Journal of Water Resource and Protection, 2023, 15, 33-50
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Development and Application of Water Quality Index (WQI) for the Evaluation of the Physico-Chemical Quality of Groundwater in Gold Mining Areas of Southeastern Senegal

Mor Diop[1], Ibrahima Mall[2], El Hadji Mamadou Sonko[1], Tidiane Diop[3], Liengsy Badji[4], Cheikh Mbow[1]

[1]Environmental Sciences Institute (ISE), Cheikh Anta Diop University, Dakar, Senegal
[2]Amadou Mahtar Mbow University of Diamniadio (UAM), Dakar, Senegal
[3]Department of Chemical, Cheikh Anta Diop University, Dakar, Senegal
[4]Faculty of Medicine, Pharmacy and Dentistry, Cheikh Anta Diop University, Dakar, Senegal
Email: mor31.diop@ucad.edu.sn

How to cite this paper: Diop, M., Mall, I., Sonko, E.H.M., Diop, T., Badji, L. and Mbow, C. (2023) Development and Application of Water Quality Index (WQI) for the Evaluation of the Physico-Chemical Quality of Groundwater in Gold Mining Areas of Southeastern Senegal. *Journal of Water Resource and Protection*, **15**, 33-50.
https://doi.org/10.4236/jwarp.2023.152003

Received: December 31, 2022
Accepted: February 10, 2023
Published: February 13, 2023

Abstract

Water is the most essential requirement for life. It provides a variety of purposes such as a source of water supply for drinking, domestic and industrial use, irrigated agriculture, livestock, and mining activities. Evaluating the status of water quality from traditional approaches does not guarantee the whole overview of the water quality situation. Therefore, developing a tool that can convert multiple parameters data into information that is understandable by both technical and non-technical personnel is vital. In this context, the purpose of this paper was to develop, calculate, and apply a water quality index for assessing the suitability (for drinking purposes) of groundwater in the gold mining areas in south-eastern Senegal. The development of this index based on WHO water quality guidelines followed the five standards steps *i.e.*, parameters selection, sub-index formation, parameters weighting and sub-index aggregation and evaluation. Finally, the WQI summarized twelve key water quality parameters into 05 simple terms (excellent, good, medium, poor, and very poor) which is more relevant for reporting to managers and the public in a consistent manner. Thus, it was observed in the study area, that the water quality indexes in artisanal and industrial mining areas are either poor or very poor while in the reference stations (where there are no mining activities) WQI are either good or excellent. This situation was attributed to the effects of mining activities in such zones which contribute to the pollution of groundwater with heavy metals, nitrates, and suspended solids.

Keywords

Water Quality Index, Groundwater, Gold Mining, Pollution, Heavy Metals

1. Introduction

The study area belongs to the Gambia River watershed and is located in the south-eastern part of Senegal. This area has significant gold potential, which is currently under intense exploitation, with industrial exploitation (in Sabodala) and artisanal and small gold mining (ASGM) in Bantako and Tinkoto. Both types of exploitation are vital to the local economy as they represent important sources of income for the local communities. Despite this obvious importance, gold mining activities lead to severe impacts on the natural environment. In fact, according to [1], continuous exploitation of mineral resources and the deposition of mining waste will lead to various secondary environmental problems such as vegetation degradation, land occupation, ground subsidence, and biodiversity loss [2] [3] [4] which will pose challenges to the local ecological environment and the sustainable development of the social economy [5] [6] [7] [8]. In addition, pollution through the use of mercury and cyanide to amalgamate gold [9] [10] [11], water siltation [12] [13], and the discharge of metallic trace elements [14] lead to the degradation of water resources around the areas of activity. To keep the health of any aquatic system at an optimal level, some water quality indicators or parameters must be monitored and controlled [15]. Water quality monitoring and assessment include the physical, chemical, biological, and environmental parameters of its contents, based on their concentrations or attributes which are below defined limits [16] [17] [18] [19]. Evaluating the status of water quality from these approaches does not guarantee the whole overview of the water quality situation [20]. Therefore, developing a tool that can convert multiple parameters data into information that is understandable by both technical and non-technical personnel is vital. To achieve this, the Water Quality Index (WQI) is increasingly being developed by researchers and water resource management organizations.

WQI, in common with many other index systems, relates to a group of water quality parameters to a common scale and combines them into a single number in accordance with a chosen method or model of computation [21]. A water quality index (WQI) summarizes large amounts of water quality data into simple terms (e.g., excellent, good, bad, etc.) for reporting to managers and the public in a consistent manner [22]. The concept of its development is based on the comparison of the water quality parameters with respective regulatory standards [23].

In this context, we aim in this study to develop, calculate, and apply a water quality index for assessing the suitability of groundwater in the gold mining areas in south-eastern Senegal for drinking purposes. This is to verify whether exploitation activities have affected the quality of this vital resource for human communities and ecosystems.

2. Study Area

The study area, straddling the communes of Sabodala and Tomboronkoto, is located in the region of Kedougou about 700 km southeast of Dakar, the Senegalese capital.

The study area belongs to the Sudanese climate domain and is characterized by the alternation of two different seasons: a dry season from November to May and a rainy season from June to October with a rainfall of around 1200 mm/year in Kédougou and a maximum rainfall intensity recorded in August [24]. Temperatures are high and range on average between 25˚C and 33˚C. However, on a daily scale, peaks of heat exceeding 40˚C are sometimes recorded. On the hydrological level, the area is located in the Gambia river basin which has a dense river tributaries system with many streams that contribute significantly to the Gambia River flows. The most important one of which is the Niokolo Koba that drains much of the study area.

Hydrogeological context of the area is characterized by fractured, discontinuous and semi-continuous aquifers which are represented by the weathered fringe of hard rocks with yields varying from 0.6 to 30 m^3/h and high rate of unsuccessful drilling. There are essentially three types of reservoirs: weathered reservoirs (shallows that are captured by traditional wells), cracks and fractured reservoirs (captured by boreholes).

Geologically, the area belongs to the birrimian Kedougou-Kéniaba inlier (KKI), which is one of the Precambrian segments of West African craton. This inlier located between Senegal and Mali and made up of ancient crystalline formations has been the subject of many studies. Recent mapping study conducted by [25] subdivided the KKI into two Groups and three Suites which are all present in Eastern Senegal:

- ✓ The volcano-sedimentary groups of Mako and Dialé-Daléma;
- ✓ The magmatic suites of Sandikounda-Soukouta, Saraya and Boboti.

At the local level, in our study area which belongs to the Mako group, the main lithologies encountered are the following: predominantly granitic formations, sandstone or quartzitic formations, Mafic and ultramafic formations and finally Pelites, siltstones, grauwackes and volcano-sedimentary formations of Birrimian.

These Birimian terrains have been investigated for several years for gold, iron and other minerals exploration. This is because the Birimian rocks are known to bear proven ore deposed as well as gold indices in the region and in neighboring countries.

These terrains have experienced since the 70s a great development of gold research which is crowned by gold mining, discovery, and exploitation of Sabodala gold deposit and its satellites which reserves are estimated at several tons of gold

[26]. The Sabodala mine, once operated by Canadian firm Teranga Gold (by Endeavour mining actually), is currently the largest employer in the region with over 1800 employees most of whom are area nationals. In addition, artisanal and small-scale gold mining (ASGM) is intensively practiced in the area by thousands of people for whom it represents the main income-generating activities. Figure 1 below illustrates the practice of gold mining in the study area.

3. Materials and Methods

3.1. Water Sampling and Analyses

Water sampling was conducted during a field campaign in March 2018. The equipment used included: sampling bootles, multiparametric probe (for *in situ* measurement of fugacious elements such as pH, EC, temperature etc.), coolers for sample storage etc.

Once the samples are collected, they are stored in containers in order to stabilize the temperature at less than 4˚C until they are sent to the SGS lab in Bamako (Mali) where analysis are been undertaken. A total of 12 samples were taken for groundwater in 3 villages where artisanal and small gold mining (ASGM) are developed and 2 as a reference site where no activity is undertaken. The **ASGM villages** are the following: Bantako, Tinkoto, Sabodala. Kanouméring and Sofia villages are the **reference sites**.

These samples are collected from traditional wells and from manual pumped boreholes which are one the most used water supply systems for communities (see Figure 2).

The exact positions of each of these stations are presented in the map below (Figure 3).

Figure 1. Illustrative images of gold mining in the study area: open industrial pit (A), ore loading (B), ore processing plant (C), artisanal shafts (D), Uptake of ore by artisanal miners (E), artisanal ore washing (F).

Figure 2. Traditional wells and manual pomped borehole sampled in the study areas.

3.2. Development and Use of Water Quality Index

3.2.1. Basic Procedure for Developing a Water Quality Index

According to [27], a considerably number of indices have been developed since the primary index by [28], but regardless of such efforts, there is still no globally acceptable manner in which water quality indices are developed [29]. However, there is a certain possible trend, which is distinguished by the following common steps [16] [30] [31] [32]:

- **Selection of parameters**: identifying and choosing the most critical variables suitable to provide a functional sense to the water quality index. Proficiency is required to provide just enough parameters—not too few or too many. This process can be done by either expert opinion (whether individually or as a group) or through statistical techniques.
- **The formation of sub-index values:** considering that various water quality parameters have different scientific units, it becomes necessary to transform them into a single common scale, and this task is achieved by generating sub-indices.
- **Establishing weights:** weight is assigned to each variable based on the level of importance of each parameter, established through evaluating the potential impact of them when their concentration levels are outside the permissible limits.

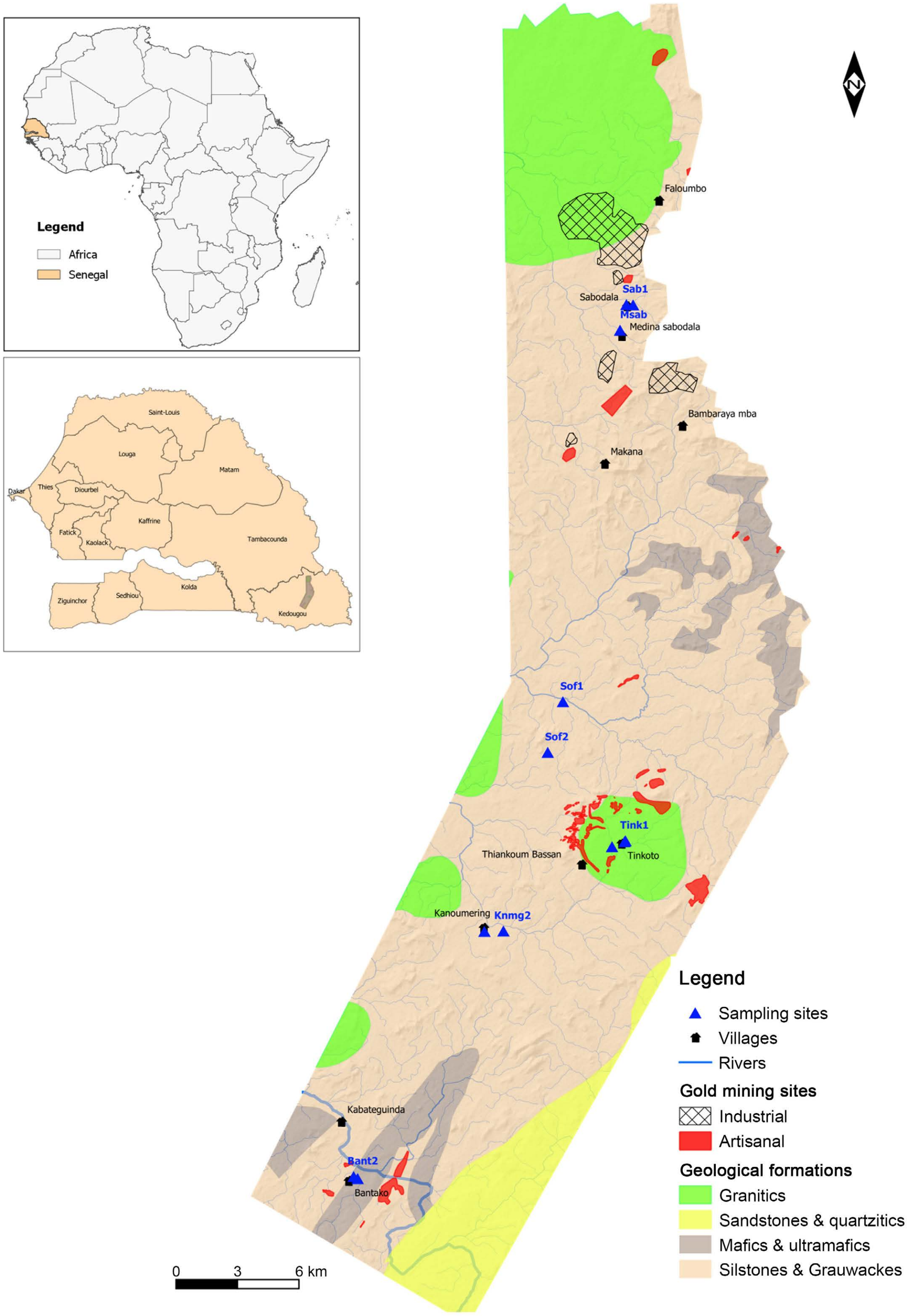

Figure 3. Location of study areas and sampling stations.

- **Aggregation of sub-indices:** if the final step toward obtaining a final cumulative index value. In understanding the assigned weights, mathematical models are used to combine all the sub-indices into one index number. Various aggregation methods available: Weight Arithmetic Water Quality Index

(WAWQI), Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI), Oregon Water Quality Index (OWQI) etc. have been formulated by several national and international organizations.

According to [33], the development process of a water quality index can be generalized in four steps:

- Selecting the set of water quality variables of concern—parameter selection.
- Transformation of the different units and dimensions of water quality variables to a common scale—developing sub-indices.
- Weighting of the water quality variables based on their relative importance to overall water quality—assignment of weights.
- Formulation of overall water quality index—aggregation of sub-indices to produce an overall index.

In this study a new water index called the LEE Water Quality Index (LWQI) has been developed to provide a simpler method for describing the quality of the ground water used for drinking water purposes.

3.2.2. LWQI for Groundwater Used for Drinking Supply

This index is developed by Mor DIOP in 2022 to assess water quality based on WHO water quality guidelines. It contains the five standards WQI components, *i.e.*, parameters selection, sub-index formation, parameters weighting and sub-index aggregation and evaluation:

- **Selected parameters**

The Lee model employed twelve physicochemical parameters including: pH, electrical conductivity, turbidity, Ca, Mg, Na, K, NO_3, SO_4, Mn, As, Hg. These parameters were selected based on their important environmental considerations such as reliability of data and the parameter significance based on the observation of a series of data where these parameters were the most preponderant.

- **Parameter weighting**

Each of these 12 parameters was weighted according to its influence on the overall quality based on three criteria (1 to 3 weight):

- ✓ Importance of the parameter;
- ✓ Occurrence of parameter in natural environment (groundwater) ;
- ✓ Health significance of the parameter.

The final weight obtained from the aggregation of the scores of these three criteria is divided by the sum of the weights obtained for all parameters to have the relative weight (wi). The parameter weight values can strongly influence the final index value.

- **Relative quality estimation**

The relative quality (qi) is estimated based on the relative importance of the water quality parameter and/or the appropriate guidelines of water quality. For the drinking purpose, world health organization (WHO) standards are used for the calculation.

The formula to calculate is $qi = 100 * (R/S)$.

R: is the recorded value of the parameter and S: is the WHO standard permissible value of the parameter.

- **Index aggregation and WQI calculation**

The calculation of the Lee WQI was done using weighted arithmetic water quality index which was originally proposed by [28] and developed by [34]. The weighted arithmetic water quality index (WQI) is simplified in the following form:

$$\text{WQI} = \sum wiqi / \sum wi$$

- **WQI evaluation**

The WQI value are classified in five categories inspired on the classification of [34] [35]. The intervals of these different classes are summarized in **Table 1** below.

4. Results and Discussion

4.1. Groundwater Quality Index

The results of calculated WQI can allow to the authorities to differentiate pollution levels to know water quality and to implement corrective or preventive actions [36]. In the study area, results recorded with the LWQI groundwater quality are presented in the **Table 2**. It appears that all the five categories of water quality are recorded in the study area. The lowest scores are observed in boreholes. Those waters meet the quality standards almost all the time and are suitable for drinking. However, the highest values are mainly observed in traditional wells which indicate contamination of waters that make them unsuitable for drinking. Finally, it is observed that at the reference stations, water quality indexes are either good or excellent. However, in artisanal and industrial mining areas water quality indexes are either poor or very poor. This can be attributed to the effects of mining activities in such zones.

Thus, it is easily noticed that the groundwater where the quality of the water is bad, corresponds essentially to traditional wells without much protection. In these wells (Bant2, Tink1, Sab2), the main parameters that make water the water quality index bad and very bad are turbidity, nitrates, iron, aluminum and manganese. These parameters are used to distinguish satisfactory water quality index and poor-quality water index. **Figure 4** below show the mapping of the WQI calculation results.

Table 1. Class intervals of water quality index.

Class	Status	Qualification
0 - 25	Excellent	Clean water, excellently suitable for drinking
26 - 50	Good	Suitable for drinking
51 - 75	Medium “marginal”	Modestly suitable for drinking
76 - 100	Poor	Unsuitable for drinking, minor treatment (purification) required before usage
>100	Very poor	Unsuitable for drinking, Appropriate treatment required before usage or seek alternative sources of supply

Table 2. Class of WQI observed in the study areas.

Class	Description	Stations	WQI	Type
Excellent	Waters in this category meet the quality criteria almost all the time. According to [37], that water quality is protected with a virtual absence of threat or impairment, conditions very close to natural or pristine levels. According to Abrahao et al, class Excellent can only be obtained if all measurements are within objectives virtually all the time. This is the case for the stations below.	Tink3	12.01	Borehole
		Knmg2	13.52	Borehole
		Sof1	15.14	Borehole
		Tink2	17.66	Borehole
Good	For waters in this class, concentrations rarely deviate from natural or desirable levels. Water quality is protected with only a minor degree of threat or impairment conditions rarely depart from natural or desirable levels. This is the case for the stations below.	Sof2	26.04	Borehole
		Knmg1	47.11	Borehole
Medium	Concentrations may deviate from natural or acceptable (desirable) levels. Water quality is usually protected but occasionally threatened or impaired, conditions sometimes depart from natural or desirable levels.	Sab2	50.98	Hand dug well
		Msab	66.07	Borehole
Poor	Concentrations often deviate from natural or desirable levels. Water quality is frequently threatened or impaired, conditions often depart from natural or desirable levels.	Bant1	78.42	Hand dug well
		Sab1	98.56	Hand dug well
Very poor	Concentrations generally deviate from desirable levels. Water is always threatened or impaired, conditions usually depart from natural or desirable levels. Those waters are unsuitable.	Bant2	185.81	Borehole
		Tink1	428.56	Hand dug well

4.2. Groundwater Quality Details

For better understanding, a detailed presentation of the groundwater quality needs to be done. The physicochemical elements used in this study as quality criteria are physical parameters (pH, EC, Turbidity), major ions (Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, HCO_3^-, NO_3^-, SO_4^{2-}) and heavy metals (As, Hg, Pb, Fe, Al, etc,). For groundwater, which is mainly used for drinking water purposes, concentrations of chemical elements are compared to WHO guidelines. It appears in our analysis results that: mean **pH** values ranged from 5.7 to 7 which indicates that the waters are neutral to slightly acidic, this may be related to the silicate nature of the aquifers present in the area. Only 02 stations (Tink 2 and Sab2) not meet the WHO recommendations for drinking water. The water salinity is generally low, with mean EC ranging from 101 to 1050 µS/cm, **turbidity** exceeded WHO water guidelines mainly in the gold mining areas of Tinkoto (with 138 NTU), Bantako (40.3 NTU) and Sabodala (39.3 NTU). At the reference stations Sofia and Kanouméring, low values (below 5 NTU) are recorded (**Figure 2**). These suspended solids that cause water disturbance may have a variety of sources, including abandoned mine discharges into the operating areas, Runoff can leach fine particles to water sources, and from the dust. Through these charged surface water, infiltrations waters can reach the groundwater and lead to an increase of their turbidity. Ca, Mg and Na concentrations were moderately elevated in down-gradient bores but were fairly consistent with up-gradient concentrations. Nutrient parameters like **nitrates** are present in present in wells and boreholes at levels ranging from 0.4 to 138 mg/L. The highest concentrations are recorded in the Bantako and Sabodala gold sectors as shown in Figure below. Sulfate concentrations (SO_4^{2-}) are low in groundwater, they are ranged from 1 to 29 mg/L well below the WHO standard of 200 mg/L.

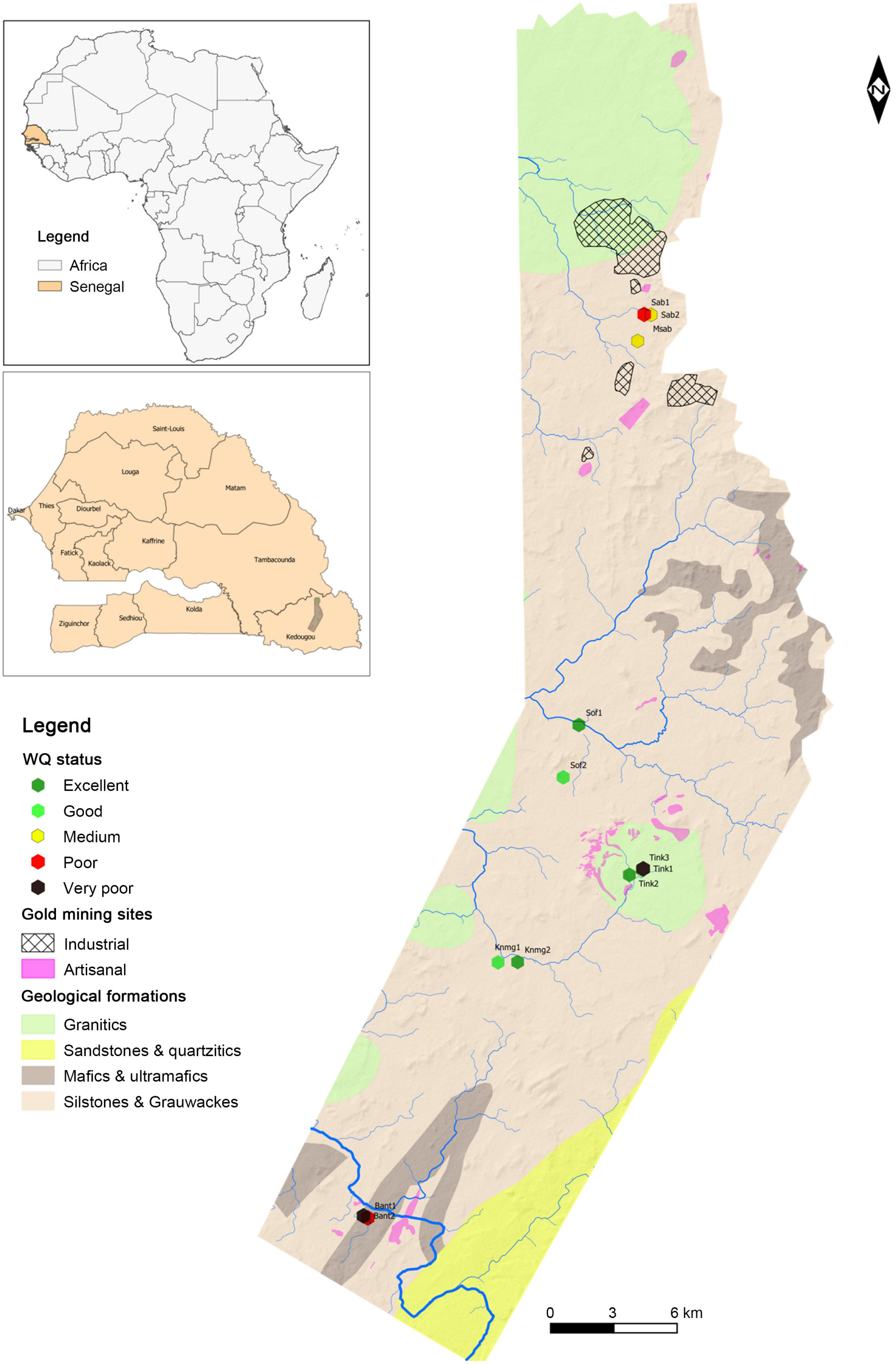

Figure 4. Mapping of the water quality index results.

Total concentrations of **iron** (Fe) exceeding the WHO guidelines are recorded in most of the stations sampled, especially in mining areas, Iron reaches its maximum level (3.1 mg/L) at the Tink3 station, located at the Tinkoto gold village. The minimum value (0.085 mg/L) is recorded in the waters of the Knmg2 reference station in the village of Kanouméring.

As with **iron**, concentrations of **aluminum** (Al) are relatively high in the water sampled, The maximum values for Tinkoto (2.1 mg/L), Bantako (0.54 mg/L) and Sabodala (0.24 mg/L) exceed the WHO standards of 0.2 mg/L, Reference station levels are very low, as shown in **Figure 5**. These results corroborate those of Mall (2017) which found high concentrations in the villages of Sabodala and Tinkoto with 0.813 mg/L and 0.7 mg/L, respectively. In the study area, high concentrations or **Manganese** were recorded at the Bantako (380 µg/L), Sabodala (360 and 180 µg/L) and Tinkoto (110 µg/L) mining areas. At reference site, low concentrations (all below 100 µg/L) are being observed. Concerning dangerous elements such as **arsenic**, the concentration levels vary from 0.5 to 9.3 µg/L therefore fall below the WHO standard. The highest concentrations are found at of Bantako village with a content of 9.3 µg/L. For **mercury** contents, the results of the measurements made show that the element is present in the waters at very low levels, usually below the detection limit. However, at the Bantako and Tinkoto stations, traces of mercury were detected in well waters and boreholes sampled with respectively a content of 0.32 and 0.31 µg/L. The results obtained for some of these parameters are presented in **Figure 5** below.

4.3. Discussion

4.3.1. Pertinence of the Use of WQI

Traditional approaches to assess water quality based on a comparison of experimentally determined parameter values with existing guidelines is important and allow in certain cases the proper identification of contamination sources and may be essential for checking legal compliance [33]. However, it does not readily give an overall view of the status of the water. To remedy this, the approach we have initiated is making it possible to bridge this gap.

In our case, our index mainly uses physicochemical parameters, some of which pose serious health problems. The selection of parameters monitored was based on their indicative characters.

- Operational monitoring parameters such as: pH, EC, turbidity were selected. They are convenient, rapid method for estimating the amount of dissolved and suspended solids present in the water.
- Major elements (Ca, Mg, Na, K) and minor elements (NO_3, SO_4) are selected because they are elements naturally **present** in the water and which ensure biological roles in the human organism.
- Heavy metals (Fe, Al, Mn) and toxic chemical elements (As, Hg) are also included in the calculation because their existence in drinking water causes more serious health effects compared to the others.

Certainly, most of these parameters can be found in other indices *i.e.*, Universal Water Quality Index [33], Canadian Council of Ministers of the Environment Water Quality Index [38], Oregon Water Quality Index [39] etc. but the difference noted is related to the fact that we wanted to contextualize water quality. In reality, the parameters we have selected are those that reflect the best quality of groundwater, especially the chemical point.

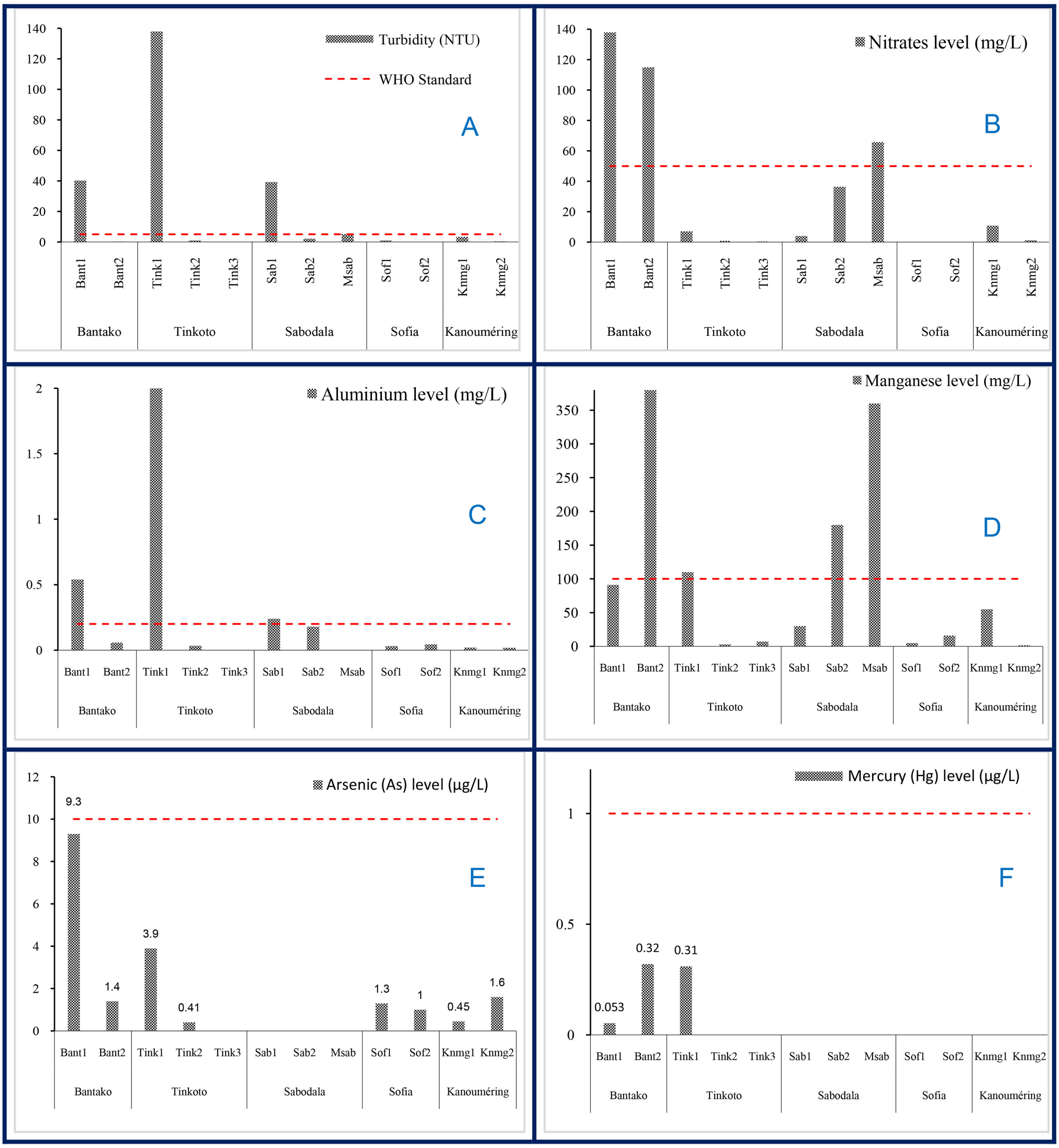

Figure 5. Water quality results for six parameters: Turbidity (A), Nitrates (B), Aluminium (C), Manganese (D), Arsenic (E), Mercury (F).

The aggregative method used, WA WQI is the approach that is most frequently used to classify water resources according to their appropriateness for drinking [40]. This method has the merits to be easy to calculate by incorporating data from multiple water quality parameters into a mathematical equation that rates the health of the water body with number [16]. It perfectly reflects the composite influence of different parameters *i.e.*, important for the assessment and management of water quality. Although it does not consider the key water quality parameters (in particular the microbiological parameters) the results obtained perfectly reflect the overall water quality in our study area.

4.3.2. Groundwater Quality Results

The results show that groundwater quality in the study area is conditioned and influenced by two main aspects: the geological nature of the land and by anthropic activities especially by mining. As regards to this last point, it is observed: **high turbidity** of groundwater around the mining areas, which reflects physical pollution due to mining activities causing a significant accumulation of detritus and suspended solids.

Nitrate contamination of groundwater (NO_3^-) with a maximum content of 138 mg/L at Bantako and 65.8 mg/L at Medina Sabodala. This is correlated with the dynamics of gold mining that causes a high of human density in these villages. In fact, according to [41], high nitrate levels is due to the oxydo reduction reactions of organic matter related to human activities or animal or plant production and domestic waste. Indeed, the long stay of animal droppings near water points contributes to the "nitrate pollution" of aquifers. Although less vulnerable, boreholes do not often escape this phenomenon, as the cracks and fractures associated with these aquifers would ensure the underground transit of nitrate by leaching that contaminate the groundwater. According to [11] the high intensity of gold mining activities at some sites also constitutes a great threat to water resources with sometimes strong human concentrations that contribute to high production of untreated waste often stored in dumps near the hydraulic structures (boreholes and hand dug wells).

Another fact is, **the contribution from mining activities to the contamination of groundwater by metals (Fe-Al-Mn)**. In fact, the highest metals levels contents ([Fe] 3100 µg/L, [Al] 2100 µg/L and [Mn] 380 µg/L) were found at the Bantako, Sabodala and Tinkoto are mining and mineral washing zones, contrary to the reference sites of Kanouméring and Sofia where there is no extraction or washing of gold ores. These high contents only observed in Mining area are far exceed the WHO recommendations, reflect anthropogenic contamination associated with the mining and mineral washing process that takes place in the vicinity of affected wells and boreholes (see **Figure 6**).

For example, in groundwater results show that levels of iron, aluminum and manganese contents are very high compared to the guideline values. These observations can be explained by the fact that, in the area geological formations are weathered to laterite, that covers the geological formations et constitute somewhere the soils. These soils are highly and rich in iron and aluminum hydroxide and manganese which could be leached by surface water runoff [42]. The presence of these elements in high contents in the waters can be explained on the one hand by soil erosion and runoff (a natural phenomenon but accentuated by mining due to excavation). On the other hand, the washing of ores, sludge and dust produced during artisanal gold mining activities contribute to the contamination of the water with these metals. Traces of mercury (generally used in gold mining) were also detected at Bantako and Tinkoto villages. Furthermore, previous studies [11] had found high concentrations in the well waters in the two villages.

The presence of arsenic in low contents in the wells at Bantako and Tinkoto villages, shows that gold mining influences the water quality because this toxic element is often associated with gold ore. The total absence of Hg in the waters at the reference stations and in Sabodala is an important observation because it confirms that, this anthropogenic origin linked to ASGM since mercury is not used in industrial mining. In our study, high content level of 9.3 $\mu g \cdot L^{-1}$ was observed at Bantako one of the biggest ASGM site. [11] confirmed that the presence of mercury in the waters at all ASGM villages in eastern Senegal, especially

Figure 6. Exposure of the well in the Tinkoto village to wash water contamination.

Figure 7. Mercury amalgamation in artisanal mining site.

in Bantako, where the highest Hg concentration was measured (19 $\mu g \cdot L^{-1}$). These high Hg contents in the waters can be explained by the fact that the village of Bantako remains one of the most active (and oldest) ASGM sites in the area with a very high human density. Furthermore, the results of [10] showed the state of contamination of certain environmental components (water and sediment) by Hg. Through on sediments and on human hairs samples, he showed that level of Hg contents was above the standard of Hg concentration in sediments at ASGM sites due to mercury use in amalgamation, which is common practice by ASGM operators as showed in **Figure 7**. These high concentrations do not spare any of the environment component, favoring thus, the concentration of mercury in soils by direct discharge into the air by the combustion of amalgam, but also in surface water as well as groundwater, either by direct discharge or by contaminated soil leaching, and animal and plant species (fish for example) by bio accumulation.

5. Conclusions

The objective of this study was to assess the water quality in the gold mining area of southeastern Senegal using a water quality index developed specifically for this area. This tool, which we are introducing in this part of Senegal and French-speaking Africa, has proved to be very simple and useful because it makes it possible to convert multiple parameters into comprehensible information for initiated or secular public.

Of course, the use of any water quality index leads to a loss of information, just as it does not make it possible to evaluate quality for all uses. A quality index is therefore developed for a specific area because, from one area to another, the parameters to be considered, the natural geochemical background and the types of dominant pollutants may vary.

In the case of the southeastern Senegal, in the Sabodala area, the parameters considered in the calculation of our WQI reflect perfectly the quality of the groundwater and show bad water quality index in some wells and boreholes.

Therefore, consumption in long term of the contaminated well waters due to the relatively high turbidity, NO_3 and trace elements, could cause health effects especially in ASGM villages such as Bantako and Tinkoto.

Acknowledgements

The authors of this paper sincerely thank the Environmental Managers of the Endeavour Mining company in Senegal, namely Messrs Maguatte Ndiaye, Babacar Diouf, Charles Pierre Sarr, Franck Atte Kouassi and Mamoudou BOCOUM as well as Mr Fallou Ndiaye IT specialist for the scientific contribution they have brought us. We appreciate their contribution and assistance.

Funding

This work has received financial and logistic support from Endeavour Mining/

Sabodala Gold Operations and Barrick Gold Corporation Senegal.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Jiang, Y., Lin, W., Wu, M., Liu, K., Yu, X. and Gao, J. (2022) Remote Sensing Monitoring of Ecological-Economic Impacts in the Belt and Road Initiatives Mining Project: A Case Study in Sino Iron and Taldybulak Levoberezhny. *Remote Sensing*, **14**, 3308. https://doi.org/10.3390/rs14143308

[2] Hirons, M., Hilson, G., Asase, A. and Hodson, M.E. (2014) Mining in a Changing Climate: What Scope for Forestry-Based Legacies? *Journal of Cleaner Production*, **84**, 430-438. https://doi.org/10.1016/j.jclepro.2013.11.025

[3] Kobayashi, H., Watando, H. and Kakimoto, M. (2014) A Global Extent Site-Level Analysis of Land Cover and Protected Area Overlap with Mining Activities as an Indicator of Biodiversity Pressure. *Journal of Cleaner Production*, **84**, 459-468. https://doi.org/10.1016/j.jclepro.2014.04.049

[4] Murguía, D.I., Bringezu, S. and Schaldach, R. (2016) Global Direct Pressures on Biodiversity by Large-Scale Metal Mining: Spatial Distribution and Implications for Conservation. *Journal of Environmental Management*, **180**, 409-420. https://doi.org/10.1016/j.jenvman.2016.05.040

[5] Hodge, R.A. (2014) Mining Company Performance and Community Conflict: Moving beyond a Seeming Paradox. *Journal of Cleaner Production*, **84**, 27-33. https://doi.org/10.1016/j.jclepro.2014.09.007

[6] Aragón, F.M. and Rud, J.P. (2013) Natural Resources and Local Communities: Evidence from a Peruvian Gold Mine. *American Economic Journal*: *Economic Policy*, **5**, 1-25. https://doi.org/10.1257/pol.5.2.1

[7] Loayza, N. and Rigolini, J. (2016) The Local Impact of Mining on Poverty and Inequality: Evidence from the Commodity Boom in Peru. *World Development*, **84**, 219-234. https://doi.org/10.1016/j.worlddev.2016.03.005

[8] Lechner, A.M., Chan, F.K.S. and Campos-Arceiz, A. (2018) Biodiversity Conservation Should Be a Core Value of China's Belt and Road Initiative. *Nature Ecology & Evolution*, **2**, 408-409. https://doi.org/10.1038/s41559-017-0452-8

[9] Bamba, Y. (2012) Evaluation des impacts de l'exploitation de la mine d'or de Bonikro (Cote d'Ivoire) sur les ressources en eau. Mémoire de Master en Ingénierie de l'eau et de l'Environnement. Institut international d'ingénierie de l'eau et de l'environnement (IIEE), 55 p.

[10] Niane, B. (2014) Impacts environnementaux liés à l'utilisation du mercure lors de l'exploitation artisanale de l'or dans la région de Kédougou (Sénégal oriental). Thèse de doctorat ès Sciences Mention Sciences de la Terre, Université de Genève, Genève, 110 p.

[11] Mall, I. (2017) Evaluation des ressources en eau dans le Sénégal oriental: Apports des outils Géochimiques, Géostatistiques, de la Télédétection et des SIG. Thèse de doctorat de l'Université Cheikh Anta Diop de Dakar, Dakar, 232 p.

[12] Lobo, F. (2015) Spatial and Temporal Analysis of Water Siltation Caused by Artisanal Small-Scale Gold Mining in the Tapajós Water Basin, Brazilian Amazon: An Optics and Remote Sensing Approach. Ph.D., University of Victoria, Victoria.

[13] Lobo, F.D.L., Costa, M., Novo, E.M.L.d.M. and Telmer, K. (2016) Distribution of Artisanal and Small-Scale Gold Mining in the Tapajós River Basin (Brazilian Amazon) over the Past 40 Years and Relationship with Water Siltation. *Remote Sensing*, **8**, 579. https://doi.org/10.3390/rs8070579

[14] Aranguren, S. and Miguel, M. (2008) Contamination en métaux lourds des eaux de surface et des sédiments du Val de Milluni (Andes Boliviennes) par des déchets miniers. Approches géochimique, minéralogique et hydrochimique. Thèse de doctorat de l'Université de Toulouse, Toulouse, 381 p.

[15] Boah, D.K., Twum, S.B. and Pelig-Ba, K.B. (2015) Mathematical Computation of Water Quality Index of Vea Dam in Upper East Region of Ghana. https://doi.org/10.12988/es.2015.4116

[16] Tyagi, S., Sharma, B., Singh, P. and Dobhal, R. (2013) Water Quality Assessment in Terms of Water Quality Index. *American Journal of Water Resources*, **1**, 34-38. https://doi.org/10.12691/ajwr-1-3-3

[17] World Health Organization (2008) Guidelines for Drinking-Water Quality: Second Addendum. Volume 1, Recommendations. World Health Organization, Geneva.

[18] Pande, C.B., Moharir, K.N., Singh, S.K. and Dzwairo, B. (2020) Groundwater Evaluation for Drinking Purposes Using Statistical Index: Study of Akola and Buldhana Districts of Maharashtra, India. *Environment, Development and Sustainability*, **22**, 7453-7471. https://doi.org/10.1007/s10668-019-00531-0

[19] Kouadri, S., Pande, C.B., Panneerselvam, B., Moharir, K.N. and Elbeltagi, A. (2022) Prediction of Irrigation Groundwater Quality Parameters Using ANN, LSTM, and MLR Models. *Environmental Science and Pollution Research*, **29**, 21067-21091. https://doi.org/10.1007/s11356-021-17084-3

[20] Lakshmi, E. and Madhu, G. (2014) An Assessment of Water Quality in River Periyar, Kerala, South India Using Water Quality Index. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, **8**, 11-16. https://doi.org/10.9790/2402-08821116

[21] Nasirian, M. (2007) A New Water Quality Index for Environmental Contamination Contributed by Mineral Processing: A Case Study of Amang (Tin Tailing) Processing Activity. *Journal of Applied Sciences*, **7**, 2977-2987. https://doi.org/10.3923/jas.2007.2977.2987

[22] Boyacioglu, H. (2010) Utilization of the Water Quality Index Method as a Classification Tool. *Environmental Monitoring and Assessment*, **167**, 115-124. https://doi.org/10.1007/s10661-009-1035-1

[23] Khan, F., Husain, T. and Lumb, A. (2003) Water Quality Evaluation and Trend Analysis in Selected Watersheds of the Atlantic Region of Canada. *Environmental Monitoring and Assessment*, **88**, 221-242. https://doi.org/10.1023/A:1025573108513

[24] Mor, D. (2018) Etude des impacts de l'exploitation de l'or sur les ressources en eau dans le bassin du fleuve Gambie au niveau de Sabodala et environs. Mémoire de master en sciences de l'environnement, ISE/UCAD, 109 p.

[25] Théveniaut, H., Ndiaye, P.M., Buscail, F., Couëffé, R., Delor, C., Fullgraf, T. and Goujou, J.-C. (2010) Notice explicative de la carte géologique du Sénégal oriental à 1/500 000. Ministère des Mines, de l'Industrie, de l'Agro-Industrie et des PME, Direction des Mines et de la Géologie, Dakar.

[26] Mall, I., Moctar, D., Maguette, D.N., Diakher, M.H., Malick, N.P. and Serigne, F. (2015) Evaluation of Water Resources Quality in Sabodala Gold Mining Region and Its Surrounding Area (Senegal). *Journal of Water Resource and Protection*, **7**, 247-263. https://doi.org/10.4236/jwarp.2015.73020

[27] Banda, T.D. and Kumarasamy, M.V. (2020) Development of Water Quality Indices (WQIs): A Review. https://doi.org/10.15244/pjoes/110526

[28] Horton, R.K. (1965) An Index Number for Rating Water Quality. *Journal of Water Pollution Control Federation*, **37**, 300-306.

[29] Sutadian, A.D., Muttil, N., Yilmaz, A.G. and Perera, B.J.C. (2016) Development of River Water Quality Indices—A Review. *Environmental Monitoring and Assessment*, **188**, Article No. 58. https://doi.org/10.1007/s10661-015-5050-0

[30] Poonam, T., Tanushree, B. and Sukalyan, C. (2013) Water Quality Indices-Important Tools for Water Quality Assessment: A Review. *International Journal of Advances in Chemistry*, **1**, 15-28.

[31] Paun, I., Cruceru, L.V., Chiriac, L.F., Niculescu, M., Vasile, G.G. and Marin, N.M. (2016) Water Quality Indices Methods for Evaluating the Quality of Drinking Water. In: 19*th INCD ECOIND International Symposium—SIMI* 2016, "*The Environment and the Industry*", ECOIND, Bucharest, 395-402.

[32] Abbasi, T. and Abbas, S.A. (2012) Water Quality Indices. Elsevier, Amsterdam, 353. https://doi.org/10.1016/B978-0-444-54304-2.00016-6

[33] Boyacioglu, H. (2007) Development of a Water Quality Index Based on a European Classification Scheme.

[34] Brown, R.M., McClelland, N.I., Deininger, R.A. and O'Connor, M.F. (1972) Water Quality Index—Crashing the Psychological Barrier. *Proceedings* 6*th Annual Conference*, Jerusalem, 18-23 June 1972, 787-794. https://doi.org/10.1016/B978-0-08-017005-3.50067-0

[35] Chatterjee, C. and Raziuddin, M. (2002) Determination of Water Quality Index of a Degraded River in Asanol Industrial Area, Raniganj, Burdwan, West Bengal. *Nature*, *Environment and Pollution Technology*, **1**, 181-189.

[36] Rubio-Arias, H., Ochoa-Rivero, J., Quintana, R., *et al.* (2013) Development of a Water Quality Index (WQI) of an Artificial Aquatic Ecosystem in Mexico. *Journal of Environmental Protection*, **4**, 1296-1306. https://doi.org/10.4236/jep.2013.411151

[37] Bascaron, M. (1979) Establishment of a Methodology for the Determination of Water Quality. *Boletín Informativo Medio Ambiente*, **9**, 30-51.

[38] CCME (2001) Canadian Water Quality Guidelines for the Protection of Aquatic Life. CCME Water Quality Index 1.0, User's Manual, Winnipeg.

[39] Cude, C.G. (2001) Oregon Water Quality Index: A Tool for Evaluating Water Quality Management Effectiveness. *JAWRA Journal of the American Water Resources Association*, **37**, 125-137. https://doi.org/10.1111/j.1752-1688.2001.tb05480.x

[40] Malistani, H.A., Jawadi, H.A., Sidle, R.C., Khawary, M. and Khan, A.A. (2022) Water Resources and Water Quality Assessment, Central Bamyan, Afghanistan. *Water*, **14**, 3060. https://doi.org/10.3390/w14193060

[41] Diouf, S. (1999) Hydrgéologie en zone de socle cristallin et cristallophyllien du Sénégal oriental. Application de la méthode électrique 1D et 2D à la localisation et à la caractérisation des aquifères du batholite de Saraya et ses environs. Thèse de doctorat de 3ecycle, Univ. C.A.D. de Dakar, Dakar, 159 p.

[42] Yoboue, K.K.M. (2017) La question de la remédiation environnementale résultant de l'exploitation artisanale, à petite échelle du diamant: Cas de l'Union du Fleuve Mano. Thèse de doctorat de l'Université de Toulouse, Toulouse, 278 p.