

Analysis of Mixed Water Source for Urban Underground Water Pipe Leakage by Using Water Geochemistry Model Calculation

Dun Wu

Anhui Jianzhu University

chao wei

Anhui Province Bureau of Coal Geological

yunfei li (✉ 2017170534@mail.huft.edu.cn)

Hefei Institute for Public Safety Research Tsinghua University

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Abstract

China is a country short of water resources, and the leakage of urban water pipe network not only aggravates the current situation of water shortage, but also causes major accidents such as ground collapse, so it is of great significance to study the discrimination of urban underground pipe leakage. In this paper, the conventional ions and hydrogen and oxygen isotopes of water samples are determined by ion chromatograph and inductively coupled plasma mass spectrometer, and the characteristic factors are selected by cluster analysis and principal component analysis, and the mixed water discrimination model based on conventional ions is established. According to the difference of hydrogen and oxygen isotope content between buried pipe water and groundwater, a discrimination model based on hydrogen and oxygen isotope is established, and the two models are combined to discriminate the leakage of buried pipe. The results show that, in terms of conventional ion content characteristics, the water in the pipe network is high in K^+Na^+ and Cl^- , while the shallow groundwater near the pipe network is low in K^+Na^+ and Cl^- , and the accuracy of the discriminant model based on conventional ions reaches 87.5%. In the aspect of hydrogen and oxygen isotope content characteristics, the water in the pipe network is closer to the precipitation line than the shallow groundwater, and establishing a discriminant model based on hydrogen and oxygen isotope can determine the leakage of buried pipes. This study provides a scientific basis for judging the leakage of urban underground pipes.

1. Introduction

As we all know, China's water resources are in short supply, among which 20% of cities are seriously short of water. At the same time, the problem of fresh water loss in China is also serious. In 2020, the leakage rate of water pipe network in 26 provinces and cities in China is above 15%, of which 13 provinces and cities exceed 20%. China has formulated relevant policies to reduce the leakage rate. In 2015, the State Council formulated the Action Plan for Water Pollution Prevention and Control (State Council 2015). At present, due to the lack of uninterrupted leak diagnosis technology of water supply network, the water affairs integrated information big data platform lacks accurate and reliable leak information, resulting in waste of resources, water pollution, and even fatal accidents such as pipe burst, ground collapse and casualties, which not only affects the economic benefits of water supply enterprises, but also threatens social stability and economic development (JANUSZ 2009).

The leakage of pipe network generally comes from the quality defects of pipes and construction, such as overload and high pressure operation of old pipe network, environmental temperature change, uneven settlement and other complex factors. It is one of the hot issues concerned by the water industry to grasp the distribution and development trend of leakage points in the whole region in time. Leakage control is listed as an important part in every water conference of international water association (IWA), but listening to sound is still the main method for leakage detection in China (Zhang 2012). Using the instrument to detect leakage can avoid the uncertainty of the common results of manual listening to a certain extent, but it is still interfered by various environmental factors, especially for the early detection of tiny leakage on pipelines buried deep and continuously noisy. Partition metrology (DAM) can judge the area with leakage, but it can't accurately point out the specific location of leakage point (Di et al. 2004). In addition, a variety of new pipeline leak detection methods are constantly emerging, such as magnetic flux detection method, stress wave method, eddy current detector method, pipeline endoscopy method, ground penetrating radar method, gas tracer method, etc. (Li et al. 2003; Cheng et al. 2003; Chang et al. 2003), which greatly enriches the detection technology, but its economic rationality and real-time performance still need to be verified.

Conventional hydrochemistry mainly monitors elements (HCO_3^- , K^+ , etc.) widely existing in water to identify water sources. There are many researches on conventional hydrochemistry to identify groundwater sources. Zhang Le Zhong, Chen Luwang and Wang Xinyi use conventional hydrochemistry of aquifers to establish a discriminant model to identify water source types, and the discriminant effect is good (Zhang et al. 2013; Chen et al. 2010; Wang et al. 2016). Isotope is an important method for tracing water sources and evaluating water quality. Water molecules are composed of stable isotopes of hydrogen and oxygen, and are good natural tracers (Song et al. 2002). Cook et al., Thomas et al., Paula et al., Mohammed, Chiogna et al. calculated the parameters such as groundwater flow velocity and the condition of supplementary drainage of groundwater by using the tracer effect of isotopes such as ^2H and ^{18}O (Cook 2013; Kretzschmar et al. 2013; Careira et al. 2013; Mohammmen et al. 2014; Chiogna et al. 2014). Li et al., Ma et al., Luo et al., Han et al., analyzed the hydrochemical process and recharge source of groundwater by using isotopes such as ^2H and ^{18}O (Li et al. 2013; Ma et al. 2013; Luo et al. 2013; Han et al. 2014). The purpose of this study is to establish a discriminant model by using the difference of conventional ions and hydrogen and oxygen isotopes in underground water samples and shallow underground water samples, to determine whether the buried water enters the shallow underground aquifer near the buried pipe and the amount of leakage, to achieve the purpose of determining the leakage of tap water in urban underground pipes, and to provide scientific basis for reducing the leakage rate of tap water pipe network and reducing the occurrence of related disasters.

2. Materials And Methods

2.1 Sample collection

On November 12, 2020, 15 tap water samples (recorded as UW1, UW2, etc.) were collected along the underground pipes in Hefei, and 15 shallow groundwater samples (recorded as PW1, PW2, etc.) were collected near the tap water sample collection points on November 20, 2020. The sampling points are shown in Figure 1. When sampling, first discharge the water stranded in the buried pipe and soil layer to ensure that the water sample taken is fresh. Before sampling at each sampling point, rinse the pickled 250mL polyethylene sample bottle with the water sample to be taken for 2~3 times, filter the water sample with 0.45 μm filter paper, add ultra-pure nitric acid to digest the sample pH<2, seal the bottle mouth immediately after sampling to avoid water leakage or pollution, and refrigerate the sample at 4°C and transport it to the laboratory as soon as possible.

2.2 Test methods

2.2.1 Determination of conventional ions

Ion chromatograph (model: ICS-3000) is used for conventional ions in water samples. The tested ions include K^+ , Na^+ , Ca^{2+} , Mg^{2+} , CO_3^{2-} , HCO_3^- , Cl^- and SO_4^{2-} . The concentration range of the determined elements is 1~100 $\mu\text{g}/\text{mL}$ (mg/L), and the gradient proportional accuracy is less than 0.5% (at 2.0ml/min).

2.2.2 Determination of hydrogen and oxygen isotopes

In the hydrogen and oxygen isotope content of water samples, the components of HDO and H_2^{18}O were determined by liquid water isotope analyzer (DLT-100, Los Gatos Research company, USA), and the observation accuracy was 0.3‰ and 0.1‰ respectively. The samples were determined by Karst Geology and Resources and Environment Testing Center of Chinese Academy of Geological Sciences, and the components of HDO and H_2^{18}O were expressed by δ values.

All the experiments involved in this study were completed in the Physical and Chemical Experiment Center of University of Science and Technology of China. The quality control in the testing process was completed by monitoring blank samples, inserting duplicate samples (the difference of duplicate samples was between 2% and 5%) and adding standard recovery experiments (the standard recovery rate was between 90% and 100%).

2.3 Data processing

The research data mainly include: pH, ion concentration, isotope content and so on. Excel2010 was used to count and collate the original data, SPSS software and Minitab software were used to carry out regression analysis and transposition calculation.

3. Results And Discussion

3.1 Conventional Ion Characteristics of Water Samples

Test data of PW and UW water samples (Table 1).

Table 1
Routine hydrochemical analysis data of water samples

No.	pH	K ⁺ +Na ⁺	Ca ²⁺	Mg ²⁺	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
PW1	7.46	826.30	44.01	28.25	8.43	307.23	1020.24	305.33
PW 2	7.52	864.71	35.41	18.53	9.30	341.95	1007.83	314.39
PW 3	7.91	778.71	46.77	29.78	11.16	283.62	987.64	295.85
PW 4	7.63	912.81	28.1	12.08	312.74	11.95	943.13	365.14
PW 5	7.53	835.01	36.35	14.91	309.71	17.92	943.13	300.5
PW 6	7.49	732.84	37.51	16.64	252.02	11.95	933.29	272.7
PW 7	8.37	794.88	46.62	15.33	5.54	329.00	841.47	371.5
PW8	8.55	841.16	32.79	13.03	282.38	17.92	918.77	290.00
PW9	8.31	732.84	37.51	16.64	252.02	11.95	933.29	272.70
PW10	8.36	719.80	38.06	18.52	224.69	8.96	946.62	268.80
PW11	8.31	735.59	37.43	17.69	218.62	8.96	931.96	267.70
PW12	8.24	835.93	41.71	20.51	18.45	225.16	821.44	268.12
PW13	8.23	868.37	29.11	15.54	11.16	243.91	1046.90	343.05
PW14	8.40	835.01	36.35	14.91	309.71	17.92	943.13	300.50
PW15	8.35	825.55	39.65	16.08	297.56	11.95	953.95	300.50
UW1	8.31	377.17	70.00	22.48	19.53	360.20	322.58	354.50
UW2	7.80	415.17	68.40	30.12	22.37	357.57	358.32	573.63
UW3	7.59	470.10	35.28	12.51	21.35	245.08	449.51	248.34
UW4	8.91	383.34	43.22	14.38	33.48	280.78	3403.44	325.30
UW5	8.39	504.53	47.09	15.40	5.56	326.16	347.39	374.6
UW6	8.29	506.95	55.31	20.67	5.58	278.25	231.88	278.25
UW7	8.30	460.52	28.03	6.34	38.41	473.52	216.26	249.76
UW8	8.31	459.78	25.99	6.42	76.89	281.45	225.44	325.67
UW9	8.23	417.27	14.63	14.96	43.41	250.18	259.08	109.69
UW10	8.34	464.93	25.26	11.46	39.53	337.51	221.96	333.72
UW11	8.37	434.88	46.62	15.33	5.58	329.00	341.47	371.50
UW12	8.39	514.53	47.09	15.40	5.58	326.16	347.39	374.60
UW13	7.52	371.98	82.86	28.30	25.47	357.80	237.70	445.60

No.	PH	K ⁺ +Na ⁺	Ca ²⁺	Mg ²⁺	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
UW14	8.29	306.95	55.31	20.67	257.51	278.25	331.88	278.25
UW15	7.98	415.38	40.88	13.54	321.91	253.97	271.26	266.75

According to the mathematical statistical analysis of conventional ion content in water samples, it was found that the average contents of K⁺+Na⁺, Ca²⁺, Mg²⁺, CO₃²⁻, HCO₃⁻, Cl⁻ and SO₄²⁻ in PW water samples were 809.3mg/L, 37.83mg/L, 17.9mg/L, 168.237mg/L, respectively UW water samples were 433.57mg/L, 45.73mg/L, 16.5 mg/L, 61.48 mg/L, 315.73 mg/L, 504.37 mg/L and 327.34 mg/L. On the average, the order of anion content in the two water samples is Cl⁻ > SO₄²⁻ > HCO₃⁻ > CO₃²⁻, and the order of cation change is K⁺+Na⁺ > Ca²⁺ > Mg²⁺. However, the contents of K⁺+Na⁺, CO₃²⁻, HCO₃⁻ and Cl⁻ in the two kinds of water samples are quite different, especially the contents of K⁺+Na⁺ and Cl⁻ in PW are twice as high as those in UW, which may be due to the use of sodium hypochlorite in tap water disinfection by waterworks, and the residual sodium hypochlorite causes the excessive contents of Cl⁻ and Na⁺ (Wang et al.2018).

In order to determine the hydrochemical type of water sample, draw Piper three-line discrimination diagram of water sample (Figure 2). According to Fig. 2, on Piper diagram, the hydrochemical types of PW water samples are mainly concentrated on Na-Cl-SO₄, and those of UW water samples are mainly concentrated on Na-Cl.

3.2 Sample selection for conventional ion discrimination

In this study, tap water samples from buried pipes and shallow groundwater samples were collected, and PW1-PW8 and UW1-UW were used to build the model, and PW9-PW15 and UW9-UW15 were used to verify the model.

In order to quickly and effectively establish a discriminant model based on conventional ions in cities, it is necessary to find the characteristic components that can represent PW and UW, that is, the characteristic ions of PW and UW, which can be processed by box statistical graph and statistical software classification principal component analysis, respectively, so as to provide a basis for selecting discriminant factors when further studying the discriminant model of underground pipe leakage.

The comparison of conventional ion content characteristics between PW1-PW8 and UW1-UW8 can be visually expressed by box diagram (A diagram shows conventional water chemical composition of PW and B diagram shows conventional water chemical composition of UW). It can be seen from Fig. 3 that PW and UW show different characteristics, which explain the importance of water-rock interaction in conventional water chemical composition of water samples to varying degrees, mainly reflected in K⁺+Na⁺ and Cl⁻. PW shows high K⁺+Na⁺ and high Cl⁻, UW shows low K⁺+Na⁺ and low Cl⁻, which can be used to distinguish PW from UW(Craig 1964).

The Minitab software is used to calculate the discriminant results of the best subset of conventional ions in each aquifer. Table 2 shows that the subsets of K⁺+Na⁺, Ca²⁺, CO₃²⁻ and SO₄²⁻ have the largest R-Sq(adj) value, so these ions are selected as recognition factors(Berry 2011).

Table 2
Calculation results of optimal subset of conventional ions for each water sample

Mallows												
Vars	R-Sq	R-Sq(adj)	C-p	S	pH	Na ⁺ +K ⁺	Ca ²⁺	Mg ²⁺	CO ₃ ²⁻	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻
1	8.1	7.1	3.8	0.82751								
1	7.5	6.5	4.5	0.83025								
2	11.3	9.4	2.5	0.81744								
2	11.2	9.2	2.7	0.81810								
3	13.3	10.4	2.5	0.81259								
3	13.1	10.3	2.6	0.81333								
4	14.7	10.9	3.1	0.81064								
4	14.6	10.8	3.1	0.81083								
5	15.9	11.2	3.8	0.80922								
5	14.8	10.0	5.0	0.81467								
6	16.0	10.3	5.7	0.81344								
6	15.9	10.2	5.8	0.81380								
7	16.4	9.7	7.3	0.81597								
7	16.0	9.2	7.7	0.81808								
8	16.7	8.9	9.0	0.81949								

3.3 Discrimination model of buried pipe water leakage based on conventional ions

In further analysis, factor analysis of ions extracted from the optimal subset was performed using SPSS. The results obtained are shown in Table 3. From the table, we can see that three principal factors (PC1, PC2, and PC3) are obtained under the premise that the eigenvalue is greater than 1, and the overall information interpretation rate reaches 69.43%. After orthogonal rotation, the information interpretation rates of VF1, VF2 and VF3 are 28.43%, 25.43% and 15.57%, respectively. Among them, Ca²⁺ and SO₄²⁻ have higher positive load on VF1, while Mg²⁺ has medium positive load. According to previous studies, VF1 is mainly related to the dissolution of carbonates and sulfates, while K⁺+Na⁺ and HCO₃⁻ have higher positive load on VF2, Cl⁻ has higher positive load on VF3, and CO₃²⁻ has medium positive load, indicating that VF2 and VF3 mainly represent the weathering of feldspathic silicates and the dissolution of chloride salts(Wu et al.2004).

Table 3
Calculation and analysis results of SPSS factors for conventional ions

Component	Characteristic value			Before rotation			After rotation		
	Total	Variance /%	Cumulative variance /%	Total	Variance /%	Cumulative variance /%	Total	Variance /%	Cumulative variance /%
1	2.35	29.35	29.35	2.35	29.35	29.35	2.28	28.43	28.43
2	2.00	24.94	54.29	2.00	24.94	54.29	2.03	25.43	60.86
3	1.21	15.14	69.43	1.21	15.14	69.43	1.25	15.57	76.43
4	0.96	11.99	81.42						
5	0.66	8.19	89.61						
6	0.45	5.68	95.29						
7	0.37	4.57	99.86						
8	0.01	0.14	100.00						
	FC ₁	FC ₂	FC ₃			VF ₁	VF ₂	VF ₃	
pH	-0.66	-0.51	-0.03			pH	-0.78	-0.26	-0.18
K ⁺ +Na ⁺	0.12	0.94	0.05			K ⁺ +Na ⁺	0.41	0.85	0.16
Ca ²⁺	0.79	-0.09	-0.04			Ca ²⁺	0.71	-0.35	0.08
Mg ²⁺	0.64	-0.32	0.20			Mg ²⁺	0.46	-0.52	0.27
CO ₃ ²⁻	-0.01	0.08	0.03			CO ₃ ²⁻	-0.07	0.06	0.50
HCO ₃ ⁻	-0.47	0.81	0.03			HCO ₃ ⁻	-0.18	0.92	0.03
SO ₄ ²⁻	0.28	0.06	0.84			Cl ⁻	0.13	-0.07	0.88
Cl ⁻	0.75	0.25	-0.46			SO ₄ ²⁻	0.86	0.00	-0.31

The pH, K⁺+Na⁺, Ca²⁺, Mg²⁺, CO₃²⁻, HCO₃⁻, SO₄²⁻ and Cl⁻ are determined as characteristic ions, and classified and analyzed by SPSS. the model is established according to the obtained equations. the final discriminant equations are shown in Tables 4 and 5. It can be concluded from Table 5 that the established discriminant equation is:

$$F_1 = 2.283 \times \text{pH} + 0.015 \times \text{Ca}^{2+} - 0.004 \times \text{CO}_3^{2-} + 0.002 \times \text{HCO}_3^- + 0.001 \times \text{SO}_4^{2-} - 20.136 \quad (1)$$

$$F_2 = 0.516 \times \text{pH} + 0.003 \times \text{Ca}^{2+} + 0.012 \times \text{CO}_3^{2-} - 0.004 \times \text{HCO}_3^- + 0.002 \times \text{SO}_4^{2-} - 5.014 \quad (2)$$

Where F1 and F2 were the discriminant functions, and pH, Ca²⁺, CO₃²⁻, HCO₃⁻, and SO₄²⁻ respectively represented their contents.

Table 4
Interpretation of conventional ion model information of each water sample

Function	Characteristic value	Variance /%	Cumulative variance /%	Canonical correlation
1	2.49	51.30	51.30	0.81
2	1.50	30.50	84.00	0.75

Table 5
Discrimination equation based on conventional ions

Criterion function	Function 1	Function 2	Criterion function	Function 1	Function 2
pH	2.283	0.516	HCO ₃ ⁻	0.002	-0.004
Ca ²⁺	0.015	0.003	SO ₄ ²⁻	0.001	0.002
CO ₃ ²⁻	-0.004	0.012	Constant	-20.136	-5.014

In order to investigate whether the above judgment method was excellent or not, samples PW9-PW15 and UW9-UW15 (altogether 16) from known sources were substituted into the judgment function formula for regression analysis. The regression results are shown in Table 6, where □ is the tap water sample from the underground buried pipe, and □ is the shallow underground water sample near the underground buried pipe.

Table 6
Results of Back Judgment Test

Sample No.	Discriminating result	Actual type	Sample No.	Discriminating result	Actual type
PW9	□	□	UW9	□	□
PW10	□	□	UW10	□	□
PW11	□	□	UW11	□	□
PW12	□	□	UW12	□	□
PW13	□	□	UW13	□	□
PW14	□	□	UW14	□	□
PW15	□	□	UW15	□	□

It can be seen from Table 6 that the overall discrimination effect is good, reaching 87.50%, and shallow groundwater samples near two underground pipes are discriminated as tap water samples of underground pipes. However, the discriminant model based on conventional ions is difficult to accurately describe the leakage of buried tap water, that is, the amount of tap water entering shallow groundwater.

3.4 Distribution of hydrogen and oxygen isotopes in PW and UW and its influencing factors

Atmospheric precipitation is the ultimate source of groundwater, but the composition of hydrogen and oxygen isotopes in atmospheric precipitation in different regions is different due to different natural geographical

environments. Craig(1961) found that there is a close correlation between δD and $\delta^{18}O$ in atmospheric precipitation, and put forward the correlation formula: $\delta D=8 \times \delta^{18}O+10$, because the $\delta D-\delta^{18}O$ graph is a straight line, which is called the atmospheric precipitation line (MWL)(Craig 1964). Dansgaard first proposed the concept of deuterium surplus, which was used to evaluate the degree of deviation of hydrogen and oxygen isotopes in regional precipitation from the global precipitation line. The formula is $d = \delta D-8\delta^{18}$. Atmospheric precipitation lines in different regions are slightly different due to different geographical environments (Dansgaard 1964). Rozanski et al. (1993) analyzed 206 samples from all over the world through global LAEA network stations, and obtained the arithmetic mean value ($r^2=0.99$): $\delta D = (8.17\pm 0.06) \times \delta^{18}O+(10.35\pm 0.65)$ (Rozanski et al.1982). According to the statistics of Zheng Shuhui et al. (1983), the relationship of hydrogen and oxygen isotopic composition of modern atmospheric precipitation in China is $\delta D=7.9 \times \delta^{18}O+8.2$ (Zheng et al.1983).

The distribution of hydrogen and oxygen isotopes in water samples is shown in Figure 4. It can be seen from Fig. 4 that the precipitation line in Hefei is basically parallel to the global precipitation line (due to the lack of precipitation isotope data in Hefei area, this study selects precipitation data in Anhui Province instead(Zhang et al.2017)) and slightly higher than the global precipitation line, and the hydrogen and oxygen isotope values in water samples all fall below the atmospheric precipitation line (LMWL) in China, indicating that the recent sources of PW and UW are atmospheric precipitation, and that atmospheric precipitation experienced strong evaporation before being recharged underground(Zhang et al.2020). At the same time, it is found that the water in the pipe network is closer to the precipitation line than the shallow groundwater near the pipe network. It may be that the shallow groundwater near the pipe network is irradiated by sunlight and evaporates strongly, which makes the hydrogen and oxygen isotopes in the water relatively enriched(Wang et al.2013). Therefore, it is possible to distinguish the water samples of the pipe network and the water samples of the leakage points of the pipe network according to the difference of deuterium values in the water body of the tap water network and its nearby shallow groundwater(Liu et al.1997).

It can also be seen from Fig. 4 that both kinds of water samples show the characteristics of hydrogen and oxygen isotope drift. Different reasons lead to isotope drift in different layers of groundwater. The change of $\delta^{18}O$ is mainly the exchange between groundwater and surrounding rocks, mainly carbonate rocks. The change of δD is mainly caused by the exchange of groundwater with minerals containing OH radical (gypsum, clay minerals) or H_2S (Wicks et al.1994;A et al.2010).

In a word, because there are few samples and scattered water samples at present, no obvious isotope drift characteristics can be seen, but the shallow groundwater has the characteristics of $\delta^{18}O$ drift and δD drift due to the rich silicate minerals in the soil.

3.5 Establishment of Water Leakage Discrimination Model Based on Hydrogen and Oxygen Isotope

Select conventional ions Ca^{2+} , Mg^{2+} , K^++Na^+ , CO_3^{2-} , HO_3^- , Cl^- , SO_4^{2-} and isotopes δD and $\delta^{18}O$ in water samples, and draw the correlation diagram between hydrogen and oxygen isotopes of PW and UW and conventional ions by SPSS software, as shown in Fig. 5.

It can be seen from Fig. 6 that $\delta^{18}O$ of PW has a good correlation with K^++Na^+ , and δD has a good correlation with K^++Na^+ , which indicates that the δ value of hydrogen and oxygen isotope of buried tap water sample has a great relationship with the content of K^++Na^+ . Ions with great correlation with $\delta^{18}O$ in shallow groundwater samples

include Ca^{2+} , Mg^{2+} and CO_3^{2-} , while ions with great correlation with δD are Cl^- . This result may be due to the difference of hydrogen and oxygen isotopes between PW and UW, which mainly comes from the different selectivity between ions in the process of water-rock interaction. It can be seen that hydrogen and oxygen isotopes basically have the function of water source discrimination, so the hydrogen and oxygen isotope characteristics of water samples can be used to discriminate water leakage in urban buried pipes.

The hydrogen and oxygen isotopes of water samples are shown in Table 7. The stable hydrogen and oxygen isotopes of PW and UW are different. It is found that the stable oxygen isotope $\delta^{18}\text{O}$ in PW ranges from -7.05‰ to -7.38‰, with an average value of -7.233‰. Hydrogen isotope δd ranges from -47.37‰ to -49.64‰, with an average value of -48.38‰. The stable oxygen isotope $\delta^{18}\text{O}$ in UW ranges from -5.75‰ to -6.74‰, with an average value of -6.350‰. Hydrogen isotope δD ranges from -39.36‰ to -47.48‰, with an average value of -44.239‰. Comparison shows that the stable hydrogen and oxygen isotopes in PW are lower than those in UW, and the hydrogen and oxygen isotopes in UW are more abundant. By calculating the deuterium value of each water sample, the deuterium value in PW ranges from 9.34‰ to 9.65‰, with an average value of 9.490‰, and the deuterium value in UW ranges from 6.41‰ to 6.71‰, with an average value of 6.545‰. The deuterium value in UW is obviously lower than that in PW, which indicates that the difference of deuterium value between PW and UW can be used to discriminate urban buried pipe leakage.

Table 7
Hydrogen and oxygen isotope contents of PW and UW

No.	PW			□□	UW		
	$\delta^{18}\text{O}/\text{‰}$	$\delta\text{D}/\text{‰}$	$d/\text{‰}$		$\delta^{18}\text{O}/\text{‰}$	$\delta\text{D}/\text{‰}$	$d/\text{‰}$
PW1	-7.26	-48.52	9.56	UW1	-6.54	-45.76	6.56
PW 2	-7.05	-46.81	9.59	UW2	-5.87	-40.34	6.62
PW 3	-7.38	-49.64	9.40	UW3	-5.75	-39.36	6.64
PW 4	-7.09	-47.37	9.35	UW4	-6.17	-42.91	6.45
PW 5	-7.23	-48.20	9.64	UW5	-6.34	-44.30	6.42
PW 6	-7.37	-49.31	9.65	UW6	-6.56	-45.77	6.71
PW 7	-7.35	-49.43	9.37	UW7	-6.74	-47.48	6.44
PW8	-7.14	-47.62	9.50	UW8	-6.44	-45.11	6.41
PW 9	-7.22	-48.27	9.49	UW9	-6.61	-46.22	6.66
PW10	-7.24	-48.58	9.34	UW10	-6.46	-45.14	6.54
PW 11	-7.34	-48.24	10.48	UW11	-7.24	-49.31	8.62
PW 12	-7.08	-47.58	9.06	UW12	-6.80	-46.87	7.54
PW13	-7.41	-46.97	12.31	UW13	-6.63	-45.89	7.18
PW14	-7.38	-46.37	12.67	UW14	-6.71	-46.34	7.34
PW15	-7.24	-47.26	10.66	UW15	-6.64	-45.39	7.73

In order to study the influence of water from pipe network on hydrogen and oxygen isotope of shallow groundwater nearby, and the relationship between tap water leakage and deuterium value in mixed water, this study measured the hydrogen and oxygen isotope abundance ratio of mixed water (MW) after mixing PW and UW with different proportions (0%, 5%, 10%, 20%, 40%, 80%, 100%). See Table 8 for the hydrogen and oxygen isotope abundance ratio in mixed water.

Table 8
Hydrogen and oxygen isotopes in mixed water

Proportion of PW /%	Mean value		
	$\delta^{18}\text{O}/\text{‰}$	$\delta\text{D}/\text{‰}$	$d/\text{‰}$
0	-6.48	-45.47	6.41
5	-6.52	-45.66	6.48
10	-6.56	-45.86	6.64
20	-6.68	-46.22	7.21
40	-6.83	-46.96	7.63
80	-7.16	-48.42	8.88
100	-7.35	-49.15	9.65

It can be seen from Fig. 6 that after PW leaks into shallow underground aquifer, the abundance ratio of hydrogen and oxygen isotopes in mixed water will obviously decrease, and there is a good positive correlation between PW leakage and deuterium value in MW, and the equation is $y = 0.0321x + 6.3875$, $R^2 = 0.9945$. The prediction model of deuterium value in MW (d_{MW}) and water leakage in pipe network (V_{PW}) is obtained:

$$V_{\text{PW}} = (d_{\text{MW}} - 6.3875) \div 0.0321$$

3

To verify the accuracy of the above model, the pipe network tap water samples and underground water samples with known hydrogen and oxygen isotope abundance ratio were prepared into mixed water samples and added into a 10mL centrifuge tube with plugs, in which the proportion of pipe network tap water in the mixed water samples was 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% in turn. See Table 9 for the actual and predicted values of water ratio of pipe network in mixed water.

Table 9
Actual value and predicted value of water ratio in pipe network

True value of PW scale /%	d/ ‰	True value of PW scale /%	True value of PW scale /%	d/ ‰/‰	True value of PW scale /%
0	6.40	0.39	60	8.32	60.20
10	6.73	10.67	70	8.67	71.11
20	7.05	20.64	80	9.01	81.70
30	7.38	30.92	90	9.24	88.86
40	-6.83	-46.96	100	9.64	101.32
50	8.02	50.86			

The calculated MW is 0.39% and the error is 0.39% when PW is not added. When PW is 10%, the calculated MW is 10.67%, and the error is 0.67%. When PW is 100%, the calculated MW is 101.32%, and the error is 1.32%. The error between the calculated water content and the actual water content in the whole gradient dilution experiment is about 2.0%. In practical application, it is of great guiding significance to accurately determine the leakage of tap water in urban underground pipes by measuring deuterium value in MW.

4. Conclusion

In this study, conventional ions and hydrogen and oxygen isotopes of PW and UW near PW were analyzed using conventional water chemistry methods and hydrogen and oxygen isotope techniques. The results showed that UW exhibited the characteristics of low K^+Na^+ and low Cl^- while PW exhibited the characteristics of high K^+Na^+ and high Cl^- in UW. Through principal component analysis, K^+Na^+ , Ca^{2+} , CO_3^{2-} and SO_4^{2-} are selected as characteristic factors to establish a judgment model of buried pipe water leakage based on conventional ions. In addition, the hydrogen and oxygen isotopes in UW are more abundant than those in PW, and the PW leakage has a good positive correlation with the deuterium value in MWe formed by mixing. Hence, the discrimination model of buried pipe leakage based on hydrogen and oxygen isotopes is established. In the actual application process, whether the pipe network leakage exists in the water sample point is preliminarily judged by the judgment model based on the conventional ions, and the proportion of PW in MW is accurately determined by combining the judgment model based on hydrogen and oxygen isotopes. the error of PW proportion in MW judged by the model is about 2. 0%, which indicates that the error of the prediction model can meet the actual application. Therefore, the urban underground buried pipe leakage judgment model based on conventional ions and hydrogen and oxygen isotopes can well identify the buried pipe leakage points and determine the leakage amount of the buried pipe, providing a reliable method for urban pipe network leakage detection.

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Figures

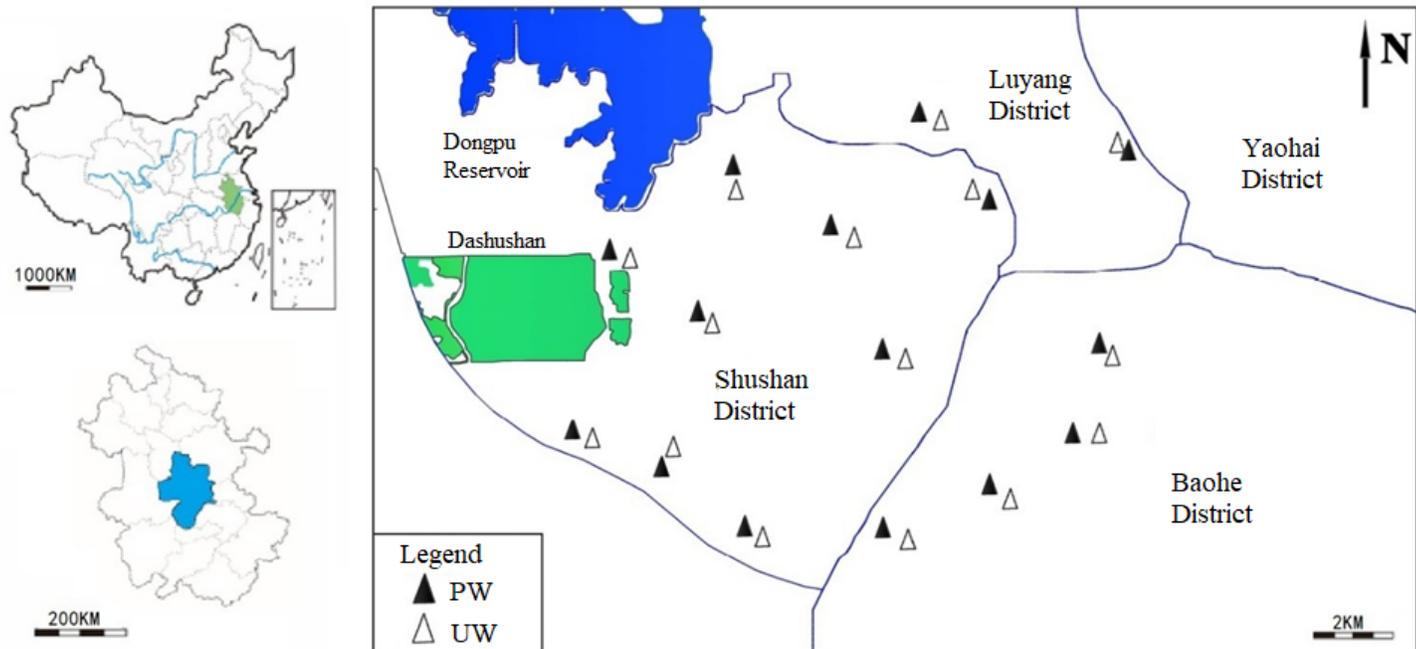


Figure 1

Distribution of sampling points

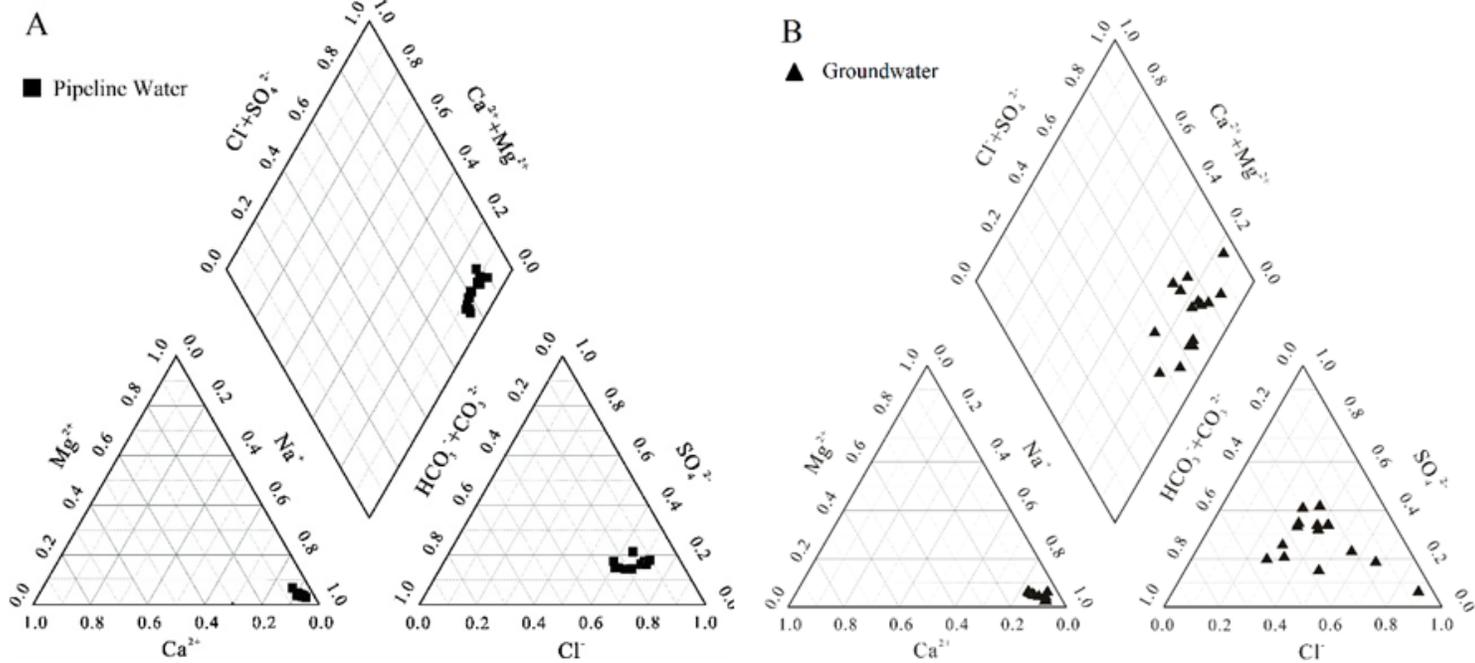


Figure 2

Piper three-line diagram of water sample

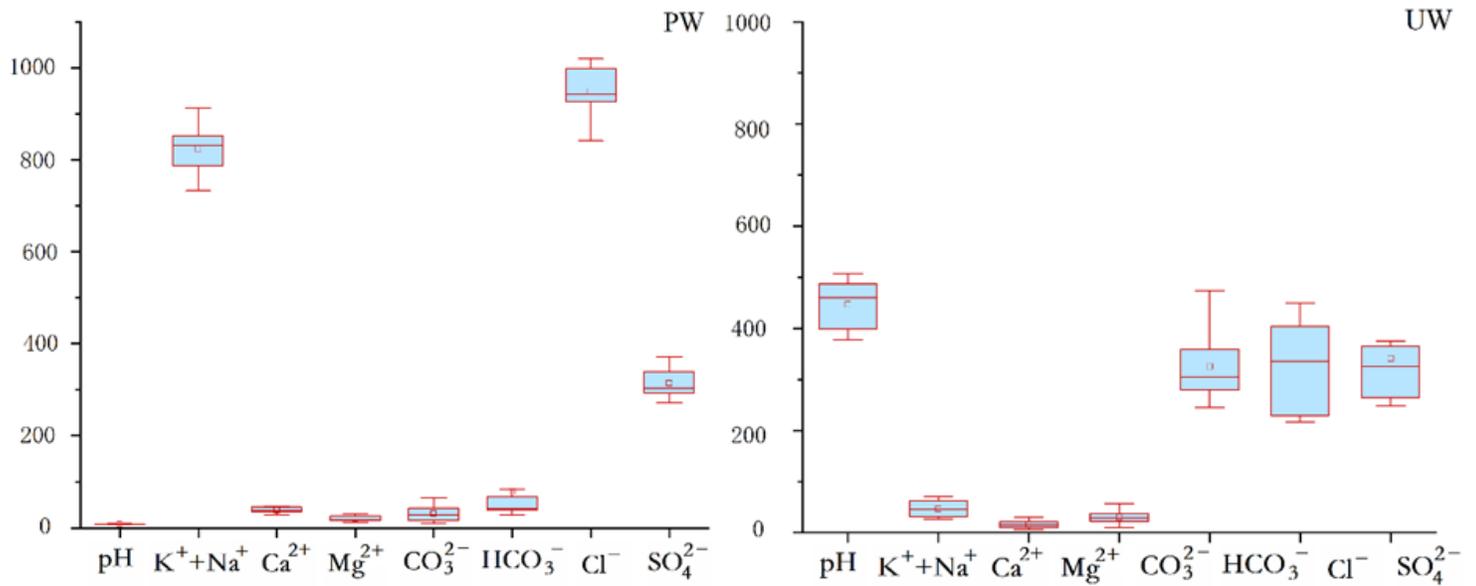


Figure 3

Box diagram of characteristic index of each water sample

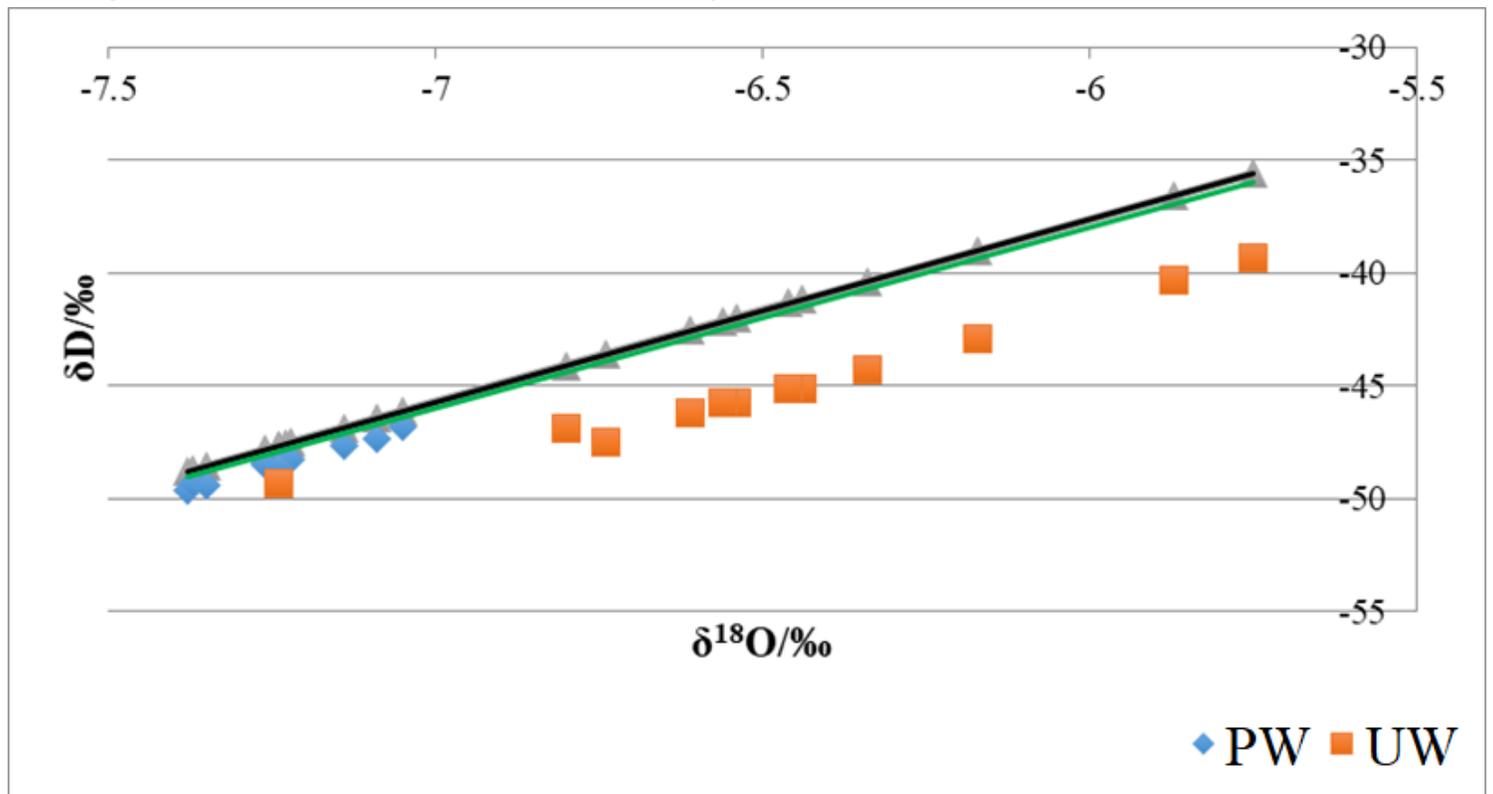


Figure 4

Distribution of hydrogen and oxygen isotopes in various water samples

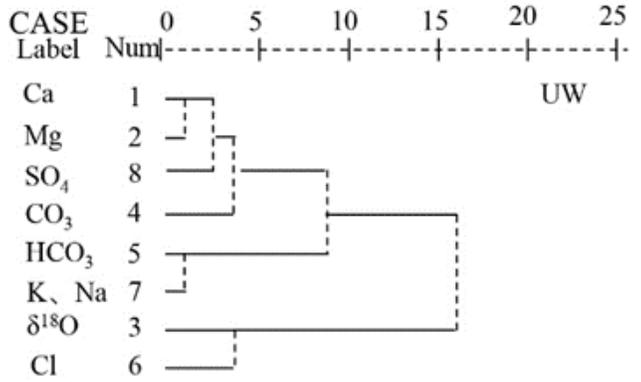
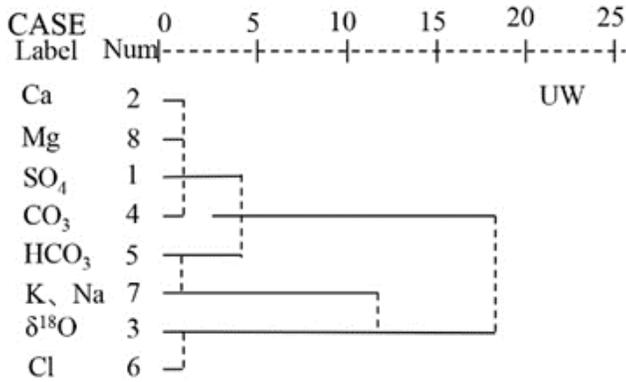
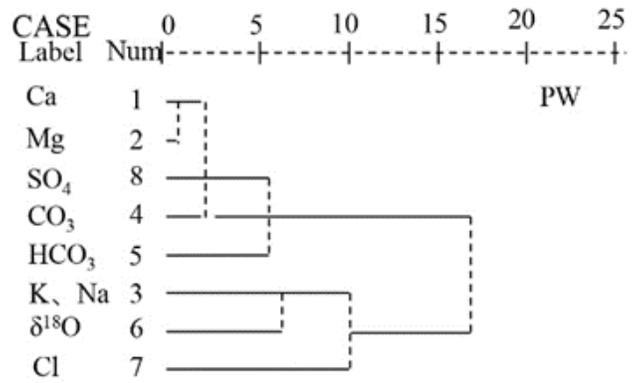
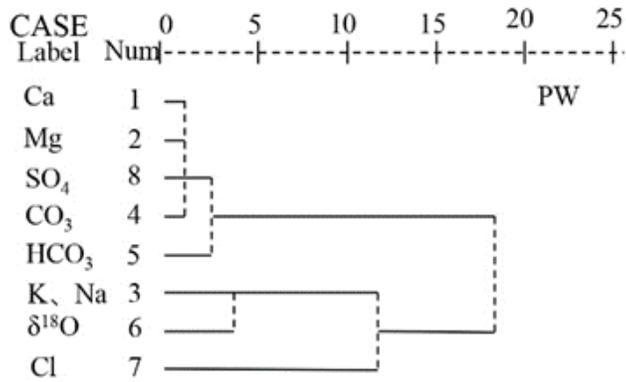


Figure 5

Cluster analysis results of hydrogen and oxygen isotopes and conventional ions in pipe network water samples and pipe network leakage water samples

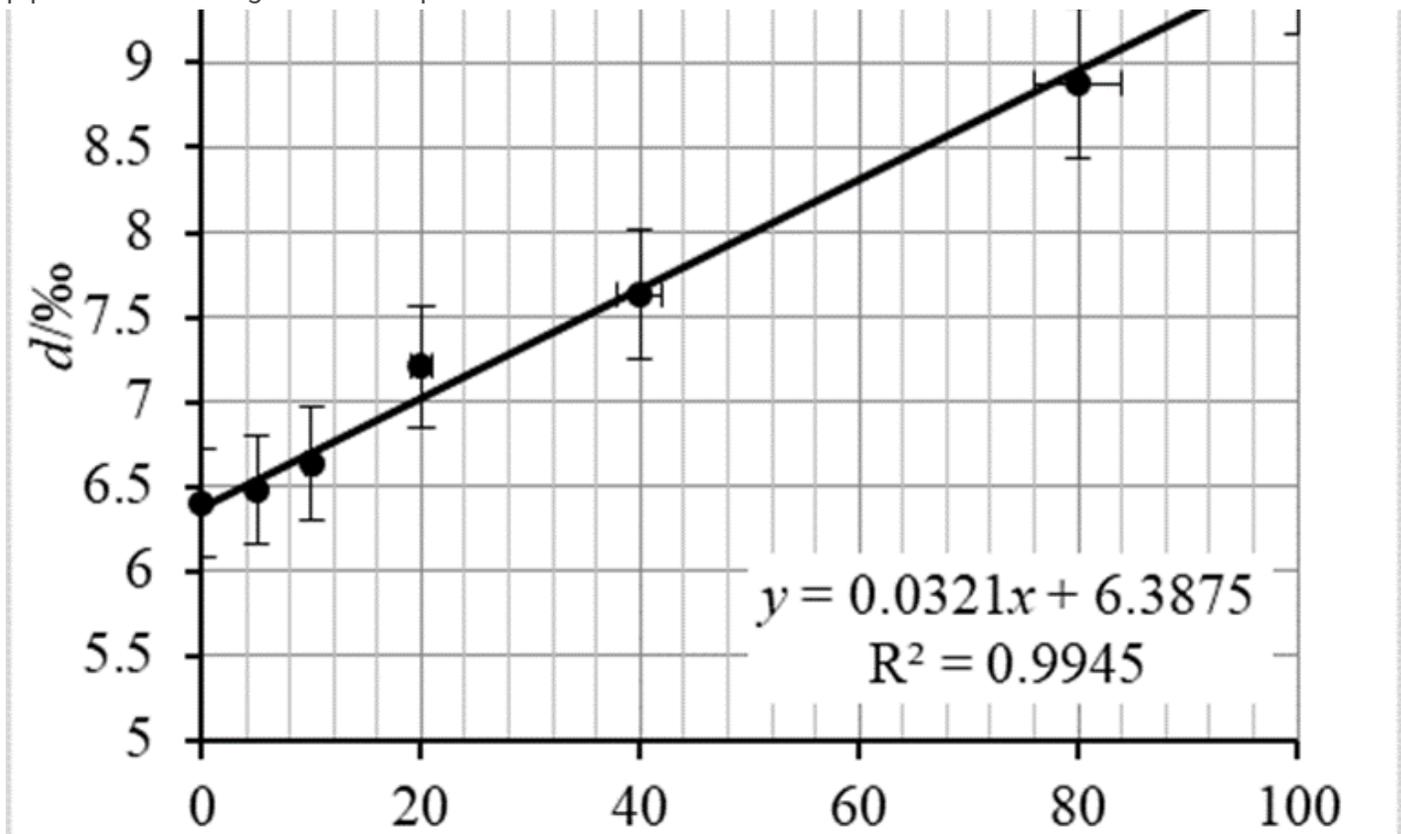


Figure 6

Correlation analysis between deuterium value and tap water leakage in mixed water