables were discussed for assessing the pattern of empirical formula. Tab.4 states that pipe diameter, horse power well diameter and dynamic head has the more similarities with well flow, but low significant values were found between WPE and measured variables.

Table. 4 Similarities between estimated items and measured variables

Estimated items	horse power h_p	pipe diameter D_p	well diameter D_w	well depth H_w	dynamic head λ_H
Well flow	0.511	0.577	0.454	0.192	-0.412
WPE	-0.296	0.325	0.094	-0.317	-0.265

Multi-variables linear regression

Assume there exist a linear relation between well flow Q, well pumping efficiency WPE and measured variables. Then the empirical formula were proposed as below:

$$\text{Q (cmh)} = c_1 h_p + c_2 D_p + c_3 D_w + c_4 H_w + c_5 \lambda_H, \quad (1)$$
$$\text{WPE (cmh/kwh)} = b_1 h_p + b_2 D_p + b_3 D_w + b_4 H_w + b_5 \lambda_H, \quad (2)$$

where, the units both of pipe diameter and well diameter are inch, well depth is meter and dynamic head is dimensionless.

Empirical formula to estimate well flow

Well flows were estimated by equation (1) and four combinations with different variables were considered. According to field investigation, pump types could be classified into three types, they are submersible pump, vertical axial pump and centrifugal pump. Sampling wells were also divided into four groups according to pump types, then coefficients in equation (1) were estimated and well flows were obtained by different regression formula. The correlations between measured and estimated well flows, listed at Tab.5, were used to assess the results of regression. It showed that formula FQ4 had the larger correlation than others, and larger correlation of submersible and vertical axial pump than centrifugal pump.

Table. 5 Correlation between measured and estimated well flow by different regression formula

Formula	Considered variables	All type pumps	Submersible pump	Vertical Axial pump	Centrifugal Pump
FQ1	D_p	0.33	0.39	0.39	0.25
FQ2	D_p, h_p	0.44	0.52	0.52	0.34
FQ3	D_p, h_p, λ_H	0.48	0.56	0.56	0.38
FQ4	D_p, h_p, λ_H, D_w	0.50	0.57	0.57	0.41

Because the regression correlations due to different pump type were not significant, then formula FQ4 with all type pumps was considered for establishing a general type of regression formula. Moreover, for increasing the accuracy the sampling wells which measured well flow less than first quartile and greater than third quartile (see Tab.2) were ignored. Then the correlation could improve to 0.64, and the general type of regression formula as below:

$$\text{Q (cmh)} = 0.16h_p + 0.11D_p + 0.02H_w - 0.33\lambda_H. \quad (3)$$

Empirical formula to estimate well pumping efficiency (WPE)

Similarly, four combinations with different variables listed at Tab.6 were considered to estimate the coefficients of equation (2). Correlations between measured and estimated WPE were calculated after regression formulas obtained with different pump type, and it showed bad regression results with low correlations. However, formulas FP3 and FP4 had the larger correlation than others. Then, formula FP3 with all type pumps was taken to establish the general type of regression formula in advanced. For increasing the accuracy the sampling wells which measured well pumping efficiency less than first quartile and greater than third quartile (see Tab.3) were ignored. The correlation with formula FP3 could improve to 0.53, and the general empirical formula for estimating well pump efficiency was got as below:

$$\text{WPE (cmh/kwh)} = -0.29h_p + 1.29D_p - 0.04H_w \quad (4)$$

Table. 6 Correlation between measured and estimated well pumping efficeny by different regression formula

Formula	Considered variables	All type pumps	Submersible pump	Vertical Axial pump	Centrifugal Pump
FP1	D_p	0.11	0.13	0.08	0.13
FP2	D_p, h_p	0.30	0.35	0.14	0.37
FP3	D_p, h_p, H_w	0.33	0.37	0.22	0.39
FP4	D_p, h_p, H_w, λ_H	0.33	0.38	0.24	0.39

Verification of regression formula

To verify the accuracy of regression formulas, six testing wells were chosen and instruments both with flow meter and electricity meters were installed to get the actual groundwater usage and electric consumption. The actual pumpage and electric consumption were recorded from June to October in 2014. The purpose of all six testing wells are agriculture irrigation, and the crop during investigation were vegetable of well 1, rice of well 2, 3 and 6, peanut of well 4 and 5, respectively. Month groundwater usage and electric consumption were arranged and listed at Tab.7 and Tab.8. It stated that water usage of rice was greater than peanut and vegetable, it found that more groundwater usage corresponding with more electric consumption besides well 5.

The estimated groundwater usage and well pumping efficiency were estimated and listed at Tab.9 and Tab.10 with regression formula (3) and (4) respectively. In Tab.9, it showed that the estimated average month groundwater usage was closed to measured value, and the mean errors were all less than 3%. In Tab.10, most of mean errors was less than 7% besides well 5 which had larger mean error of 33.6%. The main difference between equation (3) and equation (4) is dynamic head parameter λ_H . The larger well flow will be got under shallow groundwater level than deep at the same electric consumption.

Table. 7 Month groundwater usage of six testing wells

month	groundawater usage (m^3)					
	well 1	well 2	well 3	well 4	well 5	well 6
6	156	1710	1235	0	213	1941
7	109	637	0	590	0	869
8	167	1012	0	503	0	0
9	190	609	0	438	211	762
10	154	859	0	722	188	388
total	776	4827	1235	2253.5	612	3960
average	155	965	1235	451	204	990

Table. 8 Month electric consumption of six testing wells

month	electric consumption (kwh)					
	well 1	well 2	well 3	well 4	well 5	well 6
6	18	102	123	0	7	167
7	12	38	0	42	0	76
8	19	60	0	35	0	0
9	21	31	0	30	7	66
10	17	46	0	46	6	31
total	87	277	123	153	20	340
average	17.4	55.4	123	38.3	6.7	85

Table. 9 Estimated month groundwater usage of six testing wells with equation (3)

month	groundwater usage (m^3)					
	well 1	well 2	well 3	well 4	well 5	well 6
6	160	2034	1689	–	222	1978
7	108	755	–	484	–	819
8	168	1183	–	413	–	–
9	185	679	–	344	203	917
10	153	1029	–	562	177	441
average	155	1136	1689	451	201	1039
mean error(%)	0.2	1.5	2.7	2.5	0.5	0.7

Table. 10 Estimated month well pumping efficiency of six testing wells with equation (4)

month	electric consumption (kwh)					
	well 1	well 2	well 3	well 4	well 5	well 6
6	172	1435	1173	–	81	1924
7	115	533	–	462	–	881
8	182	834	–	386	–	–
9	201	435	–	331	78	764
10	163	645	–	510	69	363
average	832	3882	1177	1611	229	3931
mean error(%)	1.4	4.9	1.1	7.0	33.6	0.3

Application to estimate annual groundwater usage

To estimate the groundwater water usage of irrigation, the electric consumption records were collected from Taiwan Power Company. Well characters and monitoring groundwater level were all provided by WRA. Then, the annual pumpage of irrigation well were estimated with equation (3) from 2007 to 2014. It showed that total annual groundwater usage of irrigation varied from 307 to 398 million m^3 with averaged annual groundwater usage 344 m^3 in Changhua county, and varied from 517 to 628 million m^3 with averaged annual groundwater usage 544 m^3 in Yunlin county. According to this results, the water demand of irrigation existed gap during drought, and those gaps was approximated 69 million m^3 for Changhua and 94 million m^3 for Yunlin.

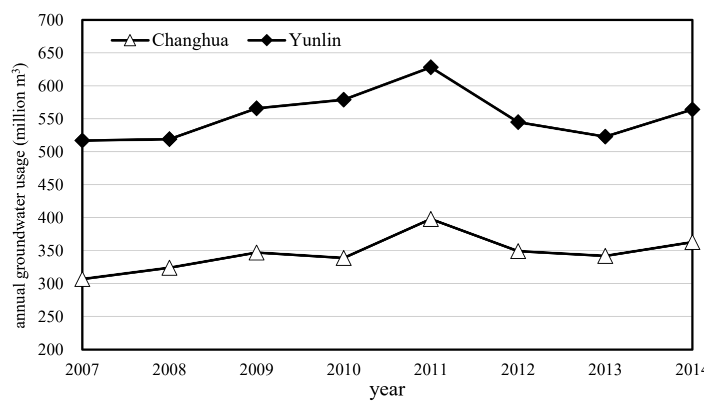

Fig. 2 Estimated annual groundwater usage for irrigation in Changhua and Yunlin county

CONCLUSIONS

For building empirical formula, the well characters of 1,043 sampling wells were investigated, where well characters content horse power, pipe diameter, well diameter, well depth and dynamic head. According similarities analysis between well flow and well characters, it showed well depth had low similarity. The correlations between measured and estimated well flow, as well as well pumping efficiency, always stated that estimation by regression formula had more reasonable values for well flow than well pumping efficiency. Moreover, to verify the accuracy, six testing wells were chosen to measure the actual well flow and electric consumption for 5 months. The verification of empirical formulas both for well flow and well pumping efficiency, and it showed that the mean error of estimated well flows were less than 3%.

Therefore, the empirical formula for well flow was used to estimate annual groundwater usage in Changhua and Yunlin county from 2017 to 2014.The results showed the water demand of irrigation existed gap during drought, and those gaps was approximated 69 million m^3 for Changhua and 94 million m^3 for Yunlin.

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REFERENCES

Chiang, C.J. (2006). Evaluating The Groundwater Budget Of The Choshuichi Groundwater Basin By Groundwater-Hydrograph Analysis.

Chang, L.C. and Liu, C.H. (2002). Assessment and Management of Regional Groundwater Resources.

Water Resources Agency (1992). Groundwater Resources of Taiwan.

Water Resources Agency (1997). Analysis of Regional Groundwater Hydrology for Choshuichi alluvial Fan.

Water Resources Agency (1998). Conjunctive Use of Surface and Groundwater in Choushui alluvial fan, the Second Stage Plan, Sinotech engineering consultants, Ltd..

Water Resources Agency (2008). Project of 2008 at the Research Center for Soil & Water Resources and Natural Disaster Prevention, National Yunlin University of Science & Technology.

Water Resources Agency (2012). The Annual Work Plan of Land-Subsidence Prevention and Reclamation Corps in 2012," Tainan Hydraulics Laboratory, National Cheng Kung University.

Water Resources Agency (2013). Planning to enhance the Efficiency of Agricultural Water in Yunlin and Changhua County, Water Resources Management and Policy Research Center, Tamkang University.

Yeh, W.G. (1998). Formulation and Evaluation of Alternatives for Mitigating Groundwater Overdraft in Taiwan's Coastal Area.