

Quality Management Challenges and Mitigation Strategies in Large-Scale Water Transfer Projects

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Abstract: *Large-scale water transfer projects are strategic infrastructure essential for optimizing water resource allocation, alleviating regional imbalances between water supply and demand, and supporting high-quality socioeconomic development. These projects are characterized by their substantial scale, extended construction periods, technical complexity, extensive geographical coverage, and significant environmental impacts. Quality management is a critical component of project construction, directly influencing structural safety and stability, water supply reliability, and long-term durability. It also plays a vital role in mitigating engineering risks and safeguarding lives and property. Taking a large-scale water transfer project as a case study, this paper systematically examines the key challenges associated with quality management during project construction. Drawing on practical construction experience, targeted strategies are proposed from technical, managerial, institutional, and personnel perspectives to provide a theoretical reference for improving quality management in large-scale water transfer projects in China.*

Keywords: Large-scale water transfer projects; Quality management; Challenge analysis; Mitigation strategies.

1. INTRODUCTION

Water resources in China are unevenly distributed, with greater availability in the south than in the north, where imbalances between water supply and demand are particularly pronounced. As strategic national infrastructure, large-scale water transfer projects play a crucial role in alleviating regional water scarcity and promoting coordinated socioeconomic development. Large-scale water transfer projects are characterized by their substantial scale, extended construction periods, technical complexity, and involvement of multiple stakeholders [1]. However, quality management in practice faces considerable challenges, including difficulties in coordinating construction activities, environmental uncertainties, and complexities in controlling materials and equipment. Therefore, ensuring effective quality management in large-scale water transfer projects is essential for successful project delivery.

International research has primarily focused on comprehensive quality management and the development of standardized management systems, emphasizing the use of advanced monitoring technologies and digital tools for quality control throughout the project life cycle [2]. In contrast, Chinese studies have largely drawn on engineering practice, focusing on construction quality control, optimization of supervision mechanisms, and risk management approaches [3]. For example, Zhang et al. [4] developed a construction quality control system for long-distance water transfer projects and proposed a process-based quality management approach. Other studies have examined construction quality control methods and regulatory frameworks in major infrastructure projects, such as the South-to-North Water Diversion Project [5]. However, existing studies have predominantly focused on individual construction stages or specific technical issues, with limited systematic analysis of the broader quality management challenges associated with large-scale water transfer projects.

Accordingly, this study examines the key challenges in quality management for large-scale water transfer projects and proposes targeted strategies for improvement. This study aims to advance the theoretical understanding of quality management in large-scale water conservancy projects and provide a theoretical foundation for improving quality management practices in China's large-scale water transfer projects.

2. CHARACTERISTICS OF LARGE-SCALE WATER TRANSFER PROJECTS AND KEY QUALITY MANAGEMENT REQUIREMENTS

2.1 Characteristics of Large-Scale Water Transfer Projects

The distinctive characteristics of large-scale water transfer projects pose unique and complex challenges for quality management, primarily in the following aspects. First, these projects are characterized by their substantial scale and extensive geographical coverage. Large-scale water transfer projects often span multiple provinces and river basins, encompassing diverse hydraulic structures, including pumping stations, canals, tunnels, aqueducts, and inverted siphons. Second, these projects typically involve prolonged construction periods. Owing to factors such as project scale, geological conditions, and construction environments, these projects generally require several years to complete, with some extending over a decade. Third, these projects involve considerable technical and construction complexity. Complex geological conditions and challenging construction environments necessitate advanced construction technologies, techniques, and equipment, imposing stringent requirements on technical expertise and quality management [6]. Fourth, these projects involve multiple participating organizations. These projects involve multiple organizations responsible for design, construction, supervision, and inspection, whose differences in management capabilities and technical expertise complicate coordination. Fifth, these projects have far-reaching social and ecological impacts. Project construction and operation can affect ecosystems, hydrogeological conditions, and the livelihoods of communities along the transfer route. The key characteristics of large-scale water transfer projects are summarized in Table 1.

Table 1: Characteristics of Large-Scale Water Transfer Projects

Characteristic Dimensions	Large-Scale Water Transfer Projects
Project Scale	Extensive project scale, spanning multiple provinces and river basins and encompassing diverse hydraulic structures, including pumping stations, canals, tunnels, and aqueducts, with substantial construction workloads.
Construction Duration	Prolonged construction periods, typically spanning several years and, in some cases, exceeding a decade.
Construction Technologies and Techniques	Complex construction techniques requiring adaptation to challenging geological and environmental conditions, supported by advanced technologies and specialized equipment.
Participating Organizations	Multiple participating organizations, including design firms, contractors, supervision and inspection agencies, and material and equipment suppliers.
Environmental Impacts	Far-reaching impacts on ecological and social environments along the transfer route during both construction and operation.

2.2 Key Quality Management Requirements for Large-Scale Water Transfer Projects

Quality management in large-scale water transfer projects encompasses a range of activities aimed at achieving construction quality objectives through the establishment of a comprehensive quality management system and the application of systematic management approaches and technical measures. It controls quality throughout construction to ensure compliance with national standards, technical specifications, and design requirements, safeguarding operational stability, water quality, and long-term structural durability [7]. The key requirements are outlined below:

First, quality management should encompass the entire project life cycle. Quality management should cover all stages, including site investigation, design, construction, supervision, inspection, and acceptance, integrating preventive measures, process control, and post-construction traceability into a closed-loop management system to prevent defects at individual stages from compromising overall project safety [8].

Second, comprehensive quality assurance should address all critical project factors. Key factors, including technology, materials, equipment, construction techniques, personnel, and environmental conditions, should be systematically coordinated, with strict adherence to technical standards and specifications, rigorous inspection of incoming materials, enhanced control of critical construction processes, and thorough acceptance inspections of concealed works to ensure structural safety and operational reliability.

Third, coordinated management across regions is essential. Given the involvement of multiple regions, administrative departments, and stakeholders, unified coordination, consistent standards, and integrated supervision should be strengthened, with clearly defined quality responsibilities to improve interorganizational collaboration and quality management efficiency.

Fourth, risk prevention and control should prioritize safety. Particular attention should be given to critical risk factors, including complex geological conditions, high slopes, and deep excavations, through specialized quality and safety assessments and improved emergency response plans to minimize the risk of quality-related incidents at their source.

3. ANALYSIS OF QUALITY MANAGEMENT DIFFICULTIES IN LARGE-SCALE WATER TRANSFER PROJECTS

3.1 Quality Management Involves a Wide Range of Influencing Factors, Making Coordination Across All Links Highly Difficult.

Large-scale water transfer projects involve long construction periods and numerous interrelated construction activities. During construction, many problems arise, including diverse quality-management factors at each link and significant difficulties in cross-link coordination [9]. During engineering construction, quality control runs through multiple stages including planning, design, construction, procurement of materials and equipment, installation, testing and inspection, and acceptance. Deviations at any stage may adversely affect overall project quality. Meanwhile, large-scale water diversion projects involve a large number of participating entities, including project owners, designers, constructors, supervisors, testing institutions, and suppliers of materials and equipment. Differences in responsibilities and objectives, together with uneven information flow, can cause management gaps, unclear accountability, and poor coordination, further complicating quality control. It can be seen that numerous and dynamically changing influencing factors as well as great difficulties in coordination among all links and participants constitute the core difficulties in the quality management of large-scale water diversion projects. These are also key issues that must be emphasized to ensure acceptable project quality and long-term safe operation.

3.2 Restricted by Complex Geological Conditions and Construction Environments, the Quality Control of Engineering Entities Faces Great Challenges.

Table 2: Analysis of Difficulties in Engineering Entity Quality Control under Complex Geological and Construction Conditions

Category	Main Geological and Environmental Conditions	Typical Construction Risks	Impacts on Engineering Entity Quality
Complex Geological Conditions	Deep-buried tunnels, fault fracture zones, strata with uneven hardness, high geostress	Rock burst, water inrush and mud gushing, large deformation of soft rock, surrounding rock instability	Tunnel overbreak and underbreak, primary support deformation, lining cracking, water seepage, and reduced structural safety
	Water-rich sand strata, silty soil, karren and karst grooves	Stratum settlement, shield blowout, segment dislocation	Pipeline alignment deviation, joint leakage, differential settlement, and reduced long-term operation reliability
Constraints of Construction Environment	Long distance, large gradient, small turning radius, deep burial, limited working space	Difficult ventilation, poor transportation, inconvenient inspection	Great fluctuation of construction quality, increased difficulty in acceptance and quality traceability of concealed works
	Undercrossing rivers, highways, railways, villages and existing pipelines	Strict settlement control and stringent vibration limits	Prone to disturbance of surrounding environment, difficult balance between structural protection and construction quality
	Adverse weather such as typhoons, rainstorms and high temperatures, as well as extensive cross operations	Difficult concrete curing and tight working procedure connection	Unstable concrete strength and poor consistency of entity quality

Large-scale water diversion projects usually span multiple geological units with complex and diverse geological conditions and harsh construction environments, presenting great challenges to the quality control of engineering entities [10]. Structures such as tunnels, buried pipelines, pump stations and inverted siphons are densely distributed along the entire project alignment. During construction, typical geological hazards may be encountered, including rockbursts under high in-situ stress, water and mud inrush under high external water pressure, large deformation of soft rock, and high ground temperatures. These adverse geological conditions can lead to various construction quality defects. Common defects include tunnel overbreak and underbreak, deformation of primary support structures, and cracking and water seepage in tunnel linings. Meanwhile, the complex construction environment further increases the pressure of quality management and control. Some tunnels are characterized by large gradients, small turning radii, deep burial and long distances [11], restricting the operating space for shield machine manipulation, ventilation and smoke extraction, material transportation and quality inspection. Certain sections need to undercross rivers, expressways, railways and existing pipelines, imposing extremely high requirements on settlement control, vibration control and structural protection. In addition, adverse weather frequently occurs along the project route. Constrained site space, frequent cross operations and tight connection of working procedures tend to cause quality fluctuations in key processes such as concrete pouring, curing and

anti-seepage treatment. Acceptance and quality traceability of concealed works are difficult, posing continuous challenges to the stability of engineering entity quality. The difficulties in entity quality control under complex geological and construction conditions are shown in Table 2.

3.3 Difficult Quality Control of Materials and Equipment, Prominent Quality Risks at the Source

Materials and equipment form the foundation of engineering construction, and their quality directly determines the engineering entity quality. Large-scale water diversion projects involve enormous engineering quantities and consume massive amounts of steel, cement, sand and gravel, pipes, electromechanical and metal structure equipment, etc. The procurement and management of substantial quantities of materials and equipment bring great difficulties to quality control [12]. First, materials and equipment come from a wide range of sources. Some materials and equipment are supplied by various manufacturers. Differences exist in manufacturers' technical capabilities, production processes and quality management levels, resulting in uneven quality of materials and equipment. Unqualified materials and equipment may flow into construction sites and trigger quality hazards. Second, quality control during the transportation and storage of materials and equipment faces great difficulties. Large-scale water diversion projects have long routes, so materials and equipment require long-distance transportation and are prone to damage and deterioration in transit. Besides, a large number of materials are susceptible to environmental factors. Poor on-site storage conditions and irregular stacking of materials and equipment may degrade their quality. Third, the inspection of materials and equipment is challenging. Large-scale water diversion projects consume huge volumes of materials and equipment, leading to heavy inspection workloads and long inspection cycles. Some inspection institutions lack adequate technical competence and responsibility. Cases such as falsified inspection data and inadequate inspection may occur, making it impossible to identify unqualified materials and equipment promptly and posing certain risks to engineering quality.

3.4 Numerous Concealed Works Exist in the Quality Management Process, Rendering the Quality Management Task Arduous

Large-scale water diversion projects feature complex terrain along the alignment and diverse construction forms. A large amount of construction work is located underground or covered by subsequent working procedures, showing prominent characteristics including a large quantity, wide distribution and complex types of concealed works [13]. Key working procedures such as tunnel excavation, underground anti-seepage treatment, foundation treatment, concrete pouring and pipeline embedding are often concealed, which greatly reduces the visibility and inspectability of construction quality. Some quality hazards cannot be detected promptly during construction and may only be exposed in the later operation stage or after accidents occur. Meanwhile, for concealed works, material properties, process parameters, construction records and acceptance documents are prone to problems such as missing data, incomplete information transmission and non-standard archiving over the long construction period. Once a quality accident occurs, it is difficult to accurately locate the source of defects, formation causes and responsible parties [14]. In addition, the project adopts multi-section contracts and involves multi-disciplinary cross operations, which makes it difficult to define the quality responsibility boundary of concealed works. There is a lack of clear traceability chains and complete data evidence chains.

3.5 Uneven Quality Awareness and Technical Proficiency of Personnel, as Well as Shortage of Professional Talents

The quality management of large-scale water diversion projects requires a high-quality and professional talent team consisting of management personnel, technical staff and construction workers. However, the construction of such projects is often plagued by uneven personnel quality awareness and technical proficiency as well as a shortage of professional talent, which undermines the quality and efficiency of quality management work. First, some management personnel have weak quality awareness and insufficient understanding of the importance of quality management, holding the mindset of prioritizing progress and investment while neglecting quality. During engineering construction, they ignore the control of engineering quality to speed up construction progress and cut costs, resulting in quality hazards in part of the project [15]. Second, technical personnel have inadequate technical competence. Large-scale water diversion projects involve complex technical processes and impose high requirements on the professional level of technical staff. Nevertheless, some technical personnel lack relevant professional knowledge and practical experience, and cannot master advanced construction technologies and quality management methods proficiently. During technical guidance and quality control, they fail to identify and resolve quality problems promptly. Third, there is a shortage of skilled construction workers and inadequate training for construction personnel. Large-scale water diversion projects require a large workforce. Against the

backdrop of the shortage of skilled workers, most construction staff lack professional construction skills and systematic training, accompanied by weak quality awareness. During construction, non-standard construction techniques and improper operations are likely to occur, thereby triggering engineering quality problems.

4. COUNTERMEASURES FOR QUALITY MANAGEMENT OF LARGE-SCALE WATER TRANSFER PROJECTS

In response to the current difficulties in quality management of large-scale water diversion and conveyance projects, practical and feasible countermeasures are urgently needed. The countermeasures for quality management of large-scale water diversion and conveyance projects are shown in Figure 1.

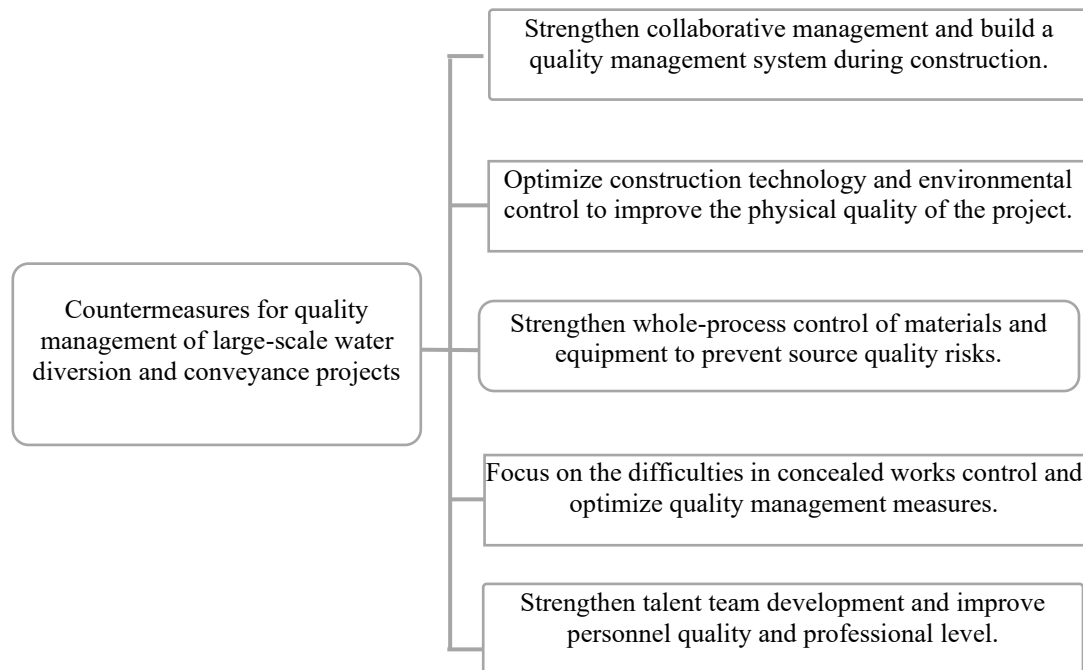


Figure 1: Countermeasures for quality management of large-scale water diversion and conveyance projects

4.1 Establishing a Quality Management System and Improving Its Effectiveness

First, during project construction, actual project conditions should be taken into account, and the participating parties (including design, construction, supervision, and the project legal person) need to establish and improve their respective quality management systems. The project quality responsibilities of each participating party should be clarified, quality control standards should be refined, and quality management requirements should be integrated into all stages of the project [16]. At the same time, it is necessary to align with relevant national codes and standards and, in light of regional characteristics and technical requirements, formulate targeted quality management rules and detailed operating procedures, so as to ensure that the quality management system is operable and pertinent.

Second, it is necessary to strengthen the efficient operation of the management system. On the one hand, the quality responsibility traceability system and assessment mechanism should be improved. Quality objectives should be systematically broken down and assigned to specific positions and personnel. Supervision and inspection throughout the construction process should be strengthened to ensure clear accountability and effective quality control at all stages. On the other hand, process control should be strengthened. Quality inspection should be reinforced at key links such as raw material entry, construction procedures, concealed works, and completion acceptance. Advanced inspection technologies and methods should be adopted to improve the accuracy and timeliness of quality control.

At the same time, a mechanism for evaluating the operation of the quality management system and for continuous improvement can be established, and the operational effectiveness of the quality management system should be regularly evaluated.

4.2 Optimize Construction Technology and Environmental Control to Improve the Physical Quality of the

Project

Geological survey and geological hazard prevention and control should be strengthened. During the project planning and design stage, in-depth geological survey work should be carried out, the geological conditions along the project route should be fully understood, and detailed geological survey reports should be prepared [17]. For areas with complex geological conditions, specific plans for geological hazard prevention and control should be developed. Advanced monitoring technologies should be adopted to strengthen real-time monitoring of geological hazards. Potential geological hazards should be promptly identified and addressed. Construction technologies and processes should be optimized. In light of actual project conditions, advanced construction technologies and processes should be adopted to improve construction quality and efficiency. For different structures and construction stages, special construction plans should be formulated, expert reviews should be organized, technical requirements and quality control points should be clarified, and technical guidance and supervision during construction should be strengthened.

Construction environment control should be strengthened. For harsh construction environments, special environmental control plans should be formulated, and effective protective measures should be taken to reduce the impact of environmental factors on project quality. For example, during winter construction in severely cold northern regions, measures such as thermal insulation curing and heated mixing should be adopted to prevent frost heave and cracking of concrete. In mountainous sections, drainage, anti-slip, and protective measures at the construction site should be strengthened to ensure construction safety and project quality. When severe weather such as rainstorms and sandstorms occurs, outdoor construction should be suspended, and protective measures should be taken for completed works to prevent quality damage [18].

4.3 Strengthen Whole-Process Control of Materials and Equipment to Prevent Source Quality Risks

Procurement management of materials and equipment should be strictly implemented. A sound procurement management system for materials and equipment should be established and improved, procurement standards and requirements should be clarified, and manufacturers and suppliers with complete qualifications, high technical levels, and good reputations should be selected [19]. Supervision over the procurement process should be strengthened, public bidding and centralized procurement should be implemented, backroom operations should be eliminated, and procured materials and equipment should be ensured to comply with relevant national standards and design requirements.

Transportation and storage management of materials and equipment should be strengthened. Professional transportation companies should be selected, reasonable transportation plans should be formulated, and effective protective measures should be taken to prevent materials and equipment from being damaged or deteriorating during transportation. On-site storage management of materials and equipment should be standardized, and storage facilities should be improved. Materials and equipment of different types and specifications should be properly arranged and stored separately. Appropriate measures should also be taken to protect them from moisture, corrosion, and direct sunlight, thereby ensuring stable quality.

Inspection and testing management of materials and equipment should be strengthened. A sound inspection and testing management system should be established and improved, testing standards, frequencies, and methods should be clarified, fully qualified and technically competent testing institutions should be selected, and incoming materials and equipment should be strictly tested. At the same time, supervision over the testing process should be strengthened to ensure the authenticity, accuracy, and reliability of testing data. Nonconforming materials and equipment must not enter the construction site or be used.

4.4 Focus on the Difficulties in Concealed Works Control and Optimize Quality Management Measures

In view of the many concealed works and the arduous quality management tasks in large-scale water diversion and conveyance projects, targeted solutions can be formulated from the institutional, technical, and supervisory aspects in light of engineering practice and regulatory requirements.

At the institutional level, special management mechanisms should be established, the rights and responsibilities of participating units should be clarified, acceptance and traceability systems for concealed works should be strictly implemented, and assessment and accountability mechanisms should be improved. Units and individuals that strictly fulfill quality management responsibilities, meet project quality standards, and have no hidden hazards

should be commended and rewarded. For those with quality violations that cause hidden quality hazards or quality accidents, the responsible units and individuals should be held accountable in accordance with laws and regulations, forming a management model of “rewards and penalties and matching rights and responsibilities.”

At the technical level, non-destructive testing technologies such as ultrasonic testing and ground-penetrating radar should be promoted to replace traditional destructive testing methods. This can achieve non-contact, high-precision inspection of the internal structure and construction quality of concealed works, and accurately identify potential hidden quality hazards such as insufficient compaction of concrete pouring, substandard thickness of the rebar protective layer, and leakage at pipeline joints. In addition, BIM technology can be used to build an information management platform. Through 3D visualized modeling, the structural layout and construction details of concealed works can be intuitively presented, which facilitates real-time information sharing and collaborative quality control among participating units. It also enables dynamic monitoring and early risk warning during construction, thereby optimizing construction processes and reducing hidden hazards [20].

At the supervisory level, standing supervision and closed-loop management should be strengthened. For key procedures and critical links of concealed works, supervision units should be required to arrange professional supervisors for whole-process standing supervision to ensure that construction procedures meet quality standards. Identified problems should be rectified promptly and then subjected to review and acceptance, so that quality problems are never left unresolved.

4.5 Strengthening Workforce Development and Enhancing Professional Competence

Quality awareness education for all personnel should be strengthened. Participating units should be organized to carry out quality management knowledge training, quality awareness education, and laws and regulations training, so as to improve the quality and legal awareness of management personnel, technical personnel, and construction workers. The concept of “quality first, safety foremost” should be established, the mindset of emphasizing schedule and investment while neglecting quality should be abandoned, and personnel should consciously abide by quality management rules and regulations and standardize construction behavior.

Professional training for technical personnel should be strengthened. Training plans for technical personnel should be developed, and professional skills training should be regularly organized. Technical personnel should be encouraged to acquire advanced construction techniques, quality management methods, and relevant industry standards and specifications. These measures can enhance their professional competence and practical skills. Technical personnel should be encouraged to carry out technological innovation and research breakthroughs. In response to difficult problems in project quality management, advanced technologies and processes should be developed to improve the level of project quality management [21].

The skill level of construction workers should be improved. Pre-job and on-the-job training for construction workers should be strengthened, and professional skills assessments should be conducted. Only those who pass the assessment may work on site. A skill grading system should be implemented to encourage construction workers to improve their skills. Construction workers with high skill levels and excellent work performance should be commended and rewarded, thereby stimulating their learning enthusiasm and work motivation.

Talent incentive and support mechanisms should be improved. The salary, benefits, and development space of high-quality professionals should be increased, working and living conditions should be improved, and outstanding talent should be attracted and retained. Talent cultivation and introduction mechanisms should be established. By cooperating with universities and research institutes, a group of professional, high-quality quality management talents can be cultivated, providing long-term talent support for the quality management of large-scale water diversion and conveyance projects.

5. CONCLUSIONS

As strategic national infrastructure, large-scale water transfer projects require comprehensive quality management encompassing all project stages, critical factors, and coordination among multiple stakeholders. Owing to their large scale, complex geological conditions, and diverse organizational structures, these projects face considerable challenges in quality management. These challenges mainly involve coordination across project stages, construction quality control, materials and equipment management, and personnel competency. Drawing on construction management practices in large-scale water transfer projects, this study systematically examines the

key challenges in quality management. Targeted strategies are proposed across five dimensions: quality management systems, construction technology and environmental control, whole-process control of materials and equipment, concealed works quality management, and workforce development. The findings provide practical insights for improving quality management in large-scale water transfer projects, thereby contributing to their long-term operational safety and reliability.

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