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1

GLOBAL OPTIMIZATION VERY FAST SIMULATED ANNEALING INVERSION FOR THE INTERPRETATION OF GROUNDWATER POTENTIAL

OPTIMASI GLOBAL INVERSI VERY FAST SIMULATED ANNEALING UNTUK INTERPRETASI POTENSI AIR TANAH

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Abstract. This study examines the inversion modelling[1] of one-dimensional Schlumberger configuration resistivity data using the Very Fast Simulated Annealing (VFSA). Detailed identification and mapping of aquifer conditions is[2] very important[3] for the sustainable development of groundwater resources in an area. Vertical electrical sounding (VES) and surface electrical resistivity surveys have proven very useful for studying groundwater due to their simplicity and cost effectiveness[4]. Global[5] optimization inversion method also provides an inversion solution that is not expected[6] to be trapped in a local minimum solution,[7] so that it will get results that are[8] closer to the actual situation. The VFSA method is inspired by phenomena in metallurgy related to the formation of crystals in materials caused by thermodynamic processes.[9] This inversion scheme was tested initially with free noise synthetic data and with noise 5%. Furthermore, the program is applied[10] to field data that has been[11] measured[12] in Ambon City, Maluku, Indonesia. The results of the VFSA inversion on field data obtained four layers consisting of top soil[13] (141.2 ± 0,61 m) with a thickness of 1.43 m, andesite breccia rock (355.90 ± 0.46 m) with a thickness of 4 m, lapilli tuff (93.40 ± 0.31 m) with 30 m thick, then[14] the last is the coarse tuff layer (34.30 ± 0.15 m) which is estimated[15] as an aquifer.

Abstrak. Penelitian ini mengkaji pemodelan inversi data resistivitas konfigurasi Schlumberger satu dimensi menggunakan teknik Very Fast Simulated Annealing (VFSA). Identifikasi dan pemetaan secara detail terkait kondisi akuifer sangat penting untuk pembangunan berkelanjutan sumber daya air tanah suatu daerah. Vertical electrical sounding (VES) dan survei resistivitas listrik permukaan telah terbukti sangat berguna untuk mempelajari air tanah karena kesederhanaan dan efektifitas biayanya. Metode optimasi global juga memberikan solusi inversi yang diharapkan tidak terjebak pada solusi minimum lokal, sehingga akan mendapatkan hasil yang lebih mendekati keadaan sebenarnya. Metode VFSA terinspirasi dari fenomena di bidang metalurgi terkait pembentukan kristal dalam material yang disebabkan oleh proses termodinamika. Skema inversi ini dilakukan uji awal dengan data sintetik bebas gangguan dan dengan gangguan 5%. Selanjutnya program diterapkan pada data lapangan yang telah dilakukan di Kota Ambon, Maluku, Indonesia. Hasil inversi VFSA pada data lapangan diperoleh empat lapisan yang terdiri atas top soil (141,2 ± 0.61 Ωm) setebal 1,43 m, batuan andesite breccia (355,90 ± 0,46 Ωm) setebal 4 m, lapilli tuff (93,40 ± 0,31 Ωm) setebal 30 m, kemudian yang terakhir ialah lapisan coarse tuff (34,30 ± 0,15 Ωm) yang diperkirakan sebagai akuifer.

INTRODUCTION

Water is the most crucial need for all living things, especially for humans. The issue of clean water quality and sanitation is a worldwide concern and is included[16] in the sustainable development goals program. In general, clean water is produced[17] from groundwater exploration. Unfortunately, the high demand for groundwater due to industrialization and population growth has resulted in excessive groundwater exploitation. This[18] is a major[19] concern to maintain[20] a sustainable aquifer condition. Detailed identification and mapping of aquifer conditions are very important[21] for the sustainable development of groundwater resources in an area. Geophysical techniques are powerful tools and play an important role in delineating the configuration of subsurface aquifers. Over the last few years, modelling[22] techniques related to this have developed a lot. In particular, the vertical electrical sounding (VES) technique and surface electrical resistivity survey has proven to be very useful for studying groundwater due to their simplicity and cost-effectiveness.[23] Steiner try[24] to applied[25] resistivity methods combined with[26] seismic methods to investigate pollutants in groundwater (Steiner et al., 2022). Besides that, the resistivity method can also be used to identify groundwater potential (Joel et al., 2020), especially in areas that are[27] still hard to get clean water supply or areas that require agricultural irrigation (Alarifi et al., 2022; Chikabvumbwa et al., 2021; Zaher et al., 2021). The difference in resistivity values due to the presence of salt minerals such as sodium chloride in the aquifer can also be used[28] to analyze the phenomenon of seawater intrusion using this method (Ammar et al., 2021; Wilopo et al., 2018).

Geoelectrical inversion problems are often non-linear[29] and complex, where the solution consists of using a set of apparent resistivity data to obtain subsurface model parameters.[30] There are two ways to do this (inverse modelling[3]), there[32] are direct and indirect methods. The indirect inverse modelling[33] method involves curve matching and forward[34] modelling[35] algorithms. VES data interpretation with this technique is widely used by practitioners of hydrogeology.[36] The direct inverse modelling[37] method (ie[38] resistivity inversion with a numerical algorithm) involves minimizing the error between the observed apparent resistivity and that calculated using optimization techniques.[39] Commonly used techniques are the Ridge Regression Technique (Meju, 1992; Narayan et al., 1994), Joint Inversion (Özyıldırım et al., 2020), and the singular value decomposition (SVD) technique (Tjong et al., 2018). The revolutionary and newly developed optimization techniques are genetic algorithms, simulated annealing, and particle swarm optimization (Hapsoro et al., 2021; Yan et al., 2020). This method is also known as the global optimization method, where this method[40] is more reliable and has a better error value because it does not get stuck on a local minimum.

The problem of inverse modelling[41] of DC current[42] resistivity was first investigated[4] in the 1930s. From that time until the late 1980s, the field survey methodology and the character of the data from the measurements did not change much[45] [44] . Then in the late 1980s and early 1990s to this day[46], there has been a significant increase in data collection and interpretation. The interpretation of VES data is greatly influenced by three events, there[47] is the linear filter theory proposed by Ghosh (Ghosh, 1971), the widespread use of digital computers, and the application of general linear inversion theory.[48] At this time, the concept of[50] inverse modelling[49] and automated analysis is[50] becoming popular, where the computational program generated from this theory can find the most suitable model automatically.

In this study, we will discuss the inversion of the one-dimensional Schlumberger configuration resistivity data using the VFSA Technique. The advantage of VFSA over other methods is that it can get the global minimum solution and[51] it can[52] prevent the local minimum from being reached[52]. VFSA inversion ensure[53] the[54] solution's stability and can be used to make the noise data robust. This technique can be used[55] in geophysical inversion problems such as seismic (Wang et al., 2021), DC resistivity (Sharma, 2012), Self Potential (Biswas & Sharma, 2014), and electromagnetic time domain (Srigutomo et al., 2021).

LITERATURE REVIEW

The Schlumberger configuration is very easy[56] to use[57] for surveying and is the most popular scheme for measuring DC resistivity sounding. The VES method injects direct electric current into the ground, which will produce[58] a hemispherical equipotential state. The relationship between apparent resistivity and layer parameters is expressed[59] in the form of[60] a Hankel integral. Koefoed expressed the equation for the homogeneous and isotropic earth model as follows (Koefoed, 1979),

$\rho aL=L20 T\lambda J1 (\lambda L)\lambda \, d\lambda$ (1)

where L is half the current electrode distance (AB/2), J1 is a first order[61] Bessel function of the first kind, and λ indicate[62] an integral[63] variable. Tλ is a resistivity transformation function obtained from the recursion relationship,

$Ti=Ti+1+\rho itanh(\lambda hi)1+(Ti+1tanh(\lambda hi)/\rho i)$ (2)

where m is the number of layers, ρi is rock resistivity and[64] hi is thickness[65] of the i-th[66] layer. Furthermore, the value of the transformation function is related to the filter coefficient to produce apparent resistivity (Bhattacharya & Patra, 1968; Ghosh, 1971). Guptasarma introduced a 19 point[67] filter (ϕr) which can be used[68] to calculate apparent resistivity (Guptasarma, 1982). This linearization filter method is considered[69] to have a better accuracy value than the method proposed by Gosh before[70] (Ghosh, 1971). The apparent resistivity value is

$\rho aL=1\alpha\phi rT\lambda$ (3)

λ can be obtained[71] from $\lambda r=10(ar-logL)$[72]. This equation is used[73] to calculate[74] the forward modelling[75] response for DC resistivity sounding[76] data.

METHODS

in this study[77] we used a very fast[78] simulated annealing method for subsurface resistivity inversion. The global minimum inversion of Simulated Annealing (SA) is inspired by a phenomenon in metallurgy related to the formation of crystals in materials caused by thermodynamic processes.[79] In annealing, the material is heated[80] until it melts into a liquid. The temperature is then slowly lowered (annealed) and controlled so that the materials freeze at energy states very close to the global minimum and become crystals. However, if the cooling process is carried out rapidly (quenching), the material will freeze at a local minimum. At high temperatures, the[81] atoms move randomly and freely, given the high kinetic energy. The cooling process is carried out[82] resulting[83,84] in atoms that are initially free to move to find an optimal place, where the internal energy required to maintain its position is minimum. The geophysical inversion problem takes an analogy from this annealing event, where the temperature cooling[85] process is represented by an iteration process to find the optimum solution.[86] Liquids represent the model, and the energy of the system[87] is analogous to a cost function or an error function (Sen & Stoffa, 2013).

The Boltzmann probability distribution function is used in SA to describe the relationship between the model probabilities m at temperature T, whose energy E is,

$Pmi=exp-EmikTj\in Sexp(-E(mj)kT)$ (4)

Where k is Boltzmann's constant, where in the future[88] the value will be set to k=1. The[89] control parameter T has the same[90] dimensions as the system energy or the error function.

In its development, SA gets modifications to obtain more efficient results. Ingber was the first to introduce VFSA for two main reasons. First, in the NM-dimensional model space, each model parameter has a different range and has a different effect on the misfit or error function. So each model parameter must have a different level of disturbance from its current position (Ingber, 1989, 1993). Second, some existing SA algorithms are not capable of performing[91] sufficiently elegant and fast calculations if the Cauchy random number is equal to the number of model parameters. Attempts to construct an NM-dimensional Cauchy distribution can be avoided[92] by using the NM product of the 1D Cauchy distribution. In such a formulation, each model parameter has its own[93] cooling schedule and sampling scheme in the model space. Ingber proposed a new probability distribution for modelling[94] so that convergence can be achieved[95,96] without a slow cooling schedule. Assuming mik[97,98] there is model parameter mi in k-iteration where,

mimin mik mimax (5)

mimin[99] and mimax[100] are the minimum[101] and maximum value[102] of each model parameter.

At first, the model parameters (resistivity and thickness of each layer) are chosen randomly from the model space. Then forward modelling[103] is carried out to get the response function in the form of pseudo resistivity[104] data. The error or energy function can be obtained[105] by comparing it with the resistivity data of the real[106] model with the second norm formula (L2) as follows,

L2=E2=1Ni=1Npiobs-pimodel2 (6)

The second norm (L2) also[107] known as the least square. While ρiobs and ρimodel are the resistivity value of the observation and model response at point-i[108]. The number of observation points is N data. In the (k+1)-iteration, the parameter values of the model get a small perturbation based on the following rules,

mik+1=mik+yimimax-mimin[109] (7)

with yi∈[-1,1] and mimin≤mik+1≤mimax. After that[110] the random number ui[111] is generated from uniform distribution ui∈[0,1]. The value of yi[112] based on temperature[113] in this iteration is,[114]

yi=sgnui-12Ti1+1Ti|2ui-1|-1 (8)

Then a new model has been[115] obtained. The error function is then resurrected[116] using the previous forward modelling[117]. If the new model's misfit error is smaller than the previous model's misfit error[118], then the new model's parameters can be accepted. However, if the misfit error of the new model is greater than the misfit error of the previous model, then a random number from 0 to 1 is generated and compared with the probability of acceptance of the model.[119] If the probability of acceptance of the model is greater[120] than a random number, the new model can be accepted, and conversely[121], the new model is rejected[122] if the probability is smaller[123,124]. The temperature in the iteration process will affect the probability value of model acceptance, where the smaller the temperature, the smaller the probability of model acceptance. The decrease in temperature is based[125] on the following cooling schedule,

Tik=T01exp(-c1k1/NM) (9)

k and c1 are constants,[126] whose values differ depending on the model parameters. T01 is the initial[129] temperature and[127] Ti is the update[128] temperature. The initial temperature value depends on the size of the optimization of the objective function (Sharma, 2012).

INVERSION RESULT

Inversion Results Using Synthetic Data

Forward modelling[130] calculations using filter theory produce synthetic pseudo resistivity[131] data. This inversion step using synthetic data aims to determine the efficacy of program development before being used to identify subsurface conditions from the real[132] data. The calculation of parameter values is carried out[133,134] 10[135] times, then[136] the best model selection is taken from the mean result. The apparent resistivity data used is free noise and[137] with 5% random noise. Giving noise aims to evaluate the performance of programming against real[138] data. We use the parameter model in Ekinci and Demirci and compare it with the deterministic inversion damp least[139] square inversion program with the Singular Value Decomposition (SVD) technique (Ekinci & Demirci, 2008). For the free noise synthetic data, we use a three-layer earth model with a Q-type[140] data (ρ1>ρ2>ρ3), with the inversion results as[141] shown in table 1.

(Table 1. here)

(Fig 1. here)

The absence of noise results in the inversion results being similar to the actual value.[142] From Table 1, it can be seen[143] that the VFSA inversion gives a better error value than the conventional method. In Fig. 1,[144] the pattern of misfit error decreases with the number of iterations. In the temperature reduction schedule[145] the values of the constants c1,k, and NM are set to 1. T01 is set[146] to 5, this[147] value[148] is taken according to Srigutomo (2021) to obtain a rapid reduction of the error misfit. The application of a low initial temperature will have an impact on[149] a low parameter selection probability value, as[150] a result, no model parameter with a larger[151] error is accepted[152] as a solution. The inversion calculation was performed[153] 10[154] times and[155] the average value was taken[156]. The number of iterations used is 2000 iterations. The results of the inversion[157] using this scheme can be seen[158] in Fig. 2 and Fig. 3.

(Fig. 2 here)

(Fig. 3[159] here)

In general, there is always noise in the measurement of geophysical data, so the synthetic data is given[160] a noise 5[161]%. The model parameter data is based[162] on Ekinci and Demirici (2008) for the QQ-type (ρ1>ρ2>ρ3>ρ4) four-layer earth model. The inversion constant used is the same as in the previous step and[163] the results are shown[164] in Table 2. The uncertainty value depends on the magnitude of the model parameters and the order of the layers[165]. The deeper the measurement, the uncertainty value tends to increase. It proves that rock resistivity measurements are less sensitive with increasing depth. The addition of the noise also affects the resistivity misfit error, although it is not significant.

(Table. 2 here)

(Fig. 4 here)

The pattern of decline in the objective function can be seen[166] in Fig. 4, which is the same as before, no[167] spikes in the objective function are received[168]. In Fig. 5[169] it[171] can also be seen that the observation data[172] and the[172] calculated inversion data are quite[170] close. Then in Fig. 6, it can be seen that there are differences in the distribution of resistivity at each depth in the model and the inversion results, where additional noise affects the efficacy of the VFSA inversion scheme, especially in deeper layers.

(Fig. 5 here)

(Fig. 6 here)

Inversion VFSA[173] to the Field Data

The VFSA inversion scheme that has been tested[174] before then[177] can be applied[175] to field data[177] or real[176] data. The resistivity survey was conducted[178] in Ambon, Maluku, Indonesia. The distribution of apparent resistivity data from field measurements can be seen[179] in Fig. 7. Based on the initial screening, the number of layers,[180] and the search range can be determined[181] as shown in Table 3. The search range/model space is selected based on graph[182] of[183] the resistivity and electrode spacing, then look at the pattern of decreasing or increasing the graph. From[184] the graph also can determination of[185] the number of[186] layers (Koefoed, 1979).

(Table 3 here)

(Fig. 7[187] here)

The VFSA inversion has succeeded in obtaining[188] model parameters that describe the subsurface conditions[189] as shown in Fig. 8. The value of the objective function or misfit error from this VFSA inversion scheme is 1.58, which means that the model and field data are quite[190] suitable and acceptable. Fitting data from model[193] and field data can be seen[191] in Fig. 7. Then[192] the distribution of rock resistivity to depth can also be seen in Fig. 8.

(Fig. 8 here)

(Fig. 9 here)

The next step is to carry out a hydrogeological interpretation based on the geological conditions of the study area and the distribution of resistivity resulting from the inversion.[194] Determination of the type of rock lithology is also based[195] on the table of rock types and resistivity (Telford et al., 1990). Field data collection is located[196] in the Leihitu area of Ambon City. In this area, volcanic rocks are exposed[197] which[198] are included[199] in the Ambon Volcanic Rock Formation (Tpav) (Fig 9). Tpav[200] was formed[201] as a result of[202] volcanism during the Pliocene, which spread almost throughout the Ambon region. The formation is composed of[203] Andesite, Dacite, Breccia, and Tuff lithology (Tjokrosaputro et al., 1993). From the sounding curve, four types of rock layers were obtained[204]. The sounding curve represents increasing resistivity with depth but ends in conductive[205] basal.

According to the geological evaluation of the inversion results, the top layer with a resistivity of 141.2 m represents the top soil[206] with a thickness of 1.43 meters. The layer below is andesite breccia lithology with a thickness of about 4 meters with a high resistivity of 355.9 m.[207] The third layer with[208] a resistivity of about 93.4 m[209] is lapilli tuff 30 meters thick. The fourth layer is coarse tuff with a resistivity of about 34.4 m. The aquifer is estimated to be at a depth of 35.43 m and[210] the cover layer is lapilli tuff which is characterized[211,212] by a higher resistivity value. In this lithological interpretation, there is no basement layer which is[214] usually characterized[213] by compact rock with high resistivity values.

Based on these results, the VFSA inversion program is effective[215] and useful[216] for resistivity data, that application is to find groundwater potential. This program is still[221] limited to one-dimensional resistivity data,[217] so that further it can[218,219,220] develop a VFSA scheme inversion program for two-dimensional or three-dimensional resistivity data.

CONCLUSION

The VFSA method as[222] a type of global optimization approach for resistivity data inversion[223] has succeeded in revealing[224] the subsurface profile. This inversion scheme was pre-tested with synthetic data free of noise and with 5% noise to test the efficacy of this program. The inversion results show satisfactory results with a small RMSE value when using both synthetic data. To further evaluate the application of VFSA inversion, a DC-resistivity data set with a Schlumberger configuration was applied. Field data is in the form of apparent resistivity to electrode spacing, then[225] inverse modelling[226] is carried out to obtain model parameters in the form of rock resistivity and thickness of each layer. From the inversion results, it was found[227] that at the measurement point[228] there were four layers consisting of top soil[229] (141.2 ± 0.61 m) with a thickness of 1.43 m, andesite breccia (355.90 ± 0.46 m) with a thickness of 4 m, Lapilli Tuff (93.40

± 0.31 m) with 30 m thick, then the last Coarse Tuff layer (34.30 ± 0.15 m). The aquifer is estimated to be located[230] from a depth of 35.43 m which is characterized[231] by a low resistivity value with a cover layer of Lapilli Tuff rock. These results indicate the usefullness[232] and effectiveness of the VFSA inversion scheme to be used more broadly for resistivity data, that application to find groundwater potential.

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Table 1. True and obtained model parameters for three-layer-QQ-type[257] model[258] without noise

Parameters

Actual Value

Search range[259]

Mean Model (VFSA)

RMSE=0.00

Earth model (SVD)

RMSE=2.86

ρ1 (Ω.m)

ρ2 Ω.m

ρ3 Ω.m

h1(m)

h2m

100

50

20

5

10

(50-100)

(20-80)

(10-30)

(2-8)

(5-15)

100.00 ± 0.00

50.00 ± 0.00

20.00 ± 0.00

5.00 ± 0.00

10.00 ± 0.00

100.01

50.08

20.00

4.99

9.99

Figure. 1. Pattern of RMS eror[260] convergence for VFSA solution with free noise data

Figure 2. Apparent resistivity curves from FVSA[261] inversion scheme result with[262] free noise data

Figure 3. Resistivity-depth distribution from FVSA[263] inversion scheme result with[2] free noise data and true[265] model

Table 2. True and obtained model parameters for four-layer-QQ-type[266][267] model with noise 5%[268]

Parameters

Actual Value

Search range[269]

Mean Model (VFSA)

RMSE=0.0416

Earth model (SVD)

RMSE=2.86

ρ1 (Ω.m)

ρ2 (Ω.m)

ρ3 (Ω.m)

ρ4 (Ω.m)

h1 (m)

h2 (m)

h3 (m)

100

50

20

10

5

10

20

(50-100)

(20-80)

(10-30)

(5-15)

(2-8)

(5-15)

(10-30)

100.00 ± 0.00

51.80 ± 0.13

23.00 ± 0.67

10.00 ± 0.00

5.00 ± 0.00

8.40 ± 0.27

19.60 ± 0.4

100.00

51.72

21.73

10.07

4.77

9.07

19.57

Figure 4. Pattern[270] of the RMS eror[271] convergence for VFSA solution with 5% noise data

Figure 5. Apparent resistivity curves from FVSA[272] inversion scheme result with[273] 5% noise data

Figure 6. Resistivity-depth distribution from FVSA[274] inversion scheme result with[2] 5% noise data and true[276] model

Table 3. Parameter models of the Field Data

Parameters

Search range[277]

Inversion Result

(RMSE = 1.58)

Geology Interpretation

ρ1 (Ω.m)

ρ2 (Ω.m)

ρ3 (Ω.m)

ρ4 ([illegible].m)

h1 (m)

h2 (m)

h3 (m)

(100-150)

(300-400)

(75-125)

(20-60)

(1-5)

(1-10)

(10-30)

141.2.00 ± 0.61

355.90 ± 0.46

93.40 ± 0.31

34.30 ± 0.15

1.43 ± 0.02

4.00 ± 0.00

30.00 ± 0.00

Top Soil

Andesite Breccia

Lapilli Tuff

Coarse Tuff

Top Soil

Andesite Breccia

Lapilli Tuff

Figure 7. Observed and calculated apparent resistivity curves for the field data

Figure 8. Inverted subsurface resistivity model from the VFSA inversion scheme for the field data

Figure 9. Geological map of Leihitu Area (Modification from Tjokrosapoetro et. al.,[278] 1993)

1.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
2.	~~is~~ → are	Faulty subject-verb agreement	Correctness
3.	~~very important~~ → essential, crucial, vital	Word choice	Engagement
4.	cost-effectiveness	Misspelled words	Correctness
5.	The global	Determiner use (a/an/the/this, etc.)	Correctness
6.	*is not expected*	Passive voice misuse	Clarity
7.	solution,	Punctuation in compound/complex sentences	Correctness
8.	~~that are~~	Wordy sentences	Clarity
9.	*The VFSA method is inspired by phenomena in metallurgy related to the formation of crystals in materials caused by thermodynamic processes.*	Passive voice misuse	Clarity
10.	*is applied*	Passive voice misuse	Clarity
11.	~~that has been~~	Wordy sentences	Clarity
12.	*been measured*	Passive voice misuse	Clarity
13.	~~top soil~~ → topsoil	Confused words	Correctness
14.	~~, then~~ → ; then, , and then, . Then	Punctuation in compound/complex sentences	Correctness
15.	*is estimated*	Passive voice misuse	Clarity
16.	*is included*	Passive voice misuse	Clarity
17.	*is produced*	Passive voice misuse	Clarity

18.	*This*	Intricate text	Clarity
19.	~~major~~ → significant	Word choice	Engagement
20.	~~to maintain~~ → in maintaining	Incorrect verb forms	Correctness
21.	~~very important~~ → essential, crucial, vital	Word choice	Engagement
22.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
23.	*In particular, the vertical electrical sounding (VES) technique and surface electrical resistivity survey has proven to be very useful for studying groundwater due to their simplicity and cost-effectiveness.*	Hard-to-read text	Clarity
24.	~~try~~ → tries	Faulty subject-verb agreement	Correctness
25.	~~applied~~ → apply	Incorrect verb forms	Correctness
26.	*Steiner try to applied resistivity methods combined with seismic methods to investigate pollutants in groundwater (Steiner et al., 2022).*	Unclear sentences	Clarity
27.	~~are~~	Incorrect verb forms	Correctness
28.	*be used*	Passive voice misuse	Clarity
29.	*non-linear; Nonlinear*	Text inconsistencies	Correctness
30.	*Geoelectrical inversion problems are often non-linear and complex, where the solution consists of using a set of apparent resistivity data to obtain subsurface model parameters.*	Hard-to-read text	Clarity
31.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
32.	~~, there~~ → ; there, . There	Punctuation in compound/complex	Correctness

		sentences	
33.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
34.	~~forward~~ → forwards	Faulty subject-verb agreement	Correctness
35.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
36.	*VES data interpretation with this technique is widely used by practitioners of hydrogeology.*	Passive voice misuse	Clarity
37.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
38.	ie,	Comma misuse within clauses	Correctness
39.	*The direct inverse modelling method (ie resistivity inversion with a numerical algorithm) involves minimizing the error between the observed apparent resistivity and that calculated using optimization techniques.*	Hard-to-read text	Clarity
40.	~~where this method~~ → which	Wordy sentences	Clarity
41.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
42.	~~DC current~~ → DC	Wordy sentences	Clarity
43.	*was first investigated*	Passive voice misuse	Clarity
44.	*From that time until the late 1980s, the field survey methodology and the character of the data from the measurements did not change much.*	Intricate text	Clarity
45.		Tone suggestions	Delivery
46.	~~to this day~~	Wordy sentences	Clarity

47.	~~, there~~ → ; there, , and there, . There	Punctuation in compound/complex sentences	Correctness
48.	*The interpretation of VES data is greatly influenced by three events, there is the linear filter theory proposed by Ghosh (Ghosh, 1971), the widespread use of digital computers, and the application of general linear inversion theory.*	Passive voice misuse	Clarity
49.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
50.	*At this time, the concept of inverse modelling and automated analysis is becoming popular, where the computational program generated from this theory can find the most suitable model automatically.*	Unclear sentences	Clarity
51.	, and	Punctuation in compound/complex sentences	Correctness
52.	*The advantage of VFSA over other methods is that it can get the global minimum solution and it can prevent the local minimum from being reached.*	Unclear sentences	Clarity
53.	~~ensure~~ → ensures	Faulty subject-verb agreement	Correctness
54.	*The advantage of VFSA over other methods is that it can get the global minimum solution and it can prevent the local minimum from being reached. VFSA inversion ensure the solution's stability and can be used to make the noise data robust.*	Unclear paragraphs	Clarity
55.	*be used*	Passive voice misuse	Clarity
56.	~~very easy~~ → straightforward	Word choice	Engagement
57.	~~to use~~	Wordy sentences	Clarity

58.	~~which will produce~~ → producing	Wordy sentences	Clarity
59.	*is expressed*	Passive voice misuse	Clarity
60.	~~in the form of~~ → as	Wordy sentences	Clarity
61.	~~first order~~ → first-order	Misspelled words	Correctness
62.	~~indicate~~ → indicates	Faulty subject-verb agreement	Correctness
63.	~~an integral~~ → a crucial	Word choice	Engagement
64.	, and	Comma misuse within clauses	Correctness
65.	the thickness	Determiner use (a/an/the/this, etc.)	Correctness
66.	*i-th*	Unknown words	Correctness
67.	~~19 point~~ → 19-point	Misspelled words	Correctness
68.	*be used*	Passive voice misuse	Clarity
69.	*is considered*	Passive voice misuse	Clarity
70.	~~before~~	Wrong or missing prepositions	Correctness
71.	*be obtained*	Passive voice misuse	Clarity
72.	~~logL~~ → log	Misspelled words	Correctness
73.	*is used*	Passive voice misuse	Clarity
74.	~~is used to calculate~~ → calculates	Wordy sentences	Clarity
75.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
76.	resistivity-sounding	Misspelled words	Correctness

77.	study,	Comma misuse within clauses	Correctness
78.	~~a very fast~~ → a speedy, a swift, a high-speed	Word choice	Engagement
79.	*The global minimum inversion of Simulated Annealing (SA) is inspired by a phenomenon in metallurgy related to the formation of crystals in materials caused by thermodynamic processes.*	Passive voice misuse	Clarity
80.	*is heated*	Passive voice misuse	Clarity
81.	*At high temperatures, the atoms move randomly and freely, given the high kinetic energy.*	Unclear sentences	Clarity
82.	*is carried out*	Passive voice misuse	Clarity
83.	results	Wordy sentences	Clarity
84.	, resulting	Punctuation in compound/complex sentences	Correctness
85.	temperature-cooling	Misspelled words	Correctness
86.	*The geophysical inversion problem takes an analogy from this annealing event, where the temperature cooling process is represented by an iteration process to find the optimum solution.*	Passive voice misuse	Clarity
87.	system's energy	Wordy sentences	Clarity
88.	future,	Punctuation in compound/complex sentences	Correctness
89.	~~. The~~ → , the	Incomplete sentences	Correctness
90.	~~same~~ → exact	Word choice	Engagement

91.	*Second, some existing SA algorithms are not capable of performing sufficiently elegant and fast calculations if the Cauchy random number is equal to the number of model parameters.*	Unclear sentences	Clarity
92.	*be avoided*	Passive voice misuse	Clarity
93.	~~own~~	Wordy sentences	Clarity
94.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
95.	*be achieved*	Passive voice misuse	Clarity
96.	*Ingber proposed a new probability distribution for modelling so that convergence can be achieved without a slow cooling schedule.*	Unclear sentences	Clarity
97.	~~mik~~ → mid	Misspelled words	Correctness
98.	mik,	Punctuation in compound/complex sentences	Correctness
99.	*mimin*	Unknown words	Correctness
100.	~~mimax~~ → max	Misspelled words	Correctness
101.	~~minimum~~ → minima	Incorrect noun number	Correctness
102.	~~value~~ → values	Incorrect noun number	Correctness
103.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
104.	pseudo-resistivity	Misspelled words	Correctness
105.	*be obtained*	Passive voice misuse	Clarity
106.	~~real~~ → actual, accurate	Word choice	Engagement
107.	is also	Incorrect verb forms	Correctness

108.	~~point-i~~ → point i	Misspelled words	Correctness
109.	~~mimin~~ → min	Misspelled words	Correctness
110.	that,	Comma misuse within clauses	Correctness
111.	~~ui~~ → UI	Misspelled words	Correctness
112.	*yi*	Unknown words	Correctness
113.	the temperature	Determiner use (a/an/the/this, etc.)	Correctness
114.	is,	Punctuation in compound/complex sentences	Correctness
115.	~~has been~~ → was	Faulty tense sequence	Correctness
116.	*is then resurrected*	Passive voice misuse	Clarity
117.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
118.	~~misfit error~~	Wordy sentences	Clarity
119.	*However, if the misfit error of the new model is greater than the misfit error of the previous model, then a random number from 0 to 1 is generated and compared with the probability of acceptance of the model.*	Hard-to-read text	Clarity
120.	~~greater~~ → more significant	Word choice	Engagement
121.	~~, and conversely~~ → . Conversely	Hard-to-read text	Clarity
122.	*is rejected*	Passive voice misuse	Clarity
123.	*smaller*	Incomplete sentences	Delivery
124.	~~smaller~~ → more negligible	Word choice	Engagement

125.	*is based*	Passive voice misuse	Clarity
126.	constants,	Punctuation in compound/complex sentences	Correctness
127.	, and	Punctuation in compound/complex sentences	Correctness
128.	~~update~~ → updated	Misuse of modifiers	Correctness
129.	*k and c1 are constants, whose values differ depending on the model parameters. T01 is the initial temperature and Ti is the update temperature.*	Unclear paragraphs	Clarity
130.	~~modelling~~ → modeling	Mixed dialects of English	Correctness
131.	pseudo-resistivity	Misspelled words	Correctness
132.	~~real~~ → actual, accurate	Word choice	Engagement
133.	*is carried out*	Passive voice misuse	Clarity
134.	~~carried out~~ → performed	Wordy sentences	Clarity
135.	~~10~~ → ten	Improper formatting	Correctness
136.	~~, then~~ → ; then, , and then, . Then	Punctuation in compound/complex sentences	Correctness
137.	~~and~~	Wordy sentences	Clarity
138.	~~real~~ → actual, accurate	Word choice	Engagement
139.	~~least~~ → most miniature, most minor	Word choice	Engagement
140.	~~a~~ Q-type	Determiner use (a/an/the/this, etc.)	Correctness

141.	~~as~~	Wordy sentences	Clarity
142.	*The absence of noise results in the inversion results being similar to the actual value.*	Incomplete sentences	Delivery
143.	*be seen*	Passive voice misuse	Clarity
144.	*From Table 1, it can be seen that the VFSA inversion gives a better error value than the conventional method. In Fig. 1, the pattern of misfit error decreases with the number of iterations.*	Unclear paragraphs	Clarity
145.	schedule,	Punctuation in compound/complex sentences	Correctness
146.	*is set*	Passive voice misuse	Clarity
147.	~~, this~~ → ; this, , and this, . This	Punctuation in compound/complex sentences	Correctness
148.	~~this value~~ → which	Wordy sentences	Clarity
149.	~~have an impact on~~ → impact	Wordy sentences	Clarity
150.	~~, as~~ → . As, ; as	Punctuation in compound/complex sentences	Correctness
151.	~~larger~~ → more significant	Word choice	Engagement
152.	*is accepted*	Passive voice misuse	Clarity
153.	*was performed*	Passive voice misuse	Clarity
154.	~~10~~ → ten	Improper formatting	Correctness
155.	, and	Punctuation in compound/complex sentences	Correctness

156.	*was taken*	Passive voice misuse	Clarity
157.	inversion results	Wordy sentences	Clarity
158.	*be seen*	Passive voice misuse	Clarity
159.	~~3~~ → Three	Improper formatting	Correctness
160.	*is given*	Passive voice misuse	Clarity
161.	of 5	Wrong or missing prepositions	Correctness
162.	*is based*	Passive voice misuse	Clarity
163.	, and	Punctuation in compound/complex sentences	Correctness
164.	*are shown*	Passive voice misuse	Clarity
165.	*The uncertainty value depends on the magnitude of the model parameters and the order of the layers.*	Unclear sentences	Clarity
166.	*be seen*	Passive voice misuse	Clarity
167.	~~, no~~ → ; no, . No	Punctuation in compound/complex sentences	Correctness
168.	*are received*	Passive voice misuse	Clarity
169.	5,	Punctuation in compound/complex sentences	Correctness
170.	~~quite~~ → pretty	Word choice	Engagement
171.	*The pattern of decline in the objective function can be seen in Fig. 4, which is the same as before, no spikes in the objective function are received. In Fig. 5 it*	Unclear paragraphs	Clarity

	can also be seen that the observation data and the calculated inversion data are quite close.		
172.	*In Fig. 5 it can also be seen that the observation data and the calculated inversion data are quite close.*	Unclear sentences	Clarity
173.	of VFSA	Wrong or missing prepositions	Correctness
174.	*been tested*	Passive voice misuse	Clarity
175.	*be applied*	Passive voice misuse	Clarity
176.	~~real~~ → accurate, actual	Word choice	Engagement
177.	*The VFSA inversion scheme that has been tested before then can be applied to field data or real data.*	Unclear sentences	Clarity
178.	*was conducted*	Passive voice misuse	Clarity
179.	*be seen*	Passive voice misuse	Clarity
180.	layers,	Punctuation in compound/complex sentences	Correctness
181.	*be determined*	Passive voice misuse	Clarity
182.	the graph, or a graph	Determiner use (a/an/the/this, etc.)	Correctness
183.	*The search range/model space is selected based on graph of the resistivity and electrode spacing, then look at the pattern of decreasing or increasing the graph.*	Unclear sentences	Clarity
184.	~~From~~ the	Wrong or missing prepositions	Correctness
185.	*From the graph also can determination of the number of layers (Koefoed, 1979).*	Unclear sentences	Clarity

186.	~~number of~~ → number of	Improper formatting	Correctness
187.	~~7~~ → Seven	Improper formatting	Correctness
188.	~~succeeded in obtaining~~ → obtained	Wordy sentences	Clarity
189.	conditions,	Punctuation in compound/complex sentences	Correctness
190.	~~quite~~ → pretty	Word choice	Engagement
191.	*be seen*	Passive voice misuse	Clarity
192.	Then,	Punctuation in compound/complex sentences	Correctness
193.	*The VFSA inversion has succeeded in obtaining model parameters that describe the subsurface conditions as shown in Fig. 8. The value of the objective function or misfit error from this VFSA inversion scheme is 1.58, which means that the model and field data are quite suitable and acceptable. Fittin...*	Unclear paragraphs	Clarity
194.	*The next step is to carry out a hydrogeological interpretation based on the geological conditions of the study area and the distribution of resistivity resulting from the inversion.*	Hard-to-read text	Clarity
195.	*is also based*	Passive voice misuse	Clarity
196.	*is located*	Passive voice misuse	Clarity
197.	*are exposed*	Passive voice misuse	Clarity
198.	, which	Punctuation in compound/complex sentences	Correctness

199.	*are included*	Passive voice misuse	Clarity
200.	~~Tpav~~ → Trav, Travel	Misspelled words	Correctness
201.	*was formed*	Passive voice misuse	Clarity
202.	~~as a result of~~ → due to	Wordy sentences	Clarity
203.	~~is composed of~~ → comprises	Wordy sentences	Clarity
204.	*were obtained*	Passive voice misuse	Clarity
205.	a conductive	Determiner use (a/an/the/this, etc.)	Correctness
206.	~~top soil~~ → topsoil	Confused words	Correctness
207.	*The layer below is andesite breccia lithology with a thickness of about 4 meters with a high resistivity of 355.9 m.*	Hard-to-read text	Clarity
208.	, with	Punctuation in compound/complex sentences	Correctness
209.	m,	Punctuation in compound/complex sentences	Correctness
210.	, and	Punctuation in compound/complex sentences	Correctness
211.	*is characterized*	Passive voice misuse	Clarity
212.	*The aquifer is estimated to be at a depth of 35.43 m and the cover layer is lapilli tuff which is characterized by a higher resistivity value.*	Unclear sentences	Clarity
213.	*is usually characterized*	Passive voice misuse	Clarity
214.	*In this lithological interpretation, there is*	Unclear sentences	Clarity

	no basement layer which is usually characterized by compact rock with high resistivity values.		
215.	~~effective~~ → practical	Word choice	Engagement
216.	~~useful~~ → valuable	Word choice	Engagement
217.	data,	Punctuation in compound/complex sentences	Correctness
218.	~~that~~ further	Conjunction use	Correctness
219.	it can further	Wordy sentences	Clarity
220.	~~further it can~~ → it can further	Misplaced words or phrases	Correctness
221.	*Based on these results, the VFSA inversion program is effective and useful for resistivity data, that application is to find groundwater potential. This program is still limited to one-dimensional resistivity data, so that further it can develop a VFSA scheme inversion program for two-dimensional o...*	Unclear paragraphs	Clarity
222.	, as	Punctuation in compound/complex sentences	Correctness
223.	inversion,	Punctuation in compound/complex sentences	Correctness
224.	~~succeeded in revealing~~ → revealed	Wordy sentences	Clarity
225.	~~, then~~ → ; then, , and then, . Then	Punctuation in compound/complex sentences	Correctness
226.	~~modelling~~ → modeling	Mixed dialects of English	Correctness

227.	*was found*	Passive voice misuse	Clarity
228.	point,	Punctuation in compound/complex sentences	Correctness
229.	~~top soil~~ → topsoil	Confused words	Correctness
230.	*be located*	Passive voice misuse	Clarity
231.	*is characterized*	Passive voice misuse	Clarity
232.	~~usefullness~~ → usefulness	Misspelled words	Correctness
233.	~~Alarifi~~ → Clarify	Misspelled words	Correctness
234.	~~of~~	Wordy sentences	Clarity
235.	~~of~~	Wordy sentences	Clarity
236.	, and	Comma misuse within clauses	Correctness
237.	a high	Determiner use (a/an/the/this, etc.)	Correctness
238.	the case, or a case	Determiner use (a/an/the/this, etc.)	Correctness
239.	~~The Application of~~ → Applying	Wordy sentences	Clarity
240.	*Guptasarma, D. (1982). optimization of short digital linear filters for increased accuracy. Geophysical Prospecting, 30, 501–514.*	Unclear paragraphs	Clarity
241.	*Very fast simulated re-annealing. Mathematical and Computer Modelling, 12(8), 967–973.*	Unclear paragraphs	Clarity
242.	vs.	Comma misuse within clauses	Correctness

243.	*Simulated annealing: practice vs theory. Mathematical and Computer Modelling, 18(11), 29–57.*	Unclear paragraphs	Clarity
244.		Incorrect citation format	Correctness
245.	~~Two dimensional~~ → Two-dimensional	Misspelled words	Correctness
246.	~~inversion~~ → inversions	Incorrect noun number	Correctness
247.	radio magnetotelluric	Misspelled words	Correctness
248.	*Global Optimization Methods in Geophysical Inversion (2ed ed.). Cambridge University Press.*	Unclear paragraphs	Clarity
249.	~~interpretation of~~ → interpreting	Wordy sentences	Clarity
250.		Incorrect citation format	Correctness
251.	*Applied Geophysics (2nd ed.). Cambridge University Press.*	Unclear paragraphs	Clarity
252.	~~Two Dimensional~~ → Two-Dimensional	Misspelled words	Correctness
253.	~~assesment~~ → assessment	Misspelled words	Correctness
254.	the sea-freshwater	Determiner use (a/an/the/this, etc.)	Correctness
255.	*Inversion and uncertainty assessment of ultra-deep azimuthal resistivity logging-while-drilling measurements using particle swarm optimization.*	Hard-to-read text	Clarity
256.	~~Integration of~~ → Integrating	Wordy sentences	Clarity
257.	~~three layer~~ → three-layer	Misspelled words	Correctness
258.	the three-layer-QQ-type, or a three-layer-QQ-type	Determiner use (a/an/the/this, etc.)	Correctness

259.	~~range~~ → Range	Confused words	Correctness
260.	~~eror~~ → error	Misspelled words	Correctness
261.	the FVSA	Determiner use (a/an/the/this, etc.)	Correctness
262.	~~with~~ → in	Wrong or missing prepositions	Correctness
263.	the FVSA	Determiner use (a/an/the/this, etc.)	Correctness
264.	~~with~~ → in	Wrong or missing prepositions	Correctness
265.	~~true~~ → accurate, actual	Word choice	Engagement
266.	~~four-layer~~ → four-layer	Misspelled words	Correctness
267.	a four-layer-QQ-type, or the four-layer-QQ-type	Determiner use (a/an/the/this, etc.)	Correctness
268.	of 5	Wrong or missing prepositions	Correctness
269.	~~range~~ → Range	Confused words	Correctness
270.	The pattern, or A pattern	Determiner use (a/an/the/this, etc.)	Correctness
271.	~~eror~~ → error	Misspelled words	Correctness
272.	the FVSA	Determiner use (a/an/the/this, etc.)	Correctness
273.	~~with~~ → in	Wrong or missing prepositions	Correctness
274.	the FVSA	Determiner use (a/an/the/this, etc.)	Correctness
275.	~~with~~ → in	Wrong or missing prepositions	Correctness
276.	~~true~~ → accurate, actual	Word choice	Engagement

277.	~~range~~ → Range	Confused words	Correctness
278.	~~et. al.~~ → et al.	Comma misuse within clauses	Correctness