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Nonlinear subsidence at Fremantle, a long-recording tide gauge in the Southern Hemisphere

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Key Points:
- The Fremantle tide gauge is and has been subsiding in a nonlinear way
- Exemplar of the need for geodetic connection between tide gauge and GPS station
- Groundwater has been used as a diagnostic for nonlinear vertical land movement

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Abstract A combination of independent evidence (continuous GPS, repeat geodetic leveling, groundwater abstraction, satellite altimetry, and tide gauge (TG) records) shows that the long-recording Fremantle TG has been subsiding in a nonlinear way since the mid-1970s due to time-variable groundwater abstraction. The vertical land motion (VLM) rates vary from approximately −2 to −4 mm/yr (i.e., subsidence), thus producing a small apparent acceleration in mean sea level computed from the Fremantle TG records. We exemplify that GPS-derived VLM must be geodetically connected to the TG to eliminate the commonly used assumption that there is no differential VLM when the GPS is not colocated with the TG. In the Perth Basin, we show that groundwater abstraction can be used as a diagnostic tool for identifying nonlinear VLM that is not evident in GPS time series alone.

1. Introduction

In order to determine reliable linear trends, accelerations or decelerations of mean sea level (MSL) from tide gauges (TGs), the TG must be vertically stable over time. For example, the vertical stability of the Australian continent and its suitability as a datum for MSL observations has been debated for decades [e.g., *Aubrey and Emery*, 1986, 1988; *Bryant et al*., 1988; *Amin*, 1993; *Belperio*, 1993; *Feng et al*., 2004; *Sandiford*, 2007; *Moucha et al*., 2008; *Watson*, 2011; *Lewis et al*., 2012].

Repeat leveling between the TG zero and proximal tide gauge benchmarks (TGBMs) only ever informs of local relative stability, so will be misleading if the TG and TGBMs are subject to the same amount of vertical land motion (VLM). Unaccounted-for VLM at TGs will cause underestimate or overestimate of MSL change, and nonlinear VLM will generate spurious accelerations or decelerations, all of which may be misinterpreted as climate change responses of the ocean [cf. *Brooks et al*., 2007; *Mazzotti et al*., 2009; *Raucoules et al*., 2013; *Ingebritsen and Galloway*, 2014].

Continuously operating GPS (CGPS) has previously been used to determine VLM at TGs [e.g., *Schöne et al*., 2009], but unless the CGPS is directly colocated with the TG or frequently releveled to monitor for any differential VLM, there remains uncertainty as to whether the GPS-derived VLM really is applicable [*Bevis et al*., 2002]. Many studies have used CGPS-derived VLM from sites that are not colocated with or geodetically tied to the TG, with distances from the TG of up to 15 km [*Wöppelmann et al*., 2007, 2009; *Bouin and Wöppelmann*, 2010; *Santamaría-Gómez et al*., 2012; *Houston and Dean*, 2012], 40 km [*Snay et al*., 2007], 50 km [*King et al*., 2012], 80 km [*Burgette et al*., 2013], and even 100 km [e.g., *Watson et al*., 2015]. In the case of DORIS-derived VLM, this has extended to 150 km [e.g., *Cazenave et al*., 1999; *Ray et al*., 2010].

Without any geodetic monitoring to ensure that there is no differential VLM between the CGPS or DORIS beacon and TG, these "corrections" to MSL rates may be erroneous. In this paper, we exemplify this for the Fremantle TG (herein termed FREM), but which does not have colocated GPS or DORIS. The CGPS used for previous VLM corrections is situated ∼31.2 km north-north-east of FREM. We will show that the FREM TG and CGPS sites are subsiding due principally to groundwater abstraction, but at different rates, with the differential VLM verified by repeat leveling.

Ongoing debate has surrounded acceleration and deceleration in MSL; see the review by *Visser et al*. [2015]. Studies that have used FREM to claim acceleration include *Calafat and Chambers* [2013], *Church and White* [2006, 2011], *Hay et al.* [2015], *Haigh et al.* [2014], *Hogarth* [2014], *Holgate and Woodworth* [2004], *Jevrejeva et al.* [2014], *Jordà* [2014], *Merrifield et al.* [2009], *Olivieri and Spada* [2013], *Watson et al.* [2015], and *Woodworth et al.* [2009, 2011]; those that claim deceleration include *Boretti* [2012], *Boretti and Watson* [2012], *Parker et al.* [2013], and *Watson* [2011]; those that claim neither include *Wenzel and Schröter* [2010, 2014].

Apparent de/acceleration in MSL measured at TGs can be caused by nonlinear VLM. Previous studies have used linear rates of VLM derived from CGPS/DORIS observations or linear models of glacial isostatic adjustment [e.g., *Spada and Galassi*, 2012]. However, nonlinear VLM can be induced by factors such as: anthropogenic subsurface resource extraction [e.g., *Raucoules et al.*, 2013], nonsteady elastic displacements driven by changing surface loads [e.g., *Santamaría-Gómez and Memin*, 2015], and postseismic transient deformation [e.g., *Bevis and Brown*, 2014].

We will demonstrate a small apparent acceleration in MSL at FREM due to negative, nonlinear VLM (land subsidence) caused by time and space-variable changes in the amount of groundwater abstraction from subsurface aquifers in the Perth Basin. We also demonstrate (i) the invalidity of the assumption of zero differential VLM between the FREM TG and PERT CGPS, which provides evidence-based caution to be applied globally that CGPS-derived VLM must be geodetically connected to the TG; (ii) it can be inappropriate to adopt linear-only VLM estimates from CGPS time series without proper inspection of these and other independent data sets for evidence of nonlinear VLM.

2. The Fremantle TG and Previous VLM Estimates

The port of Fremantle in Western Australia hosts the FREM TG (PSMSL code 111) [*Holgate et al.*, 2013], which is among the longest recording TGs in the Southern Hemisphere, having observed MSL since 1897. It thus fits *Douglas*'s [1991] criterion of >60 years and *Houston and Dean*'s [2013] criterion of >75 years for the reliable estimation of MSL trends and accelerations, respectively, though interannual and decadal variability of MSL remains problematic along the Western Australian coast [e.g., *Amin*, 1993; *Nidheesh et al.*, 2013]. Nevertheless, the length of the FREM record means that it has been used in many global and regional sea level assessments [e.g., *Holgate and Woodworth*, 2004; *Church et al.*, 2006; *Fenoglio-Marc and Tel*, 2010; *Bouin and Wöppelmann*, 2010; *Houston and Dean*, 2012; *Burgette et al.*, 2013, *Becker et al.*, 2014, as well as the references cited earlier].

The uncertainty surrounding MSL change at FREM can be inferred from several perspectives. It has been omitted from some studies that consider global analysis from only long-term TGs [e.g., *Douglas*, 1991, 1992]. Claims have been made that it is vertically stable, albeit through a personal communication [*Feng et al.*, 2004], or it has been implicitly assumed to be vertically stable [*Burgette et al.*, 2013]. Disparities have been reported with MSL at FREM versus coastal altimetry [*Holgate and Woodworth*, 2004], and *Palanisamy et al.* [2014] report anthropogenic VLM in this region, citing our preliminary work [*Featherstone et al.*, 2012]. At the low end, *Aubrey and Emery* [1986] used multiple TGs to estimate subsidence at FREM of -1.2 mm/yr between 1913 and 1976. At the high end, *Nerem and Mitchum* [2002] used satellite altimetry and FREM revised local reference (RLR) [*Holgate et al.*, 2013] TG data to estimate subsidence of -8.54 ± 2.99 mm/yr over a 4.02 year period, but the epoch was not specified.

FREM is not colocated with CGPS/DORIS, so studies that have applied VLM "corrections" to the FREM TG record have used the CGPS at Gnangara (International GNSS Service (IGS) [*Dow et al.*, 2009] code PERT), resting on the assumption that there is zero differential VLM between these sites that are separated by $\sim$31.2 km. Though we will show later that this assumption is invalid for the Perth Basin, it is first instructive to point out that previous estimates of VLM at PERT differ by more than their formally stated error. These differences are primarily dependent on the reference frame (RF) used [cf. *Collilieux and Wöppelmann*, 2011; *Bevis et al.*, 2013; *Bevis and Brown*, 2014], the epochs of CGPS data analyzed, and the color of noise used in the trend estimates. Examples of GPS-derived VLM at PERT are: -5.21 ± 0.73 mm/yr (January 1997 to November 2006 in ITRF2005) [*Bouin and Wöppelmann*, 2010], -6.30 ± 0.05 mm/yr (4 January 1998 to 29 December 2007 in IGS05 RF) [*Rudenko et al.*, 2013], -2.98 ± 0.34 mm/yr (15.98 years but epoch not specified in IGS08 RF) [*Santamaría-Gómez et al.*, 2012], and -2.1 ± 0.7 mm/yr (beyond 2000, but no end date specified or RF) [*Burgette et al.*, 2013]. In addition, the studies above have only considered linear VLM; we will demonstrate that VLM in the Perth Basin is nonlinear.

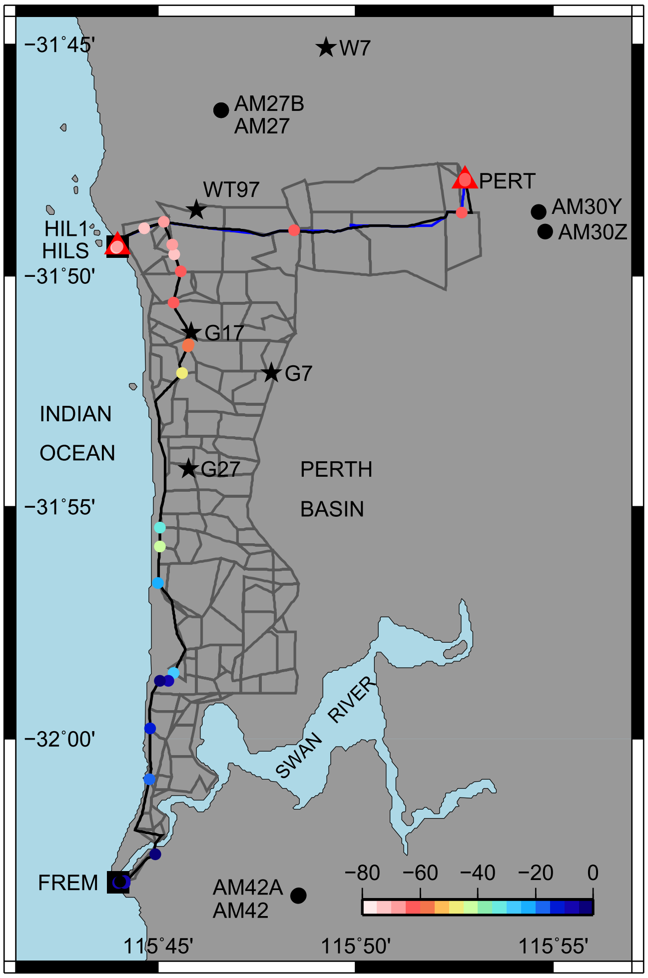

Figure 1. The Perth Basin: black squares show the HILS and FREM TGs, red triangles show the PERT and HIL1 CGPS, black circles show nearby artesian monitoring bores (AM27 is ~6.8 km from HILS, AM30 is ~3.5 km (averaged) from PERT, AM42 is ~7.2 km from FREM), black stars show abstraction bores commencing production after 2000 (G7, G17, G27, WT97, and W7), dark gray lines show circa 1975 leveling networks, and black lines show 2011 repeat leveling traverses, with the blue line (mostly obscured under the black line) showing the 1992 HIL1-PERT traverse. The colored circles and color bar show changes in leveled height differences relative to FREM (units in mm) at common benchmarks (1975–2011), showing that the differential VLM correlates spatially with the new groundwater production bores (black stars).

3. Results

3.1. Repeat Geodetic Leveling

The Hillarys TG (HILS, PSMSL code 1761) is situated ~25.4 km due north of the FREM TG (Figure 1) and has been operating since 1993, with colocated CGPS (IGS code HIL1) operating there since 1997. Repeat leveling data provided by Landgate (Western Australia's geodetic agency) between the HIL1 and PERT CGPSs and the HILS and FREM TGs are used to demonstrate differential VLM in the Perth Basin (Table 1, column 3). These comprise a leveling network observed primarily around 1975 and manually digitized from hardcopy archives (Figure 1, gray lines), and separate two-way leveling traverses between benchmarks close to HIL1 and PERT (1992.25 and 2011.25) and HIL1 and FREM (2011.83); Figure 1, black and blue lines. Later leveling was used to connect the benchmarks to the TG zero and GPS antenna reference point in the cases where the leveling predated the TG or GPS installations.

The 1975 leveling is of lower quality (allowable misclose of $12\sqrt{d}$ mm where d is the distance along the leveling route in km), but redundant measurements allow a network to be formed, thus adding robustness. The repeat leveling traverses are first order (allowable misclose of $2\sqrt{d}$ mm). Allowable misclose is an in-field quality control metric assigned to different leveling standards; it is not the standard deviation of the observations. The leveling data were least squares adjusted in the public-domain SNAP software from Land Information New Zealand (http://www.linz.govt.nz/data/geodetic-services/download-geodetic-software/snap-concord-downloads). The 1 sigma error estimates for the change in height differences in Table 1 (column 3) come from separate least squares adjustments of the network and traverses, subsequently differenced with error propagation of the standard deviations produced from each adjustment.

The 1975 leveling is connected to the FREM TG by a 1980 survey of the TGBMs. An earlier 1967 leveling connection indicates subsidence of the FREM TGBMs of ~16 mm to 1980, and a further 7 mm to 2011, relative to the FREM TG. Because PERT and HIL1 were not established until 1993 and 1997, respectively, i.e., after the 1975 leveling, local ties were made with the 1992 leveling. The 1975 and 1992 leveling shows millimetric agreement at the common benchmarks adjacent to PERT and HIL1, indicating that the VLM is not simply movement of the CGPS monuments.

Many of the 1975 benchmarks have been destroyed, but those remaining were resurveyed, allowing for height differences to be calculated at some points along the traverse; FREM was held fixed arbitrarily to

Table 1. Differential Rates of VLM Computed From CGPS Between PERT and HIL1 and From Altimetry-TGRLR Between HILS and FREM Over Different Epochs[a]

Differential CGPS VLM (mm/yr)		Differential Altimetry-TGRLR VLM (mm/yr)		Repeat Leveling Change in Height Difference (mm)	
		HILS Minus FREM		HIL1 Minus FREM (34 km)	
		1993.0–2000.0	−0.80 ± 2.15	Circa 1975–2011.83	−69.1 ± 10.9
		2000.0–2005.0	−6.48 ± 2.92		
		2005.0–2013.0	−0.86 ± 2.09		
		1993.0–2013.0	−2.48 ± 0.88		
PERT Minus HIL1				PERT Minus HIL1 (18 km)	
1998.0–2000.0	−1.52 ± 3.31			Circa 1975–2011.25	−5.8 ± 8.3
2000.0–2005.0	+1.75 ± 1.67			Circa 1975–1992.25	−13.8 ± 8.3
2005.0–2012.0	+1.18 ± 1.32			1992.25–2011.25	+8.0 ± 2.4
1998.0–2012.0	+0.08 ± 0.55				
				PERT Minus FREM (49 km)	
				Circa 1975–2011.54	−63.3 ± 12.9

[a]Leveled height differences are among all three sites, and the height difference changes with respect to time are of the form later minus earlier epoch. The distances given are along the leveling traverses.

zero to show the differential VLM. Figure 1 (colored dots) shows that the larger negative changes in height (i.e., subsidence) correlate spatially with new groundwater abstraction bores (discussed in the next section). The change in leveled height difference between PERT and FREM of −63.3 ± 12.9 mm (Table 1, column 3) demonstrates that there is differential VLM occurring in the Perth Basin. Assuming linearity for the moment, the differential VLM is −1.73 ± 0.35 mm/yr from 1975 to 2011.54, where PERT is subsiding faster than FREM. Therefore, the CGPS VLM computed at PERT should not be applied directly to FREM. More generally, CGPS-derived VLM should only be used to correct MSL records when geodetically connected to the TG, and reinforces by example the arguments in, e.g., *Bevis et al*. [2002] among others.

3.2. Groundwater Abstraction From the Perth Basin

The Perth Basin hosts several groundwater aquifers [*Davidson*, 1995], and abstraction of groundwater is known to cause land subsidence [e.g., *Chi and Reilinger*, 1984; *Galloway and Burbey*, 2011]. The Leederville and Yarragadee aquifers are the largest in the Perth Basin and have been increasingly exploited for domestic and horticultural use. Both aquifers extend laterally well beyond the extents of Figure 1, with the smaller Leederville aquifer located above the larger Yarragadee aquifer. Abstraction from Leederville began in 1974 and from Yarragadee in 1979. Total production volumes for each aquifer are shown in Figure 2. Between 2000 and 2003, five new production bores (G7, G17, G27, W7, and WT97; black stars in Figure 1) came online, each abstracting an additional 1.8–6.5 GL/yr of groundwater from Yarragadee close to HILS. These correlate spatially with the leveled height changes in Figure 1.

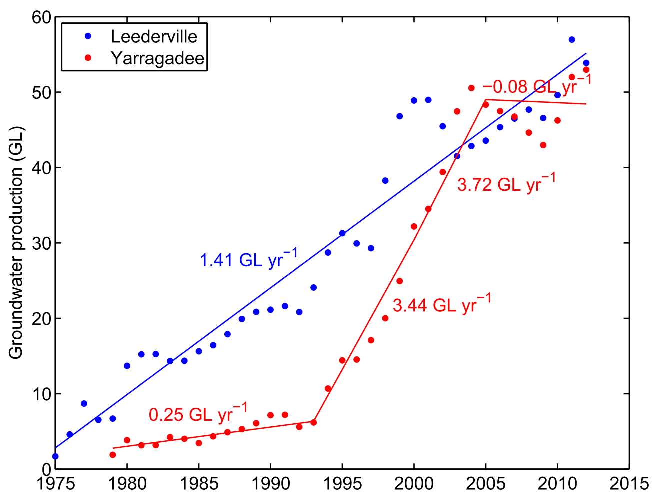

Figure 2. Rates of total groundwater production (GL/yr) from the Leederville aquifer (blue) and the Yarragadee aquifer (red).

Instead of relying solely on total production volumes from each aquifer (Figure 2), it is more informative to interrogate artesian monitoring (AM) bores located near the CGPSs and TGs. The artesian monitoring data were downloaded from the Western Australian Department of Water's website http://wir.water.wa.gov.au/SitePages/SiteExplorer.aspx (site codes: 61615043 for AM30Z, 61615127 for AM30Y, 61615063 for AM27, 61615064 for AM27B, 61615008 for AM42, and 61615009 for AM42A). Figures 3a and 3b show the piezometric heads for Yarragadee and Leederville AM bores nearest to PERT (AM30), HILS (AM27), and FREM (AM42) from the start of production until

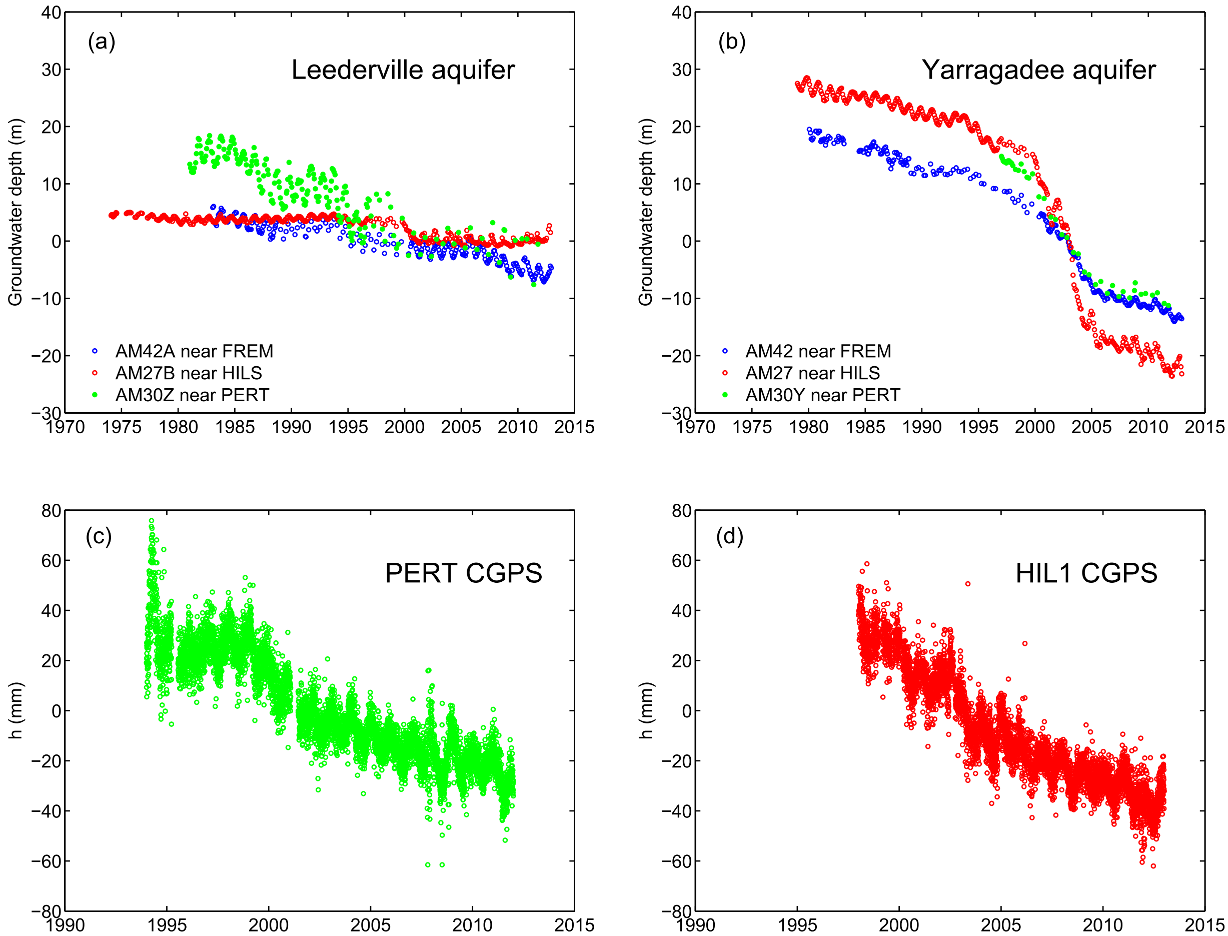

Figure 3. (top) Groundwater depth over time relative to an arbitrary datum for (a) the Leederville aquifer and (b) the Yarragadee aquifer at artesian monitoring bores near PERT (green), HILS (red), and FREM (blue). (bottom) IGS08 ellipsoidal heights over time at (c) PERT CGPS (green) and (d) HIL1 CGPS (red), with the mean removed. Note the different time epochs of observations between top and bottom plots.

2013.0; cf. Figure 1. Another AM bore (AM33, not shown) is located closer to HILS, but exhibits spurious values of unknown origin, possibly equipment malfunction. The AM27 bore is used instead because it shows a profile of drawdown that is consistent in shape with other Yarragadee AM bores. The Leederville AM bores (Figure 3a) show near-linear abstraction consistent with the production information (Figure 2). For the Yarragadee AM bores (Figure 3b), the abstraction rates appear linear before 1993.0, show a small inflection at 1993.0, and larger inflections at 2000.0 and 2005.0. These are consistent with the total production volumes (Figure 2) but are more distinct, thus providing a better diagnostic for identifying nonlinear VLM.

The strong seasonal signals in Figures 3a and 3b reflect reduced groundwater abstraction during the southern winter months [cf. *Argus et al.*, 2014], where the abstracted groundwater is replenished from gravity-driven redistribution within the aquifers [cf. *Theis*, 1935]. Comparison of piecewise linear trends estimated from simple (white noise) linear regression and linear regression plus an annual sinusoid exhibited statistically insignificant differences, showing this annual term to have high coherency. Therefore, linear trends and an annual sinusoid were solved for the entire time series for Leederville, and four piecewise linear trends and sinusoids were solved for Yarragadee with tie points corresponding to the inflections at 1993.0, 2000.0, and 2005.0 (Table 2).

The AM data in Figures 3a and 3b are irregularly spaced in time, so it is difficult to estimate and use a colored noise model in the trend estimation using public-domain software such as CATS [*Williams*, 2008] since it expects regularly spaced data, albeit with gaps permitted. However, since no groundwater depth measurements were made more than once per day, we can assume that the measurement interval was daily and that the AM time series have many large gaps throughout. We implemented a maximum likelihood estimator

Table 2. Absolute Rates of VLM Computed From CGPS at PERT and HIL1 and From Altimetry-TGRLR at HILS and FREM Over Different Epochs[a]

Absolute CGPS VLM (mm/yr)		Leederville Drawdown (m/yr)		Yarragadee Drawdown (m/yr)		ETF (mm/m)		Absolute Altimetry-TGRLR VLM (mm/yr)		ETF-Derived VLM (mm/yr)	
PERT		AM30Z		AM30Y		PERT					
1994.0–2000.0	−0.90 ± 1.97	1981.0–2012.0	−0.58 ± 0.04	1997.0–2000.0	−1.49 ± 0.13	Pre-2000.0	+0.43 ± 2.19				
2000.0–2005.0	−5.42 ± 2.36			2000.0–2005.0	−3.48 ± 0.10	2000.0–2005.0	+1.33 ± 0.44				
2005.0–2012.0	−2.51 ± 1.89			2005.0–2012.0	−0.48 ± 0.08	Post-2005.0	+2.37 ± 0.76				
1994.0–2012.0	−2.87 ± 0.86										
1998.0–2012.0	−4.21 ± 0.38										
HIL1		AM27B		AM27		HIL1		HILS			
		1974.0–2013.0	−0.11 ± 0.04	1979.0–1993.0	−0.39 ± 0.05						
1998.0–2000.0	−6.56 ± 2.69			1993.0–2000.0	−1.02 ± 0.18	Pre-2000.0	+5.81 ± 0.44	1993.0–2000.0	−5.56 ± 2.37		
2000.0–2005.0	−6.97 ± 1.30			2000.0–2005.0	−5.85 ± 0.27	2000.0–2005.0	+1.17 ± 0.19	2000.0–2005.0	−1.60 ± 2.72		
2005.0–2013.0	−3.12 ± 0.92			2005.0–2013.0	−1.02 ± 0.19	Post-2005.0	+2.76 ± 0.34	2005.0–2013.0	−7.40 ± 1.99		
1998.0–2013.0	−4.99 ± 0.49							1993.0–2013.0	−4.77 ± 0.61		
1998.0–2012.0	−4.10 ± 0.32										
FREM		AM42A		AM42				FREM		FREM	
		1983.0–2013.0	−0.38 ± 0.08	1980.0–1993.0	−0.55 ± 0.13					1975.0–1993.0	−2.49 ± 0.88
				1993.0–2000.0	−0.91 ± 0.21			1993.0–2000.0	−5.36 ± 2.63	1993.0–2000.0	−3.45 ± 1.23
				2000.0–2005.0	−2.74 ± 0.27			2000.0–2005.0	+5.41 ± 3.02	2000.0–2005.0	−3.72 ± 0.73
				2005.0–2013.0	−0.74 ± 0.20			2005.0–2013.0	−7.52 ± 2.21	2005.0–2013.0	−3.00 ± 1.10
								1993.0–2013.0	−2.20 ± 0.68		

[a]Absolute rates of groundwater drawdown at AM bores close to PERT (AM30), HILS (AM27), and FREM (AM42); see Figure 1. Empirical transfer functions (ETFs) calculated from the superposed groundwater drawdowns and absolute CGPS rates, and VLM derived at FREM from the weighted mean of ETFs at PERT and HIL1. The post-2005.0 VLM has been used pre-2000.0 because of the large variance between ETFs pre-2000.0.

using this assumption and estimated piecewise linear trends (with tie points) and the stochastic noise model. This allowed for the determination of more realistic uncertainties on the groundwater trends (Table 2).

3.3. Piecewise Linear VLM From CGPS

Two scientific, public-domain CGPS stations operate in the Perth Basin (Figure 1, red triangles), namely the PERT IGS station and the HIL1 Australian Regional GNSS Network station. HIL1 is colocated with the HILS TG, though the site is noisy because of masts of nearby moored yachts and frequent equipment changes. As with the groundwater data, all data up until 2013.0 were collated and analyzed, although the GPS time series at PERT was truncated at 2012.0 because a lightning strike caused a 6 month data gap followed by a new equipment installation, resulting in an offset that is poorly determined. The PERT and HIL1 CGPS data were processed daily in precise point positioning mode as described in *Williams and Penna* [2011], except the GIPSY 6.2 software was used, JPL (Jet Propulsion Laboratory) repro1 orbits and clocks were held fixed, and the fiducial-free outputs were transformed to the IGS08 realization of ITRF2008 [*Altamimi et al*., 2011].

Frequent equipment changes (identified in the associated log files) were made at HIL1 and PERT over the CGPS time spans considered, particularly with antenna replacements at HIL1, which can cause artificial offsets in the coordinate time series that bias the rates if treated incorrectly. Offsets were however only visually apparent (*Gazeaux et al*. [2013] found that visual inspection of coordinate time series for offsets is as reliable as any automated offset detection algorithm) at HIL1 at epochs 2002.45 and 2006.56. Initially, these offsets were both estimated using CATS and deemed statistically significant, but after comparison with the leveling data, the 2002.45 offset was considered a genuine time series feature so only the height time series after 2006.56 (equipment change) were corrected for an estimated offset of 17.8 mm. Therefore, the change in leveled height difference between HIL1 and PERT from 1992.25 to 2011.25 was useful to assist the offset detection in the CGPS time series.

Four piecewise linear trends were estimated using a modified version of CATS based on the dates inferred from the piezometric heads at nearby AM bores (Table 2, column 1). As is common in GPS time series analysis [e.g., *Teferle et al*., 2009], the functional model comprises a linear trend, annual sinusoid and semiannual sinusoid, solving for both colored and white noise terms. The inflections at 2000.0 and 2005.0 are not evident from a visual inspection of the CGPS time series in Figures 2c and 2d, whereas they are in Figure 2b. Therefore, groundwater levels from nearby AM bores can provide a diagnostic tool for identifying nonlinear VLM that is not visually apparent in a CGPS time series alone.

Table 2 (column 1) shows that there is nonlinear VLM occurring in the Perth Basin, which is statistically significant for the HIL1 site. The rates determined pre-2000 are less reliable because of the shorter time series and noise in these earlier CGPS solutions (i.e., older and frequently changed equipment). When using the entire time series and assuming linearity for each site, the estimated rate is highly dependent on the epoch chosen because of this nonlinear VLM; see the discussion in paragraph 3 of section 2. However, when using a consistent epoch (e.g., 1998.0–2012.0) and again assuming linearity, the subsidence rates are equal within error bounds, which is corroborated by the leveling (Table 1, column 3) that shows there is no significant differential VLM between the PERT and HIL1 CGPS sites. Differencing the daily CGPS solutions (Table 1, column 1) shows the same, but the 1998–2000 epoch is highly uncertain. When the whole common time series is used, the trend is also insignificant. When extrapolated to the epoch from 1975 to 2011.25, it gives a height difference of -2.9 ± 19.9 mm, which also agrees with the leveling within observational uncertainty (Table 1, column 3).

3.4. Differential RLR and Altimetry

To corroborate the absolute and relative subsidence at FREM and HILS, we apply the technique proposed by *Cazenave et al*. [1999] and refined by *Kuo et al*. [2004] [also see, e.g., *Nerem and Mitchum*, 2002; *Ray et al*., 2010; *Wöppelmann and Marcos*, 2012], whereby the differences between altimetry and TGRLR measurements are used to estimate differential VLM. This is more challenging than using geodetic-only techniques because of interannual and decadal sea level variability due to a strong El Nino Southern Oscillation signal along the Western Australian coast [e.g., *Amin*, 1993; *Nidheesh et al*., 2013], and additional uncertainty of radar altimetry close to the coasts [e.g., *Deng et al*., 2002].

We differenced monthly RLR MSL records from the PSMSL [*Holgate et al*., 2013] and monthly altimeter means produced by CSIRO [*White et al*., 2014], then computed piecewise linear VLM trends using the above modified form of CATS. Piecewise linear rates plus annual and semiannual signals were estimated for all solutions. Differencing at the observation level lessens the effect of sea level variability, but does not completely eliminate it even though these sites are separated by only ~25.4 km. This is also because the RLR senses the monthly MSL at a site, whereas the altimeter senses the sea surface height over the altimeter's footprint.

When considering the entire 20 year altimetry record and assuming linearity, Table 2 (column 5) shows that subsidence is occurring at both HILS and FREM, and HILS is subsiding at a faster rate than FREM. This is consistent with the evidence of differential VLM from the CGPS, groundwater, and differential leveling (Tables 1 and 2). Extrapolating the altimetry-RLR 1993.00–2013.00 rate to 1975.00–2011.83 gives a total subsidence of -175.7 ± 22.5 mm at HILS and -81.0 ± 25.0 mm at FREM. The derived change in height difference is -94.6 ± 33.6 mm, compared to -69.1 ± 10.3 mm from the leveling. Table 2 (column 5) also shows that the altimetry-minus RLR technique when used in an absolute sense is ineffective at determining realistic nonlinear VLM over short epochs, at least for these two particular TGs. The rates have large uncertainties and are inconsistent with VLM derived from CGPS at HILS. This is caused principally by the large sea level variability along the Western Australian coast, coupled with the shorter data spans considered.

When the double difference technique of *Kuo et al*. [2004] is used (Table 1, column 2), the altimetry-RLR relative VLM demonstrates improved correlation with the groundwater and leveling. The increased differential VLM is evident for the 2000.0–2005.0 epoch. Extrapolating the 1993.0–2000.0 piecewise relative VLM rate back to 1975 to reconstruct the 1975–2011.83 leveling epoch gives a change in height difference of -58.3 ± 22.7 mm, which closely matches the leveling (-69.1 ± 10.3 mm). However, extrapolating the double-differenced 1993.0–2013.0 rate over the 1975–2011.83 epoch gives a change in height difference of -91.3 ± 32.4 mm, which is further away from the leveling than using the nonlinear piecewise rates. This gives further evidence that the VLM in the Perth Basin is nonlinear.

3.5. Empirical Transfer Functions

We determined a relationship between the GPS-derived VLM and groundwater abstraction rates from the nearest AM bores, computing empirical transfer functions (ETFs) by dividing the GPS-derived VLM by the Leederville plus Yarragadee drawdown (Table 2, column 4). This method is limited because the AM bores are not colocated with the CGPS installations, being several kilometers away (see the caption of Figure 1 for the distances). The ETFs for the pre-2000 data are more uncertain because of the shorter GPS time series, and the shorter AM time series pre-2000 at PERT, but there is agreement within calculated uncertainty for the 2000–2005 and post-2005 epochs.

We then applied the weighted mean of the ETFs at PERT and HILS to the groundwater level at AM42 as a proxy for the VLM at FREM. Because the pre-2000 ETFs are so uncertain, we used the post-2005 ETF. Table 2 (column 6) shows that the ETF-derived VLM at FREM is also nonlinear, with a higher rate when the groundwater abstraction from the Yarragadee aquifer increased between 2000 and 2005. This difference is because Yarragadee is a confined and compacted aquifer [*Davidson*, 1995], so is expected to behave elastically [*Theis*, 1935; *Galloway and Burbey*, 2011]. In order to verify the ETF-derived VLM, we applied the rates at HIL1 and FREM and compared them to the leveled height difference. Applying the nonlinear ETFs in Table 2 (column 6) from 1975 to 2011.83 gives a total subsidence of -108.0 ± 19.8 mm at FREM over this time period. Doing likewise for HIL1 gives a total subsidence of -154.3 ± 34.0 mm. The ETF-derived difference of -51.1 ± 39.4 mm is remarkably close to the change in leveled height difference (-69.1 ± 10.3 mm), acknowledging the large uncertainty (~80%) in the ETF-derived change in height.

3.6. Removal of Acceleration at FREM

Fitting a second-order polynomial of the form $\frac{1}{2}a.t^2 + b.t + c$ (as used by, e.g., *Bos et al*. [2014]) to the PSMSL RLR record at FREM (1897.0–2013.0) indicates a small but statistically insignificant acceleration in MSL of $+0.0039 \pm 0.0132$ mm/yr^2. This however is uncorrected for any VLM. We then attempted two VLM corrections to FREM. The first is most simplistic and only generates a revised MSL relative to the land, and not absolute MSL in a geocentric reference frame. The change in leveled height difference between HILS and FREM is assumed to be a linear -1.73 mm/yr and applied back to 1974 when groundwater abstraction began. Reestimating the polynomial for 1897.0–2013.0 gives a deceleration of -0.0185 ± 0.0126 mm/yr^2. The second approach used the ETF-derived VLM at FREM (Table 2, column 6) to generate absolute MSL change, which also accounts for nonlinearity. The pre-1993 ETF was extrapolated back to 1974. This gives a larger deceleration of -0.0342 ± 0.0125 mm/yr^2. The uncertainties on the latter two decelerations are lower bounds because they do not account for the uncertainties in the repeat leveling or ETF-derived VLM, respectively. Nevertheless, accounting for nonlinear subsidence removes the small acceleration of MSL change at FREM.

4. Concluding Remarks

A combination of independent evidence (CGPS, repeat geodetic leveling, groundwater abstraction, and altimetry-TGRLR) shows that the long-recording FREM TG is subsiding, at a different rate to that determined from CGPS at remote sites in the Perth Basin, and in a nonlinear way that correlates spatially and temporally with groundwater abstraction. Depending on the epoch and technique, subsidence rates vary from around -2 to -4 mm/yr, which accounts for the range of different (though assumed linear) estimates made by previous authors (cited in sections 1 and 2). Through this example of the FREM TG, we have shown the invalidity of the often-used assumptions of linear-only VLM and no differential VLM between a TG and CGPS that are not colocated or geodetically connected.

Using repeat geodetic leveling between the FREM TG and the CGPS at PERT and HIL1, we have shown that there is differential VLM among these sites. Therefore, CGPS rates from PERT or HIL1 are not applicable to FREM and should not be used without also considering the repeat geodetic leveling. This provides evidence-based caution to be applied globally that CGPS-derived VLM must be geodetically connected to the TG to eliminate the assumptions made about zero differential VLM. In addition, groundwater abstraction data for the Perth Basin have been used as a diagnostic tool for identifying nonlinear VLM that is not so clear in the CGPS time series alone. At TG sites devoid of a geodetically connected CGPS and where groundwater abstraction occurs, groundwater records could provide a proxy for the detection of nonlinear VLM.

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