Anthropogenic land subsidence in the Perth Basin: challenges for its retrospective geodetic detection*

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* *This paper is dedicated to the memory of Kevin Pownall*

Recent-past subsidence of parts of the Perth Basin has most probably been caused by increased groundwater extraction for domestic and agricultural use. However, no dedicated geodetic monitoring programs were established when the increased extraction began in around 2000, thus setting a challenge to retrospectively quantify and map the subsidence. Differential levelling is likely to be less effective as only a few repeat traverses cover the areas thought to be subsiding. Repeat gravimetry is totally ineffective because of microseismic vibrations propagating through the Perth Basin. Repeat episodic GPS (Global Positioning System) is also likely to be less effective because of the few station occupations over several days or weeks and the inherent weakness of GPS for height determination. However, from a continuously operating GPS receiver at Gnangara and nearby artesian monitoring boreholes, we show that the rate of land subsidence has slowed from about -6 mm/yr to about -2 mm/yr since the reduction of groundwater extraction from the Yarragadee Aquifer in around 2005. A promising technique is InSAR (interferometric synthetic aperture radar) because it can map large areas, but the lack of historical radar imagery over the period of increased subsidence is a hindrance.

KEYWORDS: geodesy, GPS, gravity, InSAR, land subsidence, levelling, Perth Basin.

INTRODUCTION

A broad definition of modern geodesy is that it comprises the determination of the size, shape and external gravity field of the Earth, including spatiotemporal variations in these quantities (Featherstone 2008). One example of the latter is the quantification, mapping and monitoring of land subsidence, usually followed by interpretation and explanation of the physical causes, if possible, and any consequences. However, the proper geodetic quantification of land subsidence requires time series of observations, the longer the better (Coates *et al*. 1985), but these may not always be available in an area that was not expected to be subsiding. This will be exemplified in this discussion for the Perth Basin.

The Perth Basin largely comprises ~15 km of sedimentary rocks that contain several confined and unconfined freshwater aquifers, and which abuts the Yilgarn Craton to the east at the near-vertical Darling Fault. The Darling Fault is currently aseismic (Jakica *et al*. 2011), yet vertical ground motion of around -5 mm/yr [by geodetic convention, a negative sign indicates subsidence] has been detected by a continuously operating Global Positioning System (GPS) receiver at Gnangara (Bouin & Wöppelmann 2010), which is located on the Perth Basin. Bouin & Wöppelmann (2010 p. 204) could give no explanation for the subsidence, stating 'this may reflect a local subsidence of the GPS station, as this part of Australia is not susceptible to tectonic deformation'. This is true, as local knowledge (see later) suggests it is likely to be associated with groundwater extraction to satisfy domestic and agricultural demand.

In 2007–2008, the Western Australian news media reported an alarming amount of subsidence in the Perth Basin, claiming up to -50 mm/yr in some metropolitan suburbs, and attributed it largely to groundwater extraction. This was based on a press release originating from the University of New South Wales and promulgated by the Cooperative Research Centre for Spatial Information. It appears that this was an overestimate by one order of magnitude based on the work of Dawson (2008) and the work presented herein. The press release was based on a conference paper (Ng & Ge 2007) that had not used independent observations to cross-validate their interferometric synthetic aperture radar (InSAR) results (Zerbini *et al*. 2007), or local knowledge such as fissures and infrastructure cracking that would be likely at this rate of subsidence. The news media did not seek independent corroboration: this is akin to the exemplary case of cold nuclear fusion (Ackermann 2006), where a press release was made before subjecting the findings to peer-review.

Proper quantification, mapping and monitoring of recent-past subsidence in the Perth Basin also have implications for sea-level change measurements, because the Fremantle and Hillarys tide-gauges are located on it. Fremantle provides a long-term record (since 1897) that has been given substantial weight in global sea-level projections (Church & White 2006), notably because it is one of relatively few long-term records in the Southern Hemisphere. However, tide-gauges only measure sea-level change relative to the land, so if the land is subsiding, the relative sea-level change will be contaminated (Belperio 1993; Aubrey & Emery 1986), as will be any future projections (Mörner 2004). In short, coastal land subsidence causes sea-level rise measurements to be exacerbated, but it also makes low-lying coastal areas more vulnerable to seawater inundations (Brunn 1988).

Due to increased domestic and agricultural demand from the increasing population of the city of Perth and its environs, the Western Australian Department of Water significantly increased extraction of groundwater from the confined Yarragadee Aquifer around the year 2000. Figure 1 exemplifies this for the AM27 artesian monitoring borehole in the north Perth metropolitan region (WA Department of Water code 61615063). There has also been groundwater extraction from the confined Leederville Aquifer, but the drawdown from the Yarragadee Aquifer is more substantial over the recent past (Figure 1).

Simplistically, the extraction of groundwater from a confined aquifer allows the weight of the overlying sediments to compress the sediments that previously hosted the groundwater, resulting in land subsidence. The physics of the processes is beyond the scope of this paper, but the correlation between groundwater extraction and land subsidence is well documented (Chi & Reilinger 1984; Bawden *et al*. 2001), and will be demonstrated later in this paper.

More specifically, we will review the geodetic quantification and mapping of recent-past subsidence in the context of the Perth Basin, and somewhat uniquely in that no dedicated geodetic monitoring programs had been established before, during or after the groundwater extraction was increased. The groundwater extraction from the Yarragadee Aquifer reduced significantly around 2005 (Figure 1), so there is the additional consideration if there is any time delay of the subsidence or whether it has now slowed, stopped or if there is rebound due to replenishment of the aquifer. Again, this is problematic because of the need for historical time series of geodetic data.

LIMITATIONS ON GEODETIC METHODS IN THE PERTH BASIN

The principal problem with trying to determine land subsidence retrospectively in the Perth Basin is the lack of repeat geodetic observations, and preferably continuous or regularly sampled time series so that trends and changes in trends can be determined more reliably (Coates *et al*. 1985). The geodetic techniques comprise both terrestrial and space-borne observations. Terrestrial techniques include repeat differential levelling and repeat gravimetry. Space-borne techniques include InSAR and repeat episodic or continuous GPS observations.

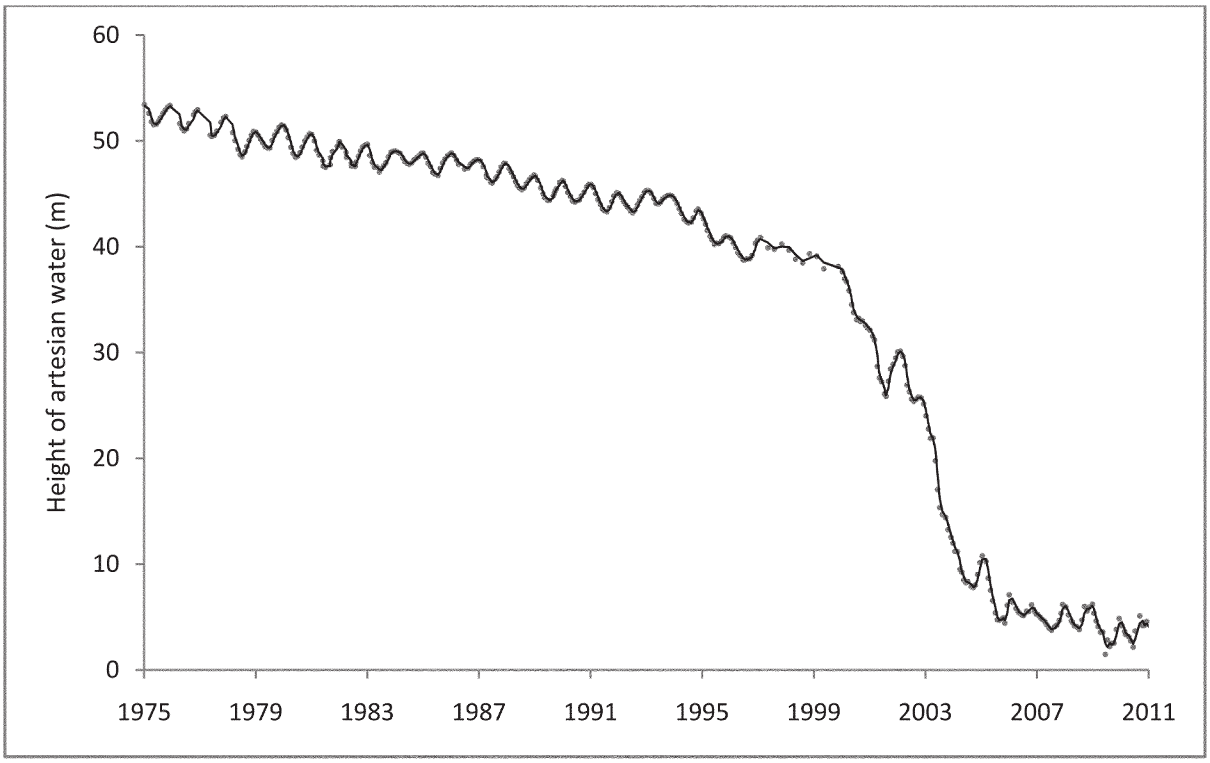

Figure 1. Change in height (in metres) relative to an arbitrary datum of the water level in the Yarragadee Aquifer, showing that it dropped by ~32m between ~2000 and ~2005 at the AM27 borehole. The oscillations are due to seasonal recharge and discharge. Data courtesy of the WA Department of Water (http://www.water.wa.gov.au/Tools/Monitoring+and+data/default.aspx).

All these techniques should be used relative to a vertically stable frame of reference. Fortunately in this case, the Yilgarn Craton to the east of the Darling Fault can provide such a reference for the terrestrial observations of repeat levelling and repeat gravimetry, where no vertical displacement is assumed. However, as will be discussed in the sequel, very few such observations have been collected on this craton. The space-based observations of InSAR and repeat or continuously operating GPS are tied to a global reference frame as implied via the satellite orbits. Nevertheless, their vertical stability could be 'calibrated' through observations on this craton, but yet again few such observations are available.

Repeat levelling

Differential levelling measures the height difference between ground monuments (benchmarks) using a levelling instrument located between two graduated and calibrated staves. It is the most precise means of determining heights and height differences (Vaníček *et al*. 1980). Details of the field and data reduction methods involved are given in any land surveying textbook and national standards are set for tolerances (ICSM 2007). Levelling has been used by Landgate, the Western Australian land information agency, and its predecessor organisations (collectively referred to as Landgate), to provide reliable heights to its stakeholders. However, this has not been specifically for monitoring subsidence in the Perth Basin.

The Australian Height Datum (AHD) forms the vertical frame of reference for heights across the continent (Roelse *et al*. 1975), and Landgate is responsible for maintaining the provision of AHD heights to its stakeholders through a network of physical benchmarks in Western Australia. Much of Landgate's levelling operations since the establishment of the AHD in 1971 have focussed on densifying the coverage of benchmarks and maintenance by replacing disturbed and destroyed benchmarks or correcting erroneous levelling traverses when identified. Virtually no past operational focus has been on repeat levelling for the purpose of detecting subsidence or uplift. As such, there are very few repeat levelling observations that can be used to retrospectively detect subsidence in the Perth Basin (Figure 2). One repeat levelling survey was conducted in 1986 following the 1968 Meckering earthquake (Wellman & Tracey 1987). However, this repeat levelling did not cover very much of the Perth Basin, with only four traverses south of the Swan River.

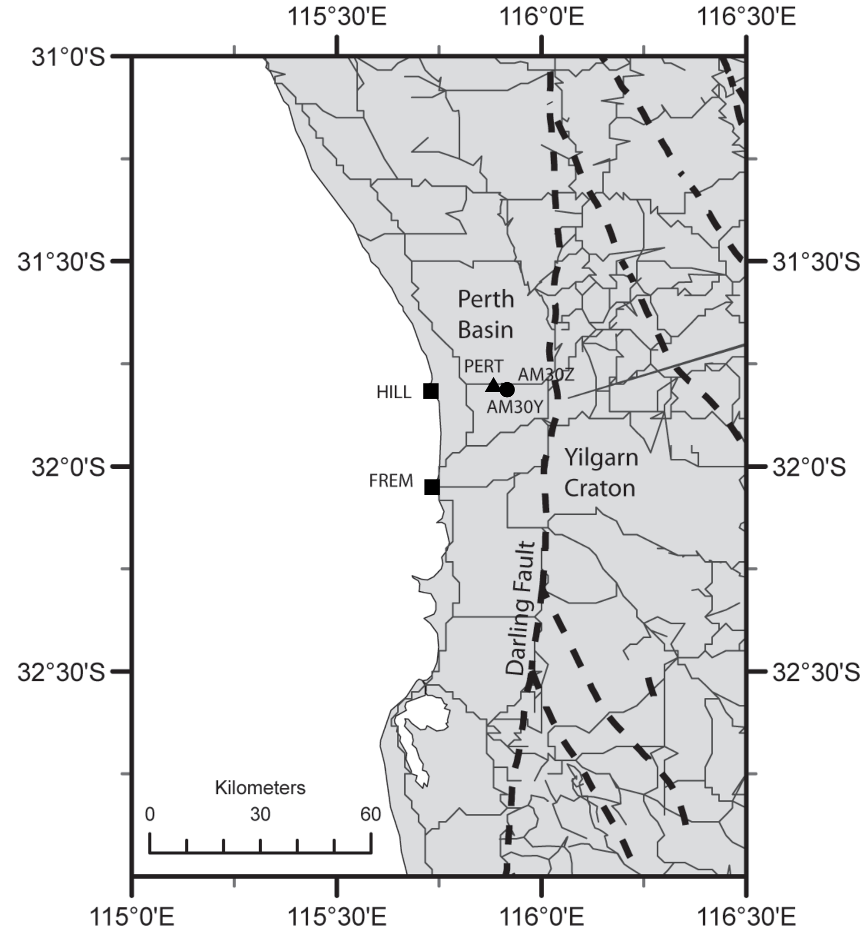

Figure 2. Levelling traverses (thin black lines) around Perth, location of tide gauges (black squares) at Hillarys (HILL) and Fremantle (FREM), location of the AM30Y and AM30Z artesian monitoring bores (black circle), and location of the PERT continuous GPS station at Ganagara (black triangle). The thick dashed black lines denote major faults, notably the north–south Darling Fault dividing the Perth Basin to the west from the Yilgarn Craton to the east. Data courtesy of Geoscience Australia and the Geological Survey of Western Australia.

When maintaining the provision of heights to users, it is convenient and cost-effective to conduct levelling from the nearest benchmarks, using as many as practically possible so as to ensure observational redundancy. For instance, if a benchmark is disturbed or destroyed, the replacement benchmark's new height is normally determined with respect to several nearby benchmarks, which may be only a few hundred metres apart in some metropolitan regions. Therefore, if that region is subsiding at the same rate, then it will be 'invisible' to differential levelling. This is where connection to a stable frame or point(s) of reference is needed. Thus, if repeat levelling traverses were begun or ended on the Yilgarn Craton, the subsidence in the Perth Basin could be detected. The principal problem is that no such observations had been collected over the period of increased groundwater extraction (~2000–2005; Figure 1).

Taking the ICSM (2007)-recommended allowable misclosure for class L2A levelling (the highest quality in Australia, but also the most labour intensive) over the ~50 km-wide Perth Basin (Figure 2) will permit a height difference of 14 mm to be detected at ~50 km west of the Darling Fault. The same value would apply to a repeated class L2A levelling traverse. If we assume that GPS-derived subsidence of around -5 mm/yr has occurred in the Perth Basin (described later), then independent repeat class L2A levelling might only be able to start to detect subsidence if re-observed after four years. If more confidence is required in any observable vertical velocity, then the re-observation time will increase accordingly.

Importantly, however, a misclosure tolerance is not the same as a standard error (Filmer & Featherstone 2009; Kearsley *et al*. 1993; Morgan 1992), and as most levelling surveys are well within the allowable misclosure, the above-stated frequency required for detection could possibly be reduced. Also, systematic levelling errors such as atmospheric refraction or staff/instrument miscalibration (Angus-Leppan 1979; Craymer & Vaníček 1986) are not accounted for in the above estimate. Another problem in terms of a future monitoring program using precision levelling is its labour-intensive nature. However, repeat levelling has already proven useful in the detection of vertical deformation elsewhere (Chen *et al*. 2011). There is some scope for detecting subsidence in the Perth Basin if levelling is repeated now or sometime in the future. However, the costs are likely to be prohibitive.

Repeat gravimetry

Since gravitational acceleration decays as an inverse square function of the distance from the attracting masses (i.e. Newton's law of gravitation), repeat gravimetry or gravity measurements can be used to infer changes in height (Biró 1983). Taking the linear decay of model gravity in free air of 0.3086 mGal/m (Moritz 1980), a change in gravity of 0.01 mGal infers a change in height of ~31 mm. However, using gravimetry to infer height changes is a non-unique problem, because changes in the mass distribution in the Earth (e.g. due to the extraction of large amounts of groundwater) also cause gravity to change. As such, repeat gravimetry is a less reliable geodetic monitoring technique, but it has been used to corroborate subsidence from other geodetic techniques (Zerbini *et al*. 2007; Hwang *et al*. 2010).

Gravity can be measured by using absolute or relative techniques (Torge 1989).

Absolute gravimetry uses the fundamental dimensions of length and time, provided by laser, to measure the rise and fall of a proof mass in vacuum. Absolute gravity meters are very expensive (~$800 000) and observations need to be conducted over several days under quite rigid operating conditions. As such, they are not realistic for quantification and mapping of subsidence over the Perth Basin. Moreover, there are very few historical absolute gravity measurements on the Perth Basin, and microseismic noise (described below) renders this technique unsuitable.

Relative gravimetry uses a spring-mounted proof mass to sense changes in gravity, akin to a very sensitive set of weighing scales. Relative gravimeters are prone to instrumental drift, so a base station must be reoccupied before and after (and ideally during) the field survey to monitor, model and account for the drift. Relative gravimeters are much cheaper than absolute ones (~$100 000). Depending on distance between observation stations, a gravity survey crew can collect many (tens to hundreds) stations in a day.

The principal restriction to using repeat relative gravimetry to estimate subsidence in the Perth Basin is the presence of microseismic noise caused by vibrations from ocean-wave action propagated through the sediments of the Perth Basin, as well as from wind action on vegetation. A feasibility survey was conducted in August 2011 to reoccupy some gravity stations observed in November 2000 (Kirby 2003). Assuming a linear -5 mm/yr rate of subsidence, the total change in height should be around -55 mm over this time period, equating to a change in gravity of around 0.017 mGal. In ideal operating conditions, a modern relative gravimeter (we used a Scintrex CG5) can observe gravity to 0.01 mGal, equivalent to ~31 mm. However, the microseismic noise in the Perth Basin in August 2011 was around ±0.2 mGal, whereas it was roughly half this for measurements made in a forested area of the Yilgarn Craton (on quite a windy day).

This amount of noise makes any gravity-based detection of subsidence in the Perth Basin totally inconclusive. A noise level of ±0.2 mGal equates to a height uncertainty of ~±648 mm, just over an order of magnitude larger than the postulated -55 mm subsidence. In addition, the ways in which regional gravity surveys are conducted mean that this uncertainty is compounded by the need to monitor instrumental drift. From the ±0.1 mGal noise at a base station on the Yilgarn Craton during the August 2011 feasibility survey, this could add as much as a further ~±309 mm height uncertainty.

Another problem in the Perth region is that some of the gravity base-station monuments that allow connection to the November 2000 survey have been destroyed. These are Mt Gunjin (Geoscience Australia code 7391.0217) and Perth domestic airport (Geoscience Australia code 9191.0117). The gravimeter calibration line between Mundaring Weir and Mt Gunjin is now defunct because the ground mark at Mt Gunjin has been removed, presumably due to vandalism. The base station at Perth airport seems to have suffered from 'aesthetic vandalism' during refurbishment of the domestic terminal, where a faint mark remains after field inspection based on the original access details. We have reported both destructions to Geoscience Australia.

The above factors compound to render repeat gravimetry a technique largely unsuitable for retrospective or future determination of the subsidence of the Perth Basin.

Repeat GPS

GPS provides the ellipsoidal height of a ground monument relative to a geometrical figure of the Earth. Although ellipsoidal heights are incompatible with those derived from levelling, repeat determinations of ellipsoidal height can be used to determine the geometrical rate of subsidence. Details of the field and data reduction methods involved are given in any GPS surveying textbook. However, GPS is inherently poorer for the determination of heights than horizontal locations, because of the geometry of the satellites above the receiver and the adverse impacts of atmospheric refraction (Rothacher 2002). A long occupation time, ideally several days or weeks, is also necessary for cyclical errors such as multipath to average out.

Just as for the repeat levelling and repeat gravimetry, very few long-occupation repeat GPS observations have been acquired on the Perth Basin. Landgate has provided information for its repeat GPS data archives, but most of these occupations are only for a few hours (and sometimes less). Nevertheless, we intend to reprocess these data to determine whether they can provide cross-validation of the subsidence determined by other geodetic techniques. However, we are not hopeful based on the inconclusive experience gained from the following example.

In 1999, Landgate occupied the tide-gauge benchmark (NMV/F/6A) near the Fremantle tide-gauge (PSMSL code 111; GLOSS code 53) with GPS for five days. This was part of a national project on heights (Johnston & Luton 2001). A tide-gauge benchmark is a stable point of reference for monitoring the height of the tide-gauge, and can also be used to maintain a more continuous time series of sea-level observations if there are changes to the tide-gauge instrumentation. Unfortunately, the NMV/F/6A benchmark has since been destroyed, but fortunately there are differential levelling connections to several nearby benchmarks. In 2010, a new ground mark was established with largely unobstructed sky views and seven days of GPS observations were collected by McMullan Nolan Group P/L land surveyors. Differential levelling to nearby benchmarks was also conducted, so there is a height connection between the GPS surveys.

We reprocessed these repeat GPS data using four independent software packages: Geoscience Australia's v1 AUSPOS service (http://www.ga.gov.au/geodesy/sgc/wwwgps/); Natural Resources Canada's CSRS (Canadian Spatial Reference System) service (http://ess.nrcan.gc.ca/2002_2006/gnd/csrs_e.php); Bernese v5.0 (Dach et al. 2007); and GIPSY-OASIS v5.0 (https://gipsy-oasis.jpl.nasa.gov/). Precise satellite orbits and other parameters from the International GNSS Service (IGS; Dow *et al*. 2009) and NASA's Jet Propulsion Laboratory (JPL) were used during the processing. The resulting ellipsoidal heights were in the ITRF2005 reference frame (Altamimi *et al.* 2007) and apply to the mean time-epoch of each GPS survey. This approach to GPS processing is quite different to using vendor packages, because of the more sophisticated modelling and processing techniques employed.

The results from this particular repeat GPS survey were inconclusive because, even using five to seven days of measurements, the GPS-determined ellipsoidal height near the Fremantle tide-gauge was determined, after height corrections for the different benchmarks, to be exactly the same in 2010 as it was in 1999. Assuming independence and the general law of propagation of the variances of each ellipsoidal height estimate at each time-epoch, the 'subsidence' over this period was (0±6) mm/yr. Within one-sigma error bounds, this is statistically consistent with the ~-5 mm/yr rate determined from the continuous GPS station at Gnangara (described next). Of course, there is also the possibility that the Fremantle tide-gauge is not subsiding or not at the same rate as Gnangara.

Continuous GPS

The concept of continuous GPS (CGPS) is to continuously operate a GPS receiver and antenna mounted on a permanent ground monument to confer the benefit of regular GPS observations to monitor the 3D position of that station. A CGPS station at Gnangara (IGS code PERT) has operated in the Perth Basin since August 1993, well before the increased groundwater extraction from the Yarragadee Aquifer (Figure 1).

These data have been analysed by various scientists, including this study. For instance, Bouin & Wöppelman (2010) computed a vertical velocity of –5.21±0.73 mm/yr between January 1997 and November 2006, noting (p. 204) 'this may reflect a local subsidence of the GPS station, as this part of Australia is not susceptible to tectonic deformation'. The Gnangara CGPS station, though not installed to monitor groundwater-extraction-induced subsidence of the Perth Basin, provides the strongest evidence that there is subsidence in the northern suburbs of Perth. Also, it refutes the ~–50 mm/yr rate determined by Ng & Ge (2007) using InSAR.

Another CGPS was installed at Hillarys in 1997 as part of a project to monitor the height of tide-gauges in the Australian region. During the review cycle of this paper, we were granted access to these data by Geoscience Australia, but they are not in a form that can be readily analysed in a short time frame, particularly because of the multiple equipment changes that make the time series very discontinuous. Several CGPS stations across the Perth region have also been installed as part of a commercial venture (http://www.rtknetwest.com.au/), which can also be used to monitor the subsidence (Baldi *et al*. 2009). However, several of the monuments are not of 'geodetic quality', being located on buildings or metal masts.

We reprocessed the CGPS data from Gnangara using daily GPS data files archived by the IGS using the GIPSY v5.0 software in precise point positioning mode (Zumberge *et al*. 1997). This processing used fiducial-free satellite orbits, satellite clocks and Earth rotation parameters from JPL. The resulting ellipsoidal heights were transformed to the IGS realisation of the ITRF2005 reference frame (Altamimi *et al*. 2007). These are plotted in Figure 3 (bottom panel), which includes a moving-average fitted curve, the width of which was determined empirically so that the general shape of the fitted curve did not alter for an increased window. Figure 3 (top and central panels) also shows the change in water depth over the same time span from artesian monitoring bores AM30Y (WA Department of Water code 61615127) and AM30Z (WA Department of Water code 61615043), which respectively monitor the Yarragadee and Leederville Aquifers, and are located within ~3.5 km of the Gnangara CGPS station.

One-year periodic signals of varying amplitudes are superimposed on all time series in Figure 3. The seasonal signal in the GPS data (bottom panel) is better defined than for the borehole water-depth data (top and central panels), most likely because of the much higher frequency of measurements. However, the GPS data processing did not include modelling of atmospheric-pressure-loading effects, which can cause annual signals (Petrov & Boy 2004). The break in the time series at the start of 2001 was due to equipment malfunction. This type of discontinuity can be detrimental to the determination of reliable trends from CGPS. The increased noise in the CGPS time series beyond 2007 seems to correlate with the irregularities in the water depths in the Yarragadee and Leederville Aquifers, but this is only associative and not necessarily causative.

We used unweighted linear regression to determine the vertical velocity of the Gnangara CGPS installation for the entire 14 year time series (1997–2011), which gave a -4.6 mm/yr rate of subsidence (Table 1). This is slightly less than the rate of -5.2 mm/yr determined by Bouin & Wöppelman (2010) between 1997 and 2007. Looking at the bottom panel in Figure 3, Bouin & Wöppelman's estimate omits the four years where the rate of subsidence has reduced (Table 1). To test the effect of length of time series used in the regression, we computed linear subsidence rates for three subsets of the time series in Figure 3: before, during and after the increased ground water extraction (Table 1). We also calculated the linear rates of extraction from the Yarragadee and Leederville Aquifers at the AM30 boreholes (Table 1).

The results in Table 1 are somewhat more telling than a simple linear regression of the entire time series and fit with expectation. First, the Gnangara CGPS station is located only ~3.5 km from the AM30 boreholes, so it is reasonable to assume that there will be good correlation between the two sets of measurements. The subsidence rate of -5.4 mm/yr before 2000 is due to the previous groundwater extraction rate of around 5 m per decade, which has been inferred from the longer time series at AM27 (Figure 1). The land subsidence rate increases to -6.1 mm/yr during the period of increased groundwater extraction (around 20 m over five years at AM30Y; Figure 3 top panel). After the extraction was reduced in 2005, the subsidence rate drops to -1.9 mm/yr, but this value is more uncertain because of the increased noise in the CGPS time series after mid-2007 (bottom panel in Figure 3).

The problem with this CGPS data set is that it determines the subsidence at a discrete point, so only inferences can be made about what may be occurring in other parts of the Perth Basin. As already discussed, repeat levelling, gravimetry and GPS data are sparse and/or unusable. As such, a technique that is capable of mapping subsidence over large areas is attractive; InSAR is one such candidate.

InSAR

Two separate radar images taken from the same satellite-borne sensor at two different times (on repeat orbits) are overlaid and the images are processed to produce interferograms. Any phase difference between two or more interferograms at the same point or 'pixel' may be interpreted as ground deformation. This is referred to as repeat-pass differential InSAR (DInSAR). For further details on the InSAR concept, see Hanssen (2001).

The observed deformation is along the radar line of sight (LoS) between the satellite's position at the time of image capture and the point on the ground. Thus, the observed deformation is a 3D displacement vector (latitude, longitude, height), but these components cannot, on their own, be resolved uniquely. Where vertical-only deformation is assumed (or indicated by levelling or GNSS) the LoS deformation can be projected into the vertical direction using the incidence angle of the LoS (angle between the local vertical and the LoS) (Hansson 2001 p. 162–163). Alternatively, methods such as combining interferograms from ascending and descending orbits have been used to resolve other components (Wright *et al*. 2004), although the north component remains inherently weaker on the assumption of a near-polar satellite orbit.

InSAR has been used successfully to detect ground deformation caused by earthquakes, faults and other tectonic processes (Massonnet *et al*. 1993), volcano deformation monitoring (Amelung *et al*. 2000), land

Table 1 Linear subsidence rates for the Gnangara CGPS station and linear drawdown rates at AM30 for the Yarragadee and Leederville Aquifersover different time periods

Time period	Subsidence rate (mm/yr)		Yarragadee drawdown (m/yr)	Leederville drawdown (m/yr)
1997–2007	-5.2	Bouin & Wöppelman (2010)	-2.54	-0.42
1997–2011	-4.6	Entire 14-year time series	-2.12	-0.34
1997–2000	-5.4	Before increased extraction	-1.19	-1.53
2000–2005	-6.1	During increased extraction	-3.21	+0.53
2005–2011	-1.9	After increased extraction	-0.09	+0.06

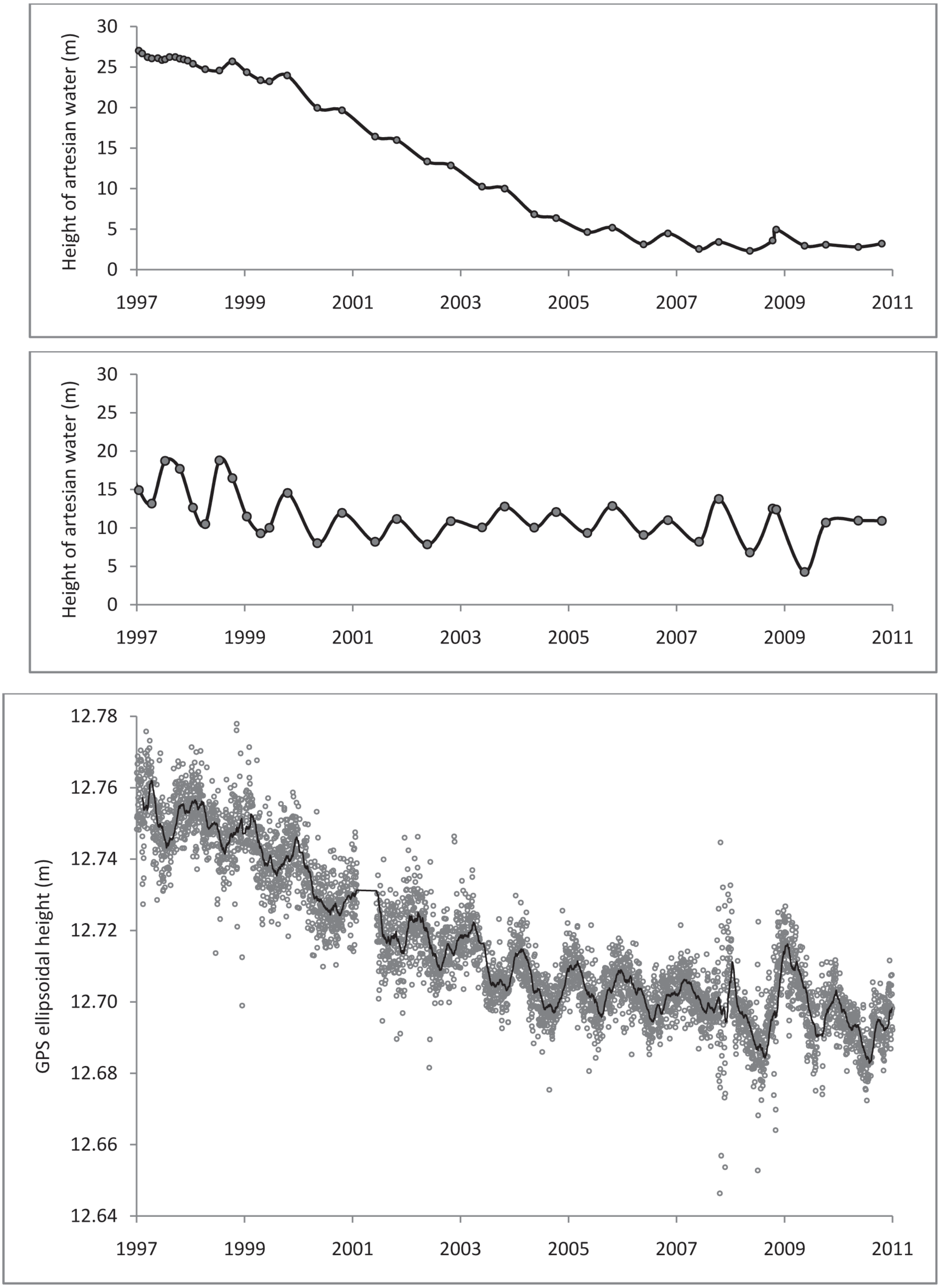

Figure 3. Top panel: change in height (in metres) of water in the Yarragadee Aquifer at AM30Y. Middle panel: change in height (in metres) of water in the Leederville Aquifer at AM30Z. Bottom panel: Time series of daily ellipsoidal height estimates (in metres) of the Gnangara CGPS station (IGS code PERT). Grey dots are the daily data points; black line is the moving average. See Table 1 for the rates and Figure 2 for the locations. Data courtesy of the WA Department of Water (http://www.water.wa.gov.au/Tools/Monitoring+and+data/default.aspx) and the IGS

subsidence due to water or hydrocarbon extraction (Galloway *et al*. 1998; Fielding *et al*. 1998) and cryospheric changes (Goldstein *et al*. 1993). The advantages of InSAR over other observation methods for detecting ground movement are high spatial resolution, the detection of sub-centimetre changes, and there are sometimes image archives over a study region. However, there are a number of restrictions on InSAR to map ground deformation. As described below, these are primarily due to spatial and temporal decorrelation and atmospheric refraction effects (Ferretti *et al*. 2001). Spatial decorrelation is caused by large distances (baselines) between the position of the satellite when the different radar images were observed (Zebker & Villasenor 1992). Temporal decorrelation occurs when the surface reflecting the radar signal within each pixel changes over time. Large temporal baselines between image pairs (e.g. several years) can cause temporal decorrelation in urban or built-up areas, while seasonal changes of vegetation usually result in total decorrelation in non-urbanised regions.

In addition, when the interferogram is coherent, variations in atmospheric conditions causing delay in the radar signal (Goldstein 1995) and errors in the satellite orbits and/or reference digital elevation model (DEM) can introduce additional artefacts into the interferometric phase. Processing multiple images in one 'stack' (Lyons & Sandwell 2003) can reduce atmospheric, orbital and DEM artefacts in the computed vertical velocities.

The InSAR method of persistent scatterers (PS) (Ferretti *et al*. 2001) uses stable backscattering characteristics from natural and man-made objects on the ground over long periods, often a number of years (Usai & Klees 1999), which can allow the detection of ground deformation where conventional DInSAR pairs would not necessarily be coherent. Different variants of the PS technique have been developed (Hooper *et al*. 2004; Kampes 2005), although these produce largely similar results (Sousa *et al*. 2011).

Dawson (2008) used InSAR to investigate vertical deformation in the Perth metropolitan region using (i) 13 ERS-1 and ERS-2 satellite images between 1992 and 1997; and (ii) five ENVISAT satellite images between 2005 and 2006. Interferograms were produced using the Doris processing software (Kampes & Usai 1999), with in-house software used for phase unwrapping and time series analysis (Dawson 2008), the latter being based on the Small BAseline Subset (SBAS) technique (Bernadino *et al*. 2002). The results from Dawson's (2008) study suggested subsidence rates of -3 mm/yr for 1992–1997, and -4 mm/yr for 2005–2006, but these are barely statistically significant because Dawson (2008 p. 185) indicated that -3 mm/yr is only just resolvable.

These InSAR subsidence rates are variable across the Perth metropolitan region but are consistent with our CGPS rates at Gnangara (Table 1). Preliminary results from our own InSAR processing (not yet ready for publication) suggest similar vertical velocities. Some care should be exercised when interpreting the 2005–2006 results from Dawson (2008), primarily because of the small number of ENVISAT images (five) available. However, Dawson's results from the 1992–1997 ERS-1 and ERS-2 images contradict the -50 mm/yr rate from Ng & Ge (2007) that was obtained from a similar set of images. Importantly, the independent CGPS supports the rate from Dawson (2008) and also refutes the rate from Ng & Ge (2007).

A limiting factor to InSAR investigations of the Perth Basin are gaps in the retrospective imagery record, as was also encountered by Dawson (2008). The incomplete record is due to the lack of a monitoring program in place at the time of the subsidence, as the satellites carrying the InSAR sensors were not programmed to acquire imagery over the Perth Basin. Hence, there is little retrospective InSAR imagery during the period of most interest (2000–2005), when large amounts of water were being extracted from Yarragadee Aquifer (Figures 1, 3).

In addition, the few images available are not necessarily captured at the same time of the year, which makes temporal decorrelation more likely. Multiple images during each year can detect seasonal height variations, such as expanding clays during wet months (Gabriel *et al*. 1989), which could then be separated from the subsidence signal. Specific acquisitions can be requested from the relevant space agencies for future work if a dedicated monitoring program is to be established in the Perth region.

CONCLUSIONS

First, there is no independent supporting evidence for the -50 mm/yr subsidence reported by Ng & Ge (2007) and sensationalised by the Western Australia news media. Evidence from reprocessed InSAR imagery and independent CGPS suggest that the subsidence is closer to -5 mm/yr, but the exact values are spatially and temporally variable (Table 1).

We have described the difficulties involved in retrospectively quantifying and mapping subsidence in the Perth Basin when there was no monitoring program, particularly for small vertical velocities of only a few mm/yr. It appears that available InSAR and CGPS data are most likely to provide the better information on recent-past subsidence, although these are hampered by the low spatial resolution of CGPS and gaps in the recent-past InSAR record. Repeat gravity observations lack the required precision to detect these small vertical velocities, but it is possible that future repeat levelling and GPS campaigns may provide more supporting evidence.

There is good correlation between changes in the depth of the water table in the confined Yarragadee Aquifer and the rates of subsidence of the CGPS installation at Gnangara (Figure 3). Depending on the time-span chosen over which linear regression is applied, different subsidence rates can be obtained. Fourteen years of data give a subsidence rate of -4.6 mm/yr, but this increases to -6.1 mm/yr during the 2000–2005 period of increased groundwater extraction. This demonstrates that the rate of subsidence is not linear, which needs to be taken into account by GPS analysts who do not necessarily have such local knowledge (Bouin & Wöppelman 2010).

Perth will need a dedicated subsidence-monitoring program if future water shortages necessitate re-commencement of increased groundwater extraction from the Yarragadee Aquifer. This would also be necessary to correct relative sea-level change measurements at the Fremantle and Hillarys tide-gauges.

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