ORIGINAL ARTICLE

Groundwater Risk Assessment of Shallow Aquifers within the Atankwidi Basin of Northeastern Ghana

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Abstract

The potential leaching of harmful chemicals (heavy metals) due to application of large quantities of agro-chemicals in an impending up-scaling of dry-season irrigational farming into shallow groundwater aquifers has necessitated the study to assess the potential risk to contamination of the shallow (weathered) aquifers within the Atankwidi basin of Ghana using the combination of DRASTIC and Arc GIS. The DRASTIC indices ranged from 41 to 117 representing the lowest to highest vulnerable (risk) areas. 34.4 km^2, 93.3 km^2 and 63.9 km^2 representing 20, 48.8 and 33.2% of the area had low, moderate and high risk with indices ranging between 41–71, 71–88 and 88–117, respectively. Moderate and high risk areas which constituted approximately 80% of the area are underlain with clay-loam and sandy-loam soils, where major farming takes place. High risk areas are located in elevated areas (recharge), having the shallowest depth-to-water table and highest conductivity values. Sensitivity analysis revealed influential parameters in order of Hydraulic conductivity (C) > Soil media (S) > Depth to water table (D) > Net recharge (R) > Impact of vadose zone (I) > Topography (T) > Aquifer media (A). Validation of the DRASTIC model using heavy metals revealed that elevated concentrations were found within the high risk and vice versa. It is recommended that pollution-prevention measures would be taken account during the planning and implementation of the up-scaling program.

Keywords Atankwidi · DRASTIC index · Ghana · Groundwater vulnerability · Shallow aquifers

1 Introduction

Groundwater is recognized as an essential natural resource which supports the socio-economic development of mankind and maintenance of the ecosystem. In most arid and semi-arid regions, groundwater continue to serve as most reliable and sustainable resource of potable water for domestic, agricultural, industrial and sometimes recreational purposes as concluded by a myriad of studies (Appelo and Postma 2005; Ghosh et al. 2000; Srivastava et al. 2011; Pelig-ba et al. 2001; Martin and van de Giesen 2006; etc.), and therefore the sustainability of the groundwater resource (in terms of quantity and quality) is of utmost importance (Wang et al. 2001).

Some processes both from natural processes and man-made actions can alter negatively the quantity and quality of groundwater in storage. Thus, groundwater, even though is considered to be better than surface water in terms of quality and quantity in arid and semi-arid regions, it could be at risk (vulnerable) as an essential natural resource to man and the ecosystem. According to Appelo and Postma (2005), hydrogeochemical processes such as dissolution of salts during water–rock and soil–water interactions, sea-water intrusion, high evapotranspiration as well as certain biological processes are common natural activities that can adversely alter the quality of groundwater resource whilst anthropogenic activities may include over-extraction of groundwater, leachates from municipal and urban wastewater sources from landfills, domestic and petrochemical facilities; industrial wastes coming from manufacturing and pharmaceutical,

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mine effluents, as well as agricultural activities (i.e. application of fertilizers, weedicides, pesticides manures etc.).

One of the most widely used means of evaluating the risk of an aquifer system to pollution or contamination is by evaluating its vulnerability. Groundwater vulnerability according to Lindstrom (2005) was first coined by the French hydrogeologist Margat in the 1960s and has since been widely used by subsequent researchers (Haertle 1983; Aller et al. 1985; Foster and Hirata 1988; Vrba and Zaporozec 1994 etc.). Varying scenarios had been considered by different researchers in determining the groundwater vulnerability. Foster and Hirata (1988) considered groundwater vulnerability in terms of pollution hazard by defining it as the probability that groundwater in an aquifer will become contaminated with concentrations above the correspondent (WHO) guideline values for drinking water. NRC (1993) defined groundwater vulnerability based on the tendency of or likelihood for, contaminants to reach a specific position in the groundwater system after introduction at some location above the uppermost aquifer; Vrba and Zaporozec (1994) applied the study of the inherent hydro-geological characteristics (intrinsic geological properties of an aquifer system) of an area to determine its groundwater vulnerability whilst Andrade and Stigter (2009) assessed specific vulnerability by integrating contaminant-specific parameters (sorption-coefficient or half-life) to soil organic matter.

The Atankwidi basin located in Ghana and Burkina Faso is a transboundary sub-catchment of the White Volta basin of West Africa. It is considered to be one of the areas with the highest groundwater-use per square kilometer in the entire White Volta basin of West Africa (Martin 2005), and well-endowed with relatively large tracks of fertile soils that can support large scale irrigational farming. Previous study by van der Ofosu et al. (2014) had revealed that over 80% of the total arable lands within the basin in Upper-East Region of Ghana remain uncultivated even after over two decades of expanding irrigational farming. The lack of reliable surficial water sources to support irrigational farming has led to the identification of groundwater from shallow aquifers to be reasonably enough to support large-scale irrigation farming over a long period of time, especially during the prolong dry season to improve crop production, food security and alleviate poverty (Barry et al. 2010; Van den Berg 2008; van der Ofosu et al. 2014).

Within the past two decade, there has been a tremendous increase in population coupled with rapid urbanization, which had resulted in increased abstraction of groundwater from weathered aquifers located with the basin for domestic purposes. Similarly, there had been an average increment of about 5% acreage of irrigable land cultivation with groundwater from wells that taps shallow aquifers serving as the sources of irrigation water, usually for the cultivation of vegetable crops such as pepper, tomatoes, lettuce, carrots etc.

to feed greater parts of the southern populations in Ghana. Intense usage of agro-chemicals such as chemical fertilizers, weedicides and pesticides is a major farming practice currently being undertaking by local farmers. These agro-chemicals are known to contain traces of heavy metals such lead, cadmium, Arsenic, mercury, nickel etc., which when leached through the soil media and eventually into the saturated zone underground at certain concentration levels, may have undesirable health implication for human and sometimes to sensitive eco-systems (Lindstrom 2005). Conclusions from previous studies (Van den Berg 2008; Barry et al. 2010 and van der Ofosu et al. 2014) had shown that favourable factors (i.e. Fertile soils, land, labour, and groundwater) exist within the basin to support potential upscaling of irrigational farming during the dry season which lasts between 7 and 8 months in a year. Upscaling of irrigational farming to improve food security and lower poverty levels by the government of Ghana implies that larger quantities of agro-chemicals usage with the consequential release of larger quantities of harmful trace metals into soils. In such situation, greater threat to groundwater quality and the potential risk implications to human health can be envisaged. To ensure proper management and sustained utilization of shallow groundwater to meet current and future population in terms of domestic and agricultural suitability, there is the need to plan and monitor various human activities to minimise the risk of contaminating groundwater resources within the basin. This study seeks to apply the evaluation of the intrinsic vulnerability of shallow aquifers within the Atankwidi basin of Ghana to assess its potential resilience (risk) to contamination from leachates from agricultural fields.

2 Materials and methods

2.1 Location, climate and vegetation

The entire Atankwidi basin (Fig. 1) is a transboundary sub-basin with a total area of about 275 km^2 and constitutes about 1% of the entire White Volta Basin of West Africa (van der Ofosu et al. 2014). The portion in Ghana where the current study was carried out is located within longitude 0°, 50′–1°, 10′W and latitude 10°, 45–11°, 00′N with an estimated total area about 156 km^2 (Martin and van de Giesen 2006). It is bounded to the west by Kasena-Nankana Municipality, east by Kasena-Nankana West south by Bolgatanga Municipality and to the north by Burkina Faso.

The area falls within the Sudan Savannah climatic region of Ghana, which is characterised by high temperatures and evapotranspiration. The area is amongst the driest with a single but short (approximately 4 months) rainfall period, occurring between May and September every year followed by a prolonged dry season with total estimated potential
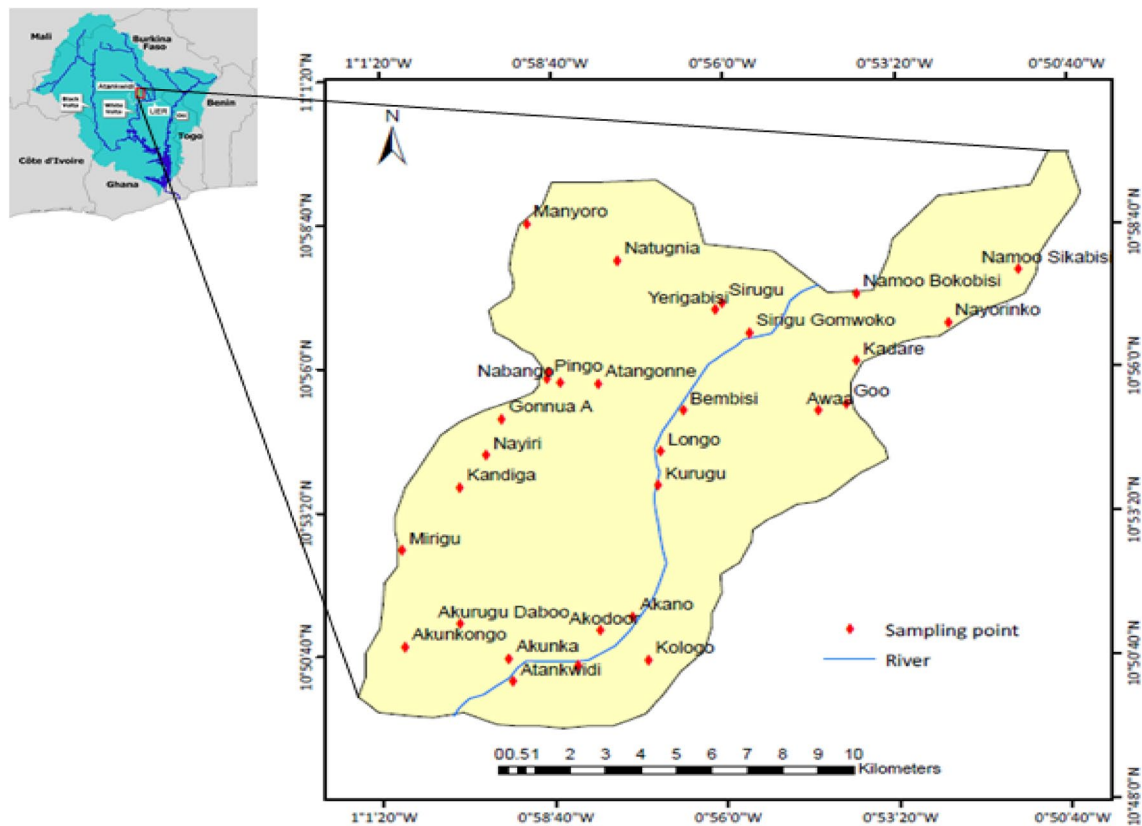
Fig. 1 Location of the study area

evapotranspiration exceeding the mean annual precipitation (Leibe 2002). Mean annual precipitation value is approximately 990 mm while mean daily maximum and minimum temperatures are about 35 °C and 23 °C, respectively (Dickson and Benneh (1998). Two major air masses, the South-West Monsoon and the Northeast Trade Winds (Harmattan) influence the climate. Common vegetation type characterizing the area include the Shea, Neem, Acacia, Baobab and grass.

## 2.2 Relief, drainage and hydrogeology

The topography of the area is generally flat with slope varying between 4 and 13% and average elevation is about 100 m above mean sea level with few isolated hills (e.g., Zambao and Bongo granitoids) along the eastern to northeastern peripheries with average height not exceeding 300 m above mean sea level. The Atankwidi River is a tributary of the White Volta with approximately 35% of its catchment (upper reach) in southern Burkina Faso whilst the remaining 65% of its catchment (lower part) is located in northeastern Ghana (Fig. 2). The hydrogeological system consists of three aquifers types, which are perched, regolith and semi-confined in form (Leibe 2002). The perched

aquifers occur at shallow depths and are discontinuous; the regolith aquifers are unconfined, continuous and occur at depth averaging to about 23 m whilst a fractured aquifers are generally semi-confined in nature. The shallow aquifer has a thickness of about 1 m, covering the less permeable clay material. This shallow layer dries up during the dry season and is only used for water supply through traditional hand-dug wells. The primary aquifer, according to Barry et al. (2010) is the regolith aquifer, which constitutes about 80% of groundwater resources occurring in unconfined regolith aquifers or weathered zone aquifers that overlies the unweathered bedrock (mostly basin and belt-type granitoids). The regolith aquifer is continuous with average saturated thickness of approximately 23 m and hydraulic conductivity of 0.2–2.2 m/d and has a transmissivity that is in order of magnitude higher than the underlying fractured aquifer (Martin and van de Giesen 2006).

2.3 Geology and Soil

The study area is underlain by Paleoproterozoic Birimian supergroup consisting of metavolcanic and metasediments with their respective associated intrusive belt-type and basin-type granitoids which formed during the Eburnian

Fig. 2 Drainage and geological map of the Catchment in Ghana
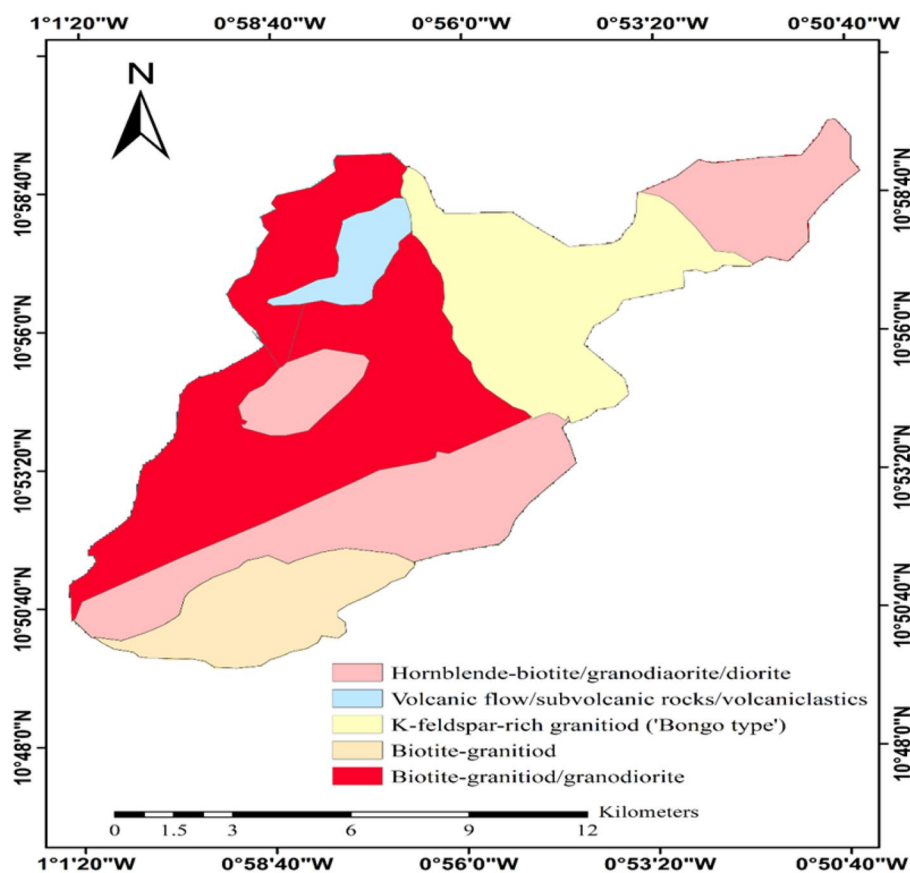
event of about 2.15 billion years ago. The largest fraction (about 90%) of rocks (Fig. 2) is the belt-type granitoids which have intruded the metavolcanics with biotite-rich granites, granodiorites, hornblende granites and hornblende-diorites consisting of highly altered feldspars, unfoliated and rich in hornblende whilst the remaining area mostly the northeastern section of the area being underlain by the potassium–rich pink Bongo granitoids (Griffis et al. 2002).

Three major types of soils (Fig. 3) namely; Fluvisols, leptosols and lixisols exist in the area. Leptosols occur predominantly along the elevated northern and eastern border of the catchment. Fluvisols are found in the flat terrains lying on both sides of the main stream. The remaining area is covered by Lixisols (Martin and van de Giesen 2006).

2.4 Determination of Intrinsic Vulnerability Shallow Aquifers

The assessment of the intrinsic groundwater vulnerability was done using the approached (DRASTIC) developed by Aller et al. (1985) in combination with GIS. DRASTIC is an acronym for depth (D), net recharge (R), aquifer media (A), soil type (S), topography (T), influence of vadose zone (I) and hydraulic conductivity (C). The assigned relative weights ranged between 1 and 5 with the most influential
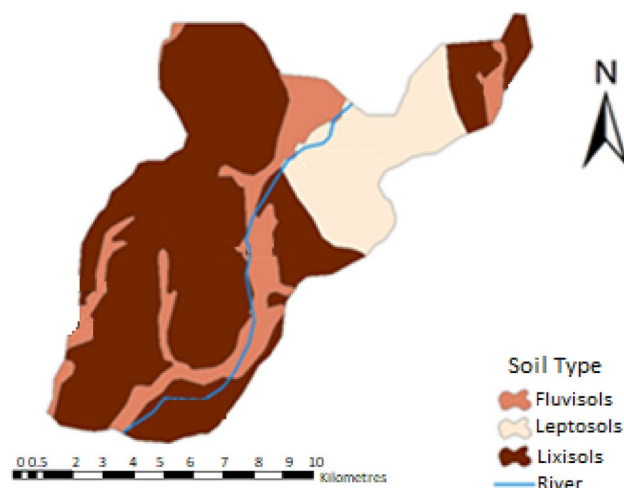

Fig. 3 The soil map of the Atankwidi Basin

factors being given a weight of 5 and the least given a weight of 1 as shown in Table 1. D was weighted 5 with the rational being that, it is the medium through which the contaminants will travel before reaching the saturated zone. Also the soil media is the portion or the zone which will serve as decontamination material, therefore, the natural attenuation capacity is dependent on it. Net recharge (R) and the hydraulic

Table 1 Assigned weight for DRASTIC parameters

DRASTIC parameter	Assigned weight
Depth to water table (D)	5
Net recharge (R)	3
Aquifer media (A)	2
Soil types (S)	4
Topography (T)	1
Impact of vadose zone (I)	4
Hydraulic conductivity (C)	3

Table 2 Rating and Index analysis for Depth to water table

Weight (Rw) = 5

Depth (m)	Average depth (m)	Ratings (Rr)	Index ($RrRw$)
4–8	6	10	50
10–15	12.5	9	45
15–20	17.5	7	35
20–25	22.5	5	25
25–30	27.5	2	10

conductivity (C) work similar to each other, thus, the volume of water which infiltrate depends on the grain size of the particle size which is a measure of the conductivity. In this study, the aquifer media possesses less significant influence due to the fact that much of the contaminants would have been attenuated before encountering the saturated zone and therefore, possible contamination would have occurred. The topography was assigned the least weight of 1 because the catchment is relatively a low-lying area and change in the slope variation (%) expected not to be significant.

2.4.1 Depth to Water Table (D)

Depth to water table represent the depth from the ground surface to the top of the water table. For a given area of similar geologic material forming the regolith or the weathered zone, the thicker or deeper the depth to water table the greater the impact of the natural, physical and chemical attenuation process, and therefore the lesser the vulnerability. In this study, the measured depths of the overburden varied from 4 to 23.09 m. The assigned ratings and corresponding estimated indices of depth-to-water table are as shown in Table 2 with the corresponding thematic map shown in Fig. 5a.

2.4.2 Net Recharge (R)

The net recharge (R) is the amount of water available to travel down to the groundwater system in a significant amount through the vadose zone to the saturated zone (Atiqur 2008). Areas with high hydraulic conductivity (K) values are expected to be more vulnerable to contamination because they may have highest rate of infiltration with respect to time. In this study, net recharge was considered based on the soil existing soil types. Table 3 shows the soil types and their assigned ratings due to their respective conductivity value with the corresponding thematic map shown in Fig. 5b.

2.4.3 Aquifer Media (A)

Aquifer media represent the consolidated and unconsolidated materials which serves as an aquifer (Anornu et al. 2012). Chilton and Foster (1993) refers to aquifers that develop in weathered zone of igneous and metamorphic lithologies as basement aquifers. Three basement aquifers exist in the area namely; shallow perched aquifer with clay material, regolith aquifer and fractured aquifer (Wilkes et al. 2004). A rating of 3 was assigned to the shallow perched aquifers due to high clay contents whilst a rating of 7 was assigned to fractured aquifer due to the highest K value (Table 4) and the corresponding thematic map Fig. 5(c).

2.4.4 Soil Media (S)

The contaminants attenuation process is controlled by the soil type, which is also dependent on the grain-size and the

Table 3 Range, Rating and Index analysis for Net recharge

Weight (Rw) = 3

Soil types	K (m³/d)	Range (m³/d)	Average (m³/d)	Component (%)	Ratings (Rr)	Index (Rr.Rw)
Fluvisols	0.034	0.034–0.43	0.232	12	2	6
–	0.43					
Lixisols	0.6	0–0.6	0.6	30	4	12
Leptosols	1.18					
–	2.04					
–	0.39	0.39–2.04	1.09	58	7	21
–	0.75					

Table 4 Range, Description, Ratings and index analysis for Aquifer Media

Weight (Aw) = 2

Aquifer media	Thickness (m)	Description	Ratings (Ar)	Index (Ar*AW)	Conductivity (m^3/d)
Perched and shallow aquifer	0.18	Characterised by a tin covering sandy soils with less permeable clay material with low permeability (Martin and van de Giesen 2006)	3	6	0.05–1.06 (Van den Berg 2008)
Regolith aquifer	18–37	Water-bearing formation within the weathered zone. The regolith aquifer does not contribute to larger groundwater flow	4	8	0.22–2.2 Martin and van de Giesen (2006)
Fractured aquifer	37–58	Fractured bedrock aquifers form an integrated aquifer system with more transmissivity. Material is slightly or moderately weathered grains	5	10	Martin and van de Giesen (2006)

Table 5 Soil characteristics within the Atankwidi Catchment

Weight (Sw) = 4

Soil type	Texture	Description	Mean permeability (m^3/d)	Ratings (Sr)	Index
Fluvisols	Clay loamy	Compacted clay loamy with low conductivity	Relative low (0.23)	1	4
Lixisols	Sandy loam to sandy clay	Consists of sandy loam to sandy clay loam with high clay content in the upper part but has an increasing coarse texture with depth	Relatively moderate (0.6)	3	12
Leptosols	Loamy sand to sandy loam	Rather shallow in thickness such that moderately weathered granitic rocks are encountered at less than 2 m depth	Relatively high (1.09)	5	20

amount of clay minerals present (Atiqur 2008). Within the basin (study area), the *Lixisols* consist of sandy loam to sandy clay loam with high clay contents in the upper part of the profile and an increasingly coarser texture as depth increases. The *Leptosol*s are found in the elevated areas in the northeastern sections (around Zoko and Namoo areas) of the area are loamy-sand which are quite shallow to such an extent that moderately weathered granitoids are encountered at depth less than 2 m. *Fluvisols* are commonly found in the low-lying areas adjacent to the Atankwidi River, and consists of compacted clay loam (Fig. 3). The characteristics of the soil and the assigned ratings and the estimated indices are shown in Table 5 and the corresponding thematic map as shown in Fig. 5d.

2.4.5 Topography (T)

According to Lynch et al. (1994), topography (slope) provides signal on whether a contaminant will run off or remain to infiltrate into the water table. Areas with high elevation are a potential sites for groundwater recharge and generally

are less vulnerable to contamination due to high surface runoffs. In this study, the slope was estimated from Shuttle Radar Topographical Mission (SRTM) DEM_90 m image and the Digital Elevation Model (DEM) was prepared in Arc map GIS software. The variation in slope (%) within the catchment ranged as follows 4–5, 5–7, 7–9, 9–11 and 11–13. Areas with low elevation were assigned the highest rating of 10, while areas with the high slope were assigned with the least rating of 1. Thus, for similar geological and soil types, the potential for contaminant transportation may be higher with respect to time. Table 6 and Fig. 5e give details of ratings, indices and the corresponding thematic map.
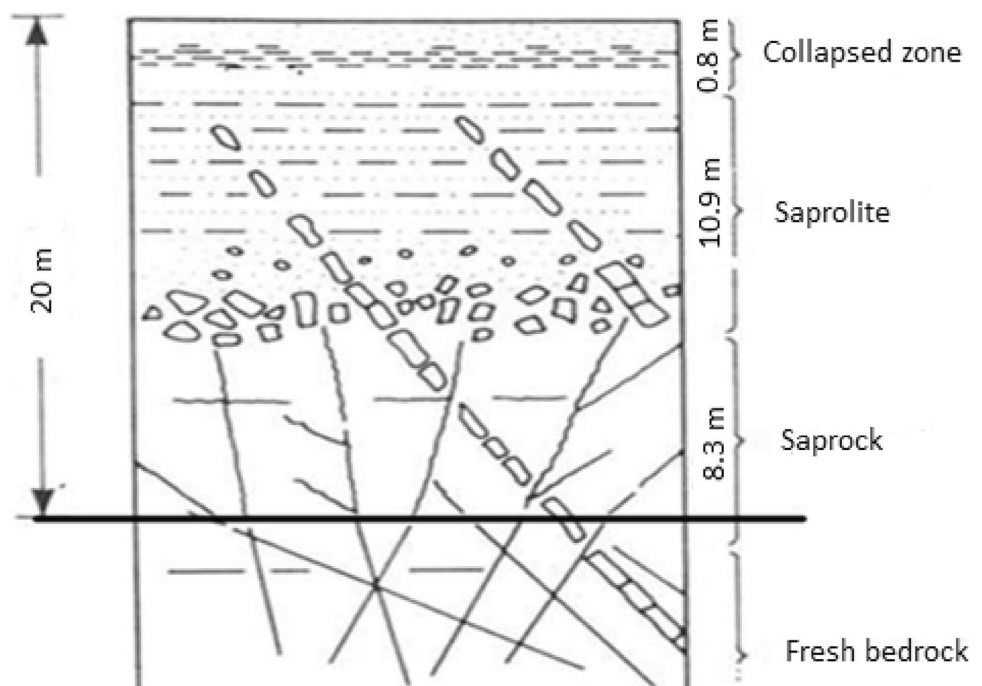
2.4.6 Impact of Vadose Zone (I)

The protection potential of any aquifer against contaminant sources is defined by the vadose zone existing above the aquifer system (Aller et al. 1985), which mode of function is similar to soil cover depending on the conductivity (Atiqur 2008). In this study, the vadose zone was found to vary from 2.6 to 13.7 m (Barry et al. 2010) with the median and mean

Table 6 Description of the Topography

Assigned Weight (w) = 1		
Elevation (% rise)	Rating	Index
4–5	10	10
5–7	9	9
7–9	5	5
9–11	3	3
11-13	1	1

values being 6.6 and 6.8 m, respectively. Within the area (Fig. 4), it is divided into three main section namely, collapse zone, Saprolite and Saprock (Wright 1992).

A rating of 2 was assigned to the collapsed and Saprolite zones because it constitutes highly weathered rock materials with high resistivity values (3.2–55.3 Ohm-m), which indicate the possibility of low permeability and transmissivity (Barry et al. 2010). Saprock was rated 4 due to the lesser development of clay minerals within the formation and also the fact that permeability increases towards its lower section

(depth). The vadose zone in this study does not extend to the region of the fresh rock. Table 7 shows the rating and index values while Fig. 5f shows the corresponding thematic map.

2.4.7 Hydraulic Conductivity (C)

Conductivity is controlled by the amount and the interconnection of void spaces. It is considered to be a factor of transmissivity which may be affected by the types of materials (clay, sandy or loam) and the grain size or the particle size of the materials. Thus, the smaller the grain size, the lower the conductivity values and the higher the natural attenuation of contaminants. In this study the hydraulic conductivity used varied from 0.23 m^3/d to 2.22 m^3/d within the basin. (Ofosu 2004 unpublished). Areas with least conductivity values were assigned a rating of 1 whilst areas with high conductivity were assigned a rating of 9 as shown in Table 8 with a corresponding thematic map (Fig. 5g). The final (DRASTIC) vulnerability map (Fig. 6) was obtained by running the seven hydro-geological data layers in an Arc GIS environment, and the results obtained were reclassified.

Fig. 4 Weathered profile at the middle of the Atankwidi Basin (Wright 1992)

Table 7 Vadose Zone analysis (Wright, 1992)

| Vadose zone	Depth (m)	Description	Ratings	Index
Collapsed zone	0.8	Compacted clay loamy with low conductivity	2	10
Saprolite	10.09	Consists of sandy loam to sandy clay loam with high clay content in the upper part but has an increasing coarse texture with depth	3	15
Saprock	8.3	Rather shallow in thickness such that moderately weathered granitic rocks are encountered at less than 2 m depth	4	25

Fig. 5 Rating and index maps:
a Depth to aquifer media(D);
b Net recharge(R); **c** Aquifer
media(A); **d** Soil media(S); **e**
Topography(T); **f** Impact of the
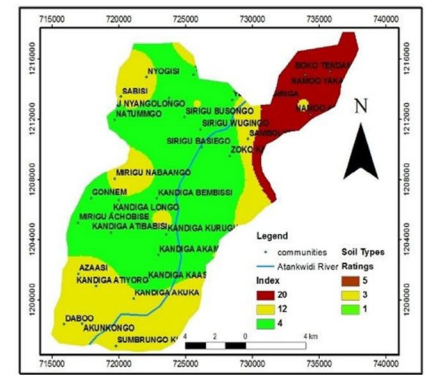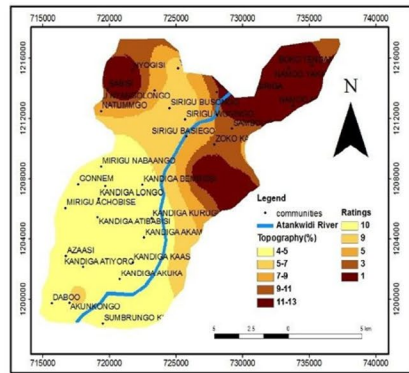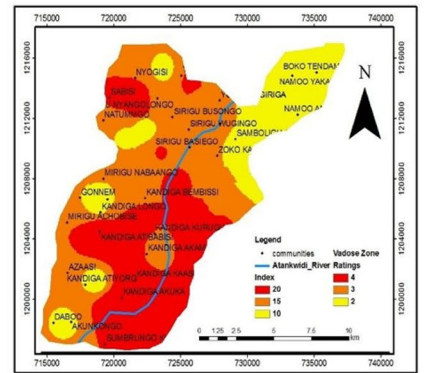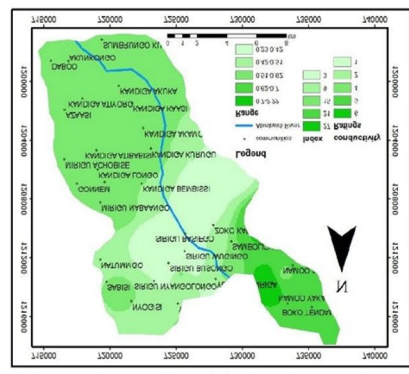vadose zone(I); **g** Hydraulic
conductivity(C)
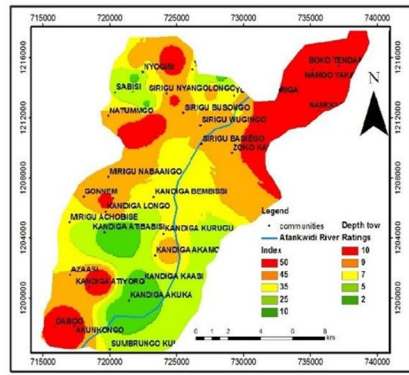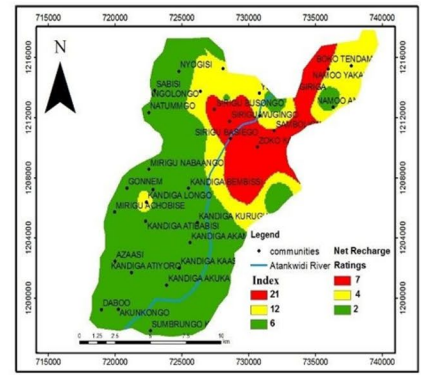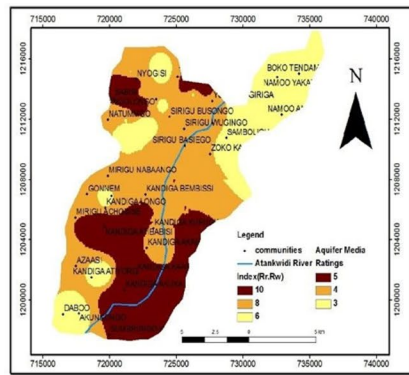
Table 8 Ranges, Ratings and indices for hydraulic conductivity

Assigned Weight (w) = 3		
Range(m³/d)	Ratings	Index
0.23–0.42	1	3
0.42–0.51	3	9
0.51–0.62	5	15
0.62–0.7	7	21
0.7–2.22	9	27

Table 9 Analysis of areas under vulnerability to groundwater pollution potential

Drastic Index	Area (km²)	Area (%)	Vulnerability classes
41–71	34.48	20	Low vulnerable
71–88	93.31	48.8	Moderately vulnerable
88–117	63.48	33.2	Highly vulnerable
Total	191.27		
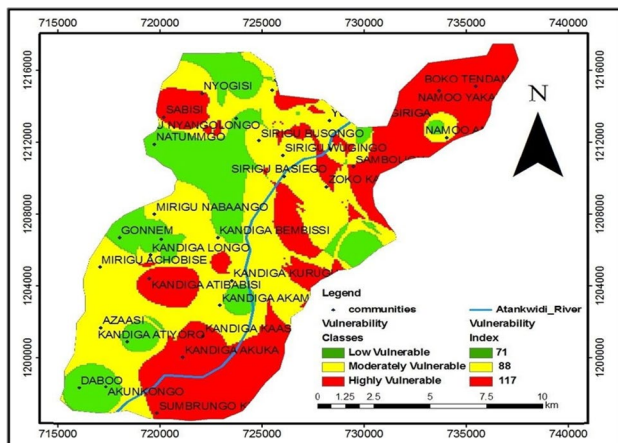
Fig. 6 Groundwater vulnerability zones of Atankwidi catchment

The Scores obtained from the DRASTIC model ranged from 40 to 117 were reclassified into three using the natural breaks (Jenks) classification scheme i.e. low, moderate and high vulnerable zones.

3 Results and Discussion

3.1 Groundwater Vulnerability map

The final vulnerability map shown in Fig. 6 was obtained by using the seven hydro-geological data layers in as shown in Fig. 5a–g.

Analysis of the vulnerability map (Fig. 6) revealed that out of the total area 191.27 km², about 34.48 km² (20%) has low risk to contamination with the DRASTIC index (DI) ranging between 40 to 71. 93.31 km² (48.8%) and 63.48 km² (33.2%) have moderate and high risks to contamination with DI between 71–88 and 88–117 respectively (Table 9). High risk areas are characterised by least depths to groundwater water table (shortest thickness of vadose zones); the presence of coarse sandy loam soils and the presence of moderately weathered granitoids with relatively high conductivity. Areas of moderate risk are characterised by deeper depth to groundwater water table (greater thicknesses of vadose zones), unconfined to semi-confined alluvial aquifer system

composed of sandy-loam to sand clay-loam with relatively higher clay content whilst the low risk zones are characterised by the occurrence of longer depths to groundwater tables (greatest thicknesses of vadose zones).

The moderate to high risk (vulnerable) areas together constitute about 80% of the entire Atankwidi catchment and cover the west-south-west, west-south-east, through the eastern sections to the north-eastern parts of the catchment. This implies that a greater part of the catchment's groundwater system could be at risk in terms of aquifer pollution potential. Furthermore, the zones of moderate and high risks are mainly located in the areas where anthropogenic activities such as modern dry-season irrigational farming, involving intensive usage of agro-chemicals chemical (e.g. fertilizers, weedicides, pesticides etc.) are predominantly used. Major farming communities located within moderate risk areas (i.e. Azaazi, Kandiga Atiyoro, Mirigu and Sirigu) are located in the central to the northern parts of the catchment whilst major farming communities located in high risk areas (include Sumbrungu, Kandiga Akuka Zoko, Natungnia, Yua, Yua, Yua, and Namoo) could be found in west- south-west and the north-east parts of the catchment.

3.2 Sensitivity Analyses

Sensitivity analysis is usually performed to ascertain the influence or contribution of individual variables or input parameters on a resultant output in an analytical model (e.g. GIS-based models). According to Bailey (1988), the effect of an individual data input on a resultant map (overall output) may depend on such factors including type of overlay operation conducted, the degree of uncertainty or errors, values of weights assigned, data layers involved and the number of map units. The application of local knowledge on geology to generate especially the intrinsic vulnerability map model by assigning ratings and weights as is the case in the use of DRASTIC model involves certain degree of subjectivity and relativity, which according to Napolitano and Fabbri (1996) could introduce some doubt in the degree of accuracy of the estimated DRASTIC index. To minimise the degree of doubt (uncertainty) that may arise as a result of some level of subjectivity involved, sensitivity analysis was carried out to evaluate the consistency of the analytical

results and obtain a more efficient interpretation on how the individual hydrogeological factors (map layers) had influenced or contributed to resultant risk (vulnerability index) map as suggested by several previous studies (Gogu and Dassargues 2000; Lodwik et al. 1990; Barber et al. 1993; Napolitano and Fabbri 1996; Babiker et al. 2005; Atiqur 2008 etc.). The widely established approaches to achieve this objective is usually through the application of such methods including map removal analysis (Lodwik et al. 1990) and single parameter analysis (Babiker et al. 2005). In this study, the map removal analysis was used to perform the sensitivity analysis.

3.2.1 Map removal Analysis

This analysis is based on the unique condition sub-areas theory developed by Lodwik et al. (1990), which is able to test the consistency of an operations between different map layers obtained from weighted sum intersections and found to be easily applicable to DRASTIC indices (Napolitano and Fabbri (1996). The map removal analysis involved the eestimation of the percentage influence of each parameter after the removal of its layer from the composite map (vulnerability map). The results are as shown in Table 10.

From Table 10, it could be observed that the highest change in the vulnerability index occurred when hydraulic conductivity (C) was removed with a mean variation index (VI) of 33%, making it the most influential parameter in the model while aquifer media (A) had the least VI with a mean variation index of 3.7%. The order (decreasing) of the estimated mean VIs for the remaining parameters soil types, Depth to water table, Net recharge, Impact of vadose zone and Topography after the removal of their respective layers are 20, 12, 11.6, 8 and 5%, respectively. The removal of the layers resulted in noticeable discrepancies in the trend of the estimated percentages of the VIs, which implies that almost all the DRASTIC parameters may be necessary to work out the vulnerability index for the Atankwidi basin.

Table 10 Summary of map removal sensitivity analysis

Vulnerability Index (VI)	Diff in VI (DVI)	Residual Vul Index (RVI)	Infl of parameter (IP)	Weight of (IP)	Sensitivity (%)	Sensitivity Factor (SF)	SF/N
Depth to water table (D)							
41–71	30	33–59	8–12	4	13.3	36	12
71–88	22	59–81	12–7	5	22.7		
88–117	26	81–110	7–7	0	0		
Net Recharge (R)							
41-71	30	28-59	13–12	1	3.3	34.7	11.6
71-88	22	59-75	12–13	1	4.5		
8-117	26	75-97	13–20	7	26.9		
Aquifer media (A)							
41-71	30	37–69	4–2	2	6.67	11.2	3.7
71-88	22	69-85	2–3	1	4.5		
88-117	26	85–114	3–3	0	0		
Soil types (S)							
41–71	30	35–59	6–12	6	20	60.2	20
71–88	22	59–73	12–15	3	13.6		
88–117	26	73–95	15–22	7	26.9		
Topography (T)							
41–71	30	38–69	3–2	1	3.3	15.5	5
71–88	22	69–85	2–3	1	4.5		
8–117	26	85–112	3–5	2	7.7		
Impact of Vadose zone (I)							
41–71	30	35–68	6–3	3	10	26	8
71–88	22	68–86	3–2	1	4.5		
88–117	26	86–112	2–5	3	11.5		
Hydraulic Conductivity (C)							
41–71	30	33–75	8–4	4	13.3	99	33
71–88	22	75–86	4–2	2	9.1		
88–117	26	86–95	2–22	20	76.9		

3.2.2 Validation of DRASTIC Model

The seemingly doubts (uncertainties) that accompany intrinsic vulnerability mapping, apart from requiring sensitivity analysis to reduce the degree of subjectivity may further require practical or actual evidence as a support (Barber et al. 1993). In most most cases, vulnerability assessment done by using index-and-overlay methods must be verified, and the most widely used approach is to compare the vulnerability map with the actual occurrences of some common pollutants in groundwater, typically such as nutrient pollution (nitrates, phosphate) and heavy metals such as Pb, Cd, As, Hg, Co, Ni (Mamadou et al. 2010; Atiqur 2008 and Gad et al. 2015). Several studies (Ahmed 2009; Dissanayake and Chandrajith 2009; Ajayi et al. 2012etc.) had revealed that heavy metals are known hazardous traces in common agro-chemicals used in irrigational farming such as weedicides, pesticides and chemical fertilizers. These heavy metals had been identified to have serious health implication to humans (WHO 2008). In this study, the validation of the DRASTIC model developed for the Atankwidi basin, was achieved by analyzing the concentrations of some heavy metals (i.e. Zn, Cu, Cr, As, Pb, Cd and Ni) instead of the usual analysis of nitrate, phosphate and sometimes sulphate to validate the DRASTIC model. This option, apart from being previously used in similar studies elsewhere as referenced above, provides diversification of methods to validate DRASTIC vulnerability models developed in areas where agriculture is the prominent human activity.

Levels of heavy metal concentrations in thirty (30) groundwater samples obtained from boreholes drilled into the shallow regolith aquifers within the different risk (vulnerability) zones (Fig. 1) in well-labelled 0.5 litre polythene containers were analysed for. Sampling was carried out in accordance with protocols described by Classen (1982) and Barcelona et al. (1985). Sample bottles were first conditioned by washing with detergent and rinsed several times with acidified water containing ten per cent (10%) nitric acid to prevent contamination. Boreholes were purged for at least five minutes to obtain fresh samples which were subsequently filtered through 0.45 micron membranes. Samples were collected at each site, filtered and acidified with 2% v/v of HNO_3 to prevent ions getting stuck onto the walls of the bottles and to keep ions in solution were for heavy metal analysis. Each acidified water sample was measured and 6 ml of nitric acid, 3 ml of HCl and 5 drops of hydrogen peroxide (H_2O_2) were added for acid digestion and placed in a milestone microwave lab station ETHOS 900. The digestate was then assayed for the presence of Zinc (Zn), lead (Pb), Copper (Cu), Chromium (Cr) and Cobalt (Co) using VARIAN AAS240FS Atomic Absorption Spectrum in an acetylene-air flame. Arsenic (As) and Mercury (Hg) were

Table 11 Results of analysed heavy metals in sampled groundwater within the catchment

Trace element	Min	Max	Mean	WHO (2016)
As	< 0.001	0.016	0.007	0.01
Cd	< 0.002	0.008	0.003	0.003
Ni	< 0.010	0.092	0.062	0.07
Pb	< 0.001	0.014	0.007	0.01

determined using argon-air flame. The results are shown in Table 11.

The concentrations of Cr, Zn and Cu were below detection limits while those detected (Pb, Ni, Cd and As), fell within acceptable limits for drinking purposes. The concentration of Cd varied from 0.001 to 0.008 mg/l with a mean of 0.005 mg/l, Pb ranged from 0.002 to 0.013 mg/l, Ni was between 0.04 and 0.084 mg/l whiles As concentration varied from 0.002 to 0.016 mg/l. The spatial distribution of the selected heavy metals within the study area are as shown in Fig. 7a–d.

The composite thematic of map showing the distribution of the concentrations of the combined heavy metals compared to DRASTIC vulnerability map of the catchment are as shown in Fig. 8. A close observation of the two maps revealed that moderate to high risk (vulnerable) zones were observed to contain relatively higher concentrations of compared to the areas found within the low risk (vulnerable) zones (Fig. 8a and Fig. 8b).

The concentration of Ni and Pb appeared to be higher within the in the areas between Zoko through Kandiga to Sumbrungu, located on south-eastern portion of the catchment whilst As, Pb and Cd were elevated within the areas between Sirigu-Namoo-Boko-Tendan area found in the northeastern portions of the catchment. As earlier stated, from the vulnerability map developed, these areas are found to be within the moderate to high risk zones. The eastern flanges of the catchment constitute the relatively highland-areas where many of the tributaries originate and incidentally are also well-noted for intensive irrigational and rain-fed farming with the usage of agro-chemicals to increase crops production. This indicate the possibility of the elevated heavy metals being the leached from agro-chemicals such as weedicides, chemical fertilizers and weedicides.

4 Conclusion

The study revealed that greater parts of the basin (80%) have medium to high risks to being potentially contaminated by infiltrating irrigational (surficial) waters. Elevated (recharge) areas were identified to be highly vulnerable while about 20% of the areas (generally, low-lying) had low vulnerability.
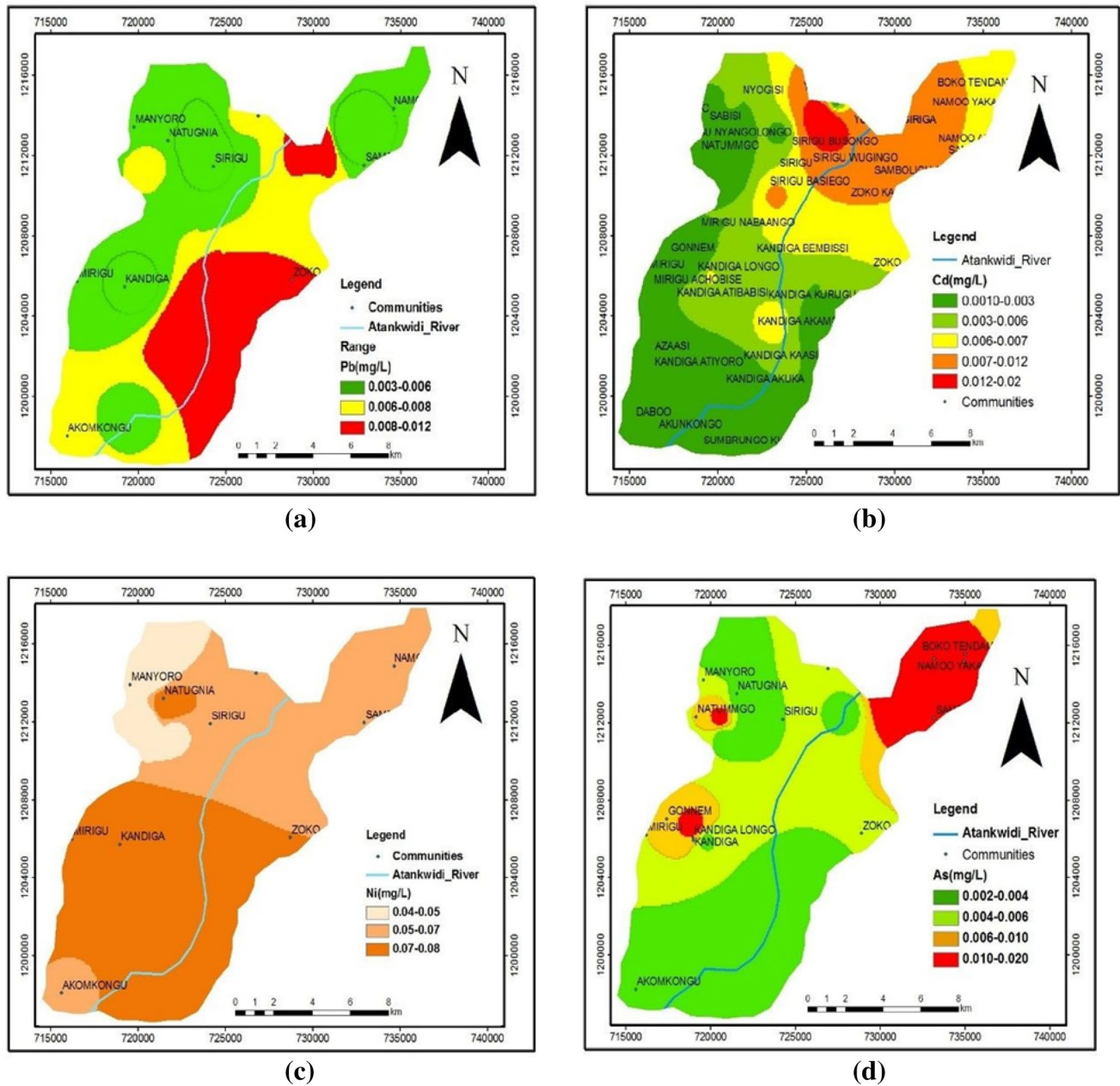
Fig. 7 Spatial distribution of some selected heavy metal within the Atankwidi basin of Ghana: **a** Lead (Pb); b Cadmium (Cd); **c** Nickel (Ni); **d** Arsenic (As)

Validation of the DRASTIC vulnerability model using some selected heavy metals in sampled groundwaters within the basin showed that areas of moderate to high vulnerability had elevated concentration of heavy metals as compared to areas of low vulnerability. Sensitivity analysis revealed hydraulic conductivity as the most influential parameter while aquifer media being the least. The observed higher concentrations of heavy metals in moderate to high vulnerable areas within the Atankwidi basin of Ghana gives the impression that their presence may be due predominantly

to the leaching from agro-chemicals such as weedicides, chemical fertilizers and weedicides whilst possible contributions from geogenic sources (water–rock and/or water-soil interactions) may not be discounted.

Areas identified to have low risk to groundwater contamination (vulnerability) were characterised by the existence of greater depth of vadose zone, deeper water tables and presence of compacted clay-loamy soils with low conductivity. Medium risk areas had lesser depths to water table, smaller vadose zone depths, presence of sandy-loam, sand clay-loam
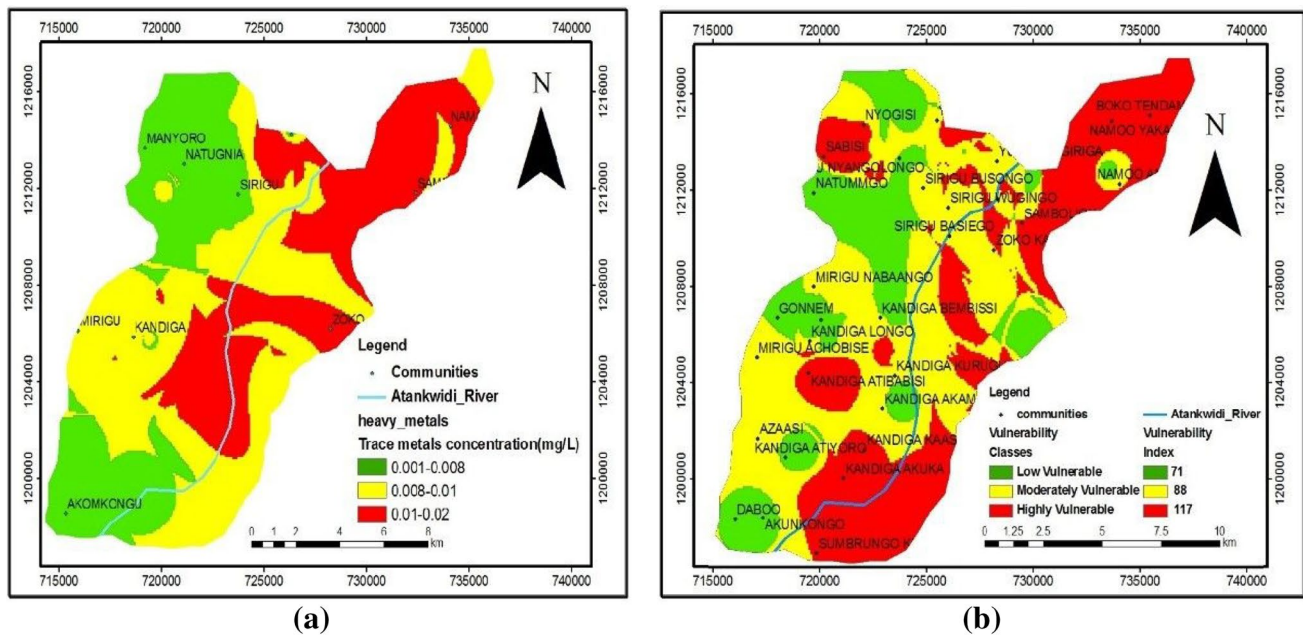
Fig. 8 Distribution of heavy metals with vulnerability map: **a** Composite thematic map of heavy metals **b** vulnerability map of Atankwidi basin

soils, with relatively lesser overall clay content whilst high risk groundwaters aquifers may be due to shallow depth to vadose zones, shallow water tables and the presence of moderately weathered granitoids with relatively high conductivity and greater recharge.

4.1 Recommendation

This research produced a decision making mechanism for those who are in management position since it clearly delineates areas within the basin in which groundwater systems may be at various degree risk (vulnerable) to potential contamination, The identification of areas with groundwater aquifers having high risk (vulnerable) to contamination makes it necessary for authorities in charge of groundwater resource utilization and management to monitor closely and develop appropriate land-use policies and norms for activities that may relate to recharge and seepage such as intense usage of agro-chemicals in irrigational farming and selection of waste-disposal and industrial sites so as to minimise possible contamination. This is extremely important because the only source of potable water during the longer dry season periods vis-a-vis the rainy season is groundwater. Accordingly, public awareness about the potential threats of pollution on groundwater resources especially in high-risk (vulnerable) areas and the consequential health-related issues is therefore highly recommended.

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