BirEx JOURNAL
Budapest International Research in Exact Sciences
Medical, Biological, Argiculture, Engineering Science and other related areas
e-ISSN : 2655-7827
p-ISSN : 2655-7835
http://www.bircu-journal.com/index.php/birex

Elaboration of the Piezometric Map of the Superficial Aquifers of the Town of Isiro (Haut- Uélé, DR Congo)

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Abstract: *This study developed in the town of Isiro in the province of Haut-Uélé, in the north-east of the Democratic Republic of the Congo, made it possible to produce a piezometric map of the superficial aquifers of this town using the triangle interpolation method. The quality of the groundwater studied was assessed by analysing a number of physico-chemical (temperature and pH) and bacteriological (total coliforms, faecal coliforms, faecal streptococcus and Escherichia coli) parameters. Two major superficial hydrogeological units have been defined, one unit consisting of lateritic formations and the other of ancient and modern Quaternary alluvium. The groundwater flow is mainly local, with water flowing over short distances from topographically high points. The hydraulic gradient varies between 0.02 (or 2%) and 0.06 (or 6%) with an average of 0.038 (or 3.8%). The depth map of the piezometric surface indicates that the water table is deeper on the plateaus (over 7m) than in the valleys. The flow rates of the springs vary according to the amount of rainfall. Temperatures ranged from 23.7 to 30.9°C. The pH values show that the analysed waters are strongly to slightly acidic (pH between 3.5 and 6.6). The groundwater studied shows a high level of bacteriological pollution.*

Keywords: *Piezometric map; surface aquifers; Isiro; Haut-Uélé, DR Congo*

I. Introduction

The measurements of the different piezometric levels must be carried out under conditions of stabilisation of the water table for the whole of the mapped region over the shortest possible period in order to have identical conditions with regard to local influences. Indeed, Castany (1982) emphasises that the piezometric surface measured constitutes the upper limit of the water table. It is a dynamic limit, therefore in perpetual fluctuation. It can rise or fall in the permeable hydrogeological formation.

The primary purpose of piezometric maps is to represent the surface of free groundwater or the pressure equilibrium surface of confined groundwater. Such maps necessarily incorporate a level of uncertainty that varies according to the density of measurement points used, the intrinsic representativeness of the data and the complexity and heterogeneity of the environment. These maps provide information on the hydrodynamic behaviour of the aquifers and the functions of the reservoir (flow directions, exchanges between aquifers and hydrographic networks, etc.). They provide a vision of the state of an aquifer at a given moment.

Numerous studies have assessed the quality of surface water intended for consumption in cities in developing countries (Kahoul and Touhami, (2014); Bricha et al., (2007); Derwich et al. (2010); Samake (2002); Tarik (2005); Baba-Moussa et al., (1995); Deme (2003); Diallo (2004) and El asslouj et al., (2007).

Large African cities are currently experiencing rapid uncontrolled growth in their surface area and demographics, leading to anarchic occupation of urban space. The installation of populations in this urban space is often not accompanied by the construction of a basic sanitation system, so that anthropic activities threaten the quality of water resources in general and groundwater resources in particular (Yameogo, 2008). Drinking water should not contain pathogenic microorganisms and should be free of bacteria indicative of faecal contamination (FUNASA, 2013).

In the town of Isiro, all the groundwater has never been mapped. No study on the quality of the groundwater or on the sources of contamination has ever been carried out. The rapid population growth in Isiro has led to the appearance of informal settlements in the outlying areas, which has also led to a shortage of water. The development of the drinking water supply network is not keeping pace with the development of informal settlements in the outlying areas, and the population is faced with problems of water supply, both in quantity and quality.

The study starts from the general idea that piezometry is dependent on topography. The depth of the water table depends on the distance between two adjacent valley floors, the altitude of the hill and the hydraulic conductivity of the aquifer. From this idea, a research hypothesis was formulated: groundwater would flow in the direction of the nearest talwegs (groundwater flow too influenced by the topography) and that rivers would drain.

The main objective of this paper is to produce a piezometric map of the town of Isiro in order to determine the direction of groundwater flow and the depth of the piezometric surface for the whole area. The quality of the water will also be assessed in relation to the WHO's 1994 drinking water standards.

II. Research Methods

2.1 Location of the Study Area

The town of Isiro is located in the province of Haut-Uélé in the northeast of the DR Congo. It is located at 2.7° North latitude, in relation to the equator, and 27.6° East longitude, in relation to the Greenwich meridian. The average altitude of the town is 758m, with a maximum of 790m on the Gossamu plateau and a minimum of about 725m in the Tely River valley. The relief is characterised by vast plateaus separated by extensive valleys occupied by rivers. The town of Isiro is bathed by a number of watercourses including the rivers and/or streams Tely, Mendambo, Modimbo, Dingilipi, Anne, Manzakayi, Mangaki, Akpokoma, Sadu.

The regional climate is tropical with two unevenly distributed alternating seasons, belonging according to the classification of Köppen and Géiger to the Am group. This type of climate constitutes the transition between the equatorial climate Af and the marked dry season climate Aw (Mbuluyo et al. 2017). The short dry season of 3 months starts in December until February and the long rainy season of 9 months starts in March until November, thus continuing the cycle of alternating seasons over the years. The monthly hydrological drought does not occur until mid-January when some wells and water sources dry up.

Over the year, the average temperature in Isiro is 24.0 °C. The average annual rainfall is 2149mm. The average rainfall in the driest months is 60mm or more (Figure 1).

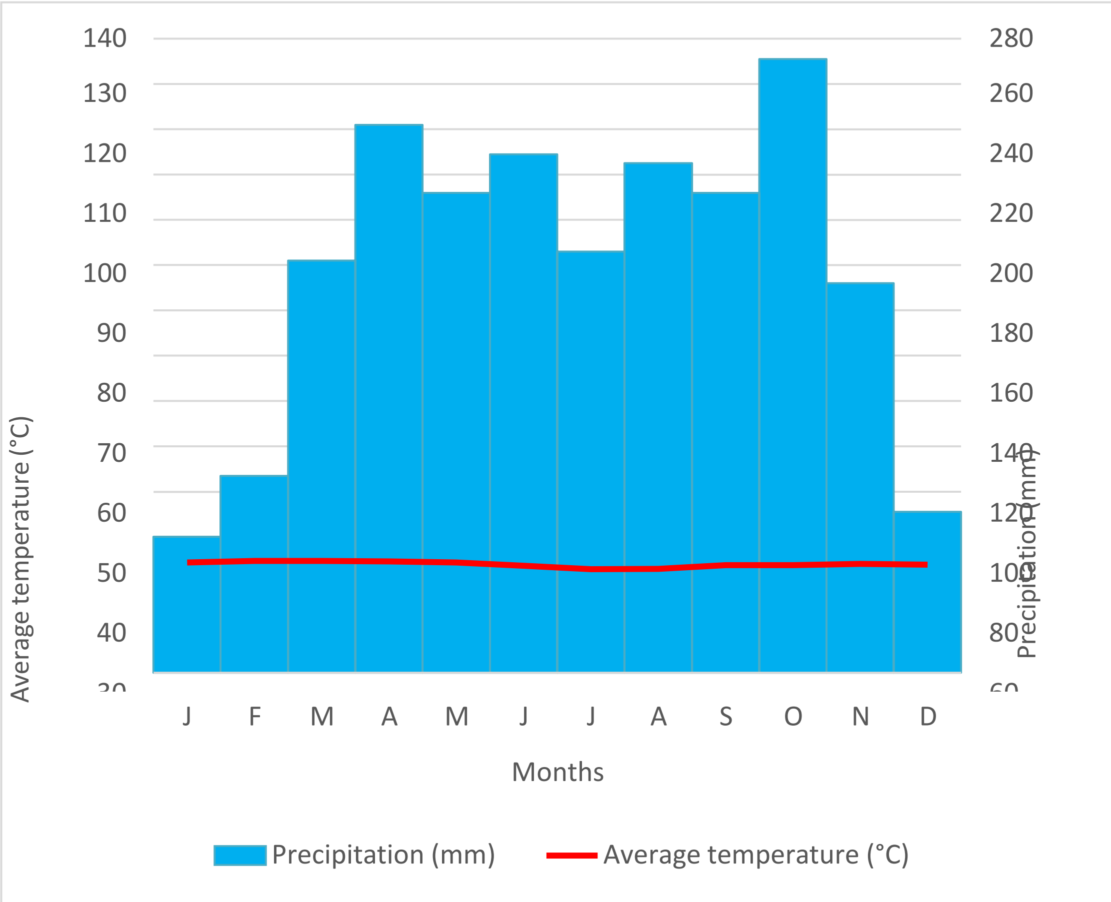

Figure 1. *Umbrothermal Diagram of the City of Isiro*

The variation in rainfall between the driest and wettest months is 211mm. With an average temperature of 24.7°C, February is the warmest month of the year. July is the coldest month ofthe year. The average temperature is 22.9 °C. There is a difference of 1.8 °C between the lowestand highest temperature over the whole year (thermal amplitude less than 5).

The soil is of the sandy-clay type (www.caid.cd/index.php/données-par-villes/ville-de-Isiro). Our study area is located on the map in figure 2.

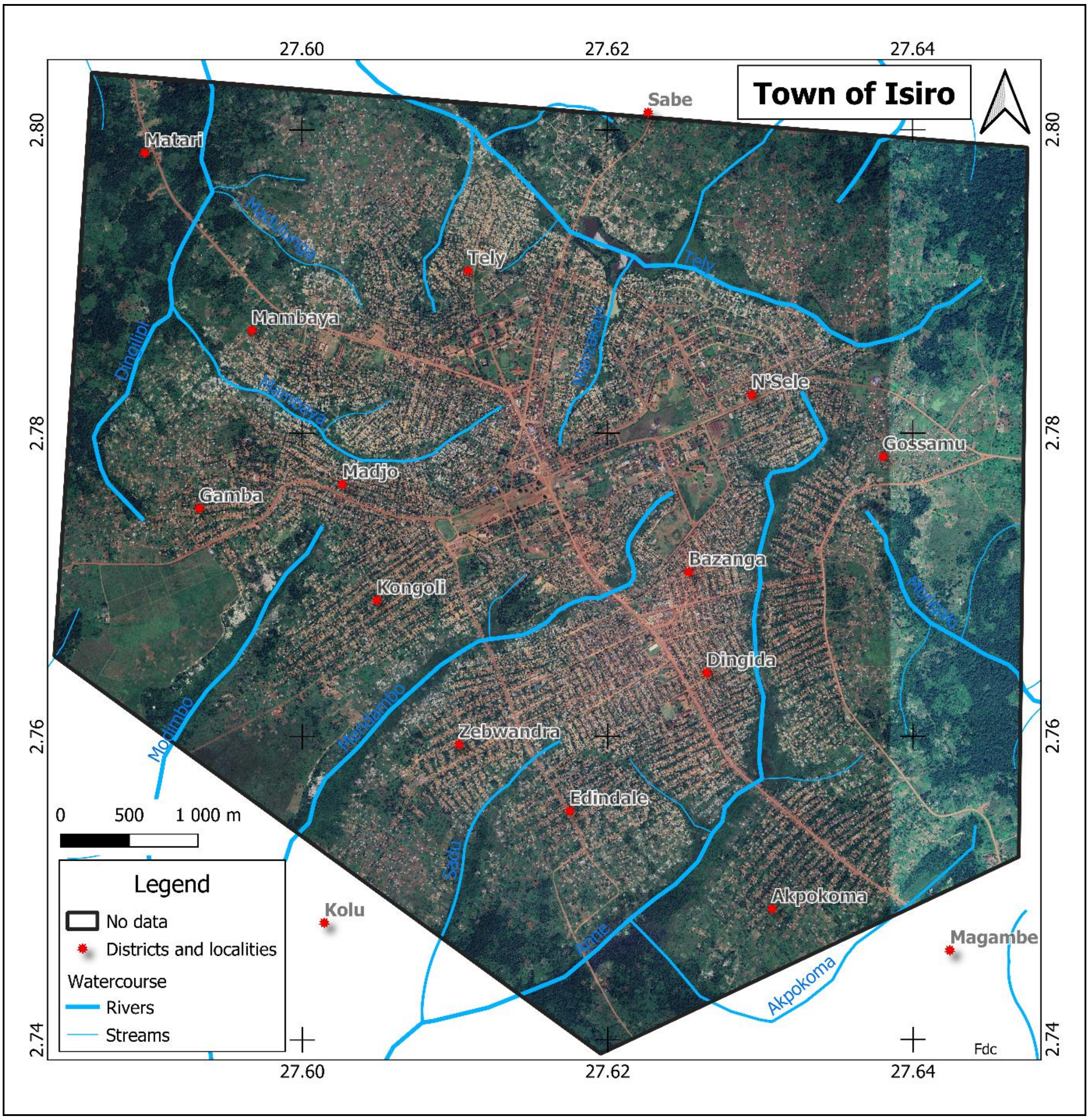

__Figure 2.__ Geographical Location of the Town of Isiro

2.2 Geological and Hydrogeological Context

a. Geological Context

The geology of the town of Isiro and its surroundings corresponds for the most part to a basement zone of Neoarchean age overlain in several places by Cenozoic superficial formations (alluvium and lateritic formations). According to the legend of the geological map of the Democratic Republic of Congo at 1:2500000 (Fernandez-Alonso et al., 2015), the lithostratigraphy of Isiro and its surroundings is as follows; from the oldest to the most recent rocks:

- Kibali Supergroup ;
- Uele granitoid complex ;
- Superficial formations.

The Kibali Supergroup is represented by metamorphic formations of sedimentary (metasediments), volcanic (metavolcanites) or volcano-sedimentary origin. The Isiro Kibalian beach comprises amphibolites, pink quartzites, ferruginous sericite schists, tuffs, itabirites, ferruginous quartzites, graphitic quartzites, sericite schists and micaschists. These rocks were described by Sekirsky (1954) and Raucq (1975). The Kibalian is presented in the form of more or less vast flakes, underlined in the morphology by high relief chains of itabirites and ferruginous quartzites. Near Isiro, the itabirites form an arc with a concavity facing north. The most metamorphic regions of the Isiro Kibalian are crossed by granitic occurrences (Lavreau and Ledent, 1975). Gneissic rocks are locally encountered around this beach.

The Uele granitoid complex corresponds to the matrix in which the greenstone belts (Kibalians)are dispersed, where these two terms together form the "granite-greestone (GG)" association. This is a typical TTG (Tonalite-Trondjemite-Granite) suite. The intrusive rocks are represented by the dolerite vein process, quartz veins and pegmatites. These intrusions cross all the basement formations.

The surface formations are represented by alluvium (ancient and modern) and laterite formations. The alluvium follows the watercourses over sometimes great distances. They are clayey or gravelly sands, sometimes with a greyish tinge, with gravels and some pebbles or blocks of a quartz nature at the base. These alluviums result from the disintegration of the rocks in place and are mixed with lateritic debris of all sizes. The lateritic formations are made up oflateritic armour and gravel overlaid by a brown soil with a sandy-clay texture and varying thicknesses. These formations sometimes mask the basement rocks. The ubiquitous lateritic cuirasses bear witness to a level of peneplanation and are highlighted by current erosion in theform of tabular mounds.

b. Hydrogeological Context

At the present stage, hydrogeological studies show that the groundwater in Isiro is contained in the alterites and within the alluvium accumulated in the river valleys. These are the superficial reservoirs, but there may be fissured reservoirs at depth in the basement formations.

In the town of Isiro, two major superficial hydrogeological units are distinguished according to geologyand geomorphology:

- a unit consisting of lateritic formations (lateritic gravels and cuirasses) surmounted by a brown soil horizon with a sandy-clay texture, observed on the plateaus and slopes of the hillsides. This layer is about 1m thick and is relatively less permeable and constitutes a barrier to water circulation at depth (Mbuluyo et al. 2017);
- a unit made up of ancient and modern Quaternary alluvium. It occupies the valleys of the rivers of the town of Isiro. These alluviums form a shallow, free water table.

All these formations are rich in silicate minerals. The healthy substratum or the saprolite of clayeynature constitute the impermeable base of these superficial aquifers.

2.3 Measurement of the Piezometric Level

The first step in carrying out the piezometric campaign was to find the measurement points (wells and springs). A total of 361 measuring points were selected in order to obtain the most uniform spatial coverage possible, including 66 springs and 295 wells.

Measurements were taken directly in the individual wells using a hand-held probe with indicator light and sound. Taking into account the altitudes of the wells' curbstones measured by GPS during the piezometric campaign, the statistical level in metres was converted into a piezometric level in relation to the normal sea level (Menge, 2013). For springs, the piezometric level corresponds to the altitude of the natural emergence (Castany, 1982).

2.4 Development of the Piezometric Map

The piezometric map of the town of Isiro was produced using the triangle interpolation method. The measurement points (wells and springs) were plotted on a digital terrain model (DTM) of the town of Isiro, with their reference code and piezometric level. Then a location map of all the measurement points was made using GIS software (Guisado, 2015) and printed out in order todraw the piezometric curves manually.

The piezometric values were associated with the three extremities in order to obtain, by interpolation between two points, the intermediate values to be transferred to the bases of the triangle. The piezometric map is obtained by connecting points of several neighbouring triangles in order to draw the hydroisohypses curves. This method has been used by several authors (Castany, 1982; Goncalves, 2010; Rouxel and Lereculey, 2006).

GIS is often used as a software package offering digital mapping, database management and spatial analysis capabilities (Mansour et al. 2012). The final piezometric map of Isiro town is the GIS representation of the hydroisohyps curves obtained from the manual plots.

2.5 Groundwater Sampling and Analysis

For this study, water sampling was done to cover the urban area in order to have a good appreciation of the physico-chemical and bacteriological quality of groundwater in Isiro town. Investigations were carried out in the laboratory and in the field because some physico-chemicalparameters are rarely kept constant during the conservation of samples and have to be measuredin the field (Ghesquière, 2015).

The physico-chemical analyses concerned the following parameters: temperature and pH. These two parameters were determined in the field with the Hanna HI9813-6 portable apparatusequipped with an electrode. The analyses covered 239 samples.

Bacteriological analyses were carried out in the microbiology laboratory of the Faculty of Sciences of the University of Kisangani. They focused on indicator germs of faecal pollution (total coliforms, faecal coliforms and faecal streptococcus) and the enumeration of Escherichia coli (pathogenic germ). These analyses were conducted on ten water samples from selected wells and springs in Isiro town during the rainy period in October 2021. The criteria for selecting the sampling points were: the distance of the latrine from the well or spring, the degree of development, accessibility, the consent of the owner, the durability of the structure and the use of the water points by the surrounding population for various activities. To determine the origin of the contamination, the faecal coliform to faecal septococcus ratio was calculated. It is generally higher than 1 if the contamination is of human origin, and lower than 1 if it is of animal origin (Kazadi, 2012).

III. Discussion

3.1 River Basins

At the scale of the area concerned by this piezometric mapping, two large hydrographic basins covering the major part of Isiro's surface aquifers can be defined: the Bomokandi basin in the northern part of the study area and the Nava basin in the south.

3.2 Overview of Groundwater Resources

The groundwater potential is considerable, with several springs and water wells identified in the town of Isiro. Indeed, groundwater in this town is exploited through wells and springs. 66 springs and 295 wells have been identified in the various districts of Isiro. Most of the wells arefound in the middle of the slope (50.8%) and at the bottom of the slope (35.3%). They are also found on the plateaus (13.9%). The wells used in this study tap the alluvial and lateritic aquifers. They vary in diameter from 0.8 to 2.5m and reach depths of less than 20m. These wells were dug in the traditional way using a hoe, shovel and buckets. Some of the wells are very close to the latrine and most are located less than 15m downstream from the latrine. This may have a negative impact on the water quality of these wells.

3.3 Spring Flows

The flow rate of the springs was measured by gauging with a graduated container. This technique consists in measuring precisely the time T needed to fill the volume V of the container and the flow rate Q = V/T is calculated. Measurements were made three times a month and monthly averages were determined for each of the 66 springs located in the town of Isiro. Figure 3 shows a temporal variation of the spring flows between March 2018 and March 2019.

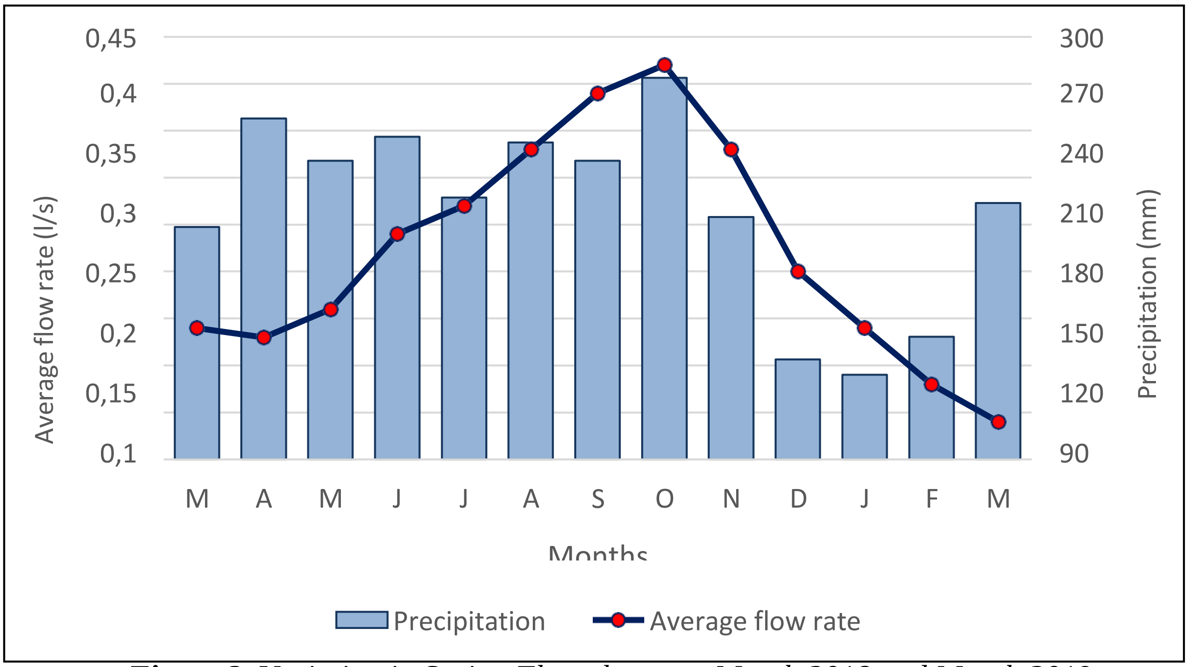

Figure 3. *Variation in Spring Flows between March 2018 and March 2019*

The flow curve shows a unimodal pattern, which is almost similar to the rainfall curve. In fact,the rains start in March, but the response in the springs is felt from May. The highest flows arerecorded during the wettest months. Spring flows vary as does the amount of water that falls. Itis therefore the rains that feed the springs in Isiro.

3.4 Piezometric Map of the Town of Isiro

a. Checking the Data

The consistency of the acquired piezometric data was checked by means of a simple graphic analysis (Figure 4). By plotting the pairs "topographic elevation - piezometric dimension" it can be seen that the piezometric surface has a similar appearance to the topographic surface. The two variables show a strong positive correlation with an R coefficient^2 of 0.881. We can therefore say that the piezometric data are consistent, and that the piezometric surface is therefore below the topographic surface.

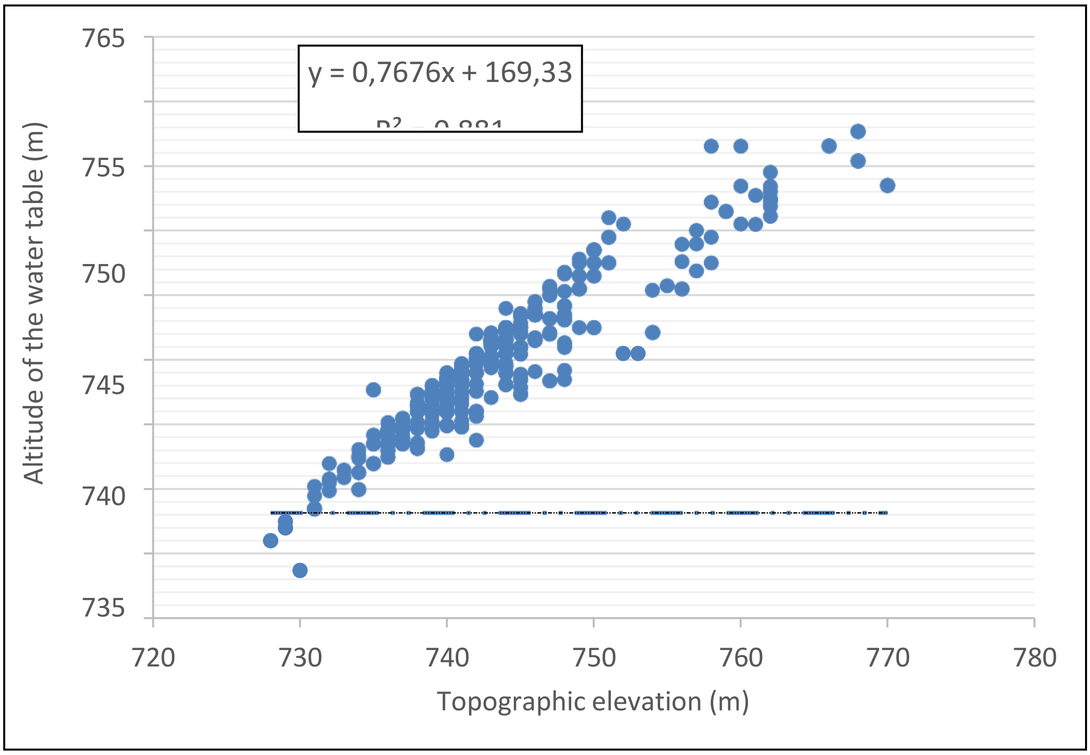

Figure 4. *Graph for Checking the Consistency of the Data Collected*

In order to be able to analyse the processes highlighted by the piezometric map, it has been annotated with the main piezometric peaks (regional and local) and the main groundwater flowaxes (Figure 5). The hydrogeological basins are characterised by a strong relationship with surface water. There are surface water tables that constitute a valuable and shallow resource forthe inhabitants of Isiro. Their boundaries correspond to the groundwater divide.

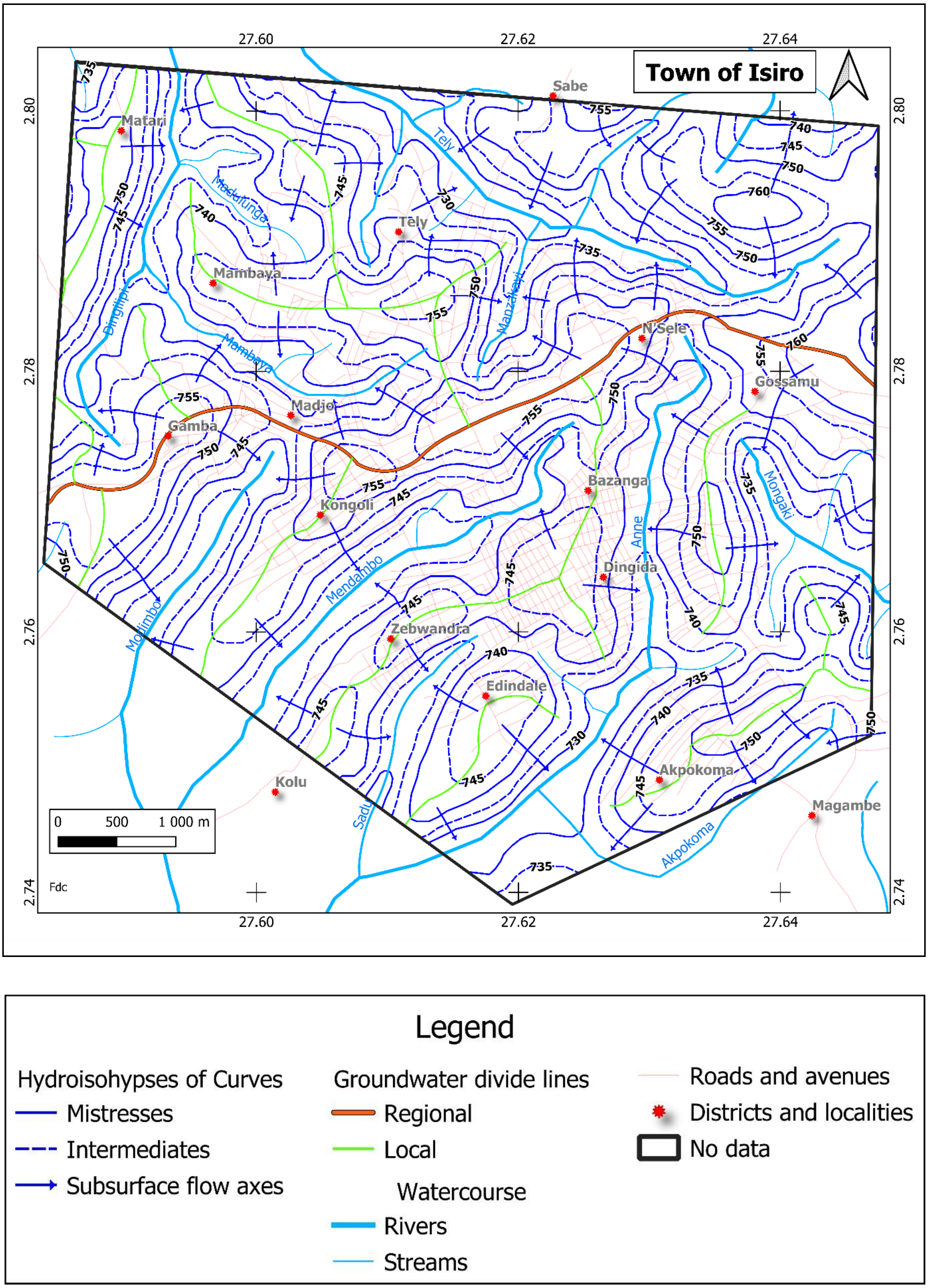

Figure 5. *Piezometric Map of Isiro Town*

b. Hydroisohypses Curves

The first significant remark that can be made on this map is the narrowing of the curves and their spacing. This narrowing is explained by the presence of a steep slope of the piezometric surface. These areas are characterised by high hydraulic gradient values. The interval betweenthe hydroisohypses is variable, as is their radius of curvature. The hydraulic gradient varies between 0.02 (i.e. 2%) and 0.06 (i.e. 6%) with an average of 0.038 (i.e. 3.8%). The low hydraulic gradients indicate good groundwater flow. The aquifer is highly transmissive and constitutes an important reservoir (IWACO, 2001).

Overall, groundwater flow in Isiro is mostly local, with groundwater flowing only short distances from topographically high points. With regard to the orientation of the hydro- isohypsis curves, it can be seen that the orientation of the concavity is downstream and the groundwater flows converge towards the talwegs of the valleys.

c. Piezometric Peaks

On this piezometric map, several groundwater divide lines appear. These lines individualise thetwo major hydrogeological basins (Bomokandi in the north and Nava in the south) and eleven

(11) sub-basins in the mapped area. The assumed groundwater divide between the basins andsub-basins was drawn by studying the local piezometric curves at 5m intervals.

From a general point of view, the piezometric map drawn during this study respects the topography, in the sense that the highest piezometric points and the piezometric peaks (regionaland local) have a geometry similar to the relief of Isiro.

d. Drainage through Watercourses

Another element that emerges from the piezometric map established is the existence of drainage axes corresponding to the valleys of the main rivers in the town of Isiro. Occasionally, relationships can exist between other watercourses and the surface water table throughout the town, so that water table-river exchanges are important. The watercourses are draining.

3.5 Depth of the Piezometric Surface

The depth map of the piezometric surface of the town of Isiro is the result of the difference in altitude between the digital terrain model (DTM) and the piezometric surface. This map gives the orders of magnitude of the depth of the groundwater. In general, the depth of the piezometric surface depends on the topography (altitude and distance between successive talwegs) and the hydraulic conductivity of the aquifer. Analysis of the map in Figure 6 indicates that the Isiro aquifers are significantly deeper in the plateaus. They are shallower in the river valleys. The majority of water wells are dug in these areas where the depth of the groundwater is less than 7m.

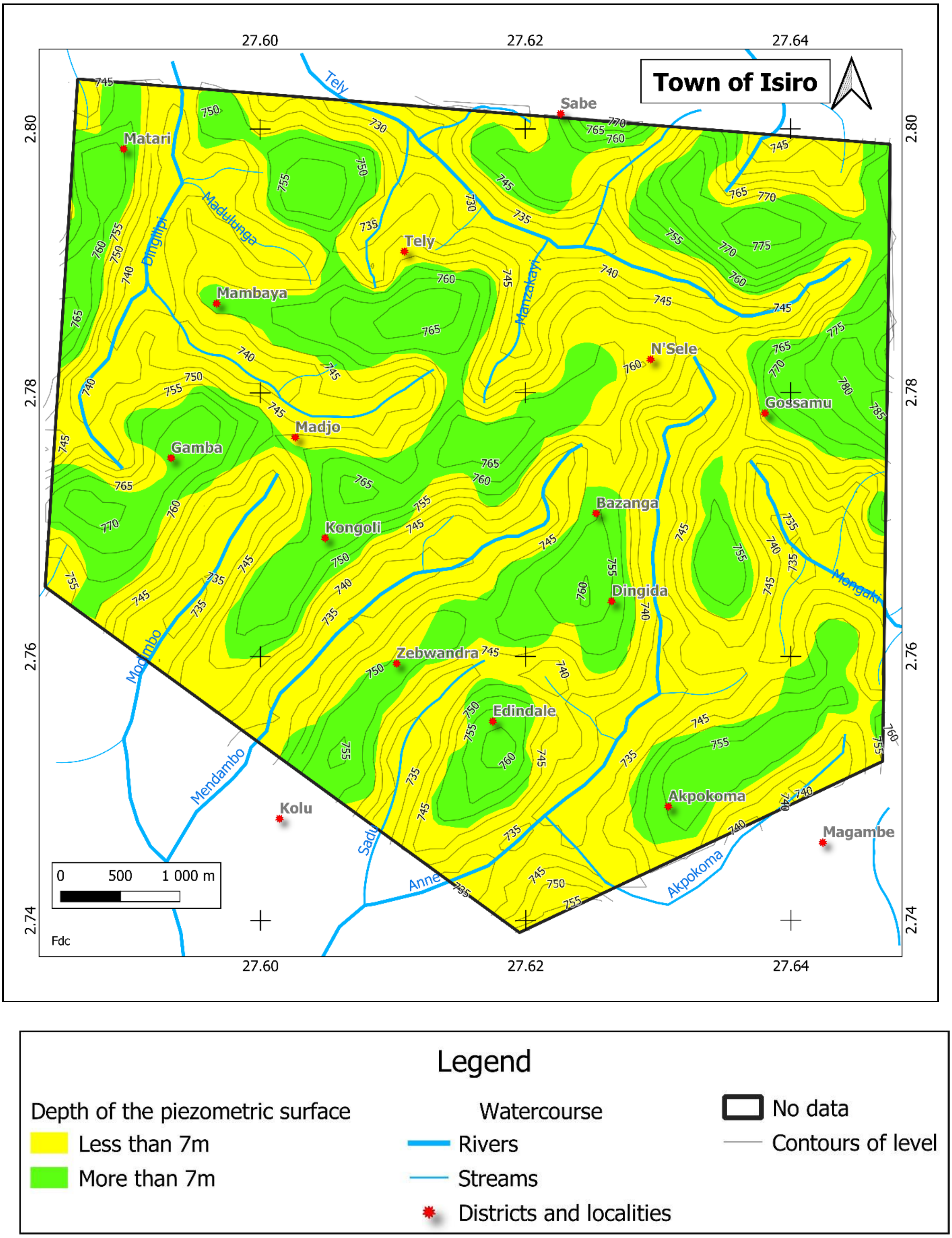

***Figure 6.** Depth Map of the Piezometric Surface of Isiro Town*

3.6 Conceptual Groundwater Flow Model

Based on the results of the hydrogeological mapping (COBARIC and UPA, 2008; Benoit et al. 2008), a conceptual flow model of Isiro's surficial aquifers was established (Figure 7). Flow inthese aquifers is mainly local, with groundwater travelling short distances from the plateaus tothe nearest streams.

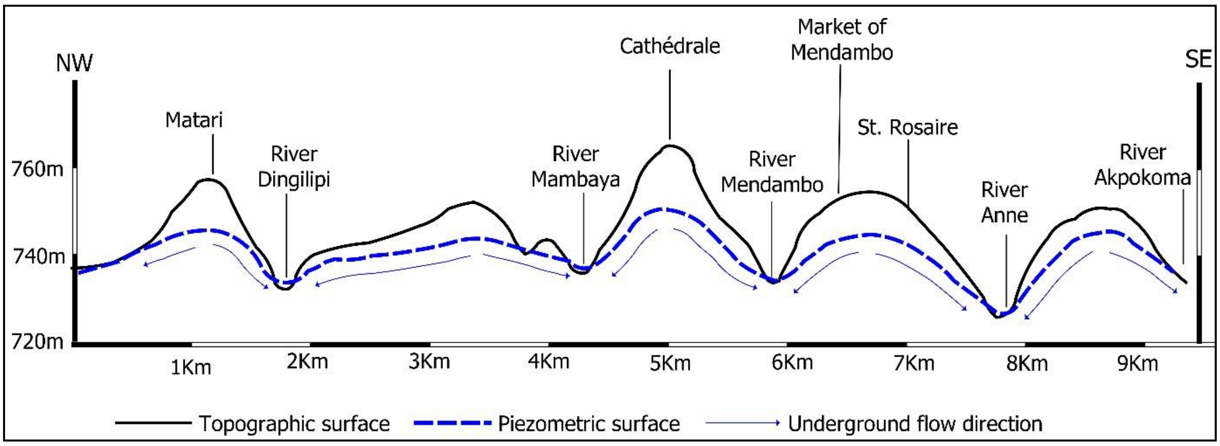

Figure 7. *Conceptual Model of Groundwater Flow in the Isiro Shallow Aquifers*

We note that the groundwater flow in Isiro is from the plateaus to the valleys. All axes convergeon the river valleys.

3.7 Physico-chemical and Bacteriological Characteristics of Groundwater

For all the groundwater analysed, the temperatures range from 23.7 to 30.9°C with an averageof 26.11°C. The standard deviation is 1.5. These values are higher than 22°C, which could meanthat the groundwater in Isiro is fair, poor and excessively polluted compared to the WHO drinking water standards. The pH varies between 3.5 and 6.6. Comparing the results of the analysis of Isiro's groundwater samples with the WHO standards (1994), it is found that the pHis strongly to slightly acidic. According to the World Health Organization (WHO, 2011), drinking water should have a pH value between 6.5 and 8.5. The silicate nature of the soil explains the acidic nature of the groundwater in our study area YAMEOGO (2008).

The results of the bacteriological analysis of the groundwater in the town of Isiro show that almost all the samples taken were polluted. The enumerations carried out on the ten (10) samples show high concentrations of faecal coliforms in the well and spring water of Isiro, ranging from 6 to 75 CFU/100ml of water. Total coliform concentrations ranged from 10 to 85 CFU/100ml. Fecal streptococci counts show values that vary between 4 and 73 CFU/100ml ofwater. Escherichia coli was observed in three (03) water samples analysed. According to the WHO, water should not contain microbial germs. Based on the ratio of faecal coliforms to faecal streptococci, the intermittent contamination, mainly due to coliforms and streptococci, is mostly of human origin. Several factors could explain the bacteriological pollution of the groundwater in Isiro, notably factors linked to the development of water points (wells and springs) or sanitation in the town, factors linked to the short distance between the water pointsand the latrines, and factors linked to the way in which household waste is managed.

IV. Conclusion

This study made it possible to produce the first ever piezometric map of the surface aquifers of the town of Isiro based on 361 measuring points (wells and springs), to give the orders of magnitude of the depth of the water tables and to assess the quality of the groundwater studied. We present the main results obtained during this work.

There are two large catchments covering the surface aquifers of Isiro, namely the Bomokandi and Nava catchments. The flow curve shows a unimodal pattern, which is almost similar to the rainfall curve. The highest flows are recorded during the wettest months. The groundwater flow is mainly local and converges towards the talwegs of the valleys, the groundwater travels short distances from the topographically high points. The hydraulic gradient varies between 0.02 (i.e. 2%) and 0.06 (i.e. 6%) with an average of 0.038 (i.e. 3.8%). The water tables studied are clearly deeper on the plateaus (over 7m). They are shallower in the river valleys. The temperatures ranged from 23.7°C to 30.9°C. The pH values show that the analysed waters are strongly to slightly acidic (pH between 3.5 and 6.6). The groundwater studied shows a high level of bacteriological pollution.

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