



Cumulative Uncertainty in Measured Groundwater Iron Content of Rigasa Watershed, Kaduna

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Authors' contributions

This work was carried out in collaboration between all authors. Author OSO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author CNO managed literature searches. Authors OSO, CNO and MON managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Fresh water quality has become the principal limitation for sustainable development in many countries and the major human and environmental health dimensions of the global fresh water quality problem is constituted in numerous effects of water borne diseases. Therefore, the assessment of water quality, its management and regulation rely on the water quality data. The aim of this paper is to establish the measurement uncertainty in groundwater quality data in Rigasa Watershed Area in the north-west of Kaduna Metropolis. Measurement uncertainty results from the water quality data monitoring methods. When uncertainty is not considered in measurements it results in un-optimized monitoring projects, unsustainable water resources development and management, and lack of ecosystem security considering their cost-effectiveness and data quality when measurement uncertainty and alternatives to reduce uncertainty are not included in the projects design and implementation. Water quality assessment of the boreholes in Rigasa Watershed was carried out for a period of 12 months to portray the regimes of the phenomena and

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establish the uncertainty in the measured data. Iron content among the various parameters measured in the boreholes water was found to be in excess of the required limits by the World Health Organization (WHO) and thus formed the focus of this paper. The measurement result showed that the Fe content in groundwater sample was 3.189 mg/l, with the expanded uncertainty measurement ± 1.482 mg/l (coverage factor, $k = 2$, at confidence level 95%). The significant uncertainties showed that the measured values were largely spread around the mean values of the measurand.

Keywords: Groundwater; measurand; measurement; uncertainty; watershed.

1. INTRODUCTION

The assessment of water quality, its management, and regulation relies on the measured water quality data, of which very little information is available on one very important component of the measured data - the inherent measurement uncertainty. It is certain that all measurements are uncertain to some degree; the uncertainty in measured data is thereby rarely if not completely not estimated and ignored and numerous benefits of the information are often not realized [1,2].

Measurements are always being carried out without the consideration of the quality of the data obtained resulting in un-optimized monitoring projects, unsustainable water resources development and management, and lack of ecosystem security considering their cost-effectiveness and data quality when measurement uncertainty and alternatives to reduce uncertainty are not included in the projects design and implementation [3,4]. The process of measurement involves direct or indirect comparison with a standard, which is accomplished by making the phenomenon of interest interact with a measuring instrument capable of producing a value that is responsive to the property of interest. If the instrument has been calibrated, then the value that it produces is meaningful in relation with a relevant standard [5].

Measurement uncertainty is a general concept associated with any measurement and can be used in professional decision processes as well as judging attributes in many domains, both theoretical and experimental. It plays a central role in quality assessment and quality standards and can be estimated by some statistical analysis and other information about the measurement process. A statement of measurement uncertainty is indispensable in judging the fitness for purpose of a measured quantity value. When the uncertainty in a

measurement is evaluated and stated, the fitness for purpose of the measurement can be properly judged [6].

Harmel et al. [7] discussed the uncertainty inherent in measured water quality data, which is introduced by four procedural categories: streamflow measurement, sample collection, sample preservation/storage, and laboratory analysis. With valuable information on relative differences in procedures within these categories, little information is available that compares the procedural categories or presents the cumulative uncertainty in resulting water quality data. As a result, quality control emphasis is often misdirected, and data uncertainty is typically either ignored or accounted for with an arbitrary margin of safety.

Also, Harry, et al. [8] carried out an evaluation of uncertainty measurement in the determination of Fe content in powdered tonic food drink using graphite furnace atomic absorption spectrometry. The specification of measurand, source of uncertainty, standard uncertainty, combined uncertainty and expanded uncertainty from this measurement were evaluated and accounted.

Uncertainty of measurement (defined as random statistical variations – Harmel, et al. [7] is usually introduced into the measured data through sample collection, sample handling, processing, management and reporting procedures. Data was collected in Rigasa Watershed Area for 12 consecutive months from boreholes and wells to determine the concentration of pollutants in the waters. Out of 20 parameters evaluated in the waters, the iron content was the most in excess of the WHO standard. The estimation of the uncertainties lying in this set of measured groundwater data from boreholes in Rigasa watershed is the subject of this paper. The methodology used is based on the quality of the data and the sources of uncertainty in the data. It also describes and summarizes current scientific understanding of an uncertainty estimation

method and estimate the uncertainty in the measured data on Rigasa Watershed Area.

2. MEASUREMENT AND SOURCES OF UNCERTAINTY

Any measurement aims at providing information consisting of a number and a unit of measurement about a quantity of interest known as measurand, which depends on the measuring system, measurement procedure, skill of the operator, the environment, and other effects [9].

Measurement uncertainty is a concept associated with any measurement and can be used in professional and decision processes as well as judging attributes in many domains theoretically and experimentally [6]. It concerns the quality of measurement and represents the doubt that exists about the result of the measurement. The "Guide to the Expression of Uncertainty in Measurements" (GUM) defines measurement uncertainty as a "parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [10]. The VIM [11] also defines it as a "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used". Harmel, et al. [7] ascertained that uncertainty arises because of an imperfect representation of the physical, chemical, and biological characteristics of the real world, because of numerical approximations, inaccurate parameter estimates, and data input. Uncertainty of measurements becomes important simply because making good quality measurements and to understand the results is always desired.

Water quality procedures are grouped into some four categories as sample collection, sample preservation and storage, laboratory analysis, and data processing and management [7,12] by which uncertainty is introduced into the measured data. Missing values assumption in estimating the missing values, and mistakes in data management reporting can also contribute uncertainty into measured data [12].

It is also indicated that low ambient concentration and transformation potentials can introduce significant uncertainty in dissolved and total nutrient concentrations [13]. But carefulness in the care of the samples with the knowledge of changes that might occur in physical, chemical, and biological characteristics was observed and thus might reduce uncertainty. Data processing

and management procedural category can account for uncertainty introduced by missing and/or incorrect data, which can result from instrument failure, data entry and processing mistakes, misplaced samples, and inadequate volume each of which can be either equipment malfunction or personnel mistakes. Hence, uncertainty from data processing and management can be low or very high depending on the number of missing or incorrect data values. The potential for high uncertainty due to missing/incorrect data emphasize the importance of frequent preventive maintenance, adequate personnel training, and attention to details to minimize uncertainty in data processing and management.

Gemma and Charles (2004) used water quality model DUFLOW to simulate discharge and water quality variables in the Dender River. The model was calibrated to the available water quality measurements. They obtained a reasonable fit between the measurements and the simulation results by trial and error. They also found that many uncertainties are associated with the development and calibration of the models, which affects the models prediction.

Sensitivity analysis is a technique used in determining how different values of an independent variable will influence a particular dependent variable under different scenarios. It is very useful when attempting to determine the impact the actual outcome of a particular variable will have if it differs from what was previously assumed. By creating a given set of scenarios, the analyst can determine how changes in one variable(s) will impact the target variable.

It is said to be the study of how the uncertainty in the output of a mathematical model or system can be apportioned to different sources of uncertainty in its inputs; the process of recalculating outcomes under alternative assumptions to determine the impact of variable under analysis. It can be computed using regression analysis involves fitting a linear regression to the model response and using standardized regression coefficients as direct measures of sensitivity (Gemma and Charles, 2004; [14,15]).

2.1 Study Area

Rigasa Watershed Area (RWA) is situated within Kaduna River Basin in the Hydrological Area II of Nigeria between latitude 10° 29'N and 10° 36'N and longitude 7° 21'E and 7° 26'E on the north-

western part of Kaduna Metropolis covering an area of about 9,946.66 ha (Fig. 1) [16]. The area has typical Savannah climate with distinct rainy season and the dry season with average annual rainfall of about 1194.7 mm [17]; mean annual evapotranspiration of about 1500 mm, and maximum temperature of about 40°C around March/April and the minimum of about 15.6°C during the harmattan in January. Rigasa River and its two main tributaries - River Gora and Mashi River with the dams at the Nigerian Airforce Base and College of Agriculture and Animal Science form the drainage system (Fig. 2). The maximum flow of the Rigasa River occurred between August and October and minimum flow between December and March in the year [17].

3. MATERIALS AND METHODS

3.1 Materials Used

The material used in the measurement included the following Wagtech instruments:

- a. Photometer 7100 to perform physico-chemical measurements;
- b. Conductivity meter measured Electrical Conductivity (Ec) and Total Dissolved Solids (TDS);

- c. pH meter (pH-RT for measuring pH of the water samples; and
- d. Turbidity meter.

3.2 Methods

The parameters judging the boreholes' water quality in Rigasa Watershed were measured on weekly basis during the study period within a monitoring network designed for the watershed area to monitor selected wells/boreholes. As environmental pollution effects can be really damaging, water pollution can cause lots of health problems including all sorts of water-borne infections, vomiting and stomach aches, and malfunction of the central nervous system among others (Irina, 2012).

3.3 Selection of Parameter

As eutrophication, acidification, and emission dispersion are environmental problems to water quality, chemical and biological intrusions are also detrimental to groundwater quality. Hence, selection of the most important water quality parameter has to be made with regard to certain aspects. Among the water quality constituents in Table 1, iron content is most significant and selected for consideration in this study (Table 2). Table 2 presents the average values of the iron content in the wells/boreholes at the locations in the measurement period.

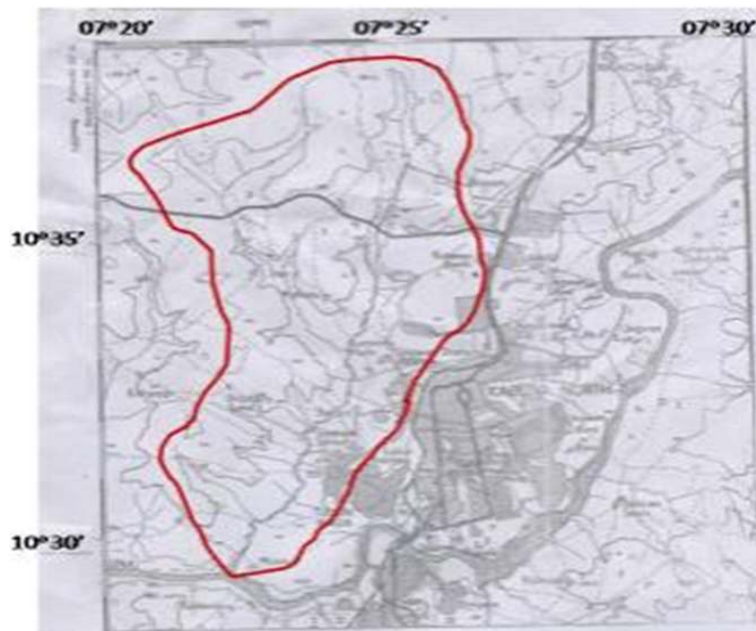


Fig. 1. Location of the study area. (Source: Owolabi and Nwude, 2015 [16]) Google earth, 2015

Table 1. Summary of the water quality parameters

No	Parameters	Abbreviation	Unit	No	Parameters	Abbreviation	Unit
1	pH	pH		10	Total Hardness	Thd	mg/l
2	Electrical Conductivity	Ec	us/cm	11	Chloride	Chl	mg/l
3	Total Dissolved Solids	TDS	mg/l	12	Iron	Fe	mg/l
4	Turbidity	Turb	NTU	13	Fluoride	Flo	mg/l
5	Temperature	Temp	°C	14	Chromium	Chr	mg/l
6	Salinity	NaCL	mg/l	15	Copper	Cop	mg/l
7	Nitrate	NO ₃	mg/l	16	Ammonia	Amo	mg/l
8	Alkalinity	Alk	mg/l	17	Potassium	Pot	mg/l
9	Sulphate	Sul	mg/l	18	Magnesium	Mag	mg/l

Table 2. Iron concentration in the water samples

Location	Nariya 2	Nariya bridge	Dan mani	Farin gida 1	Farin gida 2	Tudun wada 1	Tudun wada 2	Kabala west 1	Kabala west 2	Angwan muazu 1	Angwan muazu 2	Angwan muazu 3	Angwan muazu 4	Rigasa 1	Rigasa 2	Rigasa 3	Panteka	Mean
Iron	5.1	4.7	0.45	0.65	0.9	0.5	0.4	4.55	0.4	7.8	1.1	5.25	8.8	0.65	1.15	7.6	4.15	3.19

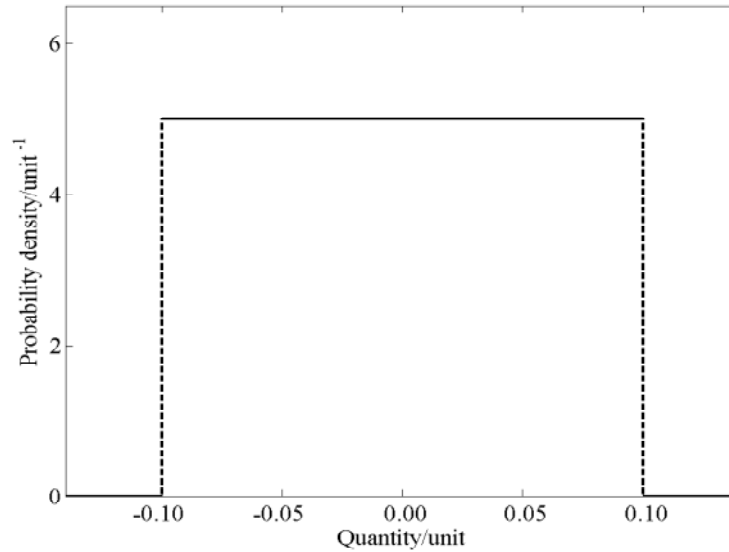


Fig. 2. Rectangular probability distribution with limits 0:1 units and -0.1:0.1 units

Iron in water imparts a disagreeable metallic taste. It causes red stains materials. As little as 0.3 ppm of iron can cause these problems. Iron can exist in water in one of two forms or both. Waters containing "ferrous iron" are clear and colorless when drawn and when exposed to air it converts into the insoluble, reddish brown "ferric iron" [18].

3.4 Propagation of Uncertainty

The measurand is the particular quantity considered for measurement. The output quantity Y depends upon a number of input quantities X_i ($i = 1, 2, \dots, N$) according to the functional relationship;

$$Y = f(X_1, X_2, \dots, X_N)$$

The model function f represents the procedure of the measurement and the method of evaluation. The set of input quantities X_i may be grouped in the two categories:

- (a) quantities that are directly measured and
- (b) quantities whose estimates are brought into the measurement from external sources.

The root mean square error propagation method of Topping [19], shown in equation 1, was used to estimate the cumulative probable uncertainty for each procedural category (sample collection, sample preservation/storage, laboratory analysis, and data processing and management) and for the overall resulting water quality data:

$$E_p = \sqrt{\sum_{i=1}^n (E_1^2 + E_2^2 + E_3^2 + \dots E_n^2)} \quad (1)$$

Where

E_p = probable range in error ($\pm\%$)

n = total number of sources of potential error

E_1, E_2, E_3 = potential sources of error ($\pm\%$).

The method is a widely accepted method that has been used for similar error calculations related to water quality constituents and it combines all of the potential errors to produce realistic estimates of overall error. It is valid for measured water quality data because potential errors are typically bi-directional and non-additive [20]. Other statistical methods are available but their applications require procedure specific distributional information, which is limited for water quality measurement [12].

3.5 Type B Evaluation of Standard Uncertainty

According to EA [21], this "refers to the estimation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty. The Type B evaluation of standard uncertainty is the method of the uncertainty associated with an estimate x_i of an input quantity X_i by means other than the statistical analysis of a series of observations. The standard uncertainty $u(x_i)$ is

evaluated by scientific judgment based on all available information on the possible variability of X_i ."

Type B evaluation of standard uncertainty can be as reliable as a Type A evaluation of standard uncertainty, especially in a measurement situation where a Type A evaluation is based only on a comparatively small number of statistically independent observations. Thus, the following cases are considered:

- (a) When only a single value is known for the quantity X_i , e.g. a single measured value, a resultant value of a previous measurement, a reference value from the literature, or a correction value, this value will be used for x_i . The standard uncertainty $u(x_i)$ associated with x_i is to be adopted where it is given. Otherwise it has to be calculated from unequivocal uncertainty data. If the number of observations cannot be increased, a different approach to estimation of the standard uncertainty given in b) has to be considered.
- (b) When a probability distribution can be assumed for the quantity X_i , based on theory or experience, then the appropriate expectation or expected value and the square root of the variance of this distribution have to be taken as the estimate x_i and the associated standard uncertainty $u(x_i)$, respectively.

The only available information is that X lies in a specified interval $[a;b]$. In such a case, knowledge of the quantity can be characterized by a rectangular probability distribution [9].

When only upper and lower limits l_2 and l_1 can be estimated for the value of the quantity X_i , a probability distribution with constant probability density between these limits (rectangular probability distribution) has to be assumed for the possible variability of the input quantity X_i . According to case (b) above this leads to:

$$x_i = \frac{1}{2}(l_2 + l_1) \text{ for the estimated value;}$$

$$u^2(x_i) = \frac{1}{12}(l_2 - l_1)^2 \text{ for the square of the standard uncertainty.}$$

If the difference between the limiting values is denoted by $2l$; therefore,

$$u^2(x_i) = \frac{1}{3}l^2.$$

Therefore;

$$u(x_i) = \frac{l}{\sqrt{3}} \tag{2}$$

l provides the average of the upper and lower limits of measurements.

The rectangular distribution is a reasonable description of one's inadequate knowledge about the input quantity X_i in the absence of any other information than its limits of variability.

4. RESULTS

Monitoring of water bodies is primarily done to detect the status and trends in water quality and to identify whether observed trends arise from natural or anthropogenic causes. Empirical quality of water quality data is rarely certain and knowledge of their uncertainties is essential to assess the reliability of water quality models and their predictions. Some sources of uncertainty were identified in the process of the groundwater monitoring and analysis. This consists of the uncertainties from the instrument calibration and resolution, under-estimation, sample collection, sample preservation and storage, laboratory analysis, and data processing and management.

The instrument used had uncertainty of ± 0.1878 state on the instrument calibration. The inherent uncertainty was determined by substituting 0.1878 in equation (3). Therefore,

$$u(x_i) = \frac{0.1878}{\sqrt{3}} = 0.1084.$$

Table 3 presents the uncertainty sources and their corresponding standard uncertainty values. The combined standard uncertainty of the measured range of concentrations of iron in the wells was estimated as;

$$U_c = \sqrt{\sum_{i=1}^n \{u(x_i)\}^2} \tag{3}$$

U_c is the uncertainty of the measurand, which is affected by the uncertainties of a number of measurements x_i in the propagation of the uncertainty [22,8].

Table 3. Well water quality uncertainty analysis

	Calibration uncertainty	Resolution	Under estimation	Sample collection	Storage	Laboratory analysis	Data processing	Estimated Sd uncert	Combined St uncert	Expanded uncertainty
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)		Us (mg/l)	Uc (mg/l)	Ue (mg/l)
Mean (m)	±0.10%	±1.0%	±0.2%	±3.0%	±1.3%	±2.0%	± 3.0%			k=2 at 95%
St. Dev.	3.185	0.188	0.0064							
St. Uncert for k = 1	0.0016	0.108	0.004	0.096	0.041	0.064	0.096	0.723	0.740	1.482

The measurement resulted to; 3.185 m/l ±1.482 mg/l

Table 4. Summary of the analysis of uncertainty (Uncertainty budget)

S/N	Source of uncertainty	Value +/-	Probability distribution	Divisor	Standard uncertainty
1	Calibration	0.0016	Normal	2	0.0008
2	Resolution of instrument (+/- 1%)	0.1084	Rectangular	1.732	0.0626
3	Under-/Over-estimation	0.0037	Rectangular	1.732	0.0021
4	Sample collection	0.0956	Rectangular	1.732	0.0552
5	Storage	0.0414	Rectangular	1.732	0.0239
6	analysis	0.0637	Rectangular	1.732	0.0368
7	Proc & Mgt	0.0956	Rectangular	1.732	0.0552
7	Standard uncertainty of the mean	0.7228	Normal	1	0.7228
8	Combined standard uncertainty		Assumed normal		0.7410
9	Expanded uncertainty		Assumed normal (k=2)		1.4820

The expanded uncertainty, U , defines an interval about the result of a measurement that may be expected to surround a large fraction of the values that could reasonably be attributed to the measurand. It serves as the most suitable quantitative indication of the quality of the result [9]. The expanded uncertainty, (U_{CF_e}) in the sample was obtained by multiplying the combined standard uncertainty by a coverage factor of 2 (at confidence level 95%) and also summarized in Table 4 as the uncertainty budget.

The results of the measurements in groundwater wells in Rigasa Watershed are produced as in Tables 3 and 4 assuming the uncertainties are non-uniformly distributed, independent, and in the absence of better information.

5. DISCUSSION

The most important uncertainty factors of water quality data are sampling and measurement or analytical uncertainties [12]. Sampling uncertainties can be categorized between uncertainties related to the selection of a representative sampling location, representative samples at a given location and the choice of an appropriate sample frequency. The choice of a sampling location may have considerable impact on the measured concentration of a given variable [4]. The error in measured values is composed of errors from a number of sources as used in the calculations; measurement process, sampling, storage/preservation, and data analysis. Measurement of iron in natural waters are uncertain because of the lability of the two states of oxidation of iron; ferrous iron (Fe^{2+}) is soluble and ferric iron (Fe^{3+}) is not [23].

Water samples were taken in selected wells/boreholes in the Rigasa Watershed area of Kaduna Metropolis and were analysed. Sources

of uncertainties were identified as sample collection, sample preservation and storage, data analysis, and data processing and management. The measurement result of the iron concentration in the well waters with the associated uncertainty was 3.189 mg/l \pm 1.482 mg/l. The analysis showed that both the combined and expanded uncertainties for the measurements were significant due to some abnormalities during the period of measurement. The reported expanded uncertainty is based on the product of the standard uncertainty and a coverage factor; $k = 2$, at 95% level of confidence. The probability incorporates all the information available about the measurand, and it is important to note that measured water quality data are uncertain, uncertainty increases without dedication, and collection of high quality data requires time, expenses, and personnel commitment (Stephanie, 2009; [12]). Also, the estimation of uncertainty in association with the measured data enhances monitoring design, decision making, scientific integrity, and model calibration and validation.

With the results and methodology presented, the water resources sector can better assess the uncertainty or "quality" of available data sets for use in water quality management. The information could be useful especially to the water quality modelers, allowing them to make realistic, science-based evaluations of model performance based on the uncertainty present in calibration and evaluation data sets. Policy, regulatory, research, and legal interests will have a quantified confidence in the result to make appropriate decisions.

6. CONCLUSION

All measured data are uncertain to some extent resulting from various data collection procedures,

which can be categorized as sample collection, sample preservation and storage, sample analysis and data processing and management. However, uncertainty from these sources was not estimated or included in the presentation of the measured data. The estimation of uncertainty measurement in the determination of iron (Fe) concentration in the groundwater within Rigasa Watershed of Kaduna was carried out. The specification of measurand, source of uncertainty, standard uncertainty, combined uncertainty and expanded uncertainty from this measurement were evaluated and accounted. The uncertainty values obtained from the analysis showed variations from the mean of the measurement values. The iron concentration was 3.189 mg/l \pm 1.476 mg/l indicating a significant amount with a coverage factor; $k = 2$, at 95% level of confidence. Adequate awareness of measurement uncertainty in project operations would produce benefits in the assessment, planning, implementation, and progress assessment of the project. Negligence of this parameter also leads to errors in most aspects of the projects, excessive costs, confusion and frustration, and non-achievement of the project objectives.

Sensitivity analysis was found to be useful in determining how different values of an independent variable can influence a particular dependent variable under different scenarios especially in the water quality assessment; but could not be included in this study.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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