Delineating a Volcanic Aquifer Using Groundwater-induced Gravity Changes in the Tatun Volcano Group, Taiwan

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Abstract

The Tatun Volcanic Group (TVG) is an active volcano that could cause volcanic hazards in northern Taiwan. The latest phreatic eruption of the TVG occurred some 6000 years ago. Understanding the state of groundwater around the TVG can be a crucial step towards effectively assessing the risk of phreatic explosion by providing information about the sources of groundwater and the media it flows. We measured gravity changes at a superconducting gravity station and several groundwater-sensitive sites to examine the way the groundwater altered the gravity values around the TVG. Groundwater-induced gravity changes are simulated by two hydrological models (A and B). Both models show coherent seasonal variations in groundwater level and gravity value in the center of the TVG (Chintiengang). This coherence indicates inter-connected porous media for free groundwater flows below Chintiengang. However, inconsistencies between the modeled and observed gravity changes occurred in the eastern part of the TVG, suggesting here highly heterogeneous formations with fractures and barriers may exist below Chihsinshan and Dayoukeng. The gravity consistencies and inconsistencies between the observations and the models are used to delineate a volcanic aquifer, which can provide additional information for assessing the probability of a potential phreatic eruption over the TVG.

1. Introduction

The Tatun Volcano Group (TVG) is located in northern Taiwan and originated from the active plate convergence in the western Pacific ring of fires. Because the TVG neighbors Taipei City and New Taipei City, its eruption will threaten the lives of about 7 million people in the two cities, and potentially damage the two nuclear power plants at the northern flanks of the TVG, creating major economic and social crises in Taiwan (Konstantinou, 2015). The latest phreatic eruptions of the TVG occurred about 6000 years ago (Belousov et al., 2010). Recent studies have shown that the TVG is a potentially active volcano (Lin et al., 2005b; Murase et al., 2014). Data from a new seismic network (Pu et al., 2014) over the TVG showed repeated occurrences of local seismic swarms associated with fluid migrations. In addition, Lin (2016, 2020) detected magma chambers below the TVG using the seismic S-wave shadows and P-waves delay. Hydrothermal reservoirs in the eastern limb of the TVG (Fig. 1a) have been detected using volcano-earthquake signals (Lin et al., 2005b), precise leveling survey (Murase et al., 2014), audio-magnetotellurics (AMT; Komori et al., 2014). The variations of fumarolic gas compositions indicated highly hydrothermal activity below the TVG (Lee et al., 2008).

Gravity observations have been used to assess the states of volcanoes around the world. For example, Rymer and Brown (1989) used time-lapse gravity changes as a precursor, on the ground that ascending magma before an eruption can lead to mass changes. Using gravimetric and geodetic measurements, Battaglia et al. (2006) showed that the fluid migration in the Campi Flegrei caldera hydrothermal system was the cause of ground deformation and geological unrest. Kazama et al. (2015) showed that gravity changes can originate from both magma and non-magma sources. Depending on the location, the largest contributor of gravity change around a volcano can be hydrological variation, which can overwhelm magma-induced gravity changes around a volcano by many orders of magnitude. Using the

absolute gravity measurements in 2004–2007 around the TVG, Mouyen et al. (2016) suggested the existence of a tube-like structure that allows a large-scaled hydrothermal fluid circulation below the TVG.

A gravity-based study of the TVG began with the installation of an AG site at a continuous GPS station, called YMSG, in the TVG in 2004 (Kao et al., 2017). In 2012, a superconducting gravimeter (SG, serial number T49) was installed at YMSG. Prior to 2012, 4 new absolute gravity sites and 27 relative gravity sites along 5 hiking trails of the TVG were constructed (Fig. 1a). In 2012, four gravity surveys were carried out and the surveys covered the approximate volcanic regime of the TVG, including Chihsinshan, Chintiengang, Dayoukeng and Dingshan in an area of about 10 km² (Fig. 1a). In the gravity surveys, one absolute gravimeter (AG) and two relative gravimeters (RG) were also used. In contrast to the continuous, one-second measurements by the SG/T49 meter, the gravity measurements by the AG and RG meters are time-lapsed with a 3-month measuring interval.

In most gravity studies of volcanoes, gravity effects originating from hydrological changes are estimated by models that do not consider 3-D flows of groundwater, which are largely affected by local hydrogeological settings. In principle, a 3-D hydrological model of an aquifer below a volcano is able to show how groundwater transports, as in an alluvial plain (Singhal and Gupta, 2010). However, over a volcano the hydraulic conductivities of volcanic materials can vary widely, at a range of nine orders of magnitude. For example, the hydraulic conductivities of lava flows and cinder beds are high and those of ash beds, intrusive dikes and sills are much lower (Fetter, 2001). Thus, validating a 3-D model for groundwater flows over a volcanic region can be challenging.

Gravity changes can be a type of data for validating a 3-D groundwater flow model because a gravimeter can sense mass changes due to groundwater re-distributions from the model. An example in Taiwan is the investigation of the active state of the Hsinchu Fault using gravity changes from a superconducting gravimeter (Lien et al., 2014). In the TVG, the sources of gravity changes are seasonal hydrological changes, transitional fluid migrations (Mouyen et al., 2016) and secular plate motions (Kao et al., 2017). In typical solid earth applications of gravimetry, gravity changes of hydrological origins (called the hydrological gravity effect) are regarded as noises and are removed from the raw gravity measurements before solid-earth applications. At a gravity site, the hydrological gravity effect is the sum of the effects over the unsaturated zone and the saturated zone below the site. Typically, the effect from the unsaturated zone is determined and removed using soil moisture measurements and the methods for this effect can vary widely, from the simple Bouguer plate model (Torge, 1989) to a sophisticated approach such as those presented by Crossley et al. (1998) and Kazama et al. (2015). Likewise, the gravity effect from the saturated zone can be modeled by a simple model such as Bouguer model (Torge, 1989) or a 3-D model such as the method for the Hsinchu superconducting gravity station (Lien et al., 2014).

In this study, the hydrological gravity effects from the unsaturated zone in the TVG will be still regarded as noises and removed. However, the effects from the saturated zone will be modeled by two approaches that are more comprehensive in 3-D extent than the Bouguer plate model. Such modeled gravity effects are then compared with the observed gravity changes from the four gravity surveys in 2012 to infer the

potential boundaries of an aquifer around the TVG. In the following development, we will describe in detail how our gravity measurements were collected and processed, and how two groundwater flow models are constructed to model gravity changes for inferring the aquifer boundaries. Because groundwater flow is important for understanding volcanic unrests (Jasim et al., 2018), this result from this study will benefit the understanding of the aquifer distribution in the TVG for volcanic hazard modeling in northern Taiwan.

2. Data

2.1 Gravity data collections and corrections

In this study, the time-lapse gravity measurements were collected by one FG5 absolute gravimeter (AG) (serial number 231) and two CG5 relative gravimeters (RG) (serial numbers 050800136 and 050800137) in April, June, September, and November, 2012. These gravity measurements in the four seasons were expected to sense the TVG hydrological changes in the wet and dry seasons. The gravity sites were installed along five hiking trails, covering the region over 25.13°N – 25.19°N and 121.525°E–121.65°E. The purpose of the AG measurements is twofold: (1) obtaining gravity changes associated with groundwater level changes, and (2) constraining the RG measurements in the relative gravity adjustments (see below). The RG measurements along a trail were collected in a double-run (back and forth) survey to eliminate drifts in the relative gravimeters and to enhance the point gravity accuracies. The 4 AG sites (YAG1–3 and YMSG) are co-located with 4 RG sites (Fig. 1b).

Following previous experiences made in studies using high-precision relative gravimetry, at each RG site and for each survey we determined a mean reading every 90 seconds using a sampling frequency of 6 Hz for the CG5 gravimeters (Debeglia and Dupont, 2002; Scintrex Limited, 2010; Mouyen et al., 2013). In total, 15 mean gravity and temperature readings were acquired at one site occupation. On average, it took about 30 minutes for such measurements at a site. From the 15 readings, we selected 8 most stable readings using the following criteria: (1) neglecting the first two readings, (2) choosing continuous readings in which the gravity changes of the last 3 readings are less than 5 μGal , and the trend of the continuous readings is less than 5 $\mu\text{Gal}/\text{reading}$, (3) selecting the readings when the temperature variations of the sensor chamber of CG5 are within ± 7 mK, and the temperature changes between two successive readings are less than 0.1 mK, and (4) selecting the readings when the ranges of tilt variations in X and Y directions are within $\pm 20''$. Note that, the tilt-induced gravity errors can be neglected when the X and Y tilt variations are less than $\pm 3''$ (Merlet et al., 2008). Criterion 3 is to use only readings when the chamber temperature is stabilized to cause little variation in reading (Fores et al., 2017).

The temporal gravity effects due to solid earth tide in all gravity measurements were removed using the model values of ETGAB (Wenzel, 2002; Dehant et al., 1999). The Newtonian effect and the loading effect of ocean tides (called OTL correction) were removed using the FES2004 tide model (Letellier et al., 2004) and the SGOTL software (Hwang and Huang, 2012), which considers the elevation of a gravity site. We also removed the effects of barometric pressure and polar motions using a SG-based gravity-atmosphere

admittance coefficient (see below) and the earth rotation parameters from the International Earth Rotation Service and Reference Systems. Finally, the gravity effects at the unsaturated zone were removed using the soil moisture measurements at YMSG and the Bouguer plate method given in Torge (1989).

2.2 Adjustments of relative gravity measurements

For each of the four gravity surveys, the RG and AG measurements were least-squares adjusted using the weighted constraint method of Hwang et al. (2002) by holding fixed the gravity values at the five AG gravity sites. The outliers in the RG measurements were detected and then deleted in the adjustments. The histograms of the residuals of the RG gravity measurements survey follow the normal distribution, suggesting that there were no systematic errors in the adjusted gravity values.

To quantify our RG data quality, two separate adjustments of the RG measurements were made: one adjustment used RG measurements based on all 15 readings at one site occupation, and the other based on the selected 8 readings (Sect. 2.1). The adjustment results are shown in Table 1, which shows that the standard deviations (STDs) of the gravity values in the case of using the selected 8 readings are smaller than those using all 15 readings. The accuracy improvements due to the use of the 8 selected reading for the four surveys are 11.1%, 53.8%, 10.0%, and 20.0%, respectively. The reductions in standard errors suggest that our data selection strategy based on the five criteria (Sect. 2.1) is effective.

Table 1
Standard errors of point gravity values (in μGal) from relative gravity adjustments using all (15) readings and the selected (8) readings

Gravity survey in 2012	Gravity reading	Gravity standard error		
		Max	Min	mean
1st (4/24 – 4/28)	15	22.0	0.2	9.0
	8	19.0	0.1	8.0
2nd (6/29 – 7/2)	15	29.0	0.2	13.0
	8	15.0	0.1	6.0
3rd (9/14 – 9/18)	15	21.0	0.1	10.0
	8	18.0	0.1	9.0
4th (11/28 ~ 12/2)	15	24.0	0.1	10.0
	8	21.0	0.1	8.0

In addition, we found that applying the OTL corrections using SGOTL has improved the point gravity accuracies in the adjustments by 1.4% to 6.2/%, compared to the cases without the OTL corrections. The improved accuracies are most pronounced at the sites with elevations > 1000 m, suggesting that the

altitude of a gravity site should be considered when computing the OTL effect. This conclusion is consistent with that made in Hwang and Huang (2012).

- Another contributor to the overall improved RG point gravity accuracy is the SG-based admittance coefficient for atmospheric pressure corrections. We experimented with two gravity-atmosphere admittance coefficients: one is the standard value of $-0.30 \mu\text{Gal/hPa}$ (Torge, 1989) and the other is $-0.35 \mu\text{Gal/hPa}$ from the analysis of the SG49 gravity and barometric records (see Fig. 1 for the SG site, YMSG). Table 2 shows the averaged standard errors of the adjusted point gravity values. In the second survey, the difference between the use of the two coefficients (-0.30 and -0.35) is $1 \mu\text{Gal}$. This is because the gravity-pressure admittance coefficient under large atmospheric pressure changes can be significantly different from the standard admittance coefficient (Hwang et al., 2009). For example, during the second survey, the air pressures around Taiwan were affected by Typhoon Doksuri on June 28 and 29, 2012. In this case, the use of an admittance coefficient of $-0.35 \mu\text{Gal/hPa}$ improves the point gravity accuracy in the second survey. Hence, SG measurements can be used to determine an optimal gravity-pressure admittance during a field work to calibrate the atmospheric pressure corrections. Although the SG-based gravity-pressure admittance coefficients improved the gravity accuracy only in the second survey, we believe such coefficients can improve atmospheric pressure corrections in future gravity data collected in the TVG.

Table 2
Standard errors of point gravity values (in μGal) based on two gravity-atmospheric admittance coefficients

Gravity survey in 2012	Averaged standard error of gravity value	
	$-0.30 \mu\text{Gal/hPa}$	$-0.35 \mu\text{Gal/hPa}$
1st	8	8
2nd	7	6
3rd	9	9
4th	8	8

Figure 2 shows the gravity changes at all the gravity sites in the TVG in April, July, September and December, 2012. A gravity change is the difference between an observed gravity value and the mean of the four observations from the four surveys. The gravity changes in Fig. 2 will be used to infer potential aquifer boundaries around the TVG using Models A and B (see below).

Gravity changes in Fig. 2 were correlated with rainfalls. As an example, Fig. 3 shows the gravity changes at sites Y01, Y02 and Y03 (see Fig. 1a), rainfalls and infiltrations at two weather stations WZS and SD. The rainfalls (red and blue bars) in Fig. 3 were converted to infiltrations (red and blue lines) using an infiltration coefficient method (Patil et al., 2019; Tarka et al., 2017) as follows: (1) multiplying rainfall with an infiltration coefficient to obtain initial infiltration, and (2) determining the final infiltration by moving average with a time lag. The observed gravity changes at Y01 to Y03 are coherent with the variations in

infiltration. This coherence is due to the fact that infiltrated rainfall recharges groundwater to create gravity changes as sensed by the gravimeters. The gravity change in September was negative, indicating groundwater discharges were more than rainfall recharges in the dry season. In general, at Y01, Y02 and Y03 the gravity changes correspond well to the groundwater level fluctuations.

2.3 Groundwater level, rain and soil moisture data

The area covered by our two hydrological models is 10 km² and the center is at YMSG, as shown in Fig. 1a. One continuous groundwater level (TB23, Fig. 1a) automatically recorded water levels at 15-minute intervals. TB23 is located 500 m southwest of YMSG. In addition, from April to December 2012 the water levels at 22 wells were manually recorded once a month. At YMSG, a rain gauge and soil moisture sensors were installed. The sensors recorded soil moistures at the depths of 10, 30, 50, 70, and 100 cm every 15 minutes. The Central Weather Bureau (CWB) and Tatun Rain Gauge Network installed additional 13 rain gauge stations that provided data for this study.

3. Methods For Modeling Groundwater Flows

3.1 Model A: a continuous flow model

We assume that the formation under the TVG area contains porous media for groundwater flows, which introduce gravity changes that can be used to infer the borders of the media. Our inference employs two models, namely Models A and B. Model A constructs a layer of groundwater-level changes by interpolations from the observed groundwater levels at the 23 monitoring wells and the river levels (the colored stars and lines in Fig. 4a). Figure 4b shows the gridded water levels in April 2012. A water level is the elevation relative to the mean sea level at Keelung, which is the origin (zero point) of elevation in Taiwan. Then, the groundwater-level changes were converted to gravity changes using the method of volumetric integration described in Lien et al. (2014). Note that the gravity contribution of the unsaturated zone has been removed from the gravity observations using the method (Sect. 2.1) and hence is not considered in the volumetric integration.

In Model A, we assume that the sum of inflow and outflow (recharge and discharge) in a unit volume is equal to the flow change in a unit time. Recharges and discharges in Model A are constrained by the groundwater levels at the monitoring wells. At the junction of land and river, the groundwater levels are equal to the river levels with a steady state. The method of minimum curvature (Wessel et al., 2013) was used to interpolate the observed groundwater levels and river levels onto a 40 m × 40 m grid. The gridded groundwater levels were used to determine the gravity changes at the gravity sites. The vertical domain for the gravity computation is bounded by the surface of the gridded groundwater levels (top) and the surface corresponding to the lowest water level of the TVG (bottom). We assume that each vertical column of a grid is isotropic and homogeneous with a constant specific yield.

3.2 Model B: a dynamic hydrological model

Model B uses the Modular three-dimensional groundwater flow model (MODFLOW) to simulate groundwater flows. MODFLOW is a widely used software developed by the United State Geological Survey (USGS; Harbaugh et al., 2000; Harbaugh, 2005). MODFLOW solves for hydraulic heads using the following governing equations (Harbaugh, 2005):

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + W = S_y \frac{\partial h}{\partial t}$$

1

where h is the hydraulic head (groundwater level for an unconfined aquifer like the one in this study) at location (x, y, z) and time t , K_{xx} , K_{yy} , K_{zz} are the hydraulic conductivity components in the x , y , z directions, W is a volumetric flux per unit volume from sources or sinks of water and S_y is the specific yield of the porous materials. MODFLOW determines multiple groundwater levels by the numerical, block-centered finite-difference method, enabling us to model groundwater levels in mountains such as the TVG that have a complex hydrogeological setting. A sample application of MODFLOW to groundwater level modeling near the Tseng-Wen Reservoir in southern Taiwan is given by Yang et al. (2009), who achieved a high consistency between the modeled (by MODFLOW) and observed groundwater levels in the mountainous region around this reservoir.

The water storage capacity of a water-bearing body is proportional to S_y , and K_{xx} , K_{yy} and K_{zz} indicate the ease of groundwater movement. Proper values of these hydrogeological parameters will result in modeled groundwater levels that match the observed levels, which serve as the boundary conditions (values) for the partial differential equation in Eq. 1. Table 3 shows the parameter settings for Model B in the TVG. Figure 5a shows the concept for Model B, which considers one aquifer that is bounded by the top and bottom boundaries at the ground surface and at the sea level, respectively, and also bounded by the two faults (Shanchiao Fault and Kanchiao Fault) to the aquifer's western and eastern sides. The boundary conditions for hydraulic values are the same as those for Model A, i.e., groundwater levels at monitoring wells and rivers. In addition, the rainfalls at the 14 stations (Fig. 1a) are fed to Model B as recharges (Fig. 5a).

Table 3
Parameters used in Model B (MODFLOW)

Model domain (km)	10×10
No. of grids	250 × 250
Grid size (m)	40 × 40
No. of layers	1
No. of hydraulic conductivity zones	7
Range of hydraulic conductivity (m/day)	0.0005 to 0.07
Range of specific yield	0.01 to 0.3
Range of porosity (%)	1.2 to 35

As shown in Table 3, the number of hydraulic conductivity zones is set to 7 according to the hydrogeology map from the Central Geological Survey of Taiwan (Fig. 1b). The hydraulic conductivities, specific yields and porosities begin with some initial values and are finalized when the modeled groundwater levels from Model B best fit the groundwater observations (boundary conditions) in the least-squares sense. Finally, Model B uses the same integration method as that for Model A to compute the gravity changes due to groundwater level changes. The two faults in Fig. 5a and b are barriers to groundwater flows in Model B. Numerical examples at Hsinchu, Taiwan, about the impacts of faults on the results of MODFLOW were given by Lien et al. (2014)

In a mountainous area like the TVG, the variations in groundwater level and the hydraulic head gradients can be relatively large compared to those in an alluvial fan in western Taiwan. However, in the TVG there are only few borehole wells that provide the needed hydrogeological parameters to address such large variations. Hence, in Model B we assume one layer of materials covering the unsaturated and saturated zones from the ground level to the sea level to avoid discontinuities in water level at the 40 m×40 m grids. The bottom of the layer is at the sea level and is a no flow setting that functions as a low permeability boundary. To estimate recharges in the TVG, the study area was divided into 14 sub-areas according to 14 geographic distributions of the rainfall stations (Fig. 1a and Fig. 5a) using the Thiessen polygons method. Each sub-area was assigned with several runoff coefficients. The runoff is the product of rainfall and runoff coefficient. The runoff coefficients in one sub-area were given according to mountain slopes and aspects (windward and leeward sides of the TVG). The recharge of groundwater in each unit area is the difference between rainfall and runoff.

The boundary conditions from the groundwater wells and river levels constrain Model B in a different way than that for Model A. In Model B, the river levels were held fixed, while the observed well levels were used to validate the modeled water levels. The geological formations of the TVG are composed of lava flows, tuff breccia, sandstone and shale (Fig. 1b). The lava flows from the latest eruption are composed of andesite on the top layer, followed by tuff breccias, Mushan formation, and Wuchishan formation. Mushan formation is composed of alternations of sandstone, shale and intercalated coal seams. The

compositions of Wuchishan formation are moderate to coarse gravels and sandstone interbedding with thin carbonaceous shales. The initial values for hydraulic conductivity, specific storage, specific yield, and porosity were from a geological map released by the Central Geological Survey of Taiwan (<http://www.moeacgs.gov.tw/>; a modified version is shown in Fig. 1b).

The hydraulic gradients can be high in a mountainous area like the TVG because of steep slopes. We assume that the vertical flow of groundwater is higher than the horizontal one. Hence the initial vertical hydraulic conductivity of volcanic rock is 10 times more than the horizontal one. Then, we adjusted these parameters by comparing the modeled groundwater levels with the observations at the wells. The adjustments were repeated until the differences between the modeled and the observed groundwater levels are less than 0.5 m for all wells. Note that this tolerable difference of 0.5 m is relatively large because the TVG is over a rugged terrain with higher elevations, and the grid size is a relatively large 100 m in Model B. If the grid size is smaller than 100 m and/or the terrain is flat, the tolerable difference should be smaller than 0.5 m.

4. Result Of The Modeled Groundwater Level Changes And Gravity Changes

The results of Models A and B show seasonal groundwater level variations, which are largely coherent with the variations in rainfall. As examples, Fig. 4b and Fig. 5b show the modeled groundwater levels from Models A and B in April 2012. In general, Model A produces very localized groundwater variations, while Model B leads to regional groundwater variations. According to the CWB precipitation data in 2012 (Appendix A), the monsoons in May and June resulted in heavy rainfalls over the TVG, where it was dry from October through November.

Figures 6 and 7 show the groundwater level changes relative to the mean levels from April to December 2012. Figure 6 (Model A) shows a dry pattern (negative water level changes) from September to November, and a wet pattern (positive water level changes) from April to June. The seasonal pattern is consistent with the rainfall pattern (see Appendix A). Due to a lack of monthly river level data, a constant river level for a given month was used in Models A and B. Hence, the monitoring wells data dominate the modeled groundwater level changes in Model A. The influence area of one monitoring well is local and depends on the method of interpolation. Figure 6 shows that the modeled groundwater levels are constant in the eastern TVG because there are no continuous water level data here, with only constant river boundaries.

Model B uses the governing groundwater flow equation (Eq. 1) to produce regional groundwater levels (hydraulic heads). Figure 7 shows clear groundwater level variations from April to December 2012. The groundwater levels are high on the windward side of the TVG. The winds over the TVG are southwesterly in August to September, and northeasterly in December. In contrast, groundwater levels are low on the leeward side. Cheng and Yu (2014) showed that the topography of the TVG affects precipitations on the TVG's windward and leeward sides. Rainfalls are the main source of recharge to the groundwater in the TVG. The settings of Model B include Shanchiao Fault and Kanchiao Faults. The area between the two

faults is the watershed of the rivers in the TVG, where groundwater is mainly recharged by rains and stream flows (Fig. 1a). Figure 5b and Fig. 7 show sharp differences in the groundwater levels at the two sides of each of the faults.

Both Model A and Model B result in seasonal gravity changes corresponding to the modeled groundwater variations. Figure 8 and Fig. 9 show the gravity changes induced by the modeled groundwater variations during the times of the four gravity surveys. Figure 8 shows that Model A-derived gravity changes in the eastern TVG are small (few μGal). Near Dayoukeng and Dingshan (see Fig. 1a for their locations), the groundwater variations are nearly zero, but not gravity changes. This suggests that the gravity changes at these two points were created by the gravitational effects of water level changes at locations not nearby Dayoukeng and Dingshan. Figure 9 shows distinct patterns of gravity changes at Chishinshan (Y20), Chintiengang (YMSG), Dayoukeng (Y08) and Dingshan (Y03), which will be discussed in Sect. 5.

5. Discussion

5.1 Gravity changes associated with seasonal groundwater changes and hydrothermal fluid migrations

The gravity changes from the observations and from the two models are mostly seasonal with the extreme values occurring in June and October (see Appendix B for the time series of gravity changes). We carried out an empirical orthogonal function (EOF) analysis to identify the leading variabilities of the gravity changes in space and time. Figure 10 shows the time variations (left column) of the first three modes from the observed gravity changes and the spatial distributions of the first-mode variabilities (right column; see also Appendix C for the spatial distributions of the second- and third-mode variabilities). The first three modes of EOF explain 100% of the variabilities of the gravity changes. For both the observed and modeled gravity changes, the first modes explain up to 78.6% of the total variabilities. Because the observed gravity changes have been corrected for temporal gravity changes (see Sect. 2.1) and are largely affected by the local hydrology of the TVG, the first-mode variabilities should be of hydrological origins. Because groundwater level data were used to constrain Models A and B, the first-mode variabilities from the two models are largely due to groundwater level changes. The second-mode variabilities of the observed gravity changes explain about 20 % of the total variabilities, followed by the third-mode variabilities.

The EOF analysis of the gravity changes enhances the spatial patterns of the gravity variabilities. From the gravity observations, the first-mode variability near Chishinshan is the largest (near 1) and the variability near Dayoukeng is the smallest (near -1). The variabilities at these two locations from Models A and B are different from the variabilities from the gravity observations. This suggests that Models A and B cannot adequately model the gravity changes here. These inconsistencies in the first-mode variabilities between the observed and modeled gravity changes over Chishinshan and Dayoukeng suggest that the hydrogeological properties here are far more complicated than the current settings used in Models A and B, which cannot produce gravity changes that match the observations.

Figure 11 shows the differences between the observed and modeled gravity changes at the gravity sites. Four gravity sites are located at Dayoukeng, namely, Y06, Y07, Y08 and Y09, where relatively large positive gravity changes were observed in September (see Appendix B). However, there was little rainfall in September (Appendix A). Because the modeled gravity changes are based purely on rainfalls, the positive gravity differences at Dayoukeng in September (Fig. 11) were probably caused by the mass surplus not predicted by the model. This mass surplus may be related to the hydrothermal fluid beneath the TVG, which cannot be detected in our hydrological models. Evidences for such hydrothermal fluid were described in Murase et al. (2014), Komori et al. (2014), Wen et al. (2016) and Mouyen et al. (2016). The differences in Fig. 11 suggests that, in September the fluid migrated from a deep hydrothermal reservoir under Chishinshan to a shallow reservoir under Dayoukeng (Fig. 1a and Fig. 12). On the other hand, in April the fluid below Dayoukeng migrated to the deep hydrothermal reservoir, causing negative differences (mass deficiency) between the observed and the modeled gravity changes (April, Fig. 11).

5.2 The aquifer boundaries from gravity consistency and inconsistency

Because the predicted gravity changes from Models A and B are largely due to hydrological effects, the discrepancies between the modeled and the observed gravity changes indicate that (1) the hydrogeological parameters for the fluid flow media in two models are imperfect at the sites of large discrepancies, (2) additional sources influencing the temporal gravity corrections for the raw gravity observations (Sect. 2.1) should be considered. Figure 11 shows that at the gravity sites around Chintiengang, i.e., YMSG, Y05, Y10, Y12, Y13, Y14, Y15, and Y24, the gravity differences are small (few μGal), suggesting that both Models A and B perform adequately in predicting gravity changes with the current settings in the models. On the other hand, at the sites near Chishinshan (Y17, Y18, Y19, Y20, Y21, and Y23) and Dayoukeng (Y06, Y07, Y08, and Y09), the discrepancies between the observed and the modeled gravity changes are much larger, indicating that the two hydrological models are inadequate here.

Model A is constrained by the groundwater level observations at the 23 wells and at the rivers without using the groundwater flowing dynamics (Eq. 1). The modeled groundwater tables are predicted from interpolations to the observed groundwater levels. The groundwater layer is assumed to be homogeneous and contains porous media without low permeable/boundary layer in vertical or horizontal directions. Thus, the sites where the gravity changes from Model A and the observations are consistent should be located in a region with porous or permeable formations without groundwater flow barriers.

Model B uses the continuous groundwater flow equations (Eq. 1) with inputs from rainfall recharges and optimized hydraulic conductivities, specific yields, and porosities (Table 3) to predict groundwater level changes. With these settings, Model B assumes that the underlying media below the study area (Fig. 1b) are porous and resemble an alluvium formation. As shown in Fig. 11, this assumption and parameter settings are valid only over the gravity sites where the observed and modeled gravity changes are consistent. This consistency occurs largely at the gravity sites over Chingtiengang, where the formation

contains inter-connected porous media for groundwater to flow as in an alluvial aquifer. The extent of the inter-connection is determined by the hydraulic conductivities in Table 3, which range from 0.0005 to 0.02 m/day. Moreover, Model B assumes that there is a low permeable layer under Chishinshan and Chingtiengang, following the concept of Komori et al. (2014). This assumption also contributes to the consistency between the observed and modeled gravity changes over Chingtiengang.

Using the gravity consistencies and inconsistencies found in this study and the findings in previous studies, we present a possible configuration of a hydrogeological scheme along profile A-B (see Fig. 1b) in Fig. 12. The aquifuge in Fig. 12 is based on Komori et al. (2014) and it prevents hydrothermal fluids below the sea level from flowing to the formation below Chingtiengang. This aquifuge also does not allow the groundwater below Chingtiengang to leak into the deep hydrothermal reservoir identified by Murase et al. (2014).

As mentioned above, Model A and Model B are expected to simulate groundwater level variations over strata containing continuous media without boundaries (low permeable materials). The observed changes in water levels are the boundary values for the two hydrological models. However, if the underlying strata contain discrete cracks, the observed groundwater levels will be in favor of a scenario in which groundwater level variations correspond to a very local fractured block, instead of a regional one. That is, a large difference between the observed and modeled gravity change at a site implies that the materials below the site may contain volcanic conduits or inter-connected cracks, rather than a continuous porous formation. Figure 11 shows that, at most of the gravity sites over Chishinshan, the differences (red circles) between the observed and modeled gravity changes (observation minus model) are positive in the first (April), second (July) and fourth (November) gravity surveys. This implies that groundwater levels over Chishinshan are underestimated. Because the hydraulic conductivities and storage coefficients in Model B are assumed to be constants along the vertical direction at each grid, the underestimated groundwater levels suggest that the hydraulic conductivities and storage coefficients in Table 3 are not suitable for Chishinshan, but are still optimal over Chingtiengang. Another interpretation is that the governing equation of MODFLOW (Eq. 1) is simply not realistic for the formations over Chishinshan, which may contain discrete volcanic conduits and fracture materials. As such, MODFLOW cannot produce reasonable groundwater flows here.

The differences between the observed and modeled gravity changes could be also caused by different recording times of the gravity and groundwater level measurements. For example, the negative gravity differences in September 2012 around Chishinshan (Fig. 11) might be caused by a sudden rise of groundwater level due to the heavy rainfall brought by typhoon Jelawat in the TVG region. This sudden water level rise was recorded in our well data and led to large gravity changes from Model A and B. However, the gravity survey in September 2012 was carried out before typhoon Jelawat, so that the Jelawat-induced water mass surplus was not reflected in the gravity observations, leading to the large negative gravity differences (observed minus modeled gravity changes) around Chishinshan in Fig. 12.

As a final remark, the Model B result suggests that there is a volcanic aquifer below the superconducting gravity station (YMSG near Chintiengang) bounded by an aquifuge at the sea level and by unknown lateral boundaries (Fig. 12). We hypothesize that this aquifer may partly supply source water to replenish the deep hydrothermal reservoir 2 km below Chishinshan (Murase et al, 2014). If the aquifuge is ruptured by earthquakes, groundwater in this aquifer will flow to the deep hydrothermal reservoir or even to the magma below Chishinshan. This rupture may greatly increase the probability of a phreatic eruption over the TVG. It is recommended that the interaction between groundwater and magma over the TVG should be investigated, based on recent works such as Jasim et al. (2018) and Hsieh and Ingebritsen (2019).

6. Conclusion

This study uses the time-varying gravity measurements in 2012 to delineate an aquifer around the TVG by hydrological modeling and EOF analysis. The gravity changes from the RG measurements in the four surveys were carefully processed to achieve a mean standard error of point gravity at about 8 μGal , which is small enough to sense the seasonal hydrological signal associated with the aquifer.

Our 3-D hydrological models (A and B) show porous media below the SG station (Chintiengang) around the TVG, where the hydraulic conductivities are optimized by the observed gravity changes through the modeled groundwater levels by Model B (Table 3). The consistency between the observed and modeled gravity changes over Chintiengang implies that the underlying strata contain inter-connected porous media above a low permeability layer (aquifuge). On the other hand, the sites with inconsistent observed and modeled gravity changes over Chishinshan imply that the subsurface layers at these sites may contain cracks and fractures that are not considered in Model B.

The aquifer identified in this study may pose a potential risk of phreatic eruption in the TVG. The risk can occur if the aquifuge below the aquifer is damaged by weathering and by external forces such as earthquakes. Groundwater leaking through a damaged part of the aquifuge can increase the water volume at the deeper parts of the TVG and thereby increase the water vapor pressure to raise the probability of an eruption. How long the aquifuge can sustain damages or whether leaking groundwater can cause a phreatic eruption can be potential subjects for future studies.

Appendix A: The TVG rainfall data in 2012

Fig. A1 shows the rainfall data from April to December 2012. The rainfall data in the TVG from April to December in 2012 shows that most of the precipitation occurred in April to June. The precipitation in July to October is mainly brought by typhoon.

Appendix B: Gravity changes from model predictions and observations

Fig. B1 shows the time series of the observed and modeled gravity changes in 2012 at the 32 gravity sites in this study. At most of the gravity sites, the maximum gravity changes occurred in June and July, and the minimum in September and October.

Appendix C: The second and third EOF modes of gravity changes

Appendix C (Fig. C1) is a supplement to Sect. 5.1 and Fig. 10 to show the second EOF modes and third EOF modes from the observed and modeled gravity changes.

Declarations

Declarations

The work in this paper is original and this paper is submitted to only this journal.

Availability of data and material

The gravity and groundwater level data used in this paper are available at <http://space.cv.nctu.edu.tw/publications/#data>.

Competing interests

The authors declare that they have no competing interest.

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Authors' contributions

C.H. and E.T.Y.C. initiated the project. T.Y.L. carried out the major computation and analysis. T.Y.L. and C.H. wrote the first draft with E.T.Y.C. C.C.C., K.F.L., R.F.C. and C.H.M. helped to collect and analyze the gravity and groundwater level data.

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Figures

Figure 1

Topography and gravity sites over the Tatun Volcano Group. (a) The topography around the TVG and the distributions of gravity sites (RG blue diamond; AG: red diamond with blue inside), groundwater wells, rainfall stations, hydrothermal reservoirs (pink circle; Murase et al., 2014), and rivers (blue lines). Note that YMSG is a hybrid SG, AG and RG gravity site, located in Chingtiengang. (b) The geological map of the TVG and the station names of the AG and RG sites. The orange line from A to B shows the

hydrogeological profile in Fig. 12. The abbreviations of the geological formations are: tb, Tuff breccia; St, Shihti formation; TI, Taliao formation; Ms, Mushan formation; Wc, Wuchihshan formation. (c) A view of Chishinshan and the YMSG site from Chintiengang.

Figure 2

Gravity changes at all gravity sites. The dates for changes are in April, July, September and November, 2012, only selected site names are shown, i.e., Y20 (Chishinshan), YMSG (Chintiengang), Y08 (Dayoukeng) and Y03 (Dingshan).

Figure 3

Gravity changes and rainfalls. Red and blue bars show rainfalls recorded at stations WZS and SD and the resulting infiltrations. Red, cyan and black squares show gravity changes at Y01, Y02 and Y03.

Figure 4

Groundwater levels for and from Model A. (a) Groundwater levels at the wells (black stars) and river levels (colored lines) for Model A. Note that the background topography is not used for constructing the gridded groundwater levels. (b) The modeled groundwater levels in April 2012 from Model A.

Figure 5

Groundwater levels for and from Model B. (a) Topography (gray background) and two major faults bounding the aquifer, water levels at groundwater wells (black stars) and rivers (colored lines), and

rainfall stations (black squares) for MODFLOW in April 2012 (see Appendix C). (b) The modeled groundwater levels from MODFLOW (Model B) in April 2012.

Figure 6

Groundwater level changes from Model A. The changes are relative to the mean groundwater levels over April–December, 2012 (Model A).

Figure 7

Groundwater level changes from Model B. The changes are relative to the mean groundwater levels over April–December, 2012 (Model B).

Figure 8

Gravity changes derived from Model A groundwater level changes (Fig. 6). The dates are in April, July, September and November, 2012.

Figure 9

Same as Fig. 8, but from Model B.

Figure 10

Three modes of variances (or variabilities) from the EOF analysis. The variances are unitless because of normalization, and they are based on observations (top), Model A (middle) and Model B (bottom). The right column shows the variabilities from the first modes. A negative variability indicates a negative correlation.

Figure 11

Differences between the observed and modeled gravity changes. The left column is for Model A and the right column is for Model B. Positive and negative differences are shown in red and blue circles, respectively. Yellow circles correspond to the sites where the gravity differences are small. Model B produces a better fit than Model A over gravity sites near YMSG (the location around SG49). This better fit implies the porous media around YMSG from Model B.

Figure 12

Possible hydrogeological structure along profile A-B (Fig. 1b). The pink solid circles are the two hydrothermal reservoirs in Fig. 1a. The porous media form an aquifer below the SG49 site (YMSG). The aquifer's aquifuge and the hydrogeological settings for Model B result in gravity changes that are consistent with the observed gravity changes.

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