Technical note

Geographical differences in the relationship between total dissolved solids and electrical conductivity in South African rivers

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ABSTRACT

Electrical conductivity (EC) is a useful surrogate for total dissolved solids (TDS). EC is more rapidly and easily measurable with reasonably-priced equipment. However, as an indirect measure EC is subject to uncertainties that are not always apparent to the user. We set out to investigate the relationship between TDS and EC in 144 643 sample results available on the Department of Water Affairs water quality database. TDS is calculated as the sum of the major solutes determined by laboratory analysis and EC is a measurement in a flow cell. The median TDS:EC ratio for 332 high priority sites was 7 mg/ℓ: 1 mS/m. Regional differences ranged from 4.8 to 8.6. Investigation of 38 of these sites using Maucha diagrams suggested that the differences are related to the dominant major ions, with sodium chloride waters having a lower TDS:EC conversion factor than calcium bicarbonate waters. The practical application of these findings is that users of EC meters should not simply apply a blanket conversion factor, but need to select an applicable factor for the river system in which they are measuring.

Keywords: conversion factors, electrical conductivity, field instruments, rivers, total dissolved solids, water quality

INTRODUCTION

Many water sector analysts routinely use total dissolved solids or salts (TDS) as a measure of water salinity. User agencies include agriculture, industry, water supply, mining and resource management. Guidelines or resource objectives for TDS help to maintain optimum production in each sector.

The units of measurement for TDS are usually milligrams per litre (mg/ℓ), grams per litre (g/ ℓ) parts per million (ppm) or parts per thousand (ppt or $^{o}/_{oo}$). Direct methods for determining TDS concentration are gravimetric, for example evaporation at 180°C (APHA, 1999), flow densitometry or determination of the major individual solutes by laboratory analysis and their algebraic summation (APHA, 1998). These methods are expensive and time consuming, and a much cheaper, easier and quicker method to infer TDS concentration is by measuring electrical conductivity (EC) using an EC meter and converting the value to TDS with a constant conversion factor. The use of EC to determine TDS in water is based on the principle that pure water is a poor conductor of electricity and the ability to conduct electricity increases linearly with increasing ion concentration. The TDS:EC ratio for natural inland waters varies from 5.4 to 9.6 mg/ℓ per mS/m, depending on the ionic composition and strength of the solution being tested, so that water containing mainly NaCl will have a ratio closer to 5, while water with a high sulphate content may have a ratio as high as 9.6 (Hem, 1985). Groundwater TDS:EC ratios in South Africa vary from <6 in the south-west to >8 in the north-east (Simonic, 2000). The South African Water Quality Guidelines assume a general conversion factor (CF) of 6.5 for TDS:EC, although it is recommended by the Guidelines that site-specific CFs be used where more accurate TDS concentrations are required (DWAF, 1996).

Many EC meters and loggers have an option to perform the conversion internally, presenting the user with a TDS reading that is no more than an estimate derived from the EC. The TDS:EC conversion factor may be based on measurement of a standard solution of, for example, KCl, or it may be the average of a number of TDS:EC ratios in samples where both measurements are known. South African water quality practitioners use this method extensively and the reliability of the approach, which we will refer to as the TDS:EC method, is the subject of this paper.

Although the TDS:EC method is capable of providing very accurate TDS concentrations, the use of a universal conversion factor can result in over- or underestimates. Users of EC meters need to follow certain basic procedures to ensure good representative TDS values, namely, proper calibration and maintenance, correct instrument use and application of the correct TDS:EC conversion factor. Personal observation of the activities of field personnel in the Department of Water Affairs suggests that instrument maintenance is acceptable but that personnel tend to apply the built-in TDS:EC conversion factor without consideration of the implications. Users of EC meters may assume that the standard instrument setting is correct, or they may not even be aware that an indirect measurement is taking place. Standard instrument settings for well-known conductivity meters used in South Africa vary between 5 and 7, depending on the make and model. An EC reading of 70 mS/m could therefore imply a TDS of 350 to 490 mg/ℓ, depending on the built-in conversion factor setting.

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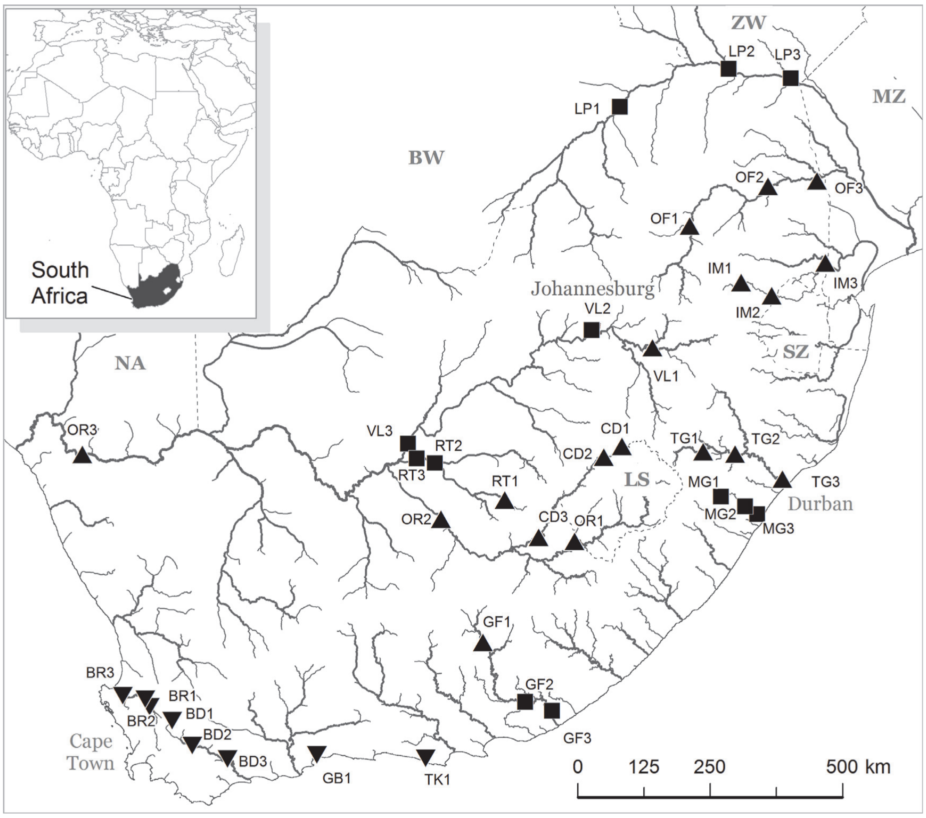

Figure 1
The 38 river monitoring sites for which detailed investigations of TDS:EC conversion factors were carried out. Site abbreviations and river names are in Table 1. Symbol codes for TDS:EC conversion factors in mg/ℓ per mS/m: ▼= 5.0–6.0; ■ = 6.1–7.0; ▲= 7.1–8.2.

METHODOLOGY

Monitoring sites

We calculated TDS:EC ratios for all 332 National Chemical Monitoring Programme (NCMP) priority river sites and examined in more detail a subset comprising 38 representative sites (Table 1, Fig. 1, Appendix A). Selection criteria were data availability and spatial coverage of major river systems. The Tsitsikamma and Groot Brak rivers have only a single monitoring site each, because of their short length.

EC data and units

The SI unit of conductivity is siemens per metre (S/m), although this unit is not commonly used. In this paper, we use millisiemens per metre (mS/m), although most field instruments report EC in millisiemens per centimetre (mS/cm) or microsiemens per centimetre (µS/cm). DWA uses mS/m as the standard EC unit of measurement (DWAF, 1996 and RQS, 2010). To avoid confusion when converting one unit to another the following rule can be applied: 1 mS/cm = 100 mS/m = 1 000 µS/cm. Using the wrong EC units can lead to confusion and the recording of erroneous results, with a potential error of several orders of magnitude (Table 2).

TDS data and units

All TDS data were sourced from the DWA water quality database and the measurement unit used in this paper is mg/ℓ. TDS concentration is calculated as the sum of the concentrations for Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, TAL, NO_3^-, F^-, PO_4^{3-} and NH_4^+ in a sample filtered through a 0.45 µm filter (RQS, 2006).

TABLE 1
The 3-character abbreviations and DWA station codes for the 38 sites referred to in this paper. Full descriptions of the sites are in the Appendix.

River	Upper reaches		Middle reaches		Lower reaches	
Limpopo	LP1	A5H006	LP2	A7H008	LP3	A91_189421
Olifants	OF1	B3H001	OF2	B7H007	OF3	B7H017
Komati	IM1	X1H018	IM2	X1H001	IM3	X2H036
Vaal	VL1	C1H012	VL2	C2H140	VL3	C9H024
Riet	RT1	C5H012	RT2	C5H014	RT3	C5H016
Orange	OR1	D1H009	OR2	D3H012	OR3	D8H003
Caledon	CD1	D2H012	CD2	D2H035	CD3	D2H036
Thukela	TG1	V1H001	TG2	V6H002	TG3	V5H002
uMngeni	MG1	U2H048	MG2	U2H055	MG3	U2H003
Great Fish	GF1	Q3H005	GF2	Q9H012	GF3	Q9H018
Tsitsikamma	TK1	K8H005				
Groot Brak	GB1	K2H002				
Breë	BD1	H1H003	BD2	H4H017	BD3	H7H006
Berg	BR1	G1H013	BR2	G1H031	BR3	G1H023

Samples where the cation-anion balance deviated by more than 10% were ignored.

Maucha ionic diagrams are a useful method for comparing water chemistry types (Maucha, 1932; Broch and Yake, 1969; Day and King, 1995). The Maucha diagram summarises the ratios of the major ions present in a water sample (Fig. 2).

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TABLE 2 Commonly-used TDS and EC units of measurement and their effect on the numerical range of the TDS:EC conversion factor (CF). The TDS concentrations are all the same, only the units differ.		
TDS	EC	CF
0.5 g/ℓ	1 000 µS/cm	0.0005
0.5 g/ℓ	100 mS/m	0.005
500 mg/ℓ	1 000 µS/cm	0.5
0.5 g/ℓ	1 mS/cm	0.5
500 mg/ℓ (ppm)	100 mS/m	5.0
500 ppm	100 mS/m	5.0
500 mg/ℓ	1 mS/cm	500

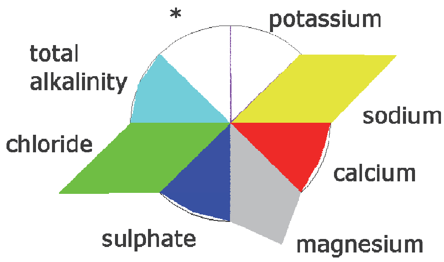


Figure 2
Maucha diagram (Maucha, 1932). The total area for the anions on the left balances that for the cations on the right. The original diagram has separate rays for bicarbonate and carbonate (*), collapsed into total alkalinity in this version. The colour-coding is arbitrary and facilitates comparison between symbols.

TDS:EC conversion factor calculation

The CFs were determined by calculating the TDS:EC ratios for individual samples and then calculating the median of all the individual ratios at that sight.

RESULTS AND DISCUSSION

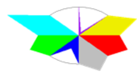
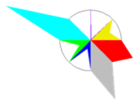
The median TDS:EC conversion factor (CF) for 144 643 samples from the 332 high priority river monitoring sites was 7.0, ranging from 4.8 to 8.6 for individual sites. The results for the 332 monitoring sites imply that using a standard instrument setting CF of 6.5 to convert EC to TDS can underestimate TDS by as much as 25% or overestimate it by up to 35%.

The results and discussions of 38 sites in 14 river systems are tabulated and grouped into 4 geographical units, namely, the major west-flowing river systems, the major east-flowing rivers, south-eastern coastal rivers and south-western coastal rivers (Tables 3–6). The median CF for the 18 363 samples from the 38 sites was 6.9, ranging from 5.0 to 8.0.

Major west-flowing rivers: Orange, Caledon, Vaal and Riet Rivers (Table 3)

The Orange-Caledon waters have a high total alkalinity, with an increase in the contribution of sodium, chloride and sulphate in the downstream reaches of the Orange River. Calculated CFs range from 7.1 to 7.8, so potential underestimates of TDS, when using a CF of 6.5, can vary from 9% in the lower Orange River to 17% in the upper Caledon River. The upper reaches of the Vaal and the Riet Rivers have higher CFs associated with the higher alkalinity. In both rivers, CFs decrease downstream, along with an increase in the proportion of sodium, chloride and sulphate. In the Riet River the underestimate in the derivation of TDS from EC varies from zero to 19%.

TABLE 3 Conversion factors and Maucha diagrams for the Orange, Caledon, Vaal and Riet River systems			
River	**Upstream**	**Middle**	**Downstream**
Orange	OR1: 7.8 	OR2: 7.6 	OR3: 7.1 
Caledon	CD1: 8.0 	CD2: 8.0 	CD3: 7.8 
Vaal	VL1: 7.5 	VL2: 6.9 	VL3: 6.8 
Riet	RT1: 8.0 	RT2: 6.9 	RT3: 6.5 

TABLE 4 Conversion factors and Maucha diagrams for the Limpopo, Olifants and Komati River systems			
River	**Upstream**	**Middle**	**Downstream**
Limpopo	LP1: 6.6 	LP2: 7.0 	LP3: 6.8 
Olifants	OF1: 6.9 	OF2: 7.1 	OF3: 7.2 
Komati	IM1: 7.3 	IM2: 7.3 	IM3:7.1 

Major east-flowing rivers: Limpopo, Olifants and Komati Rivers (Table 4)

The CFs for Limpopo (6.6-7.0), Olifants (6.9-7.2) and the Komati (7.1-7.3) rivers remained fairly constant from the upper to the lower reaches. Note that the less alkaline Limpopo River water has a CF closer to 6.5, compared with the higher CFs of the Komati River where magnesium and bicarbonate are the major ions.

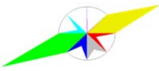
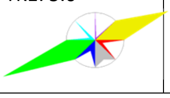
South-eastern coastal rivers: Thukela, uMngeni, and Great Fish Rivers (Table 5)

In the Thukela River, alkalinity is the major component of the anions and the CF ranges between 7.2 and 7.8. The uMngeni River contains a higher proportion of chloride and sulphate,

TABLE 5
Conversion factors and Maucha diagrams for the Thukela, uMngeni and Great Fish River systems

River	Upstream	Middle	Downstream
Thukela	TG1: 7.8 	TG2: 7.5 	TG3: 7.2 
uMngeni	MG1: 6.5 	MG2: 6.3 	MG3: 6.4 
Great Fish	GF1: 7.2 	GF2: 6.8 	GF3: 6.6 

TABLE 6
Conversion factors and Maucha diagrams for the Berg, Breede, Groot Brak and Tsitsikamma River systems

River	Upstream	Middle	Downstream
Berg	BR1: 5.4 	BR2: 5.3 	BR3: 5.3 
Breede	BD1: 5.4 	BD2: 5.2 	BD3: 5.5 
Groot Brak		GB1: 5.2 	
Tsitsikamma		TK1: 5.0 	

with CFs ranging between 6.3 and 6.5. The Great Fish River's ionic composition differs markedly between the upstream section of the river and the two downstream reaches. Both downstream sites are sodium chloride dominated with CFs of 6.8 and 6.6. In contrast, the Maucha symbol for the upstream site shows alkalinity and sodium dominance, and a higher CF of 7.2. Converting EC to TDS using the recommended CF of 6.5 might yield acceptable results at the lower two sites, but will result in a consistent 10% underestimate at the upper site. The higher CFs in the upper reaches of the Great Fish River are very likely related to the transfer of alkaline waters from the Upper Orange River, cf. OR1 in Table 3, to the headwaters of the Great Fish River for irrigation purposes (Van Niekerk et al., 2009).

South-western coastal rivers: Berg, Breede, Groot Brak and Tsitsikamma Rivers (Table 6)

In contrast with the rivers discussed previously, the Berg, Breede, Groot Brak and Tsitsikamma river waters are all sodium chloride dominated with very low alkalinity. The CFs for these rivers vary between 5 and 5.5. Using a CF of 6.5 to determine the TDS from EC in the Tsitsikamma River will overestimate the actual TDS by 30%.

CONCLUSION

The DWA-recommended CF of 6.5 to derive TDS from EC is clearly a rough guideline to be used only when the actual applicable CF is not available or cannot be calculated. Blanket application of the 6.5 CF can lead to misleading results and possible errors during water quality assessments. Discussions with water quality practitioners have revealed that many were unaware of the magnitude of the variation and had assumed that a CF of 6.5 is applicable in all instances. It is therefore important that practitioners record the original EC value so that they can do a more accurate conversion when an applicable CF becomes available.

EC is often the variable of choice when comparing rivers or river reaches in terms of salinity. When using EC, it is important to consider the effect different TDS:EC ratios might have on the final results. For example, Site BR2 in the Berg River and Site RT1 in the Riet River both have median EC values of approximately 36 mS/m (WMS database); however, their median TDS concentrations are 194.5 mg/ℓ and 288.4 mg/ℓ, respectively. Using two popular EC meter brands with standard CFs of 5 (Brand A) and 7 (Brand B) the TDS readings from Brand A will be approximately 180 mg/ℓ for both rivers and the readings from Brand B will be approximately 252 mg/ℓ for both rivers. This means that Brand A will give you a 36% under-estimation of TDS at the Riet River site and Brand B will give you a 29% over-estimation at the Berg River site.

Users of EC meters or EC data should thus be aware of the potential errors and should use a site-specific conversion factor, where one is available. Both EC and TDS data for most of the South African rivers are available at www.dwa.gov.za/iwqs and can be used to calculate appropriate conversion factors for specific study areas.

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APPENDIX A: MONITORING SITE DETAILS

Code	Site	WMS nr	Latitude	Longitude	Name	TDS: EC	n
BD1	H1H003	102019	33°22'50.0"S	19°18'06.0"E	Bree River at Ceres Commonage	5.4	1077
BD2	H4H017	102081	33°49'05.0"S	19°41'40.9"E	Bree River at La Chasseur	5.2	1088
BD3	H7H006	102119	34°03'56.9"S	20°24'15.0"E	At Swellendam on Bree River	5.5	406
BR1	G1H013	101922	33°07'50.9"S	18°51'46.0"E	At Drieheuvels on Berg River	5.4	1265
BR2	G1H031	101935	32°59'48.9"S	18°46'44.0"E	At Misverstand Die Brug on Berg River	5.3	1384
BR3	G1H023	101931	32°56'44.9"S	18°20'12.0"E	BE06-G1H023Q01 Jantjiesfontein 69-at Bergrivier Town on	5.3	322
CD1	D2H012	101808	28°41'41.4"S	28°14'05.5"E	Caledonspoort 190 the Poplars 199 at the Poplars on L	8.0	212
CD2	D2H035	101815	28°52'59.9"S	27°53'24.0"E	Caledon River at Ficksburg/Ficksburg Bridge	8.0	289
CD3	D2H036	101816	30°16'45.0"S	26°39'15.0"E	Caledon River at Kommissiedrift	7.8	204
GF1	Q3H005	102450	32°05'11.0"S	25°34'32.0"E	At Rietfontyn Waaikraal on Great Fish River	7.2	1121
GF2	Q9H012	102482	33°05'53.0"S	26°26'40.9"E	At Brandt Legte Piggot's Bridge on Great Fish River	6.8	629
GF3	Q9H018	102487	33°14'16.0"S	26°59'40.9"E	At Matomela's Reserve Outspan on Great Fish River	6.6	960
IM1	X1H018	102938	25°50'17.9"S	30°24'46.0"E	Komati River at Gemsbokhoek	7.3	185
IM2	X1H001	102931	26°02'09.9"S	30°59'52.0"E	Komati River at Hooggenoeg	7.3	255
IM3	X2H036	102979	25°26'09.9"S	31°58'55.9"E	At Komatipoort Kruger National Park on Komati River	7.1	660
LP1	A5H006	90340	22°56'05.9"S	28°00'15.0"E	At Botswana Sterkloop on Limpopo River	6.6	133
LP2	A7H008	90375	22°13'32.0"S	29°59'26.0"E	Down Stream of Beit Bridge on Limpopo River	7.0	68
LP3	A91_189421	189421	22°20'00.2"S	31°08'46.8"E	Kruger National Park at Hulukulu on Limpopo	6.8	21
MG1	U2H048	102658	29°29'34.0"S	30°12'10.0"E	Midmar Dam on uMngeni River: Downstream Weir	6.5	193
MG2	U2H055	87822	29°38'30.9"S	30°41'15"E	At Inanda Location Egugwini on uMngeni	6.3	28
MG3	U2H003	102622	29°45'32.0"S	30°56'07.0"E	At Kwa-Dabeka Richmond on uMngeni	6.4	21
OF1	B3H001	90444	24°55'36.0"S	29°23'21.9"E	Olifants River at Loskop North	6.9	594
OF2	B7H007	90503	24°11'02.0"S	30°49'26.0"E	At Oxford on Olifants River	7.1	650
OF3	B7H017	90515	24°03'06.0"S	31°43'53.0"E	Olifants River at Balule Rest Camp/Kruger Nat Park	7.2	397
OR1	D1H009	101793	30°20'09.9"S	27°21'33.9"E	Orange River at Oranjedraai	7.8	419
OR2	D3H012	101827	29°59'27.9"S	24°43'27.9"E	Orange River at Dooren Kuilen-Downstream of D3R00	7.6	366
OR3	D8H003	101888	28°45'38.9"S	17°43'49.0"E	At Vioolsdrift on Orange	7.1	859
RT1	C5H012	90816	29°39'29.0"S	25°58'23.9"E	Riet River at Kromdraai/Rietwater	8.0	183
RT2	C5H014	90817	29°02'31.9"S	24°36'05.1"E	Richie Klipdrift 109-at U/S Side of Weir on Riet River	6.9	477
RT3	C5H016	90819	28°57'36.0"S	24°14'32.9"E	At Estate Biesiesbult Aucampshoop on Riet River	6.5	632
TG1	V1H001	102695	28°44'08.0"S	29°49'14.0"E	Thukela River at Tugela Drift/Colenso	7.8	317
TG2	V6H002	102781	28°45'00"S	30°26'34.0"E	At Tugela Ferry on Thukela	7.5	318
TG3	V5H002	102779	29°08'26.0"S	31°23'30.9"E	At Mandini on Thukela River	7.2	423
VL1	C1H012	90595	27°00'07.9"S	28°45'55.0"E	Vaal River at Nooitgedacht/Gladdedrift	7.5	942
VL2	C2H140	90688	26°44'17.0"S	27°35'30.9"E	Vaal River at Woodlands/Goose Bay Canyon	6.9	597
VL3	C9H024	101770	28°42'41.4"S	24°04'22.4"E	Smidts Drift Outspan 23 Schmidtsdrift at Weir on Va	6.8	173
GB1	K2H002	102241	34°01'42.9"S	22°13'19.9"E	At Wolvedans on Groot-Brakrivier	5.2	434
TK1	K8H005	102316	34°05'47.0"S	24°26'21.0"E	At Geelhoutboom on Tsitsikamma	5.0	61