

Original Paper

Modeling of the Alteration Wedge in a Crystalline Basement Environment: Case Study of Burkina Faso Central Regions

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Abstract

The alteration wedge is unevenly distributed in the central region of Burkina Faso. Outcrops of crystalline rocks can be seen everywhere on the sheet. Water drilling data made it possible to highlight this inequality.

The frequency of the encountered alteration depths associated with the water productivity of the underlying aquifers made it possible to define four thickness bands. The average water productivities are depends on bands thickness.

Geological, topographical, pedological, geomorphological and hydrographic maps are used for the correction, verification and validation of alteration maps. They are used to estimate and interpolate alteration depths in areas where drilling and geophysical data are not available.

Taking into account the complexity of cartographic representation of alterations and the hydrogeological goal assigned to the map, it is necessary to define and determine reports and validity rates in order to better guide the users. The Validity Rate (VR) derived from the Validity Ratio (VR) which is the quotient of the statistical average over the average mapped alteration depths of a given interval.

Keywords

lithology, phreatic surface, leaky phreatic aquifer, saturated alteration, outcrop

1. Introduction

The water resource mapping is a crucial means for knowledge and monitoring of groundwater resources. It is a real necessity especially in the sub-Saharan areas where resources are increasingly rare

this is the case in Burkina Faso central regions where these resources are under heavy pressure. These pressures are linked to very high population growth, booming socio-economic activities and human activities that threaten the sustainability and quality of available water resources. Several water programs concerned this part of the country, but especially this year 2016, the city of Ouagadougou has experienced alternating distribution (across sectors) in drinking water. This crisis has been solved through a so-called “emergency” project aiming at realizing some large-scale boreholes in the city. A hydrogeological map could help to locate areas of great potential in order to cope with such situations.

1.1 Potentiality Is Defined from Studies of Productivity Factors such As Alteration Coverage

The crystalline and crystallophyllian formations of West Africa are generally covered by a mantle of alterites. These layers of alterites observed date from the Precambrian (Compaoré, 1997). They represent the product of a physico-chemical disintegration of the underlying rock, under the action of water and temperature.

These alterites are unequally distributed according to several factors including geological facies, climate, geomorphology, and tectonics. In Burkina Faso, the average weathering depths are in the range of 10 to 30 meters in granite gneiss. But locally, they can exceed 60 meters especially in the Birrimian schists (Kafando, 2014).

Alteration covers represent several interests in the knowledge and exploitation of water resources, in a crystalline basement environment (Savadogo, 1984; Nakolendoussé, 1991; Kafando, 2014).

Thus, its representation on a hydrogeological map has major advantages. However, its modeling is still not easy.

Because existing models are variously appreciated by scientific researchers, water actors and related fields. Referring to the spatial variability of alterations, their partial influence on aquifer productivity and their various roles and functions; the design of an alteration map for hydrogeological purposes had to serve several goals. Its implementation must make use of an appropriate methodological approach.

The study area (square degree of Ouagadougou) is located in the central part of the country; it is vast about 12100 km². It is limited by the parallel 12 ° and 13 ° north latitude and the meridian 1 ° and 2 ° west (Figure 1).

The study area is relatively flat, with an average elevation of 300 meters. The highest altitudes are met in the Northeast. These reliefs consist of volcano-sedimentary formations of altitude of about 500 meters high. This is the example of the massif of Tangmiga of 519 meters high. Altitude contrast is also highlighted by the network of morphological discontinuity induced by waterways. This is the case of Nakanbé and its tributaries, which locally have altitudes below 250 meters. The center of the country is the most inhabited region of the country. The province of Kadiogo has the highest density, about 300 inhabitants, compared to 50 to 100 inhabitants per km² for neighboring provinces. The pressure on water resources is no longer to be demonstrated, it could increase in the years to come.

The climate is Sudano-Sahelian. And as everywhere on the territory, the year is marked by a dry season and a rainy season.

The rainy season lasts 4 to 5 months. It operates between May and October, with an estimated rainfall between 500 and 900 mm per year.

The geology of the map is mainly dominated by granitoids. They occupy more than 80% of the map. These granitoids can be distinguished into two major groups. We have late granites, which are the most representative. These are, for the majority of granites and granodiorites, amphibole and biotite, with various grains sizes. The second group consists of early granites. They consist of granodiorite, tonalite and quartz diorite. Two facies are differentiated: one, by the presence of amphibole and biotite minerals and the second is marked by its foliated appearance

Geology is also marked by volcano-sedimentary formations and metamorphosed plutonic rocks. They are constituted by a set of rocks that are: volcanic-sedimentary schists, schists and quartzites, gabbros, amphibolitized basalts, volcanic products, and tonalities with blue quartz and amphibole. This set is flushing on a small area.

Tectonics in the square degree is part of the global West-African tectonics induced by the two orogenic phases: major phase of the eburnian orogeny is marked around 2150 M.y, by fracturing the basement along two predominant directions NE-SW and NNE-SSW. The pan-African orogeny, however, took place around 600 M.y and resulted in the appearance of folded and metamorphic facies.

At the hydrogeological level, three sets are distinguished: granitoids, metamorphosed volcanic and sedimentary formations, and recent formations. The aquifer system consists mainly of three levels: the upper or surface aquifers, the lower aquifers of alterite and/or fissures, and the aquifers of faults. The aquifers are of leaky phreatic aquifer type, discontinuous and their water tables are highly dependent on seasonal rainfall.

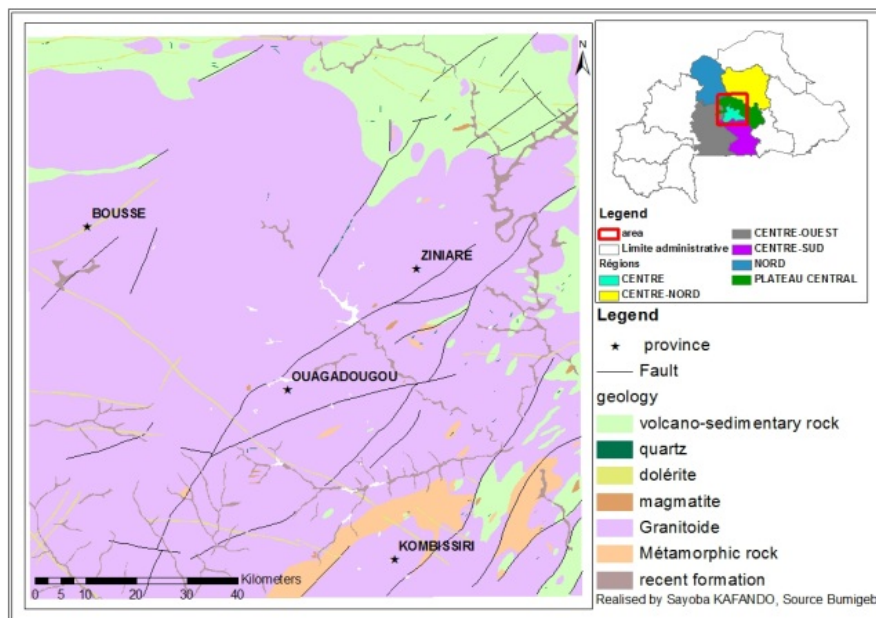


Figure 1. Map of Geographical and Geological Situation of the Study Area

2. Methodology and Design Tools for the Alteration Thickness Map Model

Defining and establishing an alteration map is primarily a problem of choice. It is first about the scale, then the selection of classes to be represented and finally the legend. The aim pursued and the particular conditions of the region to be mapped must justify and guide the choices to be made.

The interest and the content of the map remain closely related to the objectives aimed at its establishment. It is of scientific interest: that is to say, it is above all a synthetic mode of expression of average depths of alteration in the square degree. Thus it will serve as a tool for research and knowledge of groundwater resources. Thus, it will analyze, interpret and compare the water potential of study areas. It will also contribute to the location of major tectonic accidents.

A second benefit is that it allows to expose and explain part of the hydrogeological characteristics of the area concerned: it is his didactic interest.

At the technical level, to finish, it is a document of practical interest directly usable by specialists in several domains.

These include geophysicists, sounders, environmental hydrogeologists, public works technicians (road, building, and dam) and mines. It is in this overall vision that fits the development of our alteration layer model.

However, the realization of the alteration cover model for hydrogeological purpose requires an appropriate sequential methodological approach. Five steps are necessary for the realization of the alteration map, namely:

- ❖ Data collection;
- ❖ Data processing;
- ❖ Checking the influence of alterations on productivity;
- ❖ Determination of the alteration classes to represent;
- ❖ Design and validation of the map.

2.1 Data Collection

The data collected essentially come from these three sources:

We have the technical drilling data that is basic information for mapping alteration coverage. They were collected in private engineering firms (ANTEA, BERA, LAGREN, GEO-HYDRO) and in state water structures (DEIE, ONEA, BUMIGEB).

Then the results of previous works that are among other geological maps, hydrographic, topographic, soil and outcrop maps. This information is used for verification, correction and validation of the generated map data of drilling data sheets and geophysical survey interpretation.

Finally, we have the analog data from the satellite and airborne data processing (geophysics, Srtm ...). Unlike finished products from previous work, analog data is manageable. It is therefore possible to make several compositions and classifications supervised or not, to support the verification, correction and validation of the map. The data used is presented in the Table below:

Table 1. Summary Table of Used Data

Data	Source	Type/Utility		
		A	B	C
Boreholes	BE/DGERE/ONEA	+	+	+
Geophysical surveys	UO I-Pr SKZ		+	
Geological	Bumigeb database			+
Pedological	Bunasol database			+
Hydrographical	IGB database			+
Topographical	IGB database			+
Satellite	Lansat 7			+
Airborne radar	Srtm 30			+
Airborne geophysics	Bumigeb database			+

A: basic data, B: Complementary field data, C: map validation data.

2.2 Data Processing

Drilling is planned in the ordinated system in UTM zone 30 N. The holes without location coordinates and those of questionable location are just used for statistical analysis. Finally, a drill database is created for mapping. The parameters of the base are: coordinate (X, Y), depths, alteration and flow.

A second component relates to the processing of satellite data Landsat and SRTM 30m. The Landsat 7 image in RGB color composition made it possible to obtain a digital analogue field model (Figure 2). Can be distinguished wetlands and lakes, the density of vegetation, or the bare soil or armored.

The application of topographic contours improves the level of interpretation: the high altitude platforms with very sparse vegetation constitute battleships. They come in the form of chains of hills. The depths of the alterations are generally important.

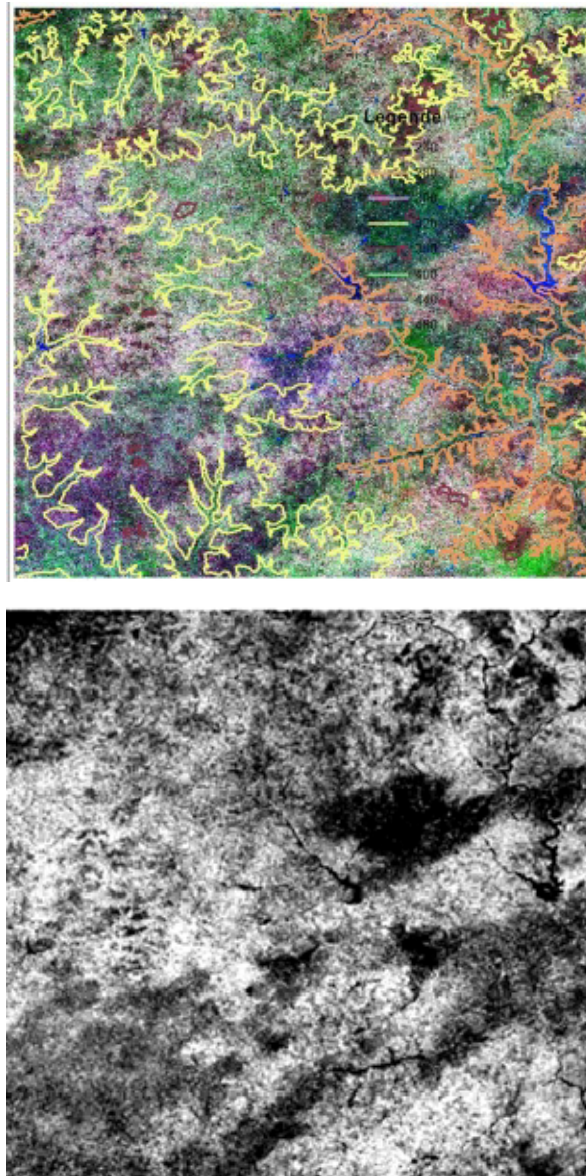


Figure 2. Colored Land Sat Image Superimposed on Level Curves (Left) and Enhanced Landsat RGB Image (Right)

SRTM (Shuttle Radar Topography Mission) refers to topographic vector and matrix files. They are provided by two US agencies namely NASA and NGA (formerly NIMA).

This altimetry information was collected in February 2000 by Space Shuttle Endeavor (STS-99) at an altitude of 233 km using radar interferometry. These data are effective for analyzing the topography especially of areas of substantially flat relief. The image of Figure 4 is the result of a curve classification of 5 meters of equidistance. The unequal distribution of the observed relief would be mainly due to erosion. As a result, the eastern half of the leaf will be dominated by low thicknesses of alteration. Only major tectonic accidents will be marked by high depths of alteration. In the western half, on the other hand, the low-contrast relief due to the hills and paleo-climate control abutments.

These reliefs generally consist of lateritic products very often covered with indurated cuirass. Depths of alteration are usually important.

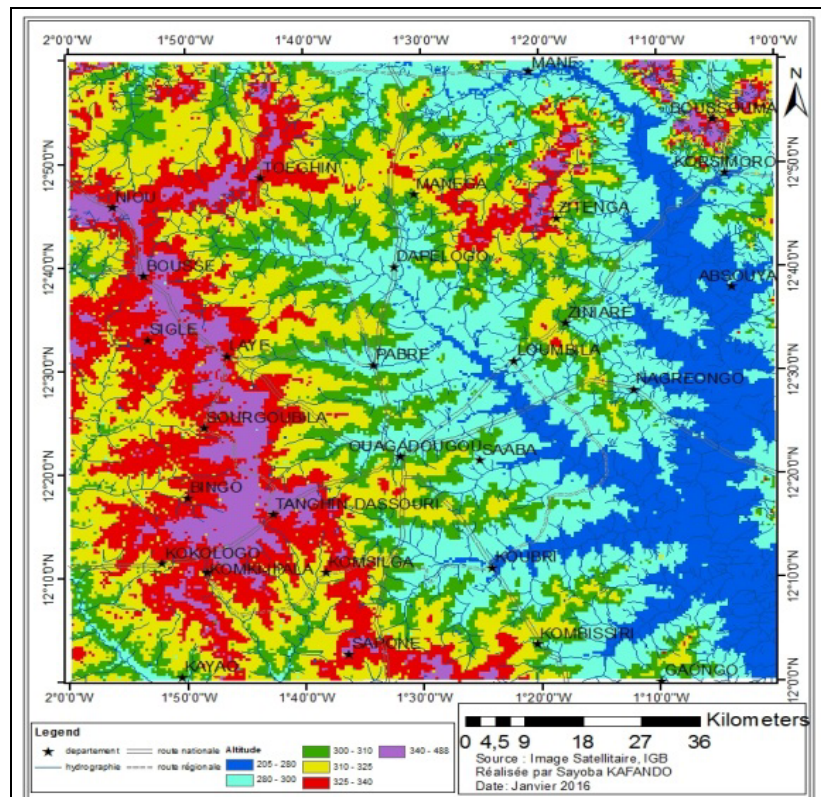
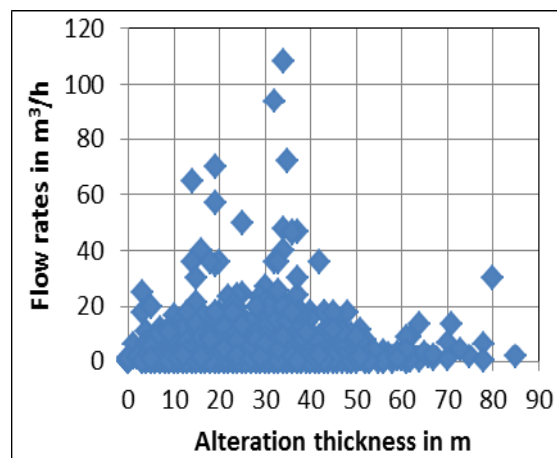


Figure 3. Altitude Map Based on the Strm's Data

2.3 Assessment Study of the Influence of Alterations on Aquifer Productivity



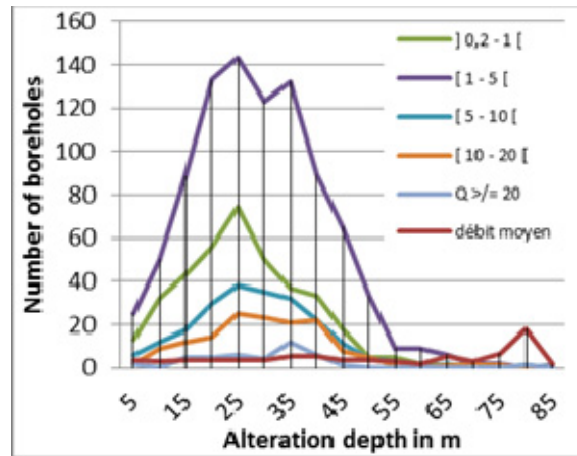


Figure 4. Distribution of Alteration Thicknesses on the Ouagadougou Sheet (on Left) and Borehole Flow Rates Evolution Related to Alteration Depth (on Right)

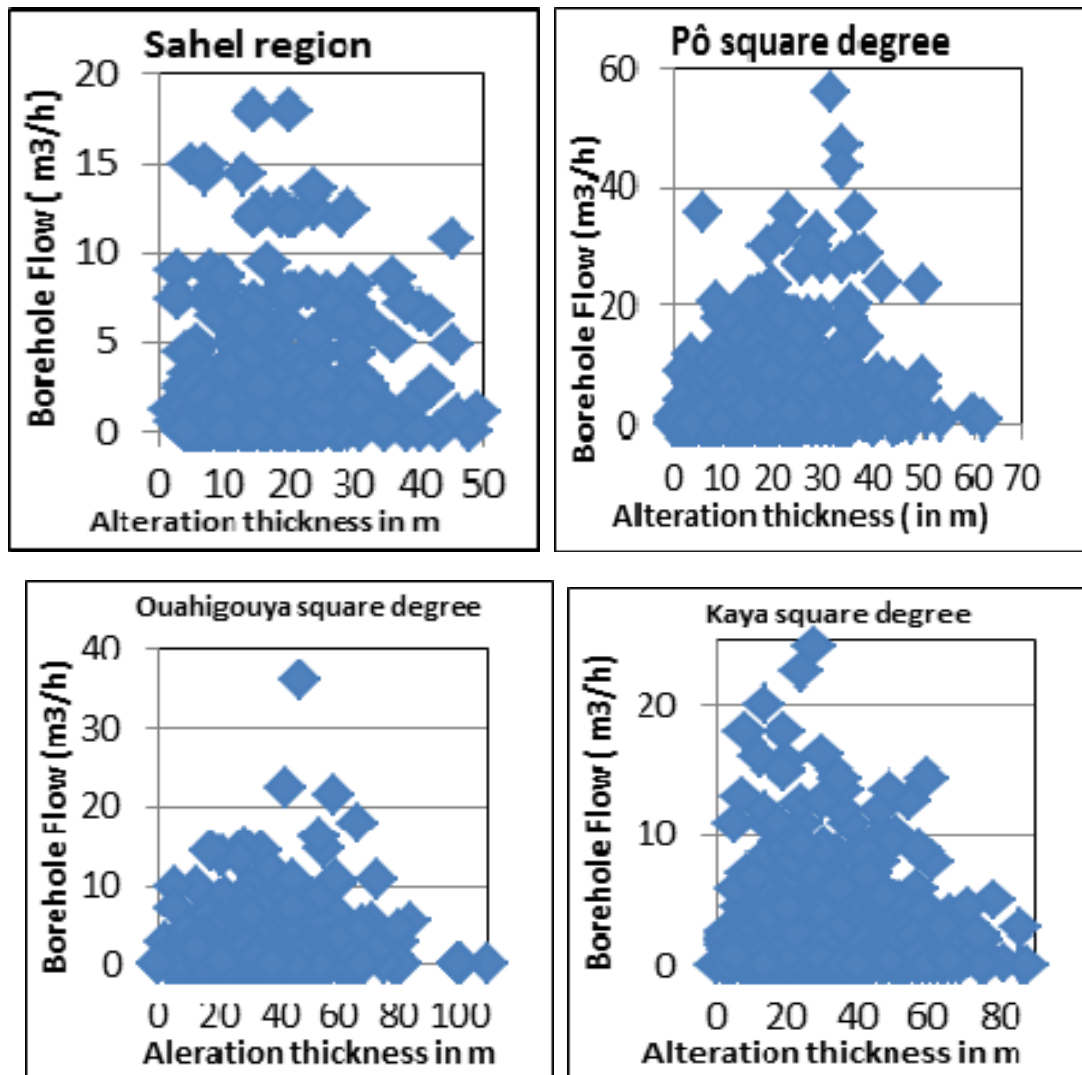


Figure 5. Comparative Analysis of Alteration Productivity Versus Alterations Thickness

The alteration thicknesses traversed by drilling vary from one anomaly to another on the Ouagadougou sheet. Here as elsewhere, they can even vary on the same structural anomaly. Approximately 7.5% of the boreholes have an alteration thickness of less than 10 m

The most common are those reaching 10 to 35 m deep. They represent 74% of the 2473 boreholes studied. Thicknesses greater than 45 m are rare cases; only 29 holes, or slightly more than 1%, have alterites columns of 60 m or more. However, these works are located in the northwest of the sheet, in the communes of Niou and Arbolé, for the most part.

Boreholes with low flows occur at all levels of alteration thickness. This is a reality in a crystalline basement environment. This is the case in the sheets of Kaya, Ouahigouya, Pô and also in the Sahel region of Burkina Faso (see Figures 4 and 5). However, the increasing flow rates often seem to isolate themselves in a given amount of depth of alteration. In our study area, the alteration thicknesses between 15 and 40 m are distinguished by the presence of boreholes of 20 m³/h and more.

Boreholes with alteration depths exceeding 60 m with flows greater than 5 m³/h are specific cases in the square degree. These boreholes are located in an alteration context similar to that of the Ouahigouya leaf and southwest of the Kaya leaf (Figure 5).

Aquifers in the Ouagadougou square degree are therefore no exception to the rule, and productivity is also influenced by the alteration depth.

2.4 Groups or Classes Determination

Alteration	average flows	]0,2-1[	]1-5[	]5-10[	]10-20[	Q>=20	Borehole rates
[0-5[	3,4	13	25	6	2	2	2,6
]5-10[	3	32	50	12	9	0	6,5
]10-15[	3,34	43	88	17	12	5	10,5
]15-20[	3,6	56	133	30	14	5	14,8
]20-25[	3,7	74	143	38	25	6	17
]25-30[	3,74	50	123	35	23	4	13,7
]30-35[	5,37	37	132	32	21	12	13,5
]35-40[	5,1	33	89	22	22	6	10,1
]40-45[	3,7	18	65	11	8	1	5,8
]45-50[	3,4	5	33	4	5	0	2,6
]50-55[	2,7	5	9	3	1	0	1,1
]55-60[	2	2	9	0	0	0	0,6
]60-65[	5,4	1	6	2	1	0	0,5
]65-70[	2,8	1	2	0	1	0	0,2
]70-75[	6,7	0	2	0	1	0	0,2
]75-80[	18	0	0	1	0	1	0,2
]80-85[	1,58	0	1	0	0	0	0,1

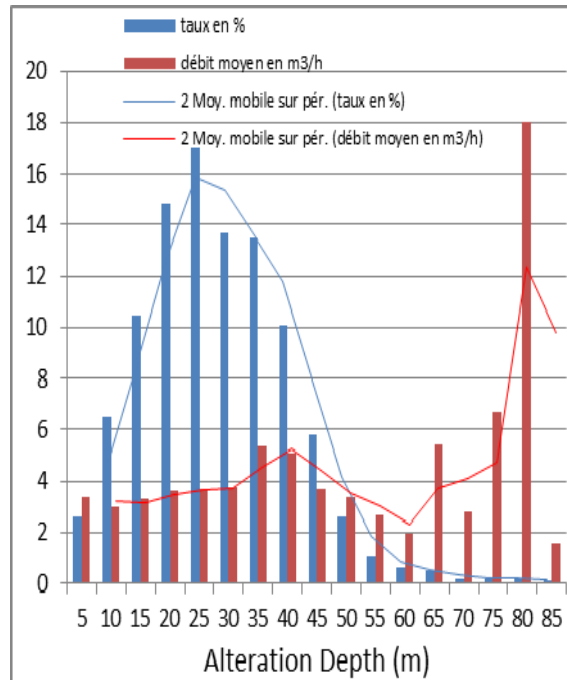


Figure 6. Analytical Table of Borehole Productivity (m3/h) Rates Related to Alteration Depth (on the Left) and Evolution of the Rate and Associated Average Flows According to the Alteration Thicknesses (on the Right)

The analysis of average flow rates of drilling rates by alteration interval and associated flow allows the distinction of the alteration classes. These alteration bands influence aquifer productivity differently.

The evolution of average flows gives four alteration classes. The productivity is increasing according to the thickness of alteration up to 30 meters. This range of alteration is represented by 65% of drilling. The productivity improves significantly for alterations from 30 to 40 meters deep. About 24% of the boreholes are concerned, with an almost constant average flow rate of 5 m3/h. productivity is decreasing in the thicknesses of 40 to 60 meters (10% of the drilling). Beyond the 60 meters we have boreholes with very different flows (Figures 8 and 9). After this analysis, we select firstly five classes, namely the thicknesses from 0 to 15, 15 to 20, 20 to 25, 25 to 50 and 50 to 80 meters. These classes are basic range for the design of the alteration coverage model of the square degree.

2.5 Modeling the Alteration Cover

The design of the alteration coverage model is guided by the flowchart below (Figure 7). The different treatments were executed with ArcGIS software. These are essentially the interpolation operations, classification, digitization and georeferencing.

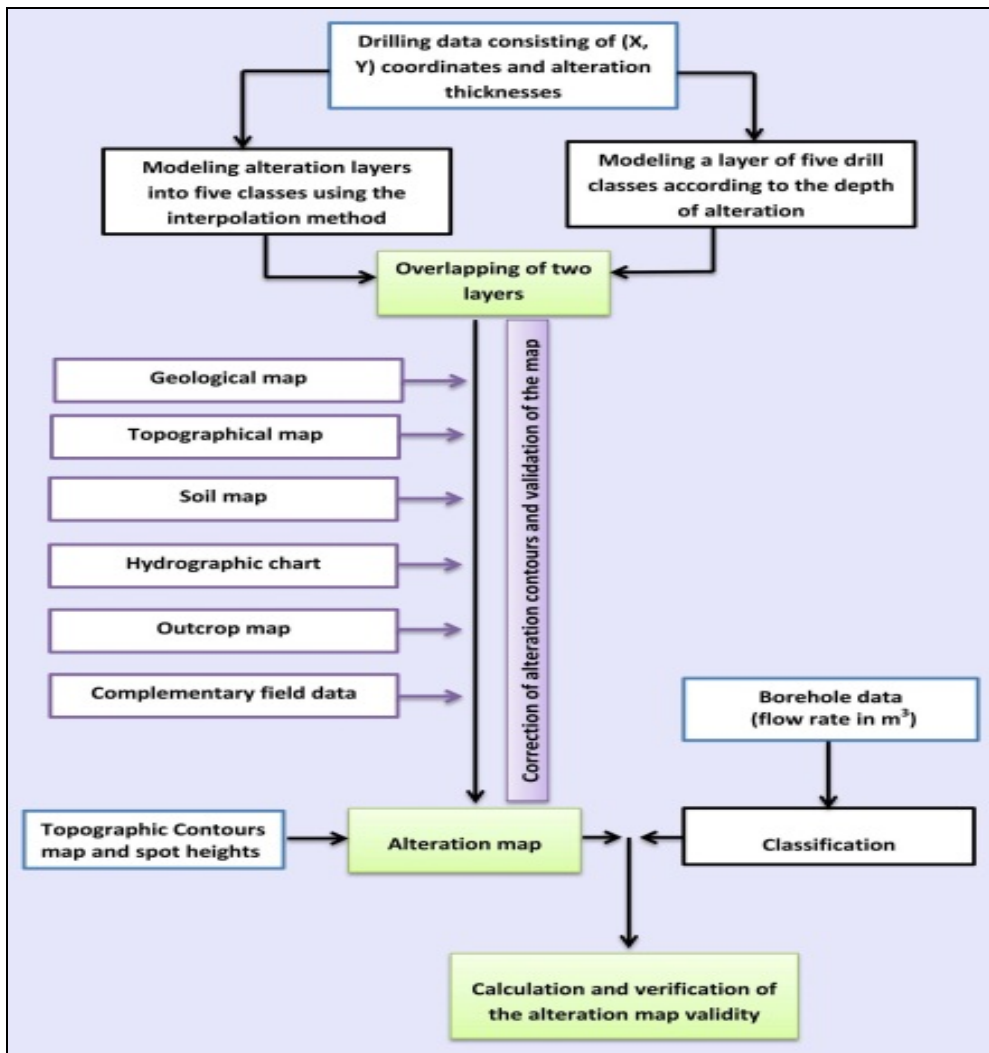


Figure 7. Design Procedure for Alteration Map

❖ kriging

It is a geostatistical estimation method that takes into account the spatial variability of the phenomenon synthesized by its variogram.

❖ Classification

We applied the unsupervised manual classification method. It was performed using the Arc-Gis software. The number of output classes and their bounds are specified as expected by the statistical results.

❖ Contours manual adjustment

The contour correction of discriminated classes is drawn from the alteration points of boreholes is a smoothing operation. Alteration points and product obtained after interpolation must be of the same classification.

❖ Maps validation through available data

In our case we used the geological map at 1/200 000 of Ouagadougou square degree, the hydrographic

map 1/200 000 of the National Topographic Data Base of the Geographic Institute of Burkina, the soil map of Burkina, a map of topographic levels from airborne radar data processing, Srtm 30 m and a Landsat 7 image. The superposition of these different products makes it possible to control and validate the alteration map. The control and validation can be done using additional field data if available such as outcrop points, geophysical surveys, drilling data.

❖ **Validity calculation and validity**

The purpose is to compare basic statistical results by classes with those determined from the map. In order to do so, boreholes in each class of alteration thickness are filtered and then submitted to the same statistical analysis. The ratio of “map results (Rc)” to “statistical results (Rs)” of departure is the Validity Report (Rv); $R_v = R_c/R_s$. The Validity Rate (TR) is defined by $1-R_v$ and appreciated through the scale shown in the Table below.

Table 2. Validity Rate Appreciation Scale (EA1: Statistical Results, EA2: Cartographic Results)

$|1-R_v| = |1 - (EA2/EA1)|$	appreciation
0	excellent
0,01 - 0,10	Very strong
0,11 - 0,20	strong
0,21 - 0,50	average
0,51 - 0,75	weak
0,76 - 1	Very weak
> 1	insignificant

3. Result

Data processing following the above stated approach has resulted in the map below (Figure 8).

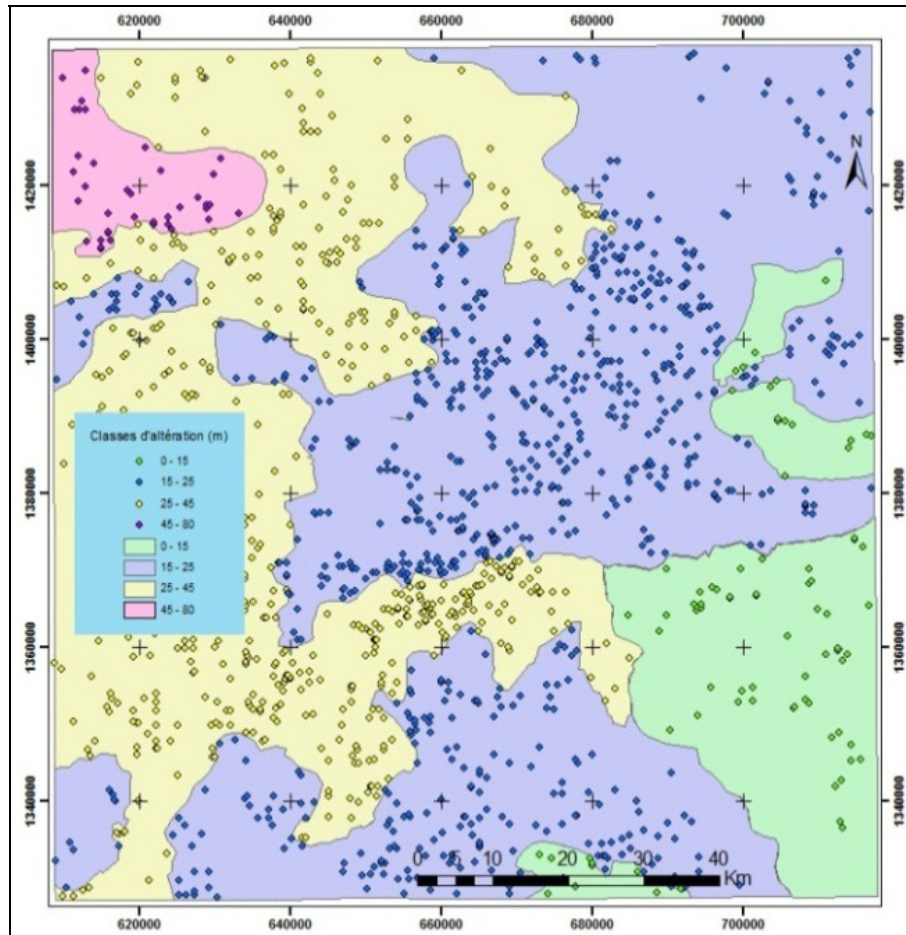


Figure 8. Determination of the Validity of the Alteration Map

3.1 Alteration Map Validity

We assessed for each class of alteration on the map, the depth or the rated average thickness EA2 and also determine the partners Qm2 average flows. The map in Figure 8 shows the alteration classes and the associated drill holes. The results obtained EA2 and Qm2 are compared with the statistical results designated by EA1 and Qm1 (Table 3).

Table 3. Comparative Table of Statistical Results (EA1, Qm1) and Cartographic Data (EA2, Qm2)

Alteration	Medium EA		Productivity	
	EA1	EA2	Qm1	Qm2
[0 - 15]	9,54	15	3,24	2,70
[15 - 25]	19,46	22,36	3,65	3,80
[25 - 45]	32,78	31	4,47	5,00
[45 - 80]	52,7	53,35	3,78	3,90

Globally, we find that the average EA2 alterations obtained after mapping are greater than those determined statistically.

This result is explained by the dispersion or spatial distribution of alteration depths at the lower bounds of each class. The class of alterations less than 15 meters is very illustrative.

On the other hand, average productivity improved significantly with map results, except at alteration sites less than 15 meters deep.

Validity Ratios ($R_v = EA2/EA1$) and Validity Rates ($T_v = 1 - V_r = 1 - EA2/EA1$) are presented in Table 4.

Table 4. Table of Map Validity

alteration	EA2/EA1	|1 - R _v|	appreciation
[0 - 15]	1,57	0,57	Weak
[15 - 25]	1,15	0,15	strong
[25 - 45]	0,95	0,05	Very strong
[45 - 80]	1,01	0,01	Very strong

The validity ratios are between 0.5 and 1.5. So the alteration map is close to the field reality.

3.2 Legend

❖ Legend's representation

The purpose of the legend is to read the map; it must be consistent with the actual terrain. The upper layers always include the lower layers.

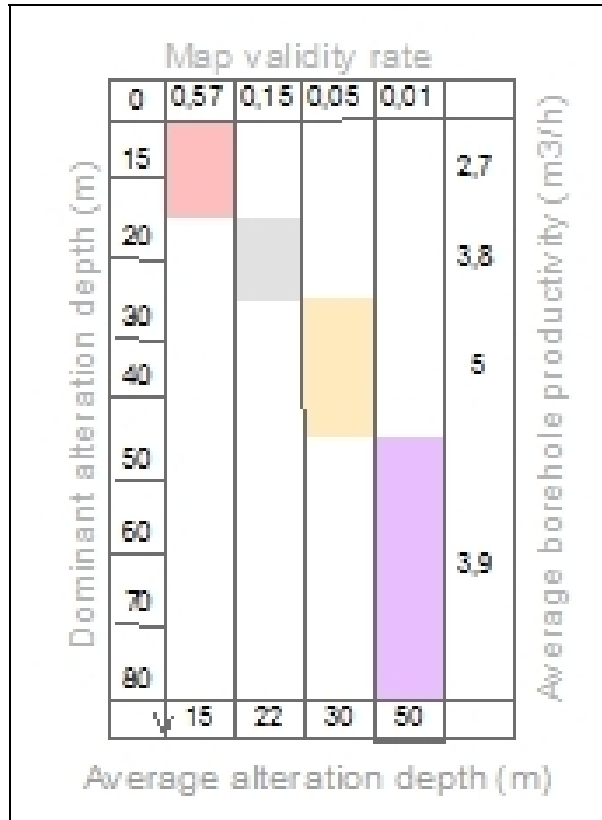


Figure 9. The Legend of Alteration Map

❖ Legend’s description

Areas deterioration rate of less than 15 meters are dominant. Fractures are marked by average depth of 15 meters with an average water productivity of 2.70 m3/h. This ground is of a very variable alteration. It has 71% weathering greater than 15 (±3) meters. The balance of variation in alterations and productivity is shown in Table 5 and Figure 10.

Table 5. Summary 1 (97) the Number (97) Makes Reference to the Number of Boreholes

	EA < 15(±3)	EA > 15(±3)
Rates (%)	71	29
Qm (Q > 0,5)	2,59	2,59
Nb, Q < 0,5	14	3

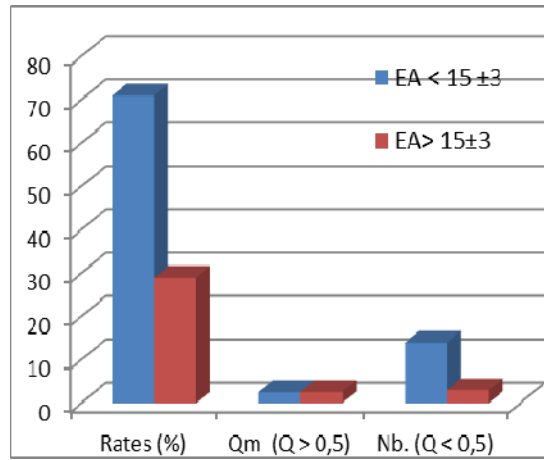


Figure 10. Productivity Graph (Q in m3/h)

Terrain of alterations less than 25 meters dominant. Hydraulic fractures are characterized by alteration depths of 15 to 25 meters with an average of 22 meters. The average productivity of aquifers is 3.80 m³/h. But about 24% of drillings have depths of alteration greater than or equal to 25 meters (see Table 6 and Figure 11).

Table 6. Summary 2 (917 Boreholes), the Number Makes Reference to the Number of Boreholes

	EA < 15	15 < EA < 25	EA > 25
Rate (%)	13,8	61,7	24,4
Qm (Q > 0,5)	3,19	3,68	4,93
Nb, Q < 0,5	17	67	16

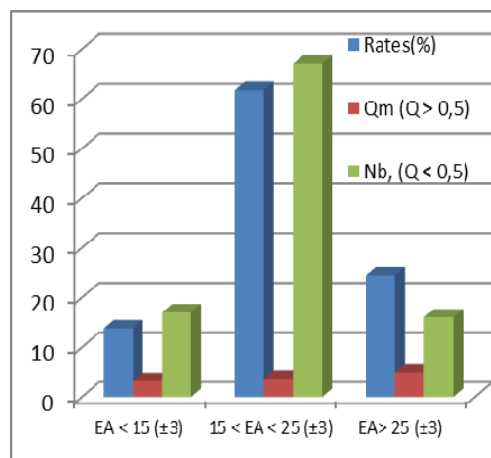


Figure 11. Productivity Graph (Q in m3/h)

Terrain of alterations less than 45 meters dominant. Hydraulic fractures are characterized by alteration depths mainly (73.7%) between 25 and 45 (± 3) meters with an average of 30 meters. The average productivity of aquifers is 5.0 m³/h.

Table 7. Summary (722 Boreholes), Nb. Refers to Number of Drilling

	EA < 25	25 < EA < 45	EA > 45
Rates (%)	21,5	73,7	4,8
Qm (Q > 0,5)	5,13	5,32	3,82
Nb (Q < 0,5)	22	41	1

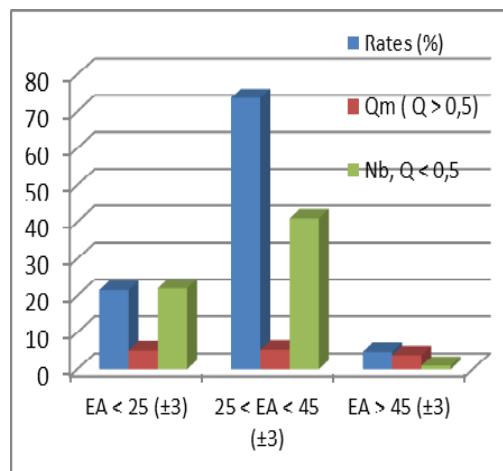


Figure 12. Productivity Graph (Q in m³/h)

Terrain of alterations less than 80 meters dominant. Fracture zones are generally marked by alteration depths of 45 to 80 meters (79.2%), with an average of 53 meters. The average yield of the water wells is 3.90 m³/h.

Table 7. Summary (722 Boreholes), Nb. Refers to Number of Drilling

	EA < 25	25 < EA < 45	EA > 45
Rates (%)	21,5	73,7	4,8
Qm (Q > 0,5)	5,13	5,32	3,82
Nb, Q < 0,5	22	41	1

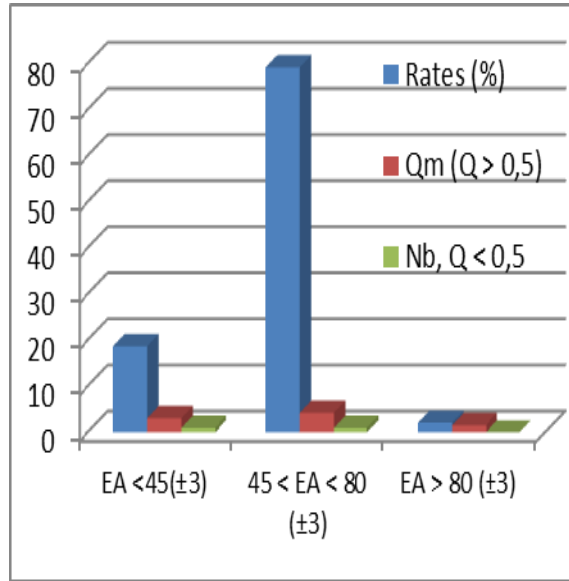


Figure 13. Productivity Graph (Q in m3/h)

3.3 Summary Overview Map

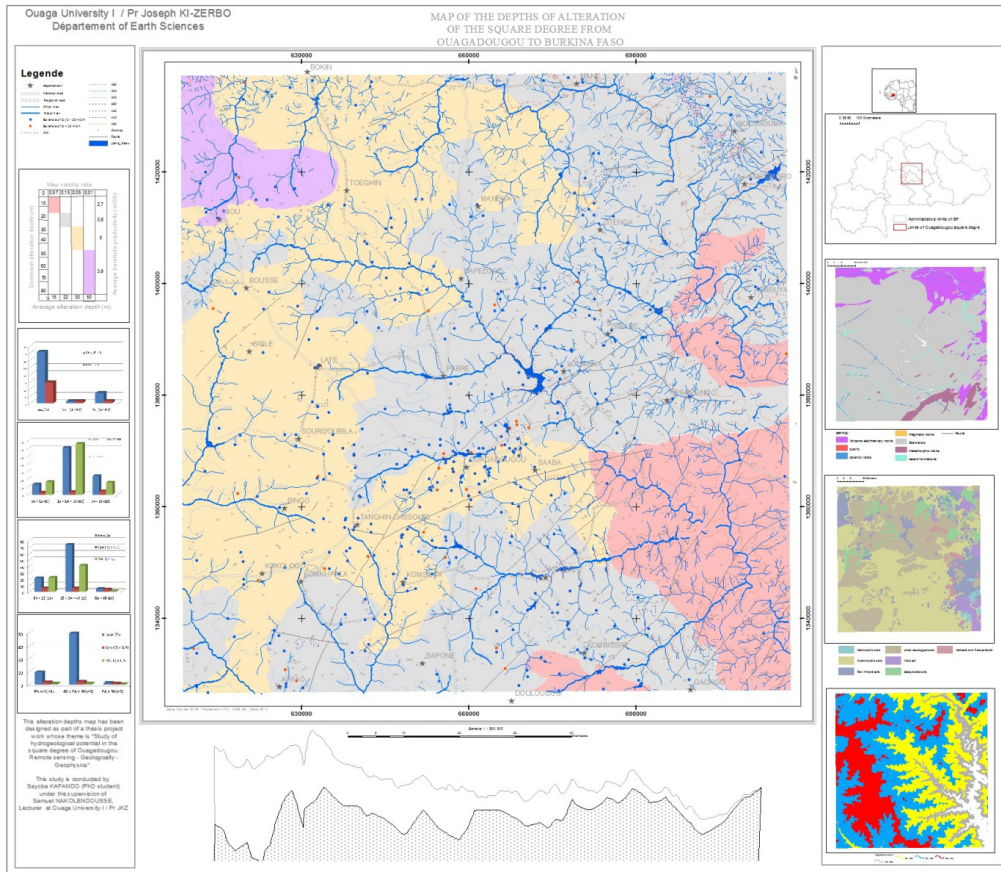


Figure 14. Model of Alteration Depths in Central Burkina Faso (Square Degree of Ouagadougou)

4. Critique and Discussion

The center of the country is mainly dominated by alteration thicknesses of less than 30 meters. Areas of severe alteration generally correspond to high elevation platforms (Kafando et al., 2016). The eastern half of the sheet, which is characterized by low depths of alteration, has a very high hydrographic density.

This proposed alteration map shows major differences with that of the “Bilan d’Eau”, carried out by the Bureau of Geological and Mining Research (BRGM) of France in 1993.

4.1 Alteration Thickness Classes

The alteration layer of the hydrogeological map of BRGM presents globally thirteen classes. Multiple colors sometimes make it difficult to read the map. For a hydrogeological utility alteration map, class definition should be a function of aquifer productivity. Thus, the four classes make it possible to better appreciate the variation of the altered depths and their influence on the productivity of the aquifers

4.2 Representation of the So-Called Saturated Alteration Thicknesses

In addition to alteration thicknesses represented at a given point, the depth of the bed rock relative to the ground, the BRGM map mentions the thickness of saturated alteration. Beyond the overload, and confusions that the representation of this layer could lead to, it is necessary to analyze the validity and the appropriateness of this parameter.

The saturated alteration thickness (EAs) is defined as the depth of alteration below the phreatic surface: $EAs = EA - NS$ (Water Balance, 1993). This definition has limitations:

[1] the statistical level (NS) is a very variable Hydrodynamic parameter in our context. In sub-Saharan countries, where aquifers are dependent on annual rainfall, this parameter has high seasonal and annual variability. Figures 15 and 16 show some water table variations.

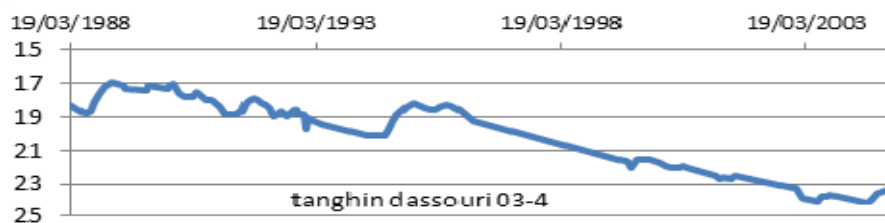


Figure 15. Variation Phreatic Surface in Tanghin Dassouri (in Square Degree Ouagadougou)

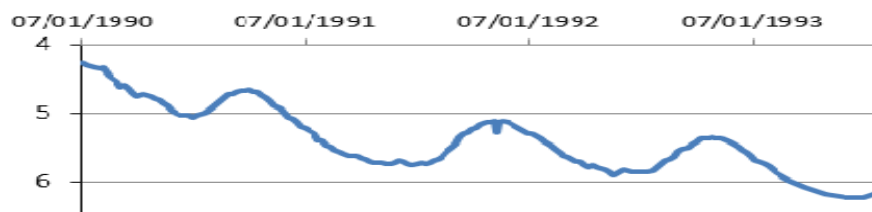


Figure 16. Variation Phreatic Surface Level in Bindé (in the Square Degree of Po)

Therefore, consideration of the static levels without the integration of the measurement periods leads of benchmarking mistakes. Average annual water tables are more appropriate for cartographic studies.

2) We are in a crystalline basement environment and the layers are of leaky phreatic aquifer type. That is to say that the sheets are discontinuous and the phreatic tables are at an altitude higher than the level of the roof of the sheet which of course is under pressure. Considering the first water coming as the roof of the water table, the water column in the borehole above the water inlet is only the expression of the pressure at the roof of the water table. This column is proportional to the pressure above the water table. So depending on this pressure, the phreatic table can go up to a few meters from the ground.

The water column inside the borehole will thus cross part of the weathered fringe. At this time, depending on the depth of alteration and the pressure at the roof of the water table, the alteration column below the phreatic table will vary from one drill to another for the same period.

In conclusion, the alteration thickness below the phreatic table does not systematically constitute a saturated thickness. It cannot be considered as a productivity factor because it has no particular hydrogeological interest. Its representation on the hydrogeological map constitutes an unnecessary overload.

4.3 Topographic Contour Line

In the absence of topographic contour lines, the depth of alteration is of little interest to the hydrogeologist. Because we are in a context of crystalline basement with numerous points of outcrop and chains of hills and lateritic plateaus. So alteration thicknesses and their influence on groundwater resources are best interpreted by joining the topographic context. Altitude contour lines must accompany an alteration map for hydrogeological purposes, this geological and geomorphological context.

Acknowledgement

The design of an alteration map for hydrogeological purposes is a demanding exercise. It requires a large amount of boreholes and geophysical data. The presence of outcrop, geological (lithology and structural) and soil maps is a major asset for validation. The same applies to satellite images, aerial photographs and airborne radar and geophysical data whose processing can contribute to the smoothing and correction of interpolations. The realization of the map begins after a statistical study of the drilling data. The purpose of this study is to establish the relationship between alteration depths and aquifer productivity. When the (partial) dependency is highlighted, the alteration classes to be represented on the map. Then we have interpolation, smoothing and validation operations. The final map obtained is finally subjected to a validity rate assessment. This standard (benchmark) is calculated by classes represented on the map, the legend description of which gives the hydrogeological characteristics. The alteration thicknesses shown on the map are of interest to the hydrogeologist when superimposed on topographic contour lines. Contours allow the taking into account of the internal geomorphology of the environment.

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Note

Authors' contributions

This work was carried out in collaboration between all authors. Authors SK and SN designed the study, performed the methodology, wrote the protocol and wrote the first draft of the manuscript. Authors SK, SN and JN managed the analyses of the study. Author SN managed the literature searches. All authors read and approved the final manuscript.