PREDICTION OF GROUNDWATER TABLE DEPTH USING DIRECT RAINFALL-GROUNDWATER STATISTICAL CORRELATIONS IN THAILAND

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Abstract

Intensive water resources development in past decades has had large impacts on hydrogeological systems at basin-scales. Decision-makers require adequate information on both surface water and groundwater potential in order to formulate sustainable water resources development strategies. The present study aims to develop statistical models through multiple linear regression analysis of rainfall-groundwater data to investigate any direct response of groundwater to rainfall at representative sites in the Chao-Phraya river basin of Thailand. The monthly rainfall and groundwater data sets from several rain gauge and piezometric stations in the study areas for the period 2007-2008 were collected from the Royal Irrigation Department, Thai Meteorological Department, and Department of Groundwater Resources (Thailand). It was initially hypothesized (and later on confirmed) that the groundwater table depth of the previous period was due to the slower movement of groundwater through recharge and infiltration processes. The multiple linear correlation analysis has been carried out to study the influence of rainfall, antecedent rainfall, and antecedent groundwater table depth on groundwater depth. The influencing variables have been selected based on the measures of multiple linear correlations. Because the groundwater database is not frequently updated compared to the precipitation and surface water database, the relationships proposed herein may be adopted to predict groundwater table depths to a reasonable degree of accuracy for better planning and management of groundwater resources of the basin.

Keywords: **Groundwater response, multiple regression, groundwater recharge, statistical analysis**

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Introduction

Groundwater is one of the most valuable natural resources, which supports human health, economic development, and ecological diversity (Zektser, 2000; Humphreys, 2009; Steube *et al.*, 2009). It has been recognized as the major and the preferred source of drinking water in rural as well as urban areas and caters up to 80% of the total drinking water requirement and 50% of the agricultural requirement in many parts of Thailand. The occurrence of drought and heavy rainfall are the most important climatic extremes having both short-term and long-term impacts on the groundwater availability. Besides the natural forces creating pressure on water resources, ever-increasing human activities have become the primary drivers of the pressure affecting our planet's water systems.

As rainfall comprises an important component of the hydrologic cycle and is proven as the primary source of recharge for many aquifers, variations of the rainfall and groundwater table depth are closely related. However, the correlation may sometimes be imperfect because differences in rainfall intensity and distribution produce different amounts of recharge for the same amount of rainfall. Consequently, the declining groundwater levels in some parts of Thailand require the necessary understanding for groundwater dynamics and to be able to qualitatively estimate the temporal and spatial variability of sustainable water resources under urbanization and changing climate.

A very useful tool for analyzing groundwater level fluctuations is the use of statistical tools, which are advantageous for water resources management and can be effectively used to derive the long-term trends of groundwater. Statistical methods for trend analysis vary from simple linear regression to more advanced parametric and non-parametric methods. A geographical information system (GIS) nowadays additionally plays an important role in the effective management of groundwater resources, as it helps in preparing a scientific geodatabase of the resources and also facilitates updating the data. A GIS has been put to effective use in many earlier groundwater studies in Thailand and found to be extremely successful.

Several analytical techniques to study the sensitivity of aquifer water levels have been proposed, including the crossing theory approach (Eltahir and Yeh, 1999), general circulation models (Loaiciga *et al.*, 2000; Allen *et al.*, 2004; Gunawardhana and Kazama, 2012), hydrologic models (Eltahir and Yeh, 1999), geostatistics (Moukana and Koike, 2008), wavelet analysis (Tremblay *et al.*, 2011), semi-analytical model (Park and Parker, 2008), and cross-correlation analysis (Venencio and Garcia, 2011). However, the application of statistical analysis techniques to surface water-groundwater response is still very scarce in Thailand.

In this study, statistical analysis of water table data was carried out at the representative areas in the Chao-Phraya river basin of Thailand. The study areas were selected because some degradation of the catchment area, indiscriminate groundwater use, and irregular rainfall have been observed, and therefore the current necessity for better planning and management of groundwater resources in the area are mandatory by conducting multiple linear correlation analysis to study the influence of rainfall, antecedent rainfall, and antecedent groundwater table depth on the current groundwater depth at special locations. The influencing variables have been selected based on the measures of multiple linear correlations. The monthly groundwater depth and rainfall data from rain gauge stations located in the basin for the period of 2007-2008 were collected from the Department of Groundwater Resources (Thailand) (DGR) and Royal Irrigation Department (RID). A monthly groundwater table depth model at each piezometric station was developed using the rainfall, antecedent rainfall, and antecedent groundwater table depth data under consideration and also the piezometric stations upstream. Multiple correlation analysis was performed to initially test the direct correlation of rainfall versus groundwater table depth and also to identify the influencing parameters. The performance of the model was verified through selected performance evaluation criteria in terms of several numerical model performance indicators, such as the coefficient of determination (R^2), root mean square error (RMSE), and efficiency coefficient (EC) which were chosen for the present study. The scattered plots of the observed versus estimated groundwater table depths are selected as a graphical indicator. The relationships proposed may be adopted to predict the groundwater table depths to a reasonable degree of accuracy for better planning and management of groundwater resources of the basin in Thailand.

Materials and Methods

Study Area

Pitsanulok and Sukhothai are the 2 focus areas selected for this study as illustrated in Figure 1. Pitsanulok and Sukhothai are located in the upper central plain of Thailand covering approximately 38000 km^2 (180 km × 300 km). The main landuse is 63% agricultural, out of which 21% is irrigated and 24% is forest. The basin is surrounded in the east and west by volcanic rocks. The average elevation of the basin is 40-60 m above mean sea level. The basin drains into the lower basin in the south where some free discharge is partially obstructed by crystalline rocks. The 900-1450 mm annual rainfall within the study region is apportioned to 81% in the wet season (April-September) and 19% in the dry season (October-March).

General Model Development

The monthly groundwater table depth and rainfall data in Pitsanulok and Sukhothai from the piezometric and rain gauge stations were collected for the period of 2007-2008 and employed for model development. Tables 1 and 2 present the rainfall and groundwater table depths at the rain gauges and monitoring wells, respectively. The groundwater table depth data show that there is no systematic trend with rainfall as the processes are complex exhibiting a high degree of both spatial and temporal variability. The model coefficients, however, may be updated to obtain the refined model for better forecasting accuracy.

Aerial representative rainfall in each study area was generated using the Thiessen polygon technique. The time series monthly

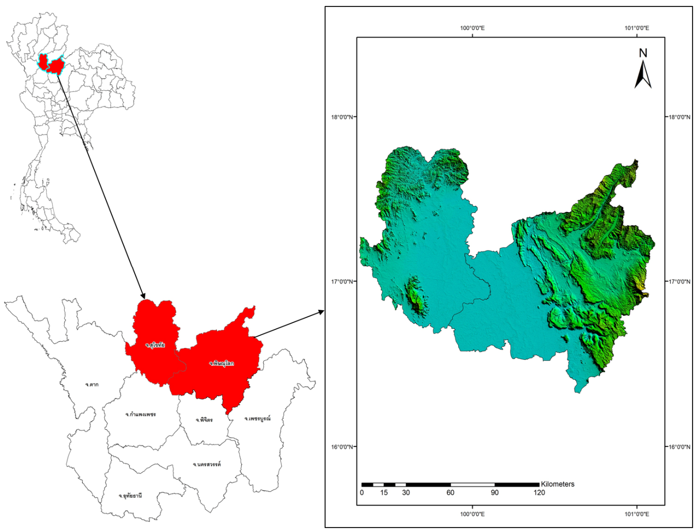

Figure 1. Digital elevation model of the study areas of Pitsanulok and Sukhothai

rainfall data at representative rainfall stations were paired up with the monthly groundwater level from piezometric stations located within the same representative Thiessen polygon as illustrated in Figure 2. Correlations of rainfall and groundwater level were acquired from scattered diagrams of time-series data of rainfall versus groundwater level for each pair of stations. Rainfall and groundwater level pairs which yielded high correlations were

Table 1. Monthly rainfall in *mm* at the selected rain gauge stations in the study area

Rain gauge station	Year	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
39013	2006	0.0	0.9	1.2	2.6	6.2	6.6	6.6	5.9	9.3	8.3	1.8	0.0
	2007	0.0	1.4	0.2	4.0	11.1	4.1	9.9	4.9	11.3	6.7	0.1	0.1
	2008	0.0	0.2	0.7	1.4	5.2	3.1	4.4	9.2	9.4	6.2	3.4	0.0
39042	2006	0.0	0.0	1.3	4.5	4.5	7.7	10.1	10.7	6.3	5.2	0.2	0.0
	2007	0.2	1.5	0.4	1.0	8.2	5.1	2.3	0.0	7.4	6.7	0.0	0.0
	2008	0.0	0.0	2.7	2.8	3.2	5.2	8.1	6.1	6.8	5.5	0.9	0.0
39062	2006	0.0	0.3	0.0	1.3	6.3	5.0	6.1	9.2	11.5	2.6	0.0	0.0
	2007	0.0	0.5	0.1	3.5	8.7	8.7	4.5	6.6	7.0	5.4	0.4	0.1
	2008	0.0	0.0	0.4	0.0	3.3	2.3	6.8	4.1	8.8	5.1	0.4	0.0
39161	2006	0.0	0.0	0.0	1.1	7.8	6.4	9.2	11.5	14.7	7.7	0.0	0.0
	2007	0.0	0.0	0.0	2.8	12.0	9.3	3.6	7.2	10.2	6.0	0.0	0.0
	2008	0.0	0.3	0.8	2.7	4.1	5.0	4.4	7.3	5.2	4.3	1.2	0.0
59022	2006	0.0	0.0	0.0	5.2	18.5	4.2	1.5	4.0	15.5	3.5	0.1	0.0
	2007	0.1	0.1	0.0	0.4	8.3	4.0	2.5	5.6	8.3	4.3	0.0	0.0
	2008	0.0	0.0	0.0	1.4	3.1	2.2	3.4	2.3	6.6	12.0	4.3	0.0
59032	2006	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2007	0.1	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2008	0.0	0.0	2.1	3.6	4.0	5.3	4.4	4.9	5.0	7.6	1.3	0.1
59082	2006	0.0	0.0	0.0	4.3	11.1	3.1	6.3	9.2	18.1	2.8	0.0	0.1
	2007	0.2	1.1	0.5	0.0	10.1	7.7	1.9	7.5	12.3	3.8	0.0	0.0
	2008	0.0	0.0	2.8	2.7	3.4	5.7	3.5	5.7	1.8	6.2	1.0	0.0

Table 2. Monthly groundwater table depth in *m* at the piezometric stations

Piezometric Station	Months									
	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar	May	Jul
NT50/1	27.68	27.57	29.34	29.40	28.88	28.22	30.40	26.60	27.31	27.00
NT50/2	31.68	31.73	29.88	30.93	29.98	29.60	30.86	29.98	30.00	30.03
NT48/1	13.56	13.41	27.46	15.58	-	13.93	13.89	28.76	28.79	28.00
NT48/2	37.12	37.00	36.99	37.37	-	37.00	35.69	37.86	37.91	37.65
NT54/1	34.68	34.50	34.74	34.80	34.59	34.50	35.62	31.60	32.00	33.22
NT54/2	31.98	31.88	32.00	31.90	31.87	31.29	31.98	29.37	30.03	30.88
NT53/1	26.91	27.15	26.82	27.10	26.91	26.78	27.68	27.78	28.00	27.92
NT53/2	27.29	27.03	27.02	27.35	27.30	27.04	27.83	24.99	25.12	26.22
NT53/3	38.85	38.97	39.42	39.73	39.59	39.00	39.38	36.30	37.38	37.90
NT93	32.60	32.94	33.00	-	-	32.74	32.22	32.65	32.70	32.78
NT96/1	30.98	27.31	28.20	29.92	29.48	29.15	27.99	28.11	28.19	28.40
NT96/2	30.61	27.00	28.09	29.60	29.03	29.00	27.48	28.20	28.25	28.49
NT96/3	31.35	24.92	28.02	29.43	29.04	28.92	21.98	25.14	26.00	26.18

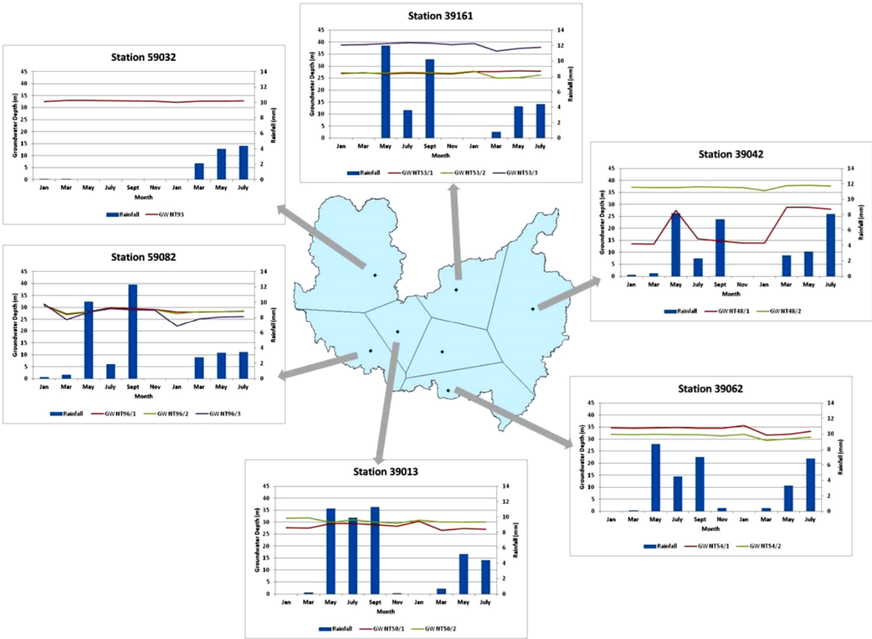

Figure 2. Comparison of observed and estimated groundwater table depths of the study areas of Pitsanulok and Sukhothai

further employed in multiple regression analyses.

An association of 3 or more variables is best investigated by multiple regression and correlation analysis, since linear equations are easier to treat than nonlinear relations and variables of nonlinear relations for the purpose of development of a multiple regression model. If there are *m* variables to correlate, including 1 dependent and (*m-1*) independent variables, the multiple linear regression model can be generally expressed as:

$$X_1 = b_1 + b_2X_2 + b_3X_3 + ... + b_iX_i + ... + b_mX_m \quad (1)$$

where b_1 is the intercept and b_i (i = 2, 3, …, m) are the multiple regression coefficients of the dependent variable X_1 on the independent variable X_i (i = 2, 3, …, m) with all other variables kept constant.

Applying the least squares method of the sum of residuals, the *m* partial differential equations in b_1, b_2, …, and b_m yielded *m* linear equations. The solution of these equations facilitates determination of *m* parameters.

Linear Regression Model

In this study, the monthly groundwater table depth model at a peiezometric station was developed using the rainfall, antecedent rainfall, and antecedent groundwater table depth data of the piezometric station under consideration and also the piezometric station upstream. The modeling steps briefly include: 1) identification of influencing parameters; 2) development of a model; and 3) performance evaluation of the developed model.

Identification of Influencing Parameters

The identification of influencing parameters is based on multiple correlation analysis. The values of multiple and partial correlation coefficients indicate the degree of influence of independent variables on the dependent one.

Development of Model

The linear regression model in terms of influencing parameters is expressed as a simple linear model as follows:

$$G_t = b_1 + b_2 R_t + b_3 R_{t-1} + b_4 G_{t-1} + b_5 G_{t-1(us1)} + b_6 G_{t-1(us2)} + \dots \quad (2)$$

where G_t is the groundwater depth in m in the t^{th} month; b_1, b_2, … are empirical constants; R_t is the rainfall in mm in the t^{th} month; R_{t-1} is the antecedent rainfall in *mm*; and G_{t-1} is the antecedent groundwater depth also in *m* at the stations. $G_{t-1(us1)}$ and $G_{t-1(us2)}$, … are the groundwater table depths at the piezometric stations upstream of the piezometric station under consideration.

Performance Evaluation Criteria

The performance of the model is verified through selected performance evaluation criteria as explained below. Out of several numerical model performance indicators, the coefficient of determination (R^2), root mean square error (*RMSE*), and efficiency coefficient (*EC*) are chosen for the present study. The scattered plot of the observed versus estimated groundwater table depths is selected as a graphical indicator. The R^2 is the square of the correlation coefficient (R) and the correlation coefficient can be expressed as:

$$R = \frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)\left(\hat{y}_i - \bar{\hat{y}}\right)}{\left[\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2 \sum_{i=1}^{n}\left(\hat{y}_i - \bar{\hat{y}}\right)^2\right]^2} \times 100 \quad (3)$$

where y_i and $\hat{y}_i$ are the observed and estimated values respectively. $\bar{y}$ and $\bar{\hat{y}}_i$ are the means of the observed and estimated values.

The *RMSE* yields the residual error in terms of the mean square error and can be expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{n}} \quad (4)$$

where n is the number of observations.

The *EC* is used to assess the performance of the models and can be given as:

$$EC = \left(1 - \frac{F}{F_o}\right) \times 100 \quad (5)$$

Where

$$F_o = \sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2 \quad and \quad F = \sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2$$

A value of the *EC* greater than 90% generally indicates a very satisfactory model performance while a value in the range 80-90% represents a fairly good one. Values in the range of 60-80% would generally indicate an unsatisfactory model fit.

Results and Discussion

The mean monthly groundwater levels for the representative Thiessen polygons of individual rainfall stations in the 2 study areas are illustrated in Figure 2 along with the rainfall bar graphs of the corresponding rainfall stations. Figure 2 reveals that the rainfalls in Pitsanulok and Sukhothai are fairly large compared to those at other stations throughout the year. The groundwater levels at those stations are also relatively higher than other stations in the same study area, suggesting that the groundwater levels are influenced by large amounts of rainfall among other factors.

The results of regression analyses between monthly rainfall and groundwater level data for the period of 2007-2008 are depicted in Table 3 for the total of 13 locations. Apparently, the R^2 values for the 13 rainfall stations in both Pitsanulok and Sukhothai are greater than 0.5, indicating that the groundwater levels are influenced by rainfall at some level in all these locations. However, the response of groundwater to antecedent rainfall yields relatively poorer correlations (R^2<0.25; multiple correlation coefficients shown in Table 3) at some stations (such as stations NT48/2, NT54/1, NT53/2, NT53/3, NT96/1, and NT96/3). The overall correlation between surface water-groundwater pairs suggests the direct response of groundwater to rainfall. Literally speaking, the correlation analyses additionally demonstrate the possible hydraulic connectivity among the study sites or similarity in the response of groundwater among the sites due to hydrological and anthropogenic factors. Further attempts are being investigated to statistically analyze the temporal response of groundwater to rainfall based on the monsoon pattern of the study areas.

The high multiple correlation coefficients literally indicate that the monthly groundwater table depth at any station can better be correlated with rainfall, antecedent rainfall, and groundwater table depths of the station and the upstream stations. Lower correlation coefficients of antecedent rainfall observed

Table 3. Multiple linear correlation of groundwater and rainfall at the 13 locations

Piezometric Station	Multiple Correlation Coefficient	
	R_t^2	R_{t-1}^2
NT50/1	0.92	0.73
NT50/2	0.84	0.83
NT48/1	0.62	0.61
NT48/2	0.68	0.05
NT54/1	0.87	0.23
NT54/2	0.70	0.33
NT53/1	0.73	0.84
NT53/2	0.83	0.20
NT53/3	0.95	0.12
NT93	0.87	0.26
NT96/1	0.65	0.19
NT96/2	0.54	0.38
NT96/3	0.83	0.18

Table 4. Regression equations

Piezometric Station	Regression Equation
NT50/1	$G_t = 0.1224R_1 + 0.2344R_2 - 0.1382R_3 + 0.3183R_4 + 26.6751$
NT50/2	$G_t = 0.0635R_1 + 0.1839R_2 - 0.0077R_3 + 0.2112R_4 + 28.2122$
NT48/1	$G_t = 0.0830R_1 - 0.1548R_2 - 0.1548R_3 + 0.1500R_4 + 26.1034$
NT48/2	$G_t = 0.0672R_1 - 0.0635R_2 + 0.0807R_3 + 0.0899R_4 + 38.9392$
NT54/1	$G_t = 0.0324R_1 - 0.0552R_2 - 0.0088R_3 + 0.0772 + 34.3177$
NT54/2	$G_t = -0.0623R_1 + 0.0178R_2 + 0.1702R_3 + 0.0477R_4 + 30.3891$
NT53/1	$G_t = 0.0710R_1 - 0.0373R_2 + 0.0188R_3 - 0.006R_4 + 26.8748$
NT53/2	$G_t = 0.1944R_1 - 0.5011R_2 + 0.3427R_3 + 0.1805R_4 + 26.0033$
NT53/3	$G_t = 0.1944R_1 - 0.5011R_2 + 0.3427R_3 + 0.1805R_4 + 26.0033$
NT93	$G_t = 0.0366R_1 + 0.3375R_2 - 0.5377R_3 + 0.1418R_4 + 32.4985$
NT96/1	$G_t = 0.0437R_1 + 0.1119R_2 + 0.0854R_3 - 0.0010R_4 + 27.7827$
NT96/2	$G_t = 0.0494R_1 + 0.0957R_2 + 0.0977R_3 - 0.0387R_4 + 27.7117$
NT96/3	$G_t = 0.5109R_1 - 0.0306R_2 + 0.5765R_3 - 0.1542R_4 + 22.9779$

at some locations in the study areas may be due to the fact that rainfall perhaps directly recharges to the groundwater aquifer underneath quite rapidly or groundwater in the basin may be overexploited at the higher rates than the recharging rate during that period.

The linear regression models created in terms of the influencing parameters are

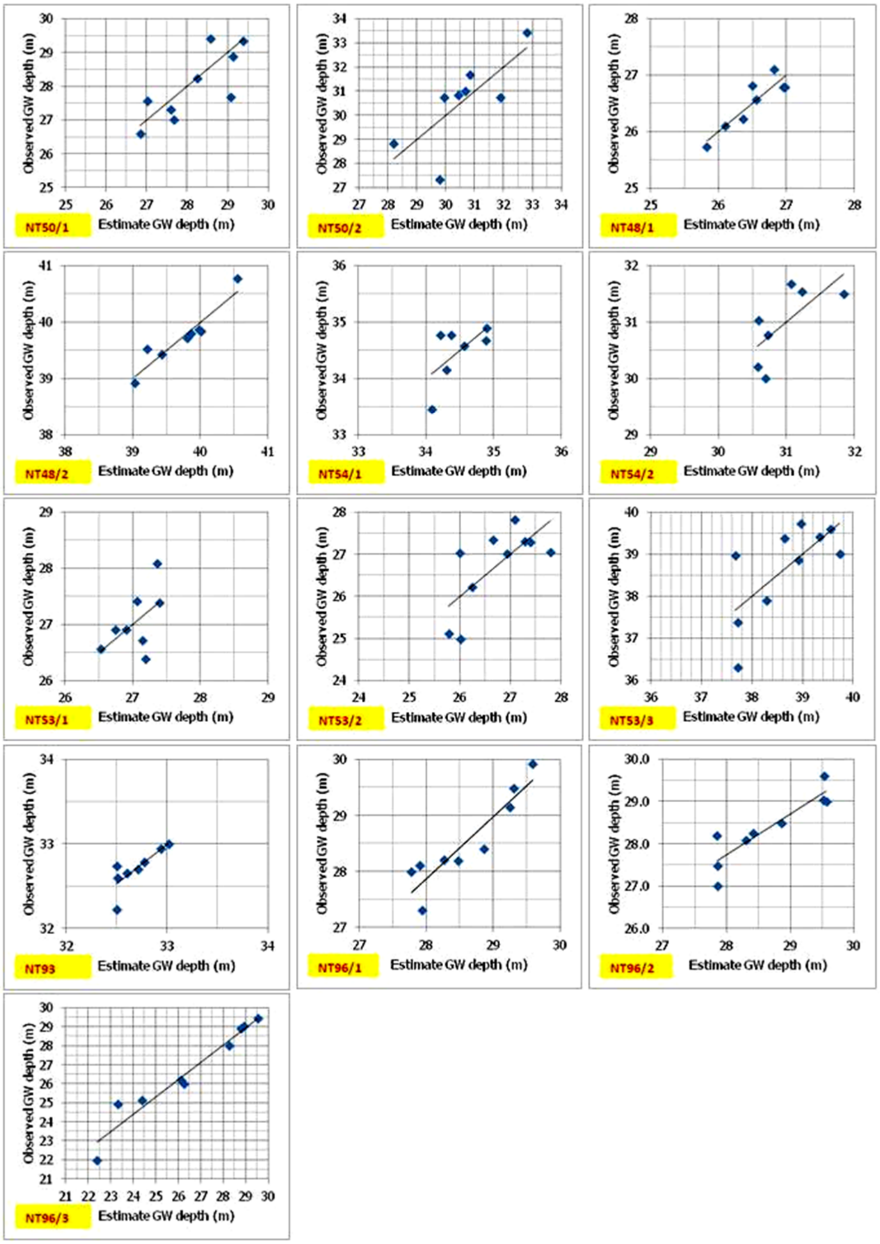

Figure 3. **Comparison of observed and estimated groundwater table depths using the linear regression model**

presented in Table 4. The scattered plots of observed versus estimated groundwater table depths are shown in Figure 3.

The results of this study have been closely evaluated through the R^2, *RMSE*, and *EC* as tabulated in Table 5. The higher values of the R^2 and *EC* in the majority, combined with the lower values of the *RMSE*, indicate that the regression models are fairly good and yield quite satisfactory results in the study areas. Therefore, the developed regression models may be adopted for reasonable estimation of groundwater table depths at the particular piezometric stations based on rainfall, antecedent rainfall, and antecedent groundwater table depth for effective planning and management of groundwater resources of the basin of interest.

Conclusions

Groundwater is one of the most valuable natural resources in Thailand as it serves as the major and the preferred source of drinking water in rural as well as urban areas of the country. The response of the groundwater levels to rainfall was investigated in this study via statistical analyses. Statistical analysis of water table data was carried out in Sukhothai and Pitsanulok provinces located in the Chao-Phraya river basin of Thailand. The study areas were selected because some degradation of the catchment area, indiscriminate groundwater use, and irregular rainfall have been observed. The current necessity for better planning and management of groundwater resources in the area are mandatory.

Necessary data, including rainfall, groundwater level, antecedent rainfall, and antecedent groundwater table depth from the period of 2007-2008 were gratefully provided by the DGR and RID. Multiple correlation analysis was conducted to initially test the direct correlation of the rainfall versus groundwater table depth and also to identify the influencing parameters. Linear regression model in terms of influencing parameters was then developed. The performance of the model was verified through selected performance evaluation criteria in terms of several numerical model performance indicators, such as the R^2, RMSE, and EC. The scattered plots of the observed versus estimated groundwater table depths were selected as a graphical indicator.

The results indicate that the R^2 values for the 13 rainfall stations are higher than 0.5, suggesting that the groundwater levels are influenced by rainfall at some level. On

Table 5. Performance evaluation indicators

Piezometric Station	R^2	*EC(%)*
NT50/1	0.55	55.13
NT50/2	0.58	57.86
NT48/1	0.81	81.32
NT48/2	0.89	88.65
NT54/1	0.40	39.61
NT54/2	0.48	47.88
NT53/1	0.30	29.51
NT53/2	0.51	50.68
NT53/3	0.49	49.24
NT93	0.64	63.54
NT96/1	0.84	84.46
NT96/2	0.80	80.30
NT96/3	0.94	94.42

the other hand, some lower correlation coefficients of antecedent rainfall observed at some locations may be due to the fact that the rainfall in the area directly recharges to the groundwater aquifer underneath quite rapidly or the groundwater in the basin may be overexploited at higher rates than the recharging rate during the period. Similar and dissimilar responses of groundwater levels at Sukhothai and Pitsanulok indicated the extent of hydraulic connectivity in the aquifer system underlying the observed sites. Such information is particularly important for efficient groundwater management.

Linear regression models created in terms of the influencing parameters are proposed with high R^2 and EC and lower RMSE. The relationships proposed may be adopted to predict the groundwater table depths to a reasonable degree of accuracy for better planning and management of groundwater resources of the basins in Thailand.

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