BDS Empowers Smart Water Conservancy Construction: Current Status, Challenges, and Future Opportunities

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Abstract

The BeiDou Navigation Satellite System (BDS) is a critical spatial-temporal infrastructure in China, and since its inception, it has been widely applied across various socio-economic sectors. Smart Water Conservancy is the most prominent indicator of high-quality development in the water conservancy sector during the new phase, and one of its six key implementation paths. The BeiDou system provides robust technical support for Smart Water Conservancy, offering essential spatial-temporal benchmarks, high-precision positioning, and communication services for the construction of digital twin water conservancy. This paper first introduces the development process of the BeiDou system, reviewing its technological advancements from regional navigation to global coverage. Then, from the functional perspective of the BeiDou system, it analyzes its current applications in typical scenarios such as water conservancy project deformation monitoring, water conservancy inspection, and water monitoring data transmission. The paper also discusses the application of BeiDou remote sensing technology in water level monitoring, soil moisture inversion, and atmospheric water vapor inversion. Additionally, this paper explores the challenges the BeiDou system faces in enabling Smart Water Conservancy, such as limitations in short message capacity and frequency, a lack of standardization, and difficulties in cross-departmental collaboration and data sharing. Finally, the paper examines the future development trends of the BeiDou system in the water conservancy sector, emphasizing that as the integration with new technologies progresses and commercialization accelerates, the BeiDou system will play an increasingly important role in Smart Water Conservancy, driving the modernization of the water conservancy industry.

1. Introduction

The BDS is a satellite navigation system independently developed and operated by China to meet national security and socio-economic development needs. It provides global users with all-weather, all-time, high-precision positioning, navigation, and timing services, and serves as a crucial spatial-temporal infrastructure for the nation. Since the successful completion of the global BeiDou network on July 31, 2020, it has been providing global users with continuous, high-precision services, widely applied across sectors such as transportation, agriculture, forestry, fisheries, hydrological monitoring, meteorology, communication, power dispatch, disaster relief, and public safety, yielding significant economic and social benefits.

Smart Water Conservancy is the most prominent indicator of high-quality water management in the new phase, and one of its six key implementation pathways. With the continuous enhancement of the BDS, particularly after the full deployment of BDS -3, service accuracy has significantly improved, and data transmission efficiency has been greatly enhanced, bringing transformative changes to the water conservancy industry. It provides crucial spatial-temporal benchmarks, high-precision positioning, and communication services for the construction of Smart Water Conservancy and digital twin water management systems. Today, the BeiDou system's positioning, navigation, and short message services have been widely adopted in various aspects of the water conservancy industry, including precise deformation monitoring of water infrastructure, hydrological data transmission, and water resources inspection. These capabilities, enabled by high-precision positioning data and real-time communication, have effectively enhanced water security and accelerated the digitalization and intelligence of the water conservancy sector. Despite the broad application prospects of the BDS in water conservancy, its promotion and deeper application still face several challenges, such as the lack of standardized technology and insufficient cross-departmental collaboration and data sharing. Therefore, this paper aims to explore the current state of the BeiDou system's role in enabling Smart Water Conservancy, analyze the challenges it faces in promoting the digital transformation of the water sector, and discuss the opportunities and future directions for its development.

2. The Development of the BDS

The BDS is a global satellite navigation system independently developed by China. Over many years of development, it has become part of the Global Navigation Satellite System (GNSS), alongside GPS, GLONASS, and Galileo. The development of the BDS can be divided into three major phases: BeiDou-1 (BDS-1), BeiDou-2 (BDS-2), and BeiDou-3 (BDS-3), each representing significant advancements in China's satellite navigation technology(Lu, 2024).

The construction of the BDS-3 system began in 2009 with the aim of achieving global coverage, and by July 2020, the system was fully completed and began providing services to global users. BDS-3 comprises 30 satellites, including 24 Medium Earth Orbit (MEO) satellites, 3 GEO satellites, and 3 IGSO satellites. Compared to the previous BDS-2 system, which primarily relied on GEO and IGSO satellites, the visible satellite count showed significant regionality—8 to 12 visible satellites in the Asia-Pacific region, while service was unavailable in the Americas (as shown in Figure 1). BDS-3 provides global coverage with 5 to 12 visible satellites, averaging 8.5 satellites globally. Moreover, when BDS-2 and BDS-3 satellites are used together, most areas around the world can see more than 8 satellites, with an average of 13.1 satellites. This improvement significantly enhances the constellation's geometric configuration, expanding service coverage and improving positioning accuracy, availability, and continuity. BDS-3 also features comprehensive upgrades in terms of positioning accuracy, time synchronization, communication capacity, and global coverage, offering sub-meter level or even higher precision services. In addition to traditional positioning, navigation, and timing (PNT) functions, it introduces global short-message communication, Satellite-Based Augmentation System (SBAS), and international search and rescue services, further enhancing its capabilities and broadening its application range.

The completion of the BDS-3 signified China's leap from a regional navigation system to a global navigation system, establishing BDS as a world-class navigation system. With the internationalization of BDS, China is actively promoting global cooperation, expanding the system's applications across a variety of sectors including transportation, agriculture, forestry, fisheries, energy, communications, and public safety.

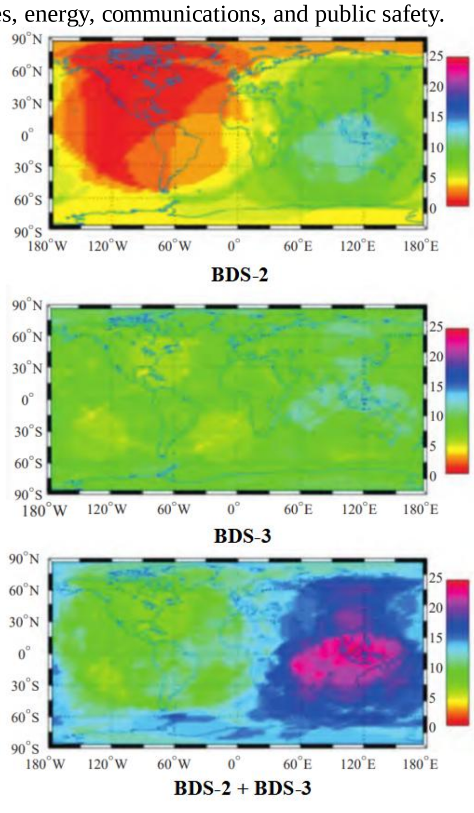

Figure 1. Comparison of the number of visible satellites of BDS.

3. Current Applications of the BDS in Water Conservancy

The water conservancy industry has long utilized GNSS technologies, primarily relying on GPS products from the United States in the early stages, particularly in water infrastructure construction. Since the development of China's BDS, its short message function has been applied to hydrological monitoring and reporting services starting in 2002. After the BDS was fully completed and launched in 2020, its applications have expanded to cover precise deformation monitoring of water infrastructure, hydrological measurement, water conservancy inspection, and flood and drought disaster investigation. Furthermore, as part of the GNSS framework, the BDS has enriched the development of GNSS-based remote sensing technologies. This paper also examines the current research on BDS remote sensing applications in the water conservancy sector.

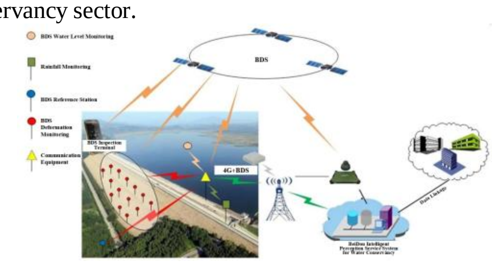

Figure 2. BDS Water Conservancy Application Scenarios.

3.1 BDS Empowering Smart Water Conservancy Project Deformation Monitoring

The BDS has become a critical technical support for the construction of Smart Water Conservancy due to its high-precision positioning services. After the global network was completed, BDS's positioning accuracy in most regions reached 5 meters or better, with localized accuracy ranging from 2 to 3 meters. Additionally, through the BDS Ground-Based Augmentation System, a network of ground reference stations provides real-time, high-precision navigation and positioning services with accuracies of 1-2 meters, decimeter-level, and even centimeter-level precision. These technological advancements offer strong support for managing water conservancy projects throughout their lifecycle.

In the Smart Water Conservancy system, deformation monitoring plays a crucial role in ensuring the safety of water infrastructure, especially for critical structures such as reservoirs, dams, and slopes. China has a large number of reservoirs and dams, with complex geological conditions, which often face issues of deformation and settlement, posing significant threats to public safety and economic stability. Slope deformation is also a critical factor influencing the safety of infrastructure and triggering geological disasters, particularly near key facilities such as reservoirs, riverbanks, and mountain roads. The stability of these slopes is directly related to the safety of lives and property, as well as the normal operation of engineering facilities. Smart Water Conservancy demands more efficient, real-time, and automated monitoring methods, which traditional manual monitoring struggles to achieve due to high labor costs and limited coverage.

The BDS, with its high-precision positioning and real-time communication capabilities, offers an innovative solution for deformation monitoring in Smart Water Conservancy projects. By deploying BDS monitoring terminals at key locations on reservoirs, dams, and slopes, the system can capture displacement and deformation data continuously and automatically, providing early warnings for potential safety hazards. This intelligent monitoring, enabled by the BDS, not only improves monitoring efficiency but also delivers high-quality real-time data for the safe management of water infrastructure, meeting the needs of Smart Water Conservancy for data precision and real-time monitoring. For example, Wei-Ping Jiang developed GPS deformation monitoring software

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applied to the Xilongchi Reservoir for safety monitoring, achieving real-time, continuous, high-precision, and automated monitoring, demonstrating the effectiveness and accuracy of the Smart Water Conservancy monitoring system(Jiang, 2012). Xi through an experimental platform, validated the potential of the BDS in high-precision deformation monitoring, with results showing that the BDS is fully suitable for high-precision deformation monitoring in Smart Water Conservancy(Xi, 2015). Mingjie Fan conducted a study using BDS technology to monitor the static and dynamic deformation of reservoir dams, showing that the system is more intelligent than traditional methods in monitoring dam deformation(Mingjie, 2022). Youcang Yuan validated the feasibility and practicality of using the BDS and GPS dual-star systems for slope monitoring by installing deformation monitoring terminals on high slopes at the Changheba Hydropower Station, further expanding its application in Smart Water Conservancy(Yuan, 2013).

With the BDS's high-precision positioning and real-time communication capabilities, deformation monitoring in Smart Water Conservancy projects has become more efficient and intelligent, enabling timely detection and early warnings of potential safety hazards. This technological advancement provides a robust data foundation for the safe operation of water conservancy projects and disaster prevention and mitigation, ensuring that monitoring and management in Smart Water Conservancy are more intelligent and reliable, aligning with the modernization needs of the water conservancy industry.

3.2 BDS Empowering Smart Water Conservancy Inspection Management

In the construction of Smart Water Conservancy, the BDS's high-precision positioning and navigation functions provide comprehensive technical support for various water conservancy inspection tasks. Whether responding to sudden flash flood disasters or conducting routine inspections of rivers, lakes, and water conservancy projects, the BDS significantly enhances the safety, efficiency, and informatization of inspections through its precise positioning, real-time communication, and intelligent navigation capabilities.

In the field of flash flood disaster prevention, flash floods are often accompanied by landslides and other natural disasters, with strong suddenness and high concealment, posing great challenges for inspection and early warning efforts. Traditional manual inspection methods rely on basic communication equipment and manpower, making it difficult to respond to sudden disasters in real-time. However, with BDS's wearable inspection terminals, personnel responsible for flash flood prevention can achieve precise positioning and real-time communication while on duty. These terminals can monitor the health status and location of inspectors in real-time and can send out emergency distress signals in case of danger, ensuring the safety of the inspection personnel. Additionally, when hidden risks are detected, the inspection records and hazard reports can be immediately transmitted to higher management departments, significantly improving the efficiency of flash flood disaster early warnings and emergency response.

In river and lake inspections, where systems are widespread and complex, traditional inspection methods face various practical difficulties, especially in adverse weather and complex geographic conditions. The BDS provides an innovative solution in this area. Inspection personnel can use the system to precisely locate their positions, follow predefined routes to complete inspection tasks, avoid missing or duplicating inspections, and transmit real-time inspection data. The safety of inspectors is further ensured through real-time monitoring of vital signs via the BDS terminal, ensuring that emergency assistance can be quickly dispatched if needed.

Regarding inspections of water conservancy projects such as dams, reservoirs, and sluices, the safe operation of these facilities depends on regular inspections. However, traditional manual inspections are often time-consuming, and it is difficult to ensure the accuracy and timeliness of the inspection data. The BDS, through providing high-precision positioning services to inspectors, combined with its short message communication function, ensures that inspection data is transmitted in real-time, even in environments without public network access, and that potential safety hazards are rapidly identified. This technology significantly improves the efficiency and accuracy of water conservancy project inspections, ensuring the long-term safe operation of water facilities.

Overall, the BDS provides robust technical support for Smart Water Conservancy inspections. It not only addresses the challenges of low efficiency and poor safety in traditional inspection methods but also enhances the quality and accuracy of inspections through digital means. By utilizing BDS's intelligent inspection equipment, water conservancy inspection work becomes more efficient and secure, fully supporting the construction and development of Smart Water Conservancy.

3.3 BDS Empowering Smart Water Conservancy Data Transmission Management

The BDS's short message communication function is a distinguishing feature compared to other navigation systems. Users can send text and location information through BDS, and based on this capability, specialized services can be developed. BDS-3's short message service is renowned for its all-weather, all-time operation, featuring global coverage and independence from ground communication base stations. Compared with BDS-2, the short message capacity of BDS-3 has significantly improved, ensuring continuous and stable communication under various weather conditions. This service is crucial in industries requiring efficient and reliable communication, especially in remote monitoring and automated monitoring applications. The water conservancy industry initially applied BDS short messages for transmitting hydrological monitoring data, but due to limitations in data capacity and transmission frequency, it was not widely adopted. Since the completion of the BDS-3 global network, short message communication functions have been effectively applied in the water conservancy sector, becoming a vital technology to solve the "last mile" issue in data transmission. The following examples illustrate the practical application of BDS short messages for data transmission in areas lacking public network coverage and during emergency situations.

3.3.1 Data Transmission in Areas Lacking Public Network Coverage: Many remote areas in China’s reservoirs and rivers suffer from poor communication infrastructure coverage due to their geographic isolation. Traditional wired or wireless networks cannot provide reliable data transmission, posing challenges for real-time data uploading and monitoring, and affecting the safe operation of reservoirs and the timely acquisition of hydrological information. To address this issue, BDS’s short message communication technology has been widely applied in the hydrological monitoring of small and medium-sized reservoirs.

Through BDS short messages, water level, rainfall, and other hydrological monitoring data (such as reservoir deformation, seepage pressure, and leakage) from reservoirs can be transmitted to water management departments in real-time, even without public network signals. This technology not only solves data transmission problems in remote areas but also significantly enhances reservoir management, ensuring efficient and reliable daily operations in regions without network coverage. BDS short messages play an essential role as the “data lifeline” in these regions, ensuring continuous monitoring and stable data transmission.

3.3.2 Data Transmission in Emergency Situations: During extreme weather events or natural disasters, ground communication infrastructure is often damaged, leading to network outages, which severely impact the transmission of hydrological data and, consequently, affect disaster early warning and emergency response efficiency. In such situations, the BDS's short message communication function can serve as the primary means of emergency communication, ensuring the timely reporting of hydrological data and rapid response from emergency management departments.

For instance, during the 2021 severe flooding in Henan province, extreme weather caused network and power outages in several areas, cutting off most hydrological monitoring stations. However, 621 telemetry stations using BDS satellite communication continued transmitting data, and over 870,000 BDS messages were received within eight days. These data provided crucial decision-making support for flood forecasting, early warning, dispatch, and flood control efforts. The reliable performance of BDS's short message communication in emergency situations fully demonstrated its importance and reliability under extreme conditions.

3.4 BDS Remote Sensing Technology Empowering Smart Water Conservancy

With the advancement of GNSS technologies, BDS remote sensing has become a key tool in building Smart Water Conservancy. The BDS not only provides high-precision navigation, positioning, and timing services but also captures L-band signals reflected from the Earth's surface to monitor environmental changes. In water conservancy, BDS remote sensing demonstrates significant advantages. With its low power consumption, low cost, high spatiotemporal resolution, and global coverage, BDS remote sensing plays a crucial role in water level monitoring, soil moisture detection, and atmospheric water vapor observation, significantly enhancing the intelligence and precision of water conservancy management.

3.4.1 Water Level Monitoring: In the Smart Water Conservancy system, water level monitoring is a core element in flood prevention and disaster mitigation. BDS remote sensing technology analyzes signals reflected by water surfaces from BDS satellites, enabling high-precision, fully automated, real-time monitoring of water level changes. Compared to traditional radar water gauges and ultrasonic water level meters, BDS remote sensing provides wider coverage and higher spatiotemporal resolution. This technology addresses the limitations of traditional monitoring methods in terms of cost and geographic coverage, thereby improving flood disaster response. Research has shown that using BDS-reflected signals for water level monitoring can achieve centimeter-level height accuracy, providing reliable data support for disaster early warnings and emergency decision-making in water conservancy departments. For instance, Wang proposed a multi-site, multi-signal GNSS-R combination method that achieved millimeter- to centimeter-level accuracy in water level inversion for the first time(Wang, 2021).

3.4.2 Soil Moisture Inversion: Soil moisture is a critical variable affecting the hydrological cycle and climate change, playing a key role in agricultural growth, flood prediction, and drought monitoring. BDS remote sensing technology leverages L-band signal reflections, which, through analyzing soil-reflected signals, enables dynamic soil moisture monitoring at high frequency and low cost. Compared to traditional soil moisture measurement methods, BDS remote sensing reduces monitoring costs while providing large-scale, high-precision monitoring. This innovation presents new opportunities for managing water resources and monitoring agricultural hydrology within Smart Water Conservancy. For example, Yang proposed a soil moisture inversion method using BDS geostationary satellite reflections aided by support vector regression, achieving a relative error of less than 3% based on actual measurement data(Yang, 2016). Similarly, Changzhi Yang developed single-satellite inversion models based on BDS C3 and C59 geostationary satellites, with both models yielding regression coefficients greater than 0.65 and root mean square errors (RMSE) below 2%(Yang, 2022).

3.4.3 Atmospheric Water Vapor Inversion: The spatiotemporal distribution of atmospheric water vapor directly influences precipitation patterns and is crucial for monitoring and predicting extreme weather such as floods and droughts. The BDS, by observing tropospheric delay, can achieve high-precision inversion of atmospheric water vapor content. This technology supports short-term precipitation forecasting and extreme weather early warnings within Smart Water Conservancy. It has already demonstrated good accuracy and feasibility in regional applications. For example, Li evaluated BDS precipitable water vapor (PWV) inversion accuracy, finding a root mean square error of 2 mm compared to GPS, confirming the reliability of BDS water vapor detection(Li, 2015). Lu validated the feasibility and stability of BDS in near-real-time atmospheric water vapor inversion, with precision slightly lower than GPS. As BDS continues to develop and integrates with other satellite systems and multi-source data, future rainfall predictions will become more accurate and timely, significantly improving disaster warning capabilities in water conservancy(Lu, 2015).

4. Challenges of BDS Empowering Smart Water Conservancy

Despite the significant potential and application prospects of the BDS in enabling Smart Water Conservancy, several challenges remain in its practical implementation and promotion. These challenges are particularly pronounced in the areas of technology, standardization and adoption, inter-departmental collaboration, and data sharing.

4.1 Technical Challenges

4.1.1 Limitations in BDS Short Message Capacity and Frequency: The short message function of BDS is a unique advantage, especially in remote areas without ground communication networks and in emergency situations where data transmission can be achieved via satellites. However, the current capacity and transmission frequency of BDS short messages remain limited. The length of each message is relatively short, and the transmission frequency is also constrained. In Smart Water Conservancy scenarios that require frequent and large-scale data transmission, such as hydrological monitoring and disaster early warnings, this limitation becomes a significant challenge. For instance, short messages cannot meet the needs of large-scale real-time data transmission, especially for big data such as images and videos. This presents challenges for the real-time precision monitoring of hydrological information. Therefore, improving the capacity and transmission frequency of BDS short messages, or utilizing data compression techniques to enhance transmission efficiency, will be crucial for the BDS system in Smart Water Conservancy applications.

4.1.2 Adaptation of High-Precision Positioning in Complex Terrain: The high-precision positioning capability of the BDS performs well in flat areas and open environments, but in complex terrains such as mountainous regions, river valleys, or densely populated urban areas, signal obstruction or reflection significantly affects positioning accuracy and stability. Since water conservancy facilities are often located in such complex terrains, the BDS faces higher adaptation requirements. Overcoming signal interference in complex environments and improving the reliability of high-precision positioning is a key technical challenge for BDS in Smart Water Conservancy applications.

4.2 Challenges in Standardization and Technology Adoption

4.2.1 Lack of Unified Technical Standards: The application of BDS in the water conservancy sector is still in the gradual promotion stage, and relevant technical standards are not yet fully unified. Currently, different regions and departments use varying technical standards and specifications for BDS technology, leading to issues such as data incompatibility and poor device interoperability. This lack of standardization not only limits the widespread promotion and application of BDS but also affects the overall technical integration of Smart Water Conservancy systems.

4.2.2 Difficulties in Technology Adoption and High Costs: The promotion of BDS technology in the water conservancy industry faces challenges in terms of cost and application complexity. Particularly in remote areas with weak infrastructure, the cost of deploying BDS-related equipment and technologies is high, and providing technical support and maintenance can be difficult. Additionally, the level of acceptance and operational capability of water conservancy practitioners toward new technologies also affects the adoption of BDS. Reducing costs, simplifying operational processes, and enhancing ease of use will be critical to driving large-scale adoption of BDS in the water conservancy sector.

4.3 Challenges in Inter-Departmental Collaboration and Data Sharing

4.3.1 Insufficient Mechanisms for Data Sharing Across Departments: The broad application of BDS relies on collaboration and information sharing across multiple departments, especially in areas such as hydrological monitoring, disaster early warning, and river and lake regulation, where data from different departments is often required. However, the mechanisms for inter-departmental data sharing remain inadequate. Structural and technical barriers prevent smooth data exchange between departments, resulting in information silos, which weaken the overall effectiveness of the BDS. This data isolation issue hinders the collaborative management and development of Smart Water Conservancy systems.

4.3.2 Barriers to Collaborative Management: The water conservancy sector involves multiple management departments and stakeholders, such as water resources departments, environmental protection agencies, and meteorological services. These departments often face unclear divisions of responsibility and inefficient collaboration mechanisms in practice. This issue is especially evident during emergency response and disaster early warning, where effective coordination and information flow are lacking. The absence of efficient management collaboration increases the difficulty of applying BDS in Smart Water Conservancy, limiting its potential in critical scenarios such as flood prevention and disaster mitigation.

5. Future Development Trends

The effective application of the BeiDou System's positioning, navigation, and short-message functions in key water conservancy areas such as hydrological monitoring, disaster early warning, and water resource management has proven that BDS is a crucial technological force in enhancing the intelligence and precision management of the water conservancy sector. The successful implementation of BDS in water conservancy not only highlights its value in traditional water applications but also lays a solid foundation for its deeper application in meeting the new development demands of the sector. As China continues to implement the policy decisions of the Central Committee of the Communist Party of China and the State Council to accelerate the large-scale application of BeiDou, balancing development with security, innovating new application scenarios and models for BeiDou in water conservancy, upgrading PNT (Positioning, Navigation, and Timing) devices, and promoting the systematic scale application of BeiDou in water conservancy, several significant trends in the system's development within the water sector are expected to emerge:

5.1 Expansion of Application Fields and Scenarios for BDS in Water Conservancy

As BDS continues to mature and improve, its application in the water conservancy industry is becoming increasingly broad, presenting new development opportunities. BDS is already showing significant potential in areas such as flood and drought disaster prevention, water resource management, hydrological information transmission, water conservancy project construction and safety management, river and lake regulation, soil and water conservation monitoring, and many other business fields. For example, BDS’s precise positioning service can be used for real-time monitoring and maintenance of water infrastructure to ensure stable operations. In flood warning systems, BDS’s time synchronization function can improve the accuracy and efficiency of warnings. Furthermore, BDS plays an important role in improving water resource utilization efficiency and promoting water-saving initiatives. Through accurate geographic positioning, it can optimize irrigation systems, reduce water waste, and in urban and rural water supply management, BDS’s real-time monitoring can effectively reduce leakage and enhance the efficiency and reliability of supply systems.

5.2 Increasing Scale of BDS Application in Water Conservancy

With the gradual improvement of relevant standards and regulations, some established services within the BDS system, such as short-message services, water conservancy inspections, and intelligent compaction monitoring, have entered a new phase of commercialization. This marks a significant increase in the market acceptance and technological maturity of BDS within the water conservancy industry and suggests broader promotion and application in the sector. Through these commercial applications, communication efficiency in hydrological monitoring and disaster warning systems will greatly improve, inspection management of water facilities will become more intelligent, and the quality and safety of water conservancy project construction will also improve further. Commercial development will accelerate the digitalization and intelligent transformation of the water sector, improving the efficiency of water resource management and utilization, thereby promoting water security and sustainable development.

5.3 Enhanced Integration of BDS with Emerging Technologies in Water Conservancy

In the future, the integration of BDS with emerging technologies will be a key driver of smart water conservancy development. Specifically, the combination of BDS with artificial intelligence (AI), 4G/5G communication technology, satellite internet (space network) communication, and remote sensing technology will bring broader and more diverse application scenarios to the water sector. This technological integration can not only improve the efficiency and accuracy of hydrological data processing but will also optimize disaster warning and emergency response processes, enhancing the intelligence of smart water management. For example, through integration with AI, BDS can provide more accurate predictions and monitoring for dynamic water resource management; by working with 5G and satellite internet technologies, BDS will be able to transmit hydrological information faster and more comprehensively, providing smarter and more efficient solutions for the water conservancy industry.

In conclusion, by expanding application scenarios, driving business commercialization, and enhancing cross-sectoral coordination and integration, BDS has broad prospects for application in the water conservancy sector. This will not only accelerate the adoption and application of BeiDou technology in water conservancy but also promote technological advancement and efficiency improvements in the industry. In the future, as technology advances and its applications deepen, BDS will play an increasingly important role in the construction of smart water conservancy, becoming an indispensable technological support for the industry.

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