USING MICROGRAVITY TO CHARACTERISE WATER STORAGE AND USAGE AT KINGS PARK, PERTH, WA

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SUMMARY

Since March 2015 the UWA in collaboration with the BGPA has conducted a time-lapse microgravity study of groundwater storage in Kings Park. Data collection has focused on seasonal to inter-annual change, with bi-monthly measurements extending across multiple days. Relative measurements are taken with a Scintrex CG-5 gravity meter and are referred to the Helena Valley reference station, which is located in the granite-dominated Perth Hills. Interim results (July 2017) suggest that measurement methods are sufficiently sensitive to characterize change, with measurement precision of ~2 microgals, or approximately 40 mm of stored water. Two-month storage-changes are defined from the gravity data, and usage is further defined as rainfall minus storage-change. Storage-changes are positively correlated with rainfall (r=+0.697) and negatively-correlated with solar exposure (r=-0.555). Thus, a fairly strong signal is seen of increase during the winter wet season, and decrease during the summer dry season. Usage is weakly positively correlated with solar exposure (r=+0.202) but also shows dry periods in late summer, where estimated usage is near-zero despite high solar exposure, and a high-usage period at the start of the wet season. Interannual change is substantial, and seems to be strongly linked to the Indian Ocean Dipole, which was strongly positive in winter 2015, strongly negative in winter 2016 and positive to neutral in winter 2017.

Key words: Microgravity, Hydrology, Western Australia.

INTRODUCTION

Kings Park in Perth is a well-known urban parkland and tourist attraction, and is one of few urban parks to preserve extensive native bushland. A key question in assessing ecosystem health is water availability and use, especially in periods of drought. More generally, how water storage and usage operates within the park, and how it is related to weather and climate variations. For this research program, which also includes a wider range of studies across multiple scales, we seek to understand the reasons behind tree-decline of Banksia species, and in particular episodic decline events.

Here we used high-precision gravity measurements (microgravity) in a time-lapse survey, in an attempt to better understand the total hydrologic system of the park, mapping changes across time. Our key aims were, firstly to understand if microgravity could be successfully applied to understand such subtleties, and secondly, to understand seasonal to interannual changes in water storage within the park, that might have a bearing on water-availability, with the attendant implications for ecosystem health.

METHOD AND RESULTS

Our time-lapse microgravity monitoring program commenced in March 2015, and is still ongoing, and scheduled to be completed in the autumn of 2018. Methods follow generally established principles as outlined below. Familiarisation and "teething problems" affected the first season of data, with more robust procedures established over time. We present here the more robust methods as applied in the later parts of the program, as an example of optimised practice, at least for this particular survey. Variations to the method are discussed in the text where they might influence the accuracy of results.

1 Physical basis of the method

Changes in subsurface water storage are a feasible target for detection with terrestrial or satellite gravity meters depending on the scale of investigation. Detection of change is contingent upon a number of factors. Fundamentally, the gravity method requires sufficient signal, in terms of changes in stored mass, to be detectable by the meter used. For the meter model we have used here (Scintrex CG-5) typical station repeatability is stated as 5 μGal with a reading precision of 1 μGal (Scintrex, 2006). Therefore, a single measurement might be expected to resolve a 1D mass-excess (or deficit) of approximately 120 kg/m^2 (equivalent to a 120 mm thick layer of fresh water), with a best possible result of 24 kg/m^2. In practice the true repeatability over long periods of time has tended to be about 2-10 μGals depending on methods and environment (Hector et al., 2015; McClymont et al., 2012). Additional contaminants to the sought water signal include imperfect knowledge of tidal corrections, changes in station elevation (e.g. due to swelling of clays), compaction of sediments and changes in biomass, as well as unaccommodated instrument drift. Unless these are minimal, measures must be put in place to correct for them.

2 Site selection and frequency and timing of sampling

In Perth, with a total seasonal winter rainfall typically of ~390 mm from June to August, and only ~40 mm on average from December to February, there is a limited opportunity to detect change through a high-quality survey. Within Kings Park, four sites were installed at which to monitor change, all in a "bush" setting on closed trails reasonably distant from well-frequented and irrigated areas (Figure 1). The sites consist of a ~30 cm concrete square, dug into the ground. As such these are semi-permanent installations that can be removed at the end of the program with little environmental disturbance. Two sites (KP1 and KP2) were placed at relatively low elevations (ca. 20 m) in the southwest of the park, while another two sites (KP3 and KP4) were placed at higher elevations (ca. 60 m) in the northern part of the park (Figure 1). This allows for potential differences in hydrology through the park to be detected, and also provides redundancy should a site become unusable or noisy for some reason. In practice, although the individual stations varied somewhat no systematic difference was detected between sites (Figure 2).

Sampling was undertaken at fairly regular two-monthly intervals, which allows for the detecting of seasonal changes. Measurements were made near the ends of the months of March, May, July, September, November and January, providing an annual cycle with a "dry" reference at the end of the summer. Each survey was made across two separate but closely spaced days, which are treated as independent records of the state of the system, and provide an indication of error produced by shorter-term and experimental variability in the system.

3 Sampling procedure

3.1 Gravity meter calibration

Each sampling used a similar systematic procedure to minimise experimental error. Throughout the survey the same gravity meter was used, a Scintrex CG-5 (Serial No 41050). The first step was to ensure that the gravity meter was correctly calibrated and configured, so prior to the survey the gravity meter was checked and if necessary re-set for drift correction, tilt offset and tilt sensitivity as suggested by the manufacturer (Scintrex, 2006). Although fairly young, the gravity meter in general showed little change through these tests.

Figure 1: Kings Park, showing the locations of stations, with elevations labelled. City74 is a DGPS benchmark

Calibration of the meter against the absolute reference network was undertaken every survey day using the calibration range near Perth. This range involves two stations, one located at Guildford Cemetery, and another at Helena Valley, with a total gravity difference between the sites of 58.4 mGal. If the meter reading differed from the calibration range value, it may be considered necessary to re-calibrate, but in practice, the difference was always very close, within a few μGal. The calibration-factor of the gravity meter was kept constant throughout, allowing to detect seasonal change between the Helena Valley and Guildford sites (Figure 2). Long-term change of the Guildford station relative to Helena Valley is slightly positive, however, it is small in comparison to seasonal changes and any long-term drift in the calibration cannot be separated from plausible hydrological change.

3.2 Remote reference site

All change is referenced to a site distant and hydrologically separate to Kings Park. An ideal site would have zero-change, however in the natural environment this is unlikely. Our survey used the Helena Valley station as the remote reference station for several reasons. Firstly, the Helena Valley site is located in the Perth Hills, which have a granite bedrock under shallow regolith cover, suggesting very limited storage capacity. Secondly it is by far the least noisy of the stations, with a minimum amount of ambient cultural noise. Nonetheless, this site cannot be considered a true zero, and water storage at Helena Valley will be reflected in the results, generating a false low in the Kings Park data. This may be particularly significant in the early stages of rainy periods, or for a few days after significant rain events.

3.3 Drift management

Short team instrument drift and residual tidal drift were managed through repeat measurements stretching through each day. Measurements were made in three “loops” of the four Kings Park stations, each taking approximately 1.5 hrs, with additionally a series of loops of the reference stations, each taking approximately 50 minutes. These loops provide a drift estimate roughly every 25 minutes. Transit between Kings Park and Guildford takes approximately an hour. Any substantial breaks were bookended by measurements at the same station (usually KP4). Initially, the reference station loops were done at the start of the day, however, the single tie between the base station loops and the Kings Park loops was found susceptible to ill-constrained drift during particular parts of the tidal cycle. From July 2016, the procedure was modified to include an initial loop of Kings Park prior to the reference station loops, providing a second tie. Normal procedures were followed to minimise instrument drift due to handling and vibration.

3.4 Measurement procedure

Gravity was recorded at each station for 240 seconds. The gravity meter was settled upon the levelled tripod for a short period before each measurement, and once each measurement was commenced noise and movement etc were minimised where feasible. Although some studies have settled the gravity meter for relatively long periods of time (e.g. McClymont et al., 2012) this must be traded off against the capacity to collect additional data. For this study, with stations close together and no rugged handling needed, it was considered that more certainty was to be gained through more repeats, rather than fewer longer observations. All measurements were subjected to onsite QC by the operator before leaving the site, and repeat measurements were made when there were a large number of rejected samples, where the tilts or other parameters drifted out of tolerance, or when the result was otherwise outside of expectations. Transport between sites was by walking and/or slow driving.

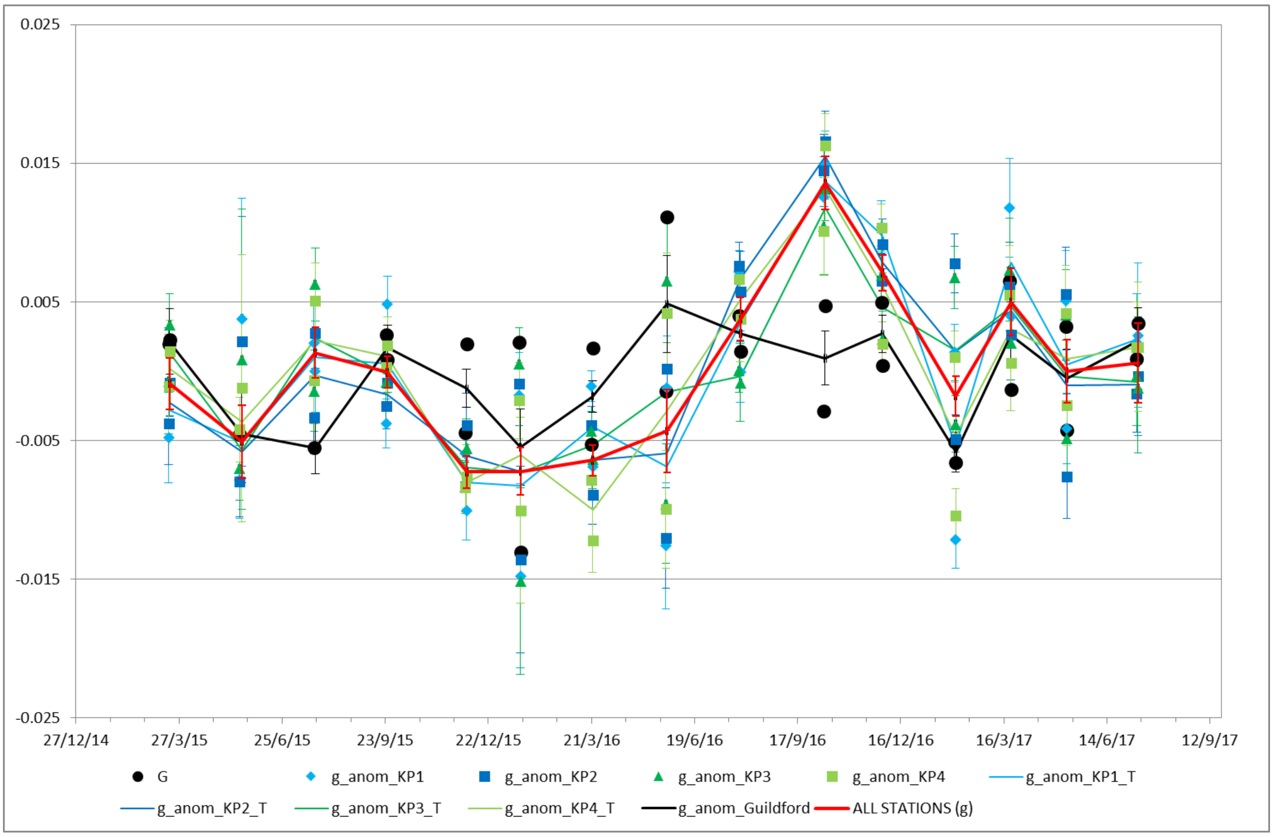

Figure 2: Gravity variations with time at the Kings Park stations (blue, green) and Guildford (black), relative to Helena Valley. The collective record of all four Kings Park stations is shown in red. Vertical scale is in mGal.

4 Data Reduction

4.1 Tide Correction

For our primary tide correction, we use the tide correction integral to the Scintrex CG-5 gravity meter. Although this tide correction corrects for the vast majority of the tidal gravity variation, a residual is often observable in the data (Figure 3). Currently these additional tidal effects are removed as part of the drift correction. Tidal effects of the river level are not currently included.

4.2 Pressure Correction

A pressure correction is applied to each measurement accounting for the mass of air above the station. We correct all data to 1 Bar using an adjustment of 4.27e^{-4} Gal/Bar. The pressure values are derived through linear extrapolation from measurements recorded for the Perth Metro station at 9 AM and 3 PM on the day of the survey. The pressure correction is typically small (Figure 3).

4.3 Weighted Mean and Anomaly Value

For each station, the measurements at that station are combined through a weighted average, inverse weighted by the standard error of each measurement, so that highly variable measurements are down-weighted relative to quiet ones. The weighted mean of each day’s observations at a station constitutes value from which the anomaly is defined as the residual misfit of each measurement.

4.4 Residual Drift Correction

Following the above corrections, anomaly values are further corrected for drift. A third-order spline function is fitted through the entire anomaly array, which is necessary to correct for the curved geometries evident in some anomaly arrays (Figure 3). These curved geometries relate to residual tidal effects.

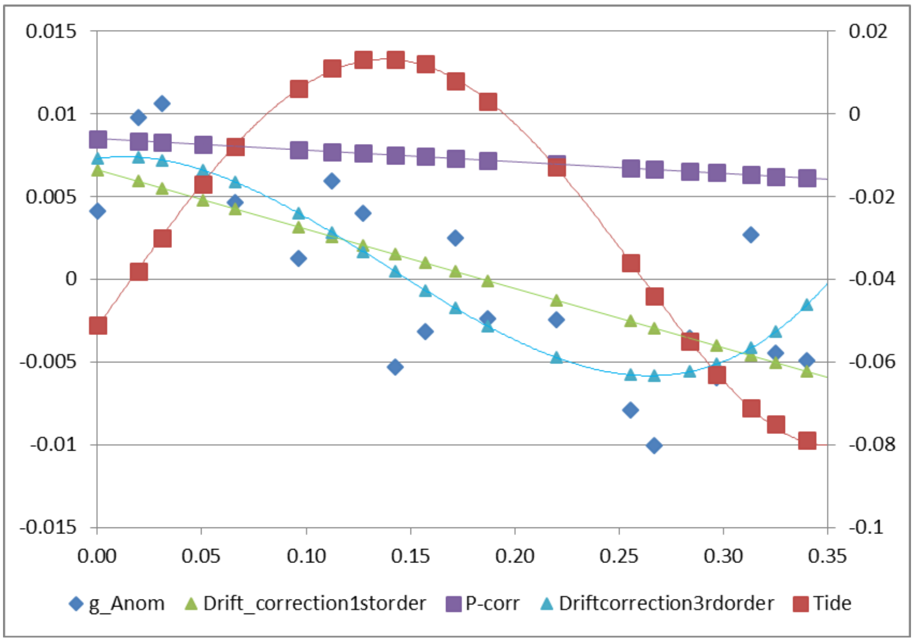

Figure 3. One day's data (July 10th 2017), showing the main tide correction in maroon (on the right axis); the pressure correction in purple; and the residual gravity anomalies (blue diamonds), both on the left axis. Linear (green) and third order (cyan) polynomials through these anomaly values are shown, the latter indicating the drift correction applied. Note the curvature of the drift associated with the tidal cycle. Both vertical axes are in mGal, horizontal axis in "days" relative to the first measurement.

The drift corrected values are referenced back to the Helena Valley station, providing an absolute gravity value for each measurement. The mean of the absolute gravity value measurements for each station represents the daily result for that station and is shown in Figure 2 (with station mean removed). Finally, the two daily station measurements are averaged into a monthly estimate weighting each days' data equally. Finally, a park-wide monthly average is derived using all stations, equally weighted.

4.5 Error Estimation

We propagate errors though the analysis as follows. Firstly, for each measurement we derive standard error, based on the standard deviation over the square of the measurement duration (constant at 240 seconds). Then, for each station we derive the euclidean norm of these standard errors, and divide by the number of measurements. Finally, we take the euclidean norm of this value and the error derived for the Helena Valley station. These daily station errors are typically ± 3 μGal. For the monthly error estimate, we use the euclidean norm to define the error for each station. These monthly station errors are typically ± 2 μGal. For the park-wide estimate, we average the errors when combining stations, because a precise measurement at one station does not help to understand another.

5 Data Interpretation

For simple interpretation, we convert the observed gravity variations into the equivalent water-depth in mm, assuming an infinite Bouguer slab. Notwithstanding the geometrical simplifications, this conversion allows to compare observed gravity changes with rainfall data. For interpretation, we presume that gravity variations reflect changes in the storage of water in the subsurface of Kings Park (storage change). We note that storage elsewhere, such as at Helena Valley, or above the station as biomass will affect these interpretations. Secondly, we presume that rainfall constitutes the major input to the hydrological system, for which we use the total rainfall recorded at Perth Metro station between measurement dates. Significant amounts of recharge from the Swan River are not suspected, but could potentially be a source of change to the deeper storage beneath the park. Finally we take the difference between these, rainfall minus storage change to indicate "usage" of water within the park. This usage includes evapotranspiration, runoff and any recharge to the river. Although these three definitions are fairly crude they provide the first possibility to understand seasonal and interannual change in water storage and use within the park.

6 Results

6.1 Seasonal variations in storage (gravity), rainfall and usage

Figure 4 shows the evolution of storage-change, rainfall and usage through the period monitored so far. We note that storage change is generally positive in winter and negative in summer, as expected, and that usage is highest in the spring and autumn, also expected.

Some subtleties are detected, however. A decline in storage between July-September 2015, is compared with a significant increase in storage over the same period in 2016. This is partly due to reduced rainfall, but our data also suggest usage was greater in 2015. For September-December both 2015 and 2016 show similar storage change, with rainfall and usage being slightly higher in 2015 (across a longer time period). The November to January storage change in 2015-2016 was almost zero, associated with near zero rainfall, and hence usage, however, the same period in in 2016-2017 saw a significant reduction in storage, with some rainfall, but very high usage. January to March is highly variable, with essentially no rain, storage change or usage in 2016, but a large storage change in March 2017. This is due mainly to the significant rain event of the 10 February (114 mm). March to May storage change is variable with negative storage change in 2015 and 2017, but near zero change in 2016. 2015 and 2016 both saw significant rain during this period, with little in 2017, but usage was similarly high in all three years. May to July is, in 2015 and 2016 associated with significant positive storage change associated with ongoing rainfall, and low usage, however in 2017 the storage change was close to zero, with moderate rainfall and relatively high usage.

6.2 Potential drivers of water storage and usage in the park

These data suggest a seasonal cycle of water-storage that is correlated with rainfall (correlation coefficient 0.697) and anti-correlated with solar exposure (correlation coefficient -0.555). This suggests that usage is mostly dominated by plant uptake and evapotranspiration. The subtleties described above suggest that the usage is paced by two factors: Solar exposure is most important during the winter and the spring with the lowest usage in May to July, increasing through September, with high usage extending through to November (Figure 4). During the summer, usage becomes controlled by water availability, with usage reducing to near zero in the January-March period. The onset of reduced usage was early in 2015/2016, with virtually no usage in the November-January period, whereas in 2016/2017 high usage continued into this period. Water-availability continues to be a driver of usage into the autumn, with early rains being predominantly used rather than stored (e.g. March-May 2015 and 2016). 2017 was unusual, with an intense February rain event followed by a dry autumn, with little rain in May and June. Nevertheless March to May usage was close to normal, suggesting that water-availability was sufficient.

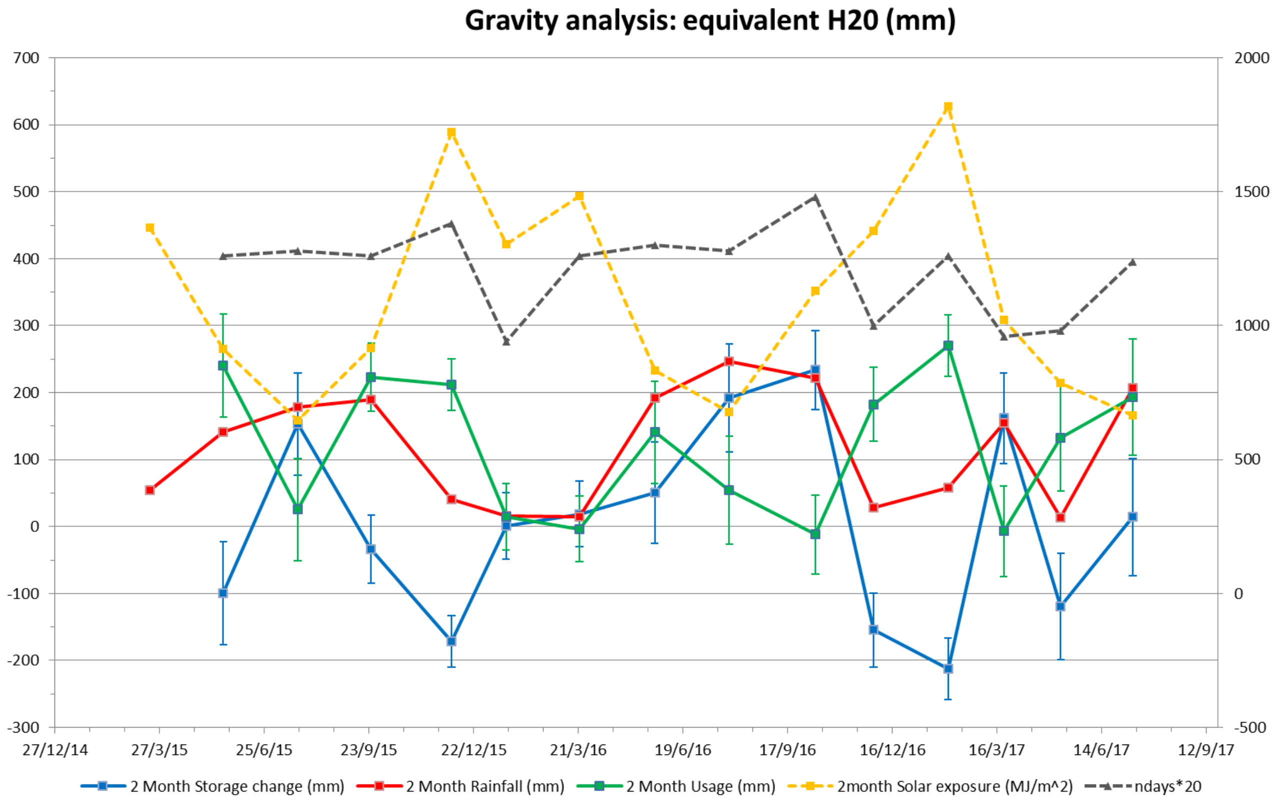

Figure 4: Interpreted hydrological change at Kings Park, including rainfall, storage change derived from gravity change, and usage derived from rainfall minus storage change (all left axis). Also shown is total solar exposure and the length of the record between measurements (dashed, right axis).

6.3 Links to large-scale climate drivers (IOD and SAM)

Rainfall in south-western Australia has previously been linked to the major climate drivers of the Southern Annular Mode (SAM) and the Indian Ocean Diploe (IOD). For the SAM, a positive phase is associated with frontal systems being pushed further south, and reduced rainfall, while a negative phase is associated with increased rainfall. The effect of SAM on southwest WA rainfall is most evident in autumn and winter (Hendon et al., 2007). For the Indian Ocean Dipole (IOD), a positive phase involves more easterly winds in the Indian Ocean, and less rainfall, whereas a negative phase brings more rain on westerly winds. For southwestern Australia, the influence of the IOD is most significant from June to October (Risbey et al., 2009).

The period of observation here has coincided with several excursion from “normal” index values including, for the IOD, a positive excursion from August to November 2015, and a negative excursion from May to October 2016, anf for the SAM, a negative excursion from October 2016 to March 2017. Our data suggest that storage change in Perth’s groundwater is sensitive to these drivers, in particular the IOD.

Comparing the late-winter and spring of 2015 and 2016 shows the potential influence of the IOD on water storage in Kings Park. The positive IOD excursion of 2015 is associated with low winter rainfall (Figure 4). Our data show a strong reduction in water storage during the period of this positive excursion (Figure 4), suggesting high usage in late-winter corresponding with low rainfall. Usage is reduced by September, and by November is virtually nil, suggesting the onset of limited water-availability in the spring, and very limited water availability by early summer. The dry, low usage, conditions persisted until first rains in the March to May period.

In contrast, the negative IOD excursion of 2016 is associated with high winter rainfall. Our data show significant positive storage change through winter and into spring, and subsequently high usage conditions extending into the new-year, suggesting that water remained available well into the summer. This may partly indicate the continued availability of water stored in the winter of 2016, but the negative SAM event of 2016/2017 was associated with increased rain and slightly reduced solar exposure, and this too likely contributed to the availability of water.

CONCLUSIONS

This study aimed to establish, firstly, if microgravity methods could be used to monitor hydrological change in the setting of Kings Park, and, secondly, if from monitoring this change a better understanding could be gained of seasonal to interannual water conditions within the park. In the first case our data and method permitted a final measurement precision for our bi-monthly data of 2−3 μGal. This is sufficiently precise to allow interpretation of hydrological conditions in the park. We define a seasonal signal of storage through the winter offset by usage in the spring and autumn, suggesting that the predominant use is plant uptake and evapotranspiration. The later part of summer is characterised by dry conditions, with neither storage nor usage. At an interannual level we define significant differences between positive and negative IOD excursions in 2015 and 2016 that are, respectively, associated with negative and positive storage changes in late winter. Our data suggest that winter storage is important for sustained water availability in the summer, although for 2017 this was complicated by a negative SAM and an unpredictable rain event.

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