SPATIAL ASSESSMENT OF GROUNDWATER VULNERABILITY TO POLLUTION USING THE SINTACS MODEL- MUKONO UGANDA

Ocen Emmanuel[1] and Bamweyana Ivan [2]

[1,2] Department of Geomatics and Land Management, College of Engineering Design Art and Technology, Makerere University, P.O. Box 7062, Kampala, Uganda

ivanson5@gmail.com

Abstract:

The groundwater assets are under anthropogenic threat, this is largely due to urbanization, land-use changes and increment of water demands for domestic and agricultural purposes. The reversal of the groundwater quality and quantity relies upon rational management and the determination of the aquifer's protection zones. This research aimed at evaluating the level of groundwater vulnerability to pollution hotspots in Mukono district using the SINTACS model. Consequently, the vulnerability index was calculated by considering different hydrogeological parameters namely; water table depth, effective infiltration, unsaturated conditions, soil media, aquifer hydrogeologic characteristics, hydraulic conductivity, and topographic slope. All parameters were evaluated, classified, weighted and integrated into a Geographic Information System (GIS) environment. Mukono's Vulnerability index estimate ranged from 54-176 and was classified into area zones of High, Moderate and low vulnerability. Results show that out of the total area, 20% lies in high vulnerability zone (which is mostly the urbanized region of the study area), and 30% in the moderate vulnerability zone while at least 49% of the area is in the low vulnerability zone. The results of the sensitivity analysis indicate that depth to the water table is the most influential parameter in the vulnerability index computation. More so, depth to the water table, vadose zone, and soil media have been found to be more effective in assessing vulnerability index in the model. The study concluded that Mukono generally has a low potential of groundwater vulnerability to pollution and Mukono urban (central) is the area with the highest potential of groundwater vulnerability to pollution. This study proposes the implementation of environmental management decisions and greater distribution of piped water to manage groundwater vulnerability. The study implores that this model can, therefore, be an effective tool for local authorities and decision-makers for managing groundwater resources.

Keywords; *Groundwater vulnerability, pollution, SINTACS Model*

1. Introduction

Groundwater vulnerability alludes to pollution resulting from nonpoint sources or really appropriated point wellsprings of pollution and does not address singular point wellsprings of contamination nor any circumstance where a pollutant is intentionally set into the groundwater framework [1].

Groundwater is an essential, important and inexhaustible common asset which comprises about 95% of fresh water on our planet Earth, making it fundamental to human life and financial improvement. Groundwater supplies 85% and half of the rural and urban water needs individually [2]. Most recent 50 years have seen a phenomenal improvement of groundwater asset. At the regional level groundwater is of immense significance in Africa, Asia and Central and South America. Broadly, nations from Palestine to Denmark are dependent on groundwater and precedents of neighbourhood dependence can be attracted from Mexico City to little towns in Ethiopia. An expected 2 billion individuals overall depend on aquifers for their drinking water supply [3].

In Uganda. Groundwater improvement has been going ahead since the 1930s through the development of profound boreholes, shallow wells and protected springs. The shallow aquifers are exceptionally vulnerable to pollution i.e. microbial contamination has been seen in numerous urban areas of the country because of insufficiently contained faecal waste [4]. There are roughly 20,000 profound boreholes, 3000 shallow wells and 12,000 secured springs in the country developed for the most part for rural local water supply. During the 1990s groundwater was increased to accommodate town water supply. For instance, 782 residential areas were recognized for the arrangement of channelled water by June 2006, and 70% of this water was to be provided by groundwater sources like the profound boreholes. Boreholes and shallow wells are typically introduced with hand-pumps with a limit of 1 m3/hour and their yields are normally low [5].

Because of its moderately low vulnerability to contamination in contrast with surface water, and its tremendous storage capacity, groundwater has been treated as a vital wellspring of water supply. Given the health and financial effects related to groundwater contamination, ventures to quantify the vulnerability of groundwater must be taken for sustainable groundwater security and management planning. Susceptibility of groundwater alludes to the inborn qualities that determine the sensitivity of the water to being adversely affected by an imposed contaminant stack [6].

Last few decades have seen the advancement of numerous techniques to evaluate groundwater vulnerability which includes;- indexing, rating, hybrid, statistical and simulation methods. The indexes strategies, for example, DRASTIC [7], GOD [8], AVI [9], SINTACS [10], DRISTPI [11], EPIK [12], PI [13] and COP depended on the European methodology [14]. The SINTACS model will be utilized in this research. This model is gotten from the DRASTIC model. This technique evaluates groundwater pollution vulnerability by utilizing seven Hydro-Geological parameters. The seven parameters of SINTACS display are S - water table depth, I - net recharge, N - unsaturated conditions (Vadose zone), T – soil media, A – aquifer media, C – pressure-driven conductivity and S – topographic slope [15].

Study area

Mukono District is one of the districts in the central region of Uganda with a land area of 1875.1 km² (724 sq. miles). Mukono District is bordered by Kalangala District to the south-west, Luweero District to the north-west, Kayunga District to the north, Buikwe District to the east, Kira Town and Wakiso District to the west. Mukono has 1683 domestic water points which serve a total of 489,865 people. 340,750 in rural areas. 224 water points have been non- functional for over 5years and are considered abandoned.

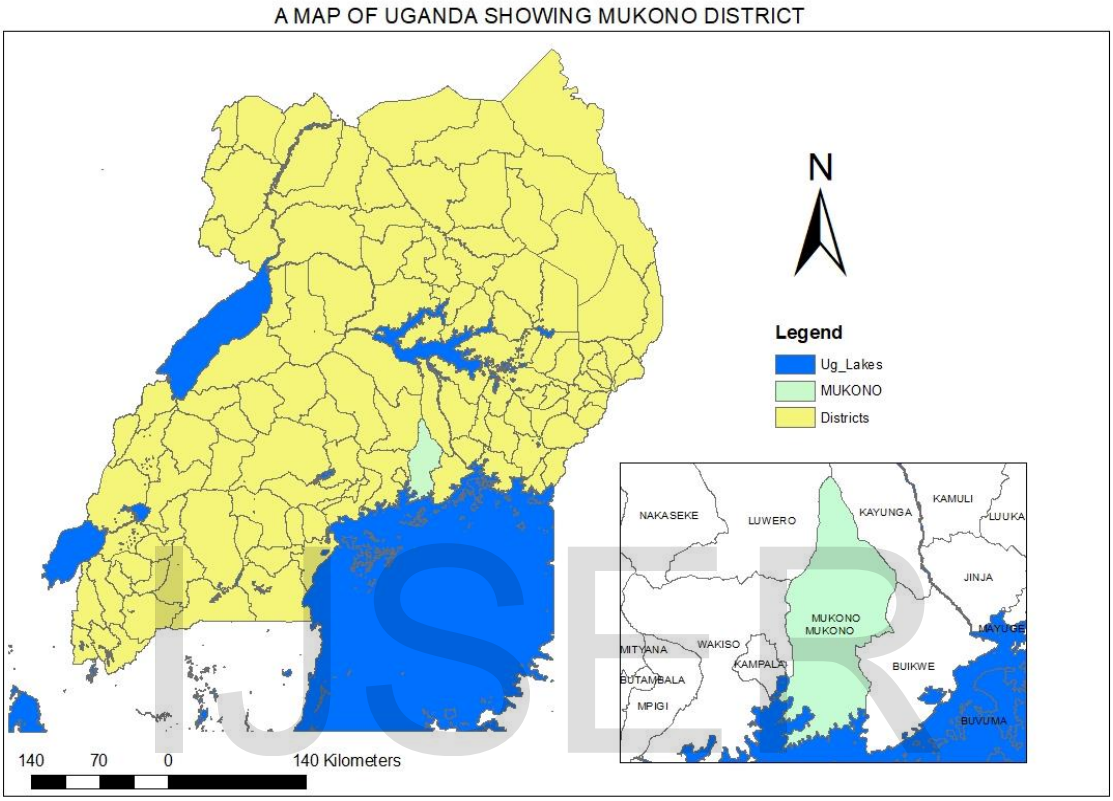

Figure 1: A map indicating the study area location

2. Methodology

The SINTACS model deployed was produced by [10] to survey the intrinsic vulnerability of groundwater. The acronym SINTACS originates from the Italian names of the factors that are utilized: Soggicenza (profundity to groundwater), Infiltrazione (successful penetration), Non saturo (unsaturated zone constriction limit), Tipologia della copertura (soil/overburden lessening limit), Acquifero (soaked zone characteristics), Conducibilita` (water-driven conductivity), and Superficie topografica (topographic surface incline) [16]. The utilization of SINTACS is more reasonable for evaluation at a small-medium scale territory. Unlike DRASTIC, SINTACS method allows using, at the same time and in different cells, weighting factors variable according to certain situations. The extra weight is set in connection to environmental attributes, for example, high dispersion phenomena from surface water bodies to groundwater or widespread contamination sources. The parameters of the SINTACS model are similar to DRASTIC but they have different rating and weighting coefficients [17]

Table 1: SINTACS Model Parameters

Parameter	Description	Weight
Water table depth(S)	It signifies the depth of the water table from the ground surface, the deeper the water table lesser will be the chances of the interaction of pollutants with the groundwater because the travelling time for pollutant will be higher than for the shallow water table	5
Effective infiltration(I)	It is the net amount of water percolating and travelling up to the groundwater from the surface. It acts as a medium to travel for the pollutant or contamination	5
Unsaturated conditions (N)	The unsaturated zone above the water table is referred to as the vadose zone; it controls the passage and attenuation of the contaminated material to the saturated zone	4
Soil media (T)	It is the uppermost weathered portion of the surface and controls the amount of percolating water that can infiltrate downward	5
Aquifer Media(A)	It is the potential area for water storage, the contaminant attenuation of aquifer depends on the amount and sorting of fine grains, lower the grain size higher the attenuation capacity of aquifer media	3
Hydraulic Conductivity(C)	It signifies the ability of the aquifer to transmit water, hence determines the rate of flow of pollutant within the groundwater system.	2
Topographic Slope (S)	It signifies to slope or steepness, areas with mild slopes tend to hold water for longer, this allows a higher percolation of water and a greater potential for contaminant migration and vulnerable to groundwater contamination and vice versa.	2

2.1. Data Layer Preparation

Each of the SINTACS parameters has been expressed as a thematic layer using ArcMap. A Personal Geodatabase using ArcCatalog has been created to hold data for these parameters. The seven parameters were subdivided into ranges (or) zones, representing various hydrological settings and assigned different rating in a scale of 1 in 10 based on the rating chart [18].The rating assigned to each of the ranges or zones indicates their relative importance within each parameter, in contributing to aquifer vulnerability. These layers have been multiplied with their assigned weight and overlaid using raster calculator tool in ArcGIS and the final output vulnerability index map generated

Both primary and secondary data were used. The primary data was obtained by the Ministry of Water and Environment using a Dipper meter and water level meter for borehole depth. Test pumping was carried out to obtain hydraulic conductivity factors recorded in borehole logs. Secondary data included a geology layer, soil media layer and a 30m resolution digital elevation model obtained from Shuttle Radar Topography Mission (SRTM). The data used for creating the SINTACS model are summarized in Table 2

Table 2: Data Used To Create SINTACS Input Data

Parameter	Data type	Format	year	Custodian Source	Output layer
S	Borehole	Point shapefile	2005-2018	Water Resources Management Department(WRMD)	Depth to the water table
I	Annual infiltration	Raster	2017	WRMD	Recharge map
N	Geology layer	KMZ	2018	W&E consult	Vadose zone
T	Soil	Polygon shapefile		WRMD	Soil media map
A	Geology layer	KMZ	2018	W&E consult	Aquifer media
C	Borehole logs	Point shapefile	2005-2018	WRMD	Hydraulic conductivity map
S	SRTM	DEM	2018	WRMD	Slope map

2.2. SINTACS Intrinsic Vulnerability Index (SIVI)

The seven parameters are themselves not considered to be equally important in vulnerability assessment. In order to reflect the relative importance of these parameters, weights in the scale of 1 to 5 were assigned to each of these parameters (table 1). The SINTACS intrinsic vulnerability index (SIVI) is computed using the following equation.

$$SIVI = \sum_{i=1}^{7} Pi * Wi \quad (1)$$

Where the Pi is the rating of each of the seven parameters that the method considers and Wi is the relative weight. The index is useful at a regional scale to prioritize area of high, moderate, low and very low vulnerability regions.

2.3. Sensitivity Analysis

Sensitivity analysis studies the contribution of individual variables and of input parameters, on the resultant output of an analytical model. The seven classified maps were overlaid using expression (1) to obtain the vulnerability map. With a "crossing" operation all the possible combinations of the effective weight of each layer.

An investigation was made to look at the “effective”or “real” weight that every parameter has in each subarea with the hypothetical weight assigned by the SINTACS model. The effective Weight (Wpi) in %, for each subarea, was computed as below:

$$W_{pi} = \frac{P_{Ri}P_{Wi}}{Vuln_i}10 \quad (2)$$

Where PRi and PWi are the ratings and the weights respectively of the parameter P assigned to the subarea i, and vulni is the vulnerability index as computed in expression (1)

3. Results and Discussion

3.1. The SINTACS Vulnerability Index

The SINTACS vulnerability index (SVI) were obtained by overlaying the layer maps. Each layer was multiplied by their significant weights and ratings by mapping algebra in GIS toolbox using the (Eq. 1)

The application of the SINTACS method combined with a GIS allowed obtaining the groundwater vulnerability to pollution map of the Mukono district. This map is used to view the main risk areas linked to the high index. Showing areas of low, moderate and high vulnerability. The district's geological and hydro-geological set up determines the aquifer characteristics and in Mukono district, the groundwater resources are well protected by the soil, aquifer media, vadose zone, and also topography.

The final SINTACS vulnerability thematic layer (fig 2) was developed by counting the number of pixels in each SINTACS thematic parameter. Every parameter was multiplied by its weight. The final index values vary from 53 to 176. This step allowed for expressing vulnerability in three classes: low, moderate, and high as a standard measurement.

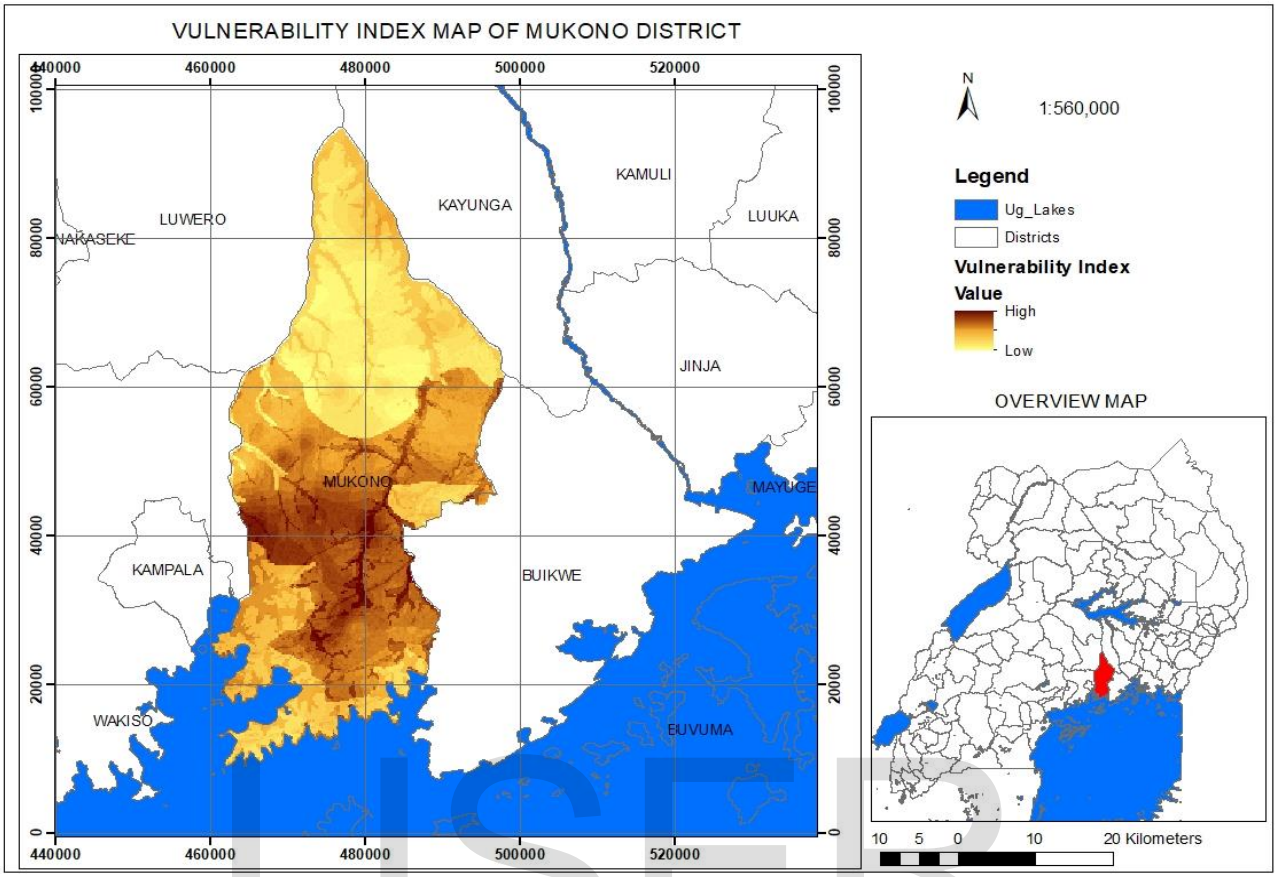

Figure 2: Vulnerability Index map of Mukono District

Around 20% of the area shows high vulnerability and around 30% shows moderate vulnerability while at least 49% of the area has a low vulnerability. The high, moderate and low vulnerability has been assigned as given in Table 3.

Table 3: Classes Of SINTACS Vulnerability Index

SINTACS VULNERABILITY INDEX	
Low	53-91
Moderate	91-115
High	115-176

The SINTACS index map indicates that the potential for polluting groundwater is high (shades of brown) in the central areas of Mukono District (Mukono town). This is justified as Mukono is an industrial district i.e. The harbouring of the industrial park and Agro-processing plants at the centre. This as well as having the highest population of over 700000 [19] which has greatly resulted to sewage spreading, uncontrolled dumping of waste materials and chemical leakages from industrial parks hence the high vulnerability levels of groundwater to pollution.

The moderate vulnerability levels in the southern parts and central parts of the district are due to the high infiltration rates, low slope and shallow depth to the water table and high alluvium deposits respectively.

The low vulnerability index in the northern regions of Mukono district is evident as the areas harbour clay loams, grey humour clays and sandy clay loams. These type of soils have a fine texture there have low porosity levels this supplemented by the low rainfall totals in that area have resulted to low vulnerability levels as pollutants are not easily moved to the underground aquifer.

Table 4: Percentage Of Mukono District Area Falling Within Each Vulnerability Class

Value	vulnerability class	count of pixels	Percentage of total area (%)
1	High	17964	20.2309
2	Moderate	26825	30.2100
3	Low	44006	49.5591
Sum		**88795**	**100**

3.2. Sensitivity Analysis

The last step of the procedure, the interpretation, is based on the analysis and comparison of the vulnerability maps, the maps representing the seven layers, the maps representing the real weight for each subarea with the associated tables, and the tables with resulting statistics. The "effective weight" of each parameter in each subarea is dependent not only on the "theoretical weight" assigned by the SINTACS method but on the value of the single parameter in the "context" of the values of the other parameters.

Table 5: Summarized Statistical Table From Sensitivity Analysis

Parameter	Theoretical weight	Theoretical weight (%)	average weight (%)	standard deviation (%)	Median (%)	Maximum Value (%)	Minimum Value (%)
S	5	19	27	10	27	56	5
I	4	15	12	7	10	39	3
N	5	19	17	10	19	45	4
T	4	15	14	6	15	34	0
A	3	12	13	7	12	37	2
C	3	12	9	4	8	20	0
S	2	8	4	3	4	15	1

The “effective” weight is a function of the other six parameters as well as the weight assigned to it by the SINTACS model. The “effective” weights of the SINTACS parameters exhibited some deviation from the “theoretical” weight.

The depth to the water table, S, tends to be the most effective parameter in the vulnerability assessment for this study with an average weight of 27% against the “theoretical” weight (19%). In particular, its removal would broadly decrease the vulnerability index. The parameter slope has the lowest theoretical weight and lowest effective weight with an average value of 8%. The “effective” weight of the depth to water table parameter, S (27%) greatly exceeds the “theoretical” weight assigned by SINTACS (19%). On the contrary, the calculated

weights of the Recharge, I, Vadose zone, N, Soil media, T, Hydraulic conductivity, c, (12%,17%,14% and 9% respectively) do not exceed their "theoretical" weights.

The statistical table (table 5) above shows that depth to water mostly influences the vulnerability index, with an average weight of 27% against the theoretical weight of 19.

4. Conclusions and Recommendations

4.1. Conclusions

The research aimed at assessing groundwater vulnerability to pollution in Mukono District. Using SINTACS vulnerability index values which ranged from 53-176, the overall assessment of vulnerability to pollution of groundwater in Mukono District was obtained. Areas with low vulnerability to pollution had an index ranging from 53-91, those with moderate vulnerability ranged from 91-115 while those with high vulnerability ranged from 115-176.The research performed groundwater vulnerability to pollution in Mukono District using ArcGIS 10.6 and the SINTACS model. The results show that Mukono's largest area lies in the low vulnerability zone hence a low potential of pollution of groundwater.

Mukono town council in Mukono central was identified as the area with the highest index of groundwater vulnerability to pollution. Mukono is a major industrial district in the country with industries concentrated in the following areas; Mukono Town Council: Lwanyonyi – Industrial pack, Kyetume abattoir and railway. Carpentry, Welding, Agro-processing, hatcheries with a total population of over 700000 [19].This has greatly resulted in sewage spreading, uncontrolled dumping of waste materials and chemical leakages from industrial parks that have threatened groundwater quality. The population of the district town council is increasing further and so is the water demand and hence, the stress on groundwater also increases, which would further increase the groundwater exploitation.

The single parameter sensitivity analysis showed that depth to the water table, vadose zone and soil media is the most significant hydrogeological factors determining the vulnerability of groundwater to pollution. Therefore, the sensitivity analysis is very useful in revising the weight factors to obtain more realistic results.

4.2. Recommendations

The continuous rise in population levels and economic explode i.e. the expansion of commercial activities such as industries in Mukono district is inevitable due to its closeness to Kampala central business district. This will, therefore, broaden the stress and threat of groundwater quality. State bodies such as National Water and Sewerage cooperation should, therefore, ensure that piped water is highly accessible especially by the population in Mukono central so as to suppress the usage of borehole water that is highly vulnerable to pollution.

It is noticed that industrial leakages and human waste are the major reasons for high levels of vulnerability of groundwater to pollution in Mukono town council. Environmental Management decisions should be implemented to force industries to be sited or operated in areas whose geologic nature prohibits or obstructs

pollutants from reaching the groundwater layers. Restrictions should also be made to excessive usage of fertilizers by farmers to so as to boost harvest.

Based on the findings of this study, a rescaling of the SINTACS rating is proposed and justified based on the analysis of the "effective" weight. The vulnerability map using the calculated "effective" weights should be obtained and compared with the initial map for broader analysis and study of parameter significance for vulnerability assessment. Single parameter sensitivity analysis is important both for the experts that implement vulnerability models and for the users of vulnerability maps. The former can use sensitivity analysis for validation and consistency evaluation of analytical results. They can also select layers and subareas which is more critical for the analysis and require more detailed information and accuracy. Results of such an analysis can be used for more efficient interpretation of the vulnerability index. In particular, the production of maps representing the effective weight of each parameter helps decision-makers, usually not GIS-specialists, in understanding and using the model results.

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