Modelling of Spatial and Temporal Variations in Groundwater Rest Levels in Nairobi City Using Geographic Information System

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Abstract

In the vicinity of Nairobi City, groundwater is extracted from more than 2,500 boreholes to supplement surface water supply. Reports of water rest level measurements in boreholes in certain localities indicate drawdown. There is a concern that the intensive and unsupervised water extraction will lead to depletion of groundwater in the aquifers and result in surface subsidence. The objectives of this study were to analyse the multi -temporal and spatial groundwater rest level variations during the last 8 decades and provide a geovisualization framework in Geographic Information System environment. The multi-temporal data was geospatially modelled and geostatistically analyzed. The continuous trend of falling groundwater rest levels in the aquifers beneath urban Nairobi was detected robustly and reliably from the modelling. Overlays of static level surfaces for the 1940s and 2000s decades expressed an average drop of 61.5 m. Considering that the fear of depletion is not fully backed by aquifer constants, such as the coefficient of storage and transmissivity of the individual aquifers that exist, more emphasis should be put on proper establishment of the capacities of individual aquifers on the basis of which conclusive decisions could be made regarding the management of groundwater in this region. There is also the need to continuously monitor the rest levels, to develop a numerical ground water model and to study the quality of groundwater from all aquifers in the study area.

Key words: Kenya, geographic information systems, static levels, groundwater management, groundwater monitoring.

1. INTRODUCTION

Nairobi City is the capital as well as the social, economic and communication hub of Kenya. The city is located on the eastern flank of the East African Rift Valley (Figure 1). It is mainly underlain by pyroclastic volcanic rocks intercalated with sediments that were deposited in a large lake or series of lakes that covered over 7,000 km² (Morgan, 1967). The study area bounds are λ [36º40′00″ - 36º55′00″] East, and φ [01º10′30″ - 01º25′00″] South, encompassing an area of close to 840 sq km. The general direction of the dendritic drainage network is West-East, with little structural control.

Public surface water supply for Nairobi City flows by gravity from Sasumua and Ndakaini dams located 50 km away. The bulk surface water supply is affected by reservoir siltation associated with catchment deforestation and by the poor state of the distribution system that results in about 50% losses due to leakage and illegal connections (Foster and Tuinhof, 2005). Due to the scarcity of the water, supply is rationed by closing some distribution lines while serving others. Heavy water users such as industries, business enterprises and individuals have drilled boreholes as back-up supply during such periods. To date, there are more than 2,500 boreholes in the City vicinity extracting water from aquifers at depths ranging between 20 and 280

Reports of water rest level measurements in boreholes in certain localities indicate that the levels have been falling. There is a public concern that the intensive and unsupervised water extraction will lead to depletion of groundwater in the aquifers and result in surface subsidence. The objectives of this study were to analyse the multi-temporal and spatial groundwater rest level variations during the last 8 decades and provide a geovisualization framework in Geographic Information System environment.

2. THE GEOLOGICAL SETTING

City of Nairobi lies within a volcanic setting that resulted from rift valley formation. Figure 2 gives the full extent of the study area. The volcanic rocks overlie metamorphic basement rocks of Neo-Proterozoic Era. The metamorphic rocks consist of ancient sediments that were metamorphosed as a result of high temperatures and pressures. Following the metamorphism and folding of the Basement System, the area was subjected to erosion lasting for more than 400 million years, leaving an erosion surface dated to end Cretaceous Age (Ministry of Works, 1987). In the Upper Miocene times, phonolitic lava flowed across the eroded Basement surface from the edge of the newly formed Rift Valley. This lava is known as Kapiti Phonolite since it underlies the Kapiti Plains. The Kapiti phonolite is a rock with large white crystals of feldspar and waxy-looking nephelines set in a fine-grained dark-green to black ground mass (Saggerson, 1991). Some exposures reveal the vesicular nature of parts of the phonolite and small patches of calcite and zeolite-filled amygdales are common (Gevaerts, 1964).

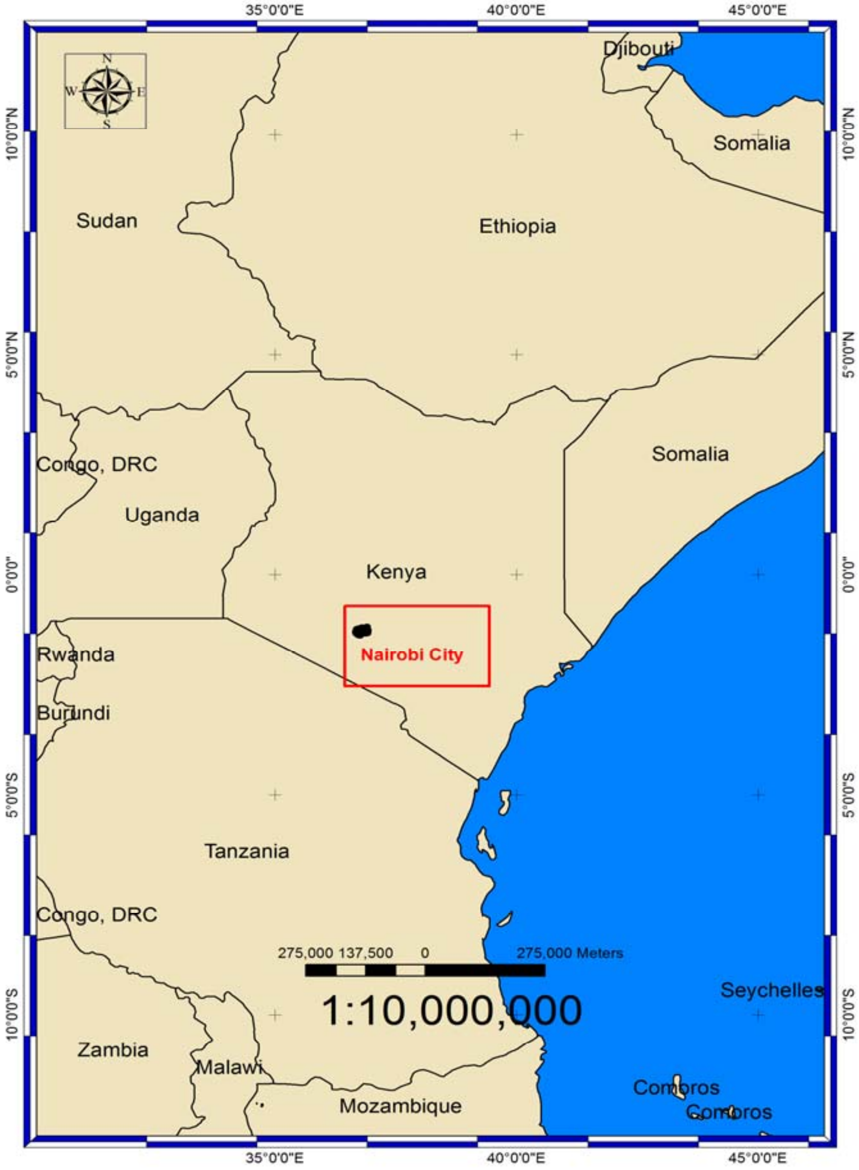

Figure 1: Location map of Nairobi City.

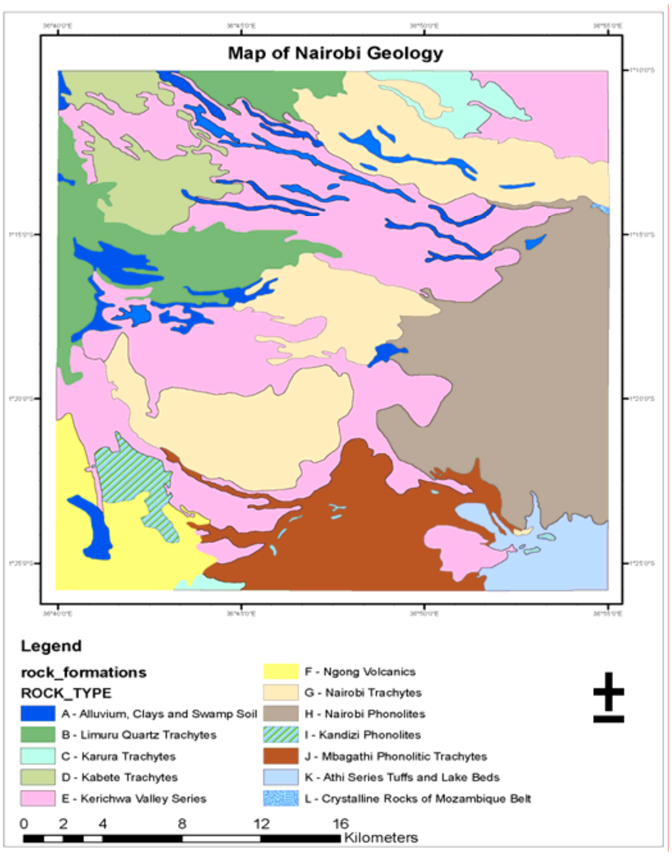

Figure 2: Geological map of Nairobi City

The Kapiti Phonolite is overlain by pyroclastic rocks with interbedded lacustrine sediments which were deposited in a large lake or a series of lakes that extended over an area of 7000 km². These rocks are referred to as Athi Tuffs and Lake Beds or simply as Athi Series. The colour of the tuffs ranges from black to grey to yellow but are generally fine-grained. The beds contain plant remains and show signs of desiccation. The Athi Series is divided into three parts: the Upper Athi Series, Middle Athi Series and Lower Athi Series. The Upper Athi Series (UAS) mainly consists of sandy sediments and tuffs, clays being subordinate. The Upper Athi Series also includes basalts, which are thin, intercalated black non-porphyritic flows. The UAS is generally soft and friable in character. A hard yellow tuff band (6 m) forms a good marker horizon. Generally, the series is characterized by the presence of obsidian but with much lateral variation.

In between the UAS is Mbagathi Phonolitic Trachyte, which is porphyritic lava with tabular insets of feldspar. The most striking feature of the Mbagathi Phonolitic Trachyte is its texture of crowded feldspar laths set in a gray-brown matrix, the colour of which is emphasized by rusty brown weathering and alteration products. In many places Mbagathi Phonolitic Trachyte is vesicular and the feldspars, which are up to a centimetre in length, are frequently flow oriented (Saggerson, 1991). Middle Athi Series (MAS) consists of basalt flows and basalts sands and agglomerates. The lavas show abundant insets of feldspar and the sands often have a clay matrix common (Gevaerts, 1964). Lower Athi Series (LAS) are predominantly clayey deposits between the basaltic Middle Athi Series and the uppermost flow of the Kapiti Phonolite (Saggerson, 1991).

Overlying the Athi Series rocks are the Nairobi and Kandizi phonolites**.** Nairobi Phonolite is dark-grey, porphyritic lava with tabular insets of feldspar and a few flakes of biotite. The lava is distinguished in drilling samples by the presence of biotite. The Kandizi phonolite is non-porphyritic lava with only very sporadic insets of feldspar, biotite being absent. The groundmass of Kandizi phonolite is like that of the Nairobi Phonolite. In some places, Nairobi Phonolite is overlain by Nairobi Trachyte. Nairobi Trachyte is greenish grey, occasionally porphyritic with tabular phenocrysts of feldspar. The groundmass is fine-grained with a silver lustre. Nairobi trachytes have great affinities to phonolitic rocks though lacking in nepheline. Ngong' Volcanics overlie Kandizi Phonolite and overlap onto the Mbagathi Phonolitic Trachyte. They are dark-grey lavas of basalt and nepheline interbedded with sands. In boreholes they occur immediately below Nairobi Trachyte.

Kerichwa Valley Series (KVS) is a group of pumice-rich trachytic tuffs and agglomerates younger than the Nairobi Trachyte. The tuffs overlie the Nairobi Trachyte and nearly every other older formation and have some resemblance to some of the Athi Tuffs and Lake Beds. The deposits of KVS buried a pre-existing landscape, the former valleys of which are now being re-excavated to reveal Nairobi Trachyte and Nairobi Phonolite. The tuffs range from cemented fine-grained, wind-sorted pumiceous ash to agglomeratic tuffs with rock fragments up to 0.5 m size. The tuffs are referred to as "agglomeratic tuffs" not agglomerates because of the larger proportion of fine material that forms the rock. The colour of Kerichwa Valley tuffs is generally yellow, grey or black.

The north of the study area is covered by Kabete Trachyte, Karura Trachyte and Limuru Quartz Trachyte. These trachytes overlie the Kerichwa Valley Series. Kabete Trachyte is greenish-grey porphyritic rock that weathers to soft grey colour and has similarities with Nairobi Phonolite. It has limited lateral extent and has a maximum thickness of 30 m in Kabete. Karura Trachyte is fine-grained, dull grey to lustrous rock, similar to Nairobi Trachyte but higher in succession and spotted when weathered

There are three main types of aquifers beneath Nairobi: aquifers in fractured volcanic rocks, aquifers in fluviatile sediments within volcanic rocks and aquifers in lacustrine sediments. In fractured volcanic rocks, aquifers with yields between 6-12 m^3/hr are common (Mailu, 1987). The tuffs and lavas give no supply being as a whole intact and impervious. The former may to some extent be porous but do not transmit water (Gevaerts, 1964). Important springs feeding the main rivers often issue from the contact between the soft and weathered rocks underlying impervious lavas (Saggerson, 1991). The aquifers of low yields are common in trachytes and phonolites where boreholes do not encounter any sediment as observed in north and south east of Nairobi (Mailu, 1987).

Table 1 gives the stratigraphic profile and a summary of the thickness ranges of the main geologic units as established from water supply borehole logs in Nairobi City.

Table 1: Geologic profile and summary of thickness ranges of geological units.

Age	Geologic unit	Thickness range (m)
Quaternary	Alluvium, clays and swamp soils	1.5-22
Pleistocene	Limuru Quartz Trachytes	0-25
Tertiary	Karura Trachytes	0-40
	Kabete Trachytes	0-32
	Kerichwa Valley Series	8-45
	Nairobi Trachytes	0-91
	Ngong Volcanics	0-58
	Nairobi Phonolites	0-110
	Kandizi Phonolites	0-60
	Mbagathi Phonolitic Trachyte	0-100
	Athi Series Tuffs and Lake Beds	16-305
	Kapiti Phonolite	0-53
Precambrian	Crystalline Rocks of Mozambique Belt	Extending beyond drilled depths

3. PREVIOUS WORK

Sikes (1934) reports Nairobi City as an area comprising of several swamps and that the first two boreholes were drilled in 1927 to depths of 20 and 22 m. The peak of drilling in pre-independence Kenya was in 1950-1951, when 169 boreholes were drilled all over urban Nairobi (Gevaerts 1964). As a result of intensive abstraction, groundwater rest levels in individual boreholes dropped rapidly; for example, the artesian pressure of one borehole in the Kamiti area (north-east of Nairobi City centre) fell by 13 m within four years after its completion. The drawdown was also apparent in other areas, such as Ruaraka and Karen, where the density of drilling and rate of abstraction were exceptionally high. Some boreholes such as C-2473 experienced a residual drawdown of 82 m after initial test pumping. In 1953, the Kenya Government declared Ruaraka and its immediate surroundings a conservation area with the objective of maintaining better control of groundwater resources. Outside the conservation area no restrictions of any kind were placed on borehole drilling except within a kilometre from any existing borehole.

Gevaerts (1964) monitored groundwater levels in various boreholes drawing from KVS and Athi Series aquifers in 1963. He noted that confined aquifers suffered loss of storage in Kahawa, Ruaraka and Athi River due to continuous large abstraction. However, water level rose in boreholes drawing from KVS aquifers after a rainy season indicating adequate replenishment. In 1972, the World Health Organisation (WHO) carried out a feasibility study on augmenting the Nairobi surface water supply with groundwater. It was found that the major problem of the groundwater was its characteristic high fluoride content (Hove, 1973). Hove (1973) also noted that the yield reported in old boreholes suffered the major limitation of representing the pump capacity. Also, the yield expressed is a function of the capacity of individual aquifers, and yet no effort had been made to measure capacity for each aquifer and its fluoride content. Mailu (1987) suggested two possible sources of high fluoride concentrations: the feldspathoids; or, the transportation of volcanic gases from Rift Valley along the faults.

Groundwater rest levels in the vicinity of Nairobi City were monitored monthly between 1971 and 1975. The monitoring was stopped in 1975 due to the lack of funds (Mwangi 2005). A more recent study by Foster and Tuinhof (2005) gives a report of biannual groundwater level measurements in a 275 m deep borehole during the period of 1958-1996. The borehole showed a decline that started in 1970 and reached up to 40 m in 1996. Groundwater level hydrographs of measurements made in some selected boreholes in the period 2006-2008 also point to a declining trend. As a result, there has been a concern that the amount of groundwater being extracted by the existing 2,500 boreholes could lead to depletion of aquifers and ground subsidence.

Monitoring water level fluctuations in observation wells is considered as the principal source of information of the hydrologic stresses on a groundwater system. Both short term and long term records are invaluable in understanding the state of the groundwater system and in addressing problems that might develop in response to groundwater abstraction and changes in land use (Taylor and Alley, 2001). However, most aquifer properties, such as transmissivity, specific storage, storativity and storage capacity for the study area are calculated from test pumping without observation in the nearby wells. The transmissivity values are in the range of 0.000181 to 0.083 m^2/day, while storativity values are in the range of 0.00063 to 0.0549.

There are three main types of aquifers in the study area as follows: aquifers in fractured volcanic rocks; aquifers in fluviatile sediments within volcanic rocks; and, aquifers in lacustrine sediments. The tuffs and lavas give no supply being as a whole intact and impervious. The former may to some extent be porous but do not transmit water (Gevaerts, 1964). Important springs feeding the main rivers often issue from the contact between the soft and weathered rocks underlying impervious lavas (Saggerson, 1991). The aquifers of low yields are common in trachytes and phonolites where boreholes do not encounter any sediment as observed in north and south east of Nairobi (Mailu, 1987). The storage capacities of the aquifers are in the range of 0.5 and 8 m^3/hr/m. The following are depth ranges within which one would expect to encounter an aquifer: 10-30 m (Limuru Trachytes, Kabete Trachyte, Karura Trachyte and Kerichwa Valley Series), 40-48 m, 76-134 m (Nairobi Trachyte, Nairobi and Kandizi phonolites and Mbagathi Phonolitic Trachyte), 138-144 m, 150-162 m, 170-180 m, and 196-220 m (Athi Tuffs and Lake Beds). The rest level measurements made and aquifer properties calculated are a function of all aquifers.

Whereas the previous studies of groundwater rest level variations in Nairobi City have indicated a decline in certain localities, they have not provided a general picture of the spatial variations. The main objective of this study was to investigate groundwater rest level variations in space and time using Geographic Information System (GIS). The use of GIS in this study was to enable analysis of the spatial and temporal groundwater rest level variations because it provides a complete analysis and processing framework as well as visualisation in 2-D and 3-D. These GIS analysis capabilities facilitate the necessary multi-temporal and spatial digital investigations required, thus the outcomes can be used for future groundwater planning and monitoring (Cohen 2005; Ta'any *et. al.* 2009).

4. METHODOLOGY

Because of variation in personnel and reporting procedures over the study period (roughly 80 years), discrepancies were evident in the way in which the borehole locations and aquifers were reported. For all boreholes drilled before 1990, the position was identified based on existing topographic contour map such that the accuracy of the planar positioning was usually less than 100 m. The positions of boreholes drilled after 1990 were reported using the Global Positioning System (GPS) measurements with an accuracy of around 10 m in their planar positioning. Water level readings used in this study are those measured two weeks after drilling just before test pumping and were taken using a dip meter with an accuracy of about 10 cm.

To eliminate geospatial analysis problems that could be related to the borehole locations, a preliminary quality assurance was carried out on the raw data from all 2,500 boreholes by plotting them on a map of the area. Data points that plotted on positions inconsistent with location name in records were rectified where possible or otherwise eliminated. Boreholes without rest level records were also eliminated. Due to the fact that the boreholes are not evenly spaced and that no continuous measurement of groundwater rest levels for all boreholes exists (each borehole has a specific single 'time-stamp' reading), a straightforward method was devised whereby boreholes were grouped in terms of the decades in which they were drilled. Each borehole drilled in a certain decade would consist of a single point on the rest level surface for the temporal analysis of groundwater level variations. Correspondingly, rest level measurements starting from late 1920's and ending in 2010 were divided into 7 decade-epochs. Observations for the 1960's and 1970's were few and were thus combined and considered as a single epoch.

Groundwater level in each borehole was taken under consideration with its surrounding for the geostatistical analysis. It is worth noting that two steps of interpolation were implemented as follows:

- Step 1: Interpolation of terrain elevation at the borehole position from a given Digital Terrain Model (DTM); and
- Step 2: Interpolation of groundwater rest level surface from the measured rest levels in boreholes for a specific epoch (e.g., decade).

In the absence of precise altitude measurements at borehole positions, an Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) 1" (approximately 30 m) planar resolution DTM was used as terrain reference for elevation at borehole location. This DTM is geo-referenced to the WGS84 geoid with an estimated vertical accuracy of 8 m at 68% confidence, and 12 m at 68% confidence for the horizontal one. Each borehole position was registered to the DTM for calculating its precise height (elevation), thus enabling a precise geospatial modelling to take place. The assumption in this approach was that no terrain modification - or very little - had occurred during the decades analysed. The terrain heights at all borehole positions were obtained in reference to the recently generated DTM. Since borehole position and the DTM have different resolutions, an interpolation was carried out in order to calculate the exact and precise terrain height. Bi-linear surface interpolation was carried out for each DTM local grid cell-plane that has a borehole position, as depicted in Equation 1 (Burrough and McDonnell, 1998).

$$z(x,y) = a_0+a_1\cdot x+a_2\cdot y+a_3\cdot x\cdot y \tag{1}$$

Where,
a_i $[i \in 0:3]$ are the coefficients derived from the four corners heights of the local cell-plane,
(x,y) is the normalized position within the DTM cell, and,
$z(x,y)$ is the predicted value at location (x,y).

For interpolation of the water "surface", the accuracy of the methods depend on the distribution of the reference points (rest levels), and the interpolation's underlying mathematical assumptions. Since the hypothesis here is that groundwater rest level should present a phenomenon that is continuous and smooth by nature, the geostatistical interpolation method chosen in the vicinity of the borehole has to maintain this hypothesis. Interpolation mechanisms can be divided to two groups: deterministic ones, which do not consider the natural phenomenon and data characteristics within the interpolation mechanism, and, stochastic mechanisms, which consider both the data properties and natural phenomenon throughout the whole process of interpolation. Both methods are widely implemented in reality when interpolating groundwater levels (Goovaerts, 2000; Meyer, 2006). Still, it should be emphasized that all methods rely on the similarity of nearby reference sample points to create the surface of the groundwater rest level.

There are a number of interpolation methods available (Lam, 1983) but one of the most frequently used interpolation method in GIS is Kriging (Siska and Hung, 2008). In Kriging, interpolation estimates are made based on values at neighbouring locations plus knowledge about the underlying spatial relationships in a data set. Variograms provide knowledge about the underlying relationships. Kriging is usually superior to other means of interpolation because it provides an optimal interpolation estimate for a given coordinate location, as well as a variance estimate for the interpolation value (ESRI, 2004). Bancroft and Hobbs (1986) analyzed the distribution of Kriging errors based on deviation from normal distribution. They found that Kriging interpolation offered reliable results.

The sample correlation states that the distance and direction between sample points are the major factors governing the estimated values at unknown points (Gold, 1989). The weights values are calculated by taking into account spatial structure of data distribution represented by the sample variogram derived by the distances between boreholes. Formulation of Kriging is depicted in Equation 2.

$$\lambda Z(s_0) = \sum_{i-1}^{n} \lambda_i \cdot Z(s_i) \qquad (2)$$

Where, n is the number of samples used for the estimation; $Z(s_i)$ is the sample value at location s_i; λ_i is the unknown weight for the measured value at location s_i (determined using the fitted Variogram); and, $Z(s_0)$, is the predicted value at location s_0.

After the interpolation by Kriging, groundwater "surfaces" were generated for each of the seven epochs. Because of the difference in elevation between the eastern and the western extremes, it was easy to identify some boreholes that were plotted at wrong locations because they showed significant anomalous peaks in respect to their surroundings. A filtering process was carried out by indentifying the boreholes represented by these peaks, and counterchecking with the information in records and positions plotted on hard copy maps after drilling. Approximately, 10% of data points were found to be plotted at different locations on the hard copy maps and GIS. In most cases these sample points were eliminated from analysis because it was not possible to determine their true position on the ground. After this stage, 771 boreholes were found to be valid for GIS analysis. Table 2 shows a list of the number of boreholes analysed per decade

Table 2: Number of boreholes per decade analysed in GIS framework

Decade	Number of boreholes
1927-1939	20
1940-1949	101
1950-1959	133
1960-1979	32
1980-1989	61
1990-1999	210
2000-2009	214

Other significant peaks in the generated groundwater surfaces were found to be related to the method of reporting locations, mainly approximation on maps (and rarely only GPS measurements), that could result in an error in position of up to 300 m. After omitting or rectifying sample data points affected by the above-mentioned error factors, modelling of the "surface" of groundwater for all epochs and regeneration of spatial models was done to represent the variation in groundwater rest levels in space and time. Visualization of the groundwater surface in 2-D and 3-D was generated for the various decades with due regard to the structural geology and hydrogeology of the borehole locations.

5. RESULTS AND DISCUSSION

Figure 3 depicts the DTM with an outline of the study area (blue) on which the sample boreholes data points are superimposed; each point's colour corresponds to a certain decade. It can be observed that the data points are fairly representative of the study area. There is a global correspondence between the rest levels measurements and the local terrain as well as the general west-east trend of the drainage network. The ground slopes from west to east with a height difference of 650 m between north-west and south-east. This slope trend is also reflected in the groundwater rest level of boreholes. Because the total drilled depth of boreholes has been increasing over time, newer boreholes tap more aquifers and tend to have higher potentiometric surfaces. When such boreholes are plotted side by side with older boreholes, the rest level surfaces are found to be closer together.

Figure 4 depicts a section of a groundwater surface presented as contour lines produced by Kriging interpolation of rest level data for the decade that ended in 1990. The figure includes a superimposition of the 10 m contour interval groundwater rest level surface (in black), existing rivers (in blue), a buffer of 100 m layer based on the position of rivers (in light blue), the borehole identities in that area (in purple) and, study area outline (blue). Some local peaks that can be related to the structural geology are observed. For instance, the south-western part of the area has several faults that act as recharge paths thus producing groundwater rest level anomalies. Borehole 4735 (highlighted on the map) has a rest level that is almost 100 m higher than the levels in the surrounding boreholes. River influence is also observed in certain boreholes, such as boreholes 5018 and 4876 (highlighted on the map), where groundwater rest levels are in the range of 30 to 60 m higher than those in the surrounding boreholes.

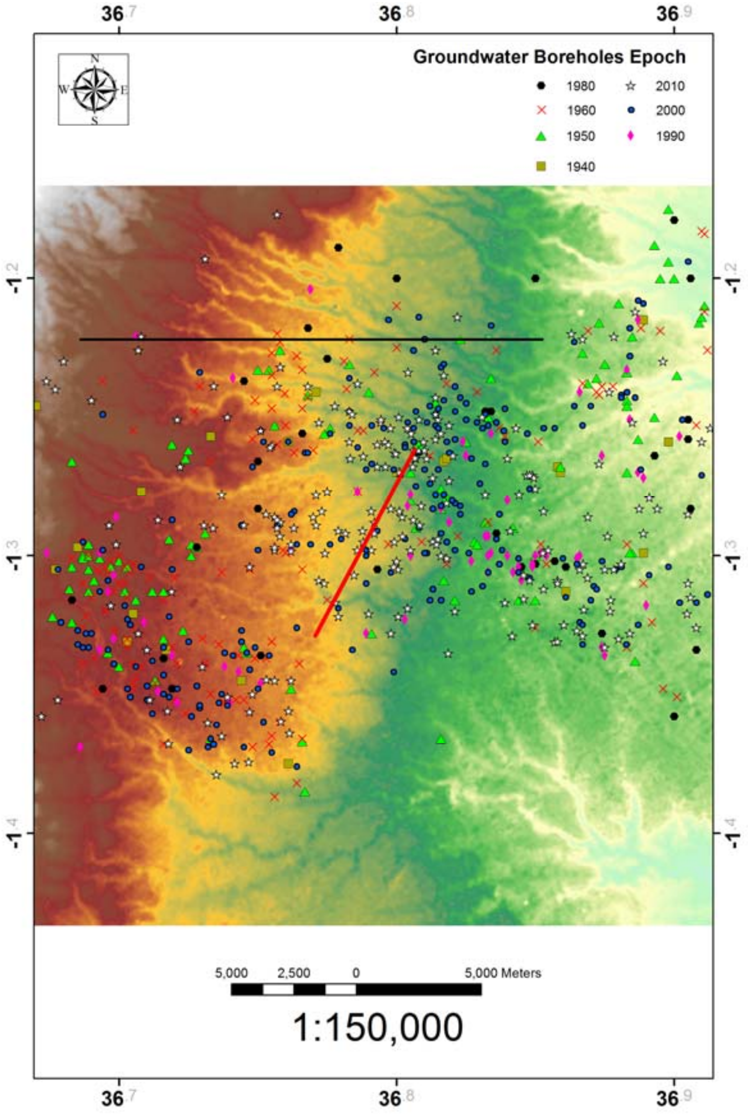

Figure 3: Sample boreholes superimposed on DTM

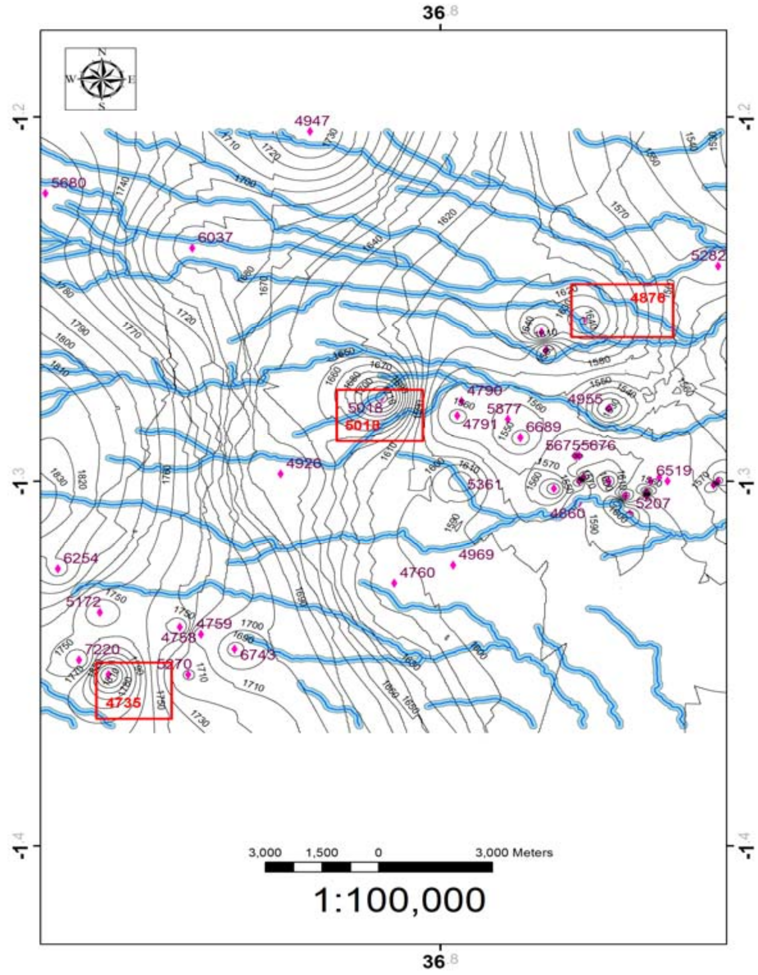

Figure 4: 10 m Contours of groundwater surface

Figure 5 depicts profiles of groundwater surfaces along a 20 km distance for decades ending in 1950 (in blue) and 1990 (in green) as compared with the terrain (in brown). The planimetric extent of this profile is also depicted in black in Figure 3. The 1950 profile is closer to the terrain with an average altitude difference of 50 m, while the 1990 profile is further away from the terrain with an average altitude difference of 70 m. This indicates an average drop of 20 m between 1950 and 1990. This trend is explainable as it represents a 40-year period in which the number of boreholes in the city increased from 300 to 1,800.

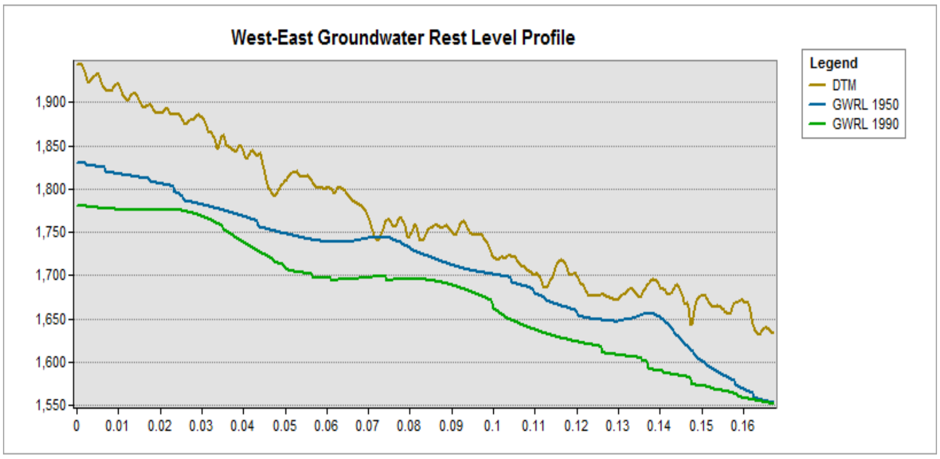

Figure 5: West-East profile of 1950 and 1990 groundwater rest level surfaces, and terrain (brown). (X-axis in decimal degrees, Y-axis in metres)

Figure 6 shows a superimposition of 3-D groundwater rest level surfaces of 1950 and 2010 together with rivers for the area outlined in Figures 3 and 4. Within nearly the entire analysis area, the 1950 groundwater rest level surface is above the one for 2010. When considered together, Figures 5 and 6 demonstrate that the groundwater rest level descended over the 60- year period: before 1950, through 1990 to 2010. The exposed 2010 surface to the North-West part of the area on Figure 6 is the result of missing data points for the decade that ended in1950. The two peaks from the 2010 surface that are visible in the centre were explained by high precipitation that preceded drilling of the two boreholes leading to localized rises in rest level. Table 3 shows the statistics of the height difference between the 1950 and 2010 surfaces in Figure 6 after omitting the exposed 2010 surface. From this table, it is clear that the majority of the area is experiencing a descent in groundwater rest level, with a mean value of 61.5 m, and a standard deviation of 30.2 m

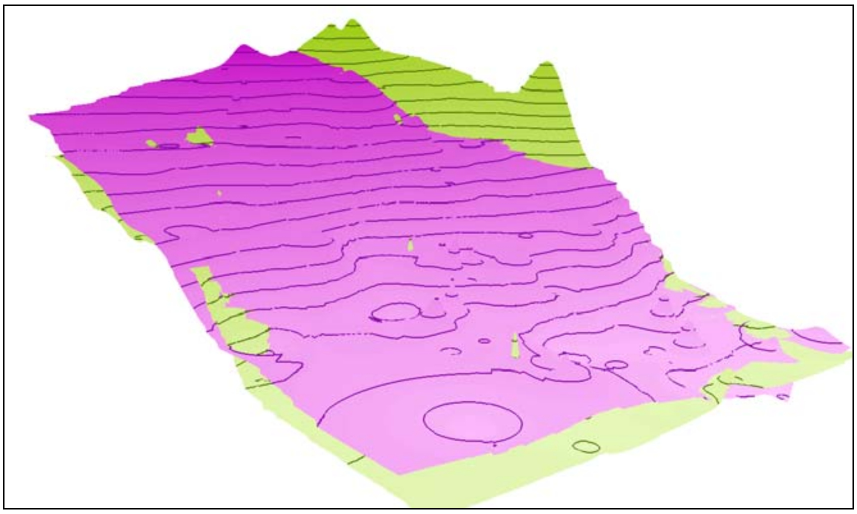

Figure 6: 3-D Superimposition of 1950 (pink) and 2010 (green) groundwater rest level surfaces.

Table 3: Statistics for height difference values between 1950 and 2010 r rest level surfaces

	Value in meters (1950-2010)
Max	196.9
Min	-26.4
Mean	61.5
STD	30.2

Figure 7 depicts profiles along a 10 km distance for three surfaces representing groundwater rest level of 1950 (in blue), 1990 (in green) and 2010 (in red) against the terrain (in brown). The planimetric extent of this profile is also depicted in red in Figure 3.

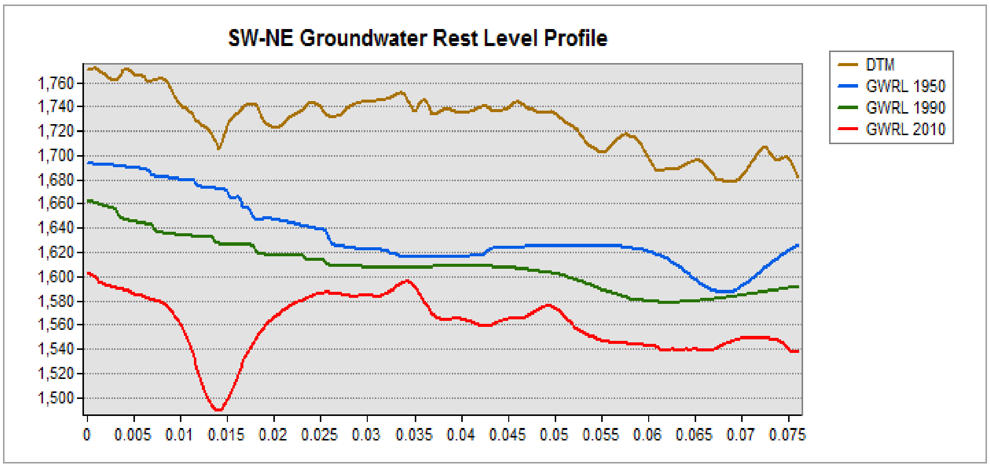

Figure 7: South-West – North-East profile of 1950, 1990 and 2010 groundwater rest level, and terrain. (X-axis in decimal degrees, Y-axis in metres)

By comparing the profiles, it is clear that there exists a clear groundwater rest level drop, as quantified in Table 3. The huge depression on the 2010 profile represents Ngong' Road, where disappearance of fluids during drilling is common and thus could be representing a fault. This depression aside, there exists high altitude correlation of all three profiles along the profile, depicting consistent descent of groundwater rest levels for the durations under analysis.

6. CONCLUSIONS AND RECOMMENDATIONS

Modelling of groundwater rest level variations in aquifers beneath urban Nairobi as a result of intensive abstraction was carried out in GIS environment. GIS analysis capabilities together with 2-D and 3-D geovisualization of spatio-temporal models are useful in eliminating erroneous sample data points as well as enabling integration of other data resources.

During the 80 years of active groundwater abstraction, records for continuous water level monitoring accounted for only six years. In the absence of time-series data, boreholes were grouped into various decades corresponding to the time they were drilled while water rest levels taken as those recorded two weeks after drilling and just before test pumping. The spatial positioning of boreholes with their groundwater rest level for various decades on the DTM together with 2-D and 3-D groundwater surface modelling indicate a clear trend of descent of groundwater rest levels in aquifers beneath urban Nairobi. Further analysis of Kriging geostatistical estimators considering the quality of the interpolated surfaces could be used to derive measures in regard to the reliability and accuracy of the results. To produce good groundwater rest level models that can be overlaid to study the trends, it is necessary that all parts of the test area are represented in all decades. However, drilling trends in the urban Nairobi vary from time to time leading to concentration of data for some localities in certain decades.

The investigation has revealed that many aquifers exist at various depths and their capacities are varied. Considering that the fear of depletion is not fully backed by aquifer constants, such as the coefficient of storage and transmissivity of the individual aquifers that exist, more emphasis should be put on proper establishment of the capacities of individual aquifers on the basis of which conclusive decisions could be made regarding the management of groundwater in this region. Some boreholes should be drilled for purposes of observation only, especially in the vicinity of meteorological stations, so as to estimate natural recharge and determine safe yield. If separate pumping is done from each individual aquifer, calculations of the effects of pumping and the aquifer constants would be made. There is also the need to continuously monitor the rest levels, to develop a numerical ground water model and to study the quality of groundwater from all aquifers in the study area.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. Bancroft B A, and Hobbs G R, 1986, *Distribution of Kriging Error and Stationarity of the Variogram in a Coal Property*, Mathematical Geology 8(7):635-651.
2. Burrough P A, McDonnell R A, 1998, *Principals of Geographical Information Systems*, Oxford University Press.
3. Cohen K M., 2005, *3D Geostatistical Interpolation and Geological Interpretation of Palaeo-groundwater rise within a Holocene Coastal Prism, in: L Giosan and J P Bhattacharya (Eds) River Deltas - Concepts, models, and examples*. SEPM Special Publication 83, pp. 341-364.
4. ESRI. Environmental Science Research Institute, Inc., 2004, ArcView software.
5. Foster S S D and Tuinhof A, 2005, *The Role of Groundwater in the Water Supply of Greater Nairobi, Kenya,* World Bank, GW-MATE Case Profile No. 13, March 2005.
6. Gevaerts E A L, 1964, *Hydrogeology of Nairobi Area*. Survey of Kenya Technical Report No. 59.
7. Gold C M, 1989, *Surface Interpolation, Spatial Adjacency and GIS, Three Dimensional Applications in Geographical Information Systems*, Taylor and Francis, pp. 21-35.

8. Goovaerts P, 2000, *Geostatistical Approaches for Incorporating Elevation into the Spatial Interpolation of Rainfall*, Hydrology, 228, pp. 113–129.
9. Hove A, 1973, *Sectoral Study and National Programming for Community and Rural Water Supply, Sewerage and Water Pollution Control*, Report No. 7, Groundwater Resources in Kenya, World Health Organization, Brazzaville.
10. Lam N S, 1983, *Spatial Interpolation Method: A Review*, American Cartographer 10:129-220.
11. Mailu J, 1987, *Hydrogeology of the Upper Athi Basin*, MSc. Thesis, University of Nairobi
12. Meyer C, 2006, *Evaluating Water Quality using Spatial Interpolation Methods*, P2085: ESRI, USA.
13. Ministry of Works, 1987, *Foundation Conditions in Nairobi City Centre*, Materials Branch Report No. 182, Nairobi.
14. Morgan W T W, 1967, *Nairobi: City and Region*, London, Oxford University Press.
15. Mwangi L W, 2005, *Water and Sewerage Services: Nairobi City Council*, Integrated Water Resources Management Seminar in Kenya, pp. 110-121.
16. Saggerson E P, 1991, *Geology of the Nairobi Area*, Degree Sheet No. 51, Survey of Kenya.
17. Sikes H L, 1934, *Underground Water Resources of Kenya Colony*, London: Crown Agents.
18. Siska P P and Hung I K, 2008, *Assessment of Kriging Accuracy in the GIS Environment*, Proceedings of ESRI User Conference, A professional Paper. On
19. http://proceedings.esri.com/library/userconf/proc01/professional/papers/pap280/p280.htm
20. Ta'any R, Tahboub A, and Saffarini G, 2009, *Geostatistical Analysis of Spatiotemporal Variability of Groundwater Level Fluctuations in Amman–Zarqa Basin, Jordan: a case study, Environ,* Geology, 57, pp. 525-535.
21. Taylor C J, and Alley W M, 2001, *Ground-water Monitoring and the Importance of Long-term Water-level Data*, U.S Geological Survey Circular 1217, 68p.

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