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Groundwater levels estimation and forecasting by integrating precipitation-based period-dividing algorithm and response surface methodology

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ABSTRACT

Groundwater is one of the major sources of water supply for domestic, industrial, and agricultural purposes. Intensive water resources constructions in past decades have had huge impacts on hydrological systems. Recently, groundwater dams have received consistent attention as alternative water supply systems with minimal environmental destructions. Groundwater dams are usually of smaller capacity and costs much less compared with river dams. Therefore, it can be a very attractive solution especially for those small provincial cities suffering severe months-long drought every year. As an application of computer science technologies develops, a number of information systems are utilized for the sustainable development for water resources. Recently, groundwater dams have received consistent attention as alternative water supply systems with minimal environmental destruction. Since groundwater dams are constructed at the height close to sea level, optimal water-pumping strategy based on accurate forecasting of groundwater levels is critical to prevent seawater intrusion. However, there exist few methodologies that provide the operation guideline considering groundwater amount and quality. For this reason, the main objective of this paper is to develop a new integrated forecasting system to provide a guideline for sustainable groundwater management. To achieve this objective, the main purpose of this paper is four-fold: First, a new precipitation-based period-dividing algorithm is proposed. This algorithm can effectively apply to forecast the groundwater levels directly interacted to precipitations with high accuracy for a short-term period by using the concept of exponential smoothing and simulation. Second, an advanced estimation method for groundwater level forecasting by using response surface methodology is then proposed, which is a useful statistical tool for

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modeling and analysis in situations where the groundwater levels are affected by several factors, such as precipitation, temperature, and altitude. Finally, a case study for Sangchun watershed in Eastern South Korea is conducted for verification purposes.

Keywords: Groundwater level; Groundwater dam; Forecasting; Response surface methodology; Optimal water pumping strategy

1. Introduction

Since provincial cities in Eastern South Korea have been suffered from a serious drought every year because of a peculiar geographical feature, the study associated with alternative water supply systems has received consistent attentions from researchers for past decades. The alternative source of freshwater is urgently needed in Eastern South Korea because the shortage of water resources, resulted from the industrialization and urbanization, became one of serious social problems in this area. Groundwater is one of the major sources of a water supply for domestic, industrial, and agricultural purposes. Intensive water resources constructions in past decades have had large impacts on hydrological systems. Negative effects are aquifer depletion, cease of base flow, drying of wetlands, degradation of riparian ecosystem and water quality, and induced land subsidence and ground cracks [1].

In order to effectively utilize groundwater, groundwater dams have received consistent attention as alternative water supply systems with minimal environmental destructions. Groundwater dams are usually of smaller capacity and costs much less compared with river dams. Therefore, it can be a very attractive solution especially for those small provincial cities suffering severe months-long drought every 2~3 years. The Sangchun groundwater dam in Eastern South Korea could be an applicable example. Management of water resources must consider a river basin as an integrated system. The system interacts among surface water, groundwater, and water resources. Decision-makers require adequate information on these interactions in order to formulate sustainable water resources development strategies. The major element of management for groundwater can be groundwater levels. Groundwater models play an important role in the development and management of groundwater resources, and in predicting effects of management measures [2,3].

Since groundwater dams are constructed at the height close to sea level, the optimal water pumping strategy based on accurate forecasting of groundwater levels are critical to prevent seawater intrusion. It is extremely difficult to forecast the groundwater level with enough accuracy because complex variety factors, such as temperature, precipitation, and quantity of pumping groundwater must be considered. Interpretation of natural phenomena, needed also in water resource management area, requires analysis of complex mathematical models and processing of tremendous data. It has naturally induced a number of information systems utilized for the sustainable development of water resources. Development steps for regional groundwater models [4] can be identified as follows:

(1) Conceptualization, a hydro-geologic framework model is established to describe the structure of geological units and features;
(2) Data collection, *in situ* and remotely sensed data are collected to define model parameters and initial/boundary conditions;
(3) Model development, hydro-geologic framework is converted to a groundwater flow model at a resolution suitable for numerical solutions;
(4) Calibration and uncertainty quantification, site-specific data are used to calibrate the flow model and quantify model prediction uncertainty.

Prediction for a groundwater potential of an area is a spatial problem. The groundwater potential could be spatially predicted by using various factors of hydro-geologic importance. However, the degree of influence of factor on groundwater occurrence varies among factors. This may also be space dependent [5]. The regional groundwater models that have been developed for only one purpose may no longer yield satisfactory results if the modeling objective is changed [6]. A groundwater modeling software has the capability to use spatially variable data-sets as input parameters to improve their modeling results [7]. In addition, the use of a high-quality digital elevation model and high-resolution remote sensing data as inputs are also used to improve model accuracy [8]. Discretization of a model domain is a fundamental aspect of a groundwater modeling, and the cell size may have an effect on the model outputs [9].

A wide variety of models have been developed and applied for forecasting of groundwater levels.

These models could be classified into three categories, such as empirical time series models, physical descriptive models, and artificial neural network models. The empirical time series models have been widely used for water table depth modeling [10–12]. Unfortunately, the empirical approach includes many difficulties for forecasting when the dynamical behavior of the hydrological system changes over time [12]. Similarly, physics descriptive models for practice require enormous data and particular data pertaining to soil physical properties of the unsaturated zone. The model is generally difficult or expensive to simulate water table fluctuation in developing countries [13]. Although artificial neural network models are often appropriate for groundwater levels which become non-linear functions [14], it is known that these models are incongruent for long-term forecasting of groundwater levels as well as for implementing computer science technologies because of their lack of flexibility associated with modeling of many different situations. The need for the assessment of quality, reliability, and methods used for forecasting subsurface water levels, in particular, in the context of climate changes, is demonstrated in reference Yakimova [15].

Although a number of groundwater level forecasting methods have reported in literature, there is room for improvement associated with interaction between many environmental input factors including precipitations. The primary objective of this research is to develop a new integrated forecasting methodology to provide a guideline of water supply management with better modeling flexibility. In order to achieve this objective, the proposed procedure in this paper differs from previous studies of the groundwater level-forecasting problem in four ways. First, a new precipitation-based period-dividing algorithm is proposed. This algorithm can effectively apply to forecast the groundwater levels directly interacted to precipitations with high accuracy for a short term period by using the concept of exponential smoothing and simulation. Second, an advanced estimation method for groundwater level forecasting by using response surface methodology (RSM) is then proposed, which is a useful statistical tool for modeling and analysis in situations where the groundwater levels are affected by several factors, such as precipitation, temperature, and altitude. Finally, a case study for Sangchun watershed in Eastern South Korea is conducted for verification purposes.

2. Proposed groundwater levels forecasting methods

2.1. Precipitation-based period-dividing methodology

The prediction for fluctuations of groundwater levels could be forecasted more accurately in short term than long term. In this case, the precipitation-based period-dividing methodology is used to divide the analysis term from long term into short term. In the drought period, even if there is a little precipitation, the groundwater levels fluctuation is affected dramatically. Conversely, in the typhoon period, groundwater level is high, the large fluctuation does not occur. For analysis of the whole long term, it cannot forecast groundwater level with low accuracy in the drought period. Therefore, it is necessary to divide long-term into short-term periods. The groundwater levels will change when it soaks into ground surface after the precipitation. Therefore, a critical factor that is used to divide the period is precipitation which has impact on the groundwater levels fluctuations and penetration time. Therefore, two corresponding parameters are established for the groundwater characteristics with the minimum precipitation "a" for groundwater levels fluctuation and the minimum penetration term "b" for the precipitation time. The precipitation-based period-dividing methodology can be separated into three sub-stages. Firstly, the first period section can start at discretion. Secondly, the period section is not divided when the occurred precipitation at the $t+1$ day is less than the one at the t day. In case, the precipitation at the $t+1$ day is less than "a", the period section is also not divided. Thirdly, if the interval from the beginning day, t, to the ending day, $t+n$, is smaller than b, then the period section is not divided. The proposed precipitation-based period-dividing procedure is illustrated in Fig. 1.

2.2. Exponential smoothing method for transformation of precipitations

Exponential smoothing is a specific technique that can forecast time series data which has a sequence of observations. The future forecasts can be achieved by calculating the simple average of the observed data in the last n periods instead of using the old data in the early stage that can be no longer relevant [16]. This method, named exponential smoothing, can initially generate the future forecasts as follows:

$$F_{t+1} = \frac{1}{n}\sum_{i=1}^{n} x_t \quad (1)$$

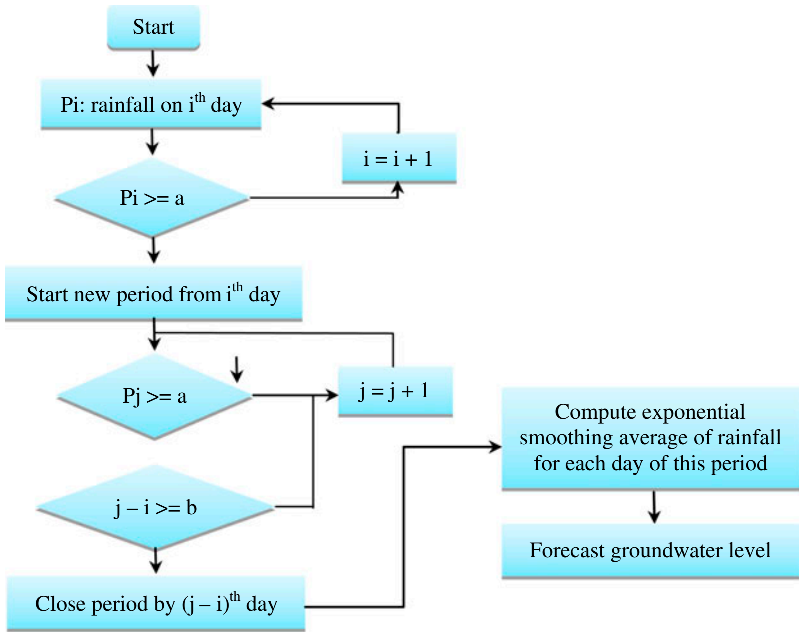


Fig. 1. The proposed precipitation-based period-dividing procedure.

where n, t, F_{t+1}, x_t denote the number of days, the observed tth day, the moving average value at time $t+1$, and the actual observed data on the tth day, respectively. Obviously, all observations have the same importance and they are given an equal weight for the future forecasts. In addition, the forecasts can be easily updated in each period by lopping off the first observation and adding the last observation at each point of time [17].

In case, it may be sensible to assign high weights to more recent observations than to observations from the distant past. Forecasts are calculated by using the weighted averages, and this will lead to the equivalent forms of simple exponential smoothing. In the weighted moving average form, the forecast at time $t+1$ can be the combination of the weighted average between the most recent observation and the most recent forecast. It can be defined as:

$$F_{t+1} = \alpha x_t + (1-\alpha)F_t \tag{2}$$

where α $(0 \le \alpha \le 1)$ represents the smoothing parameter. Another alternative representation for the exponential smoothing technique as a component for m can be developed as follows:

$$F_{t+1} = F_t + \alpha(x_t - F_t). \tag{3}$$

In the latter form, the forecast at the time $t+1$ comprises the preceding forecast and the forecasting error between the forecast and the actual observation at that time with the rate α.

2.3. Response surface methodology

In general, the exact functional relationship between the input and output variables of product/process is often unknown or extremely complicated. However, this functional form can be estimated by using RSM. RSM is a collection of mathematical and statistical techniques that is useful for modeling and analyzing problems when the response of interest is influenced by several factors, and an objective is to optimize (either minimize or maximize) this response. To a comprehensive presentation of RSM, [18–20] provided insightful comments on the current status and future direction of RSM. Based on RSM, the quadratic functional form between the response of interest and the input factors can be represented as follows:

$$\hat{y}(x) = \hat{\beta}_0 + \sum_{i=1}^{p} \hat{\beta}_i x_i + \sum_{i=1}^{p} \hat{\beta}_i x_i^2 + \sum_{i=1}^{p} \sum_{i<j}^{p} \sum_{j=1}^{p} \hat{\beta}_{ij} x_i x_j \tag{4}$$

where $\hat{\beta}$ denotes coefficients of an estimated function.

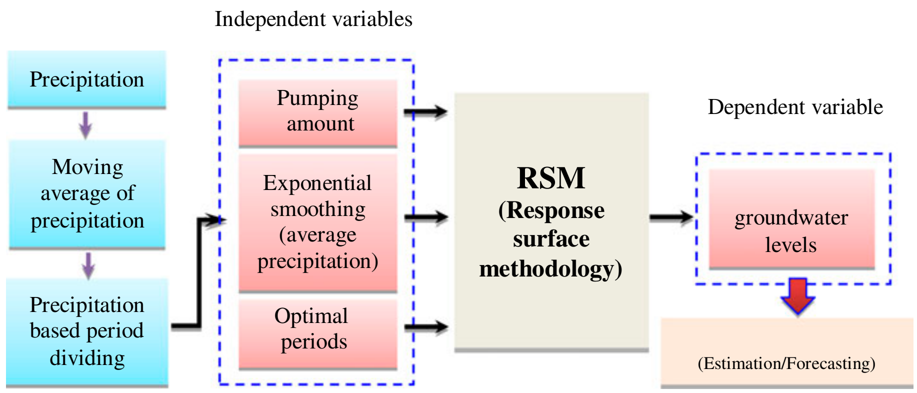


Fig. 2. The proposed groundwater level forecasting procedure.

2.4. Development of groundwater level forecasting procedure

In order to conduct specific statistical estimation for groundwater levels regarded as precipitation with enough precision, the large variability of precipitation for a long-term period must be considered. For this reason, a scientific method to divide into a number of short-term periods based on precipitation can be required. The proposed groundwater levels forecasting method includes three sequential procedures, such as a new precipitation-based period-dividing algorithm, the optimized exponential smoothing technique based on a simulation, and RSM. The proposed method comprises four sequential steps. First, the moving average of precipitation is calculated in the period that the fluctuation of the groundwater level is affected. The attention in this stage is that the total days that is used to calculate the moving average can be selected from the minimum to maximum days. Second, two parameters (i.e. the minimum precipitation and penetration term) can be chosen from the corresponding minimum to maximum candidates based on precipitation. The precipitation-based period-dividing technique is conducted in this stage. In the next step, the exponential smoothing average precipitation in each period is calculated based on the calculated moving average precipitation and the information of dividing of period in the previous stage with the chosen smoothing parameter in the range [0.01–0.5]. Finally, in order to conduct RSM, the independence variables including exponential smoothing average precipitation, the quantity of pumping groundwater in each day, and the dependent variable including the observed groundwater level must be defined. The final results of this procedure can be analyzed based on some statistical criteria such as the coefficient of determination (R^2) and the statistical hypothesis test (*F*-test). The overview of the forecasting groundwater level procedure is illustrated in Fig. 2.

3. Case study to forecast the groundwater levels at Sangchun watershed

3.1. Sangchun watershed

A case study is conducted for Sangchun watershed which is located in the northeast part of Sorak National Park in Eastern South Korea with the watershed area of 65.33 km^2 [16,21]. In that area, Sangchun groundwater dam is located at the estuary of Sangchun watershed and produces 43,000 m^3/day of freshwater from pumping. The Digital Elevation Map (DEM) of Sangchun watershed is also represented in Fig. 3.

3.2. Input characteristics at Sangchun watershed

The hydrologic characteristics of Sangchun watershed, such as temperature, relative humidity, precipitation, evaporation, and wind velocity, were collected from the Sokcho observatory inside the watershed. Particularly, the annual average temperature is 12.0˚C, while the highest and lowest temperatures are 35.9˚C in August 1997 and –16.2˚C in February 1981, respectively. For the relative humidity, its annual average is 67.1%. In regarding to the annual average evaporation and annual average wind velocity, their values are 1,290 mm and 3.1 m/s, respectively. Another important parameter of hydrologic characteristics is the annual average precipitation with 1,481 mm, and this is higher about 200 mm in comparison with the annual average precipitation of South

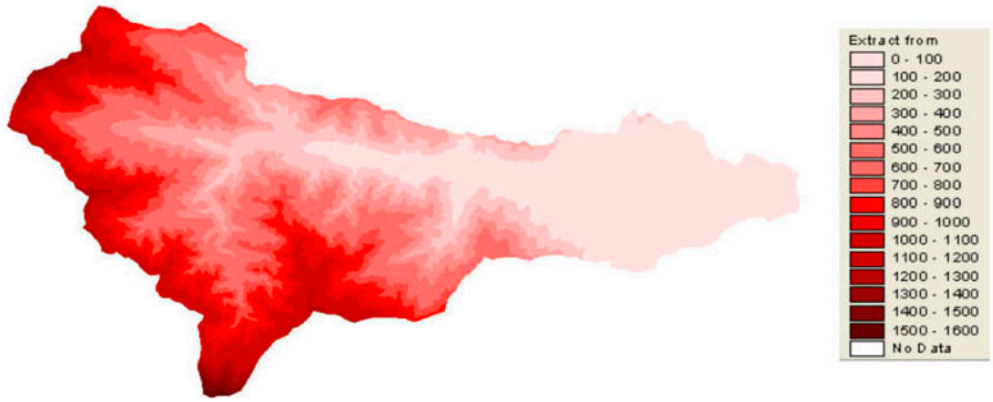


Fig. 3. DEM of Sangchun watershed.

Korea which is 1,283 mm. Unfortunately, this precipitation is unevenly concentrated on the season, such as about two-thirds of annual precipitation is on the typhoon period (from June to September), and the remainder is from November to April.

Some features of the river that can affect the water level must be considered such as the steep slope of riverbed being rather high (1/25–1/88), its width being comparatively small, and its length being pretty short. Because of the great run-off coefficient of the river (direct runoff/precipitation), the water of the river is rapidly discharged into the sea when the rainfall intensity is high. As a sequence, Sangchun watershed cannot usually maintain enough water levels.

3.3. Statistical analysis for precipitations and observed groundwater levels

In Sangchun watershed, there are three different observation holes. However, there is one hole which has the completely higher altitude than two others based on the sea level. Therefore, that hole is not affected by amounts of precipitation. Two remaining holes have quite similar altitude, namely hole A and hole B.As a sequence, hole A and hole B are chosen in this case study. The observed data of both groundwater levels and the amounts of precipitation in long-term period from December 04 2003 to December 03 2004 for both holes A and B in Sangchun watershed are drawn together in Figs. 4a and 4b, respectively. As shown in this figure, a specific

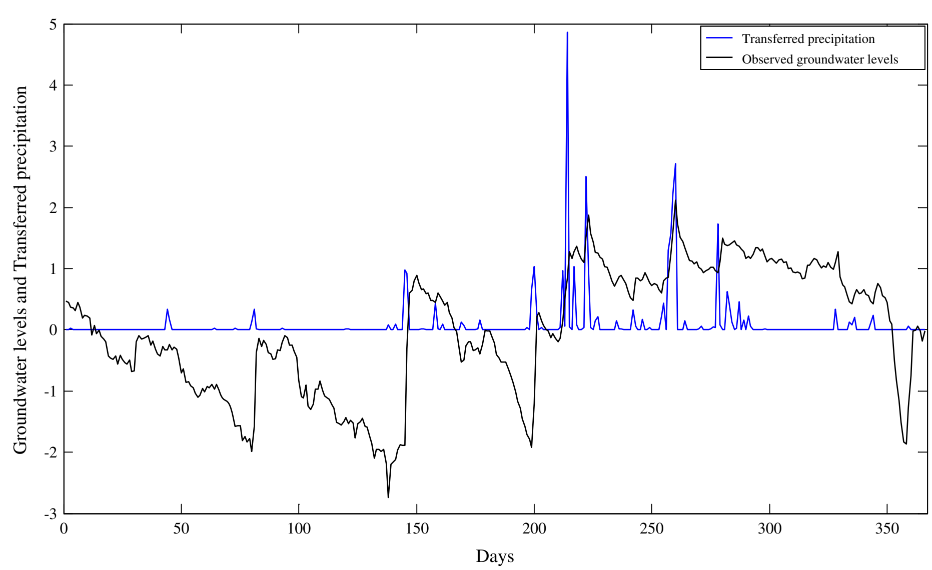


Fig. 4a. The groundwater levels vs. the amounts of precipitation of hole A.

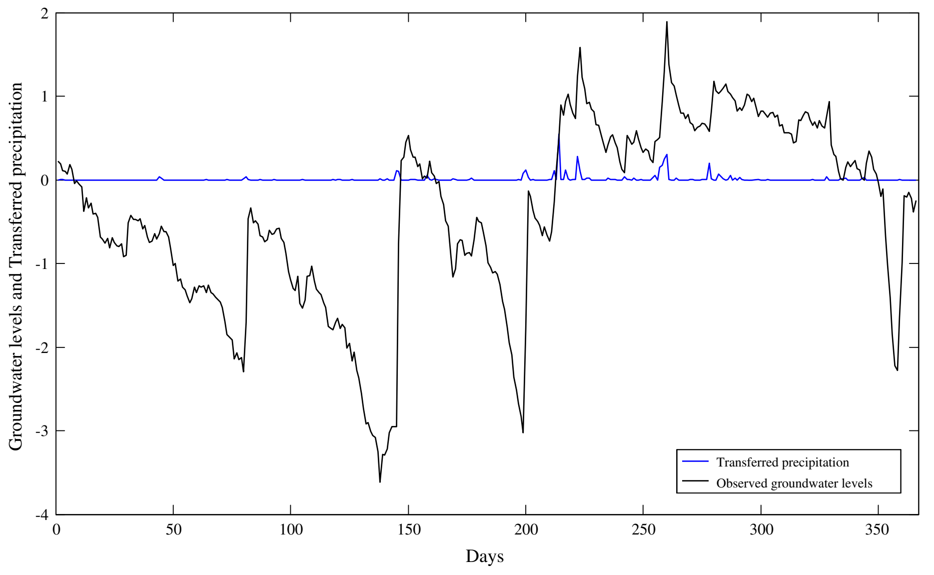


Fig. 4b. The groundwater levels vs. the amounts of precipitation of hole B.

relationship between precipitations and groundwater levels can be detected. The amounts of precipitation are the transferred amount from the original amounts of precipitation and are calculated using the following equation.

$$\text{Transferred amount} = \frac{\text{The original amounts of precipitation}}{\left(\frac{\text{Max of original amount} - \text{Min of original amount}}{\text{Max of observed values} - \text{Min of observed values}}\right)}. \quad (5)$$

3.4. *Analysis results of precipitation-based period-dividing algorithm*

Based on the precipitation data shown in Figs. 4a and 4b, this long-term period can be divided into

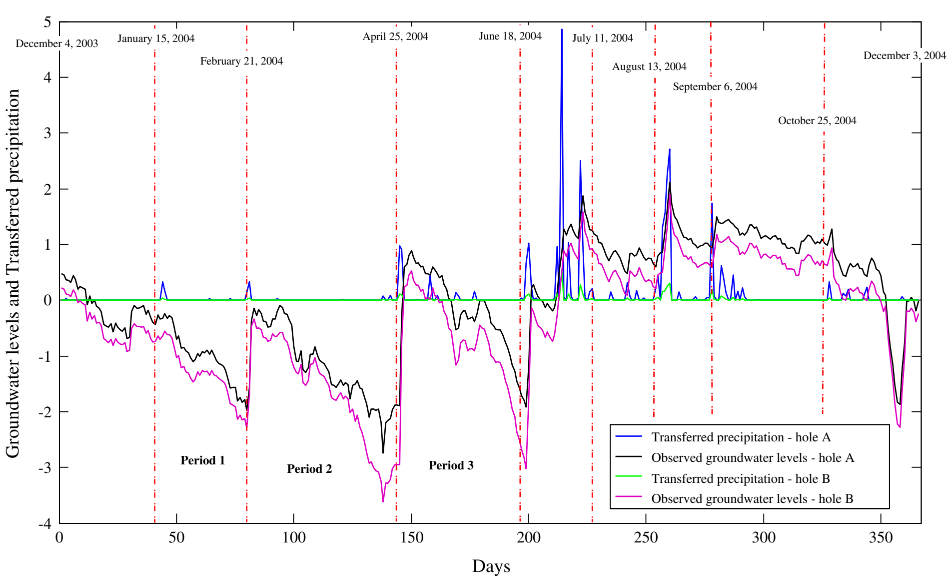


Fig. 5. Results of precipitation-based period-dividing algorithm.

Table 1a
Results of RSM (observation hole A)

	Period								
	1	2	3	4	5	6	7	8	9
α	0.46	0.03	0.01	0.04	0.01	0.25	0.01	0.12	0.01
R^2	0.91	0.98	0.92	0.95	0.99	0.95	0.98	0.85	0.91
F_0	69.8	138.2	69.8	88.5	101.8	48.6	92.8	24.2	118.6
F	2.04	2.25	2.06	2.1	2.71	2.32	2.65	2.13	1.97

Table 1b
Results of RSM (observation hole B)

	Period								
	1	2	3	4	5	6	7	8	9
α	0.46	0.03	0.01	0.04	0.01	0.25	0.01	0.12	0.01
R^2	0.93	0.98	0.96	0.94	0.98	0.94	0.98	0.8	0.93
F_0	92.8	114.8	141.9	82.7	64.8	38.8	66.9	17.3	149.3
F	2.04	2.25	2.06	2.1	2.71	2.32	2.65	2.13	1.97

short-term period by using the proposed algorithm in Fig. 2 in order to conduct the groundwater levels forecasting of Sangmun watershed with enough precision. As shown in Figs. 4a and 4b, nine short-term periods based on precipitation can be achieved. Based on these periods, the second-order model of RSM can be utilized for estimating and forecasting groundwater levels by using Eq. (4). The correlation coefficient R^2 can be a significant criterion to evaluate model efficiency.

3.5. Analysis results by using RSM

The exponential smoothing with different weights is then conducted by the divided periods as shown in Fig. 5. Tables 1a and 1b demonstrate the results of RSM for both holes A and B, respectively. In these tables, all correlation coefficients (R^2) are larger than 0.7 (70%). In all periods, F_0 values are greater than the corresponding critical values F (k, $n-k-1$, 0.05) on significant level 0.05 in the global F-test. In Fig. 5, three significant periods were selected for further analysis.

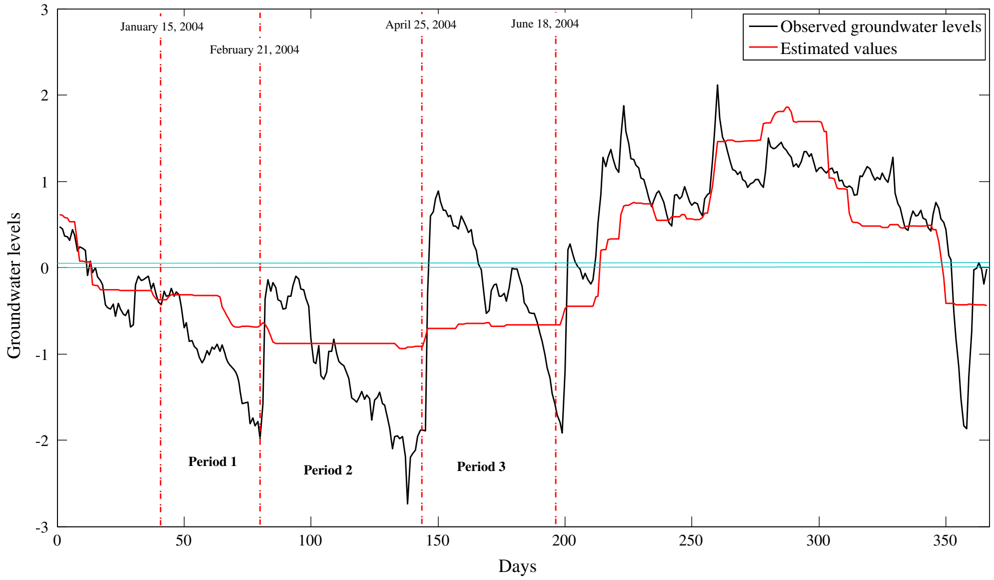
Using the second-order RSM function demonstrated in Eq. (4), Tables 2a and 2b represent the estimated

Table 2a
Estimated functions (observation hole A)

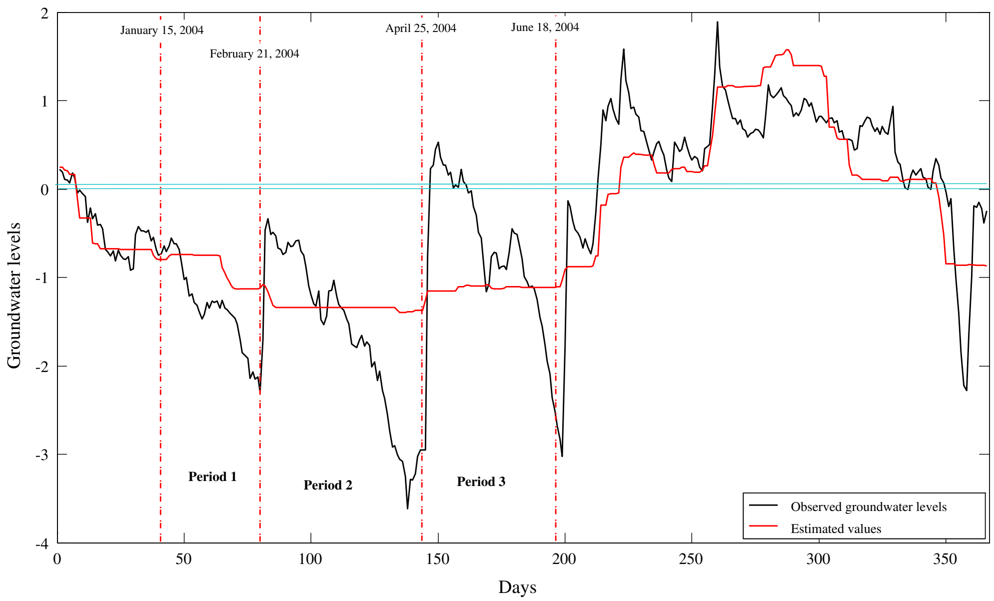
Period	Coefficient parameters								
	β_0	β_1	β_2	β_3	β_{11}	β_{22}	β_{33}	β_{12}	β_{23}	β_{13}
1	126.77	11.27	−0.01	−1.54	−0.29	0.00	0.07	0.00	0.00	0.14
2	538.08	−337.33	0.03	−58.30	28.73	0.00	0.54	0.00	0.00	12.28
3	−1691.25	150.20	0.11	−4.25	85.60	0.00	−0.01	−0.01	0.00	0.98
4	200.63	49.97	−0.03	20.16	−3.91	0.00	0.00	−0.01	0.00	0.98
5	−9.74	39.10	−0.03	20.16	−3.91	0.00	0.00	−0.01	0.00	0.98
6	−115.37	19.53	0.00	14.83	−0.23	0.00	−0.15	0.00	0.00	−0.40
7	5371.07	−1332.52	−0.06	247.22	87.27	0.00	0.59	0.01	0.00	−16.37
8	−1342.04	93.65	0.06	34.67	−1.40	0.00	−0.20	0.00	0.00	−0.50
9	−144.44	−81.22	0.05	−6.92	12.81	0.00	0.06	0.00	0.00	−0.50

Table 2b
Estimated functions (observation hole B)

Period	Coefficient parameters								
	β_0	β_1	β_2	β_3	β_{11}	β_{22}	β_{33}	β_{12}	β_{23}	β_{13}
1	288.39	4.04	−0.02	−2.22	−0.27	0.00	0.06	0.50	−0.50	0.12
2	682.03	−364.60	0.02	−58.15	29.03	−2.00	0.51	0.00	0.50	6.13
3	−2340.03	2224.55	0.09	21.88	−298.37	−7.00	−0.13	−0.03	−1.50	−6.87
4	263.88	73.35	−0.04	25.39	−6.09	2.00	−0.57	0.00	2.50	−2.76
5	406.13	45.38	−0.05	−26.46	0.34	8.00	2.26	−1.50	2.00	−1.40
6	−149.06	26.71	0.00	23.64	−0.26	2.00	−0.14	−1.50	−2.00	−0.39
7	6635.32	−1430.44	−0.13	248.70	90.46	8.00	0.61	0.01	0.50	−16.81
8	−769.90	48.08	0.05	26.97	−0.12	−5.00	−0.19	0.00	−3.50	−0.23
9	−254.37	−87.33	0.05	−4.78	17.47	−4.00	0.05	0.00	−2.00	−0.07



(a) Hole A

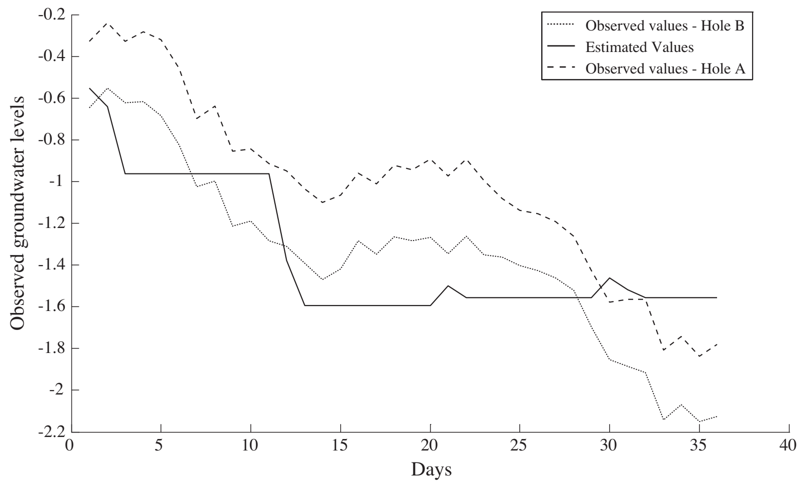


(b) Hole B

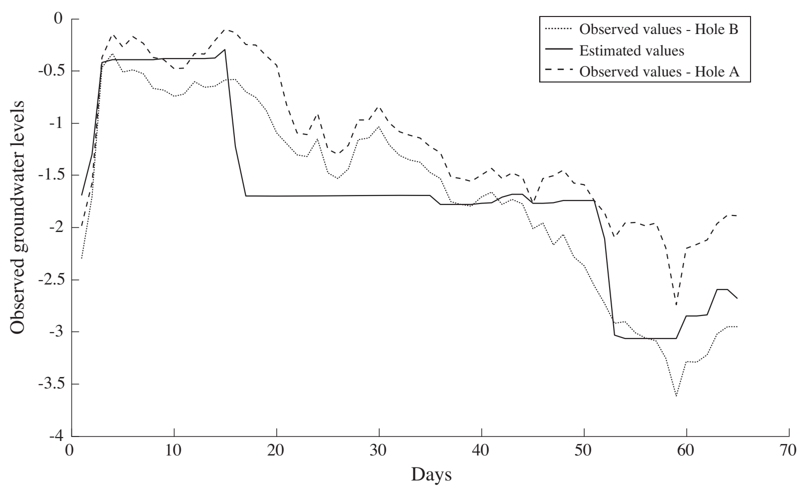
Fig. 6. Comparison between observed values and estimated values without using the proposed precipitation-based period-dividing algorithm.

quadratic functions of both holes A and B for nine divided periods, respectively. Based on the estimated models for all periods of both holes A and B in Tables 2a and 2b, the predicted groundwater levels can be drawn and compared with the actual observed values. Based on the high values of the coefficient of determination R^2 in Tables 1a and 1b, the high accuracy of the estimation results can be obtained from the proposed method.

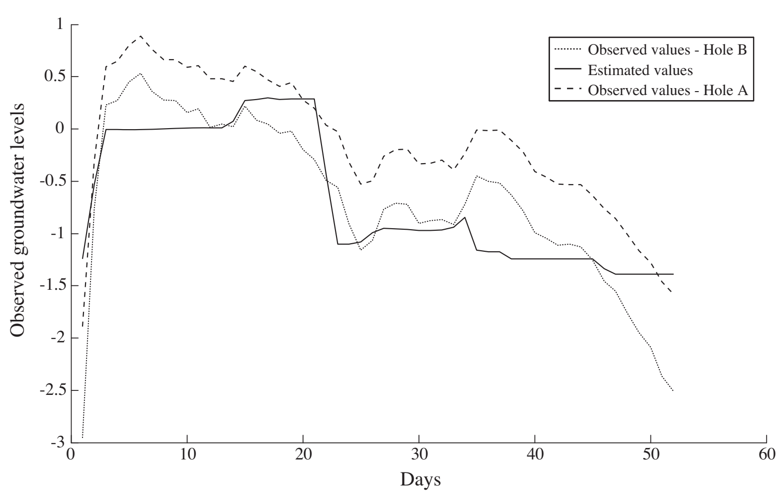
Figs. 6 and 7 illustrate different results using exponential smoothing and RSM without and with applying the proposed precipitation-based period-dividing algorithm, respectively. As shown in Fig. 6, the estimated results provided large difference between the observed and predicted values for both holes A and B because this attempt performed forecasting by applying to the entire period. Further analysis for the selected periods by using the second model of RSM is then conducted as illustrated in Fig. 7. Fig. 7 clearly demonstrates the significantly better forecasting results than those in Fig. 6.



(a) Period 1



(b) Period 2



(c) Period 3

Fig. 7. Forecasting results by using the proposed precipitation-based period-dividing algorithm and RSM for critical three periods.

4. Conclusions

In this study, fluctuations in the groundwater levels could be forecasted by using the amount of precipitation, quantity of pumping groundwater, and number of days based on the proposed forecasting procedure. The proposed procedure utilized the common hydrologic factors to forecast the groundwater levels not to use the other geographical factors. Successful model application requires a comparison of the results predicted by the model with measured data. The suggested forecasting procedure comprising the exponential smoothing method, precipitation-based period-dividing methodology, and RSM could provide enough precision for the prediction of the groundwater levels throughout the entire periods. It could give the estimation in the drought periods. In terms of statistics, the high values of R^2 from 0.8 to 0.99 in the case study of Sangchun watershed demonstrated the efficiency of the proposed method. By performing simulations better, the periods must be divided and controlled. There is little doubt that more precise simulations can be achieved if the periods are controlled. Results of the proposed method matched and verified the observed values. Consequently, the results present a better insight into the dynamics behavior of groundwater levels in Sangchun watershed. The proposed model for predicting groundwater levels presented significantly effective results for Sangchun watershed. This preliminary work can save time, manpower, and our environment. For further study, all of factors that affect to the groundwater levels such as precipitation, temperature, altitude, and so on can be investigated in order to investigate fully and precisely. Besides, the autoregressive integrated moving average method could be applied as an alternative method of the exponential smoothing method.

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