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Seawater Intrusion Vulnerability Assessment of a Coastal Aquifer: North Coast Of Mombasa, Kenya as a Case Study

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ABSTRACT

Groundwater pollution in the north coast of Mombasa is not only from surface sources but also from the intrusion of seawater via the Indian Ocean and creeks. This study assessed the vulnerability of the coastal aquifer to seawater intrusion using GALDIT index overlay method with the aid of GIS. Thematic maps of six major factors affecting seawater intrusion were prepared, and given appropriate weightages and ratings. These maps were overlaid, spatially analyzed to produce vulnerability maps and described based on low, moderate or high vulnerabilities. The results revealed a significant increase in percentage land cover for low vulnerability areas and a slight increase for high vulnerability regions between the pre-rains and the peak of raining season. The outcomes of this study provide useful insights on effective groundwater management for the study area.

***Keywords* –** GALDIT index, Vulnerability, Seawater intrusion, GIS, Groundwater pollution, Mombasa, Coastal aquifer

I. INTRODUCTION

Geological formations such as aquifers are important sources of freshwater to humans for domestic, agricultural and industrial purposes. Over 90% of the world's readily available freshwater is found as groundwater [1]. The geological formations, the groundwater stored in aquifers, as well as several complex dynamic processes all make up the hydrogeological system. The quality of groundwater resources in a place vary with time, and concentration based on factors influencing the hydrogeological system. Groundwater can be termed highly vulnerable if it easily gets contaminated or loses its freshwater characteristics. The concept of groundwater vulnerability as a way of protecting groundwater resource could be traced to the work of Albinet & Margat (1970) [2] [3]. Aquifer vulnerability connotes that different parts of an aquifer may offer different degrees of protection to the groundwater contained in them [4]. The aquifer may be vulnerable to environmental influences such as surface pollutants (leachates from domestic and industrial wastes), high concentration of effluents in rivers through the process of diffusion and advection, or intrusion of seawater. The latter mostly influences coastal aquifers and aquifers in proximity to salt water bodies. Some pollution findings have been reported in East African region such as; Surface pollution studies by Munga et. al., (2006) [5] in Mombasa, Kenya; seawater intrusion investigation in the Quaternary aquifer of Dar es Salaam, Tanzania by Mtoni et. al., (2013) [6]; seawater intrusion and seasonal changes investigation on the coastal Aquifers of Dar es Salaam (Sappa et al., 2015) [7]. Approaches such as Hydrochemical methods and DRASTIC index are two foremost methods used.

Seawater intrusion is not a new phenomenon, in fact it can be considered a natural dynamic occurrence. However, anthropogenic activities may significantly affect its extent and severity in a particular place and time. Saltwater intrusion may be explained as the diffusion or movement of saltwater into a freshwater aquifer close to a saltwater body- ocean, sea or lagoon cut off from the larger sea. Overexploitation has been identified as one of the principal causes of seawater intrusion as it leads to a lowering of piezometric or water table level [8]. The coast of East Africa is one of the coastal regions with the highest proportion of least modified land [9]. Though the region has been identified as the least urbanized region in the world, it has the shortest doubling time for urban population [10]. Hence, it is highly imperative to assess the vulnerability of the region to seawater intrusion in order to forestall the attendant challenges of inadequate freshwater provisioning.

Several proposed methods for assessing vulnerability of aquifers to pollution have been identified [11] such as; the GOD rating system [12]; DRASTIC Index [13]; AVI rating system [14]; SINTACS method [15]; ISIS method [16]; and EPIK method [17]. These overlay methods have been applied for many studies, and in some cases, more than one method was combined in the same studies [3] [18]. Other identified methods are PI method [19]; and the GALDIT method [20]. The names ascribed to all these methods are acronyms of the most important parameters identified for the vulnerability assessment in each case. The GALDIT method; an adaptation from DRASTIC method for assessing the vulnerability of coastal aquifers to seawater intrusion was applied for this study.

GALDIT method is an open-ended model which utilizes a numerical ranking system for evaluating the saltwater intrusion potential of a coastal aquifer within the framework of the hydrogeological settings using certain established factors [21]. These factors also known as GALDIT factors, have been identified as the most important map-able factors controlling seawater intrusion [20] [21] [22]. The factors include;

- “Groundwater occurrence (Aquifer type; confined, unconfined, leaky confined)
- Aquifer hydraulic conductivity
- Level of the Groundwater depth above sea level
- Distance from shore (distance inland perpendicular from shoreline)
- Impact of existing status of seawater intrusion in the area
- Thickness of the mapped aquifer”

The acronym GALDIT was derived from the first letter of each parameter. The parameters are drawn up into map layers which are then overlaid based on weightages, ranges and importance rankings. The final vulnerability map provides useful information on areas which are more susceptible to the intrusion of saltwater than the others. The index has been widely applied in several places to map out the vulnerability of coastal aquifers to seawater intrusion [20] [21] [22] [23] [24] [25].

This research is based on the application of GALDIT Index for assessing the Coastal Aquifer of the North thrust of Mombasa in Kenya. The aim is to map out the region based on susceptibility to seawater intrusion in order to provide a better perspective for the groundwater management of the study area. Geographic Information System was extensively used for the overlays, spatial analysis as well as the final cartography.

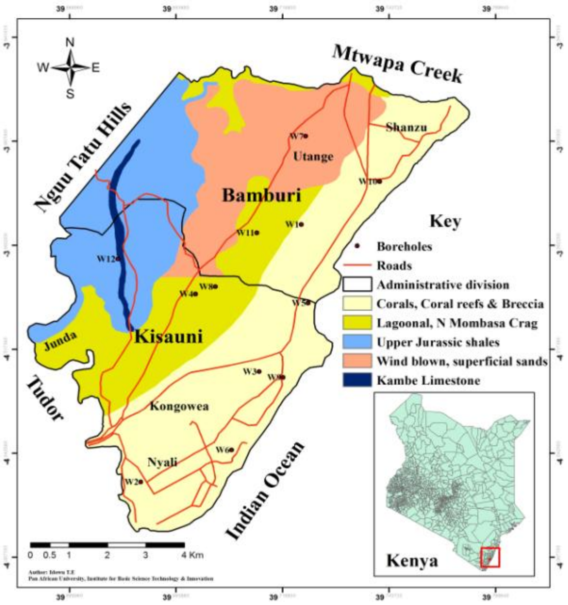


Fig 1: Map of the North coast of Mombasa

II. STUDY AREA

The study area is located on the north thrust of Mombasa Coast, Kenya. It lies between latitudes 3° 95” and 4° 07” south of the equator and between longitudes 39° 68” and 39° 72” East of the Greenwich meridian. The area, 74.2 Km^2 in size is the main populated area of the kisauni administrative division of Mombasa. It covers Nyali and parts of Kisauni parliamentary constituencies within the division of kisauni. The study area is bounded by creeks on the north and south, Nguu Tatu hills on the west and Indian Ocean on the east (Fig. 1).

The geological formation of this region is sedimentary in nature, formed during the Pleistocene age, they are composed mainly of alluvium, wind-blown superficial sands, corals and coral breccia [26] [27]. The rocks dip gently and become progressively younger towards the coast. The lithology is composed mainly of limestone, sandstone, and shale of varying depths [26] [27] [28]. The geomorphology comprises creeks, coral reefs, sandy beaches, muddy tidal flats and rock-strewn shores [29].

The region is hot, humid, and tropical, with the South Eastern and North Eastern Monsoon winds playing significant roles in defining the seasons. There are two rainy seasons – the short and long rains. The SE Monsoon winds blow between April and September coinciding with the long rains while the NE Monsoon winds blow between October and March influencing the short rains. The long rains occur between the month of March and July while the short rains take place between October and December. The annual mean temperature is 26.3^{0}C while total annual precipitation averages 1072.7mm [30].

From exact measurements of digitized topographic images and DEM of the study area, the highest elevation is found in Nguu Tatu hills whose peak is about 124m above sea level and perpendicularly located some 6.5km to the Oceanfront. Other parts of the study area mostly range from sea level to 50m above sea level. The general lowly characteristics of the study area influences surface runoff, as infiltration and deep percolation makes possible quick recharge of the aquifer.

The annual population grows at a rate of 3.4% in the region and has seen its population more than doubled in the last two decades [31] [32]. In 2009, population stood at 405,930 with Nyali and Kisauni constituencies in the study area having a population of 185,990 and 194,065 respectively [33].

III. METHODOLOGY

The methodology for this study involved the collection, processing and spatial analysis of data. The various data obtained and used were; field data (Geographic coordinates of borehole points, field water quality parameters, and static water levels); secondary data (geological maps and data, topographic maps, 30m SRTM digital elevation model, and historical data of boreholes); and results of laboratory data analysis of water samples. The general methodology is expressed in Fig 2.

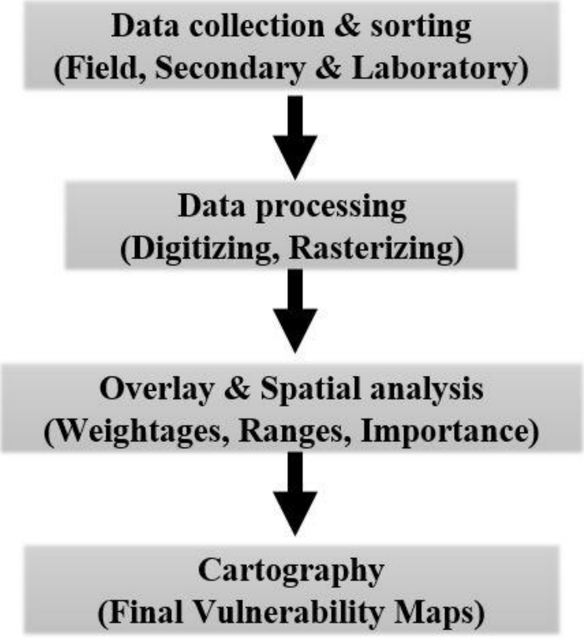


Fig 2: General methodology for the vulnerability analysis

The field data collection and laboratory analysis for this research took place from March to April 2016 and June to July 2016. All six factors comprising the GALDIT index were obtained from the field, laboratory, and secondary data. The "static factors" which do not change considerably over a period of time are **G**roundwater occurrence, **A**quifer hydraulic conductivity, **D**istance to the shore and **T**hickness of the aquifer while the "dynamic factors" which experience temporal variation with time are the **L**evel of groundwater above sea level and **I**mpact of existing seawater intrusion. Overlay maps were prepared for the pre-monsoon rains (March 2016) and the peak of the rains (June 2016). The same static factors were used for both periods while the dynamic factors for each period were computed and applied accordingly.

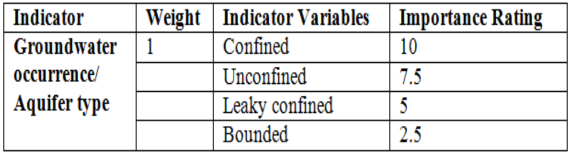
The numerical ranking system based on [20] was in three parts; weights, ranges and importance ratings. The weights are the product of extensive and elaborate discussions with the experts, academics, researchers and all other relevant stakeholders and are regarded as standards while the ranges varied for each factor (Table 1). The importance rating is a measure of the value of the factor's contribution to vulnerability. This study as with [22] [25], puts the importance rating on a scale of 2.5 to 10. The Decision Criterion which is a summation of all the individual scores was obtained by multiplying the values of the importance ratings with the corresponding Indicator weights.

Table 1: Standardised weightages for GALDIT factors [22]

Factors	**Weights**
1. Groundwater occurrence (aquifer type)	1
2. Aquifer hydraulic conductivity	3
3. Height of groundwater above sea level	4
4. Distance from the shore	4
5. Impact of existing status of seawater intrusion	1
6. Thickness of Aquifer being mapped	2

- **G**roundwater occurrence- The ratings for the parameter G are expressed in Table2. The aquifer under study is unconfined comprising limestone, coral reefs, sandstone and shale ([27] Pg. 27). It, therefore, gets a rating of 7.5

Table 2: Ratings for GALDIT parameter G



Indicator	Weight	Indicator Variables	Importance Rating
Groundwater occurrence/ Aquifer type	1	Confined	10
		Unconfined	7.5
		Leaky confined	5
		Bounded	2.5

- **A**quifer hydraulic conductivity**-** By definition, it is the flow per unit cross-sectional area of the aquifer when subjected to a unit head (hydraulic) per unit length of flow [34]. Higher hydraulic conductivities increase the risk of seawater intrusion and also results in wide cones of depression during pumping. This implies hydraulic conductivity K does not only influence the influx of seawater inland but also the rate at which fresh groundwater move seawards. The hydraulic conductivity of the porous media covering the study area varies from less than 4m/day to 12 m/day [5]. The modified rating for hydraulic conductivity in the area under study is given in table 3.

Table 3: Ratings for GALDIT parameter A

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Aquifer hydraulic conductivity (m/day)	3	High	>40	10
		Medium	12 – 40	7.5
		Low	4 – 12	5
		Very Low	<4	2.5

- **L**evel of groundwater above the mean sea level- Groundwater level above mean sea level is an important factor because it heavily influences the freshwater hydraulic pressure required to counterbalance the intrusion of seawater. The higher the groundwater level above sea level, the higher the hydraulic pressure and hence, the lower the risk of seawater intrusion. Ghyben-Herzberg relationship illustrates that every metre of freshwater above mean sea level, translates to 40m of freshwater stored directly below [35]. Static water levels of boreholes/wells were taken at the peak of the dry season when the groundwater levels are lowest and the risk of saltwater intrusion highest and also taken at the peak of the wet season when the reverse is the case. Digital Elevation Model (DEM) for the study area was used in conjunction with static water level measurements to estimate the groundwater levels above the mean sea level. The groundwater levels above sea level for the study area were found to vary from 1 to 26m and -1 to 32 for wet and dry seasons respectively. The table of modified GALDIT ratings for the groundwater levels above the sea is given in table 4.

Table 4: Ratings for GALDIT parameter L

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Height of groundwater above sea level	4	High	<1	10
		Medium	1 – 5	7.5
		Low	5 – 10	5
		Very Low	>10	2.5

- **D**istance from the saltwater body- The closer a point is to the saltwater body, the higher the vulnerability to saltwater Intrusion. The study area is bounded by the Indian Ocean to the south and by creeks on the west and east. Unsurprisingly the boreholes with the farthest distance to a saltwater body are the ones located almost at the centre of the study area. The modified table for the ratings is represented as table 5.

Table 5: Ratings for GALDIT parameter D

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Distance to the Shore	4	Very small	<1000	10
		Small	1000– 1500	7.5
		Medium	1500 – 2000	5
		Far	>2000	2.5

- **I**mpact of the existing status of sea water intrusion- Chachadi and Lobo-Ferreira [20] suggests the ratio of chloride and bicarbonate also known as Revelle's coefficient for representing the existing status of seawater intrusion. This ratio was found to range from values 1.16 to 3.97 and 0.57 to 4.09 for representative samples taken in March and in June respectively. A strong positive correlation of 0.97 was equally observed between the Revelle's coefficient and the NaCl measurements which may indicate that the sources of the salinity in the groundwater are the Ocean and creeks (Fig 3). Table 6 represents the modified GALDIT ratings for the impact of the existing status of seawater intrusion.

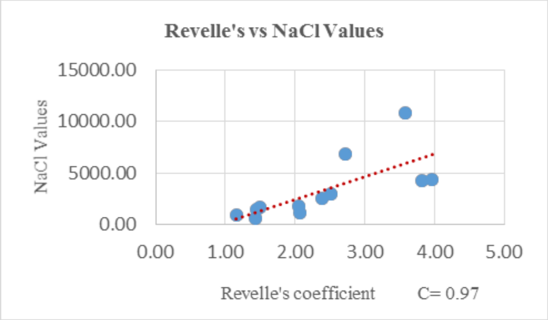


Fig 3: Graph showing the relationship between Revelle's coefficient and NaCl values for March 2016

Table 6: Ratings for GALDIT parameter I

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Impact of existing status of Seawater Intrusion	1	High	>2	10
		Medium	1.5 – 2	7.5
		Low	1 – 1.5	5
		Very Low	<1	2.5

- **T**hickness of the aquifer being mapped- The Saturated thickness of an unconfined aquifer influences the extent and magnitude of saltwater intrusion. The larger the thickness of the aquifer, the greater the extent of saltwater Intrusion and vice versa [22]. From the sparse boreholes and log data gathered, the lithology of the study area is heterogeneous in nature showing varying layers of limestone, sandstone, and shale [27]. Furthermore, cross-sectional views of the lithology of the study area as shown in the geological Map reveal that coral reefs, kilindini sands/North Mombasa crag, and the wind-blown superficial sands extend far below 100m in most parts of the study area [26] [28]. The aquifer thickness for the study area is given a maximum importance rating of 10 (Table 7).

The computed GALDIT indices and weightages are given in Table 8.

Table 7: Ratings for GALDIT parameter T

Indicator	Weight	Indicator Variables		Importance Rating
		Class	Range	
Thickness of Aquifer being mapped	2	Large	>2	10
		Medium	1.5 – 2	7.5
		Small	1 – 1.5	5
		Very Small	<1	2.5

Table 8: GALDIT Index computation

SN	Indicators	Weight	Range of Importance ratings			Range of scores (weight importance)		
			Min	In- between	Max	Min	In between	Max
1	Groundwater occurrence	1	2.5	5 7.5	10	2.5	5 7.5	10
2	Aquifer hydraulic conductivity	3	2.5	5 7.5	10	7.5	15 22.5	30
3	Height of groundwater above sea level	4	2.5	5 7.5	10	10	20 30	40
4	Distance from the shore	4	2.5	5 7.5	10	10	20 30	40
5	Impact of existing status of seawater intrusion	1	2.5	5 7.5	10	2.5	5 7.5	10
6	Thickness of the aquifer being mapped	2	2.5	5 7.5	10	5	10 15	20
				Total Score (TS)		37.5	75 112	150
				Galdit Index		2.5	5 7.5	10

Decision Criteria

GALDIT Index = $\frac{TS}{\sum_{i=1}^{6} W_i}$

Where;

TS = $(W_1 \text{ x } G) + (W_2 \text{ x } A) + (W_3 \text{ x } L) + (W_4 \text{ x } D) + (W_5 \text{ x } I) + (W_6 \text{ x } T)$

W_1 to W_6 are the respective relative weights given to the six hydrogeological factors.

$\sum_{i=1}^{6} W_i = 15$

The vulnerability classes are then based on the GADIT index scores which are divided into three categories- low, moderate and high (Table 9).

Table 9: Vulnerability classes

SN	GALDIT Index range	Vulnerability classes
1	<5	Low
2	5 – 7.5	Moderate
3	>7.5	High

IV. RESULTS & DISCUSSION

The maps for each factor prepared with the aid of ArcGIS are represented by figs 4 to 11. The factors A, L and D had the highest influence on the vulnerability of the study area to seawater intrusion. This may be due to their high weightages and high spatial variations across the study area. The dynamic factors **L** and **I** for the two time periods are shown as figures 5 and 8 respectively.

The total scores (TS) for the final vulnerability map ranged from 55 to 120 for the month of March and 57.5 to 132.5 for the month of June. The TS values were resized into three classes of low, moderate and high vulnerability (Figs 10 & 11)

The regions classified highly vulnerable for both GALDIT index maps have much lower elevations and higher proximities to the Indian Ocean. This implies that factors L and D are the most significant factors for the vulnerability of the study area to seawater intrusion.

The least vulnerable regions are observed to be towards the high elevation areas of Nguu Tatu hills. Statistically, March’s GALDIT index reports a land cover percentage of 13%, 64%, and 23% for low, moderate and high vulnerability while the vulnerability classes are 20%, 55% and 25% for the month of June across the region (Table 10). The increase in land cover of low vulnerability regions may be due to the increased volume of fresh groundwater as a result of rainfall recharge. Groundwater recharge increases the hydrostatic pressure of freshwater against the seawater based on Ghyben Herzberg principle [35].

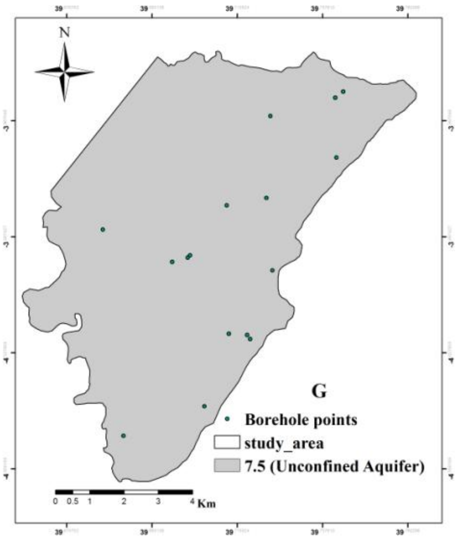


Fig 4: Parameter G (Groundwater occurrence)

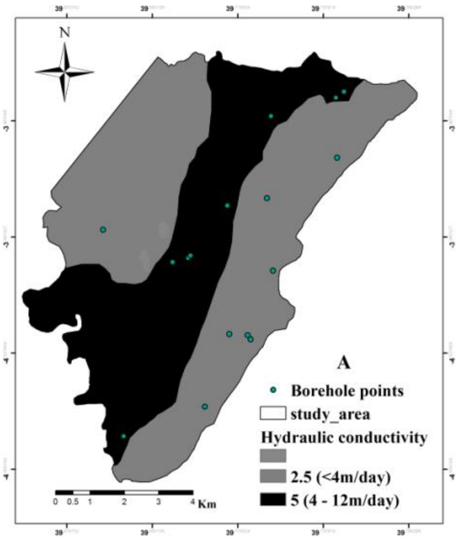


Fig 5: Parameter A (Aquifer hydraulic conductivity)

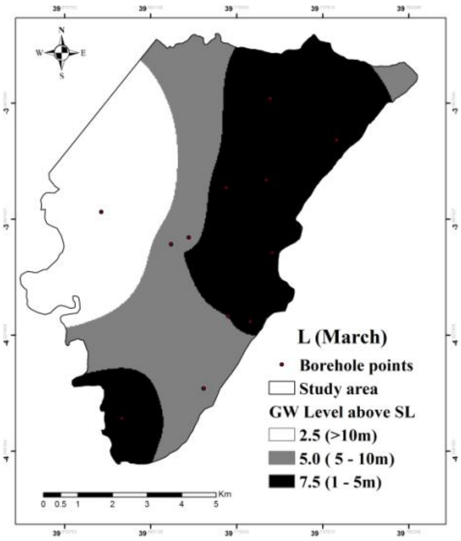


Fig 6a: Parameter L (Level of GW above SL in March)

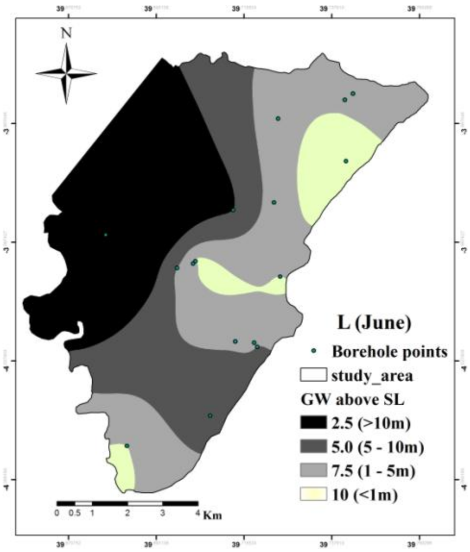


Fig 6b: Parameter L (Level of GW above sea level for June)

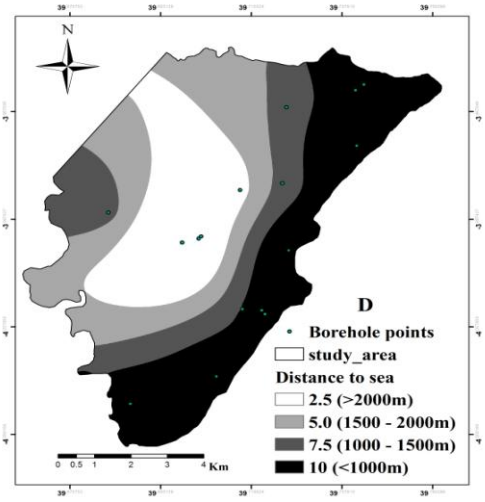


Fig 7: Parameter D (Distance to the shore)

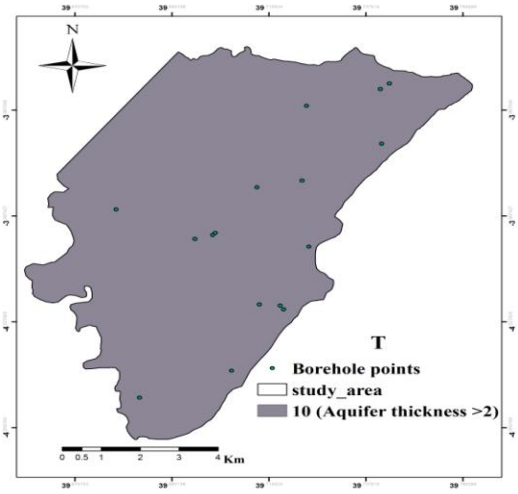


Fig 8: Parameter T: (Thickness of the mapped aquifer)

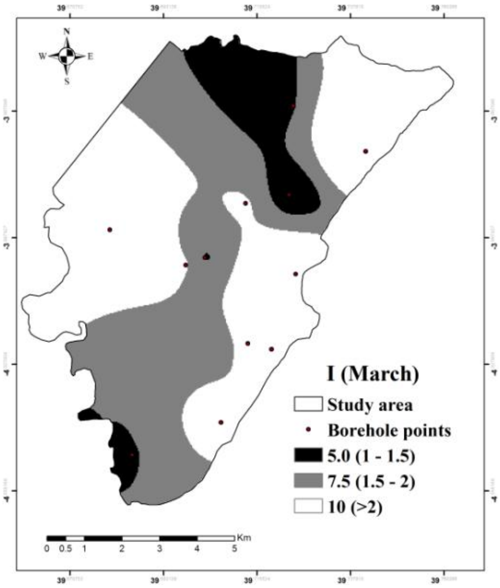


Fig 9a: Parameter I- Existing status of SWI (March)

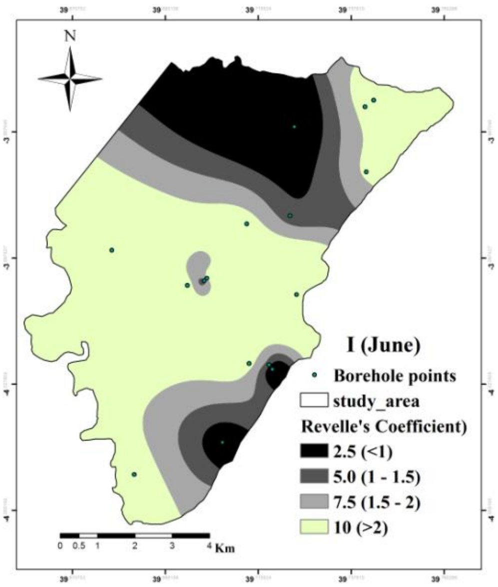


Fig 9b: Parameter I- Existing status of SWI (June)

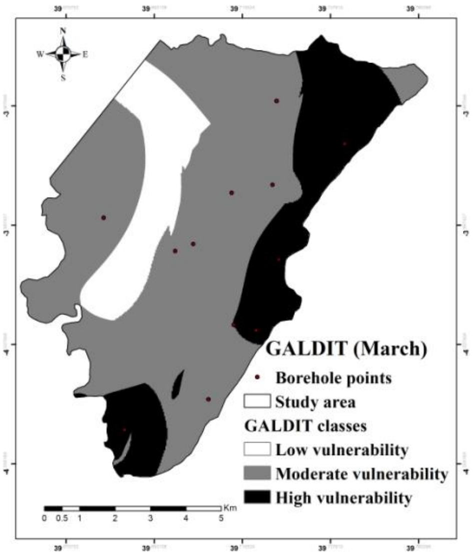


Fig 10: Computed GALDIT index for the month of March

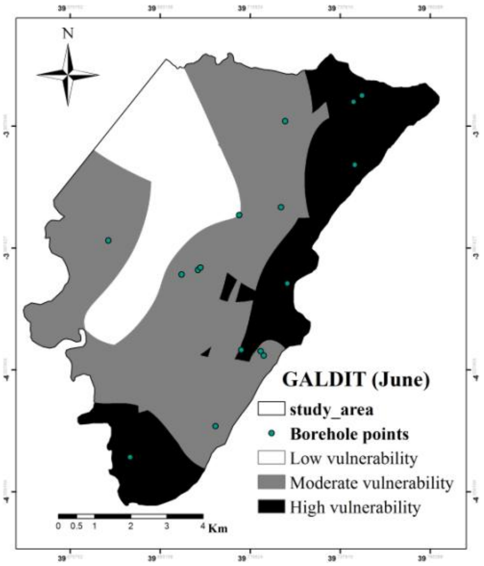


Fig 11: Computed GALDIT index for the month of June

Table 10: Percentage changes in vulnerability classes between pre-rains and peak rain period

SN	Vulnerability class	March 2016 (%)	June 2016 (%)
1	Low	13	20
2	Moderate	64	55
3	High	23	25

V. CONCLUSION & RECOMMENDATION

The GALDIT index method was successfully applied for assessing the vulnerability of Kisauni North Coast of Mombasa's coastal aquifer to seawater intrusion. This gave good insights into the nature of the interaction of seawater with the fresh groundwater. The vulnerability analysis was done for both the pre-rains and the peak of rainfall. The coastal aquifer tends to experience a lesser impact of seawater intrusion in the wet season than the dry season, as observed by the significant increase in the percentage area of low vulnerability class from 13% to 20%. Groundwater levels were not observed to vary significantly between the dry and wet season, implying a generally good balance between abstraction and recharge.

All the maps were drawn to a scale of 1/70,000. These may be extracted with the permission of the author or requested for decision-making purposes in the siting of boreholes/wells and general groundwater management. Attention should be paid to regions which consistently fell under high vulnerability class for the two periods, especially in the context of authorization for groundwater abstraction.

Similar studies can be applied to the coastal aquifers of the other parts of East Africa, sub-Saharan Africa and across the globe to provide insights for groundwater management and conservation of such aquifers against the intrusion of seawater.

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REFERENCES

[1] Boswinkel J. A., Information Note, 2000. International Groundwater Resources Assessment Centre (IGRAC), Netherlands Institute of Applied Geoscience, Netherlands

[2] Albinet M, Margat J (1970) Cartographie de la vulnérabilité à la pollution des nappes d’eau souterraine Orleans, France. Bull BRGM 2ème série, 4 : 13–22.

[3] Draoui, M., Vias, J., Andreo, B., Targuisti, K., & Stitou El Messari, J. (2007). A comparative study of four vulnerability mapping methods in a detritic aquifer under mediterranean climatic conditions. Environmental Geology, 54(3), 455–463. doi:10.1007/s00254-007-0850-3

[4] Recinos, N., Kallioras, A., Pliakas, F., & Schuth, C. (2014). Application of GALDIT index to assess the intrinsic vulnerability to seawater intrusion of coastal granular aquifers. Environ Earth Sci Environmental Earth Sciences, 73(3), 1017-1032. doi:10.1007/s12665-014-3452-x

[5] Munga, D., Mwangi, S., Ong’anda, H., Kitheka, J. U., Mwaguni, S. M., Mdoe, F., ... & Opello, G. (2006). Vulnerability and pollution of groundwater in Kisauni, Mombasa, Kenya. Groundwater pollution in Africa. Taylor and Francis (Balkema), The Netherlands, 213-228.

[6] Mtoni, Y., Mjemah, I. C., Bakundukize, C., Camp, M. V., Martens, K., & Walraevens, K. (2013). Saltwater intrusion and nitrate pollution in the coastal aquifer of Dar es Salaam, Tanzania. Environ Earth Sci Environmental Earth Sciences, 70(3), 1091-1111. doi:10.1007/s12665-012-2197-7

[7] Sappa, G., Ergul, S., Ferranti, F., Sweya, L. N., & Luciani, G. (2015). Effects of seasonal change and seawater intrusion on water quality for drinking and irrigation purposes, in coastal aquifers of Dar es Salaam, Tanzania. Journal of African Earth Sciences, 105, 64-84. doi:10.1016/j.jafrearsci.2015.02.007

[8] Brehme M, Scheytt T, C¸ elik M, Dokuz U (2011) Hydrochemical characterisation of ground and surface water at Do¨rtyol/Hatay/ Turkey. Environ Earth Sci 63(6):1395–1408. doi:10.1007/s12665- 010-0810-1

[9] UNEP (2008), Vital Water Graphics - An Overview of the State of the World’s Fresh and Marine Waters. 2nd Edition. UNEP, Nairobi, Kenya. ISBN: 92-807-2236-0

[10] UN Habitat (2008). United Nations Human Settlements Programme The state of African cities. Nairobi:UN Habitat.

[11] Gogu, R. C., & Dassargues, A. (2000). Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environmental Geology, 39(6), 549–559. doi:10.1007/s002540050466

[12] Foster SSD (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: Duijvenbooden W van, Waegeningh HG van (eds) TNO Committee on Hydrological Research, The Hague. Vulnerability of soil and groundwater to pollutants, Proceedings and Information. 38 : 69–86

[13] Aller L, Bennet T, Lehr JH, Petty RJ (1987) DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrologic settings. US EPA Report, 600/2–87/ 035, Robert S. Kerr Environmental Research Laboratory, Ada, OK

[14] Van Stempvoort D, Evert L, Wassenaar L (1993) Aquifer vulnerability index: a GIS compatible method for groundwater vulnerability mapping. Can Wat Res J 18 : 25–37

[15] Civita M (1994) Le carte della vulnerabilità degli acquiferi all’inquinamento. Teoria and practica (Aquifer vulnerability maps to pollution) Pitagora, Bologna

[16] Civita M, De Regibus C (1995) Sperimentazione di alcune metodologie per la valutazione della vulnerabilità degli aquiferi. Q Geol Appl Pitagora, Bologna, 3 : 63–71

[17] Doerfliger N, Zwahlen F (1997) EPIK: a new method for outlining of protection areas in karstic environment. In: Gü- nay G, Jonshon AI (eds) International symposium and field seminar on ”karst waters and environmental impacts“. Antalya, Turkey. Balkema, Rotterdam, pp 117–123

[18] Corniello A, Ducci D, Napolitano P (1997) Comparison between parametric methods to evaluate aquifer pollution vulnerability using GIS: an example in the ”Piana Campana“, southern Italy. In: Marinos PG, Koukis GC,

Tsiambaos GC, and Stournaras GC (eds) Engineering geology and the environment. Balkema, Rotterdam, pp 1721–1726

[19] Goldscheider N, Klute M, Sturm S, Ho¨tzl H (2000) The PI method—a GIS-based approach to mapping groundwater vulnerability with special consideration on karst aquifers. Z Angew Geol 46(3):157–166

[20] Chachadi A.G. & Lobo-Ferreira, J.P (2001), Sea water intrusion vulnerability mapping of aquifers using GALDIT method. Proc. Workshop on modelling in hydrogeology, Anna University, Chennai, pp.143-156, and in COASTIN A Coastal Policy Research Newsletter, Number 4, March 2001. New Delhi, TERI, pp.7-9, (cfhttp://www.teriin.org/teriwr/coastin/newslett/coastin4.pdf).

[21] Lobo Ferreira JP, Chachadi AG, Diamantino C, Henriques MJ (2005) Assessing aquifer vulnerability to seawater intrusion using GALDIT method: Part 1 Application to the Portuguese Aquifer of Monte Gordo. Fourth Inter-Celtic Colloquium on Hydrogeology and Management of Water Resources, Portugal, 11–14, July 2005, CD Of Proceedings

[22] Chachadi AG, Lobo-Ferreira JP (2005) Assessing aquifer vulnerability to sea-water intrusion using GALDIT method: Part 2—GALDIT Indicators Description, Fourth Inter-Celtic Colloquium on Hydrogeology and Management of Water Resources, Portugal, 11–14, July 2005, CD Of Proceeding

[23] Kallioras A, Pliakas F, Skias S, Gkiougkis I (2011) Groundwater vulnerability assessment at SW Rhodope aquifer system in NE Greece. In: Lambrakis N, Stournaras G, Katsanou (eds) Advances in the research of aquatic environment. Environ Earth Sci. Springer 2:351–358. doi:10.1007/978-3-642-24076-8_41

[24] Gontara, M., Allouche, N., Jmal, I., & Bouri, S. (2016). Sensitivity analysis for the GALDIT method based on the assessment of vulnerability to pollution in the northern Sfax coastal aquifer, Tunisia. Arabian Journal of Geosciences, 9(5),. doi:10.1007/s12517-016-2437-3

[25] Sophiya MS, Syed TH (2013) Assessment of vulnerability to seawater intrusion and potential remediation measures for coastal aquifers: a case study from eastern India. Environ Earth Sci 70(3):1197–1209. doi:10.1007/s12665-012-2206-x

[26] Caswell, P. V. (1956a). Geology of the Kilifi-Mazeras area degree sheet 66 SE quarter [Map]. Nairobi: Survey, Min., Colony and Protectorate of Kenya

[27] Caswell, P. V. (1956b). Geology of the kilifi-mazeras area (Report No 34, pp. 1-54) ,Reprinted 2007 Kenya, Ministry of Mining, Geology Department. NAIROBI, Nairobi Area.

[28] Caswell, P. V. (1953). Geology of the Mombasa-Kwale area degree sheet 69 ; with coloured map [Map]. Nairobi: Survey, Min., Colony and Protectorate of Kenya.

[29] Abuodha, P.A.W., (1992). Geomorphology and Sedimentology of the Mombasa-Diani Area: Implications of Coastal Zone Management. Nairobi, Kenya: University of Nairobi, Master's thesis, 155p

[30] Climatemps, 2015. (2009). Mombasa climate Mombasa temperatures Mombasa weather averages. Retrieved July 24, 2016, http://www.mombasa.climatemps.com/

[31] Kebede, A. S., Nicholls, R. J., Hanson, S., & Mokrech, M. (2012). Impacts of climate change and sea-level rise: A preliminary case study of Mombasa, Kenya. Journal of Coastal Research, 278, 8–19. doi:10.2112/jcoastres-d-10-00069.

[32] UNPD (United Nations Population Division), 2007. Population Division of the Department of Economic and Social Affairs, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision. http://esa.un.org/unup (accessed August 19, 2009)

[33] KNBS (2010). 2009 Kenya Population and Housing Census, Population Distribution by Political Units, Vol.1B, KNBS

[34] Deb, P. K. (2014). Pumping tests and Aquifer parameters. In P. Kumar Deb, An Introduction to Mine Hydrogeology, SpringerBriefs in Water Science and Technology (pp. 13–21) DOI: 10.1007/978-3-319-02988-7_3

[35] Verruijt, A. (1968). A note on GHyben-Herzberg Formula. Bulletin of the International Association of Scientific Hydrology, XIII, 4-12