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PAPER

Estimating the specific yield of the Pampeano aquifer, Argentina, using superconducting gravimeter data

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Abstract

Specific yield is a key parameter for the sustainable management of unconfined aquifers, since it relates water-table fluctuations to aquifer storage-changes and thus impacts water supply. However, estimating specific yield is still a challenge due to theoretical and methodological limitations. Water-storage changes in the aquifer and in the overlying unsaturated soil profile cause local changes in gravity that can be recorded by high-precision superconducting gravimeters. In this work, a novel methodology to estimate specific yield from superconducting gravimeter data is presented. The proposed methodology is based on a hydrogravimetric model that estimates the gravity response due to the loss and gain of water mass in the soil profile using rainfall, water-table and air-temperature data. The model is applied to a study site of the Pampeano aquifer in Argentina where a continuous 1-year record of superconducting gravimeter measurements is available. The specific yield value obtained using this methodology is 0.11 ± 0.039, which is validated by means of a long-term pumping test performed at the study site. The proposed method constitutes a promising alternative to the available tools for estimating specific yield, by taking advantage of superconducting gravity data.

Keywords Specific yield · Superconducting gravimeter · Gravity variations · Geophysical methods · Argentina

Introduction

Specific yield (S_y) is a key parameter in hydrology and water management, as it allows quantification of the available water resources of unconfined aquifers. Hydrological applications of this parameter include assessments of groundwater-storage changes and recharge, drainage of agriculture lands, and groundwater modelling, among others (e.g. Dettmann and Bechtold 2016; Chinnasamya et al. 2018; Gribovszk 2018; Seraphine et al. 2018). Although S_y appears to be a simple hydrogeological concept, its formal definition is not straightforward. Freeze and Cherry (1979) define the specific yield as the volume of water that an aquifer releases from or takes into storage per unit aquifer area per unit change in water-table depth. Some authors express S_y as (Meinzer 1923; Healy and Cook 2002; Crosbie et al. 2005):

$$S_y = \phi - S_r \qquad (1)$$

where ϕ is the porosity and S_r is the specific retention, which can be defined as the water content retained in the porous medium against gravity when the water table is lowered. In agriculture and hydrology, the specific retention is usually called field capacity. The foregoing definition is valid when the drainage from the unsaturated zone is instantaneous and complete for all points above the water table (Healy and Cook 2002; Dietrich et al. 2018). Note that S_y defined by Eq. (1) is a constant parameter in time, also known as drainable porosity.

A more complex definition of S_y, that considers water-table depth and time dependency, is given by Bear (1972). Here, S_y is defined as the average amount of water per unit volume of

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soil drained from a soil column extending from the water table to the ground surface, per unit lowering of the water table. Based on this definition, S_y can be expressed as:

$$S_y(t) = \frac{1}{\Delta z}\int_{z_0}^{z_{top}}[\theta(z,t_2) - \theta(z,t_1)]dz, \qquad t_1 < t < t_2 \tag{2}$$

where $\theta(z,t)$ is the water content at time t and depth z, $\Delta z = z_2 - z_1$ is the change in water-table position between time t_1 and t_2, z_0 is the aquifer bottom, and z_{top} is the soil surface position.

Note that S_y defined by Eq. (2) is not an intrinsic property of the porous media. It depends on the water-table depth, drainage process, type of soil, and water content history. When the drainage process is taken into account, S_y estimated by Eq. (2) is also called the readily available specific yield (Loheide et al. 2005) or apparent specific yield (Crosbie et al. 2005). When the drainage has ceased, Eq. (2) is equivalent to Eq. (1). In order to avoid the time dependence of S_y, Duke (1972) assumed that the initial and final soil profile are in static equilibrium above the water table.

Although many advances have been made during the last decades, estimating S_y is still a challenge since different values are obtained depending on the selected methodology and the time scales involved (Healy and Cook 2002). The value of S_y that is estimated under particular conditions must be used carefully in different situations since it could lead to unreliable results (Duke 1972).

Estimates of S_y can be derived from laboratory or field methods. Laboratory techniques usually involve column-drainage experiments, determination of the water content curves, and particle size distributions using regression equations (Neuman 1987; Song and Chen 2010). Laboratory methods commonly provide higher values of S_y than field techniques since they can be run long enough to drain fully the sample (Moench 1994). Moreover, laboratory methods are representative at the point scale (~10^{-4}–1 m) and are not suitable for realistic recharge assessments.

Field methods include aquifer tests (e.g. pumping test and slug test), water budgets, and geophysical surveys, among others (e.g. Neuman 1987; Frohlich and Kelly 1988; Nachabe 2002; Maréchal et al. 2006; Pool 2008; Boucher et al. 2009; Dietrich et al. 2018). The constant-rate pumping test is a standard technique used to assess the hydraulic transmissivity and storativity of aquifers. Estimations of S_y using this technique often depend on the duration of the test or on constructive characteristics of the wells (Wu et al. 2005; Moench 2008). As a consequence, determinations of S_y has an associated uncertainty, ranging from 0.005 to 0.038 (Heidari and Moench 1997), and sometimes give unrealistic values (Yeh and Huang 2009). Nevertheless, a pumping test still represents one of the most reliable methods for estimating S_y at the field-scale (Trabucchi et al. 2018).

Geophysical techniques are typically noninvasive and give quantitative information about subsurface hydrological parameters or processes such as drainage and imbibition (Rubin and Hubbard 2005). In particular, magnetic resonance sounding (MRS), electrical resistivity tomography (ERT) and gravimetric methods have been used to estimate S_y (e.g. Gehman et al. 2009; Pool 2008; Boucher et al. 2009; Dietrich et al. 2018).

Magnetic resonance sounding is a promising tool to monitor water level fluctuations, and to estimate transmissivity and storativity of shallow aquifers (Descloitres et al. 2008; Vouillamoz et al. 2008). Some work has been performed to estimate S_y using this technique (e.g. Boucher et al. 2009; Vouillamoz et al. 2012) but these studies concluded that MRS estimates the effective porosity rather than S_y. ERT allows for mapping of the electrical resistivity of the soil, to identify heterogeneities and recharge zones, among other applications. Recently, Dietrich et al. (2018) proposed a novel approach to compute S_y through time-lapse ERT surveys showing how this hydrological parameter depends on time and space.

Ground-based gravimetric methods provide a direct measure of water-storage changes, integrating from local to continental scales. Gravimetric methods have been successfully used to study local water-storage variations (e.g. Naujoks et al. 2008; Creutzfeldt et al. 2010; Pfeffer et al. 2013; Hector et al. 2013; Piccolroaz et al. 2015) and for calibration of hydrological models (e.g. Krause et al. 2009; Naujoks et al. 2010; Christiansen et al. 2011). Besides, ground-based gravimetry can be used to estimate S_y as it relates water-table fluctuations to changes in unconfined aquifer storage. Montgomery (1971) made one of the first estimations of S_y from a correlation of gravity and water level changes. Then, a number of gravity surveys, with relative spring gravimeters, were conducted to estimate S_y (e.g. Pool and Eychaner 1995; Howle et al. 2003; Gehman et al. 2009; Seraphine et al. 2018). In addition, S_y was also estimated by the use of absolute gravimeters (e.g. Jacob et al. 2009; Pfeffer et al. 2011; Hector et al. 2013, Chen et al. 2018). Wilson et al. (2012) made the first estimate of S_y by means of superconducting gravimeter data.

A typical application of the hydrogravimetric approach is to estimate S_y by a regression analysis that relates water-table fluctuation with local gravity variations (Pool 2008). This analysis sometimes gives unreliable values of S_y due to the influences of the unsaturated zone on gravity. Therefore, hydrological processes in the unsaturated zone must be known and their gravity response must be calculated and removed from the regression analysis as pointed out by Pool (2008) and Creutzfeldt et al. (2010).

In this general context, the main goal of this work is to develop a new methodology to estimate S_y using superconducting gravimeter data, and then apply it to the Pampeano aquifer in Buenos Aires Province (Argentina). The Pampeano aquifer is composed of silty sand sediments from the middle-upper Pleistocene and is usually referred to as Pampeano loess (Sayago 1995). The widespread spatial distribution coverage and the good water quality of this aquifer made it one of the most exploited resources for human and agricultural supply in the region (Mascioli et al. 2005).

The study site is located at the Argentine-German Geodetic Observatory (AGGO) in Parque Pereyra Iraola, Berazategui, Argentina (Fig. 1a). A superconducting gravimeter SG038 was installed at AGGO in December 2015 and has since then provided a continuous record of gravity variation (Mikolaj et al. 2019). The climatic conditions at the study site are characterized by mean annual air temperature of 17.4 °C and a mean rainfall of 916.6 mm year^{-1}; meteorological time series are published in Mikolaj et al. (2019).

In the next section, the new method to estimate S_y from superconducting gravimeter data is presented. The different hydrological contributions to local gravity variations are modelled using rainfall, water-table depth, and air temperature data measured at AGGO. Then, temporal gravity variations provided by this approach are compared to the gravity residuals obtained from the gravimeter SG038. Finally, the specific yield value is computed by an inversion process and is validated by a long-term pumping test performed at the study site.

Conceptual hydrogravimetric model

Groundwater in an unconfined sedimentary aquifer is stored in the pore spaces between grains. When the water table drops, a certain amount of water is drained out of the pore space and is replaced by air. The amount of water drained by gravity is directly related to the S_y value of the unconfined aquifer. Hence, variations in aquifer storage depend on both water-table fluctuations and S_y. From a gravimetric point of view, variations in aquifer storage generate a redistribution of groundwater mass that changes local gravity. These changes in gravity can be measured by a superconducting gravimeter and used to determinate S_y.

Figure 1b shows a schematic section of the aquifer, the monitoring well and the superconducting gravimeter. Water flow in flatland areas, like in Buenos Aires Province, is dominantly vertical due to its negligible topographic slopes (<0.1%). Thus, the main hypothesis of the proposed model is that groundwater only moves in the vertical direction z and the water table is horizontal. Let it be assumed that the drainage by a water-table drawdown, Δz, takes place between two stationary moisture profiles in a homogeneous soil (see Fig. 2a). Under this assumption, S_y defined by Eq. (2) is constant and can be considered as a representative parameter of the mean conditions of the study site. Note that water content curves in Fig. 2a have the same shape. The shaded area in Fig. 2a represents the amount of water per unit area that is released from storage due to the water level decline and it could be computed as $S_y \Delta z$.

The gravity contribution of an infinitely Bouguer slab of differential thickness dz and density $\rho(z,t)$ is given by (Telford et al. 1992):

$$\mathrm{d}g(z,t) = 2\pi G \rho(z,t)\mathrm{d}z \qquad (3)$$

where $G = 6.673 \times 10^{-11}$ m^3 kg^{-1} s^{-2} is the universal gravitational constant, and $\rho(z,t)$ is the density of the soil profile. Note that ρ depends on the soil solid matrix and water content $\theta(z,t)$, and can be modeled as follow:

$$\rho(z,t) = (1-\phi)\rho_\mathrm{m} + \theta(z,t)\rho_\mathrm{w} \qquad (4)$$

where ϕ is the porosity, and ρ_m and ρ_w are solid matrix and water density, respectively.

The gravitational attraction of a soil profile ($z_0 < z < z_{\mathrm{top}}$) at time t can be estimated from Eqs. (3) and (4):

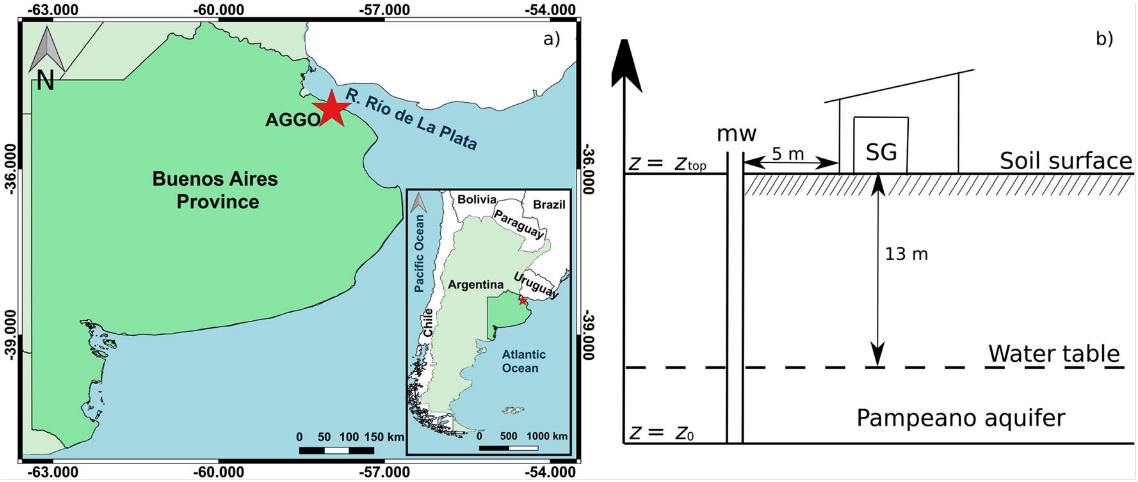

Fig. 1 **a** Location of the study site in Buenos Aires Province, Argentina; **b** schematic section of the aquifer, the monitoring well (mw) and the superconducting gravimeter (SG), where z is the vertical coordinate

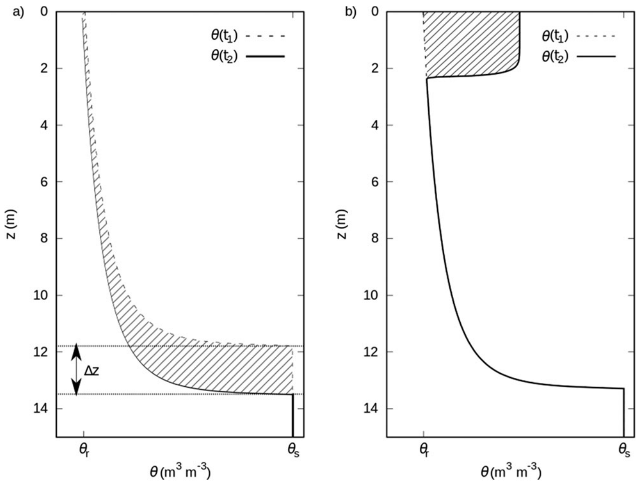

Fig. 2 Water content curves for different soil conditions, where θ is the volumetric water-content, θ_r and θ_s are residual and saturated water-content, respectively, and z is the depth below the surface: **a** initial $\theta(t_1)$ and final $\theta(t_2)$ water-content curves at equilibrium conditions before and after a water-table drop, Δz, where the hatched area represents the volume of water released per unit area; **b** initial $\theta(t_1)$ and final $\theta(t_2)$ water-content curves before and after a recharge event, where the volume of rainwater infiltration into soil per unit area is represented by the hatched area

$$g(t) = 2\pi G \int_{z_0}^{z_{\mathrm{top}}} [(1-\phi)\rho_{\mathrm{m}} + \theta(z,t)\rho_{\mathrm{w}}]\mathrm{d}z \tag{5}$$

Then, the gravitational change due to a decline of water table, Δz, between times t_2 and t_1 can be computed as follows:

$$\Delta g_{\mathrm{gw}} = g(t_2) - g(t_1) = 2\pi G \rho_{\mathrm{w}} \int_{z_0}^{z_{\mathrm{top}}} [\theta(z,t_2) - \theta(z,t_1)]\mathrm{d}z \tag{6}$$

Finally, by combining Eqs. (2) and (6) an expression for estimating the gravity changes in terms of S_y is obtained (Montgomery 1971):

$$\Delta g_{\mathrm{gw}} = 2\pi G \rho_{\mathrm{w}} S_{\mathrm{y}} \Delta z \tag{7}$$

Note that Eq. (7) is valid for gravity changes between two stationary moisture profiles. However, close to the terrain surface of the soil profile, water-storage may change due to the infiltration of rainwater (see Fig. 2b) or evapotranspiration, and Eq. (7) is no longer valid.

In order to estimate the influence of evapotranspiration and rainfall on gravity, the following empirical model, proposed by Crossley et al. (1998), is used:

$$\Delta g_{\mathrm{r}}(t) = 2\pi G \rho_{\mathrm{w}} r(t_{\mathrm{r}}) f(t), \qquad t > t_{\mathrm{r}} \tag{8}$$

where Δg_r is gravity effect of rainfall, $r(t_r)$ is the rainfall at time t_r, and $f(t)$ is a function that represents the accumulation and consumption of water due to infiltration and evapotranspiration. This function has the following expression:

$$f(t) = \left(1 - e^{-(t-t_{\mathrm{r}})/\tau_1}\right) e^{-(t-t_{\mathrm{r}})/\tau_2} \tag{9}$$

where τ_1 and τ_2 are the recharge and discharge time parameters. Parameter τ_1 describes the accumulation of water in the soil, whereas τ_2 represents its consumption due to evapotranspiration. The approach assumes that there is no loss of water by direct surface runoff but that all rainfall either infiltrates or evaporates. According to Neumeyer (2010), the time parameters must be adapted empirically depending on the hydro-geological characteristics of the site and of its surrounding. Moreover, Mouyen et al. (2013) suggest that the model described by Eq. (8) is suitable for continuous gravity time series.

Based on Eq. (8), gravity changes caused by hydrological effects in the unsaturated zone in the time interval Δt can be modeled as:

$$\Delta g_{\mathrm{uz}} = \Delta g_{\mathrm{r}}(t_2) - \Delta g_{\mathrm{r}}(t_1) = 2\pi G \rho_{\mathrm{w}} r(t_{\mathrm{r}})(f(t_2) - f(t_1)) \tag{10}$$

Assuming that there is no surface deformation due to water-storage changes, gravity residuals measured by the superconducting gravimeter Δg_{SG} can be expressed as the contribution of unsaturated zone and groundwater gravity effects:

$$\Delta g_{\mathrm{SG}} = \Delta g_{\mathrm{vz}} + \Delta g_{\mathrm{gw}} \tag{11}$$

Finally, the hydrogravimetric model for estimating the gravity residuals is obtained by substituting Eqs. (7) and (10) into Eq. (11):

$$\Delta g_{\mathrm{SG}} = 2\pi G \rho_{\mathrm{w}} \left[S_{\mathrm{y}}(z_2 - z_1) + r(t_{\mathrm{r}})(f(t_2) - f(t_1))\right] \tag{12}$$

Equation (12) models the expected gravity residuals measured by the superconducting gravimeter due to unsaturated zone and groundwater-storage variation. This hydrogravimetric model depends on water-table depth and rain data, and three model parameters: S_y, τ_1, τ_2. The proposed methodology to estimate S_y is based on the inversion of superconductivity gravity residuals. Note that Eq. (12) is defined for a single rainfall event, but it can be easily adapted to a sequence of events by computing the gravimetric response due to individual rainfall events, and then, stacking those gravimetric effects. The meteorological instrumentation installed at AGGO provides hourly rainfall data. This sampling interval allows definition of individual rainfall events on a 1-h basis.

Model parameters

In this section, model parameters are estimated by an inversion process. The recharge time parameter τ_1 depends on the field capacity of the soil and is assumed to be constant in time (Harnisch and Harnisch 2006; Mouyen et al. 2013; Carbone et al. 2019). The time parameter τ_2 represents the loss of water mass mainly due to

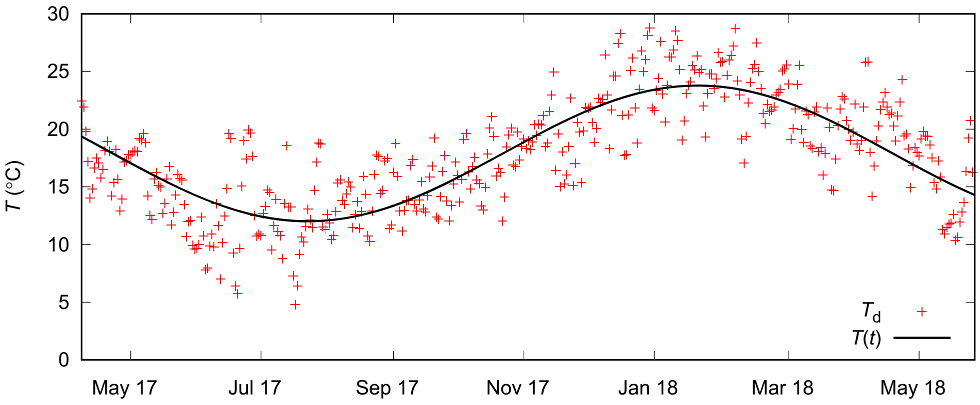

Fig. 3 Daily mean air temperature T_d recorded by the weather station at AGGO for the period 5 April 2017 to 30 May 2018, and the proposed temperature function. The adjusted values of A, B and C (see Eq. 14) are 5.9 °C, 167.86 days and 17.9 °C, respectively

evapotranspiration. It is assumed that τ_2 depends on air temperature as evapotranspiration is mainly controlled by this meteorological variable. Harnisch and Harnisch (2002) define three ranges for daily air temperature with different values of τ_2. Here, it is proposed that τ_2 varies as a continuous function of the daily air temperature. Then, according to Eq. (9), the time parameter τ_2 should decrease with temperature. Based on this observation, the following parametrization of τ_2 is proposed:

$$\tau_2 = a/T(t) \tag{13}$$

where a is a fitting parameter and $T(t)$ is the mean hourly air temperature. In order to obtain an expression for $T(t)$, the air temperature time series recorded by the weather station at AGGO are fitted using the following sinusoidal expression:

$$T(t) = A\sin((t+B)2\pi/365) + C \tag{14}$$

where A, B and C are fitting parameters. Figure 3 shows the temperature data (Mikolaj et al. 2019) and $T(t)$ adjusted with a nonlinear least squares Marquardt–Levenberg algorithm (Marquardt 1963).

In order to apply the proposed methodology, three time-invariant parameters must be estimated: S_y, τ_1 and a—(parameter related to τ_2 through Eq. (13)). These parameters are obtained through an optimization procedure that compares the simulated gravity residuals (Eq. (12)) to the gravity residuals obtained from the SG038 observations at AGGO. The objective function (ObjF), to minimize during the optimization procedure, is defined as:

$$\mathrm{ObjF}(s_y, a, \tau_1) = \left(\sum_{i=1}^{N} \frac{\left(\Delta g^{\mathrm{i}}_{\mathrm{obs}} - \Delta g^{\mathrm{i}}_{\mathrm{SG}}\right)^2}{N} \right)^{1/2} \tag{15}$$

where $\Delta g^{\mathrm{i}}_{\mathrm{obs}}$ and $\Delta g^{\mathrm{i}}_{\mathrm{SG}}$ are the observed and simulated gravity residuals at time $t = i$, respectively, and N represents the number of total observations. The ObjF is minimized using the grid search method (Sen and Stoffa 2013).

Data

A period of approximately one year (from 5 April 2017 until 30 May 2018) with hourly temporal resolution data was selected for this study. The methodology described in previous sections was applied to hydro-meteorological and gravity data measured at AGGO to estimate the specific yield of the Pampeano aquifer. A detailed description of this data set is given in Mikolaj et al. (2019) and the data are available from Mikolaj et al. (2018). Here, from this data set, time series of precipitation, air temperature, groundwater level and gravity residuals are used. For precipitation, the level 3 product of

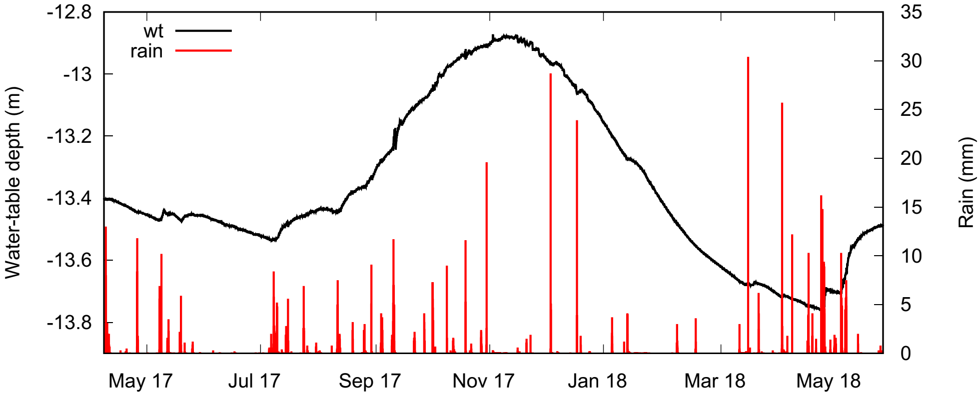

Fig. 4 Hourly precipitation (rain, mm) and water-table depth (wt, m) time series recorded in AGGO; first record on 5 April, 00:00 h

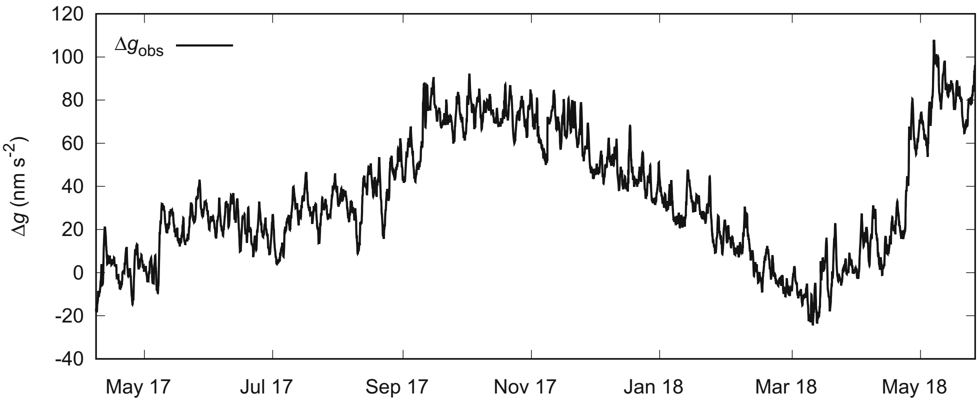

Fig. 5 Hourly gravity residuals of SG038 raw data at AGGO; first record on 5 April, 00:00 h

Mikolaj et al. (2019) is used, i.e., a revised gap-filled time series based on the combination of the records of two tipping buckets at the site. For air temperature, the time series of a CS215 is used. For groundwater, the gap-filled level 2 data of Mikolaj et al. (2019) of a groundwater well located at a distance of 5 m from the superconducting gravimeter is used. Precipitation and groundwater level, expressed as water-level depth below the terrain surface, are shown in Fig. 4. These data exhibit distinct wet and dry seasons that correspond approximately to winter and summer, respectively.

Gravity residual time series (Δg_{obs}) are the hourly level 3 data of SG038 as described by Mikolaj et al. (2019) (Fig. 5). The gravity residuals time series represents the gravity observations at AGGO corrected for tides, polar motion and length of day effects, local air pressure and instrumental drift of the gravimeter, and the series is additionally reduced for the attraction effects and loading effects of global atmospheric, oceanic and hydrological mass variations. Global hydrological effects are computed using the mGlobe toolbox described in Mikolaj et al. (2016). The input data for mGlobe are provided by large-scale gravity models for atmospheric (ICON 384, ECMWF, ERA-Interim), hydrological (GLDAS, MERRA, NCEP) and non-tidal ocean effects (ECCO1, ECCO2, TUGOm, OMCT RL06). The oceanic mass variations considered here also include storm surges (Oreiro et al. 2017) in the La Plata River estuary, which can have a marked effect on the gravity changes at AGGO.

Results and discussion

The hydrogravimetric approach depends on three independent parameters: τ_1, τ_2 and S_y. Values of these parameters are obtained when the optimal fit between the observed gravity residuals Δg_{obs} and the simulated gravity residuals Δg_{SG} is achieved. The grid search method is implemented to find the minimum ObjF, and the initial parameter ranges are 1–24 h for τ_1, 2,400–48,000 °C h for a, and 0.01–0.20 for S_y, with increments of 1 hr, 240 °C h and 0.005, respectively. The optimal set of values obtained from the inversion procedure are presented in the Table 1.

The root mean square error of the fit is 7.94 nm s^{-2}, and the correlation coefficient between Δg_{obs} and Δg_{SG} is 0.96. These statistical values also demonstrate the overall good model performance. According to the Eq. (13) and the optimized value of a, the time parameter τ_2 takes values between 1111.6 and 2201.8 h for the whole period analyzed. Maximum and minimum values of τ_2 are related to winter and summer, respectively. Figure 6a,b shows unsaturated-zone (Δg_{uz}) and groundwater (Δg_{gw}) gravity effects computed by Eqs. (7) and (10) using the parameter values listed in Table 1.

While Δg_{uz} represents predominantly the short-term hydrological effect on the gravity residual, Δg_{gw} shows a distinct seasonal pattern with an amplitude of about 41 nm s^{-2}.

The proposed hydrogravimetric model defined by Eq. (12) reproduces reasonably well the main features of the measured gravity residuals (Fig. 7). In particular, the longer-term dynamics are adequately well represented, indicating that the model can capture the (seasonal) groundwater variations.

The estimated value of the specific yield for the Pampeano aquifer, $S_y = 0.11$, is consistent with previous estimates, ranging from 0.09 to 0.13, that were made by other researchers using GRACE (Gravity Recovery and Climate Experiment) satellite products (Guarracino et al. 2011) and a graphical approach based on the correlation between rainfall and water-table rises (Quiroz-Londoño et al. 2012; Varni et al. 2013).

Table 1 Parameters of the proposed model estimated by means of the search grid method

Parameter (units)	Estimated value
S_y(−)	0.11
a(°C h)	26,400
τ_1 (h)	1

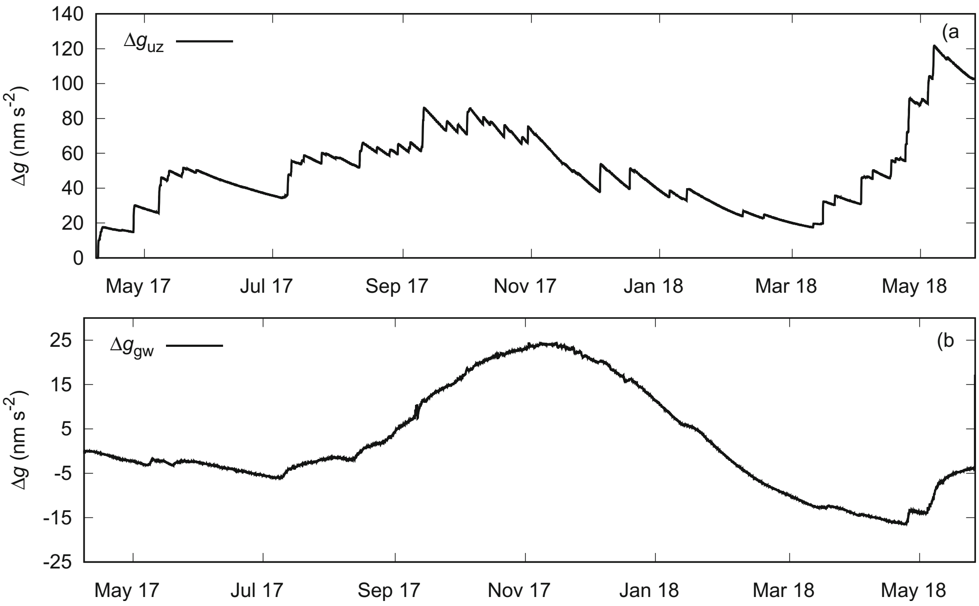

Fig. 6 **a** Unsaturated-zone gravity response due to rainfall, infiltration of rainwater and evapotranspiration; **b** gravity response due to changes in groundwater level

Uncertainties

The estimate of S_y using the proposed hydrogravimetric approach depends on gravity residuals (Δg_{SG}), water-table fluctuation (Δz) and precipitation data (r). Then, the uncertainty in S_y estimate can be computed by propagation error through Eq. (12). Assuming that the variables are uncorrelated, the propagated uncertainty of S_y is:

$$\sigma_{S_y} = S_y \sqrt{\left(\frac{\sigma_{\text{grav}}}{<\Delta g_{\text{SG}}>}\right)^2 + \left(\frac{\sigma_{\Delta z}}{<\Delta z>}\right)^2 + \left(\frac{\sigma_r}{<r>}\right)^2} \qquad (17)$$

where σ_{grav}, σ_z, σ_r are the uncertainties of gravity residuals, water level fluctuations and precipitation, respectively. The symbol <> denotes the mean value of the variable for the whole period of analysis. According to Mikolaj et al. (2019b), the uncertainty in hourly gravity residuals is estimated to be 0.2 nm s^{-2}. According to the manufacturers, the measurement errors associated to the pressure transducer are 0.05% full scale, and 2% for the rain gauges up to a precipitation of 25 mm h^{-1}. Hence, the uncertainty of S_y equals 0.039. This value is in agreement with the uncertainty values obtained by Gehman et al. (2009), who estimate S_y using a different method based on temporal gravity surveys. Moreover, the S_y uncertainty estimated in this work is concordant with values estimated by Heidari and Moench (1997) and Chen et al. (1999) from different pumping test analysis.

It is worth mentioning that the estimated uncertainty represents approximately 35% of the S_y value. This percentage is relatively high, but it is not possible to establish a conclusion about the utility of the proposed gravimetric method in comparison to other techniques, in view of their respective uncertainties. The comparison of the results of various types of measurements suggests that specific yield values depend upon the type of test, the timescale of the test, and the method of data analysis (Nwankwor et al. 1984). At present, there is still no consensus on which technique is more reliable for estimating specific yield values (Nilsson et al. 2007; Maliva 2016).

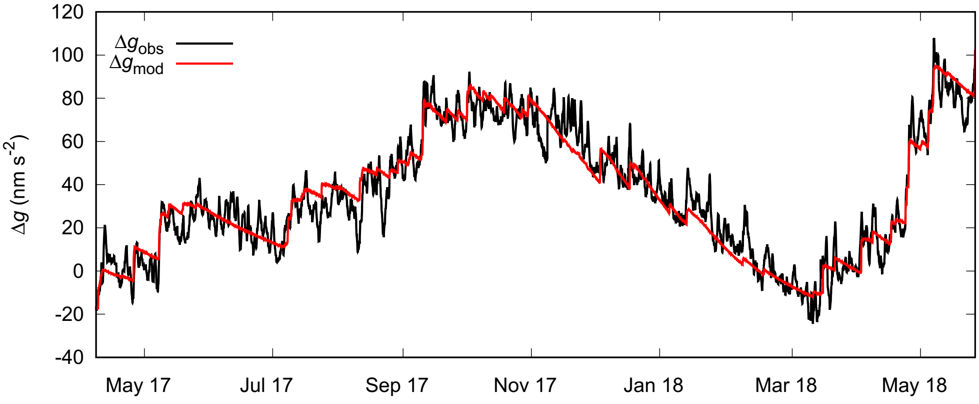

Fig. 7 Comparison between the observed gravity residuals (SG038) and the modeled gravity residuals by the hydrogravimetric model

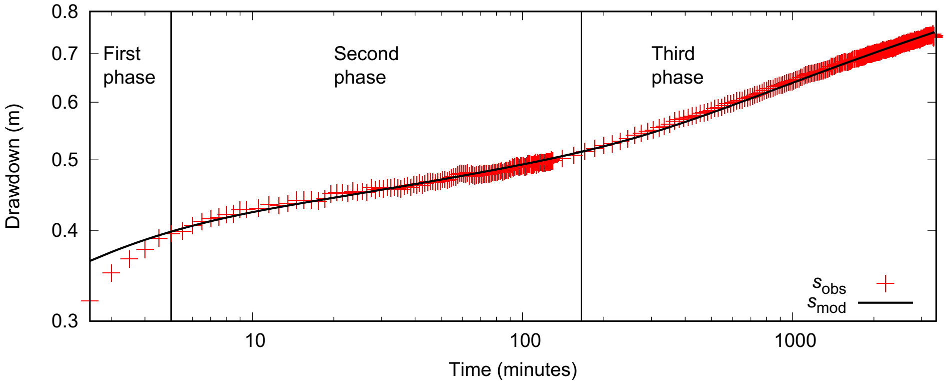

Fig. 8 Comparison between measured (s_{obs}) and theoretical drawdowns (s_{mod}) at the observation well in the Pampeano aquifer at AGGO

Estimation of specific yield from a pumping test

A constant-rate pumping test was performed at the AGGO study site in order to validate the S_y value obtained from the proposed method. A pumping test is a well-known field method to compute the hydraulic properties of a geological formation. The S_y value estimated by this test represents the mean aquifer storage over the screened region (Chen et al. 2018). The test should be long enough to reach a phase that is dominated by gravity drainage and thus allows for estimating a reliable value of S_y (Nwankwor et al. 1992). Here, the pumping test was conducted for approximately 56 h at AGGO in May 2017 using two groundwater observation wells located at close distance to the superconducting gravimeter (Mikolaj et al. 2019). Water level drawdowns (s) were measured at the pumped well and an observation well by means of pressure transducers. The radial distance between both wells is 3.15 m. The top and bottom of the well screens are 15 and 32 m below the surface, respectively. The initial water-table position was 13.8 m below the surface. Throughout the whole test, the pumping rate was approximately 6.1 $m^3 h^{-1}$. The water extracted was discharged at a distance of 130 m from the pumping well to avoid any interference with the drawdowns measured. The hydraulic properties of the Pampeano aquifer were estimated with the computer program WTAQ (Barlow and Moench 1999). This program provides an indirect estimation of the hydrogeological parameters of the aquifer (vertical and horizontal hydraulic conductivity, the specific storage and the specific yield) by means of different analytical equations. The Mathias and Butler (Mathias and Butler 2006) approach provided with WTAQ was selected to estimate the hydraulic properties of the Pampeano aquifer. This approach couples flow in the saturated zone with vertical flow in the unsaturated zone using a linearized Richards' equation and the Gardner model (Gardner 1958). The Mathias and Butler model parameter is composed of the hydraulic properties of the aquifer (saturated thickness, vertical an radial hydraulic conductivity, specific yield and specific storage), and the moisture retention and relative permeability exponents required by the Gardner model. The lower boundary is assumed impermeable, whereas the upper boundary is the water-table position, where the flow conditions are known. The WTAQ program was adapted to allow an automatic parameter estimation by means of the grid search method.

The measured time-drawdown curve in the observation well is shown in Fig. 8. This curve exhibits the typical three drawdown phases of an unconfined aquifer. The first phase indicates that water is released from storage by an elastic mechanism and follow the Theis (Theis 1935) solution. This phase can last a few minutes and the flow is considered to be in the horizontal direction. In the second phase, the rate of drawdown slows down and time-drawdown curve tends to be horizontal due to the delayed drainage from the unsaturated zone. Delayed drainage can last a few hours to days. Finally, in the third phase, the flow is essentially horizontal since the water pumped is mainly released from gravity drainage. Hence, pumping tests in this phase are controlled by S_y. This is the main reason why a pumping test for estimating S_y needs to be long enough to cover this phase.

The comparison between the observed and the theoretical drawdowns at the observation well is shown in Fig. 8. The Pampeano aquifer hydrological properties and Gardner model parameters estimated by this experiment are listed in the Table 2. The estimated value of S_y based on the Mathias and Butler model result in 0.10. This value is in good agreement with the specific yield value estimated from the hydrogravimetric model.

Table 2 Hydrological parameters estimated by the pumping test: K_r and K_z are the horizontal and vertical hydraulic conductivity, respectively, S_s represents the specific storage, a_c and a_k are the moisture retention and relative permeability exponents of the Gardner model

Parameter (units)	Estimated value
K_r (m day^{-1})	6.9
K_z (m day^{-1})	1.3
S_s (m^{-1})	3×10^{-5}
S_y (−)	0.10
a_c (m^{-1})	2×10^{-2}
a_k (m^{-1})	2×10^{-2}

Conclusions

In this work, a hydrogravimetric method for estimating S_y from times series of superconducting gravity residuals is presented. The gravimetric data are complemented with standard hydro-meteorological variables that are frequently monitored. Thus, the model is assumed to be easily applicable at other sites as long as continuous terrestrial gravity observations are available. The gravity response of local water-storage in the unsaturated zone and in the aquifer are modelled using three independent parameters. Model parameter optimization for the Pampeano aquifer at AGGO results in a value of 0.11 ± 0.039 for the specific yield. Time-drawdown curve analysis of a long-term pumping test at the site results in a value of 0.10 for S_y, which is in the range of uncertainty of the proposed method. However, the slight difference between these values can partly be attributed to the different spatial scales covered by the two methods: in the case of the pumping test, the effective hydraulic properties of the aquifer average over the radius of the depression cone, which was 80 m in the experiment run here. For the hydrogravimetric approach, the radius of sensitivity of the gravimeter from which there is 95% of the local hydrological signal is about 500 m around the instrument for flat terrain (Creutzfeldt et al. 2008). Thus, S_y derived from the hydrogravimetric method can be expected to be the effective parameter representing a larger volume of the aquifer.

From a geodetic and geophysical perspective, the local hydrological signal is considered a noise to be removed from terrestrial gravity observations. The hydrogravimetric model showed good performance in capturing the main dynamic features of the gravity residuals. Hence, this model provides a comparatively simple procedure, compared to full hydrodynamic modelling (e.g. Kazama et al. 2012), to remove the local hydrological effects from the raw gravity time series.

To the authors' knowledge, this study represents the first successful estimation of S_y using superconducting gravimeter data. This result also illustrates the potential of superconducting gravimeters as hydrological monitoring devices.

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