



## Research papers

# Characterizing subsurface hydraulic heterogeneity of alluvial fan using riverstage fluctuations



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## ABSTRACT

The objective of this study is to demonstrate the ability of riverstage tomography to estimate 2-D spatial distribution of hydraulic diffusivity ( $D$ ) of Zhuoshui River alluvial fan, Taiwan, using groundwater level data from 65 wells and stream stage data from 5 gauging stations. In order to accomplish this objective, wavelet analysis is first conducted to investigate the temporal characteristics of groundwater level, precipitation, and stream stage. The results of the analysis show that variations of groundwater level and stream stage are highly correlated over seasonal and annual periods while that between precipitation is less significant. Subsequently, spatial cross-correlation between seasonal variations of groundwater level and riverstage data is analyzed. It is found that the correlation contour map reflects the pattern of sediment distribution of the fan. This finding is further substantiated by the cross-correlation analysis using both noisy and noise-free groundwater and riverstage data of a synthetic aquifer, where aquifer heterogeneity is known exactly. The ability of riverstage tomography is then tested with these synthetic data sets to estimate  $D$  distribution. Finally, the riverstage tomography is applied to the alluvial fan. The results of the application reveal that the apex and southeast of the alluvial fan are regions with relatively high  $D$  and the  $D$  values gradually decrease toward the shoreline of the fan. In addition,  $D$  at northern alluvial fan is slightly larger than that at southern. These findings are consistent with the geologic evolution of this alluvial fan.

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## 1. Introduction

For managing groundwater resources in a basin, information about hydraulic property distributions, which controls water and contaminant movement and their distributions in the basin, is essential. With this information, numerical surface water and groundwater models can be used for long-term management of water resources through estimation, prediction, and scenario analysis of surface water and groundwater systems.

Hydraulic tomography (HT) is a recently developed technique for characterizing subsurface heterogeneity. The rationale of HT is a joint interpretation of non-fully-redundant information about aquifer heterogeneity carried by drawdown fields induced from pumping tests at different locations. Specifically, successive pumping tests at different locations create different flow fields. Each flow field allows given observation wells to observe heterogeneity at certain parts of an aquifer at one perspective. Different flow fields thus facilitate viewing the heterogeneity at many different perspectives, using the same observation wells. HT can also include different types of information, such as observed head and flux (Zha et al., 2014; Tso et al., 2016), and prior geologic information such as layering (Tso et al., 2016; Zhao et al., 2016; Zhao and Illman, 2017). It has been successively applied to small-scale synthetic aquifers (Hao et al., 2008; Yeh and Liu, 2000; Zhu and Yeh, 2005, 2006), laboratory sandboxes (Illman et al., 2007; Liu et al.,

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2002, 2007), plot-scale fields (Berg and Illman, 2011, 2013, 2015; Bohling et al., 2007; Cardiff et al., 2012; Huang et al., 2011; Li et al., 2007a; Straface et al., 2007; Vesselinov et al., 2001), and fractured granite field sites (Illman et al., 2009; Zha et al., 2014, 2015). Its usefulness has been well documented by many studies.

HT relies on artificial excitations such as pumping or injection of water. However, it is difficult or impractical to apply HT to basin-scale aquifer characterization because of ineffectiveness of artificial hydraulic tests for altering groundwater flow fields over kilometers or basin scales. Natural stimuli, such as atmospheric pressure variations (Rojstaczer, 1988), solid earth tides (Hsieh et al., 1988; Rojstaczer and Riley, 1990), ocean tides (Davis et al., 2000; Li et al., 2007b), precipitation (Jan et al., 2013), and even earthquake (Lin et al., 2004), are found to induce groundwater fluctuation from local to regional flow systems. For these reasons, Yeh et al. (2008) proposed utilizing natural stimuli as excitation sources for basin-scale hydraulic tomographic surveys.

River-stage tomography is a concept of extracting subsurface heterogeneity information from groundwater variation induced by changes in the river water level and migration of the flood wave from the upper to downstream. The time scale of variations could be event, seasonal, or even annual basis. Yeh et al. (2008, 2009) explored this possibility of characterizing basin scale subsurface heterogeneity. They used a synthetic stream-aquifer system to demonstrate the potential of river-stage tomography utilizing event-based flood waves. Furthermore, recharge rates to groundwater aquifer from river through stream bed were simulated from Darcy's flux and were utilized to represent the surface water-/groundwater exchange in the work of Yeh et al. (2009). This rate in the real world applications is unknown. Besides, groundwater level information recorded in a basin is likely influenced by many factors (such as precipitation, pumping, regional flow, and others). How to extract useful information from these data sets for characterizing basin-scale aquifer heterogeneity remains to be a challenge. For all these reasons, the applicability of the riverstage tomography for aquifer characterization in real world scenarios remains to be assessed.

While in this paper, interaction between surface water and groundwater is introduced by treating the river as a prescribed head boundary. This choice is due to the reason that the hydraulic conductivity ( $K$ ) of the stream bed usually is not available in the field dataset. As a result, the objective of this paper is to estimate basin-scale  $D$  fields using stream induced groundwater level variations utilizing both synthetic and field data. In addition, the validity of treating the river as a prescribed head boundary on the hydraulic parameter estimation is discussed.

In order to achieve this goal, we first use wavelet analysis to analyze long-term precipitation, riverstage, and groundwater time series collected at the Zhuoshui River alluvial fan, Taiwan to select appropriate time span and data sets for spatial cross-correlation analysis. We compare the contour maps of the maximum cross-correlation and lag time between the riverstage and groundwater with the map of geology of the site to check the feasibility of the approach. We then use flow model to simulate groundwater level responses to the fluctuations of riverstage in a synthetic alluvial fan resembling the field site. The simulated groundwater responses and the riverstage information are then used to evaluate the performances of the cross-correlation and riverstage tomography analyses. The results from the noise-free and noise corrupted groundwater responses shed lights on the validity of those for the alluvial fan using field data, which may be influenced by many factors not considered. Afterward, the riverstage tomography is applied to estimate  $D$  spatial distribution at the Zhuoshui River alluvial fan and the results are discussed.

## 2. Site description

The ideal candidate for the application of the river-stage tomography would be a groundwater basin that has been well instrumented and monitored. That is, the basin must have a large number of observation wells at different locations with screens opened at different depths and a sufficient number of river gauging stations. Most importantly, long term and high frequency (at least hourly) records of groundwater levels, riverstage, precipitation, and other hydro-meteorological processes over the basin are required. Few basins in the world meet this requirement because of costs associated with the operations and maintenances. The Zhuoshui River alluvial fan in Taiwan is uniquely qualified for this purpose because a massive amount of hydro-geological data has been collected since 1992 primarily for the purpose of irrigation groundwater management and earthquake investigations.

### 2.1. Topography

The Zhuoshui River alluvial fan (Fig. 1a) is located at mid-west part of Taiwan. It is about 70 km long and 40 km wide and has an area of 1800 km<sup>2</sup>. It is bounded by Wu River at the north, Beigang River at the south, Taiwan Strait at the west, and the Central Mountain Range at the east. The Zhuoshui River cuts through the mountain pass of the ridge between Bagua Plateau and Douliu Hill at the center of the fan, and flows from east to west through the middle part of the fan and discharges into Taiwan Strait. The elevation of the fan is about 100 m at the apex and 0 m at the tail. The elevation drops from 100 to 30 m within 10 km after exiting the mountain pass between Bagua Plateau and Douliu Hill. Groundwater level is generally 30 m below the ground surface at the upper fan and 10 m below the ground at middle and tail.

### 2.2. Geology

The Central Geological Survey (1994, 1999) constructed 12 hydro-geological profiles for the alluvial fan based on the core samples from drilled wells. An unconfined and three confined aquifers, namely, layer 1 to layer 4, were approximately identified from shallow to 300 meters depth. The geological investigation indicated that all of the aquifers are connected to each other at apex of the fan where the deposition is mainly gravel (blue zones in Fig. 1b). This alluvial fan consists of several layers of Holocene to Pleistocene sands and gravels, which form the three confined aquifers separated by marine mud (Central Geological Survey, 1994, 1999). It suggested that the rising and falling of the mean sea levels caused by global climate change late in the Quaternary Period created the layered structure of the alluvial fan (Water Resources Agency, 2014). Massive gravels and coarse sands, which comprise many layers of the upper fan, pinch out toward the west of the fan at shoreline, while the mud layers thicken. An interface between the gravels and the arenaceous sediments was identified that separates the partially confined and confined aquifers.

The distribution of sediments in the alluvial fan follows gravel, sand, and clay from the apex to the tail of the alluvial fan. This pattern agrees with the sedimentation process of the river that angular conglomerates and breccias tend to settle down at the headwater where transport energy is relatively high, while the arkose and finer materials such as silt and clay tend to be at the middle and tail of the river, which has low transport energy. Due to the drift of the flow path of Zhuoshui River in the past, the sediment profile at northern part of middle alluvial fan exhibits interlocked sand and silt/clay features. On the other hand, the southern part of the alluvial fan does not manifest such features. This is probably attributed to the fact that the sediment in the southern

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