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Basil T. I. Ong'or
Shu Long-cang

Groundwater overdraft vulnerability and environmental impact assessment in Arusha

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B. T. I. Ong'or (✉) · S. Long-cang
College of Water Resources
and Environment, Hohai University,
Nanjing 210098, China
E-mail: basil_iro@yahoo.com
Tel.: +86-25-83787491
Fax: +86-25-83787355

B. T. I. Ong'or
College of Science and Technology,
Western University, P.O. Box 190,
Kakamega 50100, Kenya

Abstract A simple approach is proposed for identifying areas vulnerable to groundwater overdraft. The methodology utilizes GIS techniques to analyze and evaluate controlling factors in areas with little data. The proposed methodology was applied in Arusha. Water demand in Arusha Municipality and its environs has increased to about 5.3% annually since 1999. Groundwater levels have declined. The aquifer hydrogeological variables were evaluated for impact to potential groundwater overdraft by overlay and index techniques. The spatial distribution of overdraft vulnerability was discussed. The northwestern part of Arusha is the most vulnerable to overdraft and possible serious environmental impacts. The Loruvani area has the most potential for aquifer development due to its permeability, high recharge rate, massive aquifer thickness and low drawdown.

Keywords Environmental impacts · Geographic information system · Groundwater overdraft · Groundwater spatial and temporal vulnerability · Hydrogeological · qualitative hydrogeology · Arusha · Tanzania

Introduction

Rapid socio-economic developments and increasing population coupled with agricultural and industrial growth in Arusha Municipality and its environs has put more stress on groundwater resources. The water demand and abstraction has been continually increasing since 1999 at an annual increment rate of about 5.3%. Groundwater resources are not projected to meet its industrial, domestic and agricultural water demand by the year 2015. The challenge faced by the Water Planning and Supply Authority is to develop a management plan for increasing water demand and to delineate areas more vulnerable to overdraft.

This study proposes a quantitative approach for evaluating groundwater vulnerability. Five factors are chosen for establishing the overdraft vulnerability: net recharge, pumping rate density, drawdown, aquifer thickness and the aquifer hydraulic conductivity. Due to the spatial and temporal variation in groundwater withdrawal, recharge and aquifer hydraulic properties, and the fact that groundwater resources are the main water supply for the urban and peri-urban settlements, Arusha Municipality aquifer presents an excellent showcase for this kind of approach.

Use of groundwater assessments

When surface water supply declines and basin water use efficiency drops, greater exploitation of groundwater emerges. Lower water tables culminate in environmental and ecological problems: land subsidence, groundwater contamination, depletion of stream flow, land drainage, drying of wetlands and salt water intrusion (Wolfgang et al. 2003). Lower water tables also increase extraction costs. Changes in environmental variables, e.g., precipitation and river runoff, affect groundwater quality in a complex cycle of groundwater extraction and environmental change (Zektser et al. 2005). Reconciling groundwater sustainability with over-exploitation is very difficult. There has been more concern for the consequences of intensive groundwater abstraction than in its absolute levels (Walid 2005).

Groundwater vulnerability cannot be directly measured in the field (Gogu and Dassargues 2000). Some aquifer areas are more vulnerable to groundwater contamination and/or overdraft than others. Vulnerability assessment is a general planning and decision-making tool, which should be included within groundwater management strategy (Lindström and Scharp 1995) to provide a basis for initiating protective measures, guidance for use of groundwater resources and prediction of possible effects of overdraft. There is no universal methodology for groundwater vulnerability assessment. A number of different approaches have been used. Gogu and Dassargues (2000), Gogu et al. (2003) and Zwahlen (2003) present some recent vulnerability mapping methods. Index and overlay methods are based on the assumption that a few major parameters largely control groundwater vulnerability, and that these parameters are known and can be evaluated. These methods are, in general, based on limited basic data, used in regional studies, and usually cover extensive areas (Lindström and Scharp 1995). Scoring, integration or classification are used to produce an index, rank or class of vulnerability, which can then be interpreted. Index approaches are used to create maps using geographic information systems (GIS) (Corwin et al. 1997). GIS has the capability to store, retrieve, organize, analyze and present geographically referenced spatial data. A geographic information system is used for the evaluation of groundwater vulnerability in this study. GIS as an analysis tool relies on the groundwater model's output data. In this study, Visual MODFLOW was used (McDonald and Harbaugh 1996).

Study area

Arusha Municipality in Arusha District is on the southern slopes of mount Meru in Arusha region, Tanzania. It occupies an area of about 96 km^2. The area of this study lies between 36°40′E ~ 36°43′E and 3°18′S ~ 3°24′S, an area of about 40 km^2 with a population of about 321,748 in 2000 (Fig. 1). Topography ranges from 4,566 m a.m.s.l to about 1,180 m a.m.s.l on the lower south. Arusha is comprised mainly of thick overlays of recent sediments, alluvial soils and mantling ash. Clastic volcanic sediments of thickness greater than 50 m are predominant around the town. Within the town itself, black clay-rich soils termed "*mbugas*"(local term) and recent sediments and weathered mantling ash prevail. Clastic volcanic sediments of thickness 30–50 m and patches of parasitic cones are evident on the eastern side of study area. To the west of the study area, clastic volcanic sediments of sand, gravel and boulders with unknown thickness is predominant, with some patches of lava streams. The hydraulic conductivity (K) of the study area varies from 0.55 to 5.90 m/day, with an average of 4.442 m/day. Specific yield varies from 0.25 to 0.4, with an average of 0.346. In the well field around Loruvani, Sakina and Oltulelei, Moivo2 and Sekei (Fig. 2), where the sediments are predominantly Clastic volcanic sediments, sand, gravel and gravel, K values range from 5.5 to 5.9 m/day. In the center of town, where clayey sediments of low hydraulic conductivity occur, K values are about 0.55 m/day (Arusha Urban and Water Sewerage Engineering 1990).

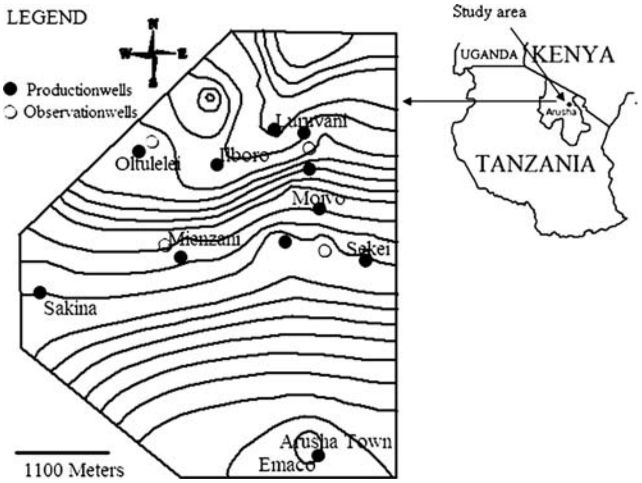

Fig. 1 Location of study area

Groundwater is the principal source of water supply for all uses. The unconfined Arusha aquifer has varying depths of 92–205 m, and discharges through 13 pumping wells and a number of springs. The pumping intensity varies as high as 2,200 m^3/day km^2 in the northern and northwestern parts of the aquifer to 300 m^3/day km^2 in the south. General groundwater flow is from the north to the south. Overall production capacity fluctuates seasonally from an average of 32,000 m^3/day in the dry season to 44,000 m^3/day during the rainy season. Daily water demand is estimated to be 42,000 m^3/day. Presently, water supply service coverage is 94% of the targeted population; the remaining 6% are in rural and peri-urban areas where the supply network has not reached. Arusha has a temperate climate despite its proximity to the equator (at latitude 3°30′S) due to its altitude and the influence of Mount Meru. Arusha has bimodal rainfall regimes, one period from mid-March to

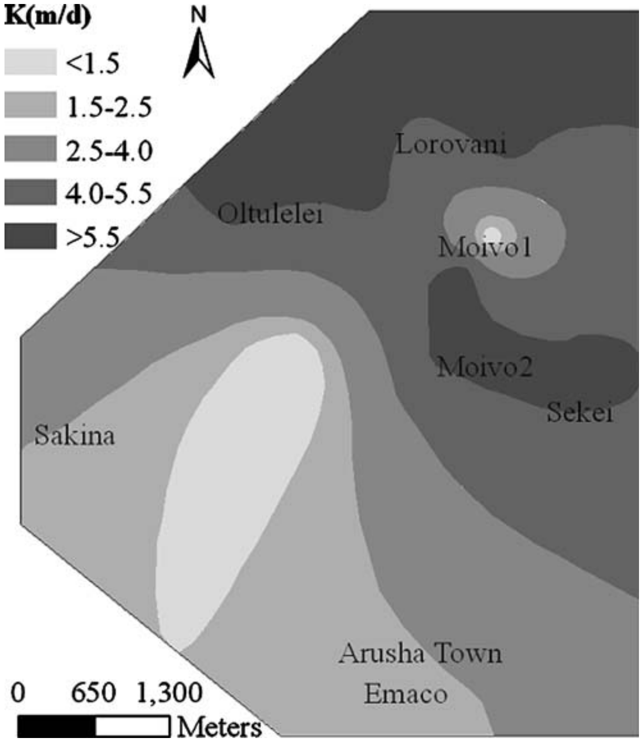

Fig. 2 Spatial distribution of hydraulic conductivity (*K*)

June, referred to as *Masika* (local term), and another from October to December, referred to as *Vuli* (local term). April is the wettest month with an average rainfall of 231 mm, while August is the driest month with an average rainfall of 6.5 mm. The average annual rainfall (data of 1980–1990 from the three meteorological stations in Arusha) is about 956 mm, with an average evapotranspiration rate of about 383 mm. Arusha has an average annual temperature of about 19.7°C. March is the hottest month with an average temperature of 21.3°C. The coolest months are July and August with an average temperature of 17.2°C.

Many studies related to groundwater and geotechnical aspects in Arusha have been performed. Ong'or (2000) developed an optimal management option for aquifer sustainability.

Methodology and procedure

The greatest challenges in assessing groundwater overdraft impact are the proper identification, analysis and mapping of significant factors. An index and overlay method was used in this study. Index and overlay mapping often utilizes a parametric method by assigning point ratings and weights to individual factors. The most utilized method for identifying areas characterized by greatest potential to aquifer contamination in many parts of the world is probably DRASTIC (Aller et al. 1987), even though this method has real limitations. A modified but similar approach was used for the quantitative groundwater overdraft vulnerability assessment in this study. Index maps that defined the hydrogeological characteristics of the groundwater system were created and overlaid using ArcGIS to determine, locate and quantify spatial and total groundwater vulnerability to depletion. Index maps were created based on ranges, ratings and weights of the controlling factors. Weights were determined through the classical analytic hierarchy process method. The five factors used were: net recharge (*R*), pumping rate density (*P*), drawdown (*D*), aquifer thickness (*H*) and the aquifer media (*M*). The pumping rate density (*P*), or groundwater pumping rate per square kilometer, is an indicator of the intensity of groundwater resource abstraction. The higher the value of *P*, the more vulnerable the aquifer is to land subsidence, contamination, overdraft and other environmental impacts. The net recharge rate (*R*) represents the total quantity of water applied to ground surface through precipitation and infiltrating to the aquifer, less evapotranspiration. *R* does not take into account the intensity and distribution of the recharge events, just rainfall totals. The higher the net recharge, the less the overdraft vulnerability to the aquifer. The aquifer thickness (*H*) refers to the difference in depth between the water table elevation and the aquifer base elevation. *H* is an indicator of the available water in the unconfined aquifer. The higher the value of *H*, the less vulnerable the aquifer. The aquifer media (*M*) refers to the hydraulic conductivity of the geological formation. The higher the value of *M*, the less vulnerable the geological formation. The drawdown (*D*) is an indication of the difference in depth between the original water table before groundwater pumping in large scale and the current water table. *D* indicates the severity and intensity of the groundwater withdrawal and points to the likelihood of aquifer depletion, formation of cone of depression and land subsidence.

These factors were partly obtained from a 3D numerical model, Visual MODFLOW, which was initially used to simulate flow in the unconfined heterogeneous Arusha aquifer, and from existing reports of hydrogeological investigations. The factors were weighed. For each factor, ranking and rating was based on its attributes for varying potential for overdraft. The ratings of attributes in thematic maps are in direct proportion to potential effects for overdraft vulnerability (Tables 1, 2, 3, 4, 5). Due to the spatial heterogeneity of all the relative indexes, a geographic information system (GIS) was used to delineate the attributes. The score of each index aspect and relative spatial distribution was spatially analyzed.

The equation to determine overdraft vulnerability is:

$$V = P_r P_w + R_r R_w + K_r K_w + H_r H_w + D_r D_w \quad (1)$$

Table 1 Pumping rate density (*P*)

Range (m^3/day km^2)	Ratings
0–300	1
300–600	2
600–1,000	4
1,000–1,600	6
1,600–2,200	8
> 2,200	10
Weight = 0.411	

Table 2 Net recharge (*R*)

Range (mm/year)	Ratings
0–75	5
75–100	4
100–145	3
> 145	1
Weight = 0.278	

Table 3 Aquifer hydraulic conductivity (*K*)

Conductivity (m/day)	Ratings
0–1.5	9
1.5–2.5	7
2.5–4.0	5
4.0–5.5	3
> 5.5	1
Weight = 0.161	

Table 4 Aquifer thickness (*H*)

Thickness (m)	Ratings
0–60	5
60–80	3
80–100	2
> 100	1
Weight = 0.06	

Table 5 Drawdown (*D*)

Range (m)	Ratings
0–5	1
5–10	2
10–15	3
15–20	4
> 20	5
Weight = 0.089	

where V, P, R, K, H and D are overall vulnerability to depletion, pumping rate density, net recharge, hydraulic conductivity, aquifer thickness and drawdown, respectively. r and w are ratings and weighting for each factor. Equation 1 can be written as:

$$V = \sum_{i=1}^{n} w_i V_i \tag{2}$$

where V is the overall vulnerability to depletion, V_i is the vulnerability for the Ith index, w_i is the weight of the ith index and n is the number of indexes selected into the evaluation system. High index values indicate high vulnerability.

Results and discussion

Index maps that defined the spatial distribution of physical characteristics or controlling factors of the groundwater system were created (Figs. 2, 3, 4, 5, 6). The spatial distribution of groundwater withdrawal vulnerability based on the final scorings and weights of each index (calculated) is represented in Fig. 7.

The vulnerability analysis shows that Ilboro, Oltulelei, Moivo1 and Mienzani are the most vulnerable areas (Fig. 6). These areas are characterized by moderate aquifer thickness (60–180 m), high to very high pumping rate density (600–2,200 m^3/day km^2) and recharge rate of 75–145 mm/year. Ilboro and Oltulelei lie over an excellent geological formation with high hydraulic conductivity (2.5–5.5 m/day), but clastic volcanic sediments, sand, gravel, and high pumping rates make them very vulnerable. The low hydraulic conductivity of the clayey sediments in Mienzani and the ash beds in Moivo1 (less than 1.5 m/day) makes them very vulnerable (Fig. 2).

Arusha Town and Loruvani are the least vulnerable areas. Loruvani is characterized by an aquifer of great thickness (80–100 m), recharge rate of more than 145 mm/year, high pumping rates density (1,000–1,600 m^3/day km^2) and high hydraulic conductivity from the clastic volcanic sediments, sand and gravel. Arusha town, situated within the low permeable clayey sediments (1.5–2.5 m/day), is characterized by low pumping rate density of less than 300 m^3/day km^2, recharge rate of about 2 mm/year and a very thick aquifer (more than 100 m). Sekei, Moivo2 and Sakina are of medium vulnerability. Moivo2 and Sekei in the east are characterized by clastic volcanic sediments of sand and gravel with high hydraulic conductivity, but has moderate recharge and aquifer thickness. Moivo2 has a relatively high pumping rate density (1,000–1,600 m^3/day km^2) and drawdown of less than 5 m. Sekei has a moderate pumping rate (600–1,000 m^3/day km^2) and drawdown ranging from 5–10 m. Sakina in the west has

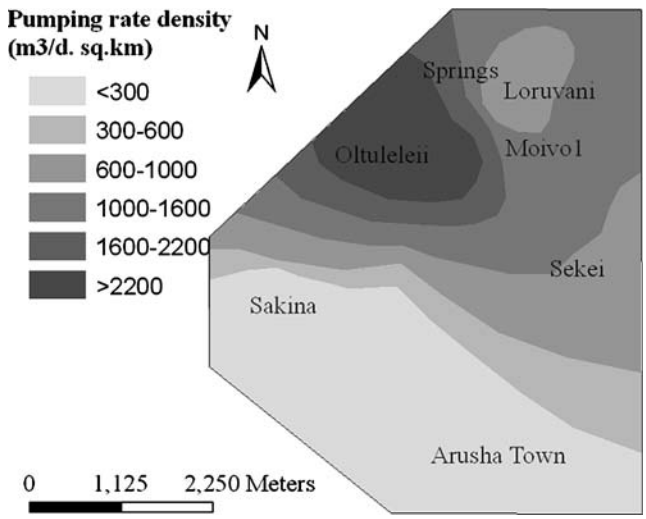

Fig. 3 Spatial distribution of pumping rate density (*P*)

the same characteristics as Arusha town, except that its aquifer thickness is less than 60 m.

Conclusions

This study presents a simple but effective qualitative methodology for determining groundwater overdraft vulnerability. The five major factors for analysis are: net recharge, pumping rate density, drawdown, aquifer thickness and hydraulic conductivity. The transmissivity, pumping rate and recharge rate are more significant in groundwater overdraft vulnerability analysis in the Arusha aquifer. The pumping rate and recharge rate can be altered and managed to some extent, but the geological formation and its orientation in Arusha aquifer presents a challenge for groundwater development and

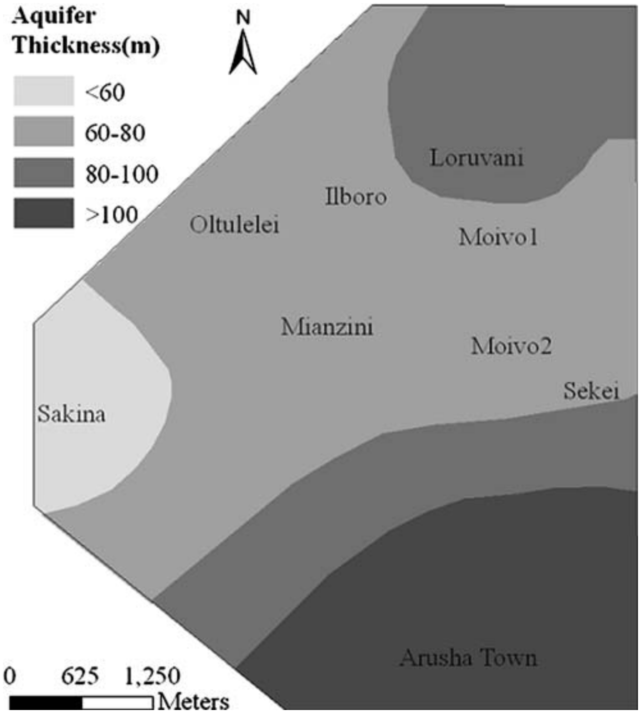

Fig. 5 Spatial distribution of aquifer thickness (*H*)

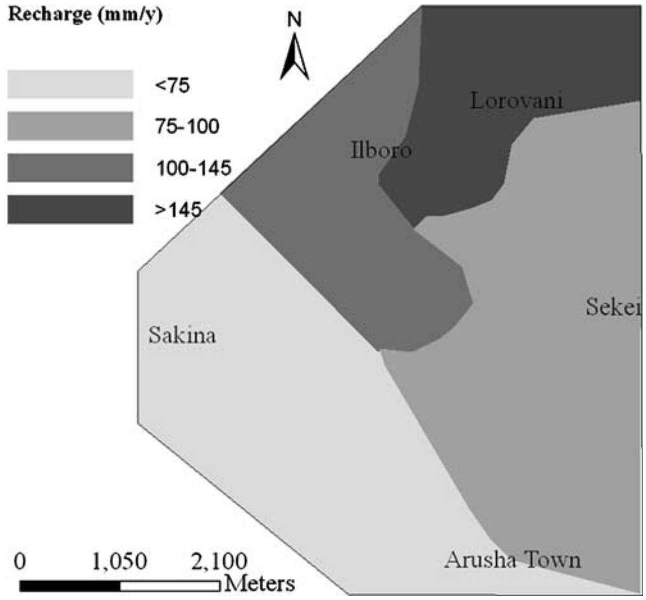

Fig. 4 Spatial distribution net recharges (*R*)

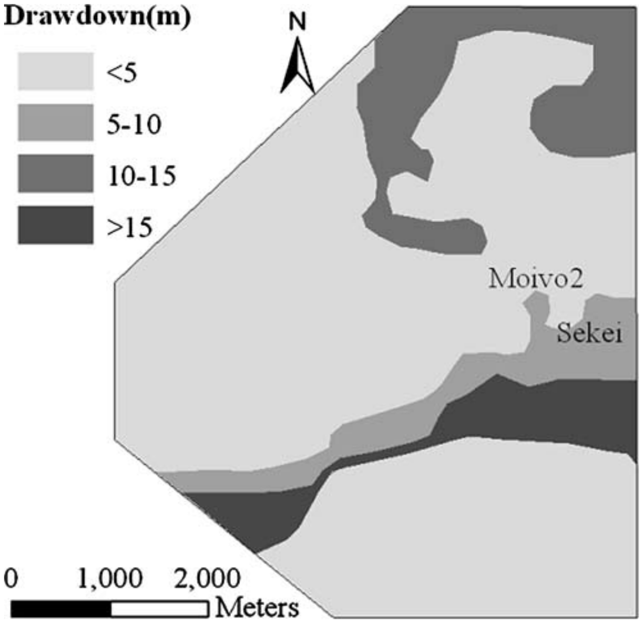

Fig. 6 Spatial distribution of aquifer drawdown (*D*)

management. The northwestern region of the aquifer is the most vulnerable region. Any additional wells or increased pumping rates of the existing wells in the northwest may have serious environmental impacts. The Loruvani area has the most potential for aquifer development due to its excellent transmissivity, high recharge rate, massive aquifer thickness and low drawdown.

The method used in this study can also be used in other areas to assess groundwater overdraft vulnerability. Groundwater vulnerability maps developed by this method will better identify areas of greatest potential to overdraft and serious environmental impacts for sustainability of the aquifer. This study highlights the need for adequate monitoring and evaluation of groundwater quantity prior to future development or utilizations and the importance of understanding hydrogeological factors affecting groundwater quantity in tropical terrains.

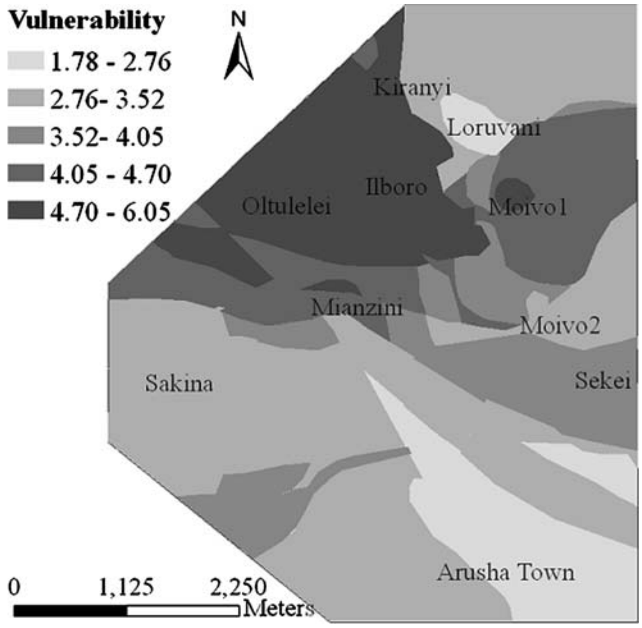

Fig. 7 Spatial distribution of vulnerability (*V*)

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