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Independent component analysis for characterization and quantification of regional groundwater pumping

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SUMMARY

The objective of this study is to develop a method that combines signal analysis with a groundwater simulation model for the characterization and quantification of regional groundwater pumping. We first use independent component analysis to identify the characteristics of the main pumping types from hourly groundwater head observations. Then we fit the drawdown variation at each observation well caused by each pumping type with a calibrated groundwater simulation model. We then use the results to estimate the quantity of each pumping type.

We apply the proposed method to a regional aquifer system in Sijhou Township, located in the Jhuoshuei River alluvial fan in central-western Taiwan. The independent component analysis identifies three main pumping types: Agricultural type, Industrial type A, and Industrial type B. All three pumping types have the same sine-wave shape with one-day frequency, but differ in peak time, valley time, and peak-to-valley amplitude. Agricultural pumping occurs during daytime farming hours, while industrial pumping occurs during off-peak hours to take advantage of much lower nighttime electricity rates.

Quantitative results indicate that the total amount of groundwater pumping in Sijhou is 37,565 tons per day, of which more than 58% is for agricultural use, while the remaining 42% is for industrial use. The percentage of industrial pumping is higher than expected, which may imply that industry use of groundwater is changing. The results indicate a large amount of pumping takes place at depths of more than 40 m. For further investigation, the installation of more monitoring wells is recommended at deeper aquifers.

1. Introduction

According to statistical reports of the Water Resources Agency of Taiwan (2010), the average annual water demand in Taiwan from 2000 to 2009 is about 18.1 billion tons, of which about 5.6 billion tons (more than 30%) are supplied by groundwater. Because of the relatively low development cost and easy accessibility, a large amount of groundwater is extracted for agricultural, industrial, and domestic water uses. Over the years, over-pumping of groundwater in Taiwan has caused various problems, such as land subsidence and seawater intrusion. There is an urgent need to understand regional pumping characteristics as well as related pumping quantities so that over-pumping can be identified and controlled. There are basically four methods that have been used to estimate groundwater pumping: (1) pump electricity consumption analysis, (2) water budget method, (3) groundwater hydrograph analysis and (4) numerical model simulations. These methods are reviewed below.

1.1. Pump electricity consumption analysis

Groundwater is pumped out by water pumps through pumping pipes. By conducting flow discharge rating tests with pumps of different horsepower and diameter, the relationship between pump electricity consumption and pumping quantity can be obtained. Specifically, the total pumping quantity of each well is a product of total electricity consumption and the pumping quantity per unit of electricity consumption (Haiduk and Ishemo, 2011; Karimi et al., 2012). Since the relationship between electricity consumption and pumping quantity is stable and credible, the accuracy of this method depends on whether the pumping well census and records of pump electricity consumption are complete and accurate. More

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accurate data leads to a more accurate pumping estimation. Furthermore, the pumping quantity for different water uses can be evaluated better if the type of business enterprise associate with each well is recorded.

1.2. Water budget method

Since performing a pumping well census is time-consuming, laborious, and expensive, the commonly used method for pumping estimation is the water budget method. This is the most traditional hydrological estimation method. Various hydrologic components, such as rainfall, runoff, evaporation, and infiltration, can be quantified by field measurements. Then pumping quantity can be evaluated by the mass conservation equation. This method is suitable for estimating pumping of the entire catchment area (Croke et al., 2000; Ruud et al., 2004; Claessens et al., 2006; Martinez-Santos and Martinez-Alfaro, 2010). Clearly, the results are influenced by the accuracy of hydrologic measurements. However, the water budget method is not suitable for identifying the distribution or characteristics of pumping.

1.3. Groundwater hydrograph analysis

Groundwater pumping causes changes in groundwater levels, and, in principle, pumping quantity can be estimated using water level observations. The amount of groundwater in storage in an aquifer can be estimated using the product of the groundwater level, the storage coefficient and the representative area. The time series of storage is referred to as the groundwater hydrograph. When groundwater is extracted, the hydrograph will decline; in contrast, if the groundwater system is recharged the hydrograph will rise. The amount of pumping or recharge that is related to the decline or rise of the hydrograph, can be calculated (Healy and Cook, 2002; Moon et al., 2004; Marechal et al., 2006; Wang and Cai, 2009; Hsu et al., 2013). The accuracy of using groundwater hydrograph for estimating groundwater pumping relies on the density of observation wells as well as the quantity and quality of observations. However, groundwater hydrographs reflect the aggregated results due to pumping and recharge; hence, it suffers from the same limitation as the water budget method.

1.4. Numerical model simulations

In recent year, dynamic groundwater simulation models have been used for source identification. To ensure that the simulation model is an accurate representation of the real groundwater system, the model must be calibrated in advance so that the simulation results match with head observation data. For pumping estimation, the calibration procedure is completed by adjusting the pumping rate of the pumping wells. The best estimation of pumping is obtained when the simulated groundwater head at monitoring wells matches the observed head (Aral et al., 2001; Tung and Chou, 2004; Ayvaz and Karahan, 2008). The advantage of utilizing simulation models is that the temporal and spatial distribution of pumping can be evaluated. But such distribution is still an aggregated result of the various pumping types. The characteristics of pumping activities are still unknown.

Over-pumping is a major concern in Taiwan. In order to understand and control over-pumping, several researchers have focused their studies on pumping source identification (Lin and Yeh, 2008; Cheng et al., 2009; Saffi and Cheddadi, 2010; Liu and Hsu, 2014). For source identification one must estimate not only the amount of pumping but also the locations of the pumping sources. So far, the published literature only deals with simplified synthetic cases or small areas with few pumping sources. For a realistic regional groundwater basin, the number of pumping wells is far more than the number of monitoring wells. With such a limited amount of observations, it is impossible to identify each pumping source separately. Moreover, pumping for different uses exhibits different characteristics, something seldom discussed in the literature. In this study, we propose a new method for regional pumping characterization and quantification.

Since it is impossible to identify the pumping activity of each pumping well, in this study we introduce the concept of pumping characterization for source identification. Different pumping wells have different purposes, such as industrial, agricultural or domestic and groundwater level changes caused by different pumping activities have significantly different characteristics. Signal analysis can be applied to identify the main pumping characteristics from the observation data. Then a numerical model can be used to simulate variations in groundwater level and evaluate the pumping quantity. Signal analysis utilizes statistical tools and information processing techniques to decompose or transform the original signal into many components containing different information. Commonly used signal analysis techniques include spectral analysis, time-frequency analysis, principal component analysis and independent component analysis. Among them, independent component analysis (ICA) is mainly used to deal with the blind source separation problem (Hyvärinen and Oja, 2000). The unknown original source signals can be isolated from the observed and multiple mixed signals. ICA is a technique that can be used to separately extract the characteristics of different kinds of pumping from the observed heads at monitoring wells. Such information is very helpful in quantification of groundwater pumping (Liu and Hsu, 2014). Consequently, it is possible to evaluate multiple components of pumping in a regional groundwater basin.

The proposed new estimation method first utilizes ICA to identify the main pumping types and the resulting variations in groundwater level. Second, we employ a groundwater simulation model to estimate the quantity of pumping for each main pumping type by matching the simulation with groundwater level variations. Third, we obtain the characteristics and quantities of regional pumping sources. Last, we apply the proposed method to a regional aquifer system in Sijhou Township located in the Jhuoshuei River alluvial fan in central-western Taiwan.

2. Methodology

Fig. 1 shows a flowchart of the proposed methodology. First, the hourly groundwater level observation data is collected. The commonly used daily observation data are not appropriate here because pumping activity varies with hours. Pumping characteristics can be clearly revealed on an hourly scale but not a daily scale. A simple frequency analysis of groundwater level observation data confirms this assumption.

The second step is to subtract the mean value of groundwater level from observation to obtain the fluctuation of groundwater level. These fluctuation data are the mixed signals. Then utilize independent component analysis (ICA) to decompose the hourly fluctuation of groundwater level into several independent main head variation time series caused by pumping. These main head variation time series are the original signals. Each variation time series is caused by a specific pumping activity of a specific enterprise, such as agriculture, industry, or domestics use. By the analysis of ICA, we can also obtain the mixing matrix, which describes the relationship between original signals (head variation) and mixed signals (fluctuation of groundwater level). When the head variation is multiplied by the mixing matrix, the variation or drawdown at each observation wells caused by only one pumping type is obtained. In other words, the pumping for a specific purpose at numerous wells causes a lumped head variation (original