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Conservation of groundwater from over-exploitation—Scientific analyses for groundwater resources management

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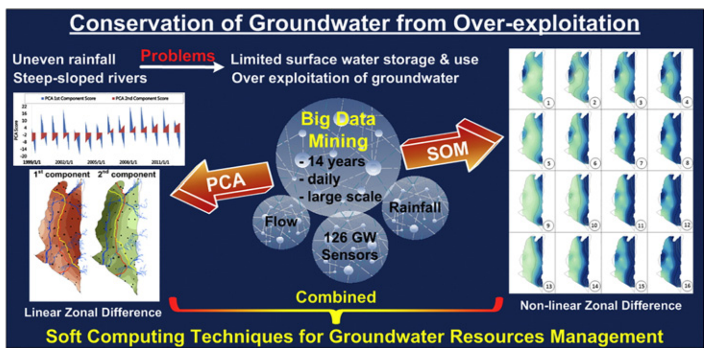
HIGHLIGHTS

- Provide scientific analyses of the groundwater systems for future groundwater management plans
- Relate spatial-temporal patterns of groundwater with surface water based on large datasets
- PCA classified the groundwater systems into eastern, western and transition zones
- SOM visibly explored regional groundwater variations and inter-relations among variables
- Build inter-relation between surface water with groundwater mechanisms at a watershed-scale context

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater over-exploitation has produced many critical problems in the southern Taiwan. The accumulated stresses and demands make groundwater management a complex issue that needs innovative scientific analyses for deriving better water management strategies. In this study, we aimed to provide scientific analyses of the groundwater systems in the Pingtung Plain through soft-computing techniques to explore its spatial-temporal and hydro-geological characteristics for the elaboration of future groundwater management plans and in decision-making process. We conducted a study to assess the essential features of the groundwater systems based on the long-term large datasets of regional groundwater levels by using the principal component analysis (PCA), and the self-organizing map (SOM) with regression analysis. The PCA results demonstrated that two leading components could well present the spatial characteristics of the groundwater systems and classify the region into eastern, western and transition zones. The SOM results could visibly explore the behavior of regional groundwater variations in various aquifers and the multi-relations among climate and hydrogeological variables. Results revealed that the potential of groundwater recharge made by precipitation or river flow was higher in the eastern zone than in the western zone. Analysis results further showed an increase of the groundwater levels in the western zone after year 2006, while there were no obvious increases of the groundwater levels in the eastern or transition zones. Based on the investigated characteristics, we suggest that a sound groundwater management plan should consider zonal difference of the groundwater systems to achieve groundwater conservation.

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1. Introduction

While very uneven rainfall and steep-sloped rivers constrain the storage and use of surface water resources in Taiwan, groundwater becomes a substitute for surface water in many areas (Liang et al., 2016). Especially in the southern Taiwan, exploitation of groundwater has been extracted not only for drinking purposes but for irrigation and cultivation in agricultural and aqua-cultural sectors (Hu et al., 2006; Jang et al., 2016). A year-round domestic water demand and aqua- and agricultural operations have resulted in intensive groundwater exploitation (Jang et al., 2016). The over exploitation of groundwater has led to many problems, such as the contamination of groundwater that caused the arsenic intrusion in drinking water, which greatly increase the risks of diabetes and cancers (Das et al., 2016; Lamm et al., 2004; Liu et al., 2003; Liang et al., 2016). Another serious problem caused by groundwater over-exploitation is land subsidence and groundwater depletion (Burbey, 2008; Hung et al., 2012; Wada et al., 2012). Along the coastal region, a serious vertical land movement was observed in the range of −0.7 to −2.8 cm per year in the Pingtung Plain (Hsieh et al., 2011) leading to the other serious groundwater salinization problems (Chen et al., 2007).

With the purposes to remediate these serious problems caused by intensive groundwater exploitation, an amendment of the Regulations on Groundwater Conservation (RGC) was passed in year 2002 for regulating and limiting the use of groundwater in Taiwan. Under this amendment, the Water Resources Agency and the associated governmental agencies in Taiwan are endowed with the power to determine and regulate where and how much groundwater can be exploited. Since 2002, both previously and newly constructed wells in the regulatory zones need to apply for licenses and renewals. At present, the RGC has been enacted for more than ten years. In addition, the Water Resources Agency has launched groundwater level monitoring programs in the regulatory zones. Under better protection of the groundwater resources, an increase of the groundwater storage in the regulatory zones is expected. As such, this study was conducted as a part of a regional groundwater assessment and modeling study requested by the Water Resources Agency of Taiwan in the context of sustainable groundwater management.

Groundwater aquifers are complex and heterogeneous systems, which pose great challenges in the modeling of groundwater systems as well as systematically quantification for sustainable water resources management (Alley and Leake, 2004). The level of groundwater is affected by a combination of several natural and anthropogenic factors like precipitation, geology, slope and water withdrawal (Redwan and Moneim, 2016). Prediction of the regional groundwater level often involves using precipitation and/or stream flow as primary sources to the recharging mechanisms of groundwater aquifers (Tsai et al., 2016). However, the interactions vary among different hydrogeological systems (Krause et al., 2007), and the distribution of precipitation differs temporally and spatially. These spatial-temporal features require local- and regional-scale studies (Cheng and Wiley, 2016) to catch the changes in the groundwater system and realize the dynamic balance of the abstraction, replenish, and storage process in space and time (Bekesi et al., 2009). Without enough understanding of the mechanisms and forces that control the level of groundwater in the Pingtung Plain, plus insufficient data to account for the actual magnitude of groundwater withdrawn or the real precipitation distribution, sustainable management of groundwater resources in this area has been very challenging. To pursue sustainable use of groundwater, scientific investigations of the groundwater recharge/discharge mechanisms and classifications of the complex spatial-temporal groundwater features in the Pingtung Plain are needed. As such, the comprehensive characterization of the region from a groundwater perspective can provide useful elaboration for future groundwater management plans and in decision-making process.

In this paper, we developed a groundwater modeling study to explore the changes of the groundwater level in the Pingtung Plain and evaluated the effectiveness of the RGC amendment that has been executed for more than 10 years. The objective of this study was to make a preliminary assessment of the groundwater responses to meet the need for decision making on groundwater resources management with a focus on groundwater conservation from over exploitation. We first applied a principal component analysis (PCA) to the groundwater level data collected during dry seasons to investigate the characteristics of the groundwater systems. Following that, we performed the self-organizing map (SOM) based on year-round groundwater level data to classify the patterns of groundwater levels. Then we employed a regression analysis between groundwater level and precipitation as well as river flow. We coupled all the results to discuss spatial and temporal differences associated with the hydro-geophysical characteristics in the plain. Last, we provided a comprehensive understanding of the groundwater systems for sustainable groundwater resources management and the evaluation results for the effectiveness of the RGC amendment.

2. Methods

2.1. Study area

The Pingtung Plain is located in southwestern Taiwan with a total drainage area of 1210 km^2. It consists of alluvial fans of three major rivers, including the Kaoping River, the Tungkang River and the Linbian River. The rivers are originated from the Central Mountain Range in the northeast, progress through the plain, and eventually drain into the Taiwan Strait (Fig. 1).

The geological setting of the main stratigraphic compositions in the Pingtung Plain was investigated by several drilling studies and stratigraphic analyses since 1995 (Liang et al., 2016). The investigation results revealed that the plain were comprised by multiple overlapping sequences, and the Central Geological Survey in Taiwan defined it into four aquifers A, B, C, and D by depths of 0–70, 40–130, 90–180, and 160–250 m, respectively (Fig. 2). Daily groundwater level data were recorded by 126 groundwater monitoring sensors installed in a total of 55 observation wells spreading across the four aquifers (Fig. 1). Daily precipitation records and daily flow data were monitored at 15 and 3 gauging stations in the plain, respectively (Fig. 1).

2.2. Data collection and preprocessing

Provided by the Water Resources Agency in Taiwan, 14-year (1999–2012) time-series data of daily groundwater levels, along with precipitation and flow records were aggregated for the Pingtung Plain. To compare the variation of groundwater level in the region, we transformed groundwater elevation data into relative groundwater levels prior to the analysis process. The relative groundwater level (R_{GL}) was calculated by subtracting the observed minimum groundwater elevation from the observed groundwater elevation (Eq. (1)).

$$R_{GLi} = O_{GLi} - M_{GLi} \tag{1}$$

where R_{GLi} is the relative groundwater level of the i^{th} groundwater sensor, O_{GLi} is the observed groundwater elevation of the i^{th} groundwater sensor, and M_{GLi} is the observed minimum groundwater elevation of the i^{th} groundwater sensor. In this way, the variation of groundwater level can be captured and standardized for making comparisons among different groundwater sensors.

2.3. Computational methods

2.3.1. Principal component analysis (PCA)

The PCA is a widely used analysis that helps reduce the dimensionality of the data sets but retain most of the variations for easier data exploration (Noori et al., 2010; Azid et al., 2014; Zahra et al., 2014). We used the PCA to extract principal components in the order of their significance representing the features of the groundwater levels among