Research on Regional Agricultural Irrigation Water with Navigation Monitoring Technology of Unmanned Vessels

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Abstract: With the development of science and technology, unmanned vessels offer a transformative solution for modern water management, combining enhanced safety, labor cost savings, and automated sampling with real-time data for rapid decision-making. This research involved the sampling and monitoring of irrigation water from 19 medium-sized agricultural districts by navigation monitoring and data transmission of unmanned vessels. And the navigation data and map information were integrated and displayed through visual representation of the potential influencing factors. It was demonstrated that the water quality of the agricultural irrigation area was acceptable generally, without any heavy metal contamination. However, the major transnormal parameters were fecal coliform, total salinity, and chloride. And the comprehensive pollution index of the 19 irrigated areas ranged from 0.54 to 3.8, with 15 areas classified as moderately clean and the remaining 4 as polluted. In general, when considering the influence of geographic location and saltwater intrusion, the comprehensive pollution index evaluation of the 19 irrigation districts belonged to the clean level, which could meet the irrigation needs of residents. However, the potential risks of high salinity and chloride should be taken into account seriously on long-term agricultural sustainability.

Keywords: Unmanned Vessels; Navigation Monitoring; Agricultural Irrigation Water; River; Quality Assessment

1. Introduction

The development of science and technology has led to notable advancements in unmanned vessels technology, initially utilized in military applications, across a range of industries. The unmanned vehicle is equipped with a variety of sensors, a global positioning system (GPS), and a wireless transmission module, enabling it to autonomously navigate under real-time data interaction with a shore control center. Currently, our country has made noteworthy advancements in unmanned vehicle technology [1-5], while Europe and the United States have established leading entities in this field. The technology of unmanned vehicles' self-information perception is relatively mature, whereas the information perception of the surrounding environment is not. This presents a significant opportunity for further research [6,7].

Nowadays, unmanned vessels play a pivotal role in water quality assessment by integrating advanced navigation systems and real-time data transmission capabilities, which collectively enhance the accuracy, scope, and efficiency of monitoring. Usually, unmanned vessels follow pre-programmed routes to sample water bodies comprehensively, avoiding gaps in traditional manual sampling. They navigate shallow waters, estuaries, or polluted areas where human access is limited, ensuring representative data collection across diverse environments. Meanwhile, AI-powered navigation allows unmanned vessels to avoid obstacles and adjust sampling frequency based on real-time conditions. Besides, unmanned vessels deploy sensors to collect continuous, high-frequency data, eliminating gaps between manual samples. GPS-tagged data pinpoints pollution sources and tracks changes over time. Data is transmitted via satellite or cellular networks to operators, enabling immediate detection of contamination events, which provide ground-truthing for remote sensing data, improving accuracy in large-scale water quality assessments. Generally, unmanned vessels is cost-effective long-term monitoring, which reduce labor dependency, lowers human resource costs for repetitive or seasonal monitoring tasks and minimize variability from manual sampling errors.

The quality of irrigation water is a fundamental guarantee for the quality and safety of agricultural products. Besides, the quality of irrigation water has a significant impact on a number of important factors, including the physical properties of agricultural soil [8,9], soil chemical characteristics [10,11], and ultimately, crop yield and quality [12,13]. And it is also a core factor affecting crop growth [14-16]. Furthermore, the utilization of sewage water for irrigation results in the accumulation of heavy metals in the soil, which can be absorbed by crops and pose a threat to human health through the food chain [17-19]. One of the most illustrative examples is the phenomenon of pain-pain disease, which is caused by the pollution of cadmium. Domestic research indicates that the use of heavy metals in irrigation water is harmless to crops and human beings, provided that the levels of such metals remain within the standard range [20]. The primary sources of contamination in irrigation water are industrial wastewater and urban sewage discharges. Additionally, agricultural activities have been identified as a significant contributor to regional water quality degradation [21]. The combination of precipitation and fertilizer application is a major factor driving surface pollution in watersheds [22], with fertilizer representing the primary source of nitrogen and phosphorus input to agricultural lands [23-25].

This survey employed the use of unmanned vessels' navigation monitoring technology to conduct research on the quality of irrigation water in 19 districts. The objective was to gather scientific data that would facilitate a comprehensive understanding of the quality of irrigation water, thereby contributing to the protection of freshwater resources and the improvement of agricultural irrigation practices.

2. Methods

2.1 Introduction to Unmanned Vessels

2.1.1 SL40 Automatic Water and Underwater Integrated Unmanned Vessle

The SL40 (Figure 1) is primarily utilized in rivers, lakes, reservoirs, and other watersheds. The vessel is equipped with a high-definition camera, sweepingsonar, and positioning and directing instruments, which are applied for a variety of purposes, including port security, underwater scanning, inland waterway management, obstacle sweeping, environmental protection investigation, and river sewer sweeping. The automatic unmanned ship platform is capable of remote control, satellite navigation, autonomous navigation, and automatic obstacle avoidance, making it adaptable to a multitude of water operations.

Figure 1. SL40 Automatic Water and Underwater Integrated Unmanned Vessle

2.1.2 SE40 Unmanned Vessel for Online Water Quality Monitoring

The SE40 (Figure 2) is primarily utilized in riverine, lacustrine, and reservoir environments, as well as other watersheds. The SE40 is equipped with a modularized mission module, which allows for the integration of various instruments and equipment to achieve a range of functions. The module can accommodate an ADCP (acoustic Doppler current profiler) for hydrological flow and velocity measurement, a single-beam sounder for bathymetry and underwater topography mapping, a multi-parameter water quality online analyzer for real-time monitoring of water quality, a sampling system for water sample collection, and a sweeping sonar for underwater environment investigation and environmental protection. Additionally, the module can be configured with a dark pipe investigation system.

The fully automatic unmanned ship platform is capable of unmanned remote control, satellite automatic navigation, autonomous navigation, and automatic obstacle avoidance. It is also able to carry different instruments and equipment for a variety of fields of water operations. Furthermore, it can be used to maximize the avoidance of personnel safety hazards and greatly improve the mobility and efficiency of underwater detection.

Figure 2. SE40 Water Quality Online Monitoring Unmanned Vessle

2.2 Study Site

The fundamental principles of surveillance and distribution for farmland irrigation water should be based on an assessment of the extent to which water pollution poses a hazard to agricultural production. This assessment should identify the key points and take a comprehensive approach to consideration. The monitoring sites should be arranged in accordance with the distribution of pollutant sources and the water flows in the irrigation area. This is based on the principle that more monitoring should be conducted at points of water inlet, and less at points of water outlet. Furthermore, more monitoring should be conducted in areas with heavy pollution, and less in areas with slight pollution. The monitoring should concentrate on the most significant environmental pollution issues affecting agriculture and the most crucial factors influencing the development of the agricultural economy in this region. Additionally, the rivers were monitored by unmanned surface vehicles to preliminarily identify the sources of pollutants.

The inspection was conducted primarily in three districts, eight towns, and nineteen irrigation areas, encompassing a total of 148 manual monitoring sites. Additionally, a range of 500 kilometers of irrigation area along the rivers, river gushings, and drainages were subjected to unmanned vehicle voyage monitoring, ensuring comprehensive coverage. During the inspection process, the trajectory of the unmanned vehicles, video footage of the water surface, and sonar images of the underwater environment were recorded. Additionally, monitoring was conducted for various factors, including COD, pH, dissolved oxygen, conductivity, ammonia, and nitrogen. The variation in water quality data during navigational monitoring could assist in analyzing the impact of the water outlet on the surrounding watershed. For all instances of abnormal water quality, on-site manual sampling was conducted for secondary confirmation.

2.3 Field Measurements

The monitoring period was determined based on the main irrigated time and the laboratory surveillance was conducted once in each of the rainy and dry seasons. The monitoring items included BOD5, COD, suspended solids, anionic surfactant, water temperature, pH, total salt, chloride, sulfide, total mercury, and total. The parameters included in the study were as follows: cadmium, total arsenic, hexavalent chromium, total lead, total zinc, selenium, fluoride, total cyanide, petroleum species, volatile phenols, benzene, acrolein, boron, fecal coliform, trichloroacetaldehyde, roundworm eggs, and 27 additional parameters. Concurrently, an unmanned vehicle equipped with online testing apparatus was employed to conduct navigation monitoring of the rivers within the irrigation zone and an investigation of the sewage outlets into the rivers. The irrigation zone and monitoring sites are illustrated in Figure 3. The laboratory data were processed in accordance with the Monitoring Technical Specifications of Agricultural Water Source Environmental Quality (NY/T396-2000) for statistical analysis.

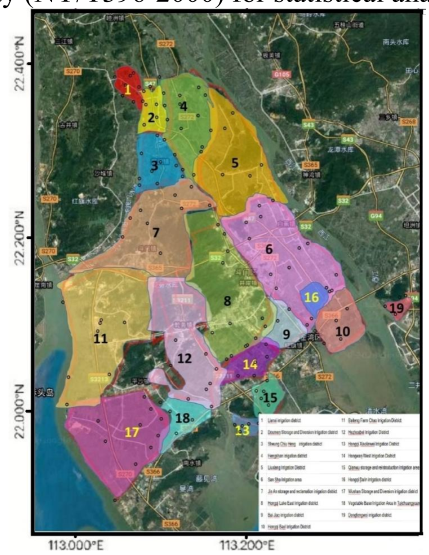

Figure 3. The Irrigation Zone and Monitoring Sites

2.4 Analysis and Evaluation of Irrigation Water During Different Seasons

The study employed a methodology of surveillance, conducted during both the rainy and dry seasons. The findings of the water quality assessment are presented in Table 1. The primary parameters that exceeded the permissible limits were fecal coliform, chloride, and total salt. Furthermore, instances of pH exceedance were observed during the wet season.

A total of 229 samples were collected from 148 monitoring sites in 19 irrigation districts during the rainy period, resulting in a total of 5,382 data points. The overall exceeded rate was 1.90%, with the fecal coliform exceeded rate reaching 25.1% and a single pollution index of 0.19. The chloride exceeded rate was 13.9%, with a single pollution index of 0.67. The total salt exceeded rate reached 3.1%, accompanied by a single pollution index of 0.28.

A total of 228 samples were collected from 148 monitoring locations in 19 irrigation districts during the dry season, resulting in 5,439 data points. The overall exceeded rate was 2.69%. The exceeded rate of fecal coliform was 25.7%, with a single pollution index of 0.36. The exceeded rate of chloride was 22.1%, with a single pollution index of 1.62. The exceeded rate of total salt amount was 16.7%, with a single pollution index of 0.93.

Table 1. The Exceeded Rate of Irrigation Water Quality Standards on Agricultural Irrigation Districts During Different Periods

Serial number	Name of agricultural irrigation district	exceeded rate: %			Comprehensive pollution index
		Rainy season	Dry season	Average value	
1	Lianxi irrigation district	0	1.75	0.87	0.54
2	Doumen Storage and Diversion irrigation district	1.5	1.2	1.35	0.55
3	Sheung Chiu Heng irrigation district	0	0	0	0.56
4	Hengshan irrigation district	0.77	1.7	1.24	0.56
5	Liuxiang Irrigation District	0	0.85	0.42	0.56
6	San Sha irrigation area	1.52	1.63	1.56	0.57
7	Jin An storage and reclamation irrigation district	1.59	2.05	1.82	0.57
8	Hongqi Lake East Irrigation district	2.35	1.88	2.11	0.58
9	Bai Jiao irrigation district	1.07	1.93	1.13	0.59
10	Hongqi Bayi Irrigation District	0	0	0	0.59
11	Baiteng Farm Chao Irrigation District	2.04	0.51	1.28	0.62
12	Hezhoubei Irrigation District	2.35	1.47	1.91	0.63
13	Hongqi Xiaolinwei Irrigation District	2.8	1.2	2.4	0.8
14	Hongwan West Irrigation District	1.64	4.92	3.28	0.85
15	Qianwu storage and reintroduction irrigation area	0.94	5.16	3.05	1.03
16	Hongqi Dalin irrigation district	7.06	4.71	5.88	1.47
17	Wushan Storage and Diversion irrigation district	2.54	10.15	6.49	2.02
18	Vegetable Base Irrigation Area in Taichuangyuan	4.35	7.36	6.07	2.53
19	Dongfengwei irrigation district	6.94	7.56	7.27	3.8
Total	19	1.90	2.69	2.29	0.93

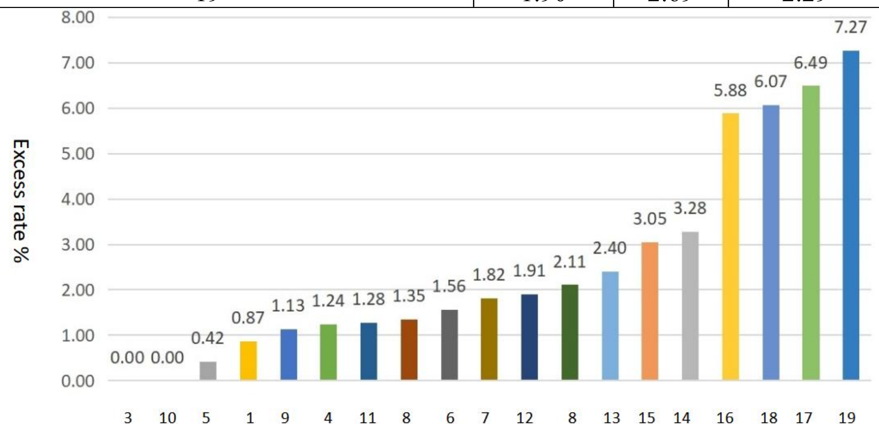

Figure 4. The Excess Rate of Irrigation Water Utilized on Agricultural Districts

The overall rate of exceedance and the rate of single indicator exceedance were observed to be lower during the rainy period than during the dry period. The levels of pollution associated with fecal coliform, chloride, and total salinity were markedly lower during the wet period than during the dry period.

The status of comprehensive exceedance among the 19 irrigation districts is shown in Figure 4, which indicates that Dongfengwei Irrigation District had a significantly elevated exceeded rate, while samples from Shanghong Irrigation District and Hongqi Bayi Irrigation District did not exceed the set threshold. Lianxi Irrigation District had a low pollution index, while Dongfengwei Irrigation District had the highest overall pollution index, making it the most polluted of the 19 irrigation districts. The main cause of the elevated pollution index in the irrigation areas was the significant exceedance of fecal coliform, chloride, and total salt.

2.5 Implementation of Online Water Quality Monitoring

The data obtained from the unmanned vehicle's navigational monitoring were integrated with the Yunzhou Intelligent Water Ecology Supervision System for real-time visualization and advanced data processing. During the course of the survey, the system is capable of providing a real-time rendering of the unmanned vehicle's dynamic survey trajectory, the distribution of water quality categories, the distribution of data, detailed parameter information at detection points, and so forth. Subsequent to the surveillance, the data can be subjected to a detailed analysis, including the visualization of water quality distribution trends of the crosstown river in the form of charts or water quality distribution maps.

The comprehensive outfall inspection and online water quality surveillance are achieved through the utilisation of the SL40, SE40 water and underwater integrated unmanned boat, online monitoring, field verification and other means. The survey encompassed 227,552.04 kilometers of river (sea) outfall inspection, during which the locations of outfalls and sluices were recorded and organized. A total of 2,298 outfalls were investigated, comprising 1,165 open pipes (in drainage), 531 open pipes (without drainage), 465 sluices, 88 junctions, 41 drainage outfalls, and 8 concealed pipes.

3.1 Analysis of Total Salinity and Chloride Impact on Irrigation Water Quality

The transnormal items of two sampling test included mainly fecal coliform, chloride, and total salinity, and the excess of chloride and total salinity played a relatively significant role, which had a great impact on the sampling results. High salinity and chloride concentrations risk soil degradation, reducing permeability and increasing sodium adsorption. Over time, this could harm root development in sensitive crops (e.g., tomatoes, lettuce) and degrade soil structure, lowering agricultural productivity. As illustrated above, during the rainy period, the chloride exceeded rate was 13.9%, with a single pollution index of 0.67, and the total salinity exceeded rate reached 3.1%, accompanied by a single pollution index of 0.28. While during the dry season, the exceeded rate of chloride was 22.1%, with a single pollution index of 1.62, and the exceeded rate of total salt amount was 16.7%, with a single pollution index of 0.93. Since the jurisdiction is located in the downstream of the Zhujiang River Estuary, the results of whether total salinity and chloride were involved in the evaluation of the integrated pollution index and exceeded rate of the irrigation water were compared to illustrate the results, as shown in Table 2.

3. Analysis

Table 2. Comparison of Whether Total Salt and Chloride Involved in the Evaluation or Not

		rainy season	dry season
Involved in evaluation	Comprehensive pollution index	0.62 (moderately clean)	1.47 (polluted)
	exceeded rate (%)	1.90	2.69
Not invloved in evaluation	Comprehensive pollution index	0.61 (moderately clean)	0.52 (still clean)
	exceeded rate (%)	1.28	1.14

Acoording to Procedural Regulations regarding the Environment Quality Monitoring of Water for Agricultural Use (NY/T 396-2000), thresholds for pollution severity were assigned according to the following ranges: a comprehensive pollution index of 0.5 or less represents clean water. When it is between 0.5 and 1, the water is considered moderately clean. When it is equal to or greater than 1, the water is considered polluted. As Table 2 indicated, total salt and chloride had no impact on the assessment of water quality comprehensive pollution index during the rainy period. However, during the dry period, these elements exerted a more pronounced influence on the water quality comprehensive pollution index and the exceeding rate. Evaporation and concentration of water occurred more rapidly during the dry season, when the replenishment of freshwater sources was inadequate. In contrast, precipitation and seawater exerted a significant influence during the rainy season, resulting in the following characteristics: sufficient water sources, high flow rates, fast flow speeds, interlaced local water networks, large volumes of water, and more even water quality.

3.2 Impact Analysis of Rising and Falling Tides on Irrigation Water Quality

The total salt and chloride levels exceeded the permissible limits, resulting in a significant deterioration in the comprehensive pollution index of the irrigation area. The area is situated in the downstream region of the Zhujiang River Estuary, characterised by low-lying terrain, slow-moving water, and a pronounced influence of tidal fluctuations on water quality. To investigate the fluctuations in water quality at different tidal stages, 318 samples were collected from 159 sensory tidal monitoring sites, encompassing 27 testing items. The function change of the Hongwan West Irrigation District was not included in the calculation of the overall exceeded rate of high and low tides. Ultimately, 8,555 test results were obtained. The results were subsequently subjected to analysis.

The exceeded rates of the high and low tide samples exhibited no significant difference (Figure 5). Furthermore, the types of exceedance metrics observed in the high and low tide samples were identical. There was also no substantial variation between the exceeded rates of the corresponding items in the two samples. Among these, the exceeded rates of fecal coliforms, chloride, and all-salt were greater than 10% (Figure 6). Furthermore, the highest exceeded rates for fecal coliforms, chloride, and total salt were comparable between high and low tide samples, with chloride exhibiting the highest exceeded rate.

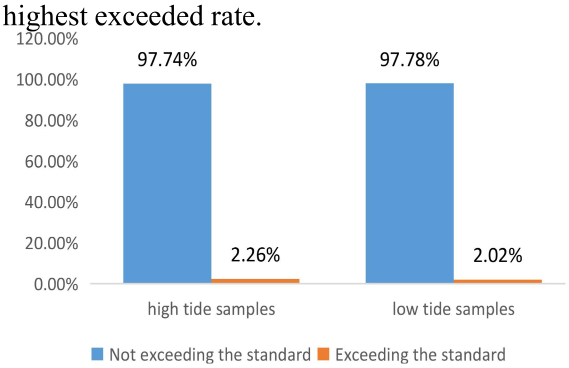

Figure 5. The Exceeded Rates of the High and Low Tide Samples

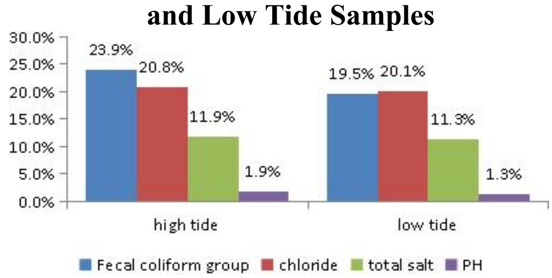

Figure 6. The Individual Exceeded Rates of the High and Low Tide Samples

No discernible differences were observed in the overall pollution indices of the high and low tide samples. Furthermore, the individual pollution indices of the detected metrics exhibited minimal variation between the high and low tide samples, with chloride demonstrating the highest pollution index. A T-test was conducted on the data collected during the high and low tides for the items that exceeded the standard. The statistical analysis demonstrated that the exceeded rate and pollution index of the primary exceedance items exhibited no statistically significant difference between high and low tide ($P > 0.05$).

In conclusion, there was no discernible variation in the water quality between the high and low tides. In other words, there was no discernible discrepancy in the frequency of water quality violations, the nature of the violating substances, their associated violation rates, the highest violation multiples, the overall pollution index, and the individual pollution index between the high and low tide samples. Among these, the violation rates of fecal coliform, chloride, and total salt exceeded 10%, with the violation multiple and the single pollution index of chloride being the highest.

3.3 Causes of Excessive Fecal Coliform

Fecal coliform is a component of total coliform bacteria that is used to elucidate the degree of contamination of water, mainly from fecal matter. The monitoring of fecal coliform provides insight into the quality of water that has been contaminated by domestic sewage.

In addition to the Shangheng Irrigation District and Hongqi Bayi Irrigation District, other irrigation districts exhibited fecal coliform exceedances to varying degrees. The monitoring results of the irrigation towns demonstrated that the fecal coliform exceeded the standard significantly in Pingsha Town, Hongqi Town, Qianwu Town, and Jing An Town. The primary contributing factors to this excessive were identified as aquaculture water and domestic sewage.

The term *Aquaculture Self-pollution* is used to describe a situation in which the pollutant content of the aquaculture water and the surrounding water exceeds the acceptable level due to the activities associated with aquaculture. This, in turn, affects the ecological function of the water system. The primary sources of aquaculture self-pollution are land-based pollution around the farms, excessive inputs such as artificial feeds, aquatic seedlings, fishery drugs, fertilizers, and other non-pharmaceuticals, as well as solid and liquid wastes including residual bait, metabolites, and dissolved constituents of solids. Furthermore, the aquaculture industry in the irrigation area is well-developed. However, many aquaculture owners discharge untreated wastewater containing large amounts of fish feces into the river through ditches. This results in a bloom of reproduction as well as cross-contamination of fecal coliform bacteria in the water system, leading to an excessive of the water quality standard.

Similarly, in some densely populated areas, the construction and management of the sewage network and the sewage treatment facilities for residents are inadequate, resulting in the discharge of sewage containing feces directly into the river. Additionally, some residents discharge domestic sewage, including kitchen water and laundry water, directly into the river. This has resulted in an increase in the fecal coliform content of the river. In addition, the improper treatment of livestock manure, the mismatch of sewage pipe networks and sewage treatment plants, the incomplete rainwater and sewage diversion, and the poor maintenance of pipe networks are also contributing factors to the excessive levels of fecal coliform. Similarly, the improper treatment of livestock waste, the mismatch between sewage pipe network and sewage treatment plant, the incomplete separation of rainwater and sewage, and the inadequate maintenance of pipe networks are also contributing factors to the exceeding of the fecal coliform standard.

3.4 Potential Risks of High Salinity and Chloride

Elevated soil and water salinity, driven by factors like irrigation with saline water, excessive fertilizer use, or seawater intrusion, pose significant threats to agricultural sustainability. High salinity exacerbates soil salinization over time, creating a feedback loop. For example, 1 ton of saline irrigation water can deposit ~200 kg of salts per hectare annually. And chloride in drainage water contaminates groundwater, threatening drinking water supplies and ecosystems.

Without intervention, high salinity and chloride buildup threaten agricultural resilience, forcing shifts to less profitable crops or abandonment of farmland. This undermines global food security, particularly in regions reliant on irrigated agriculture. Sustainable solutions are urgently needed, such as salt-tolerant crop breeding, improved drainage systems, and deficit irrigation, which require integration into policy and farming practices to mitigate risks.

4. Conclusions and Suggestions

4.1 Conclusions

The project team collected a total of 457 water samples from 19 irrigation districts and 148 monitoring sites, representing both rainy and dry periods. A total of 457 sets of testing data and water quality characteristics were evaluated, and it was determined that the rate of fecal coliform bacteria, chloride, and total salt were excessive among 16 basic control items and 11 selective control items. In contrast, the remaining items exhibited concentrations that were lower than the standard limits, as defined by the Agricultural Irrigation Water Quality Standards. The proportion of samples exceeding the standard was 1.90% and 2.69% in the two periods, resulting in an overall water quality grade of 2. In accordance with the Technical Specification for Environmental Quality Monitoring of Agricultural Water Sources (NY/T396-2000), it was determined that:

1. The combined pollution index of the irrigated agricultural land under the jurisdiction was 0.62 and 1.47, respectively, during the abundant and dry water periods.
2. The composite pollution index of the 19 irrigation districts was 0.93, indicating a pollution level of 2. This level was still considered clean. Among the districts, Lianxi Irrigation District had the lowest pollution index of 0.54, while Dongfengwei Irrigation District had the highest at 3.80, making it the most polluted area among the 19 districts.
3. The quality of irrigation water in the irrigation area was, for the most part, satisfactory, and no instance of a heavy metal concentration exceeding the standard was identified. The items that exceeded the standard were concentrated in fecal coliform, total salinity, and chloride. The comprehensive pollution index of each irrigation area ranged from 0.54 to 3.8, with 15 irrigation areas belonging to the still-clean level and four belonging to the polluted level. If the effects of total salinity and chloride are excluded from consideration, the comprehensive pollution index evaluation of the 19 irrigation areas is found to be consistent with the still-clean level.
4. This study introduced the use of advanced monitoring and investigation technology,

employing unmanned vehicles to conduct comprehensive assessments. These vehicles are equipped with a range of functions, including water quality sampling, monitoring, and screening of concealed pipes, as well as on-site video recording. The data and technical insights generated by these assessments provide invaluable decision-making resources and tools. By providing actionable, high-fidelity data, unmanned vessle would empower policymakers to address pollution at its source, prioritize restoration efforts, and track long-term ecosystem health—key to achieving sustainable water management goals.

4.2 Suggestions

These findings underscore the necessity of immediate intervention to ensure safe irrigation practices:

4.2.1 Policy Integration

Local authorities should adopt stricter water quality standards for irrigation, integrating the Water Pollution Index (WPI) framework to classify risks and enforce compliance. Regular monitoring of fecal coliform and salinity levels is critical.

Prioritize investments in water treatment infrastructure for districts with elevated fecal coliform levels, particularly near urban or coastal zones vulnerable to saltwater intrusion.

4.2.2 Agricultural Management

Short-term: Encourage farmers in moderately polluted districts to use treated water for high-value, salt-sensitive crops and implement soil leaching practices to mitigate sodium accumulation.

Long-term: Develop salt-tolerant crop alternatives for districts with chronic salinity issues and promote precision irrigation to minimize water waste and salt buildup.

4.2.3 Collection and Disposal of Domestic Sewage

The investigation process revealed a series of issues, including the existence of illegal housing, the direct drainage of sewage, interface damage leakage, and the construction of a pipe network in a disorderly and unorganized manner. It is recommended that the department assume responsibility for implementing the aforementioned measures, conducting further field studies, creating an overall plan for the configuration of the pipeline network, increasing investment in infrastructure construction, and improving rural sewage pipeline facilities in towns and cities. In sum, the general goals and tasks should be formulated and implemented in a phased manner.

4.2.4 Technology-Driven Monitoring

Expand the use of unmanned vessels for continuous spatial-temporal mapping of pollution hotspots, integrating navigation data with soil and crop health metrics to refine risk assessments.

Develop public dashboards visualizing real-time pollution indices and salinity trends to empower farmers and policymakers.

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Data Availability Statement: All relevant data are included in the paper or its Supplementary Information.

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