# Mechanism of groundwater inrush hazard caused by solution mining in a multilayered rock salt mining area: A case study in Tongbai, China

Bin Zeng<sup>1\*</sup>, Tingting Shi<sup>2</sup>, Zhihua Chen<sup>1</sup>, Liu Xiang<sup>3</sup>, Shaopeng Xiang<sup>4</sup>, Muyi Yang<sup>1</sup>

<sup>1</sup>. School of Environmental Studies, China University of Geosciences, Wuhan 430074, Hubei, P.R.China.

<sup>2</sup>. Three Gorges Research Center for Geo-Hazard, Ministry of Education, Wuhan 430074, Hubei, P.R.China.

<sup>3</sup>. Department of Geological Engineering, Hubei Land Resources Vocational College. Wuhan 430074, P.R.China.

<sup>4</sup>. Hydrological Engineering Environment Technology Consulting Co. Ltd. Wuhan 430074, P.R.China.

\*Corresponding author: Bin Zeng, Ph.D.

Affiliation: School of Environmental Studies, China University of Geosciences.

Affiliation address: No. 388 Lumo Road, Wuhan, Hubei, 430074, P.R. China.

Email: zengbin\_19@126.com. Tel: 86-27-67883473. Fax: 86-27-87436235.

#### 1 ABSTRACT

2 The solution mining of salt mineral resources may contaminate groundwater and lead to water inrush out of the ground due to brine leakage. Through the example of a serious groundwater inrush 3 hazard in a large salt mining area in Tongbai County, China, this study mainly aims to analyze the 4 source and channel of the inrushing water. The mining area has three different types of ore beds 5 including trona (trisodium hydrogendicarbonate dihydrate, also sodium sesquicarbonate dihydrate, with 6 the formula Na<sub>2</sub>CO<sub>3</sub>•NaHCO<sub>3</sub>•2H<sub>2</sub>O, it is a non-marine evaporite mineral), glauber (sodium sulphate, it 7 is the inorganic compound with the formula Na<sub>2</sub>SO<sub>4</sub> as well as several related hydrates) and gypsum (a 8 soft sulphate mineral composed of calcium sulphate dihydrate, with chemical formula CaSO<sub>4</sub>·2H<sub>2</sub>O). 9 Based on characterization of the geological and hydrogeological conditions, the hydrochemical data of 10 the groundwater at different points and depths were used to analyze the pollution source and the 11 pollutant component from single or mixed brines by using physical-chemical reaction principle analysis 12 and hydrogeochemical simulation method. Finally, possible leakage brine conducting channel to the 13 ground was discussed from both the geological and artificial aspects. The results reveal that the brine 14 from the trona mine is the major pollution source; there is a NW-SE fissure zone controlled by the 15 geological structure that provides the main channels for the leakage brine to flow into the aquifer 16 around the water inrush regions, with the large number of waste gypsum exploration boreholes being 17 the channels that supply the polluted groundwater inrush out of the ground. This research can offer a 18 19 valuable reference for avoiding and assessing groundwater inrush hazards in similar rock salt mining 20 areas, which is advantageous for both groundwater quality protection and public health.

#### 21 1. Introduction

22 Solution mining is commonly used in salt mine exploitation, as salts are soluble in water. In this method, high-pressure and -temperature water with low salinity is injected into a mineral deposit 23 through production wells to dissolve the mineral salts. After being drawn from the wells, the soluble salt 24 25 is purified and further processed. However, the high-pressure and -temperature water used in this process not only dissolves minerals but also cause fractures in the strata, which usually results in 26 hazards, such as brine leakage or groundwater inrush. In this situation, drinking groundwater for the 27 28 public is normally polluted following groundwater inrush, thus creating a hazard and threatening the health of local residents. 29

Many scholars (Clark and Fritz, 1997; Liu et al., 2015; Wu et al., 2016) have studied groundwater 30 inrush hazards in both coal and metal mines, and some adopted methods are as follows: the use of water 31 level/temperature criterion (Yuan and Gui, 2005; Ma and Qian, 2014), stochastic simulation 32 (Fernandez-Galvez et al., 2007), numerical simulation (Liu et al., 2009; Kang et al., 2012; Shao et al., 33 2013; Houben, et al., 2017), water chemical analysis (isotope analysis, water quality type correlation 34 analysis) (Robins, 2002; Fernandez et al., 2005; Hu et al., 2010; Cobbina et al., 2015; Lee et al., 2016; 35 LeDoux et al., 2016), multivariate statistics (discriminant analysis, clustering analysis) (Chen and Li, 36 2009; Lu, 2012), fractional advection dispersion equations (Ramadas et al., 2015) and nonlinear 37 analysis (fuzzy mathematics, grey correlation analysis, etc.) (Hao et al., 2010; Gao, 2012). However, 38 due to the particularity of the solution mining method and the complex chemical-physical reactions 39 during the high-pressure and -temperature mining process, researches regarding solution mining were 40 41 mainly focused on mining techniques (Jiang and Jiang, 2004; Kotwica, 2008; Namin et al., 2009), mining cavity stability analysis and sinkhole problems (Staudtmeister and Rokahr, 1997; Bonetto et al., 42 2008; Ezersky et al., 2009; Goldscheider and Bechtel, 2009; Closson and Abou Karaki, 2009; Vigna et 43

al., 2010; Frumkin et al., 2011; Ezersky and Frumkin, 2013; Qiu, 2011; Blachowski et al., 2014), and
geohazards particularly in karst areas due to human-induced underground caving (Waltham and Fookes
2003; Parise and Gunn 2007; Zhou and Beck 2011; Parise and Lollino 2011; Lollino et al., 2013;
Gutierrez et al., 2014; Parise et al., 2015), but rarely on source and channel analysis of inrush water in a
solution mining accident.

The study case of rock salt mining area is located in Tongbai County, Henan Province, China. This 49 mining area has the second largest trona reserves in the world, while its glauber salt reserves reach 45 50 51 million tons. Since trona and glauber salt were put into production in 1990 with single- and double-well convection mining as the main producing method, five inrush points appeared in the town of Anpeng, 52 Tongbai County, from June 2011 to May 2013. Among these five inrush points, four (Y1~Y4) were 53 long-term (longer than 2 years) inrush points with stable discharge, while one (Y-5) was a sudden inrush 54 point (as shown in Fig. 1 and Fig. 2). Almost 200 m<sup>3</sup> of mud and sediment erupted out of the ground at 55 the Y-5 point on 1 February 2013. The area of the inrush point was  $\sim 4 \text{ m}^2$ ; the average water inflow was 56 20-30  $\text{m}^3/\text{d}$  while the greatest inflow reached 200  $\text{m}^3/\text{d}$ . The water inrush lasted for approximately three 57 months. During the Y-5 inrush accident, according to the field investigation, a trona production well 58 named "S02," located 200 m far from the inrush point, broke at a depth of 234 m and remained broken 59 for a long period of time. It was repaired on 15 March 2013. During the entire water inrush process, the 60 groundwater inrush led to a phenomenon of salinization at the house base of many villagers, and made 61 water in many residents' wells no longer drinkable. 62

63 Since the groundwater inrush hazard involved a wide geographic area and the inrush source was 64 quite hard to distinguish due to the multi-layer distribution of the different ore bodies and the 65 complexity of the inrush water component, a targeted treatment program to stop the water inrush and 66 mitigate the groundwater pollution were needed urgently in research region. Therefore, the source and channel of the inrush water were taken as the research emphasis in this study. Furthermore, this research
can provide a valuable reference for avoiding and assessing groundwater inrush hazards in similar rock
salt mining areas, which is advantageous for both groundwater quality protection and public health.

70 **2. Geological and hydrogeological setting** 

# 71 2.1. Geological conditions

The mining area is located in northwestern Tongbai County. The landscape is characterized by hollows and ridges, with an elevation ranging from 140 to 200 m above sea level.

74 The main development period of the research area consists of strata from the Hetaoyuan, Liaozhuang, and Fenghuangzhen Formations, from the oldest to the youngest, respectively. The 75 Hetaoyuan Formation of Paleogene consists mainly of dolomite, muddy dolomite, mudstone, dolomitic 76 mudstone, sandy conglomerate, and siltstone. The third segment in the Hetaoyuan Formation is 77 composed of thick mudstone interlayered with sandy conglomerate, as well as thin layers of shale, 78 muddy dolomite and glauber salt. The second segment is composed of mudstone interlayered with 79 muddy dolomite and dolomite, as well as small amount of trona. The first segment consists of mudstone, 80 muddy dolomite, dolomite, shale, siltstone and trona. The upper part of the Liaozhuang Formation of 81 Paleogene consists of mudstone interlayered with gypsum, while the lower part consists of alternating 82 layers of mudstone and sandy conglomerate. The Fenghuangzhen Formation of Neogene and 83 Quaternary consist of alternating layers of sandy conglomerate and sandy clay (Shi et al., 2013). The 84 detailed information about strata, lithology, aquifer, and the position of different ore beds in the research 85 area are shown in Fig. 3. 86

According to geologic references and field investigation, in the northeastern mining area, a hidden east-west oriented fault develops at the bottom of the first segment of the Hetaoyuan Formation, and another four, hidden, south-north oriented faults develop at the bottom of the second segment of the

Hetaoyuan Formation. These five faults are outside the scope of trona mine, so they have little effects on the ore bed. A few small-scale hidden faults develop at the bottom of the third segment of the Hetaoyuan Formation, although within the scope of the glauber salt mine, they have little effects on the glauber salt ore bed which is distributed at the top of the first segment of Hetaoyuan Formation. A hidden east-west oriented fault is developed at the bottom of the Liaozhuang Formation in the range of the glauber salt mine, but it has little effects on the glauber salt mine because of its small scale.

# 96 2.2. Hydrogeological conditions

97 The groundwater in the mining area can be divided into pore water in the loose rock mass and 98 bedrock fissure water according to the lithology and hydrogeological features. In the upper part of the 99 Liaozhuang Formation, a mudstone interbedded with gypsum is considered a relative weak permeable 100 stratum especially under the condition of high-pressure and -temperature water injection during the 101 mining period. The shallow aquifer is unconsolidated pore water above this weak permeable stratum, 102 while the deep aquifer is a bedrock fissure beneath this weak permeable stratum.

The flow direction of the shallow groundwater is controlled by the regional terrain. Taking the 103 underground watershed as the boundary, the groundwater on the south side of the watershed is mainly 104 flowing from northeast to southwest with the Yanhong River as the drainage base, while the 105 groundwater on the north side of the watershed is mainly flowing from south to north with the Xia 106 River as the drainage base. The deep groundwater is in relatively closed burial conditions, with slow 107 velocity, and nearly the same flowing direction as the shallow groundwater. The water inflow of a single 108 well with poor water content is approximately 100  $\text{m}^3/\text{d}$ , while it can reach 1000-2000  $\text{m}^3/\text{d}$  if it has rich 109 110 water content. The annual amplitude of the groundwater level is from 2 to 4 m, while the depth is stable at 2.3-4 m. Residents in Anpeng use groundwater as their drinking water, which comes from wells in the 111 porous aquifer. 112

Gypsum mainly occurs at the top of the Liaozhuang Formation, glauber salt occurs in the third member of the Hetaoyuan Formation, and the trona occurs at the bottom of the second member of the Hetaoyuan Formation, as well as on top of the first member of the Hetaoyuan Formation (Fig. 3). The surrounding rocks of every mineral layer, including mudstone, shale, sandy conglomerate, psammitic rock and dolomite, have sufficient thickness and good water-resistance. Therefore, the effect of groundwater on the mineral deposit is minimal in the mining area.

# 119 **2.3** Distribution and characteristics of the ore body

The three ore bodies overlap in plane distribution, as shown in Fig. 4. The vertical distribution of the ore bodies from deep-to-shallow is trona (buried depth: 1560.92-2929.53 m), glauber salt (buried depth: 1003.66-1397.58 m) and gypsum (buried depth: 134-338 m). The trona and glauber salt bodies are at least 250 m apart from each other vertically.

The trona has 11 horizontal layers, with an average thickness of 2.11 m. The chemical composition of trona is mainly NaHCO<sub>3</sub> (average of 77.06%) and Na<sub>2</sub>CO<sub>3</sub> (average of 16.33%) (Wang, 1987). The glauber salt has 4 layers, with an average thickness of 8.93 m. The dip angle of the ore bed layer is less than 10°. The average mineral grade is 60.14%. The main composition of the glauber salt is Na<sub>2</sub>SO<sub>4</sub> (>90%) with a small amount of NaCl.

## 129 **3. Methods**

Based on the field investigation results, the chemical analysis of the inrush water at different sites and time, analysis of the physical and chemical reaction principles for the different brines, combined with the PHREEQC simulation method, the source of the inrush water was determined.

133 **3.1.** Sampling and testing

The five groundwater inrush points (Y1~Y5) and some shallow groundwater points (resident wells:
SY1~SY6) near the accident site were chosen as groundwater quality sampling points, as shown in Fig.

136 4. Water from each point was sampled on 9 March 2013.

Water samples were filtered using a 0.45  $\mu$ m millipore filtration membrane in the field, and then filled with a polyethylene bottle which had been soaked in acid and washed with deionised water. Filtered water samples were acidified until reaching pH<2 by addition of ultra-pure HNO<sub>3</sub> for the determination of cations; water samples for the determination of anions were not treated.

Elements tested in the laboratory included 26 cations ( $K^+$ ,  $Na^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Sr^{2+}$ , etc.) and 5 anions ( $F^-$ ,  $CI^-$ ,  $NO_3^-$ ,  $SO_4^{2-}$ ,  $NO_2^-$ ). The instrument used for the determination of cations was an inductively coupled plasma atomic emission spectrometer (Agilent ICP-OES 5100), with minimum detection limit at 0.0001mg/L. The instrument used for the determination of anions was an ion chromatograph (ICS-1100), and the minimum detection limit was 0.001 mg/L.  $CO_3^{2-}$  and  $HCO_3^-$  were tested according to the "Groundwater quality test method: Determination of carbonate and bicarbonate by hydroxide titration (DZ/T 0064.49-93)," with minimum detection limit at 0.01 mg/L.

In addition, from March to April 2013, at the Y-5 and Y-3 sites, three water quality automatic recorders (Levelogger gold, Canada) were arranged for inrush water monitoring. Monitoring indicators were temperature, water level and electrical conductivity. The purpose of the monitoring was to fully understand the inrush water quality during the whole accident, especially in the process of well reparation.

# 153 **3.2.** Analysis of the physical and chemical reaction principles in different brine mixing conditions

During the accident, the leakage brine of the trona (2000 m below the ground) or glauber salt (1000 m below the ground) might flow through the gypsum deposit (200-400 m below the ground), which is comprised primarily of CaSO<sub>4</sub>, and cause physical and chemical reactions while it inrushes out of the ground. Thus, the formation of the chemistry component in inrush water might be from glauber brine, or trona brine, or a mixture of the twos, flowing through the gypsum layer accompanying physical and chemical reactions. To provide the basis for further analysis of the inrush water source, the physical solubility of the gypsum and the reaction when the glauber salt brine, the trona brine, or a mixture of the twos flowed through the gypsum deposits were analyzed.

## 162 3.2.1. The physical solubility of gypsum (CaSO<sub>4</sub>)

163 Gypsum is slightly soluble; when in water, its acidity is apparent. Eq. (1) provides the dissolution
 164 rate equation of gypsum in water:

165 
$$R_{Gypsum} = k_1 \times \frac{A_g}{V} \left(1 - \left(\frac{IAP}{K}\right)_{Gypsum}\right)$$
(1)

Where R<sub>Gypsum</sub>: the dissolution rate of gypsum; k<sub>1</sub>: rate constant; A<sub>g</sub>: the surface area of gypsum; V: the liquid volume in contact with the gypsum surface; IAP: the product of ion activity; and K: ion solubility product.

169 
$$\left(\frac{IAP}{K}\right)_{Gypsum}$$
 is affected by the temperature, as is the case for  $R_{Gypsum}$ .

The solubility of gypsum in water reaches a maximum of 0.2097 g/100 g at 40  $^{\circ}$ C. The solubility decreases when the temperature is below or above 40  $^{\circ}$ C. The content of SO<sub>4</sub><sup>2-</sup> and Ca<sup>2+</sup> obtained by physical dissolution is very low.

# 173 *3.2.2. Gypsum (CaSO<sub>4</sub>) dissolved by glauber salt brine (Na<sub>2</sub>SO<sub>4</sub>)*

Equations (2) and (3) show the reactions of  $Na_2SO_4$  and  $CaSO_4$  with water.

175 
$$Na_2SO_4 = 2Na^+ + SO_4^{2-}$$
(2)

176

$$CaSO_4 \rightleftharpoons Ca^{2+} + SO_4^{2-} \tag{3}$$

Because of the common-ion effect, the solubility of the electrolyte will decrease when a strong electrolyte with the same ion is placed into an electrolyte-saturated solution. Thus, the solubility of gypsum will be reduced when glauber salt brine flows through and dissolves the gypsum deposits; the gypsum will be even harder to dissolve in this situation. Thus, if the glauber salt brine flows through the

- 181 gypsum deposits, the brine characteristic would not apparently change.
- 182 *3.2.3.* The reaction of trona brine or a mixture of trona and glauber salt brine with gypsum

The  $HCO_3^-$  and  $CO_3^{-2-}$  contents in trona brine or in mixed brine are very high as is the solution alkalinity and pH. If the reaction kinetics is not taken into account, the pH has little influence on the dissolution of gypsum (Yang, 2003; Xu and Li, 2011). The reaction occurs when the brine with high concentrations of  $HCO_3^-$  and  $CO_3^{-2-}$  flows through the gypsum deposits. The main chemical reactions are as follows:

188

$$Na_{2}CO_{3}+CaSO_{4} \Rightarrow Na_{2}SO_{4}+CaCO_{3} \downarrow$$

$$\tag{4}$$

$$2NaHCO_3 + CaSO_4 \Rightarrow Ca(OH)_2 + Na_2SO_4 + 2CO_2 \uparrow$$
(5)

In Eq. (4),  $CaSO_4$  is slightly soluble, while  $CaCO_3$  is insoluble. The reaction easily occurs when an insoluble substance is produced by a slight soluble substance, and the ionic equation is as follows:

192 
$$\operatorname{CO}_3^{2-}+\operatorname{CaSO}_4\cdot 2\operatorname{H}_2O \rightleftharpoons \operatorname{SO}_4^{2-}+\operatorname{CaCO}_3\downarrow + 2\operatorname{H}_2O$$
 (6)

193 The Gibbs Free Energy ( $\Delta G$ ) is -22.7 kJ/mol under the standard state. When  $\Delta G$  is negative, the 194 reaction, which is endothermic, occurs freely. The reaction is faster at higher temperatures. Eq. (5) 195 shows that  $\Delta G$  is 2102 kJ/mol under the standard state. When  $\Delta G$  is positive, the reaction will not freely 196 occur.

197 Thus, the reaction shown in Eq. (5) will not occur, but the chemical reaction will still proceed as 198 shown in Eq. (4), when trona brine or mixed brine flow through the gypsum deposits.

# 199 *3.2.4. The carbonate equilibrium effect during the reaction of different brines*

- 200 The carbonate equilibrium in the trona brine or in the mixed brine is affected by pH. The carbonate 201 in groundwater exists in three forms: free carbonic acid, bicarbonate and carbonic acid.
- In the trona brine (pH>10), the concentration of  $HCO_3^-$  is 5-20 times that of the  $CO_3^{2-}$  concentration,
- and  $\text{CO}_3^{2-}$  in the brine is dominant in this case. When the trona brine flows through the gypsum, CaSO<sub>4</sub>

reacts with  $CO_3^{2-}$  and  $CaCO_3$  precipitates. If the concentration of  $CO_3^{2-}$  in the brine decreases, a reversible reaction will take place and drive the equilibrium to the right. Thus, the reverse reaction will occur when the trona brine flows through the gypsum as follows:

$$207 CO_3^{2-} + CaSO_4 \Rightarrow SO_4^{2-} + CaCO_3 \downarrow (7)$$

$$HCO_{3} \doteq H^{+} + CO_{3}^{2}$$
(8)

The circular reactions as shown in Eqs. (7) and (8) will occur when mixed brine flows through the gypsum because it has similar properties to the trona brine. Thus, taking the carbonate equilibrium effect into account, the concentrations of  $HCO_3^-$  and  $CO_3^{-2-}$  will decrease, while  $SO_4^{-2-}$  increases after CaCO<sub>3</sub> precipitates.

# 213 **3.3.** Simulation of groundwater inrush source

For further quantitative analysis of the inrush water source and component, the international hydrological and geochemical simulation software PHREEQC was used to simulate the water-rock interaction. The PHREEQC software was developed by the U.S. Geological Survey, and is able to calculate geochemical action within a temperature range of 0~300 degrees (Wei, 2010).

Based on the deduction that the main water inrush source around Anpeng was trona leakage brine, the simulation method PHREEQC was used and combined with the possible channel of inrush water to establish a conceptual model; then, the hydrogeochemical simulation of the water-rock interaction was conducted. Subsequently, the mixed ratio of inrush groundwater and shallow groundwater around Anpeng were quantified, to better verify the source of the inrush water.

223 3.3.1. Conceptual model

Around Anpeng, the trona leakage brine flowed through the specified mineral assemblages and mixed with shallow groundwater in different proportions.

#### 226 3.3.2. Initial data input

The parameters of the trona brine were taken from the enterprise's production testing data. The parameters of the shallow groundwater were taken from the same aquifer but outside the study area, and can basically represent groundwater background values. The specific parameters are shown in Table 1.

230 *3.3.3. Setting of stratum and mineral* 

The formations from the bottom to the top during the process of the leakage brine flowing into the shallow groundwater and then flowing out of the ground were as follows: the third member of the Hetaoyuan Formation of Paleogene, the Liaozhuang Formation and the Fenghuang Formation of Neogene and Quaternary. To simplify the mining area, according to the thickness of the rock stratum and the proportion of mineral composition, it can be assumed that the layer through which the trona brine flowed contains Ca-montmorillonite, kaolinite, gypsum, potash feldspar and potash mica.

The main components are as follows: Kaolinite: Al<sub>4</sub>[Si<sub>4</sub>O<sub>10</sub>](OH)<sub>8</sub>; Gypsum: CaSO<sub>4</sub>·2H<sub>2</sub>O;
Ca-montmorillonite: (Na,Ca)<sub>0.33</sub>(Al,Mg)<sub>2</sub>[Si<sub>4</sub>O<sub>10</sub>](OH)<sub>2</sub>·nH<sub>2</sub>O; Dolomite: CaMg(CO<sub>3</sub>)<sub>2</sub>; Potash feldspar:
K [AlSi<sub>3</sub>O<sub>8</sub>]; Potash mica: aluminium silicate as K, Al, Mg, Fe and Li.

#### 240 **4. Results and Discussion**

On 9 March 2013, in Anpeng, water samples from five groundwater inrush points and six surrounding water quality monitoring points (resident well) were tested. The results of water chemical composition are shown in Table 2, and the distribution of the sampling points is shown in Fig. 4.

According to the water quality analysis, the inrush brine had a relatively high salinity, with some inrush water samples containing  $SO_4$ -Na and some containing  $HCO_3$ -Na. The crystals mainly consisted of NaSO<sub>4</sub>, Na<sub>2</sub>CO<sub>3</sub>, and NaHCO<sub>3</sub>. The composition of the inrush water and the crystals was the same as that of the high-concentrated ions in the trona brine (Na<sub>2</sub>CO<sub>3</sub>, NaHCO<sub>3</sub>, etc.) and in the glauber salt brine (Na<sub>2</sub>SO<sub>4</sub>).

#### 249 4.1. The source of the inrush water

An automatic water quality recorder was set up at the Y5 inrush point on 4 March 2013. The monitoring lasted from 5 March to 20 March 2013. Thus, the relationship between the inrush points and the S02 well can be assessed according to the correlation of the changes between temperature/electrical conductivity and the concentration of brine during the S02 production well reparation period (5 March to 14 March 2013).

The production of glauber ceased during the investigation (2 March to 15 March 2013), so it could be determined how the glauber mining affects the water inrush hazard based on a dynamic water quality situation.

# 258 4.1.1. The source of inrush water at the Y-5 point

After successful reparation of the S02 well, the conductivity and temperature of the inrush water decreased significantly. The  $CO_3^{2-}$  concentration remained at 0, the  $HCO_3^{-}$  concentration decreased to 500 meq/L, while the  $SO_4^{2-}$  concentration increased to 600 meq/L. Subsequently, the concentrations of these three ions were in a state of dynamic balance. The analysis shows that the source of the inrush water at the Y-5 point is closely related to the S02 trona well.

In order to ensure whether the glauber brine exists at this point as part of an inrush source, further analysis was performed. The depth of the trona production well rupture was 234 m, and the gypsum deposit was developed at the depth of 134-338 m, so while the leakage of the trona brine flowed through the gypsum deposit, reactions would occur as shown in Eqs. (7) and (8).

According to the ion milliequivalent concentrations  $(Ca^{2+}: 0.61 \text{ meq/L}; CO_3^{-2-}: 905.3 \text{ meq/L}; HCO_3^{-2-}: 1332.94 \text{ meq/L}; Cl^-: 107.43 \text{ meq/L}; and SO_4^{-2-}: 267.89 \text{ meq/L}) at the Y-5 point, the concentration of Ca^{2+} was negligible compared to the other main ions. Only the reaction between CO_3^{2-} and CaSO_4 had to be$ 

taken into account because of the large number of  $CO_3^{2-}$ , with fast velocity, the short contact time with

gypsum, and the high temperature. The reaction of  $CO_3^{2^-}$  and  $CaSO_4$  would take place at a ratio of 1:1 according to Eq. (7), and three types of inrush water sources could be assumed under this precondition as follows:

(1) The inrush water source was only from the trona brine.

The  $\text{CO}_3^{2^-}$  and  $\text{CaSO}_4$  in the brine reacted at a ratio of 1:1, and the  $\text{SO}_4^{2^-}$  concentration was equal to the reacted  $\gamma \text{CO}_3^{2^-}$  content. Thus, the  $\gamma \text{CO}_3^{2^-}/\gamma \text{HCO}_3^-$  ratio in the trona brine was equal to the  $\gamma(\text{CO}_3^{2^-}+\text{SO}_4^{2^-})/\gamma \text{HCO}_3^-$  ratio in the inrush water. From this calculation, it could be seen that  $\gamma(\text{CO}_3^{2^-}+\text{SO}_4^{2^-})/\gamma \text{HCO}_3^-$  was equal to 0.88, while  $\gamma \text{CO}_3^{2^-}/\gamma \text{HCO}_3^-$  ranged between 0.86 and 1.26. The content of  $\gamma(\text{CO}_3^{2^-}+\text{SO}_4^{2^-})/\gamma \text{HCO}_3^-$  was similar to  $\gamma \text{CO}_3^{2^-}/\gamma \text{HCO}_3^-$ ; therefore, the source of the inrush water was exclusively trona brine.

282 (2) The inrush water source was only from the glauber brine.

283 The  $\gamma SO_4^{2-}/\gamma HCO_3^{-1}$  ratio in the glauber brine was equal to 1237.8, compared to 0.19 in the inrush 284 water. Therefore, this assumption was incorrect because of the widely varying ratios.

285 (3) The inrush water source was from a mixed brine of glauber and trona.

Assuming that the contribution ratio of the glauber brine was X and that of the trona brine was Y, then1237.8 × X + (0.86~1.26) × Y = 0.88. This equation showed that when the contribution ratio of the trona brine was equal to 1, the contribution ratio of the glauber brine was equal to 1.6×10<sup>-5</sup>, so small that can be ignored.

Thus, it could be confirmed that the water inrush source at Y-5 was exclusively the leakage of trona brine from the broken S02 well.

4.1.2. The sources of inrush water at the Y-4, Y-3, Y-2, and Y-1 points

The inrush water quantity and the dynamic variation of the concentration of  $SO_4^{2-}$  and  $HCO_3^{-}$  at points Y1-Y4 were not obvious when the S02 well was under repair and all the glauber wells were shut down (from 2 to 15 March). This result shows that the sources of these water inrush points were not due
to the underground mining activities of the glauber brine or the rupture of the S02 well, but rather to the
brine leakage from other trona wells.

298 4.1.3. Components and mixed proportions of the inrush water

The PHREEQC simulation conditions were assumed to be as follows: (1) the trona brine did not mix with shallow groundwater after flowing through the mineral layer; or (2) the trona brine mixed with shallow groundwater in a ratio of 1:2, 1:10, 1:100, 1:200, 1:500, 1:1000 and 1:5000 after flowing through the mineral layer. The simulation results are shown in Table 3.

Table 3 shows that when the trona brine flowed through the bedrock of Hetaoyuan, Liaozhuang, Fenghuangzhen Formation and shallow groundwater successively, the concentrations of Na<sup>+</sup>, Cl<sup>-</sup> and  $SO_4^{2-}$  decreased while the HCO<sub>3</sub><sup>-</sup> concentration increased with increasing proportion of shallow groundwater. The Ca<sup>2+</sup> concentration decreased at first and then increased.

The ion concentrations at Y-5, except for  $SO_4^{2^-}$ , were similar to the ion concentrations in the trona brine. However, at the same time, the  $HCO_3^-$  concentration was nearly 0 meq/L. When the trona brine flowed through the layer, it would react rapidly and pour out of the ground directly because of the fast velocity of the inrush water at Y-5. Meanwhile, the trona brine was not continuously provided in the simulation. Thus, the concentration of  $HCO_3^-$  would be near to the concentration of trona brine in reality. Therefore, the trona brine must have a rapid inrush, almost not mixing with shallow groundwater.

The PHREEQC simulation results show that: 1) the water inrush source of Y-5 was the trona brine almost all from the ruptured S02 well; 2) the water inrush source of Y-3 was a mixture of trona brine and groundwater in a ratio of 1:10~1:100; and 3) the water inrush sources of Y-4, Y-2 and Y-1 were a mixture of trona brine and groundwater under the ratio of 1:200.

#### 317 4.2. The channel of the inrush water

## 318 4.2.1. Reasons for the brine leakage

Trona is produced by either a single well or double/multiple well convection mining method that is water-soluble mining method (Lin, 1987). The main mining unit consists of a salt cavity and production well. Thus, the instability of the salt cavity and the rupture of the production well are the main possible reasons for brine leakage.

323 (1) Analysis of salt cavity stability

The possibility of salt cavity collapse: Trona is distributed at the bottom of the second member of the Hetaoyuan Formation and in the upper part of the first member of the Hetaoyuan Formation, with dolomite strata developed at the roof and floor. The thick and hard surrounding rock structure determined that the cavity is produced by hydrofracture but it is hard to fill with large-scale fractured channels, and can remain intact and stable.

The development of a roof fracture: When a mineral is under exploitation, the surrounding rock in 329 the cavity is under pressure from the inner brine. This pressure is equal to the sum of the water injection 330 331 pressure and the water column pressure in the production well. The water injection pressure of the trona production well is approximately 10-20 MPa, while the 1560.92-2929.53 m (mineral buried depth) 332 water column pressure is approximately 15.3-28.71 MPa. Thus, the greatest water pressure on the 333 surrounding rock in the cavity is 48.71 MPa. The main lithology of the surrounding rock is dolomite 334 (500 m in thickness and 142.66 MPa in compressive strength), which is nearly 3 times that of the 335 greatest possible water pressure. Therefore, large-scale fractures in the surrounding rock of the trona 336 mineral would be difficult to develop under the effect of sustained water pressure. 337

338 (2) Analysis of production well rupture

339 The phenomenon of brine leakage caused by the S02 well rupture in Anpeng indicates that

production well damage is an important cause of brine leakage. The depth of the S02 well rupture is 234 m underground, i.e. in the gypsum deposit, which is strongly hygroscopic. The pressure caused by the water swelling is approximately 0.15 MPa (Li and Zhou, 1996), which may damage the production well and induce brine leakage. The high concentration of  $SO_4^{2-}$  (>250 mg/L) generated by the reaction of leakage brine and gypsum can also corrode the production well and lead to groundwater inrush.

# 345 *4.2.2. Analysis of water-conducting channel*

According to our analysis, the most probable reason for brine leakage in trona is the production well rupture. The leaking brine will flow along the water-conducting channel into the shallow aquifer and even pour out of the ground. However, the geological structure in the mining area shows no water-conducting fault development. Thus, the water-conducting channel, that the leakage brine flows along, is probably the structure fissure zone or the abandoned gypsum exploitation well.

Structural fissure is the main type of fissure that occurs in groundwater inrush hazards when using the solution mining method. The structural fissure is determined by the maximum horizontal principal stress, which is controlled by the tectonic stress field in the mining area. The connection direction of the S02 well and the other water inrush points is NW-SE, the same as that of the structural fissure zone development direction. This indicates that the main water-conducting channel in Anpeng is controlled by the structural fissure zone.

The inrush points in Anpeng are all at the abandoned gypsum exploitation wells, which were not closed properly. Thus, high-pressure cavity water or leakage brine can flow along the structural fissure zone, finally connect with these wells, and then pour out of the ground through boreholes. Therefore, the abandoned gypsum exploitation wells are the main channels through which the shallow polluted groundwater flowed out of the ground, as shown in Fig. 5.

#### **5.** Conclusions

This study aimed to investigate the source and channel of the inrush water in a multilayer rock salt mining area. To achieve the set objectives, an analysis of geological and hydrogeological conditions, an analysis of physical and chemical reaction principles of different brines, the PHREEQC simulation method, and an analysis of geological and artificial reasons for the conducting channel where leakage brine flowed from the damage depth out to the ground were combined.

Long-term solution mining with high-pressure and -temperature water not only dissolves minerals, 368 369 but also may cause rupture of strata and damage of the production well, which usually results in brine 370 leakage or groundwater inrush. Geological and hydrogeological conditions are the basis which determines the total risk of the groundwater inrush hazard. Physical and chemical reaction principle 371 analysis of different brines and hydrogeochemical simulation of water-rock interaction in different 372 assumed conditions using the PHREEQC simulation method can determine the exact source of the 373 leakage brine, as well as identify the mixed proportion of inrush water while the leakage brine flows 374 through the mineral layer. Other than geological reasons, mining techniques such as pressure control of 375 injection water and groundwater quality monitoring of exploitation wells may also determine the risk of 376 a groundwater inrush hazard in a multilayer rock salt mining area. 377

#### 378 Acknowledgements

This work was partially supported by the Fundamental Research Funds for the Central Universities,
China University of Geosciences (Wuhan) [Grant Numbers: CUGL100219].

381 Author Contributions

Bin Zeng and Tingting Shi contributed to data analysis and manuscript writing; Zhihua Chen proposed the main structure of this study; Liu Xiang and Muyi Yang designed and performed the experiments; and Shaopeng Xiang performed the PHREEQC simulation. All the authors read and

385 approved the final manuscript.

# 386 **Conflicts of Interest**

387 The authors declare that they have no conflict of interest.

#### 389 **References**

390	Blachowski, J., Milczarek, W. and Stefaniak, P.: Deformation information system for facilitating
391	studies of mining-ground deformations, development, and applications, Nat. Hazards Earth
392	Syst. Sci., 14, 1677-1689, 2014

- Bonetto, S., Fiorucci, A., Fornaro, M. and Vigna, B.: Subsidence hazards connected to quarrying
  activities in a karst area: the case of the Moncalvo sinkhole event (Piedmont, NW Italy),
  Estonian J. Earth Sci., 57, 125-134, 2008
- Chen, H. J. and Li, X. Bi.: Studies of water source determination method of mine water inrush
  based on Bayes' multi-group stepwise discriminant analysis theory, Rock and Soil Mechanics,
  30, 3655-3659, 2009.
- Clark, I. D. and Fritz, P.: Environmental isotopes in hydrogeology, Lewis Publishers, New York,
  USA, 35-37, 1997.
- Closson, D. and Abou Karaki, N.: Salt karst and tectonics: sinkholes development along tension
   cracks between parallel strike-slip faults, Dead Sea, Jordan. Earth Surf Proc Land., 1408-1421,
   2009
- Cobbina, S.J., Duwiejuah, A.B., Quansah, R., Obiri, S. and Bakobie, Noel.: Comparative
  Assessment of Heavy Metals in Drinking Water Sources in Two Small-Scale Mining
  Communities in Northern Ghana, Int. J. Environ. Res. Public Health., 12, 10620-10634,
  2015.
- Ezersky, M., Legchenko, A., Camerlynck, C. and Al-Zoubi, A.: Identification of sinkhole
  development mechanism based on a combined geophysical study in Nahal Hever South area
  (Dead Sea coast of Israel). Environ Geol., 58, 1123-1141, 2009
- 411 Ezersky, M. and Frumkin, A.: Fault Dissolution front relations and the Dead Sea sinkhole

412	problem.	Geomor	phology,	201,	35-44,	2013

- Fernandez, I., Olias, M., Ceron, J.C. and De la Rosa, J.: Application of lead stable isotopes to the
  Guadiamar Aquifer study after the mine tailings spill in Aznalcollar (SW Spain), Environ Geol.,
  415 47, 197-204, 2005.
- Fernandez-Galvez, J., Barahona, E., Iriarte, A. and Mingorance, M.D.: A simple methodology for
  the evaluation of groundwater pollution risks, Sci Total Environ., 378, 67-70, 2007.
- Frumkin, A., Ezersky, M., Al-Zoubi, A., Akkawi, E. and Abueladas, A.-R.: The Dead Sea sinkhole
  hazard: Geophysical assessment of salt dissolution and collapse. Geomorphology, 134,
  102-117, 2011
- Goldscheider, N. and Bechtel, T.D.: The housing crises from underground damage to a historic
  town by geothermal drillings through anhydrite, Staufen, Germany. Hydrogeol J., 17, 491-493,
  2009
- Gao, W.D.: Application of Entropy Fuzzy Discriminating methods in Distinguishing Mine Bursting
  Water Source, Mining Safety & Environmental Protection, 39, 22-24, 2012.
- Gutierrez, F., Parise, M., De, Waele, J. and Jourde, H.: A review on natural and human-induced
  geohazards and impacts in karst. Earth-Sci Rev., 138, 61-88, 2014
- Hao, B.B., Li C. and Wang C.H.: Application of grey correlation degree in the identification of
  sources of mine water bursting, China Coal, 36, 20-22, 2010.
- Hu, W.W., Ma, Z.Y., Cao, H.D., Liu, F., Li, T. and Dou, H.P.: Application of Isotope and
  Hydrogeochemical Methods in Distinguishing Mine Bursting Water Source, Journal of Earth
  Sciences and Environment, 32, 268-271, 2010.
- Houben, G.J., Sitnikova, M.A. and Post, V.E.A.: Terrestrial sedimentary pyrites as a potential
  source of trace metal release to groundwater A case study from the Emsland, Germany, Appl.

435 Geochem., 76, 99-111, 2017.

- Jiang, R.Z. and Jiang T.X.: Present Development and Prospecting of Hydraulic Fracturing
   Technology, Oil Drilling & Production Technology, 26, 52-57, 2004.
- Kang, X.B., Hu, X.W. and Xie, H.Q.: Numerical simulation on the influence of the groundwater
  flow field during tunneling, Advanced Materials Research, 1230-1233, 2012.
- Kotwica, K.: Scenarios of technological development of roadwavs mining in polish coal mines
  conditions, Gospod Surowcami Min., 24, 139-152, 2008.
- Lee, H., Choi, Y., Suh, J. and Lee, S.H.: Mapping Copper and Lead Concentrations at Abandoned Mine Areas Using Element Analysis Data from ICP–AES and Portable XRF Instruments: A Comparative Study, Int. J. Environ. Res. Public Health., 13, 384, 2016.
- LeDoux, T.M., Szynkiewicz, A. and Faiia, A.M.: Chemical and isotope compositions of shallowgroundwater in areas impacted by hydraulic fracturing and surface mining in the Central Appalachian Basin, Eastern United States, Appl. Geochem., 71, 73-85, 2016.
- Lin, Y.X.: The History of Science & Technology of well salt in China, Sichuan Science and
   Technology Pres, Chengdu, 1987.
- Li, D.D. and Zhou, Z.A.: Possibility of corrosion failure of concrete shaftwall due to water
   infiltration, Journal of China Coal Society, 21, 158-163, 1996.
- Liu, H., Yang, T., Zhu, W. and Yu, Q.: Numerical analysis of the process of water inrush from the 12th coal floor FANGEZHUANG coal mine in China, Controlling Seismic Hazard and Sustainable Development of Deep Mines: 7th International Symposium on ROCKBURST and Seismicity in Mines (RASIM7), 1&2, 1381-1386, 2009.
- Liu, R.Z., Liu, J., Zhang, Z.J., Borthwick, A. and Zhang, K.: Accidental Water Pollution Risk
   Analysis of Mine Tailings Ponds in Guanting Reservoir Watershed, Zhangjiakou City, China,

458	Int. J. Environ.	Res. Public Health.,	12, 15269-15284, 2015.
-----	------------------	----------------------	------------------------

- Lollino, P., Martimucci, V. and Parise, M.: Geological survey and numerical modeling of the potential failure mechanisms of underground caves. Geosystem Engineering, 16, 100-112, 2013
- 462 Lu, J.T.: Recognizing of Mine Water Inrush Sources Based on Principal Components Analysis and
   463 Fisher Discrimination Analysis Method, China Safety Science Journal, 22, 109-115, 2012.
- Ma, L. and Qian, J.Z.: An approach for quickly identifying water-inrush source of mine based on
   GIS and groundwater chemistry and temperature, Coal Geology & Exploration, 42, 49-53,
   2014.
- 467 Namin, F. S., Shahriar K., Bascetin A. and Ghodsypour S.H.: Practical applications from
  468 decision-making techniques for selection of suitable mining method in Iran, Gospod
  469 Surowcami Min., 25, 57-77, 2009.
- 470 Parise, M., and Gunn, J.: Natural and anthropogenic hazards in karst areas: Recognition, Analysis
  471 and Mitigation. Geol. Soc. London, sp. publ. 279, 2007
- 472 Parise, M. and Lollino, P.: A preliminary analysis of failure mechanisms in karst and man-made
  473 underground caves in Southern Italy. Geomorphology, 134, 132-143, 2011
- 474 Parise, M., Closson, D., Gutierrez, F. and Stevanovic, Z.: Anticipating and managing engineering
  475 problems in the complex karst environment. Environ Earth Sci., 74, 7823-7835,
  476 DOI :10.1007/s12665-015-4647-5, 2015
- 477 Qiu, Z.Y.: Mechanism analysis of surface collapse in the area of solution salt mining, Journal of
  478 Safety Science and Technology, 7, 27-31, 2011.
- 479 Ramadas, M., Ojha, R. and Govindaraju, R.S.: Current and Future Challenges in Groundwater. II:
  480 Water Quality Modeling, J. Hydrol. Eng., 13, 132-140, 2015.

- 481 Robins, N.S.: Groundwater quality in Scotland: major ion chemistry of the key groundwater bodies,
  482 Sci Total Environ., 294, 41-56, 2002.
- 483 Shao, A.J., Huang, Y. and Meng, Q.X.: Numerical Simulation on Water Invasion of Coal Mine,
  484 Applied Mechanics and Materials, 1112-1117, 2013.
- Shi, T.T., Chen, Z.H. and Luo, Z.H.: Mechanism of groundwater bursting in a deep rock salt mine
  region: a case study of the Anpeng trona and glauber salt mines, China, Environ Earth Sci., 68,
  229-239, 2013.
- 488 Staudtmeister, K. and Rokahr, R.B.: Rock Mechanical Design of Storage Caverns For Natural Gas
  489 in Rock Salt Mass, Rock Mech&Min.Sci., 34, 3-4, 1997.
- 490 Vigna, B., Fiorucci, A., Banzato, C., Forti, P. and De Waele, J.: Hypogene gypsum karst and
  491 sinkhole formation at Moncalvo (Asti, Italy). Z. Geomorphol., 54, 285-308, 2010
- Wang, J.M.: A Preliminary Study on the Characteristics and Conditions of forming Anpeng Trona
  deposits, Petrol Explor Dev., 5, 93-99, 1987.
- Waltham, AC. And Fookes, PG.: Engineering classification of karst ground conditions. Q J Eng
   Geol Hydroge., 36, 101-118, 2003
- Wei, Y.N.: Research and Application of Hydro-geochemical Simulation, Journal of Water
   Resources and Water Engineering, 21, 58-61, 2010.
- Wu, Q., Li, B. and Chen, Y.: Vulnerability Assessment of Groundwater Inrush from Underlying
  Aquifers Based on Variable Weight Model and its Application, Water Resour Manag., 30,
  3331-3345, 2016.
- Xu, H. and Li, H.S.: Study on CaSO<sub>4</sub> crystallization process and its influential factors, Industrial
   Water Treatment, 5, 67-69, 2011.
- 503 Yang, Y.H.: Gypsum mineral dissolution kinetics, M.D. thesis, China University of Geosciences,

504 Wuhan, China, 2003.

505	Yuan, W.H. and Gui, H.R.: The Characteristics of Geothermal Temperature and Its Application in
506	Distinguishing the Source of Water in Ren Lou Mine, Journal of Anhui University of Science
507	and Technology (Natural Science), 25, 9-11, 2005.

Zhou, W. and Beck, BF.: Engineering issues on karst. In: P. van Beynen (Ed), Karst Management.
 Springer, Dordrecht, 9-45, 2011

# **Figure captions**

**Fig. 1.** One of the long-term (longer than 2 years) groundwater inrush points with stable discharge (Y-3).

**Fig. 2.** The sudden groundwater inrush point (Y-5). The high-temperature inrush groundwater was being pumped after the ground was broken.

Fig. 3. Information about strata, lithology, aquifers, and buried positions of each ore bed in the mining area.

**Fig. 4.** Sketch map of hydrogeological conditions and the distribution of groundwater inrush points in the mining area.

**Fig. 5.** Schematic diagram of the source and channel of the groundwater inrush hazard in the multilayered rock salt mining area in Tongbai County.





Stratigraphy								Radorika da			
System	Series	Formation	Member	Thickness (m)	Lithologic profile	Petrographic description	Minerals	Aquifer	Sandy		
Quaternary					· · · · ·			fer	conglomerate		
Neogene	Oligocene	Fenghuang zhen		0-290	- , , , , , , , ,	Alternating layers of sandy conglomerate and sandy clay		Shallow aqui	Sandy clay		
		zchuang		0-634		Upper part: mudstones are interbedded with gypsum	Gypsum	Weak permeable stratum			
		Liac		50	• • • • •	Lower part: alternating layers of mudstone and sandy conglomerate			Mudstone		
			ird segment	400-500		Mudstone with interlayers of sandy conglomerate, as well as thin layers of shale, muddy dolomite	lauber		Muddy		
	Eocene				Thi			and glauber salt	0		
Paleogene		letaoyuan	Second segment	700-800		Mudstone is interlayered with muddy dolomite and dolomite, as well as small amounts of trona	Trona	Deep aquifer	Shale		
		<u></u>	First segment	1100-1700		Mudstone, muddy dolomite, dolomite, shale and siltstone	Trona		Gypsum vein Glauber vein Clauber vein Trona vein		





Туре	Temperature (°C)	pН	Na <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup> (mg/L)	SO4 <sup>2-</sup>	HCO <sub>3</sub>	CO <sub>3</sub> <sup>2-</sup>
Trona brine	70.00	10.80	85880.00	5.00	1.00	3819.00	206.00	104721.00	4565.00
Background value of groundwater	e 14.10	7.50	38.76	67.10	23.88	12.46	39.31	386.87	0.00

Table 1 Initial data of trona brine and background value of groundwater for the PHREEQC simulation

Source	Point	Na <sup>+</sup>	Ca <sup>2+</sup>	$Mg^{2+}$	Cľ	$SO_4^{2-}$	HCO <sub>3</sub> <sup>-</sup>	CO3 <sup>2-</sup>	Salinity	Depth
Source	Tomt				(	mg/L)				(m)
	Y-1	447.30	91.20	74.68	171.18	278.55	1488.89	0.00	1807.35	
Groundwater	Y-2	524.50	89.34	75.32	153.97	298.88	1525.00	0.00	1904.51	330.55
from inrush	Y-3	1132.00	146.60	158.30	125.56	4296.44	1012.93	0.00	6365.37	~
hazard points	Y-4	322.12	98.67	123.88	210.78	346.55	1122.77	0.00	1663.38	430.20
	Y-5	50300.00	12.23	53.21	3813.80	12858.63	81309.15	27159.00	107692.40	
	SY-1	46.28	76.76	17.29	64.30	14.58	319.03	0.00	378.73	
Groundwater	SY-2	28.37	98.02	27.46	26.16	10.38	453.84	0.00	417.31	
from resident	SY-3	43.14	46.20	14.42	31.02	117.12	319.03	0.00	316.26	10.00
the inrush	SY-4	118.53	278.40	72.30	425.23	175.96	568.52	0.00	1354.68	10.00
points	SY-5	31.67	95.51	19.22	53.93	22.59	351.97	0.00	398.90	
	SY-6	36.77	68.82	19.60	18.51	21.55	340.38	0.00	335.43	

Table 2 Chemical composition of groundwater from the inrush hazard points and surrounding resident wells

Conditions	Mixed proportion with shallow	Na <sup>+</sup>	Ca <sup>2+</sup>	Cl	$\mathrm{SO_4}^{2-}$	HCO <sub>3</sub> -
Conditions	groundwater			(mg/L)		
	Unmixing	87147.00	301.08	3880.15	68659.20	5.06
Trona brine	1:1	48093.00	280.00	2145.62	37900.80	9.39
unmixed or mixed with different	1:2	33235.00	184.72	1485.68	26188.80	13.97
proportion of	1:10	9586.40	148.28	436.30	7561.92	57.95
groundwater after	1:100	1098.25	90.40	141.63	873.89	306.34
flowing through the mineral layer	1:200	571.78	69.60	118.56	459.17	382.17
(simulation results)	1:500	252.77	68.32	104.60	207.84	453.66
	1:1000	144.81	67.52	99.94	105.12	481.60
	Y-1	447.30	91.20	171.18	276.55	1488.89
Water quality test	Y-2	524.50	89.34	153.97	298.88	1525.00
results in five water	Y-3	1132.00	146.60	125.56	4296.44	1012.93
inrush hazard points	Y-4	322.12	98.67	210.78	346.55	1122.77
	Y-5	50300.00	12.23	3813.80	12858.63	81309.15

Table 3 Simulation results for a mixed proportion of inrush trona brine using the PHREEQC method