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Assessing Groundwater Geospatial Variation Using Microgravity Investigation in the Arid Riyadh Metropolitan Area, Saudi Arabia: a Case Study

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Abstract A combination of relative microgravity measurements at ground surface, and depth to water and water table measurements from adjacent wells were used to estimate geospatial variation of groundwater. A highly accurate portable Grav-Map gravimeter was used for gravimetric measurements at locations nearby a 42 well water table monitoring program. To efficiently correlate the two data sets, wells were clustered into five groups by geological unit and water saturation. Microgravity data was processed, interpreted, and correlated with both the depths to groundwater and the water table levels. Regression analyses revealed a strong negative correlation for microgravity and depth to groundwater in all five clusters; correlation coefficients varied between 0.70 and 0.97, and measured 0.78 over the entire study area. Microgravity values increased as groundwater depth decreased, likely because rising groundwater fills voids and fractures within soil and rocks, increasing rock density and therefore relative gravity. To validate the correlation, we superimposed a map of depths to water on the first derivative of microgravity measurements. The shallowest groundwater depths were positively related to the zero first derivatives, having intersection areas within a 75 % significance interval. Negative first derivatives covered the rest of the study area, with relative gravity decreasing with increasing groundwater depth. This technique can precisely and efficiently determine changes in subsurface geology and geospatial changes in depths to the groundwater table. Distances between microgravity stations should be small, to better detect small changes in gravity values, reflecting density contrasts underground.

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1 Introduction

Local groundwater depletion and contamination in arid areas can become a global problem. Groundwater is the primary source of water in urban and rural areas in Saudi Arabia; however, fast economic expansion significantly affects these limited water resources (El Alfy and Merkel 2006; Metwaly et al. 2014). Conversely, waterlogging problems in urban areas have progressively increased. This study focuses on the Riyadh metropolitan area, because an overall lack of planning and adequate drainage has caused waterlogging problems, and consequently health problems.

Understanding Earth's subsurface structure at global, regional, and local scales is important for groundwater exploration. Adequate mapping of resources provides the best management practices for informed decision-making. The study of gravity variations on Earth provides insight into dynamic earth processes, as well as the subsurface geologic structure of the earth. Groundwater geospatial variation can be efficiently correlated with precision microgravity measurements. However, the effects of moisture, porosity and compaction on gravity values can be large and critical, especially if significant variations occur amongst different rock units. Variations in rock porosity cause density changes; the density of a sedimentary sequence tends to increase with depth due to rock compaction, and increase with age due to progressive cementation. Gravity anomalies result from the differences in densities between a rock body and its surroundings (Haldar 2012).

High-resolution mapping of groundwater resources cannot be carried out adequately by conventional techniques used in remote sensing and photogrammetry. However, sequential gravity surveys can be conducted from satellites to measure changes in groundwater storage over large regions with low resolution (300–400 km). This technique has the potential to facilitate near-real-time monitoring and assessment of subsurface hydrologic changes, enabling water managers to respond accordingly. In-situ hydrological observational data and that inferred from the Gravity Recovery and Climate Change Experiment (GRACE) satellite mission data agree to 20 mm (rmse) with the use of a filtering technique to improve the spatial resolution (Swenson et al. 2006; Seo 2006; Niu 2007).

Temporal variations of the earth's gravitational field are mainly influenced by tides of the solid earth, ocean-loading effects, mass changes in the atmosphere, and polar motion (Pool and Eychaner 1995). If the effects of earth tides, ocean tides, atmosphere mass changes, and polar motion are removed, the residual response is dominated by hydrological mass variations, and the major source of these variations is water storage changes. This assumes that water storage in a shallow aquifer has a significant effect on surface gravity through Newtonian attraction. High-resolution detection of density variations beneath the earth's surface offers an intuitive means for characterizing the structural makeup of the earth's subsurface. Thus incentivized, high-resolution detection of groundwater storage variation has become more accurate and reliable. Other studies have characterized the modeling parameters of gravity measurements, including Hasan et al. (2006); Virtanen et al. (2007); Hare (2008), and Gehman (2009).

Gravity offers a means to directly estimate changes in subsurface water storage, by measuring changes in the earth's gravitational field; such changes in gravity have been compared to well water level changes in unconfined aquifers, to obtain aquifer-specific yield values (Pool and Anderson 2008; Wziontek et al. 2009; Creutzfeldt et al. 2010; Jacob et al.

2010; Bonneville et al. 2015). Gravity observations allow for the identification of the hydrological system responses (Christie 1978; Maurer 1985; Watson 1987; Culek and Palmer 1987; Hannah 2001; Chapman et al. 2008). Gravimeters provide information on total local water storage changes that can be used to constrain the overall status of a hydrological system in a model. The effect of local water storage on temporal gravity measurements can be independently estimated, and the hydrology can benefit from temporal gravity measurements (Creutzfeldt et al. 2010). Repeated gravity measurements at the Takigami geothermal field, located in central Kyushu, Japan, were taken to study change associated with production and reinjection of geothermal fluids. The gravity signals were significant, reaching several tens of μgals (Nishijima et al. 2010). Detecting groundwater using a gravity signal in the Tucson Basin in southern Arizona was used to estimate groundwater storage change, groundwater budgets, and land subsidence (Pool and Anderson 2008). Gravity was also used in a karst aquifer on the Larzac Plateau in Southern France to study storage variations (Jacob et al. 2008). Atsushi (1997) and Csapó et al. (2003) investigated changes in gravity influenced by water level fluctuations. They found that gravity changes were proportional to changes in groundwater level. Christiansen et al. (2011) investigated changes in the groundwater table and gravity during a riverbank infiltration event in the Okavango Delta, finding a clear correspondence between changes in water content and changes in gravity.

Microgravity measurements have advantages over traditional groundwater-monitoring methods. They do not necessitate invasive and time-consuming well drilling. In addition, they allow storage-change measurements to be carried out at nearly any location over the aquifer. Both groundwater depletion with the lowering of the water table and waterlogging with the raising of the water table beneath urban areas are accompanied by significant gravity anomalies, and sometimes by vertical deformation of the ground surface, evidenced by differential GPS and microgravity measurements. Using small spacing between microgravity observation stations can help detect small changes in gravity values, which may reflect density contrasts underground. This technique can precisely determine changes in the subsurface geology, and efficiently detect geospatial changes in depth to the groundwater table. The main objective of our research is to study the geospatial variations of the depth to groundwater and the water table, as well as explore the geological structure across the Riyadh metropolitan using precise microgravity measurements. This will help support future hydrological investigations in similarly arid areas to solve groundwater depletion and waterlogging problems.

1.1 Study Area

The study area is located in the Riyadh metropolitan area, Saudi Arabia. It lies between 24°32′ and 24°47’N, and from 46°29′ to 46°51’E, and has an approximate area of 810 km^2 (Fig. 1). The eastern part of the study area is covered by the Wadi Sulaiy catchment, while the Wadi Hanifah catchment covers the western part. The area has moderate relief, with some ridge ranges in the eastern and western sections, and lowlands in the center. The elevation of the area ranges between 500 and 700 m above sea level, averaging 518 m. The central section is a low-lying flat area with a generally gentle slope of <4.5 %. The study area has an arid desert climate, averaging hot temperatures (33 °C), low relative humidity (29 %), and relatively low average annual rainfall (90 mm); most rainfall events occur from March–April and August–October. The total mean annual potential evaporation is >3500 mm. The mean wind speed varies between 10 and 18 km/h (ADA 2013). Riyadh metropolitan area faces large challenges with both water supplies and water demands. This is due to accelerated urbanization, high

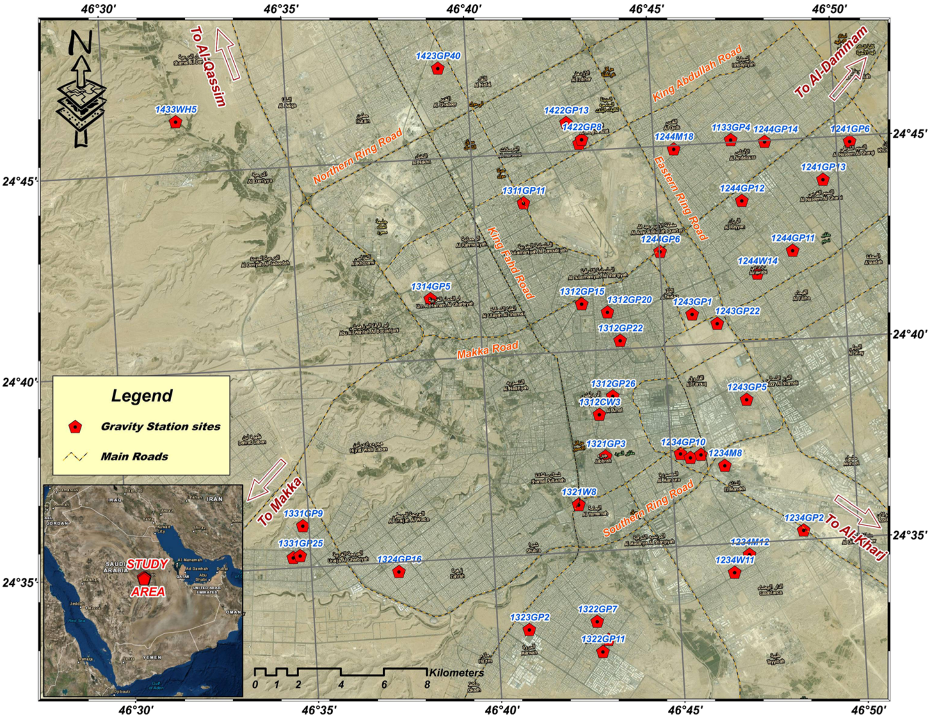


Fig. 1 Location map of the study area, showing the observational microgravity point stations

population growth, and the expansion of trade increasing pressure on limited water resources (El Alfy 2013; El Alfy et al. 2015; El Alfy 2016). Groundwater depletion is observed in water well fields in and around Riyadh. However, due to weak sanitary and storm sewer systems, groundwater is unexpectedly rising under some areas of the city, causing waterlogging problems. This poses hazards to human health, property and infrastructure.

1.2 Geological and Hydrogeological Background

Geologically, the study area is composed of gently eastward-dipping rocks, ranging in age from the Jurassic to the Holocene. The Jurassic rocks include the Jubaila and Arab Formations (Steineke et al. 1958; Powers et al. 1966; Powers 1968; Manivit et al. 1985; Vaslet et al. 1991). The Jubaila conformably overlies the Hanifah Formation, and is mainly made up of limestone. The Arab Formation is composed of limestone and progresses to anhydrite at the top, which have been transformed to gypsum, remaining only as solution residues. The Cretaceous carbonate rocks include the Sulaiy, Yamama and Buwaib Formations. The Sulaiy Formation was initially thought to be a gravel-filled channel at the foot of the Hit escarpment. The lower part of Sulaiy Formation has entirely or partially collapsed into the Arab Formation. The Yamama Formation is a pure carbonate unit composed of calcarenite, calcarenitic limestone, and aphanitic limestone. The Buwaib Formation consists of interbedded shale, siltstone, dolomite, calcarenite, and aphanitic limestone. The Cretaceous Biyadh Formation consists of cross-bedded quartz sandstone, with some shale and conglomeratic layers. The Cretaceous Wasia Formation sandstone unconformably overlies the sandstones of the Biyadh; both of

these have the hydraulic parameters to form good aquifers. Alluvium deposits are classified into two types: the recent deposits in active wadis, and the older deposits in inactive channels and hanging terraces. Alluvium is deposited in the deeply incised the Wadi Sulaiy, Hanifah and their tributaries, which cut deeply into the bedrock. Based on borehole logs, the alluvium is up to 50 m thick. The recent alluvium includes sub-rounded gravel and pebbles of Mesozoic limestone mixed with abundant reworked aeolian sand in a clayey matrix. These are fine- to very fine-grained clayey, silty, and pedogenic sediments.

The existing aquifer is composed mainly of the shallow heterogeneous alluvium deposits connected hydraulically within the succession of carbonates rocks of the Arab, Jubaila and Sulaiy Formations. In some areas, especially to the east, the highly fractured Sulaiy limestone directly overlies the Arab Formation. This is due to the dissolution of the anhydrites of the Hith Formation. These carbonate rocks have joints and fissures enlarged by dissolution, therefore creating considerable porosity, permeability and storativity. Their average hydraulic conductivity is 6×10^{-5} m/s, and their average storage coefficient is 3×10^{-4}. This aquifer mainly represents unconfined conditions, but to the east and south some confined conditions are observed. Figure 2 shows the spatial distribution of the water table and groundwater flow directions for the study area. The water table ranges from 660 to 520 m above sea level. The average hydraulic gradient is 0.5 % in the northwestern and central parts of the study area, and increases to about 0.7 % in the southeastern part. Groundwater generally flows from northwest to east and southeast, implying outflow towards the active channel of the Wadi Sulaiy. There are numerous local flow directions, especially in the central section, where several water

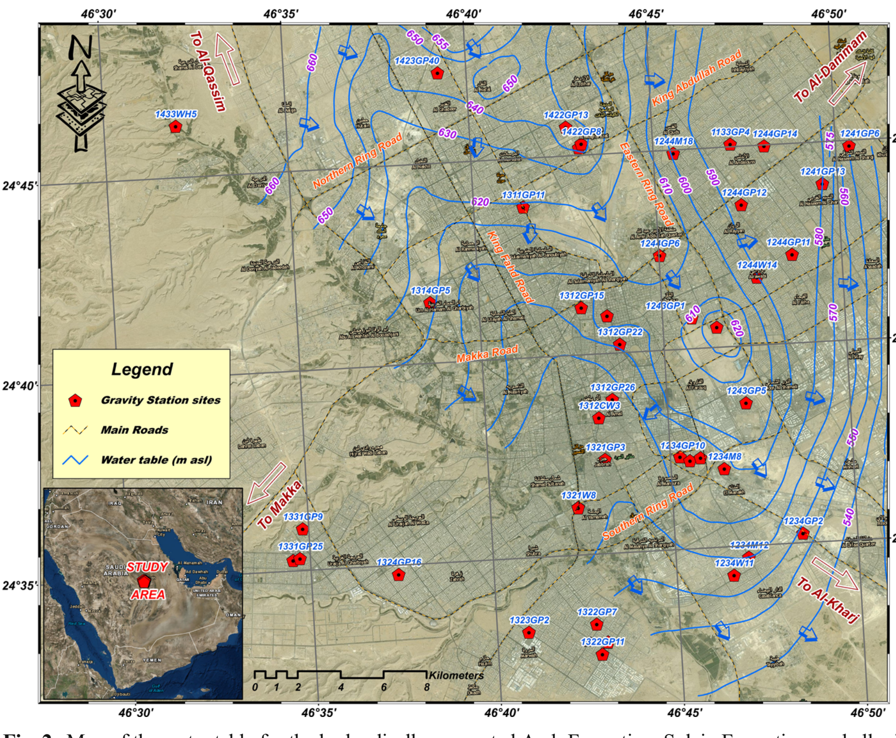


Fig. 2 Map of the water table for the hydraulically connected Arab Formation, Sulaiy Formation, and alluvium aquifers, 2015

mounds have formed as a result of surface and wastewater infiltration to the shallow aquifer. Figure 3 shows the average annual water level for selected wells located in the study area. Most of these wells show gradual rising of the water table under the Riyadh metropolitan area over the last 12 years, reflecting prolonged waterlogging problems due to water seepage from sewers and domestic water networks. Unfortunately, while water associated with waterlogging can cause dangerous health problems, the very shallow water table in some areas (<4 m) means this water is sometimes pumped for domestic purposes and small-scale irrigation.

2 Methods and Materials

To study the earth's gravity, instruments called gravimeters are used to measure gravitational acceleration at the surface. Gravimeters measure the difference in the force of gravity from one place to another. Few hydrogeological studies had accompanied gravity studies to monitor geospatial variations of groundwater. This is because the estimated signals of gravity differences are small, however, precise gravimeters can measure geospatial gravity variations as a result of groundwater mass changes. An infinite water table of 1 m thickness change causes about a 40 μgal gravity change (Fukuda 2011). The corrected microgravity data allowed groundwater-storage volume to be quantified with an accuracy of about ±0.15 m of water per unit area of aquifer (USGS 2012). Sensors used previously were bulky and heavy with relatively low accuracy. It is not easy to achieve an accuracy of 10 μGal by means of a conventional spring-type relative gravimeter. In this study, a wide area was covered with microgravity measurements through the use of the Grav-Map gravimeter produced by King Saud University and Geomatics USA, LLC. This is a new nano-technology sensor providing precise relative navigation, innovation in data processing, and affordable carrier platforms to both reduce cost and produce finer spatial resolution for gravity measurements. The Grav-Map gravimeter contains a specialized type of accelerometer designed for measuring the local gravitational field of the earth; it is easy to operate, lightweight, and has a precision of ±1 μGal (1×10^{-8} m/s^2) at 0.5 km to 1 km spatial resolution.

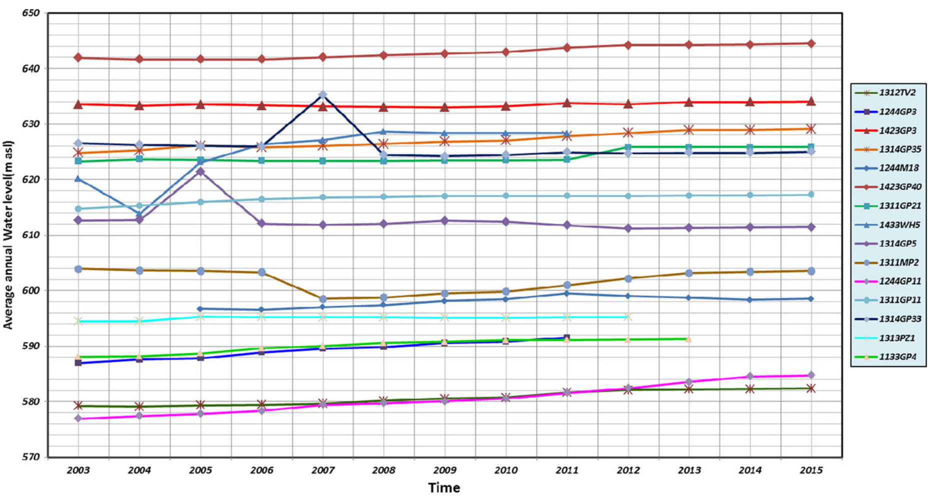


Fig. 3 Average annual water levels (2003–2015) for selected observation wells

Table 1 Relative gravity observations and water data from the 42 nearby observation wells

ID	Name	Long.	Lat.	Ground elevation	Depth to water	Water level	Microgravity	Distance between microgravity station and observation Well
		m	m	m	m	m	mGal	m
1	1244 M18	677,872	2,738,270	612.96	14.69	598.27	0.93766	9
2	1311GP11	670,833	2,736,087	622.29	5.06	617.23	0.94405	21
3	1422GP9	673,518	2,738,718	649.04	2.14	646.90	0.94812	18
4	1422GP8	673,644	2,738,897	647.95	1.41	646.54	0.95304	11
5	1422GP13	672,958	2,739,701	647.25	2.52	644.73	0.95653	7
6	1423GP40	667,152	2,742,462	647.30	2.99	644.31	0.95794	10
7	1433WH5	654,946	2,740,540	628.30	5.10	623.20	0.94901	34
8	1244 W14	681,475	2,732,380	602.40	13.07	589.33	0.94146	3
9	1243GP22	679,524	2,730,152	627.23	5.34	621.89	0.94508	2
10	1243GP1	678,387	2,730,627	633.18	3.10	630.08	0.94644	9
11	1244GP6	677,035	2,733,579	622.09	5.55	616.54	0.94767	7
12	1312GP15	673,312	2,731,326	606.11	6.03	600.08	0.94412	70
13	1314GP5	666,343	2,731,867	621.37	6.50	614.87	0.94689	24
14	1312GP20	674,486	2,730,897	609.08	2.14	606.94	0.94431	15
15	1312GP22	675,015	2,729,561	593.82	1.77	592.05	0.94868	64
16	1324GP16	664,340	2,719,372	699.43	3.32	696.11	0.94596	5
17	1331GP22	659,496	2,720,232	744.33	2.16	742.17	0.94972	3
18	1331GP25	659,820	2,720,308	741.00	2.34	738.66	0.94515	5
19	1331GP9	660,000	2,721,681	724.99	3.33	721.66	0.95019	23
20	1323GP2	670,239	2,716,431	646.51	7.30	639.21	0.94356	91
21	1322Gp7	673,389	2,716,674	596.65	3.40	593.25	0.94643	33
22	1322Gp11	673,591	2,715,284	610.03	3.60	606.43	0.94679	24
23	1322Gp10	673,877	2,715,822	599.66	1.90	597.76	0.95545	28
24	1133GP4	680,517	2,738,581	602.33	11.05	591.28	0.94139	87
25	1244GP14	682,077	2,738,429	584.54	4.40	580.14	0.95327	77
26	1241GP6	686,004	2,738,273	585.30	11.30	574.00	0.94937	56
27	1241GP13	684,693	2,736,564	587.61	5.00	582.61	0.94772	24
28	1244GP12	680,909	2,735,753	597.50	5.30	592.20	0.94923	32
29	1244GP11	683,154	2,733,367	595.12	10.38	584.74	0.94142	18
30	1312CW3	673,905	2,726,205	582.52	6.00	576.52	0.94256	23
31	1312GP26	674,561	2,727,027	584.51	3.40	581.11	0.94874	19
32	1234GP2	683,095	2,720,468	566.47	3.20	563.27	0.94905	49
33	1234 M12	680,549	2,719,461	573.30	3.07	570.23	0.95149	20
34	1234 W11	679,826	2,718,659	561.00	2.20	558.80	0.95388	26
35	1234 M8	679,590	2,723,599	558.30	3.20	555.10	0.94789	27
36	1321GP3	674,103	2,724,265	579.79	5.80	573.99	0.94786	38
37	1321 W8	672,768	2,722,102	580.07	2.20	577.87	0.95182	41
38	1321GP5A	672,769	2,722,094	688.06	2.79	685.27	0.94924	39
39	1243GP5	680,727	2,726,599	622.40	1.30	621.10	0.95159	36
40	1234GP17	677,569	2,724,233	584.77	3.18	581.59	0.94728	54
41	1234GP15	678,018	2,724,032	585.70	2.51	583.19	0.94737	52

Table 1 (continued)

ID	Name	Long.	Lat.	Ground elevation	Depth to water	Water level	Microgravity	Distance between microgravity station and observation Well
		m	m	m	m	m	mGal	m
42	1234GP10	678,509	2,724,151	590.30	1.88	588.42	0.94937	24
Min.	—	–	–	558.30	1.30	555.10	0.93766	2
Max.	–	–	–	744.33	14.69	742.17	0.95794	91
Mean	–	–	–	617.68	4.59	613.09	0.94797	29.95
Median	—	—	—	604.26	3.33	598.02	0.94788	24.00
SD	—	—	—	45.49	3.21	46.18	0.00423	22.98
Skew.				1.40	1.68	1.43	0.09621	1.08
Kurt.				1.66	2.39	1.67	0.35439	0.65

Min. Minimum, *Max.* Maximum, *SD* Standard deviation, *Skew.* Skewness, *Kurt* Kurtosis

Due to the large study area (>810 km^2), microgravity measurements and ground surface height measurements were carried out in two phases, using the Grav-Map gravimeter and differential GPS (±6 cm accuracy). Ground surface height measurements were used for topography corrections of water level data. In addition, gravity data are very sensitive to height changes of specific gravity stations relative to the reference station. The first phase of the gravimetric survey included twenty-two gravimetric observation stations (March 2–8, 2015), while the second phase included twenty observation stations (March 21–24, 2015). To examine the correlation between the changes in depths to the water table and the differences in gravity measurements, all of the microgravity stations were located at or close to the 42 pre-existing groundwater observation wells, where depths to water and water levels were measured simultaneously (Table 1).

Extra gravity measurements were recorded before, during, and after this gravimeter survey for subsequent gravimeter error checking and drift adjustment. The instrument calibration was tested and confirmed with the Geomatics USA, LLC calibration system, consisting of a set of stations with known gravity values. The gravity values were measured in a star grid for high-accuracy data; all measurements were made relative to one reference station and only to one gravity station at a time. Microgravity measurements were processed to account for the earth's tides, gravimeter drift, elevation, and regional variations in gravity. The microgravity measurements are modeled stochastically with the estimated Kalman filter as a third-order Gauss-Markov process. The selection of observation wells to place microgravity measurement points nearby was based on well data availability, ease of accessibility and good spatial presentation in the study area.

Water measurements were taken of depths to water from the top of the boreholes; the WGS84 datum was used in all measurements. The recorded measurements, dates, times, and locations were subject to quality assurance justification. Golden software Surfer 12 and ArcGIS 10.3 were used to process and analyze the microgravity data.

Several trials were done to identify the correlation between the depths to groundwater, water table levels, and the relative microgravity measurements. The first derivative of the correlation between these variables was also calculated for validation, as was the grid directional derivative, calculating the slope of the depth to groundwater surface along a given

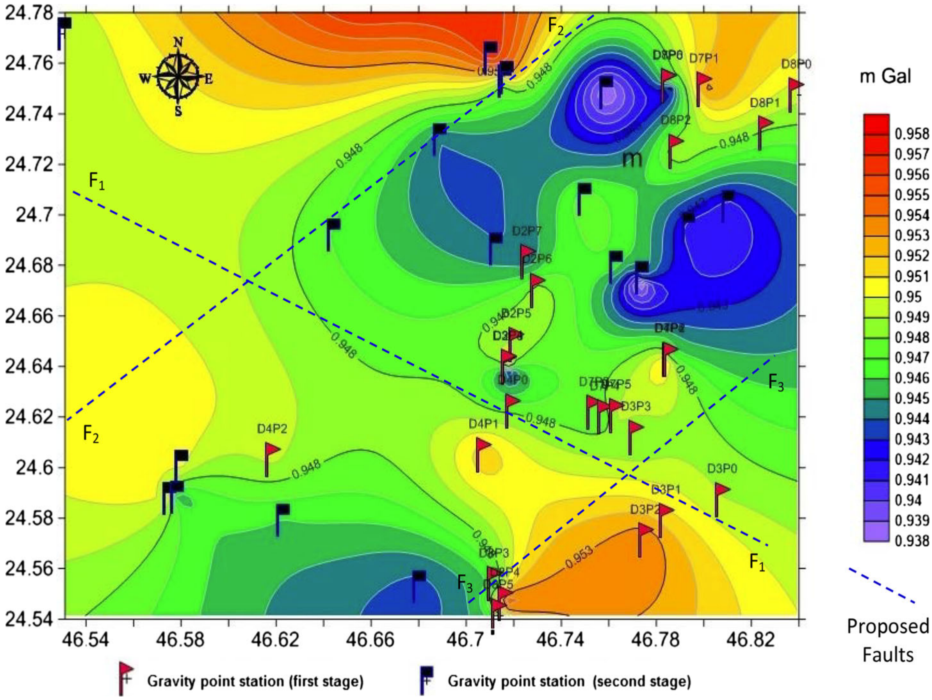


Fig. 4 Relative microgravity anomaly map results and the proposed faults of the study area

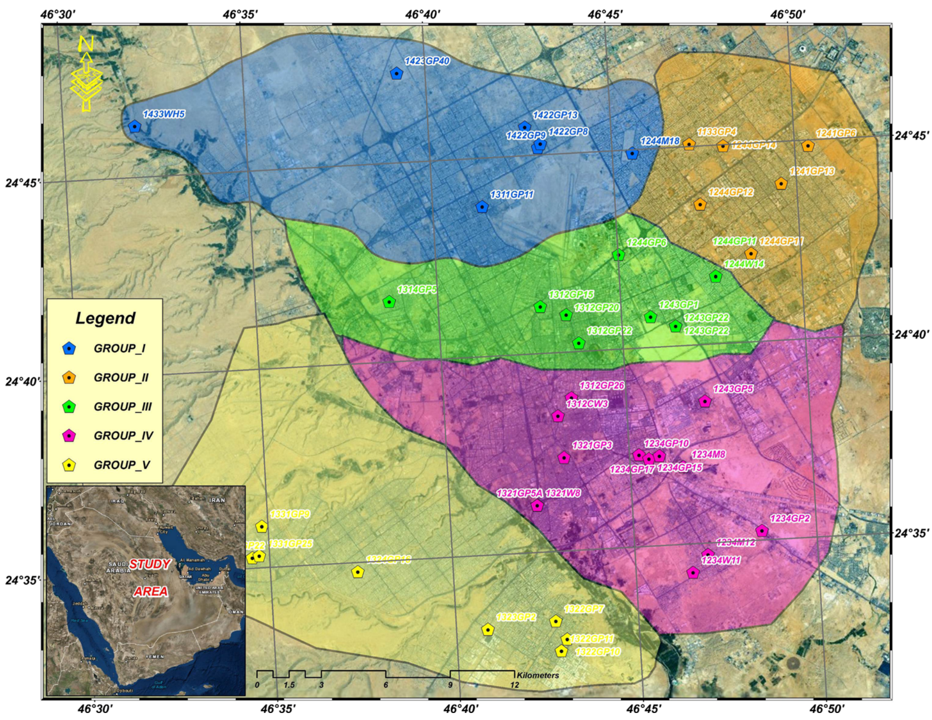
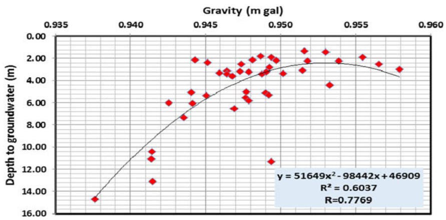


Fig. 5 The five well groups, divided by rock units

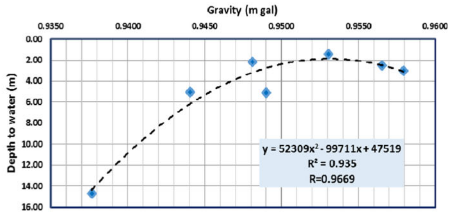
direction. A contour map was produced with the first derivative grid surface showing isoclines of the slope along each fixed direction line. This slope was either increasing (uphill slope) or decreasing (downhill slope); the increasing function gives a positive slope (positive derivative), while the decreasing function yielded a negative slope (negative derivative). Slope was reported as rise over run and can approach negative or positive infinity as the slope approaches the vertical in either the down or up directions. Surfer 12 software used the grid directional derivative file for relative gravity measurements, so directional derivatives were approximated using difference equations.

3 Results and Discussion

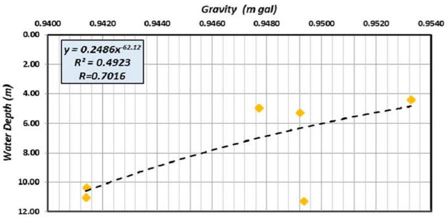
Figure 4 shows the relative microgravity anomaly map for the entire study area. Gravity variations up to 0.202 mGal were observed. The microgravity values varied between 0.9377 and 0.9579 mGal, with an average value of 0.9480 mGal, and a standard deviation of 0.0042. The highest microgravity values were observed in the north, northeastern and southeastern



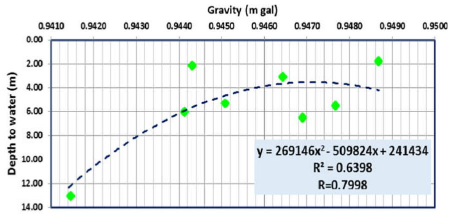
(a) Gravity values related to depths to groundwater over the entire study area.



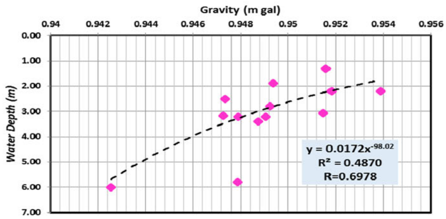
(b) Gravity values related to depths to groundwater for group I.



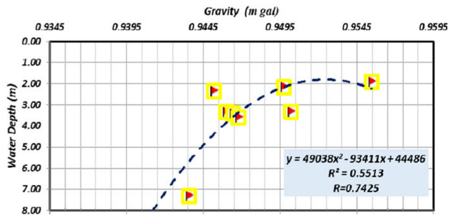
(c) Gravity values related to depth to groundwater for group II.



(d) Gravity values related to depth to groundwater for group III.



(e) Gravity values related to depth to groundwater for group IV.



(f) Gravity values related to depth to groundwater for group V.

Fig 6 **a** Gravity values related to depths to groundwater over the entire study area. **b** Gravity values related to depths to groundwater for group I. **c** Gravity values related to depth to groundwater for group II. **d** Gravity values related to depth to groundwater for group III. **e** Gravity values related to depth to groundwater for group IV. **f** Gravity values related to depth to groundwater for group V

parts of the study area, while the lower values were observed in the northeastern and southern parts. Notably, the results on the anomaly map in Fig. 4 are in agreement with Ibrahim et al.'s (2012) regional anomaly map for Riyadh province, which was constructed using high-resolution aeromagnetic data.

Figure 4 shows the study area location in a graben (low anomaly zone) between two uplifted zones (high gravity anomalies); this topography is echoed in the proposed NE-SW and NW-SE deep-seated faults. In particular, the southeastern part of the study area contains the highest recorded value for the relative gravity anomaly. The basement rocks may be closer to the ground surface in high anomaly areas, while the low anomaly values may indicate a thick sedimentary succession; this has been confirmed from drilling logs (ADA 2013).

Different correlations were calculated between gravity measurements and the depth to the groundwater table in nearby wells. Frequency histograms were plotted for microgravity variables, and they were tested for normality using the nonparametric one-sample Kolmogorov-Smirnov test with a significance level of 0.05 and a 95 % confidence level. Spearman's correlation coefficients were also calculated. To avoid the heterogeneity effects of the different rock unit densities throughout the aquifer, five different clusters of wells are identified (Fig. 5). These five well groups are clustered according to geological units and degree of groundwater saturation; the correlations between the depths to groundwater and gravity measurements were examined or each of the five groups (Fig. 5).

Figure 6a shows the general relationship between the depths to the groundwater table and the relative microgravities recorded nearby the 42 monitoring wells within the study area. This type of trend line uses a specific eq. to calculate the least squares fit through data points. It shows that the depth to groundwater is inversely proportional to the relative gravity. There is a

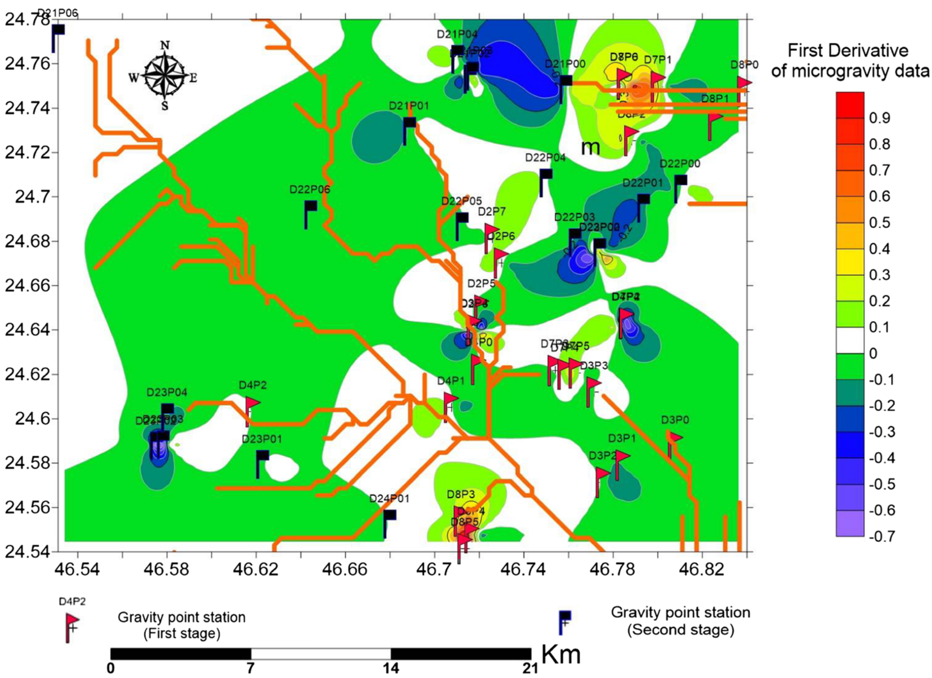


Fig. 7 The spatial distribution of the zero first derivatives of microgravity data

significant correlation coefficient (0.78), with the relationship following a polynomial regression equation (2nd order) as follows:

$$y = 51649x^2 - 98442x + 46909 \tag{1}$$

where y represents the depth to groundwater and x represents the relative gravity.

Figure 6b–f show the relationships between the different depths to groundwater and relative gravities for each of the five clustered groups. Groups were selected according to geological rock units, since the aquifer hydraulic conductivity for each unit is homogeneous. Effective porosity, specific retention and yield are important factors related to the change in aquifer material densities. However, rising water levels due to waterlogging can fill all aquifer material pore spaces, resulting in an increase in aquifer density; these increases are significant for microgravity measurements.

The correlation coefficients for depths to groundwater and gravity values in these local clusters vary between 0.70 (group IV) and 0.97 (group I). These correlation results are highly significant and confirm the validity of this large-scale and cost effective approach as reliable. This could be used in similar geological contexts to examine both groundwater depletion and waterlogging. The small distances between gravity observation stations successfully detected small changes in gravity values, which may reflect density contrasts underground. Good correlations for data grouped by geological unit prove that this method can precisely determine changes in subsurface geology and detect the water table efficiently.

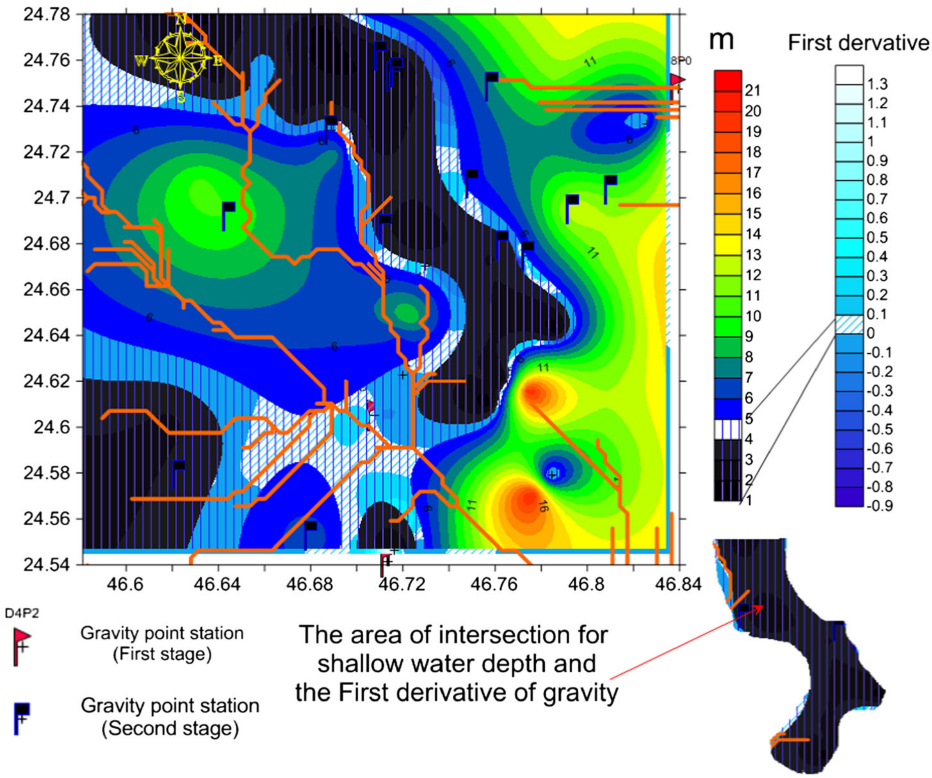


Fig. 8 The intersection area of shallow groundwater depths and the zero first derivatives of gravity data

The directional first derivative grid, taking into account the distance between data points, was calculated from relative microgravity values to validate the relationship with depth to groundwater. Comparing the isoclines obtained from this calculation with corresponding groundwater depths shows an intersecting area when the shallow water depths are superposed on the area of zero first derivatives (Figs. 7 and 8). The percentage of the study area intersected with the positive derivatives represent is approximately 78 % of the total area, where the relative gravity increases with the decrease of depths to the top of groundwater table (shallow groundwater depths). The negative first derivatives cover the rest of the study area, meaning that relative gravity decreases with increasing depths to groundwater (deep groundwater). By overlaying the area of shallow groundwater depths (1–4 m) over the area with zero first derivative of gravity, we have qualitatively estimated the area of intersection to be approximately 75 % (Fig. 8). This estimation efficiently confirms the reverse relationship between depth to the groundwater table and gravity. The correlation of the zero first derivatives with the shallow groundwater depths can be used to delineate areas potentially exposed to serious environmental problems because of rising groundwater from observed infiltration of the domestic water network and sewer drainage systems.

The correlation between microgravity measurements and absolute groundwater table levels, instead of the depth to water, was also calculated, but the correlation was low (0.1). Based on the derived general formula in Eq. 1, the groundwater table levels were predicted and superimposed on the observed groundwater tables (Fig. 9). Groundwater levels predicted with the regression equation were under-estimated at several overlap points. Generally, the two surfaces tend to match at the highest and lowest points, but there are still some areas of under- or over-estimation of the groundwater table (Fig. 9). Approximately 60 % of the water table in the study area was over-estimated. The maximum difference between the predicted and

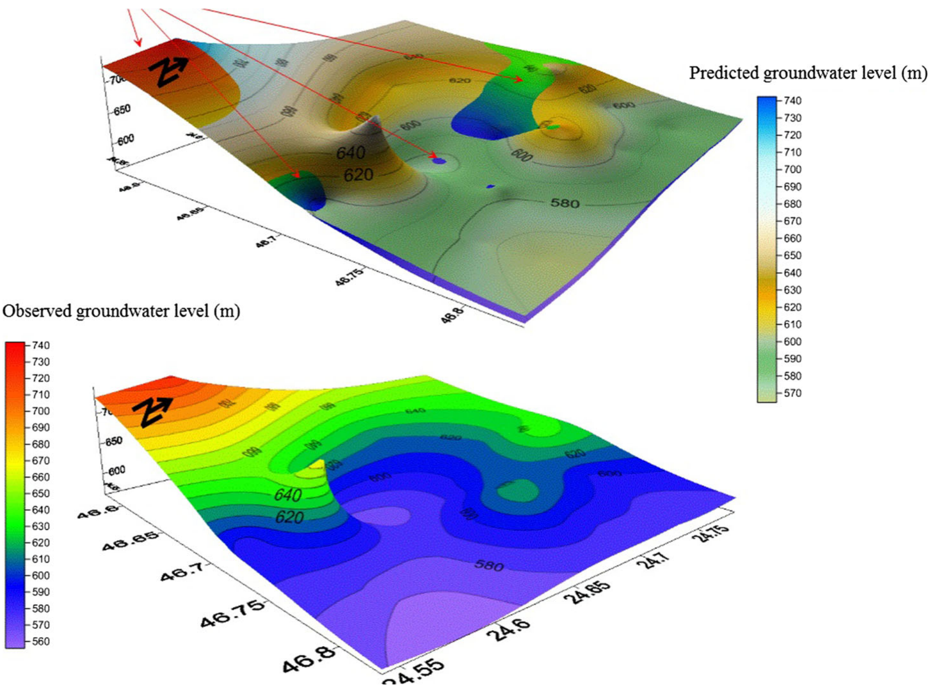


Fig. 9 3D view of isolines of both observed and predicted groundwater tables

observed grids is located in the southeastern part of the study area. This more uncertain estimate may be due to the smaller number of gravity point stations in this area, as well as additional non-gravity parameters related to the groundwater table. However, moisture, porosity and compaction effects on gravity values can be large and critical, especially if significant variations occur in different rock units.

4 Conclusions

The main objective of this research was to develop a technique for directly estimating the geospatial variation of groundwater from in-situ microgravity measurements. A case study was conducted in Riyadh, Saudi Arabia where gravity field changes were correlated with direct measurements of groundwater depth variation. Grav-Map, a small and lightweight gravimetry system capable of detecting gravity anomalies to an accuracy of ±1 μGal, was used for this purpose. The gravimetric survey was carried out at 42 station points close to existing observation wells, where the water table and depth to water were measured simultaneously. Our gravimetric anomaly map agrees with a regional gravity anomaly map previously drawn up for the Riyadh area. Superimposing an observed water-depth map on the zero first derivatives of relative gravity results gave an intersection area for shallow water depths with a significant correlation (75 %) depending on geology type, with the rest of the intersection area corresponding to greater water depth.

The good correlation between depth to groundwater and relative gravity shows that depth to groundwater is inversely proportional to relative gravity, and that the average relationship between them follows a polynomial 2nd order regression equation. The same correlation analysis applied to five local group areas, selected according to geological units, varied between 0.70 and 0.97 for group IV and group I, respectively. The variance among these strong correlations is due to rising groundwater filling voids and fractures in soil and rock, where additional groundwater mass tends to increase the rock density, and therefore relative gravity. With increasing depth to groundwater increases, rock density and thus relative gravity tend to decrease. These good correlation coefficients confirm that when closely-spaced gravity observation stations are used to detect small changes in gravity values, they reflect density contrasts underground. Our research proves that this technique can precisely and efficiently determine changes in subsurface geology and the depth to the water table. Taken periodically, these measurements could be utilized in detecting and tracing places with rising groundwater levels. Although this technique has proven good for estimating depths from the ground surface to the water table, gravity measurements do not correlate well with absolute water table levels. This may be due to local topographic variations and the small number of gravity point stations, as well as the fact that parameters in addition to gravity values may influence the water table. In future work, microgravity surveys should be integrated with other geophysical exploration tools, as well as simultaneous water table monitoring. In order to more accurately identify the parameters controlling the complex relationship between gravity and groundwater levels, our results need to be confirmed by conducting similar studies in other areas with different environmental conditions.

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