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EFFECTS OF DRILLING DEEP TUBE WELLS IN THE URBAN AREAS OF NAIROBI CITY, KENYA

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ABSTRACT

The number of boreholes for abstracting water from aquifers beneath Nairobi City increased from 2 in the year 1927 to about 2500 in the year 2009. According to the Republic of Kenya Population and Housing Census, the urban population of Nairobi City increased from 29,864 in 1928 to 3,138,295 in 2009. Substantial groundwater drawdown has been noted in individual boreholes that supply the growing population in some localities. The purpose of this study was to investigate the variation in water rest levels across Nairobi City during the 80 year period and estimate the surface settlement that can result from groundwater exploitation. The groundwater static level variations in space and time were analysed on Surfer 9 software and the average rest levels in boreholes between 1927 and 2009 were calculated. Using the hydrogeological data obtained from drilling, an estimate of ground settlement that could result from continuous drawdown was made from formulae obtained from past studies done elsewhere. The results indicate that that the groundwater rest levels have dropped with an average of 79 m in the last 80 years and a probable settlement of 0. 34 m to 5.9 m could result from groundwater depletion from aquifers and clay aquitards over a long period of time. Between the ground surface and the clay aquitards are the dense Nairobi Phonolite and/or Nairobi Trachyte. The probable settlement of 5.9 m should serve as a wakeup call to put up measures that can mitigate subsidence and the related consequences in Nairobi City. Indeed, 67% of the drop in rest levels has occurred in the last two decades during which more than 1000 additional wells have been drilled.

Keywords: tube wells, groundwater, abstraction, static level, settlement.

1. INTRODUCTION

Development of Nairobi City (shown on Figure-1) started in 1899 during the construction of the Kenya-Uganda Railway Line. The rail line survey team was the first group to pitch tents beside the crystal clear water after working through dry arid areas. Building of permanent structures began when it was decided that Nairobi be made a storage depot for railway construction materials. With the depot acting as the nucleus, the population started to grow and, by 1905, Nairobi became the capital of Kenya with a population of about 10 000 people. It became a municipality in 1919 and a city in 1950 (Mwangi, 2005). The Nairobi City boundaries have since been revised at least five times.

Exploration and drilling for groundwater in Kenya began in December 1927 when the first two wells were drilled to depths of 20 m and 22 m. By 1934, 190 such boreholes had been drilled (Foster and Tuinhof, 2005). The peak of drilling in pre-independence Kenya was in 1950-1951 due to change of the Water Act introducing subsidy for drilling of boreholes. One hundred and sixty nine (169) tube wells were drilled in two years and intensive abstraction of groundwater took place all over Nairobi City. The artesian pressure of one borehole (C-2321) in Kamiti zone (Figure-2) fell by about 13 m within four years after completion. The fall of the pressure in the years after completion of the borehole is a feature not due to depletion at the intake, but due to depletion of storage (Foster and Tuinhof, 2005).

In 1953, the Kenya Government declared Ruaraka area and its immediate surroundings a conservation area, with the object of maintaining a better control of the groundwater resources (Gevaerts, 1964). A groundwater observation network was established within the conservation area. In 1958, the conservation area boundaries were extended to include the peri-urban areas around Nairobi City and part of Kamiti area. Outside the conservation area no restrictions of any kind were placed on boreholes that were drilled more than a kilometre from any existing borehole (Foster and Tuinhof, 2005). But in the conservation area, no borehole would be sunk and no groundwater was to be abstracted without the permission of the Water Apportionment Board.

Gevaerts (1964) observed water levels in various boreholes drawing from Kerichwa Valley Series and Upper Athi Series aquifers in 1963. The following were noted during the observation:- confined aquifers suffered loss of storage in Kahawa, Ruaraka and Athi River station due to continuous large abstraction; rest levels for boreholes drawing from Kerichwa Valley Series aquifers rose after a very rainy season while majority of boreholes in the Upper Athi Series showed a fall in rest levels; and, several boreholes with large abstractions that showed depressions in pressure surface had no recovery of water level after twelve hours of monitoring. He concluded that depressions were permanent and attributed the falls to depletion of storage and permanent compaction.

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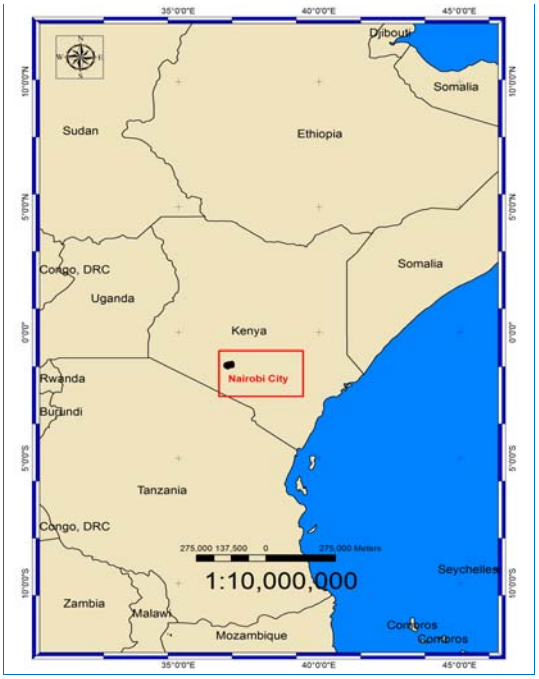

Figure-1. Location map of Nairobi City.

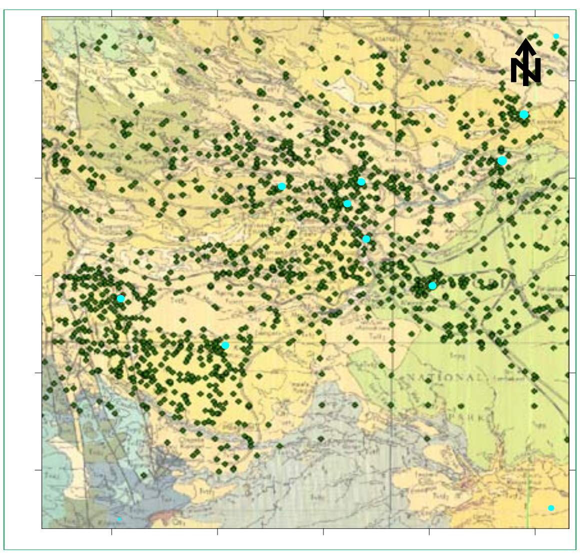

Figure-2. Borehole distribution on the geological map of Nairobi City.

Explaining further this phenomenon of permanent compaction in aquifers is a study by Poland *et al*. (1972). They note that the usable storage capacity of the aquifer system, defined as the volume that can be taken from or recharged to the system, is not changed appreciably by the compaction of the aquitards but the specific storage is greatly reduced for later cycles. As fluids are withdrawn from porous media, pore-fluid pressures decrease. Because deformation of porous media is controlled by effective stress, a decrease in pore-fluid pressure causes a decrease of pore volume. When effective stress exceeds the yield strength of the granular skeleton of the media, the compaction is permanent and irreversible.

World Health Organisation (WHO) carried out a feasibility study on augmenting the Nairobi surface water supply with groundwater in 1972. The major problem of the groundwater was found to be the characteristic high fluoride content. The possibility of blending the groundwater and surface water to make it suitable for drinking purposes was studied (Hove, 1973). City Council of Nairobi adopted the findings by WHO and drilled a number of wells to supply certain sectors of the city that were not connected to the main distribution system. By 1985, most of these boreholes were closed down and the corresponding areas shifted to surface water supply. This shift was related to increase in pumping costs and deterioration of water quality (Foster and Tuinhof, 2005).

Before large-scale groundwater development took place in Nairobi City, there used to be water flow within the aquifers from the west through the deep, confined aquifer section. The flow emerged in the east near Athi River and boreholes drilled to Kapiti Phonolite (e.g. C-252 and C-498) encountered artesian conditions at the contact with the Athi tuffs and sediments (Saggerson, 1991). Biannual water-level measurements in a 274 m deep borehole (C-2730) during 1958-1996 by a private company show a decline starting in 1970 and reaching 40 m in 1996. Comparison of data from the Ministry of Water and Irrigation for new water wells drilled at different dates during the period 1950-1998 also indicates a substantial lowering of groundwater level in the upper aquifer units (Foster and Tuinhof, 2005). The number of boreholes for abstracting water from aquifers beneath Nairobi City increased from 2 in the year 1927 to about 2500 in the year 2009. According to the Republic of Kenya Population and Housing Census, the urban population of Nairobi City increased from 29,864 in 1928 to 3,138,295 in 2009. Extensive groundwater abstraction has led to drawdown is some localities and in individual boreholes. The purpose of this study was to investigate the variation in water rest levels during the 80 year period and estimate the surface settlement that can result from groundwater exploitation.

2. GEOLOGY OF NAIROBI

Nairobi City lies within a volcanic setting that resulted from rift valley formation. The stratigraphic profile is as follows starting from the oldest (Saggerson, 1991): metamorphic rocks of Neo-Proterozoic Era that are folded and faulted; an erosion surface dating end Cretaceous Age that was formed when the area was subjected to erosion lasting for more than 400 million years; Upper Miocene rock with large white crystals of feldspar and waxy-looking nephelines set in a fine-grained dark-green to black ground mass known as known as Kapiti Phonolite; 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 (Matheson, 1966) referred to as Athi Tuffs and Lake Beds; porphyritic lava with tabular insets of feldspar (Mbagathi Phonolitic Trachyte) found intercalated within Athi Tuffs and Lake Beds; dark- grey porphyritic lava with tabular insets of feldspar and a few flakes of biotite (Nairobi Phonolite) or non-porphyritic lava with only very sporadic insets of feldspar, biotite being absent (Kandizi phonolite); greenish grey, occasionally porphyritic rock with tabular phenocrysts of feldspar (Nairobi Trachyte); dark-grey lavas of basalt and nepheline interbedded with sands (Ngong' Volcanics); and, a group of pumice-rich trachytic and agglomeratic tuffs known as Kerichwa Valley Series. 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 (Saggerson, 1991). Because this succession of rocks is made of flows that originated from different volcanic centres, not all of them can be encountered in a single borehole.

3. MATERIALS AND METHODS

Hydrogeological data and drillhole records for the 1600 water supply wells were used in this study. The borehole location coordinates were converted to comma separated values (CVS) after which they were transferred to Notepad. Using the data in Notepad, the borehole positions were plotted on the geological map in GIS environment to express their density as shown in Figure-2.

For analysis of the stratigraphy, a preliminary quality assurance was carried out on the raw data for 900 boreholes that had been drilled by different companies and over a long period of time. Discrepancy in interpretations of even the same stratum and the way in which borehole locations were recorded was evident. All poorly logged wells were not used in the analysis. To eliminate problems that could be related to borehole location, data points that plotted on positions in disagreement with location name in records were rectified where possible or eliminated. Boreholes without rest level record were also eliminated. In the end, 457 borehole logs were found suitable for use in the analysis of stratigraphy. The general subsurface profile as well as the thickness and aerial extents of the various geological units were analysed from the 457 drillhole logs. Positions of the 457 boreholes were plotted on the map so as to ensure that all the geological units covering the study area were represented in the profiles.

To harmonize the different interpretations of the same rock type by different drillers, entire borehole log profiles were typed in worksheets. The profile descriptions were then interpreted in reference to 29 cross sections prepared by Gevaerts (1964). Each drill hole log consisted of the following information: borehole identity (BHID); geographic coordinates (x,y); thickness of the stratum (from-to); the name of the geologic unit (formation) or hydrogeologic unit identity (HGUID) as well as description of the formation and code (HGUcode). Subsurface profiles for the individual boreholes were plotted using Strater 3 software (by Golden Software) and compared at several locations across the area to provide a sight into the subsurface. To establish historic variation in the shape of the groundwater surfaces in two dimensions, water rest levels in relation to sea level for the various decades were plotted as contours on Surfer 9 software (by Golden Software). The information required for plotting the Surfer contours included borehole identity, coordinates and water rest level. This information was filtered in a GIS analysis where many of the erroneous data was eliminated. The trends in the Surfer contours enabled identification of the changes in rest levels over the 80-year period.

Calculation of settlement due to groundwater withdrawal was carried out bearing in mind that consolidation due to groundwater withdrawal comprises both elastic and inelastic changes. The elastic consolidation of an aquifer refers to the compaction that can be recovered after the induced stress is lifted. This consolidation of the confined aquifer is related to its storativity and compressibility. Using subsurface profiles for 307 boreholes, the confined system in the study area was divided into aquifers, aquitards and hydraulic separators. Although the method of reporting aquifers differs from driller to driller, the average thickness of the clay layers (aquitards) within the Kerichwa Valley Series, Athi Tuffs and Lake Beds and Old Land Surfaces is 53 m. Considering a homogeneous, isotropic and horizontal confined aquifer, assuming that the stress increment producing the abnormal fluid pressure was vertical only and that the individual solid component making up the rock is incompressible, from Jacob (1940),

$$S_s = \rho_w\, g\, (\beta_p + n\, \beta_w) \tag{1}$$

Where,
S_s = the specific storage; ρ_w = the density of water; g = gravitational acceleration; β_p = the bulk compressibility of the rock; n = the porosity of the aquifer; β_w = is the compressibility of the water (4.6×10^{-10} m²/N).
Storativity is the product of specific storage and aquifer thickness:

$$S = S_s\, m = \rho_w\, g\, m\, (\beta_p + n\, \beta_w \tag{2}$$

Where,
m = thickness of the aquifer
By definition (Domenico, 1983) rock bulk compressibility is:

$$\frac{\Delta m}{m} = \beta p\ \Delta \sigma = \beta p\ \Delta P \tag{3}$$

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Where,
Δm = layer thickness change; $\Delta\sigma$ = effective stress change; ΔP = Fluid pressure change.

Combining Equations (2) and (3) and solving for Δm gives the elastic subsidence change of a confined aquifer,

$$\Delta m = \Delta P\left(\frac{S}{\rho_w g} - nm\ \beta_w\right) \quad (4)$$

Inelastic compaction refers to the compaction that cannot be recovered after the stress is lifted. It mainly occurs in the confining layers. The maximum subsidence amount in response to the water Table drawdown in aquitards is given by Domenico and Schwartz (1998) and Cernica (1995) as:

$$\Delta m' = S_s' m\left(\frac{\Delta h_1 + \Delta h_2}{2}\right) \quad (5)$$

Where,
$\Delta m'$ = the thickness change of the confining layer; S_s = the specific storage of the confining layer; m = the thickness of the confined aquifer; Δh_1 and Δh_2 = the head change in the upper and lower confining beds.

The total settlement expected is the sum of elastic and inelastic consolidation if the rest levels fall without recovery.

4. RESULTS AND DISCUSSIONS

Most of the data used in this analysis was obtained by authors dedicated to water supply development. As might be expected, the database is variable due to differences in personnel and reporting procedures over the 80 year period. In summary, thirteen geologic units are encountered in Nairobi City with a variety of subsurface profiles. The depth of encounter of the geological units varies depending on the source of the materials and the shape of the eroded surface at the time of deposition. The youngest rocks are exposed to the west and the oldest to the east (Figure-2).

Although the method of reporting aquifers differs from driller to driller, the average thicknesses were calculated considering logs from majority of the boreholes. From the core logs, it was found that the aquifer thicknesses are in the range of 28 m to 60 m; only a few localities with faulted formations have aquifer thicknesses larger than 60 m. The following are depth ranges within which one would expect to encounter an aquifer: 18-30 m, 40-48 m, 76-134 m, 138-144 m, 150-162 m, 170-180 m, and 196-220 m. Up to six aquifers have been encountered in some boreholes.

The contour maps produced by analysis of spatial and temporal static level variations for the various decades on Surfer software are presented in Figure-3 to Figure-9. The direction of ground water movement can be understood in the fact that ground water always flows in the direction of decreasing head. The rate of movement is dependent on the hydraulic gradient, which is the change in head per unit distance (Van Tonder *et al.,* 1998). The Surfer contours for 1927-1939 period show groundwater rest level surfaces with N-S trend in correspondence with the topographic contours (Figure-3). Change in static level contour trends started in the 1940s when several deep pockets developed in majority of the six main abstraction areas labelled (Figure-4). The pockets evened out in the 1960-1979 decade (Figure-6). The recovery of rest levels in the 1960-1979 decade can be attributed to control on borehole drilling and restriction in abstraction (Mwangi, 2005). The control was accompanied by development of surface water supplies from Tana River Basin and regular measurement of rest levels in some selected boreholes.

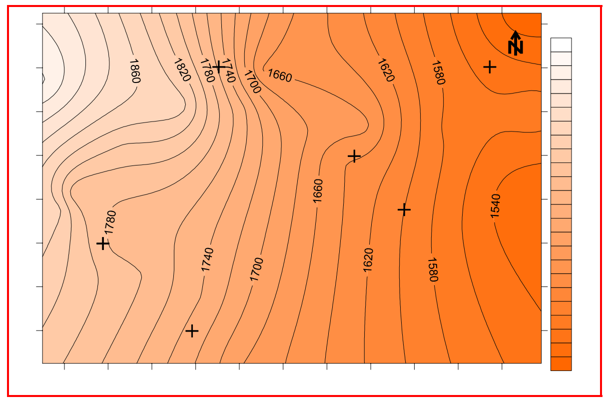

Figure-3. Contour map of water rest levels in boreholes drilled between 1927-1939.

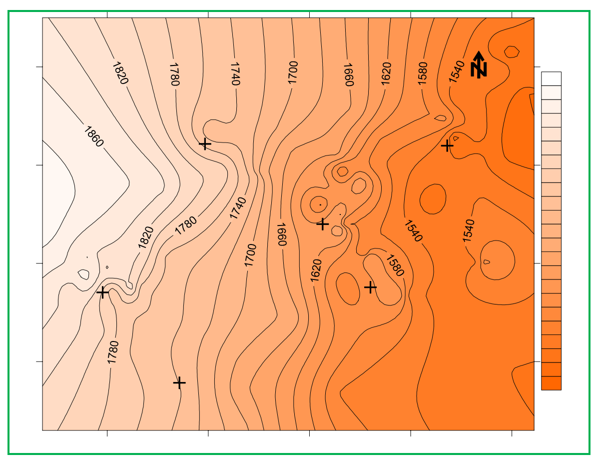

Figure-4. Contour map of water rest levels in boreholes drilled between 1940-1949.

Owing to the curfew on drilling and the control in abstraction, water levels rose by an average of 40 m between 1960 and 1979 as expressed by the contours (Figure-5 and Figure-6). However, after the control in drilling was lifted in 1985, extensive abstraction of water in Nairobi City commenced again leading to a fall of 100 m in the period between 1989 and 1999 (Figure-7 and Figure-8). Whereas Surfer contours show no rest level drop in 2000-2009 decade for boreholes in east Nairobi

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(Figure-9), the averages from records indicate a drop of 29.46 m (Table-1).

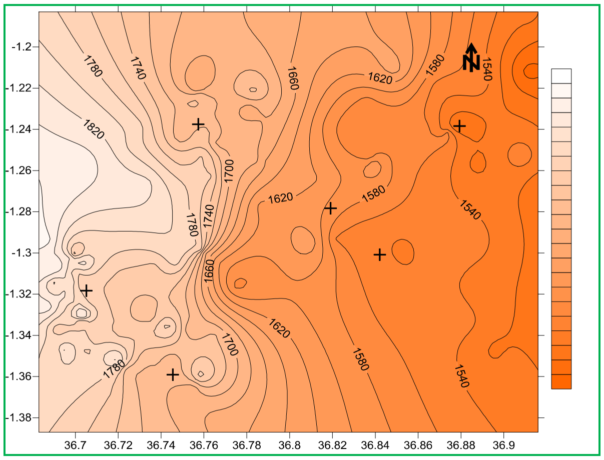

Figure-5. Contour map of water rest levels in boreholes drilled between 1950-1959.

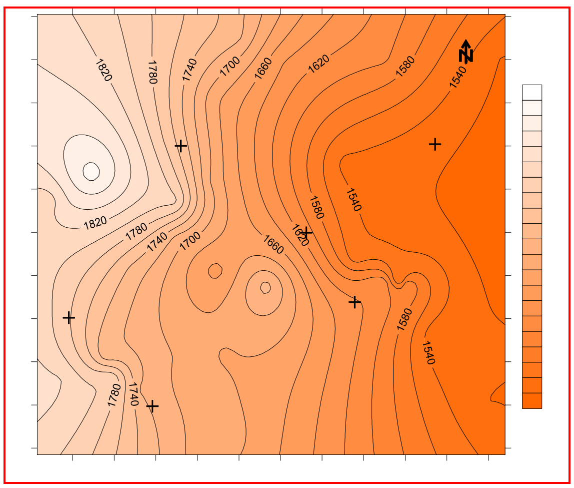

Figure-6. Contour map of water rest levels in boreholes drilled between 1960-1979.

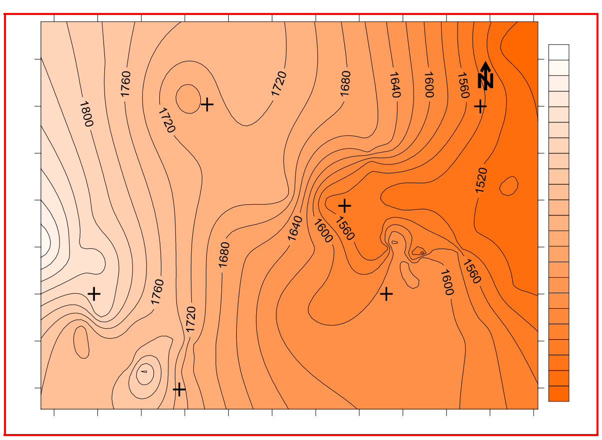

Figure-7. Contour map of water rest levels in boreholes drilled between 1980-1989.

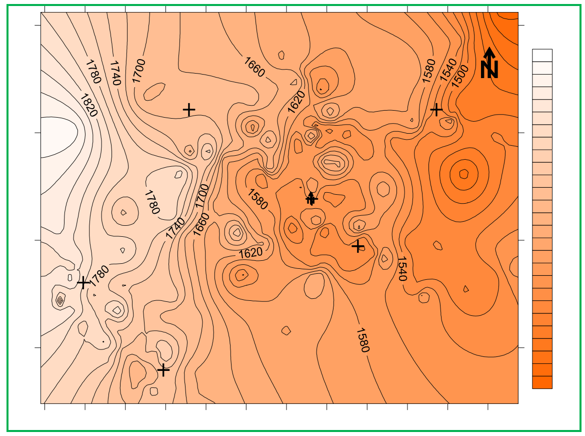

Figure-8. Contour map of water rest levels in boreholes drilled between 1990-1999.

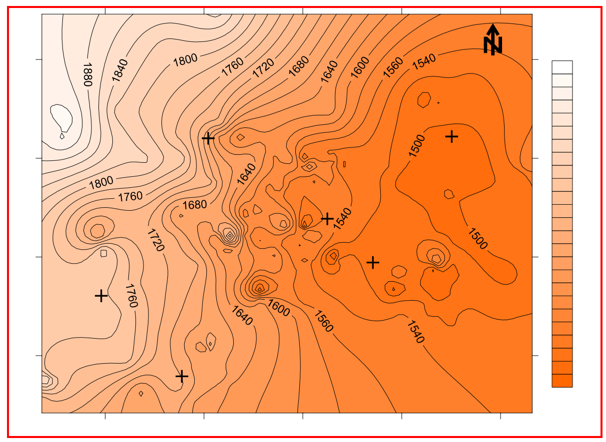

Figure-9. Contour map of water rest levels in boreholes drilled between 2000-2009.

The reason why the drop in rest levels is not reflected on Surfer contours of the 2000-2009 decade (minimum 1460 m asl) is the encounter of extensive Athi series aquifers with large storage capacities and high piezometric rises in east Nairobi. When 1927-1939 and 1990-1999 periods are compared, the deepest rest level contour on Surfer was 1500 m by 1939 and 1380 m by 1999; a difference of 120 m. The largest fall in rest levels has occurred at the City Centre in which old boreholes had rest levels at 1644 m asl while new boreholes have water rest levels at 1542 m asl. This could be related to the reduction in natural recharge as a result of increase in paved/ impermeable surfaces. Although boreholes in Karen area have low yields, they seem to have adequate replenishment through the many faults that affect the area and thus show rise and fall in rest levels throughout the investigated period. A summary of the water rest level changes depicted on the Surfer contours and the averages calculated from records for the six main abstraction areas is 79.34 m, of

Lower Kabete

City Ce

Karen

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which 53.66 m (67.6%) has occurred in the last two decades.

Table-1. Water rest levels (asl) at large abstraction localities in different decades and the calculated average drop.

Period / Locality	1927-1939	1940-1949	1950-1959	1960-1979	1980-1989	1990-1999	2000-2009	Total drop (m)
Karen	1788	1793	1803	1782	1828	1805	1781	7
Langata	1733	1738	1709	1716	1735	1712	1698	35
City Centre	1644	1641	1605	1609	1556	1562	1542	102
Lower Kabete	1752	1743	1710	1750	1702	1695	1676	76
Industrial Area	1600	1595	1551	1621	1604	1534	1515	85
Ruaraka	1553	1524	1507	1527	1546	1533	1484	69
Average drop from records (m)	5.59	5.51	6.81	-10.57	7.77	24.2	29.46	79.34

An analysis of total and per annum change in rest levels for some monitoring boreholes is presented in Table-2. The most remarkable drops in rest level are recorded at the following sites: Aga Khan Hospital with 126.2 m drop in 25 years; Langata Barracks where the water level dropped by 100 m during test pumping and never recovered; and, St Laurence University in Karen with total drop of 71m in 8 years. A few boreholes such as that at the Hindu temple in Parklands and Kenya Polytechnic men's Hostels show a rise in rest level resulting from either shut-down or controlled pumping. Calculations from actual water level monitoring values show that the minimum annual water level drop is 0.58 m and the average is 3.38 m.

Table-2. Total and per annum change in water rest levels in monitoring wells.

BH ID No. C-	Owner	Date drilled	Total depth (m)	Initial WRL (m)	Change in WRL (m)	Operating years	Av. p.a change (m)
12357	Hindu Temple Pl	1999	204	160	29.80	9	3.31
14539	Riverside Park	2004	280	149	-17.30	4	-4.33
10883	Hill Crest Karen	1994	300	110	-14.00	14	-1.00
10333	Hurlingham	1993	250	152	-31.00	15	-2.07
13860	Hotel Boulevard	2003	255	115	-2.90	5	-0.58
6310	KEWI South C	1985	169	77	-54.20	22	-2.46
8697	Trufoods	1989	164	105	-27.90	19	-1.47
4790	State House	1980	200	146	-19.20	27	-0.71
4147	Unilever	1975	258	79	-87.50	33	-2.65
11592	Uchumi Hyper	1997	250	143	-87.00	11	-7.91
5050	Aga Khan Hosp	1982	171	21	-126.20	25	-5.05
14559	Kabansora Millers	2005	200	102	-4.50	2	-2.25
12885	Kenya Poly Host	2000	200	112	-31.00	8	-3.88
15129	Jorgen L Karen	2006	170	92.7	-11.00	5	-2.20
13594	KICC	2002	250	105.4	-31.30	6	-5.22
13069	St Laurence Univ.	2000	320	55	-71.00	8	-8.88

In the calculation of probable settlement, the initial rest levels in the oldest wells were considered to indicate the original groundwater level. Storativity values for selected tube wells in each locality were calculated from test pumping results and are indicated in Table-3. Porosity of the aquifers was assumed as 0.25 (Sun *et al.*, 1999). The settlement resulting from consolidation of aquifers and clay layers was calculated for 24 sites representative of the study area as shown in Table-3. The results indicate that a probable estimated settlement of 0.34 m to 5.9 m could result from groundwater depletion from aquifers and clay aquitards over a long period of time. Subsurface profiles indicate that between the ground surface and the clay aquitards are alternating layers of weathered and fresh Nairobi Phonolite and/or Nairobi Trachyte.

Table-3. Calculation of probable settlement due to groundwater withdrawal.

Locality	**Aquifer** (m)	**Aquitard** (m)	**S**	**Δp**	**Δm** (m)	**ΔM** (m)	$\delta_{T\ (m)}$
Parklands	48.35	52	0.0107	474.3	0.05	1.45	1.50
Westlands	40.17	54	0.0083	394.1	0.03	0.81	0.84
Chiromo/River Side/ Kileleshwa	46.92	60	0.0549	460.3	0.26	5.12	5.38
Muthaiga	40.64	56	0.0259	398.7	0.11	2.61	2.71
Langata	57.27	64	0.0220	561.8	0.13	2.46	2.58
Dam Est/Kibera/Woodley	48.71	32	0.0054	477.8	0.03	0.31	0.34
Mombasa Rd	38.00	70	0.0126	372.8	0.05	1.69	1.74
Industrial Area	48.70	36	0.0331	477.7	0.16	2.14	2.30
Embakasi	38.50	54	0.0126	377.7	0.05	1.28	1.33
Runda/Kitisuru	52.60	46	0.0091	516.0	0.05	0.58	0.63
Riruta/kangemi/Kawangw	45.75	74	0.0064	448.8	0.03	0.75	0.78
Gigiri/Rosslyn	47.00	46	0.0100	461.1	0.05	0.71	0.76
Karen	38.38	52	0.0220	376.5	0.08	2.29	2.38
Lowe Hill/N-West	58.40	78	0.0121	572.9	0.07	1.18	1.25
Lavington Kilimani/Thomp	43.81	70	0.0049	429.8	0.02	0.57	0.59
Upper Hill/Milimani	58.30	64	0.0549	571.9	0.32	4.40	4.72
Lower kabete/Wangige	55.18	38	0.0091	541.3	0.05	0.46	0.51
Ngara/Pumwani/Eastleigh	50.20	58	0.0060	492.5	0.03	0.51	0.54
Ongata R/ Ngong'/Kiserian	34.82	32	0.0835	341.6	0.29	5.60	5.89
Buru/Umoja/Kayole	39.70	36	0.0128	389.5	0.05	0.85	0.90
Kikuyu/Dagoretti/Kinoo	32.37	48	0.0418	317.5	0.14	4.52	4.66
Ruaraka	48.70	38	0.0426	477.7	0.21	2.43	2.64
National Park	51.00	65	0.0254	500.3	0.13	3.24	3.37
Calculated average	**46.24**	**53.17**	**0.02**	**453.59**	**0.10**	**2.00**	**2.10**

S = storativity (dimensionless), ΔP = fluid pressure change, Δm = elastic settlement, ΔM = inelastic settlement, δ_T = Total settlement

5. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation indicate that the rest levels in tube wells in Nairobi city have been receding due to exploitation. If the trend continues in response to increase in population and increasing industrial activities, the aquifers could be depleted. This depletion could lead to long-term surface subsidence especially at localities with concealed faults. The study therefore provides a basis for establishing a reliable hydrogeological and scientific framework for monitoring and determining suitable strategies for groundwater augmentation so that subsidence does not occur.

Surface subsidence due to groundwater abstraction has not been observed and there are no defects in structures that can be related to drawdown. This is because no settlement monitoring has been carried out at the ground surface nearby the distressed structures. It would therefore be worthwhile to install a few real-time settlement meters (extensometers) at sites with high yield boreholes such as Industrial Area, and at areas with potential of large settlements such as Kiserian and Kileleshwa. So far, it is assumed that no subsidence can occur because of the thick Nairobi Trachyte and Nairobi Phonolite layers shielding the ground surface from any consolidation within the Athi Series aquifers and aquitards.

Most of the world settlement that is related to groundwater drawdown is common in sedimentary environments. However the magnitudes of probable settlement calculated for Nairobi City should serve as a

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wake-up call to put up measures that can mitigate subsidence and the related consequences.

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