Review and prospects of groundwater pollution control in shale gas exploitation

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ABSTRACT

With the successful development of shale gas in the United States, shale gas has become an effective way to solve the energy crisis. Among a series of environmental problems caused by shale gas exploitation, the most hidden and the most difficult part to control and recover is groundwater pollution in the development zone, which has been paid more and more attention by the government and the public. Starting from the shale gas exploitation process, this paper discusses the research status and problems of shale gas exploitation on groundwater pollution prevention and control from both international and domestic Chinese directions, and considers the future development of groundwater prevention and control work: to strengthen the supervision and management of wastewater treatment; to explore and evaluate shale gas resources and to plan regional water resources; to update and improve relevant environmental laws to strengthen the support for shale gas development; to make public supervision and development transparent; and to optimize the whole development process.

Key words: groundwater pollution, shale gas

HIGHLIGHTS

- Overview of shale gas exploitation.
- Current situation and problems of groundwater pollution prevention and control in international and domestic Chinese shale gas exploitation.
- Future prospects for groundwater pollution control in international and Chinese shale gas exploitation.

GRAPHICAL ABSTRACT

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**INTRODUCTION**

Shale gas is an adsorptive or dissociate natural gas occurring in organic rich shale and its interlayers by adsorption or dissociation. Its composition is mainly methane (accounting for more than 90%), but it also contains a small amount of ethane, propane and nitrogen, and belongs to one of the important types of unconventional oil and gas resources. Shale gas has attracted much attention due to its rich resources and high feasibility of exploitation and utilization. Especially in recent years, the successful exploitation of shale gas in the United States has made relatively cheap shale gas an effective way to solve the energy crisis (Xia 2019; Lan et al. 2020). However, the exploitation of shale gas resources can easily lead to a series of environmental pollution problems, such as air pollution, greenhouse gas emission, radiation and extraction water pollution, among which the most hidden and the most difficult part to control and restore is the groundwater pollution caused by the shale gas development zone (Huo et al. 2019). Due to the short history of shale gas exploitation in China, there is still a lack of sufficient research on the impact and damage of the shale gas exploitation process on the environment near the mining area, especially the groundwater environment. As the country and its citizens pay more attention to the ecological environment and health, the water pollution caused by shale gas exploitation has attracted widespread attention from the government and the public (Costa et al. 2017; Hill 2018). Based on the process of shale gas exploitation, this paper discusses the research status and problems of shale gas exploitation with regard to groundwater pollution prevention and control from both international and domestic Chinese perspectives, and forecasts the future development of groundwater pollution prevention and control.

**Overview of shale gas exploitation**

The process of a typical shale gas exploitation project mainly includes three parts: pre-drilling engineering, drilling engineering and gas production engineering. Among them, pre-drilling engineering, preparatory work before drilling, mainly includes drilling site selection, water use, well site construction, reservoir, sewage tank and sewage collection tank construction. Drilling engineering mainly includes drilling operations, fracturing operations, completion tests and disposal of pollutants after testing; gas production works, including the construction of process plant areas, waste water tanks, and shale gas extraction, can only be implemented after drilling works are completed and shale gas production is achieved (Wang 2018). According to the assessment of the US Energy Information Administration (EIA) in June 2013, there are 157 sets of shale formations in 95 basins in 41 countries around the world, with about $1.013 \times 10^{15}$ m$^3$ of geological shale gas resources and $2.207 \times 10^{14}$ m$^3$ of technically recoverable resources. They are mainly distributed in North America, East Asia, South America, North Africa, Australia and other regions. Among them, China, Argentina and Algeria ranked top three with recoverable reserves of $3.16 \times 10^{15}$ m$^3$, $2.27 \times 10^{15}$ m$^3$ and $2.0 \times 10^{15}$ m$^3$ respectively. Based on the data of the EIA in February 2018, shale gas production in the United States reached $1.51 \times 10^{11}$ m$^3$ and $4.82 \times 10^{11}$ m$^3$ in 2010 and in 2016, respectively, and the growth rate is increasing. China is the third country after the United States and Canada to successfully develop shale gas commercially. In 2012, horizontal wells in Changning, Sichuan, which is China’s first commercially viable shale gas well, were drilled and produced $15.00 \times 10^4$ m$^3$/d. After 2013, the annual output of shale gas has grown rapidly, and four shale gas producing areas, Fuling, Changning, Weiyuan and South Sichuan, have been formed as shown in Table 1. By the end of 2018, the annual output reached $108.81 \times 10^8$ m$^3$, ranking third in the world after the United States and Canada. Water pollution is currently the focus of most attention on the environmental impacts of shale gas development (Chen 2014; Yang et al. 2019).

**Table 1 | Brief introduction of four shale gas producing areas in China**

| Name of shale gas field                  | Introduction                                                                                                                                 |
|-----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Fuling Shale Gas Field                  | Started work in January 2013; drilling permit approved in April 2018; total shale gas production exceeds $2.7 \times 10^{10}$ m$^3$; SINOPEC’s first shale gas mining right; |
| South Sichuan Shale Gas Field           | China’s largest daily output shale gas field, up to 20.11 million cubic meters; distributed in Yibin, Luzhou, Neijiang, Sichuan Province; |
| Wei (Yuan) Rong Shale Gas Field         | Distributed in Sichuan Neijiang, Zigong territory; deep, normal temperature, ultra-high pressure shale gas reservoir; the first phase of $1.0 \times 10^3$ m$^3$ of capacity is steadily advancing; |
| Changning Shale Gas Demonstration Zone  | Located in Changning, Jiaxian, Xingwen and Junlian (four counties in Sichuan); PetroChina highest daily shale gas production area; total production of $7.275 \times 10^7$ m$^3$ of shale gas |
Current situation and problems of groundwater pollution prevention and control in shale gas exploitation

International exploitation

Threats to groundwater resources in pre-drilling projects. During the development of shale gas, water consumption before the implementation of a gas production project is huge. Excessive water intake can easily lead to deterioration of groundwater quality (Liu et al. 2014). Researchers at Duke University in the United States analyzed water and wastewater data from more than 12,000 shale oil and shale gas wells in the United States between 2011 and 2016, and found that water consumption in hydraulic fracturing single wells in major shale oil and gas production areas in the United States increased 7.7 times during this period, while wastewater from some shale oil and gas production areas in Texas increased 14.4 times. The researchers estimated that cumulative water consumption and wastewater production in some major shale gas wells could increase by 50 times between 2018 and 2030 if this rapid growth continues. In general, the water level of a terrestrial freshwater aquifer is higher than sea level, but after a long period of time, the groundwater level will be lower than sea level because of excessive pumping of groundwater, and seawater will seep into the terrestrial freshwater layer through the permeable layer, thus destroying groundwater resources (Zhang et al. 2021). This will bring challenges to the development of arid or semi-arid areas where groundwater resources are scarce.

Pollution of groundwater by drilling engineering. In drilling engineering, shale gas drilling produces more drilling wastewater. The wastewater produced in this process is called ‘drilling fluid’, which can be divided into water-based drilling fluid, oil-based drilling fluid and gas drilling fluid according to different media, usually containing a large amount of dissolved and suspended solids. The main causes of groundwater pollution caused by drilling operations are: (1) casing damage and cementing defects which can cause fluid leakage in the shallow layer near the surface and thus contaminate groundwater resources; at the same time, cementing is not perfect, leaving a flow space between casing and reservoir layers. Methane from shale layers can enter the groundwater layer through gaps, resulting in methane pollution of groundwater resources, and fracturing fluid and formation water may enter the groundwater layer in the same way; (2) dense shale layers are compressed to form fractures, and deep brine or fracturing fluids below the shale may also pass through otherwise dense shale layers and overlying strata to reach the groundwater layer and pollute groundwater quality. (3) in the course of drilling, if the caverns, dark rivers and large cracks lead to access to the aquifer, the drilling fluid will leak and cause pollution (Li 2015; Agarwal et al. 2020).

Pollution of groundwater by fracturing operations. Hydraulic fracturing is a commonly used fracturing technology in shale gas mining at present. The process is to inject hydraulic fracturing fluid into the ground and open the formation to form a fracture network formed by natural fractures and artificial fractures as a gas production channel. Typical fracturing fluid components are mainly water with other additives. In the course of fracturing operations, if the operation is improper or there is an accident (such as blowout), the fracturing fluid may leak and immerse the groundwater through the surface; on the other hand, after horizontal well fracturing is finished, 30–70% of the fracturing fluid is expected to return to the surface to become fracturing fluid. The possible ways of pollution during drainage treatment are: (1) surface leakage during operation, such as leakage of the reservoir isolation layer, spillage in transit; (2) direct discharge without treatment of return drainage; (3) discharge of return drainage treatment not up to standard, general sewage treatment facilities can’t effectively remove pollutants such as halogen, heavy metals and radioactive elements. Because the salinity of the back drainage is much higher than that of the surface water, even a very small amount of pollution will deteriorate the water quality.

Pollution of groundwater by gas recovery projects. The gas recovery process can produce a large quantity of high-salt organic wastewater containing suspended matter, grease, heavy metals and complex organic matter. This wastewater is called extraction liquid, which is the main pollution source in the gas recovery process. The composition of the extracted liquid varies greatly in different mining stages, mainly including heavy metals, chlorides, oils and radioactive substances, with higher salt content and wide distribution of the concentration range of each component. The high concentration of organic matter and salinity in the extract increases the risk of soil, surface water and groundwater pollution. The water quality indexes of typical shale gas fields internationally vary differently in alkalinity, oil content and metal content, but they all show the ‘three high’ characteristics: high chemical oxygen demand (COD), high total dissolved solid (TDS), and
high total suspended solid (TSS) (Lu et al. 2015). Most of the water quality indexes of the extracted liquid far exceed Chinese and foreign sewage reuse standards. The route of groundwater pollution from the extracted liquid is similar to that from returned liquid: surface leakage during operation, direct discharge without treatment or discharge under treatment will cause groundwater pollution.

In summary, groundwater pollution from shale gas development depends on the shale gas development process, the source of pollutants, the polluted water body, the cause and controllability of the pollution, as shown in Table 2 (Xia 2019).

At present, in the aspect of wastewater control, as shown in Figure 1, four main treatment methods have been developed: (1) direct deep well recharge; (2) simple treatment before hydraulic fracturing reuse; (3) discharge into municipal sewage system; and (4) reuse or discharge through three-stage advanced treatment (Wang 2016; Tang et al. 2020). For example, the management practice of the Marcellus Shale area in the United States has changed greatly with the change of control policy and the growth of the shale gas industry. Around 2000, shale gas wastewater in the United States mainly adopted the route of discharging into municipal sewage. The Marcellus Shale area, for example, had more than 400,000 cubic meters of gas field wastewater treated by municipal sewage treatment plants in 2008, but because the municipal sewage treatment plant process has little effect on the total dissolved solids in the water. The TDS concentration of surrounding rivers rose to 900 mg/L, so the state government adopted TDS500 mg/L discharge standards around 2010. From 2011 onwards, municipal sewage treatment plants in the Marcellus Shale area no longer accepted shale pressure fracturing and reflux, which led to the trend of wastewater management gradually turning to reuse, and the wastewater that can’t be reused and the wastewater that cannot is used for deep well perfusion and given desalination treatment.

**Domestic (Chinese) exploitation**

Compared with the United States, shale gas reservoirs in China are generally deeply buried. Shale gas enrichment areas are complex terrains, densely populated and with difficult engineering operations, while freshwater resources in shale gas deficient areas are limited. At present, thirteen provinces in China are listed as shale gas priority mining areas, mainly in the northwest and southwest regions with relatively low water supply. From the point of view of shale gas mining technology and development practice, water consumption and water environmental pollution are the most important environmental problems in shale gas development. According to statistics, shallow groundwater is a direct source of drinking water in many areas. Four provinces in the north and northwest of China’s shale gas mining area account for about 70% of the population’s drinking groundwater. Because shale gas is formed in the main source rock of an oil and gas basin, it has the characteristics of poor endowment and difficult exploitation, and its exploration and development often result in higher environmental risks.

**Table 2 | Basic characteristics of groundwater pollution**

| Development process                                      | Source of pollutants           | Contaminated water bodies | Pollution causes                  | Controllability |
|----------------------------------------------------------|--------------------------------|---------------------------|----------------------------------|-----------------|
| Pre-drilling engineering                                 | Saltwater encroachment         | Groundwater               | Over-use                         | Controllable    |
| Drilling engineering                                     | Drilling fluid                 | Surface/groundwater       | Construction, management defects  | Controllable    |
| Drilling engineering                                     | Fracturing fluid (for oil well)| Surface/groundwater       | Construction, management defects  | Controllable    |
| Drilling engineering                                     | Return drainage                | Surface/groundwater       | Construction, management defects  | Controllable    |
| Drilling engineering/gas production engineering          | Substandard wastewater         | Surface/groundwater       | Violations/subjective intent      | Controllable    |
| Drilling engineering/gas production engineering          | Methane/formation water        | Underground water          | Constructional deficiency         | Controllable    |
| Drilling engineering/gas production engineering          | Deep saline                    | Underground water          | Under specific address conditions inherent risk | Uncontrollable |
| Gas production engineering                               | Extraction of liquid           | Surface/groundwater       | Construction, management defects  | Controllable    |
such as surface runoff, groundwater, atmospheric environment and so on in the working area. The destruction of groundwater environment not only affects the life and work of local people, but also has a great impact on the sustainable development of shale gas. The main pollution sources of shale gas development in China are drilling fluid in drilling stage and fracturing fluid in hydraulic fracturing stage. There are three main ways to pollute groundwater in the drilling stage: (1) after a long period of contact, the drilling fluid enters the formation by leakage through the shaft wall and influences the groundwater by adsorption-resolution action with rock particles; (2) the drilling equipment leaks oil and enters the groundwater; (3) a large amount of drilling fluid leaks into the groundwater in the process of drilling if large fractures and caves are encountered. The effect of the fracturing process on groundwater is mainly through the following three routes: (1) hydraulic fracturing will aggravate the destruction of ground fissures and make shale gas leak; (2) fracturing or drainage fluid can enter the groundwater aquifer through fracture flow in the outer layer of the well bore when casing and cementing do not act as a barrier between working fluid and groundwater; (3) hydraulic fracturing will destroy individual aquifers and make them connect and mix (Wu et al. 2014).

Due to the late start of shale gas development in China, especially the relatively few studies on shale gas development and pollution of groundwater environment, shale gas exploitation mainly draws lessons from other countries in the prevention and control of groundwater pollution. There is still a big gap between wastewater treatment technology and plant. There are four kinds of waste water disposal methods for shale gas mining, namely, underground pouring, reuse after primary and secondary treatment, feeding into municipal system and self-level advanced treatment (desalination). The specific disposal method is mainly determined by comprehensive analysis of the factors such as treatment cost, pollutant quantity and water quality, operation area infrastructure, environmental protection laws and regulations framework, and geological structure of the operation area. Usually, a single treatment method cannot make the treated wastewater meet the standards of reuse and discharge (Mohammad-Pajooh et al. 2018). For underground pouring, strict management regulations should be followed for underground perfusion of shale gas extraction liquid. Generally speaking, the grouting depth must be lower than the deepest underground drinking water aquifer, and the construction, operation and monitoring of wells should also be under comprehensive supervision. In order to protect the underground drinking water, not all shale gas fields can use the perfusion method to treat the extracted liquid. In some areas, because the formation conditions can’t meet the requirements, underground perfusion is prohibited. Most parts of the United States are dominated by underground perfusion (the wastewater return rate in the United States is 8–70%) (Chen et al. 2016), however, due to the as yet underdeveloped underground recharge technology in China (wastewater return rate in Sichuan basin is 10–40%, whilst for, Chongqing Fuling it is only 5–7%), the current technology is not enough to deal with the output water from shale gas development. If a large amount of backwater is injected by deep well, it may destroy the formation and even lead to the loss of water resources available to the biosphere. On the other hand, it is impossible for the municipal sewage treatment system in China to accept the wastewater produced by shale gas mining, so the treatment of shale gas wastewater is mainly by well site treatment and reuse. The
wastewater that can not be reused mainly needs to be set up for water treatment to meet desalination standards and then discharged. At the same time, the research and application of shale gas fracturing systems have been strengthened (Liu et al. 2020).

Conclusions and future prospects for groundwater pollution control in shale gas exploitation

International shale gas exploitation

Shale gas production has significant pollution risks to the surrounding environment. According to the principle that prevention is greater than governance, the future needs to construct the supervision system from the policy (Loveless et al. 2019; Burbidge & Adams 2020). Internationally, The United States and Canada are the most successful in shale gas development and the policies are improving. It is mainly divided into four categories: market policy, production policy, R & D policy and regulatory policy. One of the key points of supervision policy is the waste-water treatment of shale gas mining (Zhang & Huang 2015). In order to greatly reduce the environmental pollution caused by waste water during shale gas exploitation, the United States has introduced a series of related waste-water treatment mitigation measures, shown in Table 3 (some information is derived from the United States Environmental Protection Agency (EPA)). The Clean Water Act requires, all releases to federal waters must first be licensed by the National Pollution Discharge Elimination System (NPDES), comply with the water quality standards (general licensing guidelines for specific industries within a specific geographical area) and Effluent Limitation Guidelines (ELGs) as prescribed by Code Federal Regulations (CFR). Unlike America, there is no large-scale commercial production of shale gas in Canada. Therefore, its relevant policies are mainly based on the current mining laws and regulations. But under the Environment Canada and Health Canada (EC&HC) framework, the Canadian government has also introduced a series of laws, regulations, industry standards and other regulations for shale gas waste-water treatment, which include the Canadian Environmental Protection Act of 1994 and the Waste-water Reduction and Recovery Act of 2011. Early Canadian shale gas production had an environmental impact. For environmental protection, the Canadian government has taken a more cautious approach to development. Quebec suspended approval for most of its new shale gas projects in 2011. British Columbia has taken similar steps to control shale gas development and avoid polluting the environment.

If there is no perfect environmental protection policy and supervision system in the development of shale gas, it will cause a lot of environmental pollution, especially the water environment. In the future development of shale gas, it is necessary to strengthen the supervision of waste-water treatment in order to prevent further water pollution and save water resources (Lu et al. 2019).

Domestic (Chinese) shale gas exploitation

Based on the mature experience of controlling shale gas groundwater pollution internationally, combined with the present situation of shale gas development, technology level and the impact of shale gas exploration and development on the water environment in China, the researchers fully considered the possible environmental problems from the principle of risk prevention.

Exploration assessment of shale gas resources and planning of regional water resources. Prior to the start of drilling operations, the distribution of local geological and shale gas resources should be investigated in advance and mining location should be reasonably selected and locations such as caverns, large-scale caverns and strong runoff zones of karst cave groundwater, as well as abandoned oil and gas wells, should be avoided as far as possible. Then the probability of groundwater pollution should be effectively reduced by means of pollutant migration with connected exhaust gas

| Table 3 | Regulatory policies and contents of shale gas wastewater treatment in the United States |
|---------|--------------------------------------------------------------------------------------|
| Regulatory policy                      | Content                                      |
| Safe Drinking Water Act (SDWA)       | Regulations for hydraulic fracturing near water source                                |
| Clean Water Act (CWA)                | Water resources protection during pollutant discharge                                 |
| Resources Conservation & Recovery Act (RCRA) | Waste water recovery and treatment requirements                                    |
and drilling fluid leakage. The tank body (surrounding the drilling operation) should focus on seepage prevention with reference to the requirements of GB/T50934-2013 (Technical Specification for Seepage Prevention of Petrochemical Engineering) and HJ610-2016 (Environmental Impact Assessment Technical Guide-groundwater Environment). Water resources should be evaluated before drilling operation. Drilling is not allowed without passing water resources evaluation, and the influence of superposition should be considered when evaluating water resources in the same area. In the process of shale gas exploitation, the construction unit should establish a perfect quality management system and realize the total quality management goal of the ‘quality, safety and environment’ trinity. It should set up a groundwater dynamic monitoring team, responsible for groundwater environmental monitoring and management, or entrust professional qualified agencies to do so. It is also necessary to establish relevant rules and regulations and create a responsibility system, formulate a risk early warning plan, and set up emergency facilities to reduce the impact of environmental pollution. In order to supervise and protect the ecological problems in the development of shale gas, it is necessary to reform the water resources supervision system, perfect the parallel system of watershed management and administrative regional management and the whole water resources supervision system, and strengthen the supervision work before, during and after shale gas exploitation. A comprehensive wastewater utilization scheme should be formulated, wastewater produced by shale gas mining should be treated and recycled, the total amount of water used in the watershed and region should be fully controlled, and an annual water use plan formulated and strictly implemented. Water resources planning objectives, a water quality monitoring plan and water quality planning should be formulated for areas rich in shale gas resources. During the process of shale gas exploitation, water intake should be carried out in strict accordance with local water resources planning. Water resources planning should include environmental infrastructure planning and enrich water resources allocation systems. A scheme of comprehensive utilization of wastewater should be formulated, and the wastewater from shale gas exploitation recycled after treatment. The total amount of water used in the river basin and region should be comprehensively controlled, and the annual water use plan should be formulated and strictly implemented.

Update and improve relevant environmental laws and regulations and increase support for shale gas development. Compared with a series of mature environmental laws and regulations for shale gas development elsewhere, China still has a great lack in this respect. Therefore, it is most important to constantly improve the various laws and regulations that are being implemented to manage the environmental problems caused by shale gas development and utilization, such as the Environmental Protection Law, the Water Pollution Prevention and Control Law, the Air Pollution Prevention and Control Law and the Cleaner Production Promotion Law. In addition, there is an urgent need to formulate systematic laws and regulations specifically aimed at all aspects of shale gas exploration and development because of their own actions (Wu et al. 2019). In order to give full play to the function of government supervision, combined with the existing laws and regulations in China and the environmental problems that may be caused by shale gas development, a more targeted and strict environmental supervision system should be established, such as an environmental impact assessment system, waste discharge permit system, shale gas operation information disclosure system, wastewater reuse and treatment system. In addition, it is necessary to clarify the responsibilities of regulatory agencies, strengthen exchanges and cooperation between them, formulate strict laws and regulations and enforcement measures, and strictly enforce them in practice to ensure the effective implementation of the regulatory system. At the same time, we should also establish a perfect environmental monitoring and early warning system, as well as formulate practical management measures to ensure the early detection, early reporting and early handling of sudden environmental problems. Environmental regulators need to make relevant data public, ensure the openness and transparency of water environmental law enforcement, and involve the public in the supervision and management of government and enterprises. Meanwhile, compared with the United States, Canada and other countries, China’s shale gas development is relatively late. In terms of increasing support for shale gas development, China can learn from the experience accumulated in North America, and adopt a more large-scale and stronger tax reduction policy, loose financial loan policy, talent support policy, technological innovation fund incentive policy, etc., so as to encourage local governments to issue supporting policies, cultivate the competitive advantage of shale gas market, and enhance the competitive advantage of shale gas in the market.
Public supervision and shale gas development transparency. Environmental governance cannot simply rely on the mode of government supervision and law-abiding enterprises, but should give full play to the ‘third party public’ to supervise the behavior of the government and enterprises, so as to realize the benign interaction triangle model of government, enterprise and public in environmental governance. The exploitation of shale gas has a conflict of interest with the residents around the development area in the use of water resources. The groundwater and surface water pollution and air pollution produced in the mining process will have a direct impact on the ecological environment of the local residents. Therefore, the public should be fully informed throughout the exploration, development, production, transportation and disposal of shale gas, so that the public can have sufficient information and procedural rights to supervise the environmental behavior of shale gas developers and the administrative behavior of environmental supervision departments. On the other hand, due to the highly specialized technology of shale gas development, people may subconsciously reject shale gas development projects because of a lack of relevant knowledge and deep understanding. Therefore, while giving the public the right to inform and participate in information, the public should be guided to use their rights rationally.

Technical optimization of the entire development process. The horizontal well drilling technology suitable for shale gas development should be improved as soon as possible through tool development, technical matching and scheme optimization. The oil-based drilling fluid system should be further improved from the aspects of rheology and plugging ability, and the water-based drilling fluid system suitable for horizontal well drilling should also be studied at the same time. In view of the fact that oil-based drilling fluid is mostly used in horizontal wells, the washing fluid, cement slurry system and cementing technology should be further improved; downhole tools, working fluids and construction techniques suitable for multi-stage fracturing technology in horizontal wells should be developed, dynamic monitoring of fracturing fractures strengthened and fracturing design optimized; new green or harmless products should be used instead of existing additives to reduce harmful substances in wastewater; waste liquid, wastewater and waste residue treatment technologies produced in drilling and fracturing operations should be formed, and importance should be attached to environmental pollution assessment of shale gas exploitation. Therefore, in order to maximize the advantages of technology, weaken the shortcomings as much as possible, and flexibly deal with the complexity of the composition of waste liquid, a method combining two or more technologies should be adopted. That is, a hybrid water treatment system will become the direction of future development. In order to achieve large-scale commercial development of shale gas, it is necessary to promote the development and innovation of geological geophysical exploration, drilling and completion, perforation and clean fracturing without water. At the same time, it is necessary to increase special investment in scientific research, focus on supporting the research of shale gas exploration and development technology and equipment, encourage all kinds of industry, university and research institutions to tackle key technologies and equipment for shale gas exploration and development through technology exchange, joint research, international cooperation, and the training of relevant high-level and specialized personnel, so that a whole industry chain of shale gas exploration and development with replicable exploration technology, equipment R & D and manufacturing, infrastructure construction, management and operation system can be built as soon as possible.

CONFLICTS OF INTEREST
The authors declare that they have no conflicts of interest to report regarding the present study.

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DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.
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