Correlation between groundwater level and altitude variations in land subsidence area of the Choshuichi Alluvial Fan, Taiwan

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**A B S T R A C T**

One of the prominent features observed in the groundwater-overdraft area is the land subsidence that creates a permanent damage to the land surface. Severe land subsidence has occurred in the western Taiwan due to excessive extraction of groundwater in the past decades. The areas of land subsidence have been gradually expanded and caused many problems such as flooding and building damage. This study examines the correlation between the surface vertical displacements from the groundwater level changes of deep aquifers can be quantitatively estimated. Furthermore, the long term subsidence trends can be derived and be used as useful reference for land and water resources management.

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1. Introduction

Water is the essential element of life and human civilizations in general developed along rivers. To expand the life span of human beings, groundwater becomes the primary source in areas where surface water is not sufficient or is limited. With continuous advancement of pumping technology, groundwater extraction increases significantly and often exceeds the natural recharge limit. Severe consequences follow the overdraft of groundwater everywhere in the world, such as groundwater level dropping, groundwater quality deterioration, salt water encroachment and land subsidence (Hix, 1995; Wilson and Gorelicks, 1996; Wang et al., 1996; Hsu, 1998; Phien-wej et al., 1998; Sun et al., 1999; Fan, 2001; Sato et al., 2003; Wang et al., 2003; Chen et al., 2007; Deng et al., 2007).

In Taiwan, groundwater resources have been depleted in the western and southwestern regions in the past decades due to excessive extraction and caused extensive land subsidence along coastal areas where pumping is intensive and recharge is very slow (Liu and Huang, 2002; WRA, Water Resources Agency, 2001). The most notorious land subsidence region is located at the Choshuichi Alluvial Fan of central Taiwan (Fig. 1), with an active subsiding area of over 600 km² and a maximum subsiding rate up to 10 cm/yr. In short, the groundwater level dropped from a value close to sea-level down to −30 m from 1974 to 2006 (WRA, Water Resources Agency, 2007).

The Choshui River, the longest river in Taiwan (186.4 km in length), provides the essential resources for domestic, industrial and agricultural water in the Choshuichi Alluvial Fan. Drilling logs in the Choshuichi Alluvial Fan showed that it consists of several unconfined and confined aquifers of Holocene to Pleistocene sands and gravels, separated by impermeable marine mud layers (WCA, Water Conservation Agency, 1997; Chen and Yuan, 1999). A typical cross-section showing the general features of three aquifers with thick aquitards in between can be found in Fig. 2 according to Wang et al., 2005.

During 1992–1997, 63 evenly distributed hydrologic stations (Table 1; a complete list can be found in WRB, Water Resource Bureau, 1999) were installed to depths ranging from 24 to 306 m in the Choshuichi Alluvial Fan (Fig. 1; Hsu, 1998). Because the Choshuichi Alluvial Fan can be divided into three aquifers for a depth of 250 m according to subsurface hydrogeology (WRB, Water Resource Bureau, 1999), each station may have one to five screens situated in different wells for fully observing changes from shallow to deep aquifers. The groundwater levels of these aquifers indicate two major flow directions: northwest in Changhua county and southwest in Yunglin county (Fig. 1).

The causes of land subsidence can be multiple and complex; consolidation of thick mud layer is the most important factor among them. However, extensive and costly observations are needed to obtain data for quantitative confirmation of consolidation in thick mud layers.

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As part of the national land management program, hundreds of continuous and campaign-mode Global Positioning System (GPS) sites have been deployed all over Taiwan in the past decades providing unique data for surface deformation studies. Thus, we have the advantage to have two independent sets of observations from the surface (GPS) and subsurface (groundwater level) to perform a quick and accurate analysis on land subsidence in the Choshuichi Alluvial Fan.

In this study, we examine the correlation between the land subsidence (deduced from GPS data) and the groundwater level variations of monitoring wells in the period between 1994 and 2006. Our aim is to quantitatively describe the relationship between vertical displacement on surface and groundwater level variation in identifying the distinctive effects among aquifers and derive the long-term trend for the land subsidence area. The behavior of aquifers is vital to the understanding of land subsidence process. The long-term trend is very valuable in developing an effective and appropriate remediation strategy for the land and water resources management in a large scale.

2. Methodology

Taiwan GPS Network was firstly established by the Institute of Earth Sciences, Academia Sinica in 1989 (Yu et al., 1997). This island-wide GPS network has been gradually expanded to more than 120 campaign-mode sites and 9 continuous sites in the early 1999. The number of continuous GPS sites had been rapidly increased to 320 after the 1999 Taiwan Chi-Chi earthquake (on 1999/9/20; Ma et al., 1999).

The GPS data are processed using Bernese 4.2 software with a fiducially free approach. Precise ephemerides provided by the International Global Navigation Satellite System (GNSS) Services are employed and fixed in the post-processing. Residual tropospheric zenith delays are simultaneously estimated with station coordinates by the least-square adjustment. The solutions are combined to the International Terrestrial Reference Frame 1997 (ITRF97) by taking the ITRF97 coordinates and velocities of an International GNSS Service (IGS) core site, TSKB (Tsukuba, Japan) as the reference station. Yu et al. (2001) gave a detailed description of the GPS data acquisition and processing. In this study, we use GPS vertical displacements from two continuous sites, PKGM (RGPSPKGM; 23.5799°N, 120.3055°E) and S103 (RGPSS103; 23.5644°N, 120.4752°E) to analyze variations of vertical motions associated with groundwater levels from 1994 to 2006 (Fig. 1).

The groundwater-levels in the aquifers are recorded digitally every hour by piezometers (WRB, Water Resource Bureau, 1999) and provide important information for subsurface variations. For a better
and consistent comparison, records of the groundwater level and vertical displacement of GPS are both transferred as monthly data, RAaqST and RGPSST, where aq and ST denote the aqth aquifer and the station, respectively. Because groundwater level and the vertical displacement records are relative to the first record and the World Geodetic System ellipsoid respectively, changes of them within the study period are utilized in the analyses. Additionally, increase and decrease of the groundwater level are also affected by the rainy and dry seasons with the solar (calendar) terms. To take off influence from the reference and reduce seasonal effects, the Aaq ST and GPS ST, are respectively calculated as the yearly changes of the RAaqST and RGPSST with a step of one month.

The linear relationship between the AaqST and GPSST can be written as:

\[ \text{GPSST} = \sum_{aq=1}^{i} AaqST \cdot x_{aq} \]  

where \( x_{aq} \) and \( i \) denote the coefficients of the AaqST and the sequence numbers of monitor aquifers, respectively. Through Eq. (1), the correlation between variations of the groundwater level and vertical displacement can be examined, but land subsidence effects caused by excessive extraction in groundwater have to be firstly taken into account. Because the groundwater level had persistently decreased between 1974 and 1994 in the Choshuichi Alluvial Fan (WRA, Water Resources Agency, 2007), land subsidence observed after 1994 could be possibly influenced by the extractions prior to 1994. Land subsidence can happen whenever the groundwater level drop due to overdraft and consolidation of mud layer, but this process is often sporadic with different scales through time. The long-term trend generally provides the accumulated and mean tendency in land subsidence area. This information is very useful when dealing with longer temporal and larger spatial scopes towards a better management for water resources and land planning. Thus, the long term subsidence that resulted from groundwater extraction between 1974 and 1994 is incorporated in this study as a basic and conservative estimation.

Because responses of land subsidence caused by excessive extraction in groundwater are generally not constant, for simplification in analysis, the unknown long term trend is expressed by a temporal function of 4 orders since 1974, and is added into Eq. (1). Thus, the linear relationship between GPS and groundwater level can be rewritten as:

\[ \text{GPSST} = \sum_{aq=1}^{i} (AaqST \cdot x_{aq}) + \sum_{j=1}^{4} (y-1974.0)^{j} \cdot x_{j} \]  

where \( y \) is the observation year and \( x_{j} \) is the coefficient of the long term subsidence.

Fig. 2. Contours of groundwater level aquifer 1 from years of 1994–2005 versus 2006 (shade scale bar is shown at the bottom; unit: meter).
Since recording the temporal period of the AaqST exceeds the unknown elements $x_a$ and $x_t$, the traditional least squares method is employed (Woodhouse and Dziewonski, 1984, Jolliffe, 2002).

\[
\begin{align*}
A \cdot x &= B \\
(A' A)^{-1} \cdot A' \cdot x &= (A' A)^{-1} \cdot A' \cdot B \\
\end{align*}
\]

Here, $A$ is the AaqST in a particular year ($y - 1974$) ($y = 1994$ to 2006), $B$ is the GPSST, and $x$ represents the $x_a$ and $x_t$ of Eq. (2). When we solve the linear relationship, the synthetic surface variations (Sv) can be simultaneously given by $A$ multiplied by $x$; and the obtained correlation coefficient (C.C.) serves as an index which expresses the strength and direction of a linear relationship between the GPS ST and Sv (Neter et al., 1982). In general, when the C.C. is larger than 0.5, the relationship is mainly a positive correlation and the GPS ST can be roughly estimated by the Sv.
3. Observations and discussion for groundwater level data

Fig. 2 shows contours of the aquifer 1 groundwater levels in years of 1994 through 2005, respectively, with their differences relative to 2006. It is apparent that the aquifer 1 groundwater levels in the period between 1994 and 2000 express positive anomalies and are relatively higher than that of 2006. In the period of 2001–2004, due to the occurrence of a severe drought, aquifer 1 groundwater levels gradually dropped down and reached to a minimum in 2004. The aquifer 1 groundwater levels rapidly bounced up in 2005 as the precipitation reached to an unusual high value. In short, the groundwater variations of the aquifer 1 are generally less than 2 m from 1994 to 2006 no matter in a normal, drought, or wet periods.

With respect to the aquifer 2, the groundwater variation is about a factor of 5 larger than that of the aquifer 1 during the study period (Fig. 3). The most conspicuous positive anomalies were present in aquifer 2 groundwater levels near the Choshui River estuary. Likewise, the area and altitude of the high anomaly were gradually reduced from 1994 to 2000 and then disappeared in 2001, due to excessive groundwater extraction within the latest severe drought period.

In contrast to the positive anomaly, the aquifer 2 exhibited a significant negative anomaly around the southwestern portion of the Choshuichi Alluvial Fan (Yunlin County) since 1996 and gradually extended toward the eastern area through time, consequently a large subsided region resulted in along the Peikang River. This low groundwater level feature continuously deteriorated towards 2004 and rose back a few meters due to the end of drought and new recharge from precipitation in 2005.

Fig. 4 shows contours of the groundwater level difference in the aquifer 3 with respect to 2006 between 1994 and 2005. The aquifer 3 groundwater levels express a similar but much smoother spatial distribution between 1994 and 2004 as compared to the upper two aquifers. Again, the negative anomaly appeared distinctly in the southwestern part of Choshuichi Alluvial Fan (Yunlin County). In 2005, after the latest drought, the groundwater level of the aquifer 3 still maintained a relatively low state mainly due to the slow recharge to this deep aquifer.

4. Relationships of groundwater levels to GPS data

To explore the relationship between the land subsidence and the groundwater level changes, records of two GPS observations, PKGM in the severe land subsidence area and S103 in a normal stable place, are compared with the groundwater variations of Peikang (PK) (Fig. 5) and Tungjung (TR) (Fig. 6) wells, respectively. Fig. 5a shows the time-series records of the $R_{GPSPKGM}$ (GPS), $R_{A2PK}$ and $R_{A3PK}$ (groundwater levels).
levels from aquifers 2 and 3, respectively) from 1994 to 2006. To the first order, it is apparent that the RGPSPKGM displays a decrease trend indicating the land subsidence on surface, while both R_A2PK and R_A3PK records show rather steady long-term tendencies. Fig. 5b shows the records of GPSPKGM, A2PK and A3PK after reducing the seasonal effect (that is, fluctuations from dry and wet periods). The normalized groundwater level records of A2PK and A3PK exhibit similar patterns with a long-term average value close to zero and a low valley level during the 2001–2004 drought period. On the other hand, the GPSPKGM record clearly shows a decreasing rate of about 4 cm/yr.

Using the least squares method, the GPS PKGM values are correlated with A2PK and A3PK, and the linear relationship without the long term land subsidence is obtained as:

\[
S_v = 0.3282A_{2pk} + 0.0162A_{3pk}
\]

where \(S_v\) is the vertical displacement of estimated subsidence. Although there is a certain distance between the GPSPKGM and PK sites, the correlation coefficient expresses a significant positive value (\(r = 0.62\)). The coefficient of \(A_{2pk}\) is 20.3 times higher than that of \(A_{3pk}\), which indicates that the \(A_{2pk}\) aquifer plays a more important role in controlling the vertical surface displacement near the PK station.

The relationship between GPSPKGM and groundwater level with the long term subsidence taken into account can also be expressed as:

\[
S_v = 0.3459A_{2pk} + 0.0471A_{3pk} + 3.4208 \times 10^{-4} \times (y-1974)^4 + 2.9088 \times 10^{-2} \times (y-1974)^2 + 8.2655 \times 10^{-1} \times (y-1974) + 7.9772 
\]

with \(y\) being the designated year from 1995 to 2006. Note that the coefficient of \(A_{2pk}\) is reduced to be 7.34 (=0.3459/0.0471) times larger to that of \(A_{3pk}\), implying that seasonal effects do play a part in differentiating the important role in land subsidence of underlying aquifers. Obviously, aquifer 2 has more weight than aquifer 3 in terms of the effect on land subsidence, probably due to a high groundwater extraction in aquifer 2. Fig. 5c shows that the long-term subsidence rate is gradually getting smaller through time.

On the other hand, Fig. 6 illustrates the relationship between TR (groundwater site with three aquifers) and S103 (GPS site) in a non-subsidence (normal) area. Instead of the decreasing tendency at PKGM and PK, all records of RGPSS103, RA1TR, RA2TR, and RA3TR have small variations and the linear trend approaches to 0 (Fig. 6a).
Similarly, Fig. 6b reveals that the relationship of TR and S103 can be expressed as:

\[ S_v = 0.0219A1_{TR} - 0.0858A2_{TR} + 0.0814A3_{TR} \]

The poor correlation coefficient (= 0.1) suggests that the vertical changes are almost independent to variations of the aquifers.

In Fig. 5, the good correlation in the Peikang site demonstrates that the vertical changes in the land subsidence area are highly related with the groundwater variations in the underlying two aquifers. There are four aquifers identified in the hydrogeological framework of the Choshuichi Alluvial Fan (WRB, Water Resource Bureau, 1999). To further examine the response of the land subsidence in other aquifers, the Tungkuang (TK) site near the PKGM with 4 aquifers (from shadow unconfined to deep confined ones) is used for comparison.

Fig. 7 shows the \( S_v \) derived by the groundwater levels at the TK station via the same analysis process. The \( S_v \) has a correlation coefficient of 0.58 when correlated with raw groundwater data from 1994 to 2006 (Fig. 7a). After removing the long-term trend.
The correlation coefficient increases to 0.67 and can be expressed as:

\[
S_v = -0.472A_{1TK} + 0.678A_{2TK} - 0.885A_{3TK} + 0.962A_{4TK} \\
-3.3177 \times 10^{-4} \times (y-1974)^4 + 3.0314 \times 10^{-2} \times (y-1974)^3 \\
-9.1166 \times 10^{-1} \times (y-1974)^2 + 8.9100 \times (y-1974)
\]

From the above function, it is apparent that the land subsidence at the TK site has also been mainly affected by the extraction in the aquifers 2 and 4.

Observations in Figs. 5 and 7 demonstrate that the positive and high correlation coefficients between the \( S_v \) and GPS ST are in the land subsidence area. By contrast, Fig. 6 indicates that the groundwater variations of aquifers in the non-subsidence area are poorly correlated with the vertical component of the GPS records. Thus, changes of vertical displacements of the GPS stations can be used to detect subsidence closely related with groundwater extraction and serve as an effective indicator for the land subsidence effect.

When the long term subsidence is ignored, a difference in vertical estimation can still exist between the \( S_v \) and GPS ST records, but the inferred strong correlation coefficient implies that the difference is most likely produced by other causes. Nonetheless, through the analyses in this study, the long term subsidence changes caused by the extraction of groundwater since 1974 can be quantitatively estimated and clearly separated from that of the GPS ST data. In this regards, the land subsidence due to the overdraft of aquifers is convincing and need to be immediately remediated in an effective way.

It is worth to mention that occurrence of the Chi-Chi earthquake resulted in large co-seismic variations in groundwater levels in Choshiuchi Alluvial Fan (Wang et al., 2001). Groundwater level in wells nearby the epicenter and/or fault rose with a height of approximately 7 m. Through RAaqST being transferred into monthly data, co-seismic effects on groundwater level are minimized. However, when GPS ST and \( S_v \) variations were examined in detail, distinctive patterns can be found between 1999/2/5 and 2000/2/5 in Figs. 5–7 (shaded parts). This phenomenon suggests that the relationship between groundwater level and vertical displacement on surface are disturbed by high loading stress associated with the Chi-Chi earthquake. Duration of disturbed groundwater levels possibly exceeded six months at the earthquake magnitude scale higher than 7.0. On the other hand, this earthquake-induced feature...
probably can be utilized to develop an index associated with earthquake occurrence in the future.

5. Conclusions

Overdraft of groundwater in the Choshuichi Alluvial Fan has been the major mechanism for a negative impact of land subsidence. The elevation changes in the subsidence area are primarily affected by two factors: the current groundwater level variations and a long term trend caused by the past excessive extraction in aquifers. The two factors can be separated and estimated by a linear relationship and temporal functions. In addition, the correlation coefficient between the synthetic and observed elevation changes can be served as an effective and quantitative indicator in differentiating the normal and/or subsidence area and weighting factor for various aquifers. The results of this study can provide a useful reference of remediation strategy for the land and water resources management in active subsiding areas.

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