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Perspective and Prospects on Applying Artificial Intelligence to Address Water and Environmental Challenges of 21st Century

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Abstract
One of the most pervasive challenges affecting human and planetary well-being is inadequate access to clean water and sanitation. Problems with water are expected to become worse in the coming decades, with water scarcity occurring globally, in the face of ever-growing populations, intensive human activities, and climatic variation. Addressing the aforementioned water security has been achieved consensus and has been included into the sustainable development goals (SDGs) set by the United Nations’ Agenda 2030. Despite these ample opportunities, it remains challenging to create reliable, sustainable, and affordable solutions to providing universal access to clean water and sanitation. In this context, the emerging artificial intelligence (AI) technology can be an attractive solution to help with this challenge. We summarized the core of the SDGs-Goal 6 (Clean Water and Sanitation) and the problems encountered during the progress to date. Building upon which, we conducted a literature review and provided a state-of-the-art analysis of leveraging AI to help achieving SDGs-Goal 6 alongside the resultant impacts. Afterwards, we highlighted the key issues necessary to be tackled in the coming years if AI is expected to be well applied with its maximum benefits. Plus, we put forward the prospects of future efforts on this revolution.

Keywords
sustainable development goals (SDGs); water security; water environment; water system; sustainable management; artificial intelligence (AI)

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Perspective and Prospects on Applying Artificial Intelligence to Address Water and Environmental Challenges of 21st Century

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Abstract: One of the most pervasive challenges affecting human and planetary well-being is inadequate access to clean water and sanitation. Problems with water are expected to become worse in the coming decades, with water scarcity occurring globally, in the face of ever-growing populations, intensive human activities, and climatic variation. Addressing the aforementioned water security has been achieved consensus and included into the sustainable development goals (SDGs) set by the United Nations’ Agenda 2030. Despite these ample opportunities, it remains challenging to create reliable, sustainable, and affordable solutions to provide universal access to clean water and sanitation. In this context, the emerging artificial intelligence (AI) technology can be an attractive solution to help with this challenge. We summarized the core of the SDG 6 (Clean Water and Sanitation) and the problems encountered during the progress to date. Building upon this, we conducted a literature review and provided a state-of-the-art analysis of leveraging AI to help achieve SDG 6 alongside the resultant impacts. Afterwards, we highlighted the key issues necessary to be tackled in the coming years if AI is expected to be well applied with its maximum benefits. Plus, we put forward the prospects of future efforts on this revolution.

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Human survival and development rely on the sustainable water resources, water environment, and water ecology. One of the most pervasive challenges affecting human and planetary well-being is inadequate access to clean water and sanitation. Problems with water are expected to become worse in the face of ever-growing populations, intensive human activities, and climatic variation. Water security has become a global concern [1]. The United Nations High-Level Political Forum on Sustainable Development in September 2015 adopted The 2030 Agenda for Sustainable Development which included 17 sustainable development goals (SDGs), and appealed to countries and regions for scientific and technological innovation and further solutions of SDGs by full cooperation [2]. SDG 6 (Clean Water and Sanitation) aims to create reliable, sustainable, and affordable solutions to providing universal access to clean water and sanitation. The emerging artificial intelligence (AI) technology in recent years has provided new ideas and paths for realizing SDG 6 [3]. We summarized the core of SDG 6 and the problems encountered during the progress to date. Building upon this, we conducted a literature review and provided a state-of-the-art analysis of leveraging AI to help to achieve SDG 6 alongside the resultant impacts. Afterwards, we highlighted the key issues necessary to be tackled in the coming years if AI is expected to be well applied with its maximum benefits. Plus, we put forward the prospects of future efforts on this revolution.

1 Core of SDG 6 and the problems encountered during the progress

1.1 Advancement of SDG 6 core

Water is the key source ensuring human and planetary well-being. SDG 6, the core of SDGs, is a basis for realizing the other 16 SDGs (Figure 1). SDG 6 contains a total of 8 specific targets and 11 monitoring indicators, covering...
multiple topics such as water resources, water environment, water ecology, water facilities, and international cooperation related to water technology. SDG 6 is a new comprehensive, systematic, and forward-looking development framework designed on the basis of the historical and practical experience of the United Nations Millennium Development Goals (MDGs) and the high expectations for future water security.

**Figure 1** SDG 6 and the other 16 SDGs

In general, the advancement of SDG 6 is reflected in the following four aspects. (1) SDG 6 focuses more on the fairness of target implementation. The MDG 7C aims to halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation, while SDG 6 is to ensure availability and sustainable management of water and sanitation for all. Moreover, SDG 6 includes the targets of paying special attention to the needs of women and girls and those in vulnerable situations and expanding capacity-building support to developing countries: (2) SDG 6 focuses more on the systematicness and integrity of water cycle management. It has clearly required to increase water-use efficiency, recycling, and safe reuse and to improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials. (3) SDG 6 focuses more on the water security crisis caused by human activities. The challenges for sustainable development of water and environment related to growing population and human activities, such as frequent water pollution, water shortage, and water ecological degradation, have become the emphasis of SDG 6. (4) SDG 6 focuses more on the integrated management of water resources and water systems by cross-border, multi-system, and inter-department collaboration, as well as the realization of equity. SDG 6 has higher requirements for the protection of water ecological integrity in cross-border basins as well as the collaborative management of water resources utilization and recycling by multiple systems, industries, and departments.

### 1.2 Challenges of realizing SDG 6

SDG 6 provides a clear direction for the sustainable development of global water and environment by 2030, while the realization of SDG 6 faces new challenges. At present, the differences in the development stages and the scientific and technological levels of different countries and regions in the field of water and environment lead to the mutual reinforcement or restriction between different targets of SDG 6 and between SDG 6 and the other SDGs. Therefore, systematic understanding of the problems encountered in the realization of SDG 6 and figuring out corresponding solutions according to local conditions is a basis for countries and regions to jointly realize SDG 6. Specifically, the realization of SDG 6 is facing three challenges.

1. **Insufficient data monitoring and analysis methods** have severely restricted the United Nations Organization and countries and regions from learning the real status and development efficiency of water and environmental sanitation. Effective measurement and monitoring of the specific targets of SDG 6 is an important part for ensuring the sustainable development of water and environment. As of 2019, the data pertaining to 4 of the 11 indicators of SDG 6 are still not provided by many countries. At present, the measurement and monitoring of the specific targets of SDG 6 mainly rely on statistical and census data, but the high labor and time costs of the census work limit the real-time obtainment and certainty of data. Therefore, it is urgent to develop long-term, multi-scale, multi-dimensional, and high-resolution data monitoring and indicator modeling methods to evaluate the progress of SDG 6.

2. **There are difficulties in the construction, monitoring, simulation, evaluation, and optimization of water cycle system.** An intact water cycle system involves multiple natural and artificial water units such as surface water, groundwater, rainwater, and urban water supply and drainage system, being a complex, diverse, dynamic, and interconnected system. The traditional research approach and management model of water system engineering is relatively closed and simple. In addition, the differences in scientific and technological levels of countries and regions make the construction, monitoring, simulation, evaluation, and optimization of water cycle system encounter great challenges. How to revolutionize the traditional research approach and management model and create an open innovative field of water science and technology is the core scientific issue to realize the integrated management of water resources and water systems.
(3) Water environment and water ecological risks have complexity. With the rapid industrialization and the expansion and diversification of human consumption needs, water pollutants have become increasingly complex in variety and different in time and space, which increases the risks to water environment and ecology\[15-17\]. How to quickly identify, deeply understand, and efficiently solve compound pollution and risks in the extremely complicated and changeable water systems is a key difficulty that needs to be resolved in the development of a healthy, sustainable, and highly resilient water system in the future.

2 Research and application of AI in the field of water and environment

AI, a branch of computer science, is a new technological science that studies and develops theories, methods, technologies, and application systems to simulate, extend, and expand human intelligence\[18\]. With the large-scale development of computing power and continuous breakthroughs in algorithms, AI has developed rapidly in recent years. This has contributed to the research and innovation with regard to the prevention and control of water pollution, the protection of water quality, the optimization and reconstruction of water facilities, and river basin ecosystem management. We reviewed the relevant literature in the past decade and found that AI technology was mainly applied in the following four aspects.

2.1 Recognition of and risk response to water pollution

Recognizing and responding to water pollution events is a prerequisite for efficient prevention and control of water pollution as well as the fundamental guarantee for water supply safety.

(1) Water quality index modeling and data fusion. AI-assisted water quality index modeling and multi-dimensional spatio-temporal data fusion provide new opportunities for improving the research, evaluation, prevention, and control of water pollution (Figure 2). For example, with the remote sensing and detection data of water quality, nonlinear water quality index models can be established using self-adapting selection of artificial neural network to provide basic data for water quality management and digital planning\[19\]. AI algorithms such as neural network, support vector machine, and classification and regression tree can be combined for integrated simulation of water quality changes and geobiochemical processes in complex water environment, which can provide important model tools for the protection and restoration of water bodies\[20-22\].

(2) Risk substance detection and toxicity assessment. Combining AI with spectrum technology is currently a hot topic. Near-infrared spectroscopy can be used to quickly determine water quality indicators such as biochemical oxygen demand, and the coupling with AI algorithms represented by least squares support vector machines can improve the accuracy of near-infrared spectroscopy in predicting water quality changes, providing a scheme for fast quantitative assessment of water pollution\[23\]. The integration of back-propagation neural network and k-means clustering algorithm in laser-induced breakdown spectroscopy help to efficiently, accurately, and economically measure the essential surface water quality indicators (e.g., heavy metals) that need long detection time and high detection cost\[24\]. Scientists have tried to apply AI to the research of environmental toxicology, aiming to provide an economical and efficient method for the assessment of toxicity and risk of new pollutants\[25\].

(3) Early warning of water pollution and construction of emergency plan. With the rapid development of in-situ monitoring sensor technology and equipment, AI technology based on deep neural networks has played a role in spatial big data analysis. This offers strong technical and decision-making support for optimizing the plan of monitoring water quality, improving the capability of pollution source analysis, and developing systems for pollution warning and emergency prevention and control\[26-29\].

2.2 Research and development of technologies for ensuring water quality security

With the continuous improvement of water treatment standards, the design and application of new functional materials for water purification, the dissection of pollutant removal mechanism, the research and development of high-efficiency technologies for pollutant removal, and the conversion of pollutants toward resources and energy have become hotspots in the research of water treatment\[30,31\].

(1) Design and application of new functional materials for water purification. Under the guidance of Materials Genome Initiative, the rapid development of AI-based technologies provides an efficient way for the design and development of environmentally friendly new functional materials\[32\]. The computational simulation and optimization of the composition and properties of new materials can be performed by inversing failed experiments and historical data in the material development process\[33\], together with the characteristics of target pollutants, which is expected to reform the traditional trial-and-error mode of materials development, which will greatly foster the industrial development of new water purification materials (Figure 3).

(2) Dissection of pollutant removal mechanism and the research and development of high-efficiency technologies for pollutant removal. The migration and transformation of micropollutants such as drugs and personal care products, endocrine disruptors, and persistent organics, which are closely related to human health, in the municipal water treatment system is the key and difficult point for the development of high-efficiency water treatment technology\[31,34\]. The emerging AI algorithms such as random forest, convergence
for the maximum absolute value, selection operators, and feedforward neural networks enable the nonlinear simulation and prediction of micropollutant behavior in water treatment, providing new ways to improve water treatment methods \(^{[35,36]}\). With the continuous in-depth study of biological wastewater treatment based on metagenomic and metabolomic methods \(^{[37,38]}\), the identification of key functional microorganisms from the microbial big data of wastewater treatment system has become the major difficulty in improving the biological treatment of wastewater. Combining AI technology with bioinformatics \(^{[39]}\) facilitates the information mining and micro-analysis of water treatment systems and paves a new way to unveil the mechanism of biological wastewater treatment (Figure 4). However, it is still a knot to improve the accuracy and interpretability of information mining at present.

(3) Transformation of pollutants toward resources and energy. The core paradigm of water pollution control lies in the shift from pollutant removal to resource utilization and energy utilization \(^{[40]}\). The state-of-the-art virtual and augmented reality technologies such as digital twin are expected to solve the technical problems of real-time simulation and achieve simultaneous regulation of the directional transfer and transformation of water pollutants. However, there are still many key technical problems to be solved \(^{[41]}\).

2.3 Optimization, reconstruction, and integrated management of water facilities

With the acceleration of urbanization and the development of social economy, urban water safety has become more and more serious, as manifested by frequent water pollution events, water shortage, and water ecological degradation \(^{[42]}\). City is the center of human activities and has an intact water cycle system with large size, complicated process, close interassociation of water units, and tendency of being influenced by human activities \(^{[43]}\). However, the traditional water

Figure 2  AI-assisted technical system for water pollutant recognition and risk response

Figure 3  AI-assisted research and development mode of new materials with environmental functions
AI-based biological wastewater treatment mechanism and directional reinforcement system engineering, taking water intake, supply, and drainage as segmented goals, is characterized by closed and simple research and management mode and lacks optimization, management, and even reconstruction of water facilities from the perspectives of system theory and holism to meet urban sustainable development. If the traditional mode is continuously applied, it will be difficult to make substantial breakthroughs in urban water safety for a long time.

In the past two decades, the emergence and iteration of information technologies such as mechanism models, sensors, and integrated analysis in the water industry, especially the explosive development of AI in recent years, have provided key support for breaking through the bottleneck in optimization and integrated management of urban water system (Figure 5). For example, the application of AI technologies such as simulated annealing algorithm to the design...
of drainage systems and the utilization and management of
rainwater resources can provide powerful scientific and
technological support for the forward-looking layout, optimal
design, and real-time regulation of drainage systems[44-46].
Furthermore, the construction of a genetic algorithm-based
secondary optimal scheduling model makes it possible to
optimize the energy consumption of water supply
system and decreasing the process energy consumption and
carbon emissions[47-49].

In recent years, AI technology has been applied to the in-
tegrated management and optimization of urban water sys-
tems and water resources[50,51]. It is expected to build a
next-generation urban smart water system with AI as the core
to adapt to the rapid urban development.

2.4 Process simulation and overall management of
river basin ecosystem

The water-environment process with complicated mecha-
nism involves the interaction of multiple spheres, processes,
scales, and elements on the earth and massive data, being a
major scientific problem and frontier in the research of earth
and ecological environment[52,53]. River basin ecosystem, as
a complex system formed by water, soil, air, organisms, hu-
man factors, and their interactions, miniatures the natural and
social coupling system[54]. Besides, it is an important scale
for exploring the overall management of water resources,
water environment, and water ecology[55]. Ensuring the
health of river basin ecosystems is of scientific and practical
significance for the realization of SDGs. In recent years, AI
technology has been integrated with satellite communica-
tions, spatial orientation, remote sensing, and geographic
information system to construct a big earth data science
platform[56], which simulates the large-scale hydrological
cycle processes such as natural precipitation[57], soil ero-
sion[58], and glacier melting[59] as well as the driving factors,
thereby providing a data basis for the process dissection and
comprehensive evaluation of river basin ecosystem.

Furthermore, the rapid development of AI provides strong
technical support for simulating the mutual feedback of
nature-society-economy system[60,61], which is the key to
realize the integrated management of multiple processes and
factors of river basin ecosystem. AI algorithms such as ran-
dom forest, gradient boosting regression tree, and regression
vector machine can quickly learn and predict the cascade
response of river basin ecosystem to dynamic factors such as
land cover type in catchment area, stress factors (e.g., nutrient
salt), and seasonal succession of vegetation[62,63], which help
decision makers to formulate objectives and measures of
river basin management.

AI algorithms will be integrated with physical models of
climate change and human activities[64-66] on the basis of
fusion of geoscience big data and social and economic
indexes for comprehensive research of nature-society-economy
system on the basin scale. This may enable the construction
and overall management of the technical system for green
river basin.

3 Key issues to be tackled in the application
of AI in the field of water and environment and
corresponding countermeasures

With the proceeding of the fourth industrial revolution and
the advancement of information technology centering AI, the
decision making in the field of water and environment has
been shifting from traditional empirical and qualitative ways
to precise, quantitative, and intelligent ways, which makes
the reconstruction of future-oriented healthy, sustainable,
highly resilient, and intelligent water system feasible. The
rapid progress of AI technology has injected new vitality into
the development and application of technologies for water
environment risk prevention and control, water quality safety
assurance, and optimal management of water system from
micro to meso and macro scales, thereby accelerating the
progress of SDG 6. Nevertheless, the process will encounter
many new challenges. There are still several key issues that
need to be tackled in the years to come if AI is expected to be
well applied with its maximum benefits.

(1) Black box and algorithm interpretability. Although
various AI technologies that use machine learning as a
breakthrough and deep learning as their implementation
method have shown excellent predictive performance in the
field of water and environment, their interpretability limits
their popularization and application. Deep neural networks
achieve their high discrimination by constructing multi-layer
nonlinear mapping functions for abstraction across layers,
with black box as the main feature[67]. In other words, though
AI technologies with data-driven machine learning as the
core can realize recognition, learning, action, and even au-
тономous decision-making, its efficiency is mainly limited
by its inability to explain the rationality of its analysis and
decision making to users, evaluate the advantages and dis-
advantages of its model, predict its generalization in new
tasks, and even cannot ensure its safety in future applica-
tion. In addition, researchers, engineers, and managers spe-
cializing in water environment-related disciplines usually do
not have knowledge and technical experience regarding AI,
and thus they have difficulties in selecting, assessing, and
understanding AI technologies for solving water and envi-
ronmental issues. As a result, AI fails to play its role fully.
Recommendation: In the future, we should advance new
interpretable AI technologies and develop the theory and
assessment methods of AI-based technical system for water
and environment, which will foster the research, application,
and education of AI in the field of water and environment.

(2) Large-scale computing power and negative environ-

mental effect. With the continuous development of monitoring, sensing, and modeling technologies, the operation mode of water industry is gradually transforming to digital mode \[68\], which means that the volume of data related to water resources, water environment, and water ecology is surging and may have the problems of data uncertainty, redundancy, etc. \[69\]. Although AI is capable of solving these problems, AI-based water and environmental solutions will consume large amounts of computing resources due to the increasing data volume, data uncertainty, and complex data connection in water system. Furthermore, computing power-intensive AI technologies such as deep neural networks is required to implement the integrated management and coordinated regulation of water cycle system, with the development of large-scale computing power as a prerequisite. However, it will consume huge resources and energy to construct and operate large-scale computing facilities, and cause environmental problems such as carbon emissions. Study has pointed out current popular deep neural network can emit more than 280 tons of carbon dioxide equivalent during mass data training, which is 5 times the carbon emissions by cars in the average life cycle in the US \[70\]. According to statistics from the United States Environmental Protection Agency, the current electricity consumption of established data centers in the world accounts for 3% of the total global electricity consumption and is doubling every four years. The greenhouse gas emissions of information and communication technologies account for about 2% of the global total, and their carbon footprint contribution is equivalent to the total carbon emissions of civil aviation industry \[71,72\]. The extensive application of AI may aggravate global energy crisis and climate change and even produce unknown spillover effect on the ecological system, thereby adversely affecting the realization of energy and climate-related SDGs. When performing perception and cognition, human brain needs to process current data and simultaneously mobilize relevant knowledge stored for understanding and reasoning, whereas the energy consumed in this process is much less than that required to train the AI model \[73\]. In machine learning, the introduction of water and environmental knowledge stored in human brain for preliminary data screening and discrimination can reduce unnecessary computing power-intensive processes, which helps reduce energy consumption and carbon emissions in AI application. Recommendation: In the future, we should develop online monitoring and sensing technologies for data pertaining to the field of water and environment and standardize the data quality, interfaces, and protocols. The development levels as well as human and material inputs in water and environment field vary among different countries and regions. In this context, it is a tendency to break the constraint of generally small amount of available data in current water system and develop AI algorithms and technical systems based on small-size data samples.

(4) Restricted application and inequality. Achieving equality is the common target of SDGs, and the limited application and generalization of AI technology may cause or even exacerbate inequality in water and environmental management in different countries and regions \[76,77\]. AI is considered to be one of the three state-of-the-art technologies in the 21st century, but the AI-related education, technology research and development, and practical application are more common in developed countries. Especially when it comes to water resources management in cross-border river basins, developed countries can leverage AI to manage and dispatch water resources, and thus they take the lead in research and have the right to speak in cross-border river management, thereby having the ability to restrict the benefit distribution of water resources in developing countries and regions. This runs counter to the target of equality sought by SDGs \[78\]. Recommendation: Considering the common problems and major challenges of water and environment in developing
countries and regions, it is essential to carry out international cooperation in science and technology, education, and investment to help developing countries and regions deploy capacity building in emerging fields (e.g., AI) and solve the inequality caused by the limited application of state-of-the-art technologies.

4 Prospects

With the purpose of realizing SDGs by 2030, we should use emerging information technologies such as AI to digitally and smartly realize the systematic management of water cycles and efficient prevention and control of environmental risks in cities or urban agglomerations, which is an important research direction in environmental engineering. In the application of AI technology in the prevention and control of water and environmental pollution, protection of water quality, optimization of water facilities, and construction of green river basins, it is recommended to combine data-driven algorithms with relevant knowledge. On the basis of ensuring the accuracy of model prediction, we should enhance the model interpretability and develop a technical system and operation model for water system management and risk prevention and control with minimal AI computing power. The construction theory and effect evaluation method with standardized model algorithms, data quality, and interface protocols should be formed, which can reduce and even avoid spillover effect in solving water and environmental problems. It is recommended to pay attention to the role of AI technology in developing countries, especially the underdeveloped countries and regions along the Belt and Road (the Silk Road Economic Belt and the 21st Century Maritime Silk Road), in the capacity building of water and environmental management, and to eliminate the inequality of global governance due to restricted application of AI. Through the integration of water and environment field with AI and their innovative and coordinated development, it is expected that a healthy, sustainable, highly resilient, and intelligent next-generation water cycle system be reconstructed on a global scale to improve the human and planetary well-being and protect the water environment.

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