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Applicability and Operation and Maintenance of Constructed Wetlands for Rural Domestic Wastewater Treatment in China

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Abstract

Constructed wetlands provide an alternative for treating rural domestic wastewater through the combined effects of substrates, plants, and microorganisms. In China, differences in settlement patterns, wastewater characteristics, climate, land availability, and local management capacity affect the suitability of this technology. Although constructed wetlands have advantages such as relatively low energy demand and simple operating requirements, their performance can be affected by substrate clogging, insufficient nitrogen removal, seasonal temperature changes, and inadequate maintenance. This paper examines the treatment principles and main configurations of constructed wetlands, identifies the conditions under which they are suitable for rural wastewater treatment, and discusses common operational problems. It also proposes practical measures for pretreatment, water distribution, water-level adjustment, vegetation management, clogging control, winter protection, and routine monitoring. The analysis emphasizes that the successful application of constructed wetlands depends not only on treatment design but also on the coordination of local conditions, appropriate wastewater management, and long-term maintenance.

Keywords: constructed wetlands, rural domestic wastewater, applicability, operation and maintenance

1. Introduction

Rural domestic wastewater treatment remains an important part of rural environmental management in China. Compared with urban areas, rural settlements often have lower population density, greater variation in household water use, and different levels of infrastructure development. Some villages are connected to centralized wastewater treatment systems, while others rely on decentralized facilities or on-site treatment. Differences in population distribution, water availability, and local economic conditions make it difficult to apply a single treatment approach to every rural area (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024).

Constructed wetlands have attracted attention as an option for decentralized wastewater treatment. They use a combination of substrates, wetland plants, and microorganisms to remove or reduce pollutants. Compared with treatment systems that depend heavily on mechanical equipment, properly designed wetlands can have relatively low energy requirements and can be operated with limited technical support. A review of constructed wetlands in rural sanitation also identifies pretreatment followed by wetland treatment as a widely used arrangement (Moreira, F. D., & Dias, E. H. O., 2020).

However, constructed wetlands should not be regarded as a universal solution. Their performance depends on wastewater characteristics, hydraulic loading, substrate conditions, temperature, and maintenance. Excessive suspended solids and grease can cause clogging, while unsuitable operating conditions can reduce nitrogen removal. In some rural areas, a lack of routine inspection and clear maintenance responsibilities can also affect the long-term use of treatment facilities (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024).

China's technical guidance provides a practical basis for examining these issues. The Ministry of Ecology and Environment issued the Technical Guide for Constructed Wetland Treatment in Rural Domestic Wastewater Resource Utilization in 2026. Its scope focuses on the use of constructed wetlands in resource utilization, including pretreatment, water storage, and the prevention of black and odorous water. The guide also addresses site selection, facility construction, and operation and maintenance (Ministry of Ecology and Environment of the People's Republic of China, 2026).

This paper examines the applicability of constructed wetlands to rural domestic wastewater treatment in China, with particular attention to the conditions required for effective use and the measures needed to maintain stable operation. Rather than treating the technology as suitable for all rural settings, it considers how wastewater characteristics, climate, available land, and local management capacity should guide technology selection and operation.

2. Treatment Principles and Main Configurations

2.1 Treatment Principles

A constructed wetland is an engineered treatment system that combines a water-retaining structure, a substrate layer, wetland plants, and microorganisms. The substrate provides support for plant roots and surfaces for microbial growth. It can also retain suspended particles and adsorb certain pollutants. Plants contribute to pollutant uptake and create conditions that support microbial activity. Microorganisms play an important role in the decomposition of organic matter and the transformation of nitrogen compounds (Vymazal, J., 2010).

The treatment process involves several mechanisms. Physical filtration and sedimentation reduce suspended solids. Adsorption and precipitation can retain some pollutants in the substrate. Microorganisms break down organic matter and transform nitrogen through processes such as nitrification and denitrification. Plant uptake also removes part of the nutrients, although its contribution varies with plant species, season, and growth conditions. The overall treatment effect depends on the interaction between these mechanisms rather than on the plants alone (Vymazal, J., 2010).

Pretreatment is an important part of the treatment process. Rural domestic wastewater may contain food residues, grease, suspended solids, and other materials that can accumulate in the wetland. Direct discharge into the wetland may increase the risk of clogging and reduce hydraulic performance. A system that combines pretreatment with a constructed wetland can reduce the load entering the wetland and improve its operating stability (Moreira, F. D., & Dias, E. H. O., 2020).

The appropriate treatment process should also reflect the intended use of the treated water. Where the objective is water reuse, the quality of the treated water must match the requirements of the intended use. A constructed wetland should not automatically be regarded as sufficient for every reuse purpose or discharge requirement.

2.2 Main Configurations

Constructed wetlands can be classified into surface-flow, horizontal subsurface-flow, and vertical subsurface-flow systems according to the way water moves through the treatment unit (Vymazal, J., 2010).

Surface-flow wetlands allow wastewater to move across a visible water surface. They can provide landscape and ecological benefits, but poor design or maintenance may lead to mosquito breeding, unpleasant odors, and the formation of black and odorous water. China's 2026 technical guide generally does not recommend surface-flow wetlands as the main configuration for the resource-utilization applications covered by the guide, although they may be used as a secondary unit in a combined system (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Horizontal subsurface-flow wetlands allow wastewater to move through the substrate below its surface. This arrangement limits direct contact between wastewater and the surrounding environment and supports filtration and microbial treatment. However, oxygen availability may limit nitrification under some operating conditions.

Vertical subsurface-flow wetlands distribute wastewater over the substrate and allow it to pass vertically through the treatment bed. This arrangement can improve oxygen transfer and support the removal of organic matter and the conversion of ammonia nitrogen. Its performance depends on uniform water distribution, suitable substrate properties, and effective control of hydraulic loading.

Combined systems can use different wetland configurations in sequence to make better use of their respective strengths. For example, a vertical-flow unit may support nitrification, while a subsequent unit may provide conditions for further nitrogen removal. However, combining treatment units also increases construction and management requirements. The additional treatment stages should be justified by the wastewater characteristics and the required effluent quality rather than added without a clear purpose (Vymazal, J., 2010).

3. Conditions for Applying Constructed Wetlands in Rural China

The suitability of constructed wetlands depends on the relationship between local conditions and the requirements of the treatment system. A technology that performs well in one village may be less suitable in another because of differences in climate, wastewater volume, land availability, and management capacity.

3.1 Settlement Patterns and Available Land

Constructed wetlands are particularly relevant to rural areas where households are relatively dispersed and centralized sewerage systems are difficult to establish economically. In these settings, decentralized treatment can reduce the need to transport wastewater over long distances. The system may also be suitable where unused land, abandoned ponds, or other appropriate sites are available.

China's 2026 technical guide indicates that constructed wetlands are generally suitable for resource-utilization applications in non-cold regions with relatively dispersed households and fewer than 500 permanent residents. This is a recommendation within the scope of that guide, not a universal population threshold for every type of constructed wetland project (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Site selection requires more than checking whether land is available. The site should allow wastewater to enter and leave the system reliably. A location with a suitable natural slope may reduce the need for pumping. The facility should also be protected from flooding, waterlogging, and groundwater contamination risks. The use of available land must be consistent with land-use requirements and should not interfere with flood control or other essential functions (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Land availability also affects the choice of wetland configuration. Subsurface-flow systems may be preferable where direct exposure of wastewater needs to be limited. Where land is scarce, the area required for a wetland may become a major constraint. In such cases, a compact treatment process or a combined system may be more appropriate than relying on a wetland alone.

3.2 Wastewater Characteristics and Pretreatment Requirements

The wastewater entering a constructed wetland should be identified before the treatment process is selected. Rural domestic wastewater can include greywater from kitchens, bathing, and washing, as well as blackwater from toilets. These sources have different pollutant characteristics and may require different pretreatment arrangements (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024; Ministry of Ecology and Environment of the People's Republic of China, 2026).

Kitchen wastewater may contain grease and food residues. If these materials enter the wetland without adequate pretreatment, they can accumulate in the substrate and distribution system. Screening, grease separation, sedimentation, or other suitable pretreatment measures can reduce this risk. Where blackwater is included, septic tanks or anaerobic treatment units may be needed before the wastewater enters the wetland (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Constructed wetlands intended for rural domestic wastewater should not be assumed to be suitable for industrial wastewater, medical wastewater, or concentrated wastewater from agricultural processing and large-scale livestock production. These wastewater streams may contain pollutants or loads that require different treatment processes. Their suitability must be assessed separately rather than inferred from the performance of domestic wastewater systems (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Wastewater quantity is equally important. Some villages experience substantial seasonal population changes because residents return during holidays or leave for work. Tourist villages may have sharp increases in wastewater generation during particular periods. If a facility is designed only around average daily flow, it may be overloaded during peak periods or receive too little wastewater during other periods. A sound design should account for permanent residents, seasonal changes, actual water use, and the quantity of wastewater that can be collected.

3.3 Climate and Intended Water Use

Climate has a direct effect on wetland performance. Low temperatures can reduce microbial activity and slow the removal of organic matter and nitrogen. In areas with severe winters, freezing may affect water distribution, the substrate, and plant survival. The 2026 technical guide calls for winter insulation and frost protection where constructed wetlands are used under cold or severe cold conditions (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Water availability also influences the suitability of the technology. In arid and semi-arid areas, evaporation can reduce the amount of water available for reuse and may increase salt accumulation. The guide recommends fully lined subsurface-flow wetlands in these settings, together with measures to control water levels and evaporation, suitable salt-tolerant native plants, and appropriate salt-management measures (Ministry of Ecology and Environment of the People's Republic of China, 2026).

The intended use of treated water should be decided before construction. If the treated water is intended for irrigation or another form of reuse, the system should be designed around the required water quality and the actual demand for that water. Where reuse demand is lower than the quantity of treated wastewater produced, an additional management or disposal arrangement is needed. Otherwise, the wetland may create waterlogging or discharge problems despite functioning as designed.

Constructed wetlands are most suitable when land, climate, wastewater characteristics, and reuse or discharge requirements can be accommodated without excessive technical or maintenance demands. Where these conditions are not met, another treatment technology or a combined process should be considered.

4. Main Problems in Practical Application

4.1 Substrate Clogging and Uneven Water Distribution

Clogging is one of the major technical problems affecting constructed wetlands. Suspended solids, grease, accumulated organic matter, and excessive biological growth can gradually reduce the available pore space in the substrate. As permeability decreases, wastewater may accumulate near the inlet, flow unevenly through the bed, or bypass parts of the treatment area.

Uneven distribution creates additional problems. Some sections may receive excessive hydraulic loading, while others remain underused. The effective treatment area becomes smaller, and the quality of the effluent may become less stable. Clogging can also increase the need for repairs and substrate replacement, raising long-term maintenance costs.

A review of constructed wetlands used for rural domestic wastewater treatment in China identified clogging, insufficient nitrogen removal, and poor maintenance as important limitations in practical application (Chen, F., & Yao, Q., 2015). These problems show why the choice of substrate and the arrangement of the inlet and outlet systems should be considered together with pretreatment and routine maintenance.

4.2 Insufficient Nitrogen Removal and Seasonal Changes

The removal of organic matter does not guarantee effective nitrogen removal. Nitrogen treatment depends on several processes that require different environmental conditions. Nitrification requires oxygen, while denitrification generally requires suitable anoxic conditions and an available carbon source. If these conditions are not balanced, a wetland may remove organic matter reasonably well but perform less effectively in removing total nitrogen.

Temperature changes can make the problem more difficult. During winter, lower microbial activity may reduce treatment performance. Plant growth also changes with the seasons, affecting nutrient uptake and the conditions around plant roots. A system that performs adequately in warm weather may not maintain the same performance during cold periods.

Hydraulic fluctuations can further affect pollutant removal. Heavy rainfall, seasonal population changes, and uneven household water use may produce sudden changes in flow or pollutant loading. Without sufficient pretreatment, flow regulation, and suitable operating controls, these changes can reduce the stability of the treatment process (Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., & Lu, S., 2024; Vymazal, J., 2010).

4.3 Weak Operation and Maintenance

A constructed wetland may appear to require little attention because it relies partly on natural processes. However, low energy demand does not mean that maintenance is unnecessary. Inlets can become blocked, water levels can move outside the intended range, plants can die or become overgrown, and accumulated sludge can affect water movement.

Maintenance responsibilities can also be unclear. Small rural facilities may lack a dedicated operator, regular funding, or access to technical support. If problems are not identified early, minor blockages may develop into more serious hydraulic failures. Poorly maintained facilities may produce unpleasant odors, allow untreated wastewater to overflow, or require expensive rehabilitation.

These problems are not caused by the wetland technology alone. They also reflect decisions made during planning and construction. A facility that is difficult to access, has no adjustable outlet, or depends on complicated maintenance procedures may be unsuitable for a village with limited technical capacity. The long-term feasibility of a wetland should therefore be assessed before construction, not only after operational problems appear.

5. Operation and Maintenance Measures

The long-term performance of constructed wetlands depends on the coordination of pretreatment, hydraulic control, vegetation management, seasonal adjustment, and routine inspection. These measures should be simple enough for local operators to carry out and sufficiently clear to support timely technical intervention when

problems occur.

5.1 Strengthening Pretreatment and Controlling Influent

Pretreatment should be regarded as an essential part of the treatment system rather than an optional addition. The appropriate units depend on the wastewater source and characteristics. Screens can retain larger solids, grease traps can reduce the entry of oils and fats, and sedimentation tanks can remove settleable material. Septic tanks and anaerobic units may be required for wastewater containing blackwater.

China's 2026 technical guide states that rural domestic wastewater should generally not enter a constructed wetland directly without pretreatment. It also distinguishes between greywater treatment and wastewater containing blackwater, specifying different pretreatment arrangements for these cases (Ministry of Ecology and Environment of the People's Republic of China, 2026).

The pretreatment units themselves require maintenance. Screens should be cleared of accumulated solids, grease traps should be cleaned, and sedimentation facilities should be checked for sludge accumulation. Otherwise, pollutants removed in pretreatment may eventually enter the wetland and contribute to clogging. The removed solids and sludge must also be collected and handled appropriately to avoid secondary pollution.

Flow regulation is useful where wastewater quantity and quality change considerably. An equalization tank can reduce short-term fluctuations before wastewater enters the wetland. The tank should be sized according to actual flow conditions and the facility's design requirements. It should not be treated as a substitute for adequate treatment capacity.

5.2 Maintaining Hydraulic Conditions

Water distribution and water-level control are central to stable operation. Operators should regularly check the inlet pipes, distribution structures, outlet pipes, and adjustable water-level devices. Uneven flow, standing water near the inlet, or an unexpected drop in water level may indicate blockage, leakage, or an imbalance between inflow and outflow.

Uniform distribution helps prevent short-circuiting, in which wastewater passes rapidly through a limited part of the wetland, and dead zones, where water remains stagnant. The Chinese technical guide recommends appropriate distribution arrangements and adjustable outlets to support changes in water level and operating conditions (Ministry of Ecology and Environment of the People's Republic of China, 2026).

Water levels should be adjusted according to the wetland configuration and the needs of the plants and microorganisms. For the resource-utilization applications covered by the 2026 guide, the recommended normal operating water level is generally 5–10 cm below the substrate surface in horizontal subsurface-flow wetlands and 10–20 cm below the substrate surface in vertical subsurface-flow wetlands (Ministry of Ecology and Environment of the People's Republic of China, 2026). These values should be applied with reference to the actual design and operating conditions rather than used as universal settings for every wetland.

Heavy rainfall and flooding require particular attention. Where flow exceeds the design capacity, properly designed overflow or diversion arrangements can help prevent hydraulic overloading. However, these arrangements should not become a routine route for untreated wastewater discharge. After flooding, operators should inspect the substrate, pipes, plants, and other structures and repair any damage before normal operation resumes.

5.3 Managing Plants and Substrate

Vegetation management should focus on plant survival, suitable growth, and the continued function of the treatment bed. Plant species should be selected according to local climate, water conditions, and maintenance capacity. Native species that tolerate local conditions are generally preferable to plants that require extensive care or may become invasive.

Dead plants should be replaced when necessary, weeds should be removed, and excessive growth should be controlled. Seasonal harvesting may help maintain the vegetation structure and remove nutrients stored in plant biomass. However, harvesting should follow the needs of the selected plant species and the treatment system. Removed biomass should be collected and handled properly rather than left to decay in the wetland.

The substrate also needs regular inspection. Operators should remove accumulated sludge and debris from accessible surfaces, particularly near the inlet. If waterlogging or reduced permeability indicates serious clogging, temporary resting and drying of the affected bed may help restore hydraulic performance. Where necessary, part of the substrate can be replaced.

Substrate replacement should be based on the location and severity of the problem. Replacing the entire bed without identifying the cause may lead to repeated failures. The new substrate should have suitable particle sizes, porosity, mechanical stability, and permeability. Used substrate should be collected and disposed of appropriately

to prevent secondary pollution, as required by the applicable management arrangements (Ministry of Ecology and Environment of the People's Republic of China, 2026).

5.4 Preparing for Seasonal Changes

Seasonal maintenance should reflect local climate rather than follow a uniform national schedule. In cold regions, the system may need additional insulation to protect the water, substrate, and microorganisms. Measures described in China's 2026 guide include increasing the effective depth of the wetland, adjusting water levels where appropriate, and using suitable insulating materials or structures (Ministry of Ecology and Environment of the People's Republic of China, 2026).

In warm seasons, higher temperatures may support microbial activity, but they can also increase plant growth and the accumulation of organic material. Operators should pay attention to vegetation density, odor, mosquito breeding in exposed water, and the condition of the inlet and outlet systems.

In dry regions, water loss and salt accumulation may become important concerns. Water levels should be managed to reduce unnecessary evaporation while maintaining sufficient moisture for plant growth and treatment. Where treated water is reused, the quantity of water produced should be matched to actual demand as closely as possible.

Seasonal maintenance also needs to account for changing population and wastewater generation. Villages with large holiday populations may need additional checks before and during peak periods. Where the facility regularly experiences overloading, operators should review the collection system, equalization capacity, and treatment design rather than relying only on temporary operating adjustments.

5.5 Establishing Routine Monitoring and Clear Responsibilities

Routine monitoring helps identify problems before they cause major treatment failures. A practical inspection record can include influent flow, water levels, visible ponding, odors, vegetation condition, blocked pipes, overflow events, and maintenance activities. Where appropriate, water-quality monitoring should include indicators such as chemical oxygen demand, biochemical oxygen demand, suspended solids, ammonia nitrogen, total nitrogen, and total phosphorus.

The monitoring frequency and required effluent quality should follow the applicable discharge or reuse requirements and the needs of the specific facility. Visual inspections alone cannot establish whether the treated water meets its intended quality requirements. Conversely, occasional laboratory results are not enough to reveal every developing hydraulic problem. Operational observations and water-quality results should be considered together.

Clear responsibility is equally important. For the facilities covered by its scope, China's 2026 technical guide recommends third-party professional operation and maintenance for systems with a design treatment capacity of 20 tonnes per day or more. Facilities below that capacity may be maintained by township governments or village committees, with regular inspections and technical support when problems arise (Ministry of Ecology and Environment of the People's Republic of China, 2026). This recommendation provides a practical basis for matching maintenance arrangements to facility size and local capacity.

A maintenance record should document inspections, cleaning, water-level adjustments, plant replacement, substrate repairs, water-quality results, and any periods of abnormal operation. Such records can help identify repeated failures and clarify whether a problem results from poor pretreatment, excessive loading, unsuitable design, or insufficient maintenance. They also provide a basis for planning future expenditure.

The aim is not to create a complicated management system for a small rural facility. It is to establish a reliable process in which responsibilities are clear, routine problems are detected early, and specialist assistance is available when ordinary maintenance cannot restore stable operation.

6. Conclusion

Constructed wetlands can provide a useful option for rural domestic wastewater treatment in China, particularly where settlements are dispersed, suitable land is available, and local conditions support decentralized treatment. Their suitability depends on more than their relatively low energy demand. Wastewater characteristics, pretreatment requirements, climate, water availability, intended reuse, and local maintenance capacity must all be considered.

Clogging, insufficient nitrogen removal, seasonal changes, uneven hydraulic loading, and weak maintenance can reduce treatment performance over time. These problems can be addressed through appropriate pretreatment, uniform water distribution, adjustable water levels, suitable vegetation, substrate maintenance, winter protection, and routine monitoring. Clear operating responsibilities and access to technical support are also necessary.

Constructed wetlands should not be selected simply because they are considered natural or inexpensive. Their

long-term value depends on whether the technology fits the local setting and whether the village can maintain it throughout its service life. A practical combination of suitable design, regular inspection, and timely repair offers a more reliable basis for rural wastewater management than construction alone.

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