



# Calibration and ISO GUM Based Uncertainty of Conductivity and TDS Meters for Better Water Quality Monitoring

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**Abstract:** Water quality monitoring is of fundamental importance for health and environmental protection. Conductivity and the total dissolved substance (TDS) are two important water quality parameters. Their monitoring requires good calibration of the measuring equipment and correct assessment of the measurement uncertainty so that the water quality limits can be well judged. Though many published research articles include conductivity and TDS measurement results, there is no published ISO GUM approach for estimation of the uncertainty in the calibration measurement results. In this work, the linearity of a conductivity meter was established using three certified reference materials (CRMs) of 100, 500 and 1410.7  $\mu\text{S}/\text{cm}$  and then a one-point calibration using CRM of 1410.7  $\mu\text{S}/\text{cm}$  was carried out. The calibration method was validated by studying its accuracy, precision and bias. The method was found fit-for-the purpose and the uncertainty sources of calibration were identified and estimated based on ISO GUM. Then a standard solution of concentration 0.01M was prepared from high purity KCl to provide conductivity of 1411  $\mu\text{S}/\text{cm}$ . The corresponding TDS value of this solution was found 745 mg/L and its traceability to the SI units was achieved by weighing the mass of KCl using a calibrated balance and by measuring the volume of water using a calibrated measuring flask. This solution was used to perform a one-point calibration of a TDS meter then the meter was allowed to read the TDS 10 times and the uncertainty of the measurement results was estimated based on ISO GUM. The results obtained proved a very good calibration of both meters. An overall approach for estimation of the calibration uncertainty was developed, which will be very useful in water quality monitoring measurements.

**Keywords:** Conductivity, TDS, Calibration, Method Validation, ISO GUM Uncertainty

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## 1. Introduction

The increase in population, industrialization and use of fertilizers in agriculture in addition to the man-made activity has resulted in an increasing pollution of water with various harmful substances. Because of this, the quality of drinking water has to be checked in order to protect the population from many water-borne diseases [1, 2]. The different types of pollutants are introduced into the natural water by weathering

of rocks, leaching of soils and mining [3]. As a result, the conductivity of water is affected specially it is related to ten factors such as temperature, pH value, alkalinity, total hardness, calcium, total solids, total dissolved solids, chemical oxygen demand, and the concentration of chloride and iron in water. Conductivity is defined as the ability of a material to conduct an electric current [4]. It is widely

applied as an essential tool for water quality assessment and is measured by conductivity meters [5]. These meters can be calibrated at specified conductivity values provided by standard KCl solutions [6]. Conductivity and the total dissolved substance are correlated by the formula  $TDS = f \times EC$  where the constant  $f$  is in the range of 0.55 to 0.9 in most conductivity meters and varies according to the chemical composition of the ions dissolved in water [7-10]. These two water quality parameters are indicators of salinity level which make them very useful as one way of studying seawater intrusion [11-15]. The liquid capacity to conduct an electric charge depends on the dissolved ions concentrations, ionic strength, and temperature of measurements [16]. For accurate and traceable measurement results of conductivity and TDS, the meters used for measurements are to be calibrated using certified reference materials (CRMs). Calibration is defined as: operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication [17]. The calibration results can be claimed traceable to the SI units if the uncertainty of the measurement results is estimated in accordance with requirements of ISO GUM [18]. On the other hand, traceability is defined as: property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [18]. In this paper, conductivity and TDS meters have been one-point calibrated and an approach to study and estimate the uncertainty sources of the calibration process has been developed based on ISO GUM. The developed approach will be very useful for water analytical laboratories in estimating their uncertainties in conductivity and TDS measurement results.

## 2. Materials and Methods

### 2.1. Chemicals

Potassium chloride (99.5-100.5%) was supplied by PanReac, Spain and ultrapure water was obtained by Millipore Milli-Q RG, USA. The certified reference materials (CRMs) of conductivity, 100, 500 and 1410.7  $\mu\text{S}/\text{cm}$  were obtained from the Slovak metrology institute, SMU.

### 2.2. Equipment

The conductivity and TDS meter used for measurements was a product of Mittler Toledo, model S230. The temperature controlled water bath used in calibration was supplied by IKA, Germany. Weighing the mass of KCl was carried out by an analytical balance with resolution 0.01 mg supplied by Mittler Toledo. The glass measuring flask used for preparation of the KCl standard solution was of class A.

## 3. Results and Discussion

### 3.1. The Standard Solution of KCl

Potassium chloride is one of the important chemicals used in the preparation of standard solutions for the calibration of the TDS and conductivity measuring instruments because it is highly soluble in water producing much ions. The TDS meters measure the electrical conductivity,  $k$  of aqueous solutions which is multiplied by a factor  $f$  to give the corresponding TDS [19]. In this work, a mass of KCl was heated in an oven at  $400^\circ\text{C}$  for two hours then left to cool to room temperature in a desiccator. After that, a standard solution of 0.01M KCl that has conductivity of 1411  $\mu\text{S}/\text{cm}$ , was prepared in a measuring flask by dissolving 186.37750 mg in 250 mL ultra-pure water. The preparation was made using equation 1.

$$C = \frac{m \times p}{V} \quad (1)$$

where,

$C$  - concentration of KCl in  $\text{mg}/\text{L}$ ;

$m$  - mass of KCl (mg);

$p$  - purity of KCl/100;

$V$  - volume of KCl solution (L).

### 3.2. Establishing Linearity of the Conductivity Meter

To measure conductivity of the KCl standard solution, linearity of the conductivity-meter was established using three CRMs of conductivities,  $99.91 \pm 0.3$ ,  $500.8 \pm 1.5$  and  $1410.7 \pm 2.8$   $\mu\text{S}/\text{cm}$  produced by the Slovak National Metrology Institute, SMU. The meter was calibrated by each CRM then was allowed to read it five times. The calibration line was plotted between conductivity values of the CRMs and the corresponding average response values as shown in Figure 1. From this figure it can be seen that  $R^2$  equals 1 indicating that the meter can give very good linear results in this range.

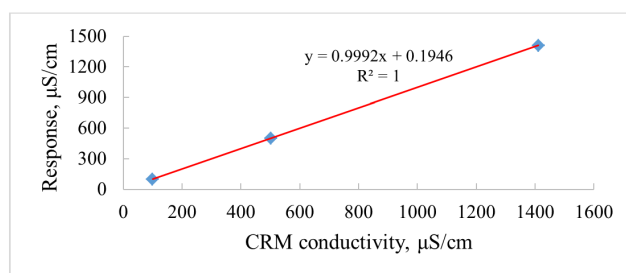


Figure 1. Calibration line of conductivity-meter using 3 CRMs.

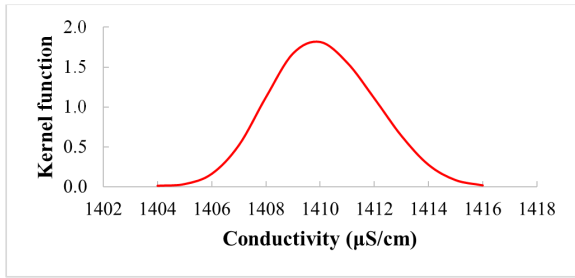
### 3.3. The One-Point Calibration of the Conductivity-Meter

The one-point calibration was performed at  $25^\circ\text{C}$  using a laboratory procedure then conductivity of the CRM solution was measured 10 times in order to verify if the calibration results lie within the uncertainty limits of the CRM. The results obtained, average, standard deviation and RSD% are shown in Table 1.

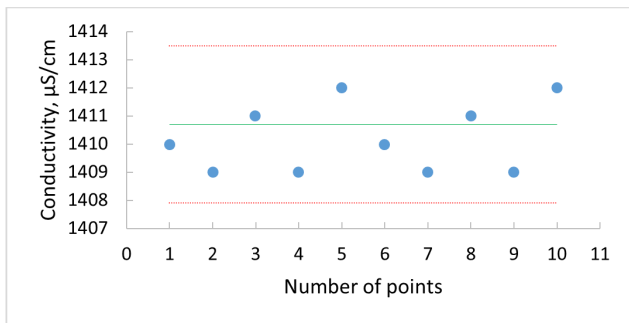
**Table 1.** Conductivity indications of the 1410.7  $\mu\text{S/cm}$ .

Conductivity ( $\mu\text{S/cm}$ )	1410 – 1409 – 1411 – 1409 – 1412- 1410 – 1409 – 1411 – 1409 – 1412
Ave	1410.2
SD	1.23
RSD%	0.09

These conductivity values were tested for outliers using Grubbs test and no outlier result was found. The normal distribution of the results was tested by the Kernel density function which showed a clear Gaussian distribution as it can be seen in Figure 2.

**Figure 2.** The normal distribution of the calibration results.

The conductivity values in Table 1 were plotted within the expanded uncertainty limits of the CRM ( $\pm 2.8 \mu\text{S/cm}$ ) as shown in Figure 3. In this Figure, the solid central line represents the conductivity value of the CRM (1410.7  $\mu\text{S/cm}$ ) and the dashed lines represent the upper and the lower uncertainty limits. It is clear that the 10 conductivity measured values lie within the uncertainty limits of the CRM confirming a strong traceability of the measurement results to the SI units.

**Figure 3.** CRM 1410.7  $\mu\text{S/cm}$  indications within the uncertainty limits.

### 3.4. Precision of the Method

Precision is defined as “closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions” [17]. In the ICH, it is mentioned that the RSD at 95% confidence limit is an indication on the precision of the method [20, 21]. Using data in Table 1, the RSD% was calculated by equation 2.

$$RSD\% = \frac{SD}{\bar{x}} \times 100 \quad (2)$$

where

RSD % - percentage relative standard deviation;

SD - standard deviation;

$\bar{x}$  - average of conductivity indications.

The obtained bias value, 0.035% was much smaller than the precision threshold (5%), indicating a very good precision of the one-point conductivity calibration method.

### 3.5. Accuracy of the Method

Accuracy is defined as: “closeness of agreement between a measured quantity value and a true quantity value of a measurand” [17]. Accuracy was calculated for each value using equation 3 and the results were reported in Table 2.

$$Accuracy\% = \frac{x_i}{x_{CRM}} \times 100 \quad (3)$$

**Table 2.** Accuracy results in case of the calibration by CRM 1410.7  $\mu\text{S/cm}$ .

$x_{CRM}$	Indication ( $x_i$ )	Accuracy %
1410.7	1410	99.95
1410.7	1409	99.88
1410.7	1411	100.02
1410.7	1409	99.88
1410.7	1412	100.09
1410.7	1410	99.95
1410.7	1409	99.88
1410.7	1411	100.02
1410.7	1409	99.88
1410.7	1412	100.09

From these results, it is clear that the calculated accuracy ranges from 99.88 to 100.09%, which means that the method produces a small measurement error giving rise to a very good accuracy of the calibration results.

### 3.6. The Method Bias

Bias is defined as: “average of replicate indications minus a reference quantity value”. Based on this definition, bias was calculated in percentage relative ( $b\%$ ) by equation 4 using the average value of the conductivity indications and the value of the CRM [17]. The average of indications was found 1410.2  $\mu\text{S/cm}$  and the bias was found 0.04% which is smaller than the pre-defined value, 0.5% assuring a good trueness of the calibration results produced by this method.

$$b(\%) = \frac{\bar{x} - x_{ref}}{x_{ref}} \quad (4)$$

where

$\bar{x}$  - average of conductivity indication;

$x_{ref}$  - conductivity of the CRM indicated in the certificate.

### 3.7. Uncertainty of the Conductivity Measurements

The estimation of uncertainty in measurements based on ISO GUM starts by writing the measurement model and identifying the uncertainty sources then quantifying uncertainty of each source [18]. Hence, the measurement

model of conductivity is defined by equation 5 [19].

$$k_{25} = \frac{k_T}{1 + \alpha (T - 25^\circ\text{C})} \quad (5)$$

where,

$k_{25}$  - conductivity at 25°C;

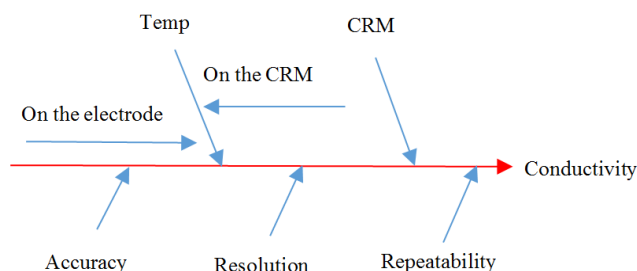
$k_T$  - CRM conductivity measured at temperature  $T$  °C;

$\alpha_{25}$  - temperature coefficient.

The temperature coefficient,  $\alpha$  can be calculated by equation 6 and was taken as 2%/K [19].

$$\alpha_{25} = \frac{1}{k_{25}} \left( \frac{k_T - k_{25}}{T - 25^\circ\text{C}} \right) \times 100 \quad (6)$$

From the model in equation 5, explicit sources of the uncertainty can be identified as: conductivity of the CRM and the effect of temperature on the CRM and on the measuring electrode. There are also implicit sources of uncertainty that come from accuracy and resolution of the conductivity-meter in addition to the repeatability of measurements. All the sources are illustrated in the fishbone structure shown in Figure 4.



**Figure 4.** Fishbone structure showing uncertainty sources in conductivity measurements.

### 3.7.1. Uncertainty from the Explicit Sources

#### (i). Reference Material (CRM)

The standard uncertainty,  $u_{CRM}$  can be calculated by dividing the expanded uncertainty provided in the certificate of the CRM by 2 according to equation 7.

$$u_{CRM} = \frac{U_{CRM}}{2} \quad (7)$$

#### (ii). Effect of Temperature on the CRM

Values of conductivity of the CRM were reported in the certificate at 20°C and 25°C. The differences in conductivity ( $\Delta_{EC}$ ) and in temperature ( $\Delta_T$ ) were calculated and the sensitivity coefficient ( $c_i$ ) was calculated by dividing ( $\Delta_{EC}$ ) by ( $\Delta_T$ ). The  $c_i$  was found  $20.6 \mu\text{S}\cdot\text{cm}^{-1}/^\circ\text{C}$  and was multiplied by the standard uncertainty  $u_{\theta}$  of the calibrated thermometer as in equation 8 to calculate the uncertainty due to the effect of temperature on the CRM. The obtained uncertainty was found  $\pm 0.11 \mu\text{S}/\text{cm}$ .

$$u_{T_{CRM}} = u_{(t \text{ thermometer})} \times c_i \quad (8)$$

#### (iii). Effect of Temperature on The Electrode of the Meter

The conductivity at the solution temperature,  $k_T$  (24.9°C)

was calculated from equation 9 and was found  $1409.9 \mu\text{S}/\text{cm}$  [19]. Then uncertainty due to the effect of temperature on the electrode was estimated as  $\pm 0.3 \mu\text{S}/\text{cm}$  resulting from the difference between conductivity at 25°C and conductivity at the solution temperature ( $k_T$ ) using equation 10.

$$k_T = k_{25} \times (1 + \alpha(T - 25)) \quad (9)$$

$$u_{T_{elect}} = k_{25} - k_T \quad (10)$$

The combined effect of the two temperature uncertainty contributions was calculated as  $\pm 0.309 \mu\text{S}/\text{cm}$  using equation 11 in which  $c_1$  and  $c_2$  are the sensitivity coefficients calculated as  $20.6 \mu\text{S}\cdot\text{cm}^{-1}/^\circ\text{C}$  and 1 respectively.

$$u_c(T) = \sqrt{(c_1 \cdot u_{T_{CRM}})^2 + (c_2 \cdot u_{T_{elect}})^2} \quad (11)$$

### 3.7.2. Uncertainty from the Implicit Sources

The implicit sources of uncertainty were combined and added as an uncertainty term ( $\Delta k$ ) so that its conductivity equals zero but it has an effect on the uncertainty [23, 24]. Thus the measurement model in equation 5 was modified to equation 12.

$$k_{25} = \frac{k_T}{1 + \alpha (T - 25^\circ\text{C})} + \Delta k \quad (12)$$

#### (i). Uncertainty of Resolution of the Conductivity-Meter

Value of the resolution was taken from manual of the conductivity meter and was divided by 2 to get the expanded uncertainty  $U_{\text{exp}}$ . Then the expanded uncertainty was divided by  $\sqrt{3}$  to get the standard uncertainty of the resolution ( $u_{\text{Resol}}$ ) according to equation 13 assuming a rectangular distribution.

$$u_{\text{Resol}} = \frac{\text{Resolution}}{2\sqrt{3}} \quad (13)$$

#### (ii). Uncertainty of Accuracy of the Conductivity-Meter

Accuracy was taken from manual of the conductivity meter as a percentage value and was divided by  $\sqrt{3}$  to get the standard uncertainty ( $u_{\text{Accu}}$ ) according to equation 14. The obtained result was multiplied by the value of the measured conductivity to get the uncertainty in ( $\mu\text{S}/\text{cm}$ ).

$$u_{\text{Accuracy}} = \frac{\text{Accuracy}\%}{\sqrt{3}} \quad (14)$$

#### (iii). Uncertainty Due to the Repeatability of Measurements

In the one-point calibration, conductivity of the CRM ( $1410.7 \mu\text{S}/\text{cm}$ ) was measured 5 times at 25°C and the uncertainty,  $u_{\text{rept}}$  was obtained by dividing the standard deviation of the mean by the square root of the number of measurements ( $n$ ) using equation 15.

$$u_{\text{rept}} = \frac{SD}{\sqrt{n}} \quad (15)$$

The combined standard uncertainty contributions of accuracy, resolution and repeatability was obtained by equation 16 in which  $c_1$ ,  $c_2$  and  $c_3$  are the sensitivity coefficients. Each of them equals 1 since they are expressed in the conductivity unit,  $\mu\text{S}/\text{cm}$ .

$$u_{\Delta k} = \sqrt{(c_1 \cdot u_{Acc})^2 + (c_2 \cdot u_{Resol})^2 + (c_3 \cdot u_{Rept})^2} \quad (16)$$

The results obtained of the three implicit sources of uncertainty were reported in Table 3.

### 3.7.3. The Combined Standard Uncertainty of the Conductivity Meter Calibration

In order to calculate the combined standard uncertainty, the model equation 12 was differentiated to derive the sensitivity coefficients shown in equations 17-19.

$$\frac{\partial k_{25}}{\partial k_T} = \frac{1}{\alpha (T - 25^\circ\text{C}) + 1} \quad (17)$$

$$\frac{\partial k_{25}}{\partial T} = -\frac{k_T \alpha}{(\alpha (T - 25) + 1)^2} \quad (18)$$

$$\frac{\partial k_{25}}{\partial \Delta k} = 1 \quad (19)$$

Using these sensitivity coefficients, the combined standard uncertainty,  $u_c$  was calculated using equation 20 and the obtained result was reported in Table 3.

$$u_c = \sqrt{\left(\frac{\partial k_{25}}{\partial k_T} \cdot u_{CRM}\right)^2 + \left(\frac{\partial k_{25}}{\partial T} \cdot u_T\right)^2 + \left(\frac{\partial k_{25}}{\partial \Delta k} \cdot u_{\Delta k}\right)^2} \quad (20)$$

Table 3. Uncertainty budget of the calibration of a conductivity-meter.

Quantity $X_i$	Estimate $x_i$	Standard uncertainty $u(x_i)$	Unit	Probability distribution	Sensitivity coefficient $c_i$	Contribution to the $u_i(y)$
CRM	1410.7	1.4	$\mu\text{S}/\text{cm}$	Normal	1.0002	1.40028
Effect of temperature	1410.7	0.304	$\mu\text{S}/\text{cm}$	Normal	-28.21	-8.57422
$\Delta k$ {	Resolution	0.29	$\mu\text{S}/\text{cm}$	Normal	1	4.122564
	Accuracy	4.07	$\mu\text{S}/\text{cm}$			
	Repeatability	0.58	$\mu\text{S}/\text{cm}$			
Combined standard uncertainty, $u_c$		9.62				
Expanded uncertainty, $U_{exp}$ ( $\mu\text{S}/\text{cm}$ )		19.23 (1.36%)				

### 3.7.4. The Expanded Uncertainty ( $U_{Exp}$ )

The expanded uncertainty was calculated by multiplying the combined standard uncertainty,  $u_c$  by a coverage factor  $k=2$  to provide a confidence level of about 95% according to equation 21.

$$U_{exp} = u_c \times k \quad (21)$$

### 3.7.5. Calibration of the TDS Meter Using the Prepared KCl Standard Solution

After the one-point calibration of the conductivity meter using a CRM of conductivity  $1410.7 \mu\text{S}/\text{cm}$ , the meter was reset to the TDS mode and was one-point calibrated by the standard solution of KCl. The calibrated meter was allowed to read TDS of the solution 10 times at  $25^\circ\text{C}$  and the results obtained were reported in Table 4.

Table 4. TDS of the KCl standard solution.

TDS (mg/L)	747 – 743 – 742 – 746 – 748 – 741 – 747 – 745 – 743 – 747
Ave	745
SD	2.47
RSD%	0.33

### 3.7.6. The TDS Calibration Uncertainty

The mathematical model used for calculation of the TDS is expressed in equation 22 [19]. From this model, the explicit sources of uncertainty can be identified as the conductivity ( $k$ ) and the factor  $f$ .

$$\text{TDS} = f \times k \quad (22)$$

In the meanwhile, the implicit sources of uncertainty are: the repeatability of measurements in addition to the inputs of concentration of the KCl solution (mass, purity and volume) as in equation 1. All these sources are shown in the fishbone structure given in Figure 5.

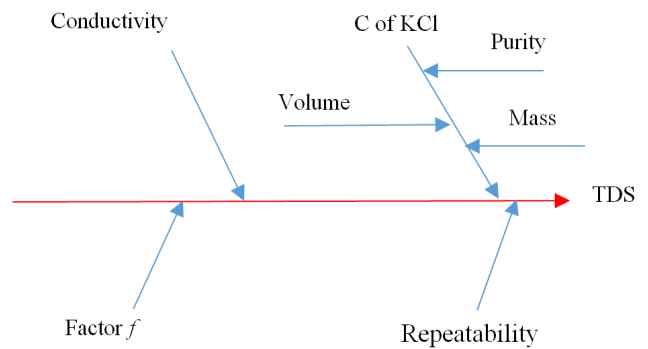


Figure 5. Fishbone structure showing uncertainty sources in TDS measurements.

The standard uncertainty of conductivity has been explained above and was found  $\pm 5.86 \mu\text{S}/\text{cm}$ . Uncertainty of the factor  $f$  ( $\text{TDS}/k$ ) was estimated as the standard deviation of the average of 5 determinations divided by  $\sqrt{5}$  and was found  $\pm 0.00082 \text{ mg.L}^{-1}/\mu\text{S.cm}^{-1}$ . The concentration of the prepared solution was calculated using the mathematical model in equation 1. From this model, the sources of uncertainty of the KCl solution concentration can be identified as: mass, purity and volume of the solution. The



uncertainty of each of them was estimated as described below.

### (i). Purity (*p*)

The purity of KCl provided by PanReac was 99.95-100.5% (i.e.  $100 \pm 0.5$ ) and its standard uncertainty  $u_p$  was obtained as  $\pm 0.0029$  by dividing the value 0.5% by  $\sqrt{3}$ .

### (ii). Mass (*m*)

The uncertainty associated with the mass of KCl was estimated using equation 23 where  $u_m$  is the mass of sample multiplied by a calibration factor quoted from the calibration certificate of the balance. The result was found  $\pm 0.0032$  mg

$$u(m) = \sqrt{2 \times (u_m)^2} \quad (23)$$

### (iii). Volume (*V*)

The uncertainty in the volume of water arises from three contributions: calibration, repeatability and temperature. The calibration certificate quotes the expanded uncertainty in volume of the flask used in the preparations of the KCl solution as:  $\pm 0.07$  mL. The standard uncertainty was obtained as  $U_{exp}/2$  ( $\pm 0.035$  mL). The effect of volume repeatability was estimated by ten fill and weigh experiments of the flask which gave a standard deviation of 0.024 mL. This was used directly as a standard uncertainty. Meanwhile, uncertainty of the temperature effect on volume of the flask was calculated from equation 24. Since the flask was calibrated at 20°C and the temperature variation in the laboratory was  $\pm 3^\circ\text{C}$ , the volume was multiplied by 3 and by the coefficient of volume expansion for water ( $2.1 \times 10^{-4}^\circ\text{C}^{-1}$ ).

$$u_T = (V) \times (\text{limit of } T \text{ variation}) \times (2.1 \times 10^{-4}) \quad (24)$$

The uncertainty of calibration, repeatability and temperature was combined to give the standard uncertainty of volume  $u_c$  (*V*) as  $\pm 3.46$  mL according to equation 25.

$$u_c(V) = \sqrt{(c_1 \cdot u_{cal})^2 + (c_6 \cdot u_{rept})^2 + (c_3 \cdot u_T)^2} \quad (25)$$

The combined standard uncertainty of the concentration of the prepared KCl solution resulting from the mass, purity and volume was estimated by equation 26 and was found  $\pm 4.08$  mg/L.

$$u_c = C \sqrt{\left(\frac{u_m}{m}\right)^2 + \left(\frac{u_p}{p}\right)^2 + \left(\frac{u_V}{V}\right)^2} \quad (26)$$

As for the implicit sources of uncertainty, a term  $\Delta_{TDS}$  including the uncertainty of the concentration of KCl and the repeatability of measurements was added to the model equation 22 in condition that its *TDS* equals zero but it has an uncertainty [23, 24]. Thus the model equation was modified to equation 27 and the combined uncertainty of both implicit sources was calculated according to equation 28 in which  $c_1$  and  $c_2$  are the sensitivity coefficients. Each  $c_i$  equals 1 since both uncertainties are expressed in the TDS unit, mg/L.

$$TDS = k \times f + \Delta_{TDS} \quad (27)$$

$$u_{\Delta TDS} = \sqrt{(c_1 \times u_{CRM})^2 + (c_2 \times u_{rept})^2} \quad (28)$$

In order to calculate the combined standard uncertainty in the *TDS* calibration results, equation 27 was differentiated to obtain the sensitivity coefficients given in formulas 29-31. Using these coefficients, the combined standard uncertainty,  $u_c$  was calculated by equation 32.

$$\frac{\partial TDS}{\partial k} = f \quad (29)$$

$$\frac{\partial TDS}{\partial f} = k \quad (30)$$

$$\frac{\partial TDS}{\partial \Delta TDS} = 1 \quad (31)$$

$$u_c = \sqrt{\left(\frac{\partial TDS}{\partial k} \cdot u_k\right)^2 + \left(\frac{\partial TDS}{\partial f} \cdot u_f\right)^2 + \left(\frac{\partial TDS}{\partial \Delta TDS} \cdot u_{\Delta TDS}\right)^2} \quad (32)$$

The expanded uncertainty was calculated using a coverage factor  $k=2$  to provide confidence level of approximately 95% according to equation 33.

$$U_{exp} = u_c \times k \quad (33)$$

The results obtained are shown in Table 5.

**Table 5.** Uncertainty budget of the calibration of a TDS-meter.

Quantity $X_i$	Estimate $x_i$	Standard uncertainty $u(x_i)$	Unit	Probability distribution	Sensitivity coefficient $c_i$	Contribution to the $u_i(y)$
conductivity	745	9.6	$\mu\text{S}/\text{cm}$	Normal	0.52	4.99
Factor <i>f</i>	0.52	0.00084	$\text{mg.L}^{-1}/\mu\text{S.cm}^{-1}$	Normal	1410.2	1.185
$\Delta_{TDS}$ { TDS Soln	0	3.46	mg/L	Normal	1	4.80
Repeatability		1.16	mg/L			
Combined standard uncertainty		7.05				
Expanded uncertainty ( $\mu\text{S}/\text{cm}$ )		14.09 (1.89%)				

The calculated expanded uncertainty in the concentration of the KCl solution ( $\pm 6.92$  mg/L) was added and subtracted from the average TDS (745 mg/L) shown in Table 4 to establish the uncertainty limits within which the measured TDS values were

plotted as shown in Figure 6. The figure shows that the 10 measured TDS values lie within the expanded uncertainty limits of the TDS of the KCl solution indicating a very good traceability of the calibration results to the SI units.

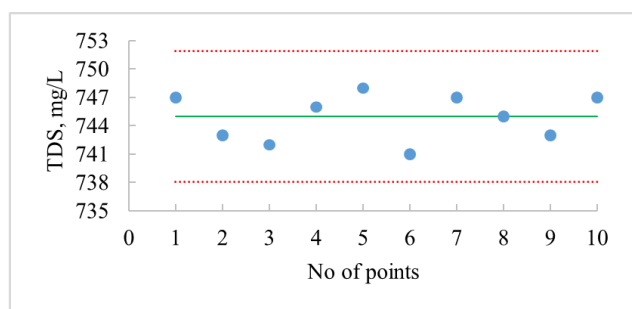


Figure 6. TDS indications within the uncertainty limits.

## 4. Conclusion

An approach for the assessment of uncertainty in the calibration results of conductivity and TDS meters has been developed in compliance with the requirements of ISO-GUM. The approach includes a clear description of the equations used and has resulted in very logic percentage uncertainties of 1.36% and 1.89% for conductivity and TDS respectively. This approach will be of very useful significance for water analytical laboratories which perform daily monitoring of water quality. Using this approach, they can produce realistic uncertainty figures necessary for judging the quality limits of water samples.

## Conflict of Interest

All the authors do not have any possible conflicts of interest.

## References

- [1] Adeyeye EI, (1994). Determination of heavy metals in *Illisha Africana*, associated water, soil Sediments from some fish ponds, International Journal of Environmental Study, 45, pp 231-240.
- [2] Patil P. N, Sawant D. V, Deshmukh R. N. (2012). Physico-chemical parameters for testing of water; A review, international journal of environmental sciences Volume 3, No 3.
- [3] Basavaraja S. M, Hiremath K. S, Murthy K. N, Chandrashekarappa, A. N, Patel E. T (2011); Analysis of Water Quality Using Physico-Chemical Parameters Hosahalli Tank in Shimoga District, Karnataka, India, Global Journal of Science Frontier, Research, 1 (3), pp 31-34.
- [4] Andres M, Maile P, Argo J. (2013). A new approach for describing the relationship between electrical conductivity and major anion concentration in natural waters; Applied Geochemistry 38 103–109.
- [5] Hem, J. D. (1989). The study and interpretation of the chemical characteristics of natural water, third ed. U.S. Geol. Surv. Water Supply Paper 2254.
- [6] Navneet, Kumar, D. K. S. (2010). Drinking water quality management through correlation studies among various physicochemical parameters: A case study, International Journal of Environmental Sciences, 1 (2), pp 253-259.
- [7] UNEP, (2004). Manual for National Training Programme. Malé Declaration on Control and Prevention of Air Pollution and Its likely Transboundary Effects for South Asia. United Nations Environment Programme. <http://www.rrcap.unep.org/male/>.
- [8] Patil P. N, Sawant D. V, and Deshmukh R. N, (2012). Physico-chemical parameters for testing of water - a review, Int. J. Environ. Sci. 3 1194–1207.
- [9] Marandi A, Polikarpus M and Jöeleht A (2013). A new approach for describing the relationship between electrical conductivity and major anion concentration in natural waters Appl. Geochemistry 38 103–109.
- [10] Daniels W L, Zipper C E, Orndorff Z W, Skousen J, Barton C D, McDonald L M and Beck M A (2016). Predicting total dissolved solids release from central Appalachian coal mine spoils Environ. Pollut. 216 371–379.
- [11] Moujabber, M. E, Samra B. B, Darwish T. and Atallah T. (2006). Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese coast Water Resour. Manag. 20 161–180.
- [12] Stigter T. Y, Ribeiro L. and Carvalho D. (2006). Application of a groundwater quality index as an assessment and communication tool in agro-environmental policies - Two Portuguese case studies J. Hydrol 327 578-891.
- [13] Nonner J. C (2015). Introduction to Hydrogeology (London: CRC Press, Taylor and Francis Group).
- [14] Han D., Kohfahl C., Song X., Xiao G. and Yang J. (2011). Geochemical and isotopic evidence for palaeo-seawater intrusion into the south coast aquifer of Laizhou Bay, China, Appl. Geochemistry 26 863-883.
- [15] Kumar S. K, Logeshkumaran A., Magesh N. S, Godson P. S. and Chandrasekar N. (2015). Hydrogeochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India Appl. Water Sci. 5 335–343.
- [16] Hem, D. (1985). Study and Interpretation the Chemical of Natural of Characteristics Natural Water 3rd edition USGS Water Supply Paper 2254 66-69 US Gov. Printing Office Washington DC.
- [17] JCGM 200 (2012). International vocabulary of metrology–Basic and general concepts and associated terms (VIM), 3<sup>rd</sup> edition.
- [18] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML (1993). Guide to the expression of uncertainty in measurement. 1<sup>st</sup> edition.
- [19] Elena H. and Christian W. (2015). Establishing a conversion factor between electrical conductivity and total dissolved solids in South African mine waters; Water SA Vol. 41 No. 4.
- [20] The International Council for Harmonization of Technical Requirements for Pharmaceuticals for Humane Use, ICH (2005). 3<sup>rd</sup> Ed.
- [21] EURACHEM, The Fitness for Purpose of Analytical Methods A Laboratory Guide to Method Validation and Related Topics (2014). 2<sup>nd</sup> Ed.
- [22] EURACHEM/CITAC Guide CG 4 Quantifying Uncertainty in Analytical Measurement (2012). 3<sup>rd</sup> Ed.

- [23] Leito, I., Strauss, L. Koort, E., Pihl, V. (2002). Estimation of uncertainty in routine pH measurement. *Accred Qual Assur*, 7: 242-249.
- [24] Shehata A. B, AlAskar A. R, AlDosari, R. A and AlMutairi F. R (2021). Uncertainty of Multipoint Calibration of pH-meters with Glass Electrode Used for Routine pH Measurements in the pH-mode; *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)*, Volume 10, Issue 12, December 2021.