Advances in Water Resources 97 (2016) 52–72

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Filtering methods in tidal-affected groundwater head measurements: Application of harmonic analysis and continuous wavelet transform

Juan Pedro Sánchez-Úbeda[a,*], María Luisa Calvache[a], Carlos Duque[b], Manuel López-Chicano[a]

[a] Department of Geodynamics, Sciences Faculty, University of Granada, Campus Fuentenueva, E-18071, Granada, Spain
[b] Department of Geological Sciences, University of Delaware, Penny Hall, 255 Academy Street, 19716 Delaware, USA

ARTICLE INFO

Article history:
Received 9 February 2016
Revised 30 August 2016
Accepted 31 August 2016
Available online 1 September 2016

Keywords:
Tidal influence
Filtering methods
Groundwater head
Coastal aquifer
Harmonic analysis
Wavelet transform

ABSTRACT

A new methodology has been developed to obtain tidal-filtered time series of groundwater levels in coastal aquifers. Two methods used for oceanography processing and forecasting of sea level data were adapted for this purpose and compared: HA (Harmonic Analysis) and CWT (Continuous Wavelet Transform). The filtering process is generally comprised of two main steps: the detection and fitting of the major tide constituents through the decomposition of the original signal and the subsequent extraction of the complete tidal oscillations. The abilities of the optional HA and CWT methods to decompose and extract the tidal oscillations were assessed by applying them to the data from two piezometers at different depths close to the shoreline of a Mediterranean coastal aquifer (Motril-Salobreña, SE Spain). These methods were applied to three time series of different lengths (one month, one year, and 3.7 years of hourly data) to determine the range of detected frequencies. The different lengths of time series were also used to determine the fit accuracies of the tidal constituents for both the sea level and groundwater heads measurements. The detected tidal constituents were better resolved with increasing depth in the aquifer. The application of these methods yielded a detailed resolution of the tidal components, which enabled the extraction of the major tidal constituents of the sea level measurements from the groundwater heads (e.g., semi-diurnal, diurnal, fortnightly, monthly, semi-annual and annual). In the two wells studied, the CWT method was shown to be a more effective method than HA for extracting the tidal constituents of highest and lowest frequencies from groundwater head measurements.

1. Introduction

Tidal influences along shorelines produce regular fluctuations in the groundwater heads of coastal aquifers, and these influences can be used to understand the hydrogeological features of coastal areas (Erskine, 1991; Millham and Howes, 1995; Trefry and Johnston, 1998; Jha et al., 2003; Trefry and Bekele, 2004; Zhou, 2008; Chen et al., 2011; Singh and Jha, 2013). However, tidal oscillations in groundwater heads are in most cases a hindrance because they can hamper the perception of other phenomena of hydrological interest(e.g., recharge or discharge processes as river-aquifer interactions, irrigation returns and rain infiltration, or even the analysis of pumping tests). Research in coastal areas very often requires tidal filtering of the groundwater head data as a starting point, regarding the attainment of tidal constituents on the groundwater signal and the subsequent removal of tidal effects, in order to keep only the non-tidal influences on groundwater heads. Some authors have addressed this practice. Erskine (1991) presented a filtering process based on the Ferris equations (Ferris, 1952) to compensate for tidal effects by computing the tidal efficiency factor (ratio between groundwater-sea level amplitudes) and time lag (delay between a sea level oscillation and the consequent groundwater head oscillation), but the extraction of the tidal influence was incomplete. The length of the groundwater head time series was also an issue because the fit was not acceptable when tidal efficiency or time lag was applied to longer time series, and significant residual tidal fluctuations still remained in the groundwater head.

To correct pumping test data in wells close to coastlines, other authors have developed methods for removing tides. Trefry and Johnston (1998) and Chattopadhyay et al. (2015) proposed a correction to the measured pumping test drawdowns for tidal influences using least-square techniques to enable a pumping test analysis (only during the pumping period), but significant residual fluctuations still remained in the head in the first case, and in both

---

* Corresponding author.
E-mail addresses: juampesu@ugr.es (J.P. Sánchez-Úbeda), calvache@ugr.es (M.L. Calvache), cduque@udel.edu (C. Duque), mlopezc@ugr.es (M. López-Chicano).

http://dx.doi.org/10.1016/j.advwatres.2016.08.016

cases the fits were inaccurate for longer measurement time series. Chen and Jiao (1999) fitted a regular tidal fluctuation to data from six days before a pumping test and then corrected the observed drawdowns by subtracting the tidal effect before calculating the diffusivity values. Chapuis et al. (2005) developed a theoretical equation for pumping under tidal influences and considered the tidal effects before and after the test; an admissible fit was achieved, but the test was limited to a short time series. None of those methods established a sufficiently accurate filtering methodology that accounted for the tides that produced the perturbations, durations of the datasets used, aquifer features, or study cases.

Filtering sea tidal effects is especially relevant in studies of recharge and discharge in coastal aquifers. Net inland recharges observed in mean groundwater levels in coastal areas can be overestimated due to the enhancement of mean groundwater heads by tides (Li and Jiao, 2003). In addition, tidal effects produce considerable impacts on seawater intrusion processes in mixing zones. Licata et al. (2011) simulated seawater intrusion with and without tidal effects on a mixing zone; their results indicated that tidal mixing results in more mixed pollutant and salinity concentrations than the distributions from an equivalent steady-state model without tidal effects. The methods proposed herein are expected to be useful not only in the filtering process but also for a general understanding of tidal features, their components and their effects on groundwater close to the sea in an attempt to fill in certain gaps in coastal research.

Tidal analyses are usually carried out using methods that allow periodic changes and magnitudes to be understood and predicted. Analogous methods could be used to understand the influence of tides on groundwater. Tidal motions comprise a set of components, and the two major components of sea-level time series with regard to tides (Godin, 1972) are as follows.

1. The *astronomical component*, which is due to the motion of celestial bodies and the interactions between them, is the most easily detectable and predictable.
2. The *hydrodynamic component* is due to the shape of the shoreline and the effects of perturbing factors such as winds, atmospheric pressure changes, storm events, or external inputs (e.g., river discharge into the sea).

The tidal astronomical component has the greatest frequency stability and can be decomposed into constituents (Doodson, 1954). They are tabulated in terms of their frequencies and phase angles for specific coastal locations and are commonly referred to by symbols such as *M2, S2,* and *SA* (lunar semidiurnal, solar semidiurnal, and solar annual, respectively). The hydrodynamic component of the tide is non-periodic due to its non-stationary nature, which makes its prediction more complicated (Parker, 2007). Moreover, Kacimov and Abdalla (2010) suggested that high-frequency fluctuations in sea level are already filtered by porous beach cushions, and the tidal oscillations measured in groundwater can be considered to be caused primarily by astronomical tidal forces.

Tide studies usually consist in the decomposition and adjustment of tidal components to predict their evolution (Godin, 1972; Foreman et al., 1995; Brown et al., 2012; Vianna and Menezes, 2005; Codiga, 2011; Erol, 2011). There are currently two main methodologies for processing tidal data.

(1) *Classic Harmonic Analysis (HA)* is based on a definition of sea surface elevation at one point as the sum of a finite number of sinusoids with distinct amplitudes, frequencies, and phases, where the frequencies of the earth-moon-sun system have been previously defined (Pawlowicz et al., 2002).
(2) *Continuous Wavelet Transforms (CWT)* are used to carry out a continuous analysis based on fitting a signal to a wavelet. This full group of processing tools was initially developed to represent data whose frequency contents evolve over time (Daubechies et al., 1992) and was then introduced to tidal analysis (Jay and Flinchem, 1995, 1997, 1999; Flinchem and Jay, 2000). These methods are continuously scalable in frequency and are thus versatile for use in tidal analyses, especially extraction (Erol, 2011).

The pros and cons of the two methods for decomposing tidal constituents have been widely discussed (Jay and Flinchem, 1999; Foreman et al., 1995; Matte et al., 2013). Pawlowicz et al. (2002) developed several programs in Matlab© based on classic harmonic analysis and grouped them into the ***T_TIDE*** package. There are other packages, including ***U_TIDE,*** which is used to unify tidal analyses and the prediction framework (Codiga, 2011) and ***NS_TIDE,*** which was implemented by Matte et al. (2013) and adapted to the study of non-stationary signals in river tides.

In this study, the HA and CWT methods were applied to groundwater head monitoring in the proximity of the coastline affected by tides with the objective of isolating the non-tidal effects in groundwater head changes. In agreement with the conclusions of Bye and Narayan (2009), we believe that groundwater tides (i.e., the influence of tides on groundwater heads) can be represented as a sum of tidal constants in a similar manner to that in the open sea. Tides and their effects on groundwater have the same features and oscillatory shapes, and the methods therefore should be successful. To corroborate this, the tidal filtering described for tidal studies was applied in a study area in southern Spain (the Motril-Salobreña aquifer), where a set of wells with different depths near the coastline show a clear impact on groundwater monitoring.

The objectives of this study are as follows.

1. Filter the groundwater head time series from the tide-induced oscillation using HA (Codiga, 2011) and CWT (Jay and Flinchem, 1995) by adapting those oceanographic methodologies for use with groundwater and testing their applicability to hydrogeological settings.
2. Estimate the impact of the length of the monitoring time series on the results.
3. Assess other parameters that affect the data such as the depth of the monitoring wells and hydrological processes in the aquifer (e.g., recharge).

2. Hydrological settings of the study area

The Motril-Salobreña coastal aquifer extends over an area of 42 km^2 (Fig. 1A). It is comprised of detrital sediments that range from coarse gravels to sand, fine silts, and clay. The Guadalfeo River, which drains the southern Sierra Nevada, is in the western sector of the aquifer. The water budgets considered by different researchers attribute the highest inputs to river recharge (30%) and irrigation excess proceeding from river-derived water upstream (30%) (Calvache et al., 2009), the relative influences of which change depending on the season (Duque et al., 2011). In the northern sector, the aquifer is limited by the alluvium aquifer of the Guadalfeo River and a carbonate aquifer (Escalate aquifer). The southern boundary is the Mediterranean Sea. On the remaining borders, detrital rocks are in contact with schists and phyllites, which can be considered impermeable. The aquifer thickness is variable and ranges from 30 to 50 m in the northern sector (alluvial sedimentary environment) to more than 250 m in areas near the coastline (deltaic sedimentary environment) (Duque et al., 2008). The estimated hydraulic gradient ranges from 5×10^{-3} to 1.6×10^{-3} (Duque et al., 2010), and the aquifer responds very quickly to recharge due to its high permeability (Duque et al., 2011).