Gravity Monitoring of Ground-Water Storage Change in Central and Southern Arizona

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INTRODUCTION

Gravity methods are being used to monitor changes in regional aquifer storage in the desert southwest of the United States. Gravity control for surveys of networks of relative gravity stations has been provided by observation of absolute gravity at selected sites. Absolute gravity observations are made with an FG5 gravimeter (Micro-g LaCoste, Lafayette, Colorado) operated by NOAA-NGS. Observations are generally accurate within +/-2 microGal, which includes observational error, instrument accuracy and precision, and estimated error for environmental corrections.

Land-based gravity methods are subject to variations in mass and position unrelated to variations in the mass of water stored in the regional aquifer. The primary non-aquifer signals in the study area include elevation change and near-surface soil-moisture variations. Gravity variation due to elevation change is equivalent to the local vertical gradient of gravity—normally about -3 microGal/cm. No measurable change in vertical position (>2 cm) has been observed at the stations. Variations in soil moisture within the root-zone may result in a significant signal where alluvial materials underlie the station. Deeper variations in soil moisture are not likely significant at the stations. Any deeper soil-moisture variations, however, probably represent water that is in transit to the underlying aquifer.

Observations at most of the stations have varied beyond observational error, which suggests that variations in water mass are being measured. Proportions of gravity variation from aquifer and non-aquifer storage need to be evaluated. Variations in observed gravity at a few of the stations display correlation with variations in regional shallow soil moisture. Removal of the shallow soil-moisture signal from the record provides trends in aquifer storage.

FG-5 Absolute Gravimeter

ABSOLUTE GRAVITY STATIONS

Semi-annual observations of absolute gravity began in 1998 at 6 stations in the Tucson Active Management Area (AMA) and 1 station in the Phoenix AMA. Eight additional stations were included in the Upper San Pedro (3) and Verde (5) Valleys in 2000. An additional 5 stations have been added since 2003. Repeat observations have resulted in semi-annual time-series of 7 to 13 observations at the 14 stations discussed in this poster (fig. 1). Several other stations are not routinely observed.

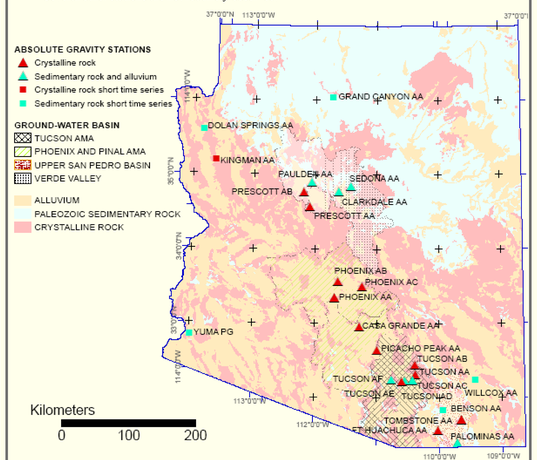

FIGURE 1. GRAVITY STATIONS IN ARIZONA.

OBSERVED GRAVITY VARIATION

Gravity has varied from 4 microGal at PHOENIX AC to 21 microGal at SEDONA AA (Table 1). Stations in areas of aquifers tend to have the greatest range of gravity variation through time, while stations on crystalline bedrock have the smallest.

Soil-moisture variations may contribute to gravity variations. Correlation of gravity at each station with monthly average values of regional soil moisture (available from NOAA) was investigated. Significant correlation with regional soil moisture occurred at only two stations, PRESCOTT AB and CLARKDALE AA. The correlation was removed from the two records resulting in a significant reduction in the range of gravity variations (Table 1).

Residual gravity variations at most stations, after removing the correlation with regional soil moisture, are greater than the expected observational error. Variations were less than 7 microGal at only three stations, all of which are located on crystalline rock. Residual gravity variations at some stations located on crystalline rock were about 10 to 14 microGal. Local soil moisture variations may contribute to the large variations. Most of the variation, however, is likely caused by storage change in nearby aquifers.

Gravity variations and trends in the Tucson AMA, Verde Valley, and Upper San Pedro Valley are compared with trends in hydrologic indicators of precipitation, soil moisture, streamflow, and water levels (fig. 2). Gravity records at most of the stations in the Phoenix area have fewer observations than stations in the other areas and are therefore not presented here. Variations in gravity at PHOENIX AA have displayed trends and magnitudes similar to those in the Tucson area.

Site Characteristics						Gravity correlation with regional soil moisture				Residual trend		
Station	Basin	Rock Type	Hydrologic Setting	Number of Observations	Observed gravity range, microGal	slope	correlation coefficient	corrected observed gravity range, microGal	reduction of range	Residual trend microGal /year	Residual trend correlation coefficient	Primary source of residual gravity variation
TUCSON AA	Tucson AMA	metamorphic	near aquifer margin	12	9.1	0.4	0.17	na	na	-0.72	-0.72	soil and aquifer storage
TUCSON AC	Tucson AMA	alluvium	aquifer near ephemeral channel	7	16.0	2.4	0.55	na	na	-2.27	-0.82	aquifer storage
TUCSON AD	Tucson AMA	alluvium	aquifer	15	16.0	-0.7	-0.26	na	na	-0.99	-0.50	aquifer storage
TUCSON AE	Tucson AMA	basalt	near aquifer margin	15	13.0	0.7	0.41	na	na	-0.38	-0.31	soil and aquifer storage
TUCSON AF	Tucson AMA	Paleozoic sedimentary	near aquifer margin	9	8.6	-0.5	-0.30	na	na	-0.27	-0.30	aquifer and soil storage
TOMBSTONE AA	Upper San Pedro	alluvium near granite	near aquifer margin	15	8.2	0.5	0.35	na	na	-0.18	-0.15	soil moisture
FT HUACHUCA AA	Upper San Pedro	granite	near aquifer margin	12	6.4	0.5	0.32	na	na	-0.30	-0.30	soil moisture
PALOMINAS AA	Upper San Pedro	alluvium	aquifer near intermittent stream	12	13.6	1.0	0.27	na	na	-1.02	-0.43	soil and aquifer storage
PRESCOTT AA	Verde	granite	remote to aquifer margin	13	8.5	0.0	-0.01	na	na	0.58	0.42	soil moisture
PRESCOTT AB	Verde	weathered granite	aquifer margin	9	18.0	1.4	0.57	14.1	3.8	0.84	0.36	soil and aquifer storage
CLARKDALE AA	Verde	alluvium	aquifer	13	12.9	0.9	0.78	7.9	5.0	-0.04	-0.03	soil and aquifer storage
PAULDEN AA	Verde	alluvium	aquifer	10	11.8	0.4	0.30	na	na	2.12	0.87	aquifer storage
SEDONA AA	Verde	Paleozoic sediments	aquifer	12	20.5	0.7	0.37	na	na	2.43	0.74	aquifer storage
PHOENIX AA	Phoenix AMA	metamorphic	near aquifer margin	12	10.2	-2.6	-0.28	na	na	-0.31	-0.33	soil and aquifer storage
PHOENIX AB	Phoenix AMA	metamorphic	near aquifer margin	4	10.2	13.9	-0.82	na	na	-0.01	0.00	soil moisture
PHOENIX AC	Phoenix AMA	granite	near aquifer margin	5	4.4	-2.6	-0.34	na	na	0.33	0.36	soil moisture
CASA GRANDE AA	Pinal AMA	granite	near aquifer margin	5	6.4	-1.8	-0.14	na	na	0.12	0.06	soil moisture

TABLE 1. SUMMARY OF GRAVITY VARIATION AT STATIONS IN ARIZONA.

SUMMARY OF GRAVITY CHANGE IN MONITORED REGIONS

TUCSON AMA

Variations in gravity in the Tucson Basin have ranged from 9 to 16 microGal and display no correlation with regional soil-moisture trends. Locally significant soil-moisture variations, however, may occur. The greatest variations, 16 microGal, occurred at stations located in alluvial aquifer areas, TUCSON AC and TUCSON AD, indicating that variations in aquifer storage has been significant at those sites. At most of the stations, gravity was greatest for the first two observations during the summer 1998 and spring 1999 respectively. This period followed large amounts of precipitation, streamflow, and infiltration during winter and spring 1998 (fig. 2). Later observations at non-alluvial aquifer stations—TUCSON AA, TUCSON AD and TUCSON AF—have varied within a range of 4 to 7 microGal, which is slightly greater than the expected range of observational error. This indicates that the gravity contribution from soil and aquifer storage is small at these stations for the hydrologic conditions that have existed after winter and spring, 1998.

VERDE VALLEY

Variations in gravity at five stations in the Verde Valley have been greater than at the other monitored regions. Gravity variations have ranged from 9 to 21 microGal. Variations in soil moisture have also been greater than in the other monitored areas, which may have contributed to correlation with regional soil-moisture trends at two stations, PRESCOTT AB and CLARKDALE AA. Locally significant soil-moisture variations may contribute to gravity variations at the stations. Removal of the soil-moisture correlation significantly reduced the range of gravity variation at PRESCOTT AB and CLARKDALE AA from—18 and 14 microGal, respectively—to 14 and 8 microGal, respectively. Local variations in soil moisture in thin alluvial soil at PRESCOTT AB probably contribute to the 14 microGal of variation that remains after correction of correlation with regional soil-moisture trends. Local variations in soil moisture, and water stored in fractured and weathered granite have probably contributed to gravity variations of 9 microGal at PRESCOTT AA, which is located in an extensive area of granitic rock.

Significant increasing long-term trends in observed gravity occur at two stations, PAULDEN AA and SEDONA AA, which indicates increasing aquifer storage in the underlying alluvial and Paleozoic aquifers, respectively. Most of the increase in gravity at these stations occurred following the wet winter of 2005, which likely resulted in increased aquifer storage.

UPPER SAN PEDRO VALLEY

Variations in gravity at three stations in the Upper San Pedro Valley have ranged from 6 to 14 microGal and display no correlation with regional soil-moisture trends. Locally significant soil-moisture variations, however, may occur. The greatest variations, 14 microGal, occurred at the station PALOMINAS AA which is located in an alluvial aquifer area. Based on the correlation of the observed gravity trend with water levels at a nearby well, variations in aquifer storage have been the main source of gravity variation at this station. Observations at non-alluvial aquifer stations—FT HUACHUCA AA and TOMBSTONE AA—have varied within a range of 6 to 8 microGal, which is slightly greater than the expected range of observational error. This indicates that the gravity contribution from soil and aquifer storage may be about 4 microGal or less at these stations.

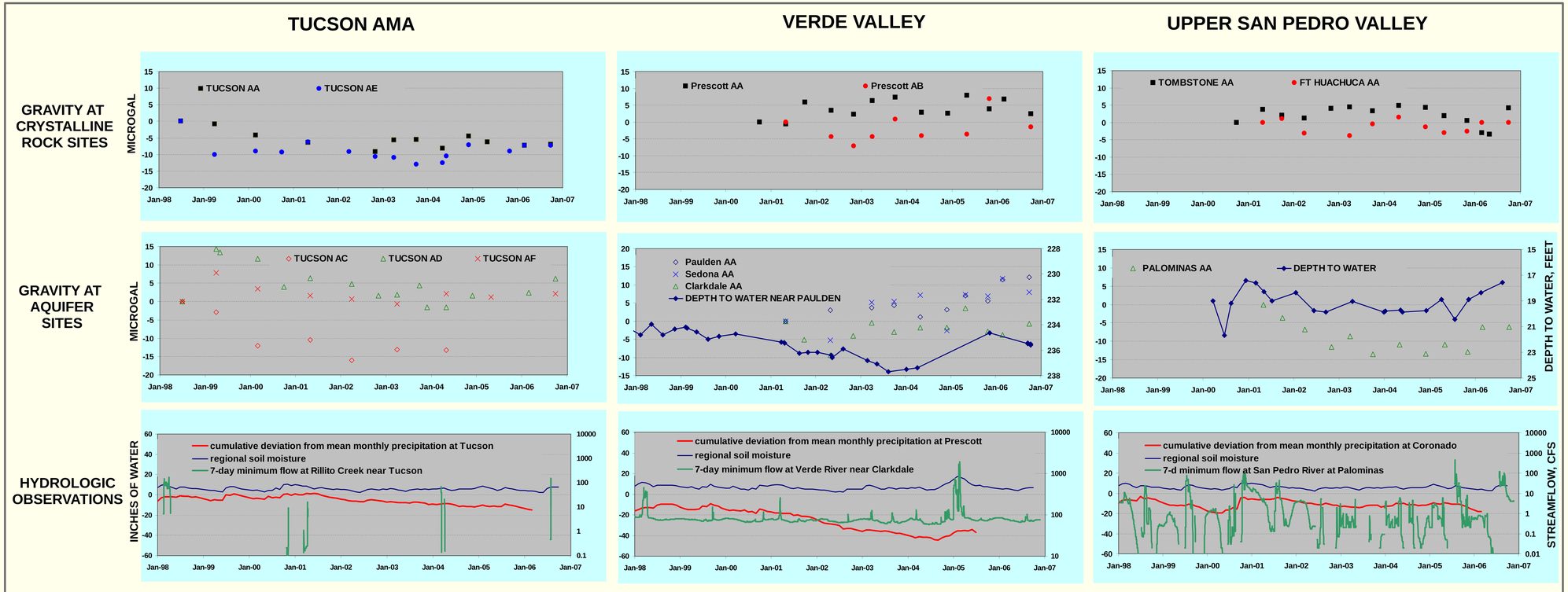

FIGURE 2. REPRESENTATIVE ABSOLUTE GRAVITY AND HYDROLOGIC RECORDS IN ARIZONA.