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A Study of *E. coli* Contamination in Household Drinking Water: A Case Study in Rural Areas of Zhangye City, Northwest China

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ABSTRACT. The objective of this study was to investigate *Escherichia coli* (*E. coli*) contamination in drinking water samples collected from a number of rural habitations of Zhangye City, Northwest China. A total of 37 villages along the Heihe River in Zhangye City were selected. The presence of *E. coli* was tested for using the MicroSnap™ *E. coli* Test Kit, which is a rapid bioluminogenic method for detection and enumeration of *E. coli* bacteria. Test results demonstrated that drinking water in 81.1% of the villages was contaminated with *E. coli* according to the Chinese Sanitary Standards for Domestic and Drinking Water. Majority of the higher *E. coli* CFU values were tested from villages located in the urban areas in Zhangye City. The data suggested that contamination of the drinking water in the rural habitations of Zhangye City was related to animal husbandry practices. In addition, the interactions of surface and groundwaters is not direct causes of the *E. coli* contamination found in Zhangye City. The occurrence of *E. coli* in drinking water may increase the risk of water-related diseases and health problems in local residents. It is therefore strongly recommended that solar energy technology be taken to protect water resources from contamination.

Keywords: E. coli contamination, drinking water safety, rural water supply, Heihe river basin, Zhangye City, solar energy sewage treatment

1. Introduction

Human consumption of water containing excessive *E. coli* amounts is likely to cause human intestinal disease. Since the 20th century, there have been many cases of *E. coli* infection around the world. The world's largest outbreak of *E. coli* O157 infections occurred in Osaka, Japan in 1996, affecting approximately 7500 people (Michino et al., 1999). Thanks to prompt action, only 3 people died during that outbreak. Another *E. coli* outbreak, in Scotland in November 1996, killed 20 of the 496 people infected (Allison and Thomson-Carter, 1997). In 2011, 4,900 people in Germany were infected with *E. coli* (around 4,000 cases of bloody diarrhea, 850 cases of the hemolytic uremic syndrome, and 50 deaths) to varying degrees due to contaminated vegetables; only 31 people died due to the government's emergency measures (Grad et al., 2012). *E. coli* infections are also common in China. In 1999, 986 people were infected with invasive *E. coli* due to contaminated food in Dazu County, Chongqing, with those infected showing varying degrees of diarrhea and other intestinal diseases (Chen et al., 2013). An *E. coli* outbreak occurred in Xuzhou, Jiangsu with 99 cases of diarrhea and acute kidney failure, including 83 deaths from May to September in 1999 (Zhu et al., 2009). Almost 90% of children die from diarrheal diseases, which are directly related to water pollution such as lack of sanitation facilities or inadequate hygiene conditions, these deaths were about 760,000 per year in 2011 (UNICEF, 2013).

Currently, more than 90 percent of cities and nearly 50 percent of towns in China have suffered varying degrees of water pollution. Among various environmental pollution problems, pathogenic microorganisms in drinking water pose one of the most serious hazards to human health (Han et al., 2016). Relevant medical literature indicates that pathogenic microorganisms might become one of the main routes for human-to-human transmission of diseases in the future (Thomas et al., 2010; Wingender and Flemming, 2011; Han et al., 2016). According to the analysis of the national water quality monitoring data, the drinking water of 710 million people in China was polluted to some extent, of which over half consume drinking water contaminated with levels of animal and human excreta that exceed maximum levels by as much as 86% in rural areas and 28% in urban areas (Wu et al., 1999).

It is reported that the pollution sources of *E. coli* and other pathogenic microorganism contamination can come from a wide range of sources such as areas with poor sanitary conditions, contaminated wastewater, meat products, cereal products and vegetables (Ekici and Dümen, 2019). Poor animal husbandry practices can lead to the growth and reproduction of pathogenic microorganisms such as *E. coli*. At the same time soil, irrigation water, animal manure and animals can all be sources of *E. coli* contamination in agricultural products. In particular, animal hus-

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bandry and agriculture are considered to be major sources of *E. coli* contamination in China.

E. coli can exist in water in its natural state, but drinking water is required to be free from *E. coli* to meet Chinese water quality standards. According to the Chinese Sanitary Standards for Domestic and Drinking Water jointly issued by the National Standards Commission and the Ministry of Health (GB 5749-2006) and 13 national standards for sanitary inspection of drinking water, the amount of *E. coli* in standard drinking water is specified as follows (GB 5749-2006) (Li, 2008): 1. Total coliform (MPN; most probable number/100mL or CFU; colonyforming unit/100 mL) should be 0; 2. Heat-resistant coliforms (MPN /100 mL or CFU/100 mL) should be 0; 3. *E. coli* (MPN/100 mL or CFU/100 mL) should be 0; 4. Total number of colonies (CFU /mL) should be less than 100.

In short, environmental water problems caused by pathogenic bacteria have become an increasingly serious issue in recent years, especially in rural China where rates of infective diarrhea and intestinal diseases as a result of pathogenic *E. coli* have been rising significantly and threatening human health (Wu et al., 1999; Kaper, 2004). Meanwhile, the large rural regions and the disorderly discharge of sewage make the control of water pollution, particularly pathogenic organisms, more difficult. Therefore, it is particularly important to investigate the pathogenic bacteria pollution in drinking water and to control pathogenic bacteria in rural aquatic environments.

There are few studies in Northwest China on the *E. coli* contamination of drinking water in the household environment. The main objectives of this study were to evaluate the current situation regarding *E. coli* contamination of household drinking water in rural areas of Zhangye City by using quantitative analysis. And assess the possible sources causing *E. coli* contamination in the drinking water.

2. Study Area

The Zhangye basin is located in the middle reaches of the Heihe River, in Gansu Province, Northwest China (Figure 1), with a population of 1.3 million (Zhang et al., 2015). Zhangye City was chosen for this study for its rather complex hydrological system. The main industries in this region are agriculture and animal husbandry. These combined cultivates an environment susceptible to groundwater *E. coli* contamination.

2.1. Geographical Location and Climatic Conditions

The Zhangye basin is located in the center of Eurasia and is surrounded by high mountains. The local climate is dominated by a mid-to-high latitude westerly circulation and influenced by polar cold air masses. The continental arid climate in Zhangye City is characterized by its large temperature differences between night and day, low rainfall (precipitation is scarce and concentrated), high levels of evaporation, low humidity, and long durations of sunshine. There are obvious differences between east and west as well as between north and south in the middle reaches of the basin. The average annual precipitation in the region is 104 to 150 mm, decreasing from east to west and from south to north (Wen et al., 2009). The average annual potential evapo-ration is 2,048 to 2,341 mm, increasing from east to west. The wet season starts in June and ends in September, accounting for more than 60% of the total annual precipitation; whereas the drought season ranges from December to February. The wind direction in the region is mainly northwesterly. The average annual occurrence of high winds above category 8 is 15 to 19 days. The perennial average relative humidity is 49 to 53% (Wen, 2007).

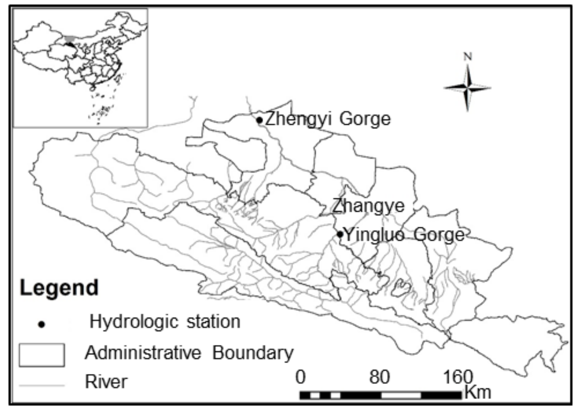

Figure 1. Location of Zhangye city in Heihe River basin.

2.2. Sources of Drinking Water in Zhangye City

The total amount of available water in Zhangye City is 2.65 billion m^3, including 2.475 billion m^3 of available surface water resources and 175 million m^3 of net groundwater resources that do not duplicate surface water resources. Total annual water consumption in 2019 was 2.064 billion m^3. This comprised 46 million m^3 of domestic water, 22 million m^3 of industrial water, 1.953 billion m^3 of agricultural water, and 43 million m^3 of ecological water supply. The surface Heihe River mainstream water quality compliance rate was 100% and the urban centralized drinking water quality compliance rate was also 100% (Zhangye Statistical Yearbook, 2019).

Urban areas of Zhangye City generally use surface (river) water that has undergone purification treatment as their source of drinking water. However, groundwater is the major source of drinking water for most rural areas, particularly remote mountainous areas. According to New Regulations on the Administration of Rural Drinking Water Supply in Gansu Province, the allocation of water resources for drinking water supply in rural areas shall give priority to the use of surface water and rational exploitation of groundwater.

2.3. Groundwater and River Water in Zhangye City

Groundwater and river water are complementary in Zhangye City, with close hydrologic connections and frequent transformation relationships between them. In recent decades, under the influence of natural factors and human activities, the transformation relationship between rivers and groundwater tends to be complicated, which causes changes to the water cycle, induces a series of negative benefits to the ecological environment, and highlights water quality problems. Once groundwater is polluted, it is very difficult and extremely costly to treat and remediate (Qi and Luo, 2005). It may be impossible to completely remedy groundwater pollution within a given period.

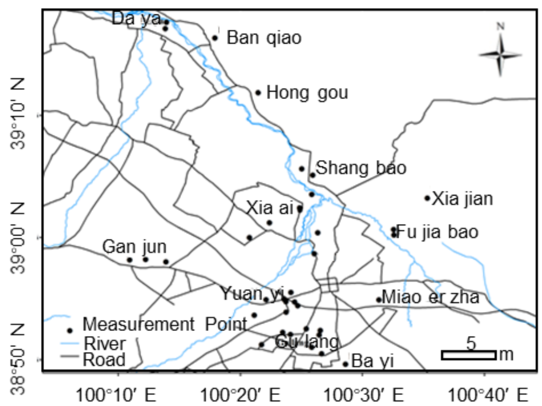

Figure 2. Sampling locations in Zhangye City.

2.4. Agriculture and Animal Husbandry

In 2019, the sown area of crops was 443.53 km^2 with an increase of 9.35 km^2, which increased by 2.15%. The sown area of grain crops was 301.47 km^2 with a decrease of 6.59 km^2, which decreased by 2.14%. The sown area of main varieties of grain crops increased by barley and decreased by wheat, corn, and potato. The area of the barley was 34.65 km^2 with an increase of 20.66%. The areas of wheat, corn, and potato were 60.93 km^2, 15.49 km^2, and 29.87 km^2 with a decrease of 3.03, 4.57, and 5.98% respectively.

The sown area of economic crops was 119.91 km^2 with an increase of 3.32 km^2 with an increase of 2.85%. Among them, the area of vegetables was 36.98 km^2 with an increase of 8.23 km^2 with an increase of 28.59%, and the area of medicinal materials was 27.04 km^2 with an increase of 0.14 km^2, increased by 0.51%. The area of other seed production was 13.78 km^2, increased by 4.64 km^2, increased by 50.78%. The area of oil plants was 34.49 km^2, decreased by 10.78 km^2, decreased by 23.8%. The area of oil plants, vegetables, traditional Chinese medicine and other seed production accounted for 93.67% of the area of economic crops.

The scale efficiency of animal husbandry in Zhangye City continued to show good levels of development, the efficiency of beef cattle and sheep breeding increased steadily. Moreover, the effect of pig regulation was obvious and the production capacity rebounded with the high price falling. By the end of 2019, there were 428,800 pigs in stock (a decrease of 13.13% from the previous year) and 631,900 pigs for selling (a decrease of 3.41% from the previous year). There were 533,600 head of cattle in stock in the same year (an increase of 6.18% from 2018). An additional 251,500 head of cattle were for selling (an increase of 10.95% from 2018). There were 2.9443 million head of sheep, 5.11% more than the previous year, and there were 4.0996 million poultry in stock with an increase of 1.15% (Zhangye Statistical Yearbook, 2019).

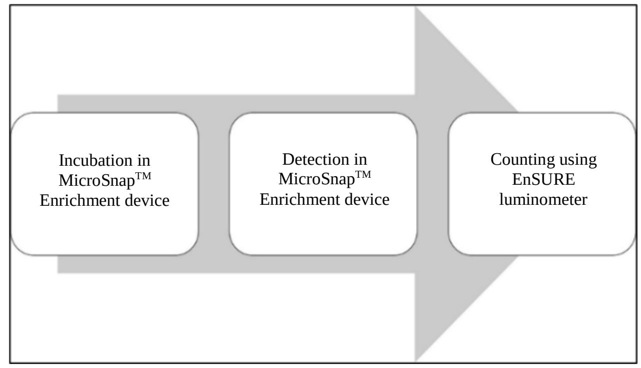

Figure 3. The methods followed to analyze the *E.coli* values of drinking water samples.

3. Methods

The study was conducted in August 2015 in Zhangye City, Northwest China (Figure 2). A systematic random sampling procedure was utilized in the selection of study households from a total of 111 households (37 villages) in the rural villages in Zhangye City. The household drinking water source is groundwater pumped from 120 meters well. Each village share a water tower and drinking water was distributed to each household through the water distribution system. Our water samples were collected directly from household water taps. All samples were collected using sterile 100 mL plastic bottles, put on ice, and transported to a field laboratory where they were analyzed for *E.coli* within 24 hours after sampling.

E.coli analysis was conducted using the MicroSnap™ *E. coli* Test Kit, which is a rapid bioluminogenic method for detection and enumeration of *E.coli* bacteria. Two steps, including *E.coli* bacteria enrichment and *E.coli* detection, were involved in determining *E.coli* values in drinking water samples.

As shown in Figure 3, in step 1 (enrichment), the drinking water sample is incubated in growth media for 6 hours to increase the number of *E.coli* bacteria present. Following this, an approximately 1 ml sample is transferred to a detection device. In step 2, the detection device is activated and samples are further incubated for 10 minutes. During this period, a specific substrate reacts with diagnostic enzymes to produce light, which is measured by using an EnSURE luminometer. Light output is directly proportional to the initial starting inoculum. Results are displayed as Relative Light Units (RLU). The equivalent colony-forming unit (CFU) values will be determined with RLU. Which will show how many Coliforms or *E.coli* CFU were present in the original samples.

4. Results

In this study, we chose 37 villages in Zhangye City as the target study areas. The 37 villages are all situated along rivers and streams, and all are at least 30 m away from the nearest waterway (Figure. 2). The villages all depend on wells for drinking water. A well of 120 m was selected in each village and samples tested for *E.coli* contamination. At the time of the investigation, there had been no known significant prior changes to the water supply system in these villages.

As previously discussed, the number of *E.coli* in 100 ml of drinking water should be 0, so the CFU value should also be 0 to be considered healthy.

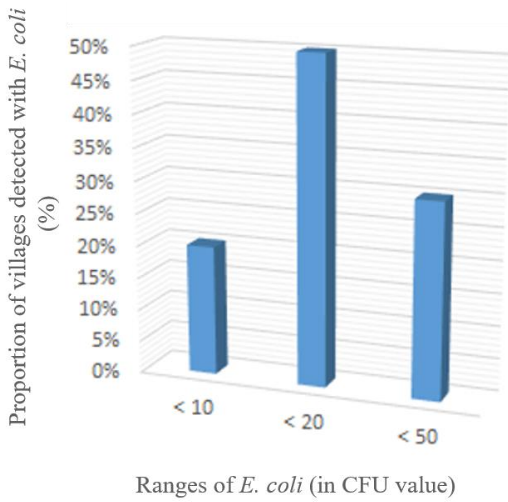

Figure 4. *E.coli* values in terms of proportion of villages.

From Figure 4, it can be concluded that drinking water in 30 out of the 37 villages assessed was contaminated with *E.coli*. Results are displayed as colony-forming units (CFU). This will tell you how many Coliforms or *E.coli* CFU were present in the original samples. Among them, 6 villages demonstrated CFU values < 10, 15 villages demonstrated CFU values < 20, and 9 villages demonstrated CFU values < 50.

In addition, the distribution of *E.coli* based on CFU values were shown in Figure 5, higher concentration of *E.coli* was mostly located near the urban area. Particularly, *E.coli* CFU values < 50 were tested in 9 villages in the urban areas including village Guo jiabao, Yang jiazha, Miao erzha, Jing ping, Shang ai, Zia ai, Su zhan, Kang ning, Zhuang dun in Zhangye City.

5. Discussions

5.1. Causes of High *E.coli* Contamination

E.coli should not be detected in drinking water at all; however, out of the 37 villages studied in Zhangye City, samples from 30 (81.08%) villages were shown to have *E.coli* contamination in household drinking water. The possible reasons for such a high frequency of contamination are summarized as follows.

In the water environment, the survival conditions are far worse than the intestinal system, and the number of *E.coli* naturally decreases (Van Elsas et al., 2011). The results of freshwater microscopic studies showed that the *E.coli* population died rapidly and dropped from one log to several logs in a period of one week to 10 days (Sampson et al., 2006). Whereas, the population in groundwater decreases more slowly, and the data of microscopic study show that the time range of one log decrease is about one to two weeks (Filip et al., 1986).

Furthermore, in a natural water environment (such as a water distribution system), *E.coli* can adapt to a viable but nonculturable (VBNC) state when they encounter conditions that do not support growth. In this state, they will not grow on the laboratory medium, but in other cases, they are still alive and can be resuscitated when the conditions are favorable (Bjergbaek and Roslev, 2005). This VBNC state may be caused by a variety of stress factors, including nutritional restriction, pH, temperature, oxygenation, osmotic pressure, and exposure to antimicrobial agents, such as drinking water disinfectants (Bjergbaek and Roslev, 2005; Chen et al., 2018). VBNC state is a major survival strategy of bacteria, which has been observed in many species.

Therefore, the fate of *E.coli* populations is not easy to predict in complex natural environments (Van Elsas et al., 2011). Some studies have shown that the organism survives several weeks in lake water at 4 ℃ (Sampson et al., 2006) and 14 weeks in filtered groundwater (0.45 μm) at 10 ℃ (Filip et al., 1986).

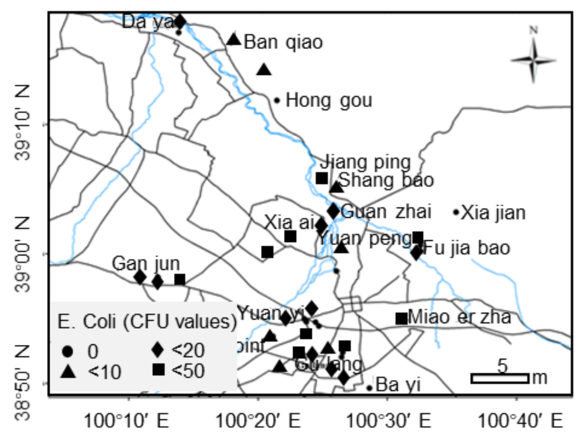

Figure 5. The distribution of *E.coli* values in Zhangye City

5.1.1. Animal Husbandry and Untreated Sewage Seeping into the Groundwater

E.coli naturally exists in the intestinal system and feces of humans and various animals. It is most common in warm-blooded animals (domestic and wild), but it can also be found in many cold-blooded animal species (Tenaillon et al., 2010; Frick et al., 2018). Because of its rapid and convenient detection, it is an important indicator of fecal pollution. Special serotype strains such as 0157: H7 have strong pathogenicity and can cause epidemic diseases (Grad et al., 2012). Fecal sources that may affect the supply of surface or groundwater sources include point sources such as sewage and industrial wastewater, septic tank systems, sewer leaks, and non-point or diffuse sources such as runoff from agricultural, urban, and natural areas (Gordon et al., 2002).

In recent years, with the rapid economic development of Zhangye City, the production of animal husbandry and poultry has raised rapidly. Zhangye City possesses a large amount of industrial-scale animal agriculture (animal husbandry). According to Zhangye statistics, in 2019, the annual output of pig, cattle, sheep, and poultry meat in Zhangye City was 116600 tons with an increase of 3.59% over the previous year. Among them, the output of pork was 43,100 tons with a decrease of 3.22%, the output of beef was 25,700 tons with an increase of 10.52%, the output of mutton was 38,700 tons with an increase of 671, and the output of eggs was 13,800 tons, increased by 1.34%. Milk output was 69,600 tons with an increase of 14.96% (Zhangye Statistical Yearbook, 2019). Animal husbandry has become one of the main pillar industries of agriculture and the rural economy in Zhangye.

Moreover, the discharge of waste water in Gansu province increased significantly. In 2015, the total amount of waste and sewage discharged in water systems is 667 million tons, of which 170 million tons are from inland river basin and the Yellow River Basin, 474 million tons in the Yellow River basin and 22 million tons in the Yangtze River Basin. According to the emission industry, 232 million tons of domestic sewage were discharged, and 436 million tons of industrial sewage were discharged (Water resources communique of Gansu Province, 2018).

Based on the results, majority of the higher *E.coli* CFU values were tested in villages from the urban areas, which shown there is a high possibility that animal husbandry and untreated sewage seeping into the groundwater are important sources of *E.coli* contamination in Zhangye City.

5.1.2. Interactions of Surface and Groundwaters

The exchange of water between surface waters and village groundwater can influence the distribution of *E.coli*. We assumed that *E.coli* does not die during this water exchange but that it would pass from the river into the groundwater. To make it simple, we only considered the water exchange between surface water and the village groundwater through the soil (or riverbank). Riverbank filtration is a natural purification process. As early as 1870, Germany used the riverbank filtration of the Rhine River to provide drinking water for residents. Riverbed percolation has been widely used in many European countries for more than 100 years. Groundwater obtained through riverbank percolation accounts for 50% of the total drinking water in the Slovak Republic, 45% in Hungary, 16% in Germany, and 5% in the Netherlands (Schubert, 2002). China also obtains drinking water through riverbank osmosis. During the process of groundwater flowing through water-bearing media, it is comprehensively affected by physical, chemical, and biological processes, including filtration, adsorption, microbial degradation, etc., improving the water quality. Riverbed percolation can purify water, including the removal of a variety of physical, chemical, and biological pollutants. There are many studies on the removal of organic carbon, turbidity, pesticides, and other organic pollutants in the literature, as well as a number on the removal of *E.coli* by riverbank filtration systems. Sampling analyses of percolating water in pumping wells and surface water have verified the removal of *E.coli*, after the surface water penetration process, the removal rate of *E.coli* reached more than 99.99% in Santan well field (Hu et al., 2016). Detecting the microbial concentrations present in groundwater in three riparian filtration facilities along the Wabash, Ohio, and Missouri Rivers in the United States for more than a year, finding shows that the riparian infiltration zones have the potential to significantly reduce microbial concentration. Cryptosporidium and Giardia are occasionally detected in river waters, but never in any groundwater (Weiss et al., 2005).

Returning to this case, all the observed wells in the 37 villages in Zhangye City are more than 30 meters from surface water, and 120 meters deep from the surface ground, where riverbed and soil percolation plays a role to exclude the *E.coli*. Therefore, the hypothesis of riparian filtration suggests that *E. coli* contamination in the 120 meters deep drinking water wells in the villages of Zhangye City cannot be related to surface water contamination because the riverbanks and soils have the function of removing *E.coli* from the water. Therefore, interactions of surface and groundwaters are not direct cause of the *E.coli* contamination found in Zhangye City.

In short, animal husbandry could be considered as a major source of *E.coli* contamination in drinking water in Zhangye City. However, there is no clear evidence that the exchange of water between surface waters and village groundwater sources causes *E.coli* contamination in the villages. The animal feces from agriculture seeps into local groundwater, polluting drinking water. There is no *E.coli* removal link in the drinking water purification process, so *E.coli* can be detected in water from taps in Zhangye City.

5.2. Current Situation of Rural Drinking Water Safety Project in Ganzhou District of Zhangye City

From 2004 to 2009, only 38% of the 21.11 million rural population in Gansu Province achieved safe drinking water, and the other 15.25 million people did not access safe drinking water. In 2005, China began to implement rural drinking water safety management and build rural safe drinking water project, and the rural drinking water problem in Zhangye City has been gradually improved (Zhao, 2008; Xue et al., 2019; Zhang, 2020). Up to 2014, Gansu Province has compiled the planning report on comprehensively solving rural drinking water safety problems in Gansu Province, and the funds for the construction of rural drinking water safety projects have reached nearly 10 billion yuan, of which 80% are supported by the central government, 15% are provincial supporting funds, and 5% are self-raised funds by the masses. Before and after the construction of a total of 5,241 centralized water supply projects, 53,600 small electric wells, water cellars and other decentralized water supply projects. In the report, it is pointed out that billions will continue to be invested in solving the problem of drinking water in rural areas to comprehensively guarantee the safety of drinking water in rural areas of Gansu Province (Zhong, 2020). By 2019, more than 100 safe drinking water projects have been completed in Gansu Province, and there are still dozens of projects in the construction process. The drinking water safety projects in Gansu Province have covered 98% of the area and population (Zhao, 2008; Luo 2019; Zhao and Wang, 2019; Zhang, 2020).

In 2017, there were 144 centralized water supply projects in 144 villages, 8 towns, 10 townships in Ganzhou District, Zhangye City. The actual water supply capacity of 8 projects met the design water supply capacity, and the actual water supply capacity of 20 projects was less than 60% of the design water supply capacity. Among 144 rural centralized water supply projects in Ganzhou District, Zhangye City, only 27.08% of them are rural safe drinking water projects, which mainly solve the problem of water shortage, only 11.81% of them are water supply projects with complete treatment, the disinfection rate of water supply is only 12.50%, and the health license holding rate is only 9.72% (Xue et al., 2019; Zhong, 2020).

Due to many factors were affecting the rural drinking water construction project, there are still some problems in rural drinking water safety in Zhangye City as follows.

5.2.1. Lack of Preliminary Planning of Construction Project and Unreasonable Design

In the early stage of the drinking water safety project, the designers and planners are lack of overall planning for the project, and due to the lack of sufficient time and funds in the planing process and incomplete engineering design data, there are loopholes in the project planning (Zhao, 2008; Zhao and Wang, 2019). Instead of analyzing the construction and operation of the drinking water safety project from a large scale, they establish small safety projects according to the administrative villages in rural areas. Make the operation process after construction often appear to have a large number of repairs, affect the operation efficiency of the project.

5.2.2. Lack of Professional and Technical Personnel in the Operation and Management of Safe Drinking Water Project

Rural safe drinking water project has not achieved scale, small projects in the construction process are basically organized by the farmers, it is also is also lack of professional and technical personnel in the management work after the construction, which is unable to repair the project equipment. To solve this problem, some areas put forward to hand over drinking water safety projects to professional companies for unified maintenance and management, but most farmers do not want to bear the extra cost (Zhao and Wang, 2019; Zhang, 2020; Zhong, 2020).

It is urgent to formulate systematic and effective management methods and rules and regulations. Since there are still many problems such as the protection of drinking water sources, the damage of water supply network facilities, the unclear and nonspecific drinking water health standards, the insufficient depth of drinking water wells in individual centralized water supply projects, the lack of water purification equipment and disinfection facilities, and the existence of a variety of hazards in domestic water use.

5.2.3. Difficult to Collect Water Charges

The rural economic level of Zhangye City is relatively backward, and farmers' income is less, which leads to the obstruction of water fee collection process, and the local government's financial expenses are also very limited, which leads to the lack of funds for later maintenance and repair of safety engineering projects (Zhao and Wang, 2019; Zhong, 2020). Most projects even have a big gap in the most basic operating costs. The project operation not only has no economic income, but also has annual losses, it cannot provide financial support for the sound operation of the project.

5.3. Possible Solutions for Rural Safe Drinking Water Projects

5.3.1. Introduction of Solar Energy Sewage Treatment Technology

Most municipal wastewater treatment plants adopt A^2/O, oxidation ditch and sequencing batch reactor (SBR) processes. By installing the photovoltaic panels on the roof of the building, the pool surface of the structure and all kinds of idle space can realize the secondary utilization of space to a certain extent (Oswald and Golueke, 1960; Rao et al., 2012; Bustamante, 2017).

Since the construction of the first solar powered wastewater treatment plant in the western United States, this kind of wastewater treatment system has attracted much attention. At present, there are several successful cases in China, such as Yangzhou Liuwei sewage treatment plant, Tangwang sewage treatment plant and the first Waterworks of waterworks company, with a total pool area of about 9.8×10^4 m^2, photovoltaic power stations are built with a total installed capacity of 9.7 MW. According to the average daily power generation, it can meet 30 ~ 40% of the power consumption of the two sewage treatment plants, while the waterworks can be completely self-sufficient (Liu et al., 2018).

The average daily power generation of solar energy is about 897 kw/h, and the average power consumption of a sewage treatment plant is about 1350 kw/h, which means that solar energy can meet 70% of the power consumption of the sewage treatment plant (Rao et al., 2012; Bustamante, 2017). Under solar irradiation, almost all (99.9%) of the bacteria were killed after 6 hours incubation at 37 ℃ in the presence of 1 mg/mL PTh/MnO_2 photocatalyst (Shang et al., 2011). Photocatalytic disinfection with UV light in the presence of TiO_2 more effectively killed *E.coli*, and the use of quartz device and TiO_2 resulted in killing of *E.coli* within minutes (Cho et al., 2002). It can be seen that the method of solar photovoltaic power generation is more suitable in small and medium-sized sewage treatment plants (Chang et al., 2019). It can not only improve the efficiency of sewage treatment in an all-round way, but also save energy consump-tion to the greatest extent.

At present, the operation of sewage treatment plants with different treatment scales in China shows an overall growth trend, especially the operation number of small sewage treatment plants most rapidly. If photovoltaic power generation is applied to small and medium-sized secondary sewage treatment plants in Zhangye city, it will have more significant effect on energy saving and cost reduction.

5.3.2. Solar Constructed Wetland

Constructed wetland is a new sewage treatment technology based on solar energy in recent years. The capital investment of this technology is relatively small, but the cost performance is very high. It has excellent treatment performance, simple operation and easy to carry out maintenance and management. It has been highly praised by relevant departments and researchers (Khatiwada and Polprasert, 1999; Korovessis and Lekkas, 2009; Alvarez et al., 2017; Mishra et al., 2018; Casierra-Martinez et al., 2020). Solar constructed wetland has the potential to detoxify wastewater containing pesticides effectively, and producing a purified effluent which could be exploited for reuse (Berberidou et al., 2017). Solar radiation plays a critical role in the removement of coliform populations, maximum removal of coliforms was obtained under conditions of high temperature and solar radiation (Zdragas et al., 2002). This technology is more suitable for rural areas in Zhangye city, with small amount of sewage and wide distribution. Since rural areas have a unique advantage of solar energy resources. Combining this advantage with constructed wetland system can effectively solve the dilemma of energy supply, greatly reduce the management cost, and help to solve the problem of sewage treatment in remote areas or areas with underdeveloped power resources.

5.3.3. Solar Sterilization Technology

Solar sterilization technology is a new type of water treatment technology with high technology content. This technology can achieve deep treatment of sewage, which has very important practical significance for sewage purification. The main principle of this technology is photocatalytic oxidation technology (Berberidou et al., 2017). The rise of photocatalytic oxidetion technology can be traced back to 1972. Fujishima, a famous Japanese scholar, published a research article on Photocatalytic Oxidation Technology in nature, he and Honda carried out photoelectrochemical water oxidation experiments on TiO_2 electrodes (Fujishima and Honda, 1972). So far, photocatalytic oxidation technology has come into people's vision, and with the indepth research in recent years, it has been widely applied to the degradation of pollutants in water (Bansal et al., 1988; Hameed and Ahmad, 1997; Zhang et al., 2017; Li et al., 2018; Negishi et al., 2019; Liu et al., 2019).

With the rapid economic development of Zhangye City, promoting the application of new clean energy source has become one of the key research topics. The introduction of solar energy technology can greatly reduce the energy consumption of sewage treatment and the cost of sludge disposal. It plays an important role in sewage treatment and is a new energy technology with great development prospects. In a word, the operation mode of solar energy in sewage treatment plant is an effective mode to realize clean production, low carbon emission and economic benefits simultaneously, thus, it will have great potential for solving various problems in rural drinking water safety in Zhangye City.

6. Conclusion and Future Studies

Water is fundamental to human survival. Thus ensuring the quality and safety of drinking water supplies is an important and urgent issue. In recent years, there are more and more cases of human food poisoning caused by *E.coli* contamination of water or food. This study analyzed the *E.coli* contamination of household drinking water quality of Zhangye City, Northwest China, based upon the onsite survey data. According to the national standard of the People's Republic of China, "hygienic standard for drinking water quality" (GB 5749-2006), the total coliform and fecal coliform should not be detected in every 100 mL water sample. Whereas the drinking water supplies in 30 of 37 observed villages demonstrated *E.coli* contamination. Besides, it is found that the possible causes of high *E.coli* contamination include animal husbandry and untreated sewage seeping into the groundwater. However, the interactions of surface and groundwater are not direct causes of the *E.coli* contamination found in Zhangye City. Furthermore, in order to solve the various problems of household drinking water safety in Zhangye City, the introduction of solar energy technology, including solar energy sewage treatment, solar constructed wetland and solar sterilization technology was highly recommended, which can greatly reduce the energy consumption of sewage treatment and the cost of sludge disposal. Since the operation mode of solar energy in the sewage treatment plant is an effective mode to realize clean production, low carbon emission and economic benefits simultaneously.

For further studies, it would be interesting to explore how varying CFU levels of *E.coli* in the drinking water impact human health. What are the health risks of long-term consumption of contaminated drinking water (at a certain level of *E.coli* contamination)? Moreover, a greater understanding of the VBNC state in bacteria relevant to drinking water is needed. Furthermore, it is strongly recommended that solar energy technology be taken to protect water resources from contamination in the study area.

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References

Allison, L.J. and Thomson-Carter, F.M. (1997). Reference laboratory investigation of a major outbreak of *Escherichia coli* O157: H7 infection. Enterohemorrhagic *Escherichia coli*. *Fortschritte der Medizin Monographie*, 84.

Álvarez, J.A., Ávila, C., Otter, P., Kilian, R., Istenič, D., Rolletschek, M., Molle, P., Khalil, N., Amersek, I., Mishra, V.K., Jorgensen, C., Garfi, A,. Carvalho, P., Brix, H. and Arias, C.A. (2017). Constructed wetlands and solar-driven disinfection technologies for sustainable wastewater treatment and reclamation in rural India: SWINGS project. *Water Science and Technology*, 76(6), 1474-1489. https://doi.org/10.2166/wst.2017.329

Bansal, N.K., Sawhney, R.L., Misra, A. and Boettcher, A. (1988). Solar sterilization of water. *Solar Energy*, 40(1), 35-39. https://doi.org/10.1016/0038-092X(88)90069-2

Berberidou, C., Kitsiou, V., Lambropoulou, D.A., Antoniadis, A., Ntonou, E., Zalidis, G.C. and Poulios, I. (2017). Evaluation of an alternative method for wastewater treatment containing pesticides using solar photocatalytic oxidation and constructed wet lands. *Journal of Environmental Management*, 195, 133-139. https://doi.org/10.10

16/j.jenvman.2016.06.010

Bjergbaek, L.A. and Roslev, P. (2005). Formation of nonculturable *Escherichia coli* in drinking water. *Journal of Applied Microbiology*, 99(5), 1090-1098. https://doi.org/10.1111/j.1365-2672.2005.02706.x

Bustamante, M. and Liao, W. (2017). A self-sustaining high-strength wastewater treatment system using solar-bio-hybrid power generation. *Bioresource Technology*, 234, 415-423. https://doi.org/10.1016/j.biortech.2017.03.065

Casierra-Martinez, H.A., Madera-Parra, C.A., Vargas-Ramírez, X.M., Caselles-Osorio, A. and Torres-López, W.A. (2020). Diclofenac and carbamazepine removal from domestic wastewater using a Constructed Wetland-Solar Photo-Fenton coupled system. *Ecological Engineering*, 153, 105699. https://doi.org/10.1016/j.ecoleng.2019.105699

Chang, C., Tao, P., Xu, J., Fu, B., Song, C., Wu, J., Shang, W. and Deng, T. (2019). High-efficiency superheated steam generation for portable sterilization under ambient pressure and low solar flux. *ACS Applied Materials & Interfaces*, 11(20), 18466-18474. https://doi.org/10.1021/acsami.9b04535

Chen, S., Li, X., Wang, Y., Zeng, J., Ye, C., Li, X., Guo, L., Zhang, S. and Yu, X. (2018). Induction of *Escherichia coli* into a VBNC state through chlorination/chloramination and differences in characteristics of the bacterium between states. *Water Research*, 142, 279-288. https://doi.org/10.1016/j.watres.2018.05.055

Chinese national standard sanitary standard for drinking water. GB 5749-2006. http://www.jdqzls.com/zcfg/zcfg1/2013-01-26/137. html

Cho, I.H., Moon, I.Y., Chung, M.H., Lee, H.K. and Zoh, K.D. (2002). Disinfection effects on *E. coli* using TiO_2/UV and solar light system. *Water Supply*, 2(1), 181-190. https://doi.org/10.2166/ws.2002.0023

Department of water resources of Gansu Province (2018). Water resources communique of Gansu Province. http://slt.gansu.gov.cn/xxgk/gkml/nbgb/szygb/201911/t20191111122952.html

Ekici, G. and Dümen, E. (2019). *Escherichia coli* and food safety. *The Universe of Escherichia coli*. https://doi.org/10.5772/intechopen.82375

Filip, Z., Kaddu-Mulindwa, D. and Milde, G. (1987). Survival and adhesion of some pathogenic and facultative pathogenic microorganisms in groundwater. *Water Science and Technology*, 19(7), 1189-1189. https://doi.org/10.2166/wst.1987.0008

Frick, C., Vierheilig, J., Linke, R., Savio, D., Zornig, H., Antensteiner, R., Baumgartner, C., Bucher, C., Blaschke, A.P., Derx, J., Kirschner, A.K.T., Ryzinska-Paier, G., Mayer, R., Seidl, D., Nadiotis-Tsaka, T., Sommer, R. and Farnleitner, A.H. (2018). Poikilothermic animals as a previously unrecognized source of fecal indicator bacteria in a backwater ecosystem of a large river. *Applied and Environmental Microbiology*, 84(16). https://doi.org/10.1128/AE M.00715-18

Fujishima, A. and Honda, K. (1972). Electrochemical photolysis of water at a semiconductor electrode. *Nature*, 238(5358), 37-38. https://doi.org/10.1038/238037a0

Grad, Y.H., Lipsitch, M., Feldgarden, M., Arachchi, H.M., Cerqueira, G.C., FitzGerald, M., Godfrey, P., Haas, B.J., Murphy, C.I., Russ, C., Sykes, S., Walker, B.J, Wortman, J.R, Young, S., Zeng, Q.D., Abouelleil, A., Bochicchio, J., Chauvin, S., DeSmet, T., Gujja, S., McCowan, C., Montmayeur, A., Steelman, S., Frimodt-Moller, J., Petersen, A.M., Struve, C., Krogfelt, K.A., Bingen, E., Weill, F.X., Lander, E.S, Nusbaum, C., Birren, B.W., Hung, D.T. and Hanage, W.P. (2012). Genomic epidemiology of the *Escherichia coli* O104: H4 outbreaks in Europe, 2011. *Proceedings of the National Academy of Sciences*, 109(8), 3065-3070. https://doi.org/10.1073/pnas.1121491109

Gordon, D.M., Bauer, S. and Johnson, J.R. (2002). The genetic structure of *Escherichia coli* populations in primary and secondary habitats. *Microbiology*, 148(5), 1513-1522. https://doi.org/10.1099/00221287-148-5-1513

Hameed, S.K. and Ahmad, I. (1997). Solar sterilization of water. *Renewable Energy*, 12(3), 321-324. https://doi.org/10.1016/S0960-1481(96)00130-9

Han, D., Currell, M.J. and Cao, G. (2016). Deep challenges for China's war on water pollution. *Environmental Pollution*, 218, 1222-1233. https://doi.org/10.1016/j.envpol.2016.08.078

Hu, B., Teng, Y., Zhai, Y., Zuo, R., Li, J. and Chen, H. (2016). Riverbank filtration in China: A review and perspective. *Journal of Hydrology*, 541, 914-927. https://doi.org/10.1016/j.jhydrol.2016.08.004

Kaper, J.B., Nataro, J.P. and Mobley, H.L. (2004). Pathogenic *Eescherichia coli*. *Nature Reviews Microbiology*, 2(2), 123. https://doi.org/10.1038/nrmicro818

Khatiwada, N.R. and Polprasert, C. (1999). Kinetics of fecal coliform removal in constructed wetlands. *Water Science and Technology*, 40(3), 109-116. https://doi.org/10.1016/S0273-1223(99)00446-1

Korovessis, N.A. and Lekkas, T.D. (2009). Solar Saltworks' wetland function. *Global NEST Journal*, 11(1), 49-57.

Li, J., Du, M., Lv, G., Zhou, L., Li, X., Bertoluzzi, L., Liu, C., Zhu, S. and Zhu, J. (2018). Interfacial solar steam generation enables fast-responsive, energy-efficient, and low-cost off-grid sterilization. *Advanced Materials*, 30(49), 1805159. https://doi.org/10.1002/adma.201805159

Liu, X., Liu, H., Yu, X., Zhou, L. and Zhu, J. (2019). Solar thermal utilizations revived by advanced solar evaporation. *Current Opinion in Chemical Engineering*, 25, 26-34. https://doi.org/10.1016/j.coche.2019.07.004

Liu, H., Bian, S., Shi, C. and Ren, Y. (2018). Operation Mode of Solar Energy in Wastewater Treatment Plant. *Progress of New Energy*, 6 (2), 90-95.

Luo, X. (2019). On the current situation of rural drinking water safety project in Ganzhou district of Zhangye City. *Agricultural Science – technology and Information*, 8, 122-123. https://doi.org/10.15979/j.cnki.cn62-1057/s.2020.08.053

Li, Y. (2008). Contrastive analyses of GB 5749-2006 and drinking water standards commonly used at abroad and home. *Technology Supervision in Petroleum Industry*, 5.

Mishra, V.K., Otter, P., Shukla, R., Goldmaier, A., Alvarez, J.A., Khalil, N., Avila, C., Arias, C. and Ameršek, I. (2018). Application of horizontal flow constructed wetland and solar driven disinfection technologies for wastewater treatment in India. *Water Practice & Technology*, 13(3), 469-480. https://doi.org/10.2166/wpt.2018.029

Michino, H., Araki, K., Minami, S., Takaya, S., Sakai, N., Miyazaki, M., Ono, A. and Yanagawa, H. (1999). Massive outbreak of *Escherichia coli* O157: H7 infection in schoolchildren in Sakai City, Japan, associated with consumption of white radish sprouts. *American Journal of Epidemiology*, 150(8), 787-796. https://doi.org/10.1093/oxfordjournals.aje.a010082

Negishi, N., Chawengkijwanich, C., Pimpha, N., Larpkiattaworn, S. and Charinpanitkul, T. (2019). Performance verification of the photocatalytic solar water purification system for sterilization using actual drinking water in Thailand. *Journal of Water Process Engineering*, 31, 100835. https://doi.org/10.1016/j.jwpe.2019.100835

Oswald, W.J. and Golueke, C.G. (1960). Biological transformation of solar energy. *Advances in Applied Microbiology*, 2, 223-262. https://doi.org/10.1016/S0065-2164(08)70127-8

Qi, S.Z. and Luo, F. (2005). Water environmental degradation of the Heihe River Basin in arid northwestern China. *Environmental Monitoring and Assessment*, 108(1-3), 205-215. https://doi.org/10.1007/s10661-005-3912-6

Rao, D.G., Senthilkumar, R., Byrne, J.A. and Feroz, S. (2012). *Wastewater Treatment: Advanced Processes and Technologies*. CRC Press.

Sampson, R.W., Swiatnicki, S.A., Osinga, V.L., Supita, J.L., McDermott, C.M. and Kleinheinz, G. (2006). Effects of temperature and sand on *E. coli* survival in a northern lake water microcosm. *Journal of Water and Health*, 4(3), 389-393. https://doi.org/10.2166/wh.2006.024b

Schubert, J. (2002). Hydraulic aspects of riverbank filtration—field studies. *Journal of Hydrology*, 266(3-4), 145-161. https://doi.org/10.1016/S0022-1694(02)00159-2

Shang, K., Ai, S., Ma, Q., Tang, T., Yin, H. and Han, H. (2011). Effective photocatalytic disinfection of *E. coli* and *S. aureus* using polythiophene/MnO_2 nanocomposite photocatalyst under solar light irradiation. *Desalination*, 278(1-3), 173-178. https://doi.org/10.1016/j.desal.2011.05.017

Tenaillon, O., Skurnik, D., Picard, B. and Denamur, E. (2010). The population genetics of commensal *Escherichia coli*. *Nature Reviews Microbiology*, 8(3), 207-217. https://doi.org/10.1038/nrmi cro2298

Thomas, V., McDonnell, G., Denyer, S.P. and Maillard, J.Y. (2010). Free-living amoebae and their intracellular pathogenic microorganisms: risks for water quality. *FEMS Microbiology Reviews*, 34(3), 231-259. https://doi.org/10.1111/j.1574-6976.2009.00190.x

UNICEF (2013). *Children dying daily because of unsafe water supplies and poor sanitation and hygiene, UNICEF says*. http://www.unicef.org/media/media_68359.html (accessed April 23, 2017).

Van Elsas, J.D., Semenov, A.V., Costa, R. and Trevors, J.T. (2011). Survival of *Escherichia coli* in the environment: Fundamental and public health aspects. *The ISME Journal*, 5(2), 173-183. https://doi.org/10.1038/ismej.2010.80

Weiss, W.J., Bouwer, E.J., Aboytes, R., LeChevallier, M.W., O'Melia, C.R., Le, B.T. and Schwab, K.J. (2005). Riverbank filtration for control of microorganisms: Results from field monitoring. *Water Research*, 39(10), 1990-2001. https://doi.org/10.1016/j.watres.2005.03.018

Wen X.H. (2007). *Study on Groundwater Vulnerability in Middle Heihe Basin Based on GIS*, Ph.D. Dissertation, Shanghai Jiaotong University, China.

Wen, X., Wu, J. and Si, J. (2009). A GIS-based DRASTIC model for assessing shallow groundwater vulnerability in the Zhangye Basin, northwestern China. *Environmental Geology*, 57(6), 1435-1442. https://doi.org/10.1007/s00254-008-1421-y

Wingender, J. and Flemming, H.C. (2011). Biofilms in drinking water and their role as reservoir for pathogens. *International Journal of Hygiene and Environmental Health*, 214(6), 417-423. https://doi.org/10.1016/j.ijheh.2011.05.009

Wu, C., Maurer, C., Wang, Y., Xue, S. and Davis, D.L. (1999). Water pollution and human health in China. *Environmental Health Perspectives*, 107(4), 251-256. https://doi.org/10.1289/ehp.991072 51

Xue, H., Li, S., Li S., Jia Q., Wang, J., Wang, L., Wang, Y. and Li, S. (2019). Investigation on the current situation of centralized water supply in rural areas of Ganzhou District in Zhangye. *Chinese Journal of Preventive Medicine*, 20(10), 941-944. https://doi.org/10.16506/j.1009-6639.2019.10.012

Zdragas, A., Zalidis, G.C., Takavakoglou, V., Katsavouni, S., Anastasiadis, E.T., Eskridge, K. and Panoras, A. (2002). The effect of environmental conditions on the ability of a constructed wetland to disinfect municipal wastewaters. *Environmental Management*, 29(4), 510-515. https://doi.org/10.1007/s00267-001-0010-6

Zhangye Statistics Bureau (2019). Zhangye statistical yearbook. http://www.zhangye.gov.cn/tjj/ztzl/tjsj/202008/t20200825_474653.html

Zhang, A., Zheng, C., Wang, S. and Yao, Y. (2015). Analysis of streamflow variations in the Heihe River Basin, northwest China: Trends, abrupt changes, driving factors and ecological influences. *Journal of Hydrology: Regional Studies*, 3, 106-124. https://doi.org/10.1016/j.ejrh.2014.10.005

Zhang, X. (2020). Discuss how to do well the post-construction operation management of rural drinking water safety project. *Modern Agriculture Research*, 26(08), 131-132. https://doi.org/10.19704/j.cnki.xdnyyj.2020.08.062

Zhao, X. and Wang, X. (2019). Difficulties and measures in construction management of rural drinking water safety consolidation and improvement project. *Journal of Hydropower and Water Conservancy*, 3(01), 47-48.

Zhang, Y., Zhao, D., Yu, F., Yang, C., Lou, J., Liu, Y., Chen, Y.Y., Wang, Z.Y., Tao, P., Shang, W., Wu, J.B., Song, C.Y. and Deng, T. (2017). Floating rGO-based black membranes for solar driven sterilization. *Nanoscale*, 9(48), 19384-19389. https://doi.org/10.1039/c7nr06861a

Zhao, Y. (2008). Research and discussion on rural drinking water safety project in Zhangye City. *Gansu Agriculture*, 6.

Zhong, X. (2020). Discussion on the problems and solutions in the implementation of rural drinking water safety project in Wujiang irrigation area. *Groundwater*, 42(6), 85-86. https://doi.org/10.19807/j.cnki.DXS.2020-06-030

Zhu, Y., Gu, L., Yu, J., Yang, J., Zhai, X., Dong, C., Qian, H., Tan, Z., Liu, J., Zhu, F. and Wang, H. (2009). Analysis on the epidemiological characteristics of *Escherichia coli* O157: H7 infection in Xuzhou, Jiangsu, China, 1999. *Journal of Nanjing Medical University*, 23(1), 20-24. https://doi.org/10.1016/S1007-4376(09)60021-6