Development of a Groundwater Level Forecasting System for the Optimal Operation of a Groundwater Dam

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Abstract: - As an application of computer science technologies, a number of information systems are utilized for the sustainable development of 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 ground water levels are critical to prevent seawater intrusion. However, there exist few methodologies that provide the operation guideline considering groundwater amount and quality. For this reason, the primary objective of this paper is to develop a new integrated forecasting system to provide a guideline of sustainable groundwater management. To achieve this objective, the main purpose of this paper is four-fold. First, we propose a new precipitation based period dividing algorithm (PPDA) as a way of effective forecasting with better accuracy. Second, we then propose an advanced forecasting system for groundwater levels using the response surface methodology (RSM). Third, we present a GUI-based prototype system with modules of data management, user-guided reliable forecasting, charting and exporting raw and result data, etc, for the real-time and optimal operation of groundwater dam. Finally, a numerical example is conducted for verification purposes.

Key-Words: - decision support system. groundwater dam operation, exponential smoothing, response surface methodology

1 Introduction

Computer science technologies play variety of roles and are rather critical sometimes in many industrial situations. 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 are utilized for the sustainable development of water resources.

The alternative source of freshwater is urgently needed in Korea because the shortage of water resources, resulted from the industrialization and urbanization, became one of serious social problem nowadays. Recently, groundwater dams have received consistent attention as alternative water supply systems with minimal environmental destruction. 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 Ssangchun groundwater dam can be a good example in South Korea.

Since groundwater dams are constructed at the height close to sea level, optimal water pumping strategy based on accurate forecasting of ground water levels are critical to prevent seawater intrusion. It is difficult to forecast groundwater levels with accuracy because the forecasting models often may consider a number of factors, such as temperature, precipitation, quantity of pumping groundwater, etc. A wide variety of models have been developed and applied for forecasting of groundwater levels. These models can be categorized into empirical time series models, physical descriptive models and artificial neural network approach models. The empirical time series models have been widely used for water table depth modeling [1]. The major disadvantage of empirical approaches is that they are not adequate for forecasting when the dynamical behavior of the hydrological system changes with time [2]. Physics based models for practice requires enormous data and particular data pertaining to soil physical properties of the unsaturated zone is generally difficult or expensive to simulate water table fluctuation in developing countries [3]. Although, artificial neural network models are often appropriate for groundwater levels which become non-linear functions [4], 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.

For this reason, the primary objective of this paper is to develop a new integrated forecasting system to provide a guideline of water supply management with better modeling flexibility by implementing computer science technologies. To achieve this objective, the proposed procedure in this paper differs from previous studies of the groundwater level-forecasting problem in four ways. First, we propose a new precipitation based period dividing algorithm (PPDA), which is an effective analysis as well as forecasting methodology with better accuracy for a short-term period by using the concept of exponential smoothing and simulation. Second, we then propose an advanced forecasting system for groundwater levels using the response surface methodology (RSM), which is a useful statistical tool for modeling and analysis in situations where the groundwater level is affected by several factors, such as precipitation, temperature, and altitude. The procedure of this system may provide the prediction of the groundwater levels with enough precision based on the associated factors. Third, we implement a prototype of the proposed system to provide the best period dividing results and to achieve the most reliable statistical inferences for the groundwater level forecasting in order to use a real-time management. Finally, a numerical example is conducted for verification purposes.

2 Summary of the Problem

2.1 Ssangchun watershed

Ssangchun watershed is in the northeast part of Sorak National Park in Korea and the watershed area is 65.33km^2. Ssangchun groundwater dam is located at the estuary of Ssangchun watershed and produce 43,000m^3/day of freshwater from pumping wells. Fig. 1 shows the Digital Elevation Map (DEM) of Ssangchun watershed.

2.2 Hydrologic characteristics

The temperature, relative humidity, precipitation, evaporation, wind velocity data sets were obtained from Sokcho observatory, which is in the watershed.

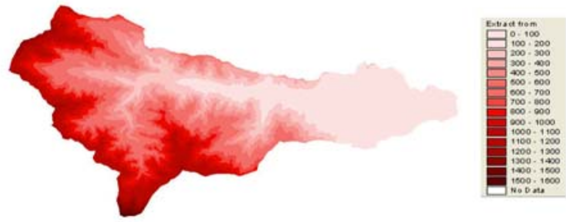


Fig. 1 DEM of Ssangchun watershed

The annual average temperature is 12.0 °C, the highest and lowest temperatures are 35.9 °C in August 1997 and –16.2 °C in February 1981 respectively, annual average of relative humidity is 67.1%. The annual average evaporation is 1,290mm, and annual average wind velocity is 3.1m/sec. The annual average precipitation is 1,481mm and this amount is about 200mm more than the annual average precipitation of Korea, 1,283mm. However about the two thirds of annual precipitation is concentrated to Typoon period (from June to September) and the precipitation from in November to April is just about one third of annual precipitation and causes severe drought every 2-3 years. The slope of riverbed is steep (1/25 – 1/88) and the width is relatively small and the length is rather short. The runoff coefficient (direct runoff / precipitation) of the river is greater than those of other rivers, therefore, river water is rapidly discharged to sea in high rainfall intensity event and Ssangchun does not usually maintain enough water levels. As shown in Fig. 2, the groundwater levels is influenced by the amount of precipitation but of rather complex pattern of various slopes making it difficult to forecast with accuracy. Section 3 describes how the proposed method handles this difficulty in detail.

3 Methods

3.1 The proposed precipitation based period dividing algorithm (PPDA)

In order to achieve accuracy of forecasting results for the groundwater level, a new forecasting method named Precipitation based Period Dividing Algorithm (PPDA) is proposed in this paper. To a drought period, which has little precipitations, the pattern of data often has a large variance with a high fluctuation on the groundwater level. A number of methods reported in the literature associated with the forecasting system for the groundwater level may not achieve high accuracy on the analysis of a given long term period in drought periods. In order to address this issue, the

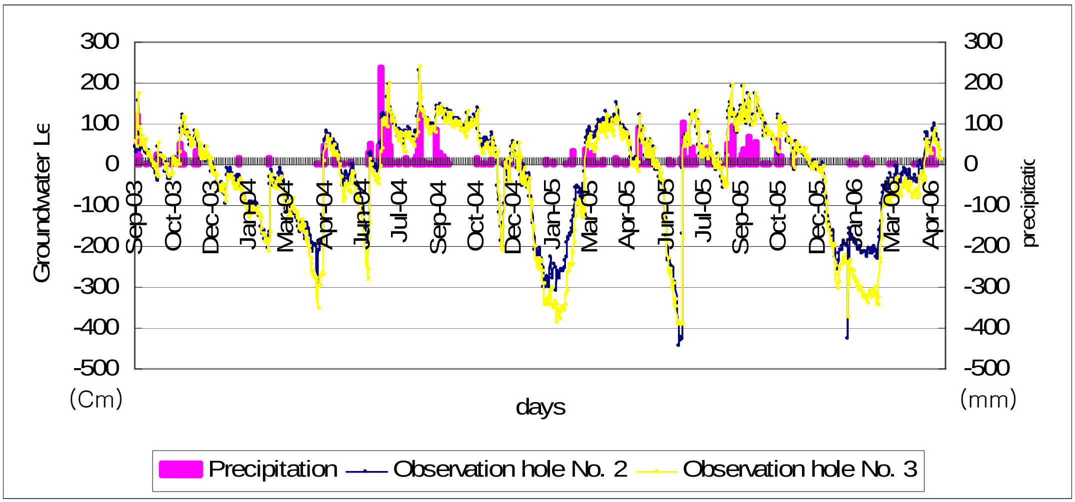


Fig. 2. Groundwater levels, Amount of precipitation

proposed PPDA developed an advanced period divide algorithm, which conducts a simulation that a long-term period is divided into a number of short-term periods. The PPDA considers two key parameters (i.e., precipitation and time) to conduct the simulation. The former is a minimum precipitation denoted 'a' which incurs significant rising of groundwater level and starts a new period, the latter is a minimum penetration time denoted 'b' and blocks to start a new period when current period duration is less than b. The proposed PPDA algorithm for the forecasting system can be shown in Fig. 3.

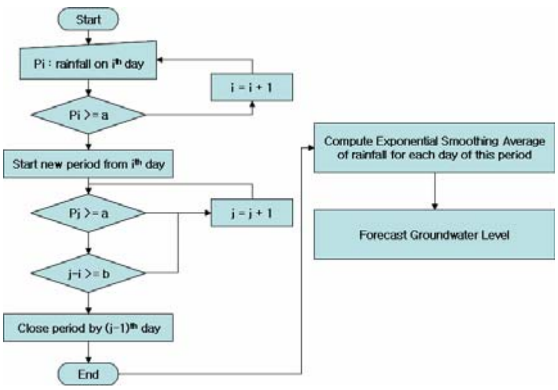


Fig. 3. Algorithm of the proposed PPDA for the forecasting system

3.2 Exponential smoothing

Rather than using data of long time lapse that may no longer be relevant, this method averages the data for only the last n periods as to forecast for the next period as follows

$$F_{t+1} = \sum_{i=t-n+1}^{t} \frac{x_i}{n} \qquad (1)$$

Where n, t, F_{t+1}, x_i denote number of days, observed time, moving average at time t+1, independent variable at time i. This forecast is easily updated from period to period. All that is needed each time is to lop off the first observation and add the last one [5].

The moving-average estimator combines the advantages of the last value and averaging estimators in that it uses only recent history and it uses multiple observations, One would expect a good method to place more weight x_{t-n+1} as on x_t intuitively, than on older observations that may be less representative of current conditions. A weighted moving average, named exponential smoothing, can be formulated by

$$F_{t+1} = ax_t + (1-\alpha)F_t \qquad (2)$$

Where α $(0 < \alpha < 1)$ is named the smoothing constant. Another alternative form for the exponential smoothing technique is given by

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

which gives a heuristic justification for this method. In particular, the forecast of the time series at time t+1 is just the preceding forecast at time t plus the product of the forecasting error at time t and a discount factor α.

3.3 Response surface methodology (RSM)

RSM is typically used to optimize the response by estimating an input-response functional form when the exact functional relationship is not known or is very complicated. For a comprehensive presentation of RSM, Box et al. [6] and Shin and Cho [7] provide insightful comments on the current status and future direction of RSM. Using this method, the response function for groundwater level estimate is given by

$$\hat{y}(\mathbf{x}) = \hat{\alpha}_0 + \mathbf{x}^T \mathbf{a} + \mathbf{x}^T \mathbf{A}\mathbf{x} \qquad (4)$$

Where

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}, \quad \mathbf{a} = \begin{bmatrix} \hat{\alpha}_1 \\ \hat{\alpha}_2 \\ \vdots \\ \hat{\alpha}_k \end{bmatrix}, \quad \text{and} \quad \mathbf{A} = \begin{bmatrix} \hat{\alpha}_{11} & \hat{\alpha}_{12}/2 & \cdots & \hat{\alpha}_{1k}/2 \\ \hat{\alpha}_{12}/2 & \hat{\alpha}_{22} & \cdots & \hat{\alpha}_{2k}/2 \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\alpha}_{1k}/2 & \hat{\alpha}_{2k}/2 & \cdots & \hat{\alpha}_{kk} \end{bmatrix} \qquad (5)$$

3.4 Development of the forecasting procedure and system for groundwater

As shown in Fig. 4, the proposed forecasting procedure for groundwater levels includes 5 steps as follows:

Step 1: Calculate moving average of precipitation that affects fluctuations of the groundwater levels. The number of days ssociated with moving average of precipitation select from the minimum to maximum days

Step 2: Conduct simulations using the proposed PPDA discussed in Section 3.1

Step 3: Perform exponential smoothing method discussed in Section 3.2. The weight-coefficient α is selected from 0.01 to 0.5

Step 4: Conduct RSM and analyze the results discussed in Section 3.3

Step 5: Check the model efficiency based on the RSM results using a statistical criterion R^2

Fig. 5 illustrates a sample screen shot of the the implemented prototype system for forecasting of groundwater levels. The system is developed with Java version 1.4 and provides GUI-based easy interfaces with modules of data management, user-guided reliable forecasting with several parameter selection options, charting and exporting raw, intermediate and result data to MS excel, etc.

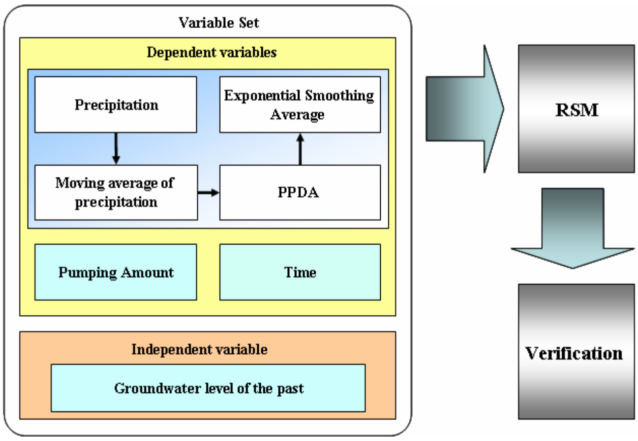


Fig. 4 The proposed forecasting procedure for groundwater levels

Fig. 5 An illustrative screen shot of the prototype forecasting system

3.5 Statistical results

With the data set plotted in Fig. 2, twenty-two periods are obtained from the proposed PPDA results to conduct further statistical analyses. In addition, we then utilize RSM, which can consider a quadratic evaluation associated with dependent and independent variables. To check the model efficiency on the utilization of RSM, correlation coefficient R^2 is an essential criterion and can provide an estimated model fitness for the proposed forecasting method.

Base on the divided periods shown in Table 1, we conducted exponential smoothing while changing weights, and had meaningful R^2 values. As shown in Table 2, the global F-test for verifying model correctness provided that the three models were significant because F_0s were greater than the critical values F (k, n-k-1, 0.05) on significant level 0.05. We found the predicted values for the groundwater levels and compared the observed values as illustrated in Fig.

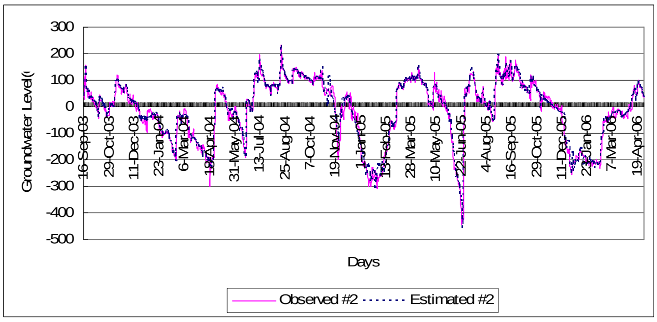
5. Fig. 5 shows that the proposed model can effectively estimate the groundwater level throughout the entire periods.

Table 1. Results of Precipitation based Period Dividing

Periods	Days			Periods	Days		
1	Sep. 16, 2003	~	Oct. 11, 2003	12	Feb. 16, 2005	~	Mar. 10, 2005
2	Oct. 12, 2003	~	Nov. 7, 2003	13	Mar. 11, 2005	~	Apr. 8, 2005
3	Nov. 8, 2003	~	Jan. 15, 2004	14	Apr. 9, 2005	~	May 5, 2005
4	Jan. 16, 2004	~	Feb. 21, 2004	15	May 6, 2005	~	Jun. 25, 2005
5	Feb. 22, 2004	~	Apr. 25, 2004	16	Jun. 26, 2005	~	Jul. 27, 2005
6	Apr. 26, 2004	~	Jun. 18, 2004	17	July 28, 2005	~	Aug. 18, 2005
7	Jun. 19, 2004	~	Jul. 11, 2004	18	August 19, 2005	~	Sept. 12, 2005
8	Jul. 12, 2004	~	Aug. 13, 2004	19	Sept. 13, 2005	~	Oct. 17, 2005
9	Aug. 14, 2004	~	Sep. 6, 2004	20	Oct. 18, 2005	~	Jan. 30, 2006
10	Sept. 7, 2004	~	Oct. 25, 2004	21	Jan. 31, 2006	~	Apr. 18, 2006
11	Oct. 26, 2004	~	Feb. 15, 2005	22	Apr. 19, 2006	~	Apr. 30, 2006

Table 2. Results of RSM

	Observation hole No. 2				Observation hole No. 3			
Periods	α	R^2	F_0	$F(k,n\text{-}k\text{-}1,0.05)$	α	R^2	F_0	$F(k,n\text{-}k\text{-}1,0.05)$
1	0.49	0.92	19.31	2.54	0.49	0.94	28.01	2.54
2	0.01	0.88	14.16	2.49	0.01	0.89	14.78	2.49
3	0.46	0.91	69.84	2.04	0.46	0.93	92.89	2.04
4	0.03	0.98	138.29	2.25	0.03	0.98	114.83	2.25
5	0.01	0.92	69.84	2.06	0.01	0.96	141.99	2.06
6	0.04	0.95	88.52	2.1	0.04	0.94	82.78	2.10
7	0.01	0.99	101.83	2.71	0.01	0.98	64.81	2.71
8	0.25	0.95	48.64	2.32	0.25	0.94	38.81	2.32
9	0.01	0.98	92.85	2.65	0.01	0.98	66.94	2.65
10	0.12	0.85	24.26	2.13	0.12	0.8	17.33	2.13
11	0.01	0.91	118.65	1.97	0.01	0.93	149.31	1.97
12	0.01	0.98	75.72	2.71	0.01	0.97	62.67	2.71
13	0.03	0.81	8.98	2.42	0.03	0.79	8.070	2.42
14	0.11	0.98	95.73	2.49	0.11	0.97	71.88	2.49
15	0.01	0.99	333.3	2.12	0.01	0.99	398.94	2.12
16	0.01	0.98	43.03	2.37	0.01	0.98	125.62	2.37
17	0.07	0.98	67.33	2.8	0.07	0.98	39.62	2.80
18	0.01	0.8	6.840	2.59	0.01	0.84	8.810	2.59
19	0.01	0.94	40.79	2.28	0.01	0.99	32.86	2.28
20	0.01	0.97	299.41	1.98	0.01	0.98	465.5	1.98
21	0.01	0.96	201.76	2.02	0.01	0.97	216.17	2.02
22	0.49	0.99	1175.76	19.38	0.49	0.99	6556.46	19.38



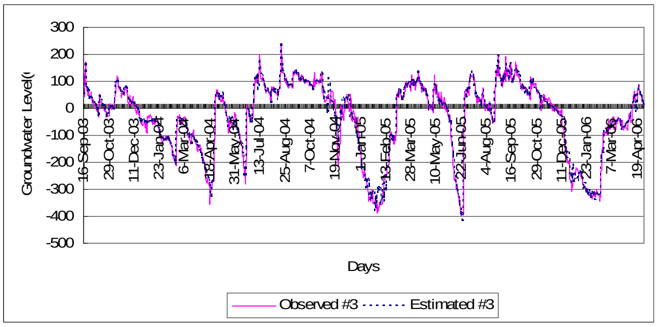


Fig. 5 Comparison of estimated values and the observed values

4 Conclusions

In this paper, we collected basic hydrological data in the Ssangchun watershed in South Korea. We then compared and analyzed the relationship between the precipitation and the groundwater level. We performed forecasting of the groundwater level using the amount of precipitation, the number of days, and the pumping amount of groundwater. In order to provide better modeling flexibility, we mainly developed and implemented an integrated forecasting system incorporating the simulation and statistical methods for groundwater levels. Using this system, a numerical example was performed. Based on the results of the numerical example, we showed how the proposed PPDA could effectively perform the forecasting of the groundwater level with considerable accuracy by using the concept of exponential smoothing and simulation. In addition, we then showed how RSM comprehensively conduct statistical analyses to contribute the integrated forecasting system. Based on the RSM results in this particular example, we obtained considerably high R^2 from0.8 to 0.99 for all models in the divided periods.

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