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Research on Data-Driven Environmental Policy in Water Resource Management

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Abstract: In the face of global water scarcity and environmental challenges, improving the efficient management and sustainable utilization of water resources has become a core issue for governments and research departments around the world. This study uses a data-driven approach to explore how advanced data technologies can enhance the efficiency of water resource management, as well as improve the accuracy and execution of environmental strategies. This article first reviews the shortcomings of traditional water resource management methods, such as strong reliance on experience, limitations of manual forecasting, difficulties in data integration, and low efficiency in policy implementation. A data-driven water resource management model has been proposed, which utilizes precise prediction, digital transformation, and intelligent management to optimize the allocation, scheduling, and protection processes of water resources.

Keywords: water resources management; data driven; environmental policies; accurate prediction; digital transformation

1. Introduction

Human life and development cannot be separated from water resources, but currently water resource management is facing increasing challenges. The traditional management approach relies mainly on subjective human judgment and experience. This model makes it difficult to respond in a timely and accurate manner to changes in water demand and environmental conditions, leading to the unreasonable use of resources and a decline in environmental quality. With the rapid advancement of information technology, new management strategies centered on data have gradually become an effective way to improve the level of water resource management. By utilizing cutting-edge technologies such as big data analysis, IoT deployment, and artificial intelligence assisted decision-making, more accurate predictions and real-time control of water resources can be achieved, providing decision-makers with more scientific data support. This article explores how to use data-driven new technologies and management strategies to construct a policy system and solution strategies that meet the needs of modern water resource management, in order to effectively address various complex issues faced in the field of water resource management.

2. Objectives of Water Resource Management

Water resource management aims to promote its sustainable development in the economy, society, and ecological environment, as shown in Figure 1. The primary goal of water resource management is to allocate and efficiently utilize limited water resources, meet the water needs of multiple industries such as agriculture, industry, and municipal water supply, and maintain the health of water ecosystems. In order to achieve this goal, it is necessary to rely on scientific methods to predict changes in the supply and demand of water resources, allocate resources reasonably, and avoid excessive resource development and unnecessary consumption [1].

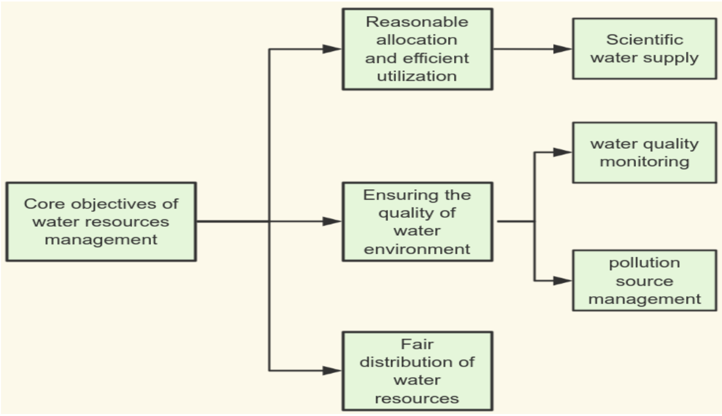

Figure 1. Water Resource Management Objectives.

Water resource management must focus on the overall health of the ecosystem, ensure the quality of the water environment, and curb water pollution and ecosystem degradation. With the acceleration of urbanization, water pollution has become increasingly serious. Therefore, monitoring water quality and controlling pollution sources are particularly crucial, as they are the core links of water resource management work. At the same time, the rational allocation of water resources is also a crucial goal. To ensure fairness in accessing water resources for all regions and social groups, especially in areas with water scarcity, measures must be taken to prevent unfair distribution.

3. Limitations of Traditional Water Resource Management Models

3.1. Limitations of Relying on Experience and Manual Prediction

The traditional water resource management model relies on experience and manual pre judgment to make decisions. In the past, this approach could still meet the general requirements of water supply and distribution. However, facing the intensification of climate change, the rapid increase in population, and the rapid advancement of industrialization, the supply-demand relationship of water resources has become more complex and difficult to predict. Manual forecasting often relies on historical data, seasonal fluctuations, and regional knowledge, but it is difficult to cope with sudden situations or grasp changes in long-term trends. Experience-based decision-making has limitations, as it cannot flexibly respond to diverse changes across different regions and time periods. Professionals rely on intuition and past experience when making decisions, ignoring many uncertain factors and complex interactions between systems. For example, under extreme weather conditions, the supply and demand patterns of water resources have undergone changes, and predictions based solely on experience are difficult to accurately grasp these new changes, which may lead to a series of problems such as insufficient water supply, resource waste, or deterioration of water quality [2].

3.2. Challenges of Data Integration and Information Sharing

In traditional water resource management systems, there are obstacles to data integration and information sharing. The scope of water resources management is broad, covering multiple fields such as hydrology, meteorology, water quality monitoring, and watershed governance. However, these data are scattered among different government departments, research institutions, and public and private enterprises, with inconsistent data formats and standards, making integration and centralized management extremely difficult. These data are not only scattered among institutions of various levels and types, but also constrained by geographical limitations, resulting in significant deficiencies in cross-regional data sharing and joint management. The emergence of data silos limits the smooth communication and sharing of information, and restricts the completeness and comprehensiveness of water resource management systems. Due to the lack of unified data standards and integration platforms, it is difficult to effectively compare data from different channels during analysis, leading to serious problems such as information asymmetry and data inconsistency [3].

3.3. Insufficient Policy Implementation and Low Implementation Efficiency

In traditional water resource management strategies, insufficient policy implementation and low efficiency have been long-standing problems. This problem mainly stems from the heavy reliance of water resource management policies on the coordination of local governments and their functional departments [4]. However, these local governments may experience biases or delays in policy implementation due to limited resources, shortage of enforcement personnel, or insufficient understanding of policies. Moreover, traditional policy implementation methods lack efficient feedback systems, making it difficult to track progress and effectiveness in real-time during the implementation process. Many measures lack clear evaluation criteria and transparency in their implementation process, resulting in the inability to quantify or evaluate their effectiveness. Driven by short-term economic considerations, some local governments may inconsistently enforce policies, especially under conditions of water scarcity. In some cases, governments may prioritize immediate economic development, which can result in insufficient attention to the long-term protection and sustainable use of water resources.

4. Water Resource Policy Formulation Driven by Data

4.1. Construction of Data-Driven Precision Prediction Mechanism

In today's rapidly advancing information technology, relying on data-driven precision prediction mechanisms has become the core means of optimizing the accuracy and efficiency of water resource management decisions [5]. Its core lies in the collection and fusion of numerous data, covering multiple parameters such as rainfall, temperature, water evaporation rate, water flow rate, and water quality. This type of information comes from hydrological monitoring stations and is updated in real-time using various modern methods such as IoT sensors, remote sensing technology, and satellite data transmission. In the field of data-driven forecasting, commonly used algorithms include regression prediction, time series inference, and neural network simulation. Regression models aim to construct linear relationships between variables, time series models are suitable for predicting hydrological data with periodic patterns, and neural networks excel at detecting nonlinear and complex patterns inherent in the data, providing more accurate predictive data for effective management of water resources. For example, to predict the water flow of a certain watershed in the next 30 days, a multivariate linear regression model can be established through regression analysis using historical precipitation, temperature, evaporation, and other data

$$Q_t=\beta_0+\beta_1 P_t+\beta_2 T_t+\beta_3 E_t+\varepsilon_t \quad (1)$$

In formula (1), Q_t represents the water flow rate on day t, P_t, T_t, and E_t represent the precipitation, temperature, and evaporation on day t, respectively. β_0, β_1, β_2, and β_3 are regression coefficients, and ε_t is the error term. After analyzing historical data, regression analysis can quantify the specific impact of different factors on water flow changes, and predict the future direction of water flow changes based on the obtained model. If a large amount of precipitation is expected in the future, the model may estimate an increase in water flow and guide water resource management agencies to deploy response strategies in advance, such as adjusting the water storage capacity of reservoirs or enhancing flood control efforts.

4.2. Digital Transformation Strategy for Data Integration Management

The intelligent management and refinement of water resources cannot be achieved without the deepening of digital transformation. In the past, water resource management was constrained by fragmented information and isolated data, making it difficult to improve work efficiency. Digital transformation has established a centralized data integration platform, enabling coordinated scheduling and efficient data exchange, thereby providing robust support for decision-making. The primary task of digital transformation is to create a comprehensive data collection and storage system, which captures key data such as rainfall, river water level, and water quality in real time through IoT devices, hydrological monitoring facilities, satellite remote sensing, and other means, and stores this information in cloud systems, ensuring the security and convenience of data acquisition. Secondly, data standardization techniques are used to clean and transform the data, ensuring its consistency and value for use [6]. An intelligent system for data analysis and visualization is developed to illustrate the spatial and temporal distribution patterns of water resources using data mining and analytical algorithms, providing reference for the rational allocation of water resources and policy improvement. Ultimately, it facilitates data exchange across departments, eliminates information silos, enables cross-departmental cooperation, and strengthens the effectiveness of policy implementation. Taking the digitalization process of water resources management in a certain region as an example, the region has compiled hydrological information from the previous five years on a digital platform and continuously collected daily water resources data through online monitoring equipment. The following is a key data Table 1 for a certain month in the city:

Table 1. Key Data Analysis.

Date	Precipitation (mm)	Water consumption (10000 cubic meters)	Reservoir storage capacity (10000 cubic meters)	Water Quality Index (0-100)
2024-12-01	5	80	1200	85
2024-12-02	0	90	1180	83
2024-12-03	10	75	1220	88
2024-12-04	15	70	1250	90
2024-12-05	8	78	1235	87

After studying the data in Table 1, the water resources management department used an intelligent algorithm model to observe that when rainfall exceeds 10 millimeters, the city's water consumption decreases by about 10%, while the storage capacity of reservoirs increases. This suggests that managers should appropriately reduce reservoir water intake during periods of abundant rainfall to prevent overflow risks, and increase water storage during droughts or periods of low precipitation to ensure supply.

4.3. Utilizing Data-Driven Approaches to Enhance Policy Implementation Efficiency

In the management of water resources, the effectiveness of policy implementation is an important criterion for measuring whether its goals can be achieved. Traditional water resource management encounters problems such as delayed information transmission, low efficiency, and poor collaboration between departments during the execution phase. Relying on the advancement of data-driven technology, the implementation capability of water resources policies has been improved through real-time data monitoring, intelligent analysis, and the improvement of feedback systems, ensuring the accuracy and efficiency of policy implementation. The core advantage of data-driven approach lies in its timeliness. After building an intelligent monitoring network, managers can instantly grasp key data in policy implementation. Taking the water resource conservation measures implemented in a certain area as an example, the government uses a data-driven system to monitor regional water usage in real time and analyze deviations from standard consumption levels. The water usage model in this region is a multiple linear regression model, represented by the following formula:

$$U_i=\alpha_0+\alpha_1 P_i+\alpha_2 T_i+\alpha_3 E_i+\alpha_4 C_i+\varepsilon_i \tag{2}$$

In formula (2), U_i represents the water consumption of the i-th region, P_i, T_i, and E_i are the precipitation, temperature, and evaporation of the region, C_i is the coefficient of water resource management measures in the region, α_0, α_1, α_2, α_3, and α_4 are regression coefficients, and ε_i is the error term. The water resource supervision system can quickly issue alerts for specific areas exceeding the prescribed water usage standards through real-time collection and analysis of various data, automatically reallocate water resource quotas and implement targeted water-saving strategies.

5. Application Scenarios of Data-Driven in Environmental Policy Formulation

5.1. Water Quality Monitoring and Early Warning System

In the process of environmental policy decision-making, a water quality monitoring and early warning system with data as its core plays a crucial role [7]. Leveraging cutting-edge technologies such as the Internet of Things, big data, cloud computing, and intelligent algorithms, the new water quality monitoring and early warning system collects water environment parameters in real time and, through in-depth data analysis and model construction, predicts the risk of water pollution, providing an accurate and rapid basis for decision-making in water resource management and environmental policy formulation. Taking the water quality supervision system of a certain area as an example, the area uses data-driven supervision methods to continuously monitor the ammonia nitrogen content and chemical oxygen demand in the water body, and constructs a mathematical model of pollutant diffusion based on flow information. The pollutant diffusion model in this region is a two-dimensional convective diffusion equation, with a mathematical expression of:

$$\frac{\partial C(x,t)}{\partial t} = D\nabla^2 C(x,t) + R(x,t) \tag{3}$$

In formula (3), $C(x,t)$ represents the variation of pollutant concentration with time t and position x, D is the diffusion coefficient, ∇^2 is the Laplacian operator (representing the diffusion of pollutants in space), and $R(x,t)$ is the intensity of pollutant release sources. By real-time monitoring of water quality data $C(x,t)$, combined with meteorological and hydrological data, the system can predict the diffusion trend of pollutants in water bodies. If the system detects that the pollution concentration $C(x,t)$ exceeds the preset safety threshold, it will automatically issue a water quality warning and simulate the pollutant trajectory using the diffusion model, guiding relevant departments to take timely emergency response measures such as closing pollution sources and increasing water purification efforts.

5.2. Optimization of Water Resource Allocation and Scheduling

Under the influence of population growth, rapid urbanization, and climate change, the imbalance between water supply and demand has become increasingly acute. How to allocate and regulate water resources reasonably and efficiently, ensure that all aspects of water demand are properly addressed, and minimize water waste as much as possible, has become the focus of water management work in countries around the world. A data-driven water resource management system can achieve real-time monitoring of water source flow, water level, and water demand through the Internet of Things, remote sensing technology, and meteorological forecasting. The system utilizes collected data and integrates historical water usage habits, meteorological changes, seasonal fluctuations, and other information to achieve dynamic allocation of water resources through advanced optimization algorithms, ensuring a balanced water supply across various regions and sectors. When a region needs to optimize the allocation of multiple water sources (such as reservoirs, groundwater, and rivers) to meet the water needs of urban, agricultural, and industrial sectors, and the water volume of each source is S_1, S_2, S_3,..., S_n, while the water demand of each region is D_1, D_2, D_3,..., D_m, the water resource scheduling optimization problem can be solved through a linear programming model aiming to minimize costs while satisfying the demand constraints of each water use region. The mathematical expression of this model is:

$$min \sum_{i=1}^{n} c_i x_i \tag{4}$$

In formula (4), c_i is the unit scheduling cost of the i-th water source, and x_i is the scheduling amount of the i-th water source (i.e. the amount of water provided). Simultaneously satisfying the following constraints:

$$\sum_{i=1}^{n} xi \geq D_j \forall_j \in \{1,2,\ldots,m\}$$

$$0 \leq x_i \leq S_i \quad \forall_i \in \{1,2,\ldots,n\} \tag{5}$$

In the optimization model (5), D_j represents the total demand of the j-th water use area, with the core purpose of ensuring the water demand of each zone while combining the economic costs of water source scheduling to minimize the overall scheduling costs. By solving this linear programming problem, the system has the ability to provide the optimal solution for water resource allocation, in order to achieve the overall optimization of resource allocation. For example, when the water level of the reservoir drops during the drought period, the system will automatically increase the mining output of groundwater and correspondingly reduce the irrigation water consumption of agriculture to ensure that the urgent demand for urban water supply is met first.

6. Conclusion

Faced with the escalating global water resource issues, traditional water resource models are no longer able to meet the needs of sustainable development. In this context, the management model relying on data-driven technology has emerged, and its optimization role in precise prediction, information fusion, and policy implementation has improved the efficiency of water resource management and the quality of decision-making. Data driven water resource management must also overcome challenges in data quality and technological application, which require continuous innovation and improvement to gradually mature. Looking ahead, with the rapid development of information technology, data-driven technology will play a more critical role in water resource management, providing a robust foundation for promoting the sustainable utilization of water resources and protecting the ecological environment.

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