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Coordinated Development Mode of Oil and Gas Resources and Water Resources in Western China

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Abstract: Western China is an important region for increasing oil and gas reserves and production in China, and it is also the most arid and water-deficient area in the country. There is a complex linkage between energy and water resources in this region; thus, it is important to promote their coordinated management. In this study, we review the prospects and deployment of oil and gas production in Western China, investigate the development mode and water utilization status of different oil and gas fields from seven companies of China National Petroleum Corporation in Western China, and analyze the guarantee risks of water resources and environment during gas and oil development. Research shows that oil and gas production has steadily increased in Western China in recent years, and the consumption of fresh water in oil and gas fields has observed little change, owing to the continuous improvement in sewage treatment and recycling efficiency. However, given the progressive development of unconventional oil and gas resources, future oil and gas development in Western China is likely to significantly affect the surface and underground water systems. It is suggested to develop precise water injection and waterless fracturing technology to stabilize oil production and control water use, increase the recycling of produced water to strengthen scientific water management, and improve the comprehensive allocation guarantee system of water resources, so as to reduce the impact of oil and gas development on the water system while ensuring water use security for the energy industry, thereby realizing the coordinated development of energy and water resources in Western China.

Keywords: Western China; oil and gas resource exploitation; water resources; energy and water; coordinated development

1 Introduction

Energy is a critical resource for the survival and development of human society, a crucial matter to national planning, livelihood, and national strategic competitiveness [1]. In China's energy landscape, the eight provinces

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—Inner Mongolia, Shanxi, Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai, and Sichuan—where the western Ordos, Tarim, Junggar, and Sichuan basins are located (hereinafter referred to as the Western Region) are rich in oil and gas resources [2]. With a low rate of proven resources and high exploration and development potentials, ensuring China's energy security is an important strategic position. Meanwhile, as the most water-scarce region in China [3], the Western Region has an average annual precipitation of 365.8 mm and total water resources of 5.2747×10^{11} m^3, accounting for only 19% of the total water resources in the country. Thus, the Western Region is the most challenging area for coordinated energy and water resource security in China, and the current water resources availability and ecological environment protection have formed constraints on the development of regional oil and gas resources [4].

To identify the risks to the water resources and energy security in the Western Region, create a policy, and build a technology system for the coordinated development of the oil and gas industry, regional resources and the environment are key to the sustainable development of China's energy industry. Hence, taking these aspects into account is an important step to promote the steady implementation of the development strategy of the Western Region. Supported by the strategic consulting project of the Chinese Academy of Engineering, "Strategic Study on the Coordinated Development of Fossil Energy and Water Resources in Western China," the study's project team explores the sustainable development of energy and water resources in the Western Region from the perspectives of climate, water resources, oil and gas, and coal. Based on the prospects and deployment of oil and gas production in the Western Region, this study analyzes the current status and problems of water use for oil and gas field development, taking seven China National Petroleum Corporation companies in the Western Region as exmaples.This study then offers technical strategies and control suggestions to ensure the coordinated development of oil and gas and water resources in the Western Region.

2 Oil and gas development and water-use status in the Western Region

2.1 Current status of oil and gas development in the Western Region

Recently, China's energy demand has been growing, and the degree of foreign dependence has been rising. The stabilization and development of the domestic energy industry are of great significance to maintaining the smooth operation of China's economy and society, thus ensuring economic development.

In China's energy landscape, the Western Region is the most fossil-energy-rich, and an important strategic replacement area in the country. It is also a major energy export area with proven oil reserves of 6.672×10^{10} t [5], conventional natural gas reserves of 5.17×10^{13} m^3, and shale gas reserves of 7.77×10^{13} m^3, accounting for 42%, 76%, and 71% of the respective resource reserves in the country. The *Strategic Action Plan for Energy Development (2014–2020)* was issued by the Office of the State Council in 2014 ([2014] No. 31) and the National Mineral Resources Plan (2016–2020) was approved by the State Council in 2016 ([2016] No. 178). These were proposed to treat Tarim, Ordos, and Junggar basins as key areas to increase oil and gas exploration and production. The documents proposed focusing on the construction of nine large oil fields with an annual production scale of 10 million tons, and eight natural gas production bases with an annual production scale of 10 billion cubic meters, including the four large oil fields in Xinjiang, Tarim, Changqing, and Yanchang, and natural gas production bases such as Erdos and Qingshui.

Since 2000, relying on geological theory innovation and engineering technology progress, China has made several major oil and gas discoveries in the Sichuan, Ordos, Tarim, Qaidam, and Junggar basins [2,6]. Thus, proven oil and gas reserves in the Western Region have grown recently, increasing from 2.71×10^8 t and 4.007×10^{11} m^3 in 2000 to 5.39×10^8 t and 6.301×10^{11} m^3 in 2018, respectively. Simultaneously, regional oil and gas production has increased (Fig. 1), with annual production growing from 2.927×10^7 t and 1.52×10^{10} m^3 in 2000 to 6.549×10^7 t and 1.32×10^{11} m^3 in 2018. The national production ratio of oil and gas increased from 18% and 55% in 2000 to 35% and 83% in 2018, respectively, and the strategic replacement position is increasingly prominent.

2.2 Analysis of the current status of water used for oil and gas development in the Western Region

Oil and natural gas exploration and development consume considerable water resources. (Table 1). Oil and gas prospecting is the first step in exploitation. In this step, drilling prospecting is an important means to study the oil storage structure and probe the oil and gas area and reserves. After the initial prospecting and discovery, a series of

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oil and gas field development and construction steps prepare the new field, including the determination of well locations for development wells and the study of specific development plans such as fracturing operations. After development and construction, the oil and gas fields enter the production operation phase. Drilling is another important step in oil and gas field prospecting, exploitation, and construction, as well as mining production. During the drilling process, water plays an important role in rig flushing and cooling and is also an important carrier for transporting rock chips and cementing construction. Moreover, recently, hydraulic fracturing technology has been widely used to fracture rock and form inflow fractures, and the fracturing process consumes a considerable amount of water; for instance, a single well can consume up to 2×10^4 m^3 of water for shale gas development in the United States [7]. Oil field water injection is also an important measure to ensure formation pressure and improve the recovery rate during oil extraction. In addition, petrochemicals are a water-intensive industry [8], and the current freshwater consumption of water-saving petrochemical refineries in China is approximately 0.4 to 0.5 m^3 per ton of crude oil processed [9].

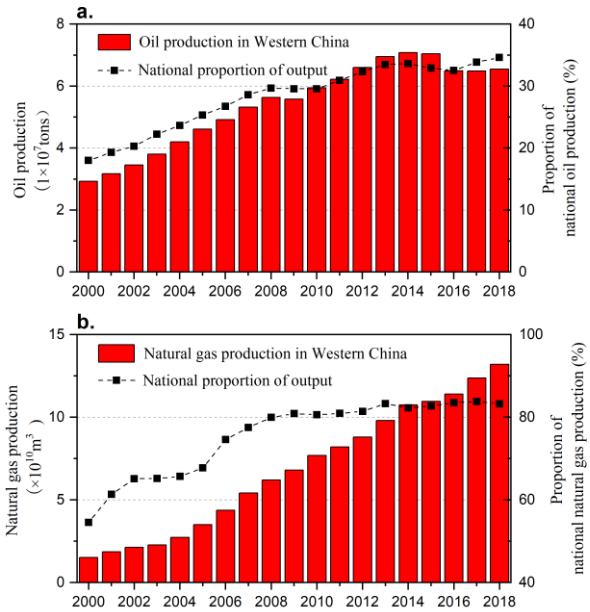

Fig. 1. Production of (a) oil and (b) natural gas in the Western Region.

Table 1. Major water-use steps in oil and gas production.

Resource exploration	Development and construction	Mining production	Petrochemicals
Blast drilling rigs	Blast drilling rigs	Water injection	Petroleum processing
Grouting	Borehole cleaning	Oil preprocessing	Boiler softening and desalination
Dust reduction	Transporting rock chips	Car transport cleaning	Circulating cooling
	Cementing construction	Domestic use at the mine site	Transport cleaning and sprinkling
	Hydraulic fracturing	Greening	Domestic use
	Dust reduction		Firefighting and infrastructure

This study takes seven oil and gas field enterprises in Changqing, Xinjiang, Tarim, Tuha, Qinghai, and Yumen as examples, to analyze the overall water consumption and development trend of oil and gas field production in the Western Region. With the scaled development of oil and gas production bases, such as Xinjiang and Changqing, the total water consumption of oil and gas fields in the west has been increasing, from 3.18×10^8 m^3 in 2010 to 3.63×10^8 m^3 in 2018, an increase of 14% (Fig. 2). However, freshwater usage did not experience much change, with 2.60×10^8 m^3 in 2010 and 2.66×10^8 m^3 in 2018 for oil and gas fields in the Western Region.

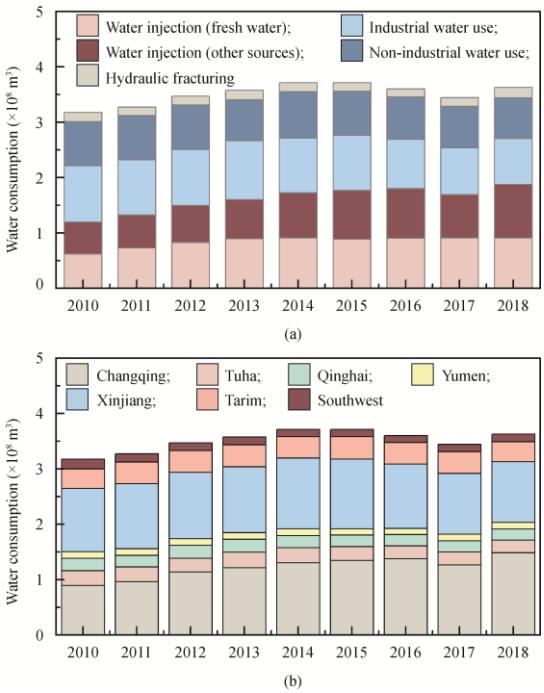

Fig. 2. Water consumption of (a) different water sources and (b) each mining area in the western oil and gas fields.

During the exploration and field construction steps, PetroChina uses approximately 0.16×10^8 m^3 of freshwater per year in the Western Region, of which water for fracturing accounts for approximately 45%. Water injection development is a major source of water use in oil and gas fields, and the total water injection in oil and gas fields in the Western Region rose from 1.20×10^8 m^3 in 2010 to 1.88×10^8 m^3 in 2018, a 57% increase. Recently, with the continuous improvement in the efficiency of wastewater recycling, treatment, and reuse, the amount of wastewater re-injection in each oil field has increased, and the amount of water injection from other water sources, such as wastewater reuse, increased from 0.58×10^8 m^3 in 2010 to 0.97×10^8 m^3 in 2018. However, to ensure the stability and efficiency of oil and gas field production, water injection quality management has high requirements for the suspended matter, dissolved oxygen, corrosiveness, etc. of water [10], and a large amount of surface water or groundwater must still be consumed. In addition, water for the oil field industry and for living and greening in the mining areas are major components of water usage in oil and gas production. The oil field industry freshwater usage of the seven oil and gas enterprises of PetroChina in the Western Region totaled 8.326×10^7 m^3 in 2018, accounting for 31% of total freshwater usage; further, freshwater for living and greening in the mining areas totaled 7.314×10^7 m^3, accounting for 28% of total freshwater usage.

With the increasing difficulty in conventional oil and gas resource exploration, the focus of exploration has gradually shifted to unconventional resources such as shale oil and gas. The Western Region is the primary area for unconventional oil and gas exploration and development. Unconventional oil and gas development is demanding in terms of technology, and water consumption for the development of low-grade or complex reservoirs is large. The Changqing, Xinjiang, and Tarim oil fields, which are characterized by low seepage, thick oil, and carbonate rocks, are major water-use fields, accounting for more than 80% of the total water consumption among oil and gas fields in the Western Region. The southwest field, which mainly focuses on shale gas development, currently only accounts for 5% of total water consumption in terms of freshwater. Although its current water consumption is not large, the production and construction of oil and gas fields may have a greater impact on the surrounding water sources and water for industrial and domestic use.

3 Water-use issues of oil and gas development in the Western Region

Within the energy development scheme, the *National Plan for Main Functional Areas* proposes focusing on building energy bases in Shanxi, Ordos Basin, Southwest, Northeast, and Xinjiang, which are regions rich in energy resources. The Western Region is the most important energy production area in China, where the proportion

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of oil and gas production has been increasing in recent years and is bound to increase further with the continued growth in the country's total energy production in the future. Meanwhile, given China's efforts to improve the energy structure and policy guidance of ecological protection, the exploitation of oil and gas resources and water resources are more closely related. The development costs of unconventional resources, such as tight oil and shale oil, have been gradually reduced by using horizontal wells and volume fracturing technology, as well as the factory operation mode, but massive water consumption is required for large-scale fracturing, and the resulting environmental issues remain major obstacles hindering the development of oil and gas resources in the Western Region.

The Western Region is the most water-scarce in China, and the large consumption of freshwater resources by oil and gas development is likely to have considerable impact on area surface and groundwater systems, in turn causing the deterioration of the ecological environment [11]. Water consumption for oil and gas development is highly influenced by natural and resource conditions and may vary greatly with changes in well section depth, horizontal good length, geological characteristics of the producing formation, and the stage in the life cycle of oil and gas well development. Owing to the influence of monsoon climate, precipitation in the Western Region is abundant in the summer and autumn but scarce in the winter and spring in terms of seasonal distribution, presenting an obvious natural cycle of water resources. However, oil and gas development is not seasonal, and the development cycle often does not match the water resource conditions. During the development of oil and gas fields, especially during hydraulic fracturing, there is significant water consumption over a short period, and during the production and construction phase, it may impact the water for local industrial and domestic use, and even cause river cut-off, which seriously affects regional water resource security and the ecological environment system.

Oil and gas formations are also endowed with groundwater, and oil-bearing wastewater is likely to pollute the groundwater in underground aquifers during the development process. During the fracturing construction process, a large amount of fracturing return fluid is brought to the surface, which contains not only natural impurities brought out from the formation but also additives in the fracturing fluid. The discharge concentrations of pollutants, such as chemical oxygen demand, petroleum, sulfides, and volatile phenols in the wastewater, are much higher than that of the comprehensive sewage discharge standard (GB 8978—1996) [12]. If drilling wastewater is not treated in time, it may pollute the surrounding surface water and groundwater environment over time, causing serious harm to human health. To simultaneously realize a sustainable increase in oil and gas reserves and production and environmentally-friendly development in the Western Region, it is imperative to identify the risks to water resources and water environment security from different types of oil and gas development and to promote the sustainable use and coordinated security of oil and gas resources and water resources in the Western Region through whole-chain innovation in terms of development scale, development mode, key water-saving production technologies, and control policies.

4 Key water-saving initiatives, countermeasures, and suggestions for oil and gas development in the Western Region

Water conservation is a priority for the oil and gas industry in the Western Region. To actively implement the *National Water Conservation Action Plan* and the *Water Pollution Prevention and Control Action Plan*, effective oil field water management countermeasures must be taken to optimize management from all aspects, such as water extraction and produced water and sewage treatment, to further strengthen water recycling, reduce water waste, promote alternative water-saving technologies, increase the number of unconventional water resources based on local conditions, and realize the refined management of oil field water use.

4.1 Developing precise water injection technology to stabilize oil production and control water use

Water injection is the main approach of oil field development in China and an effective method of increasing oil field production, improving oil field development results, and increasing the oil field recovery rate. Most oil fields in China are nonhomogeneous, multilayer sandstone oil fields, and there are large differences in the development results of different layer systems due to uneven pressure between oil layers. With further development, oil fields in China as a whole are in the late stage of "high recovery degree and high water content," and the problem of

inefficient and ineffective water circulation is prominent, resulting in the waste of oil field water and energy. Thus, due to the difficulties of water injection technology in oil recovery engineering, it is imperative to vigorously promote the digital transformation of oil fields and develop intelligent, refined stratified water injection and its supporting technologies, so that all kinds of oil layers between strata can be used in a balanced manner, thereby effectively tapping the remaining oil and maximizing the water and energy saving effect in the oil fields.

4.2 Developing waterless fracturing and energy enhancement technologies to support the green and efficient development of oil and gas resources

Oil and gas reserves in the Western Region are growing rapidly and still have a large exploration and development potential; hence, the Western Region will be the main battlefield in ensuring national energy security in the future. However, water resources are scarce in this region, and the hydraulic fracturing approach for oil and gas resources is unsustainable. There is an urgent need to develop waterless fracturing technology to significantly reduce water consumption in the oil and gas development process. Currently, nitrogen foam, carbon dioxide, and liquefied petroleum gas fracturing technologies can be used instead of water for reservoir modification to improve oil and gas seepage conditions and increase single good production. However, the gas resources required for waterless fracturing technology currently lacks sufficient guarantee, and a strategic scheme across industries is still needed to further enhance the economic and environmental benefits of energy development.

4.3 Increasing scientific water management to control and reduce water use

Oil and gas extraction is an activity with high water consumption and pollution. To promote the green and sustainable development of energy production in the Western Region, the oil and gas industry should introduce advanced technology to implement the technical transformation of existing production units; promote the application of new water-saving materials, technologies, and equipment; implement enterprise water balance tests; conduct reasonable water consumption analysis; improve the management network of measuring instruments; strengthen water quota management; and improve the efficiency of water resource utilization.

During the processes of oil and gas exploration, fracturing, and exploitation, it is suggested to conduct scientific and technological research, accelerate the research and testing of fracturing rejection fluid and purification water dispensing fluid, reduce reuse costs, implement different treatment processes based on the different oil and gas field characteristics, improve the compounding ratio of fracturing rejection fluid and purification water dispensing fluid, and reduce freshwater use. Meanwhile, it is important to research environmentally friendly fracturing fluid dispensing technology to solve the technical difficulties of fracturing fluid treatment and dispensing from the source and reduce the overall cost of oil and gas development.

Regarding mining-area living and environmental management, it is necessary to strengthen the management of greening water in the operation area, shift the greening irrigation water use from diffuse irrigation to a more efficient irrigation mode, implement the necessary technical transformations, and adopt technologies such as buried sprinkler irrigation, mobile sprinkler irrigation, and microsprinkler irrigation to save greening water. Strengthening the optimization of domestic water use in the mining area is also suggested by improving the reuse rate of sewage and reducing the use of freshwater.

4.4 Improving the assurance system of comprehensive water resource allocation, and enhancing the assurance degree of water security in the energy industry

The Western Region is the most important energy base of the country, and energy is the pillar industry of its economic and social development. Therefore, assuring the water security of the energy industry must be placed prominently. Thus, improving the assurance system of comprehensive water resource allocation for the energy industry should be accelerated, and water security strategies should be formulated according to local conditions. While the degree of water security for the energy industry should be effectively improved, it is also important to effectively prevent and control the impact of the energy industry on the hydro-ecological environment, including strictly controlling the over-extraction of groundwater, reducing the amount of wastewater discharged into rivers, lakes, and soil, and reducing the environmental impact of water extraction projects.

In terms of water sources, it is suggested to construct a diversified assurance system, maintain the reasonable

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use of conventional water sources, increase the use of unconventional water sources, and regulate the use of stock groundwater. In areas with prominent constraints on local energy industry water resources, a water conservation priority strategy should be effectively implemented to tap potential water conservation possibilities, improve efficiency, and encourage innovation at the water resources management level.

Simultaneously, it is necessary to accelerate the improvement of the water rights trading system between industry and agriculture, establish a well-rounded water rights trading platform, establish a legal basis and the related scientific and technological support, and promote cross-industry, cross-regional, and cross-basin water rights conversion. With the help of market means, water resources can be allocated efficiently, and energy companies should be encouraged to fund water-saving technology transformation in irrigation areas, thereby guaranteeing energy development based on maintaining the health of the water ecology.

5 Conclusion

As the energy innovation and strategic resource reserve area of China, the Western Region has experienced significant growth in oil and gas reserves and production in recent years, playing an important role in ensuring national energy security and promoting the steady implementation of the development strategy of the region. The Western Region will continue to vigorously develop its energy industry in the future, and oil and gas production will grow rapidly, but the constraint of regional water resources will become more prominent due to water resource shortages and the lack of potential for water resource development in the region. Given the characteristics of oil and gas development, and the current status of water consumption in the region, conducting scientific and technological research and developing precise water injection and waterless fracturing technology to reduce the consumption of water resources are suggested. It is also recommended to adapt to local conditions, increase the recycling of oil field produced water through technological progress and management innovation, increase the amount of unconventional water, and reduce the amount of freshwater extraction while reducing the level of surface and groundwater environmental pollution. In an effort to achieve the coordinated security of energy and water resources in the Western Region, the impact of oil and gas development on the water system should be reduced in all aspects and processes.

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