WEP Warwick Evans Publishing

Transactions on Environment, Energy and Earth Sciences
ISSN: 2960-1924, eISSN: 2960-2300 | Volume 2
ERET 2024

Advances and Challenges in Remote Sensing Technology for Hydrologic Environment Monitoring

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Abstract. Water is essential for human life and aquatic organisms. However, with industrial development spreading across the world, the hydrologic environment is not as stable as before due to various types of pollution. Monitoring the hydrologic environment and detecting potential threats are necessary processes. Remote sensing technology plays a key role in many monitoring processes. Since its discovery and extensive use, remote sensing technology has provided people with various types of Earth data. It is also a suitable solution for monitoring and detecting the hydrologic environment. By providing detailed data of aquatic areas, remote sensing technology can predict different situations, allowing corresponding responses to protect the environment. Recently, several studies on remote sensing technology have made significant progress; however, new challenges stand in the way of future studies on the topic. This paper gives an overview of recent studies on remote sensing technology as well as hydrologic signatures. It also discusses challenges in the field and offers suggestions for future research.

Keywords: Remote sensing technology; hydrologic environment; data collection; monitoring technique.

1. Introduction

Water sources are significant for the world, as they are the basic supply for almost all organisms. Besides supporting the living of organisms, water also plays an important role in maintaining sustainable ecology. Most usable water sources are in the form of lakes and rivers across the land, which form the hydrologic environment. Since water can directly respond to ecological changes, in many cases, hydrologic features and variables are key components for detecting the state of the local environment. Most hydrologic environments have the ability to renew themselves, but this steady state has been disrupted by climate change due to industrial development. Additionally, changes in the space and pattern of aquatic areas can provide predictions on climate change and are important to human life [1]. Therefore, monitoring work in this area is crucial for solving related problems, and the monitoring process and predictions are based on remote sensing observations and hydrologic modeling systems [1].

There are three main methods for monitoring hydrologic environments and collecting data on hydrologic signatures: eco-hydrology, watershed processes, and modeling [2]. The use of remote sensing technology is a way to create modeling systems of the hydrologic environment for future predictions. In recent decades, remote sensing technology has been applied in many different areas. This paper will compare the use of remote sensing technology in hydrologic environments with its use in land use and forest protection to conclude the advancements of remote sensing technology in recent years. Specifically for hydrologic environments, remote sensing technology has seen significant improvements. It can reflect various kinds of information based on different variables such as precipitation, temperature, soil moisture, water levels, evapotranspiration, flood extent, flow velocity, river discharge, and land water storage over regional/global areas [3]. This paper also discusses the advantages of using remote sensing technology to build hydrologic models. Finally, it addresses the limitations of remote sensing technology and offers suggestions for future study.

2. Remote Sensing technology

The remote sensing technology has been developed for more than 150 years. Over this long period, it has evolved into various systems capable of monitoring and measuring energy patterns across different electromagnetic spectra [4]. Remote sensing technology can detect information about physical objects and the environment through various recording processes, making it invaluable in numerous detection and monitoring applications [4]. While remote sensing technology has been widely utilized in urban areas for purposes such as urban planning and infrastructure development, its popularity has grown significantly in natural and environmental monitoring due to the increasing global priority on natural protection [4]. Its high efficiency and ability to record large-scale data quickly make remote sensing technology an optimal solution for many scenarios. However, despite these advancements, challenges remain, particularly concerning the cost of implementing the technology. This cost hurdle makes it difficult for many countries to integrate remote sensing technology into their monitoring and detection processes. Therefore, there is still considerable development ahead for remote sensing technology, as well as for the associated monitoring processes.

3. Using of Remote Sensing Technology

3.1. Land Cover and Land Use

In the past decades, remote sensing technology has evolved significantly, including sensors that can detect wide areas. Remote sensing technology is capable of providing data collection and analysis from various platforms such as ground-based or atmospheric, and this is integrated with GPS systems, GIS systems, and new modeling processes [5]. This capability enables remote sensing technology to gather sufficient information for land cover and land use analysis.

Land use and management have encountered various challenges because accurately collecting all types of data is not straightforward. Most methods can only capture partial data, making comprehensive land management difficult. However, even though remote sensing technology has not yet fully developed to obtain all necessary data types, it provides valuable insights into future land trends [5]. Consequently, management becomes more feasible with accurate predictions of pattern changes.

Users of remote sensing technology handle vast amounts of data. Therefore, besides its advantages, selecting the most efficient image processing techniques is crucial [5]. This involves choosing relevant data and considering factors like spatial, spectral, and temporal resolutions as top priorities.

3.2. Forest Inventory

Forest inventory is changing rapidly over time, and along with other economic and social issues, forest management and protection face numerous considerations [6]. Remote sensing technology can provide data to address these challenges and support the development of models. One such technology is Airborne Laser Scanning (ALS), also known as Lidar, which uses active sensing to detect the three-dimensional distribution of vegetation in forests, creating vertical structure models of specific areas [6]. Lidar systems emit near-infrared light towards targets and record the returned energy to generate detailed structures and models, providing an overview of the entire area for subsequent analysis.

Another technique is Digital Aerial Photogrammetry (DAP), which utilizes digital cameras. The effectiveness of DAP in imaging and data collection depends on advancements in image capture techniques. Similar to ALS, DAP can create three-dimensional forest structures, but its image-based point cloud yields less detailed information compared to Lidar, posing a primary limitation of this technique [6]. Despite these differences, the cost of ALS can be a significant barrier, underscoring the importance of a comprehensive monitoring approach that integrates multiple methods.

4. Hydrologic Monitoring

4.1. Hydrologic Monitoring and Hydrologic Signatures

Hydrologic monitoring involves using various methods and techniques to collect, analyze, and synthesize hydrologic signatures. Hydrologic signatures are quantitative metrics that describe the statistical or dynamic properties of stream flow [2]. These metrics are also referred to as hydrologic metrics or indices. Hydrologic signatures can vary from simple statistical values to complex variables, with hundreds of them identified in total [2]. These signatures are categorized into five ecological aspects of flow: magnitude, timing, frequency, duration, and rate of change. The grouping is based on earlier suggestions that classified them into flow variability, flood regime patterns, and intermittent condition extents [2]. More details on these five aspects, as per Hilary K. McMillan's article, are listed in Table 1.

Table 1. Five main aspects of hydrologic signature according to Hilary K. McMillan.

Number	Type	Explain	Relevance with ecology
1	Magnitude	Simply the magnitude of flow	Show the area and capacity of drainage basin
2	Timing	Seasonal timing of flow events in a year	Show the supplying of life-cycle requirements of insream species
3	Frequency	Frequency of flow event	Affect population by controlling the reproduction and death of instream species
4	Duration	Period of time of a specific flow event	Control life-cycle and the impact of flow events
5	Rate of change	Rate of change of flow magnitude and stage height	Strand organisms above the edge of river while make sure plant roots is above the ground water

The three main types of hydrologic monitoring are: eco-hydrology, watershed processes, and modeling [2]. Specific information is detailed in Table 2.

Table 2. Three main types of hydrologic monitoring according to Hilary K. McMillan.

Number	Type	Ways	Explain
1	Eco-hydrology	Hydrologic alteration	Detect and quantify changes to flow regime, and related changes to land use and river engineering
2	Watershed process	Process-signature relationship	Predict flow signatures from landscape and climate, relating it to hydrologic signature
3	Modeling	Evaluation	Design model structure, determine required model complexity, state modeling errors, test and application of different models

4.2. Similarity with Land Using and Forest Inventory

The main issue is that all three cases involve dynamic changes, some of which occur rapidly. The challenge lies in traditional techniques not being able to keep pace with these changes; in other words, they require time to detect and reflect information. By the time these techniques complete their detection process, changes in land cover, forest inventory, or hydrologic environments may have already occurred, making it nearly impossible to obtain sufficient and accurate data.

However, remote sensing technology can address this primary issue through its efficiency. Lasers emitted from satellites and other systems can immediately record data, enabling the collection of real-time information within a short period. As a result, the reflected information closely corresponds to the actual structure of the environment being monitored at that precise moment. Additionally, all three cases involve multiple variable aspects. Rather than recording these variables individually, remote sensing technology can provide a comprehensive view of the selected environment. Subsequently, the focus shifts to selecting highly relevant data and employing appropriate analysis methods.

4.3. Problems in Hydrologic Environment Based on Some Preview Analysis

The first challenge is the lack of equipment and core technology [7]. Establishing hydrological monitoring facilities and implementing hydrologic technologies are costly, and many countries or regions lack the resources to undertake these processes independently. Without financial support for experiments and research, it is difficult to develop complex technologies. The solution lies in seeking assistance from larger countries that possess strong experimental capabilities, can provide adequate financial support and facilities, and most importantly, have skilled technicians. Hydrological inspection is highly specialized and technical work that requires support from a workforce with expertise and skills [7]. Therefore, the involvement of professionals can significantly reduce errors and enhance efficiency. Advanced equipment is also essential, as even minor errors can disrupt monitoring processes when observing dynamic objects.

Additionally, regional monitoring is a common approach worldwide [8]. Rivers serve as typical units for monitoring the hydrologic environment and water sources globally. However, variations in methods proposed by different governments lead to significant differences in recorded data types and subsequent analyses [8]. Consequently, synthesizing results from different sections of a river becomes challenging. This fragmented approach limits the effectiveness of monitoring processes, as regional data alone cannot provide a comprehensive picture of the entire river system, rendering much of the analysis futile without integrating all available data.

Lastly, pollution in certain regions hinders monitoring processes. Severe contamination skews collected data, making it unreliable for representing standard conditions of the object. Therefore, addressing environmental issues, particularly pollution in wetlands, is crucial before commencing the monitoring process.

5. Remote Sensing Application in Hydrologic Environment Analysis

5.1. Advantage of Using Remote Sensing Technology

Remote sensing technology has high priority in the hydrologic environment monitoring process due to its effective and continuous capabilities [9]. Nowadays, remote sensing data is ubiquitous worldwide, and with advancements in satellites, drones, and other remote sensing facilities, this technology is being applied to numerous processes. The key to remote sensing technology lies in its sensors, including optic sensors, thermal infrared sensors, microwave sensors, and LIDAR systems. These sensors operate in diverse environments and provide large-scale data efficiently. Remote sensing datasets exhibit typical characteristics of big data, known as the '5V' characteristics: large volume, variety, fast update velocity, veracity, and great potential value [9]. These features enable remote sensing technology to effectively collect diverse data simultaneously within a short period, establishing connections between hydrologic environments and other ecological systems and providing ample information for further analysis.

Furthermore, the trend in scientific research increasingly revolves around big data analysis [9]. Thus, techniques capable of handling a wide range of data quickly are essential for modern processes. Remote sensing technology aligns with this trend and holds significant potential for future studies.

5.2. Recent Analysis Comparing to Other Models

Remote sensing technology can assist in hydrologic monitoring in essentially three ways. First, remote sensing products are commonly used as model inputs in hydrologic monitoring processes [1]. Remote sensing technology provides basin information to the model and facilitates the collection of a wide range of data for integration into the system.

Secondly, it is applied to parameter estimation [1]. Many hydrologic models involve numerous parameters that are challenging to obtain accurately. Therefore, these parameters require calibration to achieve the best-fit values that ensure optimal correlation between the model and variables [1].

Thirdly, remote sensing technology is applied to state estimation, also known as data assimilation, to enhance model simulations by integrating observations and improving the estimation of state variables [1]. Various data assimilation methods have been proposed, including direct insertion, where real-time data is compared with current model values and directly substituted to refine the model and produce more accurate results.

There are several examples of remote sensing technology applications in hydrologic environment monitoring. For instance, experiments using water spectral reflectance can assess sediment content feasibility and determine optimal band choices [10]. Additionally, Yuqing W. and colleagues conducted studies using hyperspectral remote sensing imagery to detect water depth and study water contamination [10].

Another approach involves deep learning models. Convolutional Neural Networks (CNN) are commonly used in deep learning systems and consist of input, convolutional, pooling, dense, and output layers. The convolutional layer is pivotal in CNNs, performing convolution operations when data pass through it [11]. Xu C. and colleagues developed integrated deep learning models (CNN-LSTM and CNN-GRU) using MATLAB. Their approach involves generating feature maps from initial data using CNN, converting these features to LSTM format for flow prediction and model construction, and using Sigmoid activation functions to output the results [11]. They tested their model using hydrologic data and found that initial watershed states affect its performance, indicating that deep learning models are less effective for time series simulations compared to more stable hydrologic models suitable for long-term predictions [11]. Despite differences between calibration and validation periods, both modeling methods perform similarly [11].

5.3. Shortage on Analysis

The primary challenge lies in the cost of operating the entire remote sensing modeling system, as mentioned earlier. Most countries or regions cannot muster sufficient financial resources to sustain a remote sensing system. Therefore, they find it more suitable to rely on other traditional and common processes. Furthermore, since all subsequent analyses hinge on models built from data collected by remote sensing systems, even a minor error can significantly impact the final output. Careful selection and data assimilation are imperative to avoid futile analyses.

In addition to these fundamental limitations at the technological level, several other obstacles exist. For instance, the proliferation of massive heterogeneous data creates new gaps, while inefficient water environment monitoring stems from low spatiotemporal resolution. Moreover, the low accuracy of water quality estimation models results from the complex composition of water and inadequate atmospheric correction methods for aquatic environments [9].

6. Conclusion

Remote sensing technology is a data collection technique that plays a crucial role in monitoring processes across various scenarios. Many of these cases involve rapidly changing variables, making it difficult for traditional detection methods to gather real-time data promptly. However, with the support of different sensors, remote sensing systems can quickly and effectively collect relevant data. Advanced remote sensing technology can provide a three-dimensional structure of the selected objective, facilitating further analysis based on comprehensive diagrams.

The monitoring of hydrologic environments relies on controlling hydrologic signatures, and there are several effective methods for this process, with modeling being the most efficient in providing direct output data. The application of remote sensing technology in hydrologic environment monitoring processes can be categorized into modeling inputs, parameter estimation, and data assimilation.

Remote sensing technology excels in long-term monitoring, which is essential for environments characterized by constantly changing conditions that require sustained observation.

Given the necessity for direct and continuous data in cases like hydrologic environment monitoring, effective solutions based on remote sensing and big data analysis can enhance natural change monitoring. Big data analysis is increasingly prevalent in scientific fields, where the collection and selection of diverse data types are core steps. Therefore, the ability to handle large volumes, diverse types, rapid updates, ensure data veracity, and exploit their potential value—commonly referred to as the '5V' characteristics—is crucial for future data analysis.

Remote sensing technology already possesses the capability to fulfill these requirements. Future data collection techniques based on it can offer significant advantages and substantial assistance in natural monitoring and protection efforts.

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