An Approach to Evaluate Groundwater Salinity Using Electrical Well Logging Data Case Study: Sandstone Aquifer in Daging Oil Field, China

Zhaohui Huang
School of Petroleum and Gas Engineering
Chongqing University of Science and Technology
Chongqing 401331
China

E. A. Elzein Mohammed
Faculty of Sciences
International University of Africa
Khartoum, Sudan

Zou Changchun
School of Petroleum and Gas Engineering
Chongqing University of Science and Technology
Chongqing 401331
China

Chen Zhenya
Chongqing University of Sciences and Technology
Chongqing 401331
China

Abstract

The salinity of water is an important parameter in groundwater evaluation research. In this paper, the total dissolved solid (TDS) was strongly correlated with apparent resistivity and spontaneous potential logs data in a sandstone formation aquifer. A large number of preexisting electrical logs data conducted for the purpose of hydrogeological studies have been gathered and used to predict the groundwater TDS. Based on the electrical characteristics analysis of a sandstone aquifer, taking the influential factors of the Archie's Equation and the creation mechanism of spontaneous potential (SP), the theoretical exponential function between the TDS and the formation spontaneous potential as well as the formation resistivity (Rt) were deduced and modeled in this paper. A reasonable value approach was introduced to read the electrical logs data and the static spontaneous potential logs data, and then, the numerical fitting method was employed to analyze the relation between groundwater salinity and the electrical logs data of the Quaternary sandstone aquifer of the Songliao plain, Northeastern China in Daging Oil field,. Finally the groundwater quality assessment was successfully carried out by this methodology in some production wells. The correlation procedure adopted in this study could be applied to evaluate groundwater salinity of new target areas in the china or elsewhere.

Keywords: Electrical logging, Formation resistivity, Static spontaneous potential, Groundwater salinity, Water quality evaluation

Introduction

The Characteristics of R_t Curve:- Sandstone formation is usually composed of clay-stone (mudstone, shale) and sandstone (conglomerate, sandstone, and siltstone), of which the partition layer of ground water is clay stone, and the ground water aquifer in the sandstone horizon. The shale's adsorption effect results in anion concentration on the surface of mineral particles to form the double electric layers with the thermal motion of the cations, which has relatively good electrical conductivity, so the apparent resistivity measured in wells shows a relatively low resistance characteristic curve.

The rock forming mineral of sandstone are mainly quartz and feldspar, which are both high resistance minerals, thus the apparent resistivity logs show a relative high resistance characteristics. Fig. 1 is a R_t curve of the typical sandstone and shale horizons, in which 0-66m and 94-133m show shale which correspondent to low resistivity while 64-94m and 133-178m show conglomerate correspondent to high resistivity. From R_t curve in Fig.1 Shale and sandstone can be divided by taking half amplitude point of resistivity from low to high as top boundary of sandstone, and then taking the bottom extreme of high resistivity also known as quick change point as the bottom boundary, then the sandstone formation can be confirmed.

The Characteristics of SP Curve:- SP in sandstone formation contains mainly diffusion potential and membrane potential from its generation mechanism. In shale horizon, the SP is mainly membrane potential generated by adsorption because where the pore-space in mudstone is very tiny so mud cannot penetrate, therefore the fluctuation of SP is small, the curve shows a relative straight baseline. In sandstone aquifer, the diameters of quartz and feldspar are relatively larger so the pore-space are well developed in the rock, thus mud can easily penetrate inside the pore-space and this leads to diffusion potential. Theoretically there is only diffusion in pure sandstone area, and the direction of diffusion electrical field is opposite to the membrane electrical field so the logging trace shows a deviation off the baseline. However, this deviation shrinks in sandstone horizons which contain mud because SP is not only diffusion potential but also membrane potential. Fig. 2 shows a typical SP logging trace in sandstone formation. 0-97m and 141-150m are mudstone where the SP curve is fluctuation tiny background and usually is called mudstone base line. 97-150m represents the sandstone horizon where SP has a negative anomaly because the salinity of drilling mud is higher than the salinity of ground water. Generally the midpoint of base line and abnormal is introduced to divide the intervals of sandstone, which is called half-amplitude method, so sandstone interval and mudstone interval are divided.

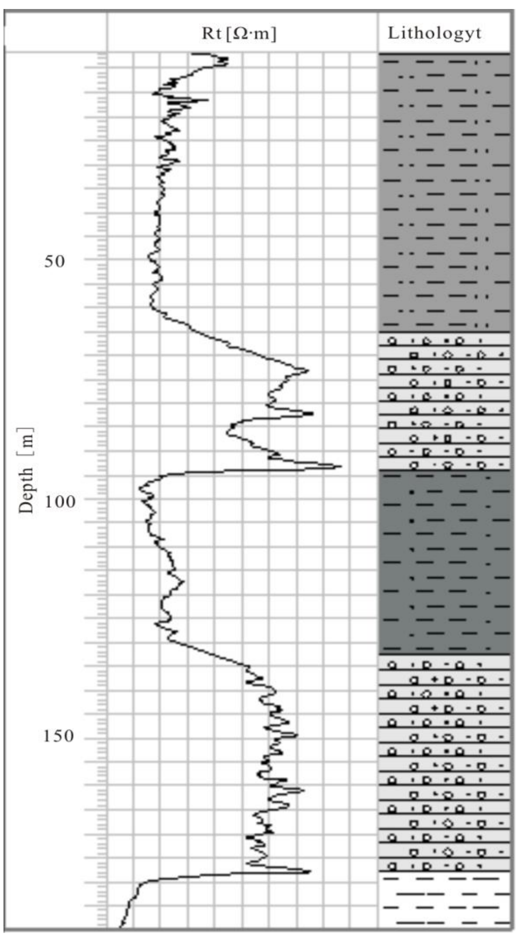

Fig. 1: A Typical R_t Curve in Sandstone Formation

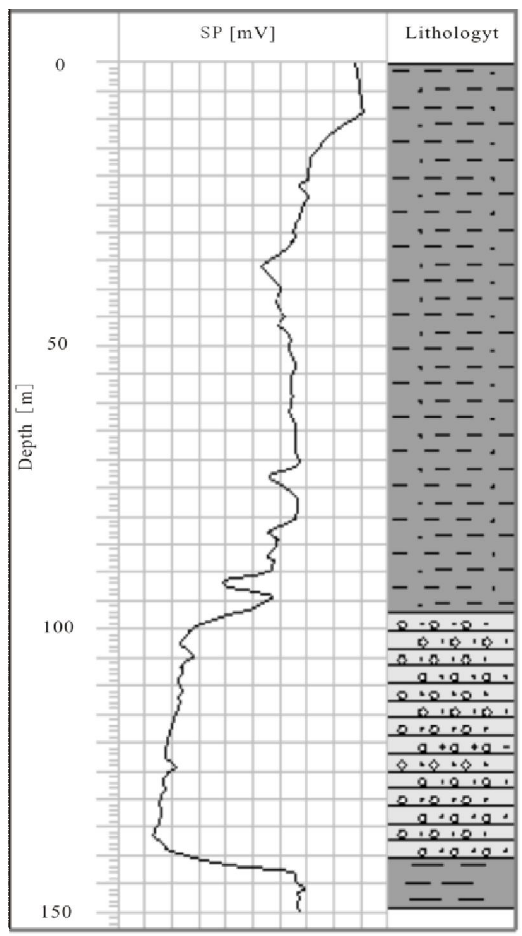

Fig. 2: A Typical SP Curve in Sandstone Formation

The Relationship between Electric Characteristics and Groundwater Salinity of Sandstone Aquifer

The Model of R_t and the TDS. From the physical model of hydrous rock, a transform of Archie's formula [11] for saturated stratum is

$$R_t=a\cdot b\cdot R_w/\Phi^m. \quad (1)$$

Where R_t is apparent resistivity of stratum, R_w is stratum water resistvity, Φ is efficiency porosity, m is the cementation index, and a, b are lithology coefficients.

The formula above shows that apparent resistivity is dependent on lithology, holes framework and resistivity of stratum water. The main factors to resistivity of stratum water include types of different ions, TDS and temperature of the stratum water. From Plate by Schlumberger [12], the following can be obtained

$$R_w=5.6\cdot C_w^{\beta}/[1+\alpha(t-18)]. \quad (2)$$

Where C_w is the TDS of stratum water, t is temperature, and α,β are coefficients.

Combine Eq.1 and Eq.2, and assume the diversifications of porosity are not huge, a new model can be figured out with the relationship of R_t and C_w (TDS).

$$TDS=(A\cdot R_t+B)^{\beta}. \quad (3)$$

Where A, B,β are fitting factors for the formula respectively.

From the principle of sectional calibrating of TDS in quick testing via water sample resistivity[13] and the approximation of β=-1 , a linear regression equation can be proposed with fitting R_t and 1/TDS. Fig. 3 shows the flow diagram of model.

The Model of SSP and the TDS:-

The difference between the SP value of the sandstone and the SP value of the mudstone is the sandstone aquifer static spontaneous potential [14]:

$$SSP = E_d - E_{da} = (K_d - K_{da})\lg\frac{C_w}{C_{mf}} = -K\lg\frac{C_w}{C_{mf}} \quad (4)$$

where SSP, E_d, E_{da} are static spontaneous potential, diffusion potential and membrane potential respectively C_w, C_{mf} are stratum groundwater salinity and mud salinity respectively, K_d, K_{da} are diffusion potential and membrane potential respectively. From Eq.4, we can get

$$\frac{C_w}{C_{mf}} = 10^{-SSP/K} \quad (5)$$

where K is a function of temperature [12]:

$$K = 70.7(273+T)/298 \quad (6)$$

Within this uniform drilling mud configuration, C_{mf} can be treated as a constant. K can be treated as a constant for the groundwater horizon where it lies in shallow layer with a constant temperature and the deeper layer temperature grad is only 3 Celsius degree per 100 meters. From Eq.2, the following model can be deduced, which shows the relation between the SSP and the C_w (TDS):

$$Y = Ae^{B\cdot X} \quad (7)$$

where X is formed by a series of X_i, each X_i is corresponding to a SSP in a certain stratum of a certain well. Y is formed by a series of Y_i, each Y_i is corresponding to a groundwater salinity datum (TDS) of the certain stratum of sandstone in the certain well, A, B, β are the multiple factors for the formula.

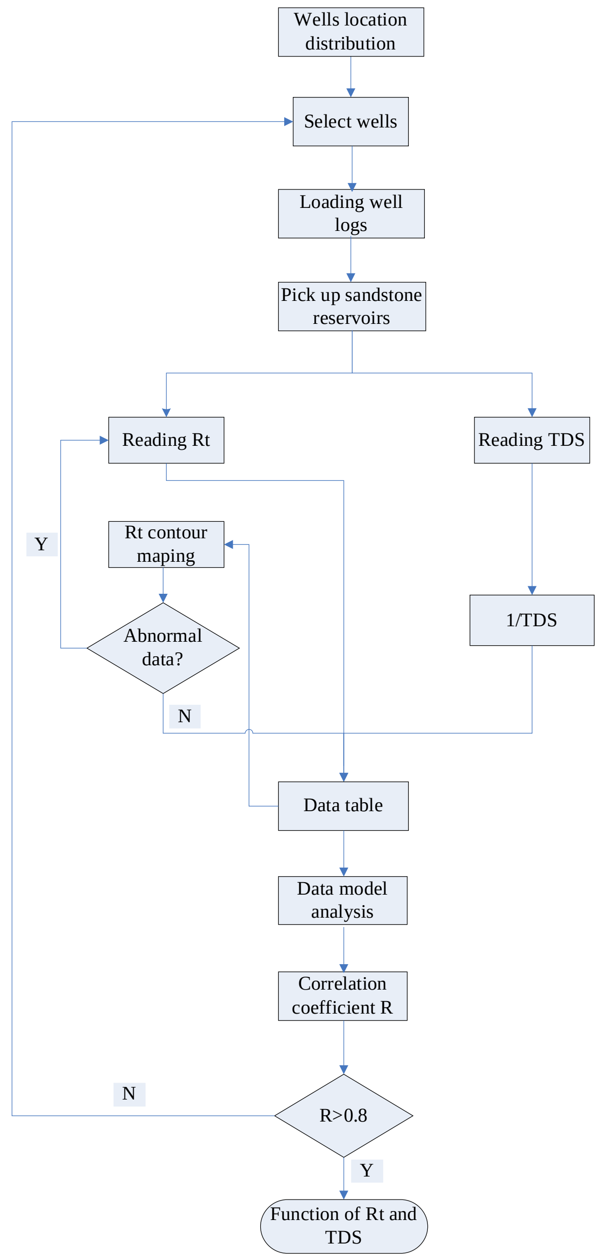

Fig. 3: Modeling flow diagram for Rt and TDS

Example of Groundwater Quality Assessment in Daging Oil field, Songliao plain

The Daging Oil field, Songliao plain is located in Northeastern part of China (Fig.4). The quaternary sediments represent the main geological unit in the area, and are composed of relatively weak consolidated sediments (clay, sand and gravels). The Quaternary sandstone horizon are the main groundwater aquifer in the area. The aquifer has a thickness of about 10 m and up to 35m and burried at adepth range from 50m and upto 100m. The ground water is relatively saline. The data of about 87 well were collected and applied for the predicting electric logs model.

Regression Analysis of R_t and TDS

The TDS data in conjunction with the R_t, have been taken from 60 wells, chosen from the study area. These data have been used to construct the groundwater quality model.

Table: 1. Employs the former modeling method, and then yields the fitting diagram for R_t and1/TDS. After computing, the model can be written as follow:

TDS=100000/(1.66Rt+23.7). (8)

The unit of TDS is ppm(mg/L), if we take g/L for the unit to TDS, then Eq.8. can be rewritten as:

TDS=100/(1.66Rt+23.7). (9)

In which the Pearson coefficient R=0.85, which indicates that there is a strong correlation between TDS and Rt. From Eq.8, when the Rt >45Ω·m, the TDS<1000mg/L, and the groundwater quality can be of a good quality (low salinity).

Fig. 4: Location Map of the Study Area

Table 1: Modeling Data of R_t and TDS in Sandstone Aquifer

Sample	Well	Rt [Ω·m]	TDS [mg/L]	Sample	Well	Rt [Ω·m]	TDS [mg/L]
1	232	32	1612	31	HW16	53	1151
2	233	36	1121	32	HW19	110	451
3	234	41	1033	33	HW41	120	462
4	235	36	1418	34	Q2	38	1220
5	236	16	2935	35	Q23	36	1430
6	239	45	1035	36	Q33	52	1269
7	303	70	550	37	L19	34	1591
8	310	55	635	38	L25	35	1651
9	612	88	544	39	L3	31	1333
10	7307	35	1506	40	L3-2	53	1393
11	8403	30	1186	41	L4	36	823
12	8404	84	513	42	X16-2	70	812
13	8514	37	1149	43	X22-4	48	919
14	8810	48	712	44	X30-2	61	735
15	7114	85	514	45	X44-2	59	819
16	G1	49	805	46	X55	61	664
17	G2	74	805	47	X62	66	706
18	G3	54	803	48	HW22	94	451
19	G4	39	851	49	HW24	77	621
20	G6	49	904	50	HW26	36	845
21	G7	45	1136	51	HW27	67	681
22	G8	45	1156	52	HW34	34	1121
23	G13	85	575	53	L15	26	1533
24	G15	38	786	54	L15-2	33	1480
25	J4	88	704	55	L16-3	35	1380
26	X1-4	63	805	56	Q5	45	1206
27	X19-2	58	1166	57	LG16	72	1054
28	X51-2	66	736	58	LG2	104	647
29	X63	68	788	59	LG3	49	1282
30	X68	96	713	60	LG8	38	1290

Regression Analysis of SSP and TDS: The depth of the main groundwater aquifer is not large, where the quaternary sediments are mainly composed of clay and gravel, which can lead to relatively weak digenesis and bad SP log trace and thus it is hard to confirm that the mudstone baseline and the abnormal trace of sandstone are unsatisfactory. A total of 21 SP data from 19 wells were fitted to develop this model as shown in table 2. The fitting of the ssp and groundwater salinity are shown in Fig.5.

Table 2: Modeling Data of SP and TDS in Sandstone Aquifer

Sample	Well	SSP [mV]	TDS [mg/L]	Sample	Well	SSP [mV]	TDS [mg/L]
1	HW26-2	12.9	845	12	HW28-4	6	1455
2	L25	10	1651	13	L6	3	1811
3	L29	4.5	2628	14	L7-2	24	911
4	Q5	14.2	1206	15	8405	36	600
5	X55	36.8	664	16	NE24	21	697
6	D1-2	13	865	17	Q2-2	20	682
7	D1-2	12.5	865	18	Q4	20	701
8	D2-3	24	772	19	Q6-2	24.5	695
9	D4-2	28	732	20	X29-2	16.5	1114
10	D4-2	29	732	21	X19-2	18	726
11	HW25-3	7.5	1850				

Fitting SSP and TDS data with Eq.6 then yield the result, and we have the following function:

$$TDS=1835\cdot e^{-0.0355\cdot SSP}. \qquad (10)$$

Where the Pearson coefficient R=0.82, which means that there is a strong correlation between TDS and SSP. From Eq.10, we can see when the SSP >17mV, the TDS<1000mg/L, where there is a good ground water quality .

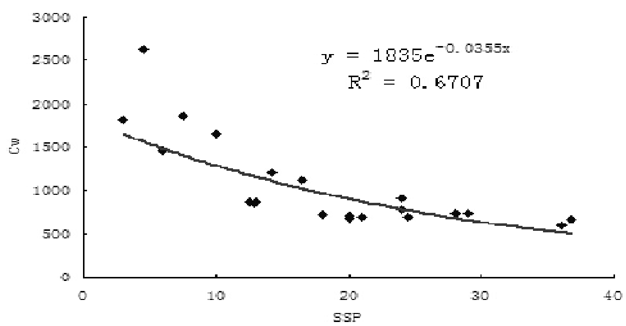

Fig. 5: The Fitting Model of SSP and Cw

From equation (10), the conclusion is that when the groundwater salinity Cw=1000mg/L, which means if SSP≈17mV, water quality approaches Cw<1000mg/L.

TDS Prediction and the Groundwater Quality Assessment

The TDS values for the rest of 87 wells have been predicted from the electrical logs data by using the above calculated models (Eq. 7 & 8). However, these wells have no TDS data from experiments and/ or the field measurements. Finally the TDS areal distribution model of the Quaternary sandstone aquifer can be mapped by kriging method, which is shown in Fig. 6. Taking TDS=1000mg/L as upper boundary conditions, the study area can be divided into three parts: in the middle part of the area where the TDS is less than 1000mg/L, corresponding to the ground water quality for drinking water standards, on the contrary, in northwest and southeast parts of the area where the TDS is more than 1000mg/L, this means that the water is not qualified for drinking without initial treatment [15].

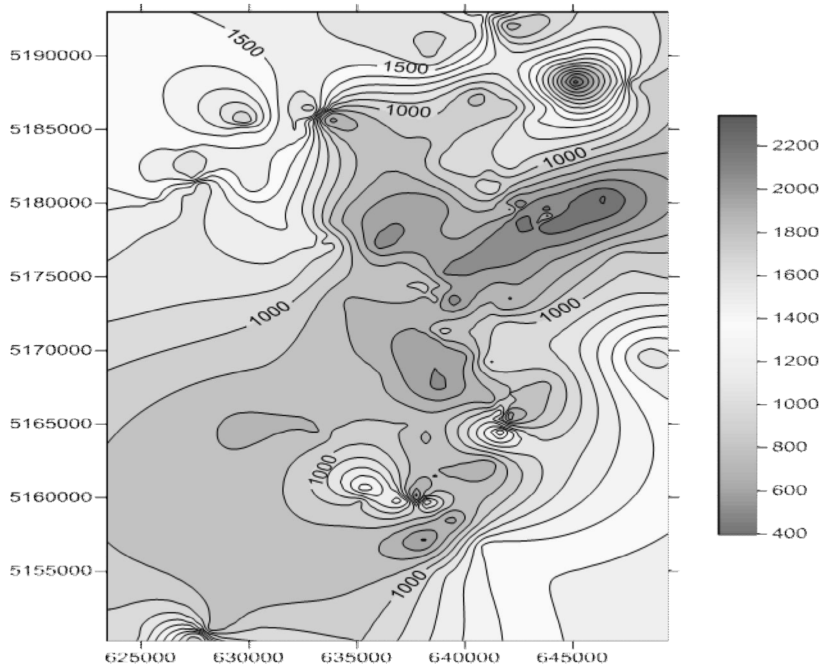

Fig. 6: The Contour Map of TDS Predication Data

Conclusions

A large number of electrical logs data have been gathered in the last few decades in China. As a kind of outspread from geophysical well logging to ecological environment, the electrical logs data is used to study the TDS and to evaluate groundwater quality. The corresponding mathematical model is established based on these data, and the two electrical indices for evaluating the groundwater quality can be determined. The proposed model has been successfully introduced for Daqing Oil Field, China. The example shows that when the SSP value is more than 17mV, and the Rt value is more than 45Ω·m, the TDS of the sandstone groundwater aquifer in Daqing oil field is less than 1000mg/L and thus, the water is qualified for drinking purposes. For groundwater planning and developing in the future it was concluded that the TDS of groundwater for such areas can be predicted, especially when old electric well logs data are available, but no water quality testing data is available. The model has limitations in the cases of insufficient porosity data, so it can be just concerned with the shallow sandstone horizons. If ultrasonic logging data can be added into the modelling prediction, the porosity can be calculated and the model will reveal more accurate results, and also the method can be applied more widely to the deep zones.

Acknowledgments

We would like to thank the Chinese Fundamental Research Funds for the suporting this work in frame of funds for Central Universities (Grant No. 2011PY0188) .

References

Asfahani, J. (2011) 'Electrical resistivity investigations for guiding and controlling fresh water well drilling in semi-arid region in Khanasser Valley, Northern Syria', *Acta Geophysic,*. Vol.59 No.1, pp. 139-154.

Khalil, M.A., Santos, F.M., et al. (2011) 'An approach to estimate porosity and groundwater salinity by combined application of GPR and VES: a case study in the Nubian sandstone aquifer', *Near Surface Geophysics*, Vol.8 No.3, pp.223-233.

Nativ, R., and Fligelman, H. (1994) 'A field test of the modified SP log interpretation method for estimating groundwater salinity', *Journal of Hydrology*, Vol.161 No.4, pp.133-144.

Mcconnell, C.L. (1983) 'Spontaneous potential corrections for groundwater salinity calculations–Carter County, Oklahoma, USA', *Journal of Hydrology*, Vol.65 No.4, pp .363-372.

Z.H. Huang, Q.Y. Di and S.L. Hou: Progress in Geophysics, Vol.21 (2006) No.4 p.1290 (In Chinese).

M.A. Khalil, M.A. Hafez, and F.M. Santos: Near Surface Geophysics Vol. 59 (2011), p. 139

Olivar, A.L. de Lima. (1993) 'Geophysical evaluation of sandstone aquifers in the Reconcavo-Tucano basin, Bahia-Brazil', *Geophysics*, Vol.58. No.11, pp.1689-1702

Zhao, F.Z., et al. (2002) 'A geophysical logging method to detect the water mineralization intensity underground' , *Progress in Geophysics*, Vol.17 No.3, pp.551-558. (In Chinese)

Jorgensen, D.G. (1990) 'Estimating water quality from geophysical logs' In *STP 1989*: *Symposium on Geophysical Methods for Geotechnical Investigations*. ASTM Special Technical Publication, Denver, USA, pp.47-64.

Hite, L. and Carlson M. (1999) 'Integrating surface and borehole geophysics in ground water studies - An example using electromagnetic soundings in south Florida', *Journal to Environmental and Engineering Geophysics,* Vol.4 No.1, pp.45-55.

Archie, G.E. (1942) 'The electrical resistivity log as an aid in determining some reservoir characteristics', *Trans. Am. Inst. Mech. Eng.*, Vol.146, pp.54~61.

Serra, O. (1986) *Fundamentals of Well-log Interpretation-2: The interpretation of logging data*. Elsevier Science Publishing Company, Inc. New York, USA.

Serra, O. (1986) *Fundamentals of Well-log Interpretation-2: The interpretation of logging data*. Elsevier Science Publishing Company, Inc. New York, USA.

Dong J.(2009) 'Rapid determination of total dissolved solids in drinking water by the conductivity meter', *Chinese Journal of Health Laboratory Technology,*Vol.19 No.10, pp.2719-2420.(In Chinese)

Dong J.(2009) 'Rapid determination of total dissolved solids in drinking water by the conductivity meter', *Chinese Journal of Health Laboratory Technology,*Vol.19 No.10, pp.2719-2420.(In Chinese)

D.V. Ellis: *Well Logging for Earth Scientists* (Elsevier, New York 1987).

World Health Organization, (2008) *Guidelines for drinking water quality, 3rd ed., Vol.1* Recommendations, Geneva. Information on http:// http://www.who.int