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Estimation of pumpage and recharge in alluvial fan topography under multiple irrigation practices

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SUMMARY

In this study, we estimate small-scale temporal variations in groundwater pumpage and recharge in alluvial fan topography. We study these variations on a monthly scale using groundwater storage hydrograph and isotope analysis along with area rainfall hydrographs and data of historical irrigation pumpage variations. We consider multiple irrigation practices whose effect was measured only on an annual basis in mostly previous studies. In previous studies, pumpage for non-irrigation or irrigation purposes was regarded as known but illegal pumping was not accounted for. Also, recharge sources include rainfall, rivers, boundary inflow, and groundwater-irrigation, which have not been individually accounted for in previous studies. Pumpage can be estimated from the pumping rate and the number of pumping days. In alluvial fan topography, the actual pumping rate, including that because of illegal wells, can be deduced from the recession slope of the groundwater hydrograph. The annual pumping rate of non-irrigation pumping is assumed to be constant, and can be estimated as the slope of the groundwater hydrograph over consecutive non-rainy days during the non-irrigation periods of the dry season. For cases where there are multiple irrigation practices, the temporal distribution of the irrigation pumping rate can be estimated from the slope of the groundwater hydrograph and also from records provided by the Irrigation Association. In this study, we regard recharge as the difference between inflow and loss. Different types of inflow can be inferred from the storage hydrograph in rainy or non-rainy days, and the loss can then be obtained by using the groundwater balance equation. The isotope mass balance equation is then used to quantify various sources of recharge. In this study, we apply the proposed methodology to the Cho-Shui River alluvial fan, Taiwan. The results show that the proposed methodology can overcome previous restrictions of groundwater hydrograph and isotope analyses to effectively and rationally estimate monthly variations in pumpage and recharge, thus making it possible to research fine flow mechanisms within a multi-layer groundwater system.

1. Introduction

Cultivated regions in middle-south Taiwan support multiple crop types, with different temporal cultivation patterns used for each type of crop (i.e., paddy or upland crop). Different temporal cultivation patterns require different irrigation practices. Therefore, multiple irrigation practices exist in the cultivated regions of middle-south Taiwan. Each irrigated region is cultivated for differing durations, and each crop has different water requirements. Owing to the huge demand for irrigation water and insufficient surface water in the semi-arid regions of middle-south Taiwan, cultivation patterns can be organized in several ways according to real irrigation capability: two periods of cultivation within 3 years, two periods of cultivation within 1 year, one period of cultivation within 1 year, rotational cultivation, or pure upland crop. The cultivation period for paddy areas lasts approximately 4 months; the first periods of cultivation tend to be distributed between January and May, and the second between June and October. Upland crops are cultivated all 12 months of the year. Hence, the quantity of water required for irrigation varies from month to month. Furthermore, the precipitation in irrigation regions varies greatly between the wet and dry seasons and the monthly volume of water supplied by rainfall and rivers is also highly variable. These variations lead to a non-uniform recharge time series. Thus,

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we note that water demand, cultivation time, and spatial distribution of multiple irrigation practices are different for different irrigation regions. Further we note that the spatiotemporal distribution of water used for irrigation is non-uniform. Therefore, the spatiotemporal distribution of groundwater irrigation pumpage (that is, the volume of water extracted from groundwater aquifers) is also extremely non-uniform.

It is common practice in Taiwan to use multiple irrigation methods in alluvial fan topography. A fan can be divided into three parts: the apex, middle, or distal regions, based on its horizontal profile; it consists of alternating aquifers and aquitards. In the apex of the fan, permeability is high and the aquifers are well-linked. The various inflows allow recharge of the middle and distal fans from the apex of the fan, but the aquifers in the middle and distal fans are blocked by aquitards and contain numerous mud layers. If the pumpage is large and non-uniform in time and space, recharge cannot occur promptly; such areas are subject to land subsidence, seawater intrusion, and groundwater pollution. The management of groundwater is very important in order to mitigate these problems. However, developing a reliable and effective groundwater management strategy requires an understanding of the variations in pumpage and recharge, and the application of an appropriate numerical model as an assessment tool. The development of an effective assessment tool requires a thorough understanding of the groundwater system, which in turn requires an accurate estimation of the variations in pumpage and recharge.

From groundwater mass balance theory, it is known that a change in groundwater during a time period, $i(\Delta Q_s(i))$, is equal to total recharge during $i(Q_r(i))$ minus total pumpage during $i(Q_p(i))$. This can be expressed as in Eq. (1):

$$\Delta Q_s(i) = Q_r(i) - Q_p(i) \tag{1}$$

$\Delta Q_s(i)$ can be computed from fluctuations in groundwater storage, and so $Q_p(i)$ and $Q_r(i)$ are the unknown variables. When using Eq. (1), groundwater pumpage and recharge can be estimated in three ways: estimate $Q_p(i)$ separately; estimate $Q_r(i)$ separately; or estimate $Q_p(i)$ and $Q_r(i)$ together using a mass balance equation. Methods of estimating pumpage and recharge can be divided into several categories: in situ investigation, empirical schemes, numerical simulations, and groundwater balance analysis. In situ investigation is costly and is therefore used less frequently. Empirical schemes are based on the concepts of statistical hydrogeology, but the accuracy of results derived from this method is insufficient for the intended use. In situ investigations and empirical schemes are used to estimate pumpage or recharge separately. When using numerical models, the model parameters must be calibrated before simulation. Input parameters must be realistic, and so the spatiotemporal distribution of pumpage and recharge must be determined before calibrating the parameters. Groundwater balance analysis is a form of qualitative analysis used to construct conceptual models of the hydrological cycle. Using observed or estimated hydrological quantities to estimate other hydrological variables by mass balance theory allows pumpage and recharge to be determined simultaneously. We therefore consider groundwater balance analysis to be the most important method for estimating pumpage and recharge.

Pumpage from illegal wells (meaning the volume of groundwater pumped from wells that do not have water extraction rights) in middle-south Taiwan is extensive and poorly recorded; only pumpage of official wells can be obtained from official sources, and hence, the actual pumpage is unknown. Furthermore, despite its importance in groundwater management, groundwater pumpage is the least measured of the water balance components. This is especially true of many semi-arid regions worldwide, where irrigation relies heavily on groundwater resources (Sanchez, 2003; Ruud et al., 2004). In a previous study, Ruud et al. (2004) developed a GIS-based water balance model to estimate basin-scale groundwater pumpage for a semi-arid, irrigated agricultural area. The water balance of the surface water supply system can be used to estimate groundwater pumpage, and the soil root zone with associated land use data can be used to estimate groundwater recharge. The change in groundwater storage can be obtained by subtracting pumpage from recharge, and estimated values can be verified using the water-table fluctuation (WTF) method. Martínez-Santos and Martínez-Alfaro (2010) described an example of the combined application of WTF and the groundwater balance equation to evaluate pumpage, and previous studies have often utilized the water balance equation in estimation of pumpage. Other water balance components, including recharge, were estimated by in situ investigation or empirical schemes, both of which introduce significant uncertainty into the estimation of pumpage.

Previous studies have tended to estimate recharge without including an estimate of pumpage; therefore, the results of these studies cannot be validated by the mass balance theory. In previous studies, groundwater recharge was most commonly estimated via hydrograph analysis (Meinzer and Stearns, 1929; Rasmussen and Andreasen, 1958; Wittenberg and Sivapalan, 1999; Arnold et al., 2000; Healy and Cook, 2002; Moon et al., 2004; Maréchal et al., 2006; Lee et al., 2008; Misstear et al., 2009), and this method is regarded to give the most realistic results. Meinzer and Stearns (1929) and Rasmussen and Andreasen (1958) extended the recession limb of the groundwater hydrograph before rainfall to estimate the groundwater recharge of each event, yet neither of these studies considered groundwater pumpage. Arnold et al. (2000) applied water balance analysis and the WTF method to evaluate groundwater recharge and base flow, with both methods producing similar results. Healy and Cook (2002) reviewed previous use of the WTF method in estimating groundwater recharge, and highlighted limitations of the method. For example, the process of recharging a deep aquifer may be dispersed over long distances, so groundwater levels react slowly and the rise in level is small. Furthermore, water-table fluctuation is affected by recharge and loss at the same time, and so the gross input does not accurately represent the net recharge. Moon et al. (2004) identified five typical groundwater hydrograph types according to the relationship between groundwater levels and hyetographs and used this method to evaluate the groundwater recharge of every river basin in Korea. Misstear et al. (2009) applied multiple approaches such as soil moisture budgeting, well hydrograph analysis, numerical groundwater modeling, and catchment water balance to estimate groundwater recharge, although well hydrograph analysis did not consider pumpage, boundary inflow, and loss. The above studies suggest that groundwater recharge mostly occurred due to rainfall seepage or river seepage, or a combination of both, after precipitation. Recharge from boundary inflow and groundwater irrigation was rarely considered to be an important factor.

Groundwater balance analysis has been researched and developed in recent years for the purposes of groundwater investigation, planning, and management. Shentsis and Rosenthal (2003) and Umar et al. (2008) analyzed the groundwater balance of each aquifer. However, pumpage and recharge were estimated separately by in situ investigation or empirical schemes, which included approximated assumptions or simplistic parameters, and so the accuracy of each estimated groundwater balance component could not be guaranteed. In order to address these problems, Hsu et al. (2011) applied the groundwater storage hydrograph to analyze the annual groundwater balance. Because we could not separate the influence of different types of irrigation practices in the previous study area by Hsu et al. (2011), pumpage could only be calculated by summation. Recharge can be due to rainfall, river, and flow of groundwater across the boundary. However, neither the pumpage of each source nor the time series of pumpage and recharge at small scales have