

REVIEW

Remote Sensing Approaches to Track Climate-Induced Changes in Hydrological Systems

Zhenghao Han, Zhigang Ye *, Ying Zhou, Yin Cao

College of Geographical Science, Inner Mongolia Normal University, Hohhot 010022, China

ABSTRACT

Climate change is rapidly altering hydrological systems through changes in precipitation patterns, increase the rate of glacier retreat rates, altered snow dynamics, and groundwater stress. Although remote sensing has been extensively deployed in hydrological research, existing reviews typically focus on a single hydrological variable or on particular satellite missions. The review synthesizes remote sensing technologies to monitor climate-related hydrological variations across various components of the water cycle. It is a systematic examination of major satellite missions, sensor technologies, and analytical methods used to monitor precipitation, soil moisture, snow cover, surface water processes, and groundwater variability. The review will employ a structured literature review methodology, focusing on recent peer-reviewed articles that apply optical, microwave, radar, and gravimetric remote sensing methods for hydrological monitoring under changing climatic conditions. It has paid specific attention to the provision of the comparative capabilities, spatial-temporal resolutions, and practical applications of key satellite missions, such as Landsat, Sentinel, MODIS (Moderate Resolution Imaging Spectroradiometer), GPM (Global Precipitation Measurement), and GRACE (Gravity Recovery and Climate Experiment). Moreover, to illustrate the use of remote sensing in detecting glacier retreat, drought formation, and coastal groundwater salinization, regional case studies are selected and analyzed. The review identifies new opportunities to use multi-sensor data, machine learning, and high-resolution monitoring to enhance hydrological analyses. This study is useful in practice by synthesizing existing technological opportunities and research trends to enhance climate-responsive water resource

*CORRESPONDING AUTHOR:

Zhigang Ye, College of Geographical Science, Inner Mongolia Normal University, Hohhot 010022, China; Email: 20090034@imnu.edu.cn

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monitoring and by outlining future research directions in remote sensing-based hydrological analysis.

Keywords: Remote Sensing; Climate Change; Hydrological Systems; Water Resource Management; Satellite Monitoring

1. Introduction

Hydrological Systems are very sensitive to climatic variability and long-term climatic change. Climate change, including rising temperatures, shrinking glaciers, and rising sea levels, is significantly affecting the water supply, flow of rivers, groundwater reservoirs, and snowpacks in most parts of the world. The implications of these changes are significant for the management of water resources, agricultural output, ecosystem sustainability, and the risk of disasters related to floods and droughts. This, in turn, has made ongoing observation and proper evaluation of hydrologic processes even more significant regarding comprehension of alterations caused by climate, as well as facilitating competent water management measures^[1-5].

Conventionally, hydrological observation has been ground-based, including rain gauges, streamflow stations, and groundwater monitoring wells. Whereas these measurements are reliable sources of local information, they are, in most cases, sparse, uneven, and limited in their coverage, especially in remote or developing areas. Also, long-term monitoring networks may also be expensive and difficult to maintain. These shortcomings limit the capacity of traditional observation systems to observe both large-scale hydrological processes and fast-changing environmental processes.

The power of remote sensing has been realized as a means of addressing most of these shortcomings through allowing scale and repetitive study of both the surface and the atmosphere of the Earth. The satellites and air-based platforms, and unmanned aerial vehicles have become useful in monitoring important hydrological parameters, including precipitation, soil moisture, snow cover, glacier behavior, surface water cover, and groundwater storage. The growing potential in satellite missions and sensor technologies has greatly enhanced the observation of the hydrological processes through various spatial and temporal levels^[6,7].

Although the number of papers utilizing remote sensing in hydrological research studies is increasing, the literature review tends to center on one or another of the hydrological elements, individual satellite missions, or methodology. This

has led to the fact that integrative reviews, which have synthetically integrated the potentials of various remote sensing technologies in order to trace the climate-induced changes that occur in the entire hydrological cycle, are still lacking. Moreover, there has been a lack of consideration of comparisons between the capabilities and the constraints of different satellite missions and sensor systems in a common framework.

Thus, the purpose of this review is to conduct an in-depth synthesis of the application of remote sensing to track changes in hydrological systems caused by climate. The paper is an assessment of key remote sensing technology, satellite missions, and analysis techniques employed to monitor the important hydrological variables such as precipitation, soil moisture, snow cover, surface water dynamics, and groundwater variability. Moreover, case studies are selected, and they are discussed in a way to explain how remote sensing can be used in cognizing climate-related hydrological changes in various environmental scenarios. This review aims to provide better monitoring strategies and future research in climate-driven hydrological studies by combining existing knowledge and emphasizing future research directions^[8-11].

2. Climate Change and Hydrological Systems

Human activities, especially the burning of fossil fuels, deforestation, and industrialization, which are the main causes of climate change, are generating significant changes in the world's hydrology. These systems, which include processes involving the precipitation, streamflow, groundwater recharge, snowmelt, and the allocation of wetlands, are part of the process of offering the water resources they need to the ecosystems, agriculture, industry, and human consumption. With increasing climate warming of the earth, the hydrological cycle is changing dramatically, and this has led to a shift in the distribution of water resources. These transformations are posing a threat to water security, the ecosystem, and human livelihoods, which will require deeper insight into

the effects of climate change on the hydrological systems and the monitoring indicators that can be applied to track the shifts. Remote sensing technologies have also become very critical in monitoring and reasoning about such changes, and enable scientists and policymakers to make knowledgeable choices about water management and climate adaptation measures^[12,13].

2.1. Overview of Climate-Induced Changes in Hydrology

Climate change is transforming the hydrological systems in many ways. The change in the pattern of precipitation is one of the most important effects since it forms the basis of most hydrological processes. With the warming of the global climate, more moisture can be held in the air, and the precipitation levels, frequency of precipitation, and distribution are altered. This, in its turn, leads to (and causes) major changes in the regional hydrological systems. There are parts where the magnitude of rainfall is on the rise, thus causing floods, and there are areas where droughts are prolonged, and therefore, the water supply is reduced. The variations in the precipitation pattern are not globally homogeneous but have a lot of variation in different regions and latitudes^[14].

The change in the precipitation patterns also directly affects the runoff timing and quantity. Flooding and drought conditions have been exacerbated by the changes in seasonal hydrological dynamics in most areas as a result of the rising intensity of rainfall during the wet season and decreased rainfall during the dry season. This consequently puts more pressure on water-based systems, including agriculture and urban infrastructure^[15].

Other than the alterations in precipitation, glacier melting, and ice sheets, which occur due to the increase in temperature, are another significant impact of climate change. The melting of glaciers releases water in rivers and lakes because glaciers act as natural water storage systems. This can help in augmenting water supply to downstream populations in the short term. But in the long run, as the glaciers melt and eventually vanish, the water flow of these sources decreases, which is quite threatening to the water supply of highly glacially dependent areas, including those of the Andes, Himalayas, and Central Asia^[16].

The withdrawal of glaciers also changes the time when water is available since there is an early onset of snowmelt,

which impacts the seasonal water flow patterns of rivers. Such alterations may cause shortages of water and imbalances in ecosystems in areas that depend on snowmelt to provide water in the dry season. These changes in the timing of the snowmelt can be attributed as a direct result of the warming temperatures and the decreasing levels of the level of snow accumulation phenomena which is very sensitive to the climatic conditions^[17].

In addition to this, the increasing sea levels, which are a result of both thermal expansion of seawater and polar ice melting, are impacting coastal aquifers by enhancing the intrusion of saltwater. As the levels of sea rise, fresh water aquifers along the coast are also exposed to the seawater, which contaminates the water, causing salinity to increase. This is at risk of affecting the availability of fresh groundwater to be used in agriculture and also by human beings, especially in the low-lying coastal areas, where groundwater is a major source of water^[18].

2.2. Hydrological Indicators of Climate Change

To identify and evaluate the effects of climate change on hydrological systems, there is a need to observe certain hydrological indicators that denote the water cycle changes. These pointers are streamflow, water levels, soil moisture, snow cover, evapotranspiration, and vegetation health. The observation of these indicators gives the essential information regarding the dynamics of the hydrological system changes and the areas that are most susceptible to the impact of climate change. The remote sensing technologies have proved to be essential in monitoring these hydrological indicators in extensive spatial regions, as well as at high temporal frequencies, providing an international view of the water assets^[19].

Streamflow is one of the most observed hydrological indicators, which represents the quantity of water flowing in rivers and streams. Alteration of streamflow is directly related to the alteration in precipitation, the timing of the release of the snow, and land use. The streamflow in most areas is increasingly getting unpredictable and is rising in frequency, whereby there is excessive flow when it rains heavily and less flow during dry seasons. Streamflow monitoring is critical in the management of water resources, especially in areas that depend on rivers to irrigate, to generate power, and to drink water. The remote sensing systems, like the

GRACE system, offer quality information on the change in the water storage and can be compared to the change in the streamflow, and this information can be used to enhance the standards of water management^[20,21].

The other important hydrological indicator is the groundwater, which is a vital source of farming, drinking water, and the sustainability of the ecosystem. Altered precipitation patterns and the rising water demand brought about by climate change regularly tend to influence the changes in the groundwater levels. Groundwater resource depletion is a very important issue in most arid and semi-arid areas where groundwater is the main source of freshwater. GRACE gravimetric data and satellite radar altimetry can be used as some of the sources of valuable data on trends in groundwater storage. Such information aids in the detection of zones that are experiencing over-pumping of the groundwater, or diminishing recharge rates following changing rainfall patterns, resulting in long-term groundwater depletion^[22].

Another indicator of water availability is soil moisture. The balance of soil moisture from precipitation, evaporation, and infiltration is reflected in the changes in soil moisture. The moisture content of soil is one of the main determinants of crop productivity, as well as the occurrence of drought and floods. There is real-time information on soil moisture on the Earth using satellite-based sensors, including the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) missions. The observations are invaluable in drought monitoring, early warning mechanisms, and agricultural planning since they aid in extrapolating the areas where water stress might be experienced^[23].

The important hydrologic indicators also include snow cover and the date of snowmelt, especially in areas that rely on the date when snow melts to provide water in the dry season. The quantity of snowfall and when it melts can influence the supply of downstream water, especially in the western United States, the Andes, and the Himalayas. The extent of the snow cover and the time of snowmelt are extensively determined with the help of satellite-based systems like MODIS and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E). Even variations in these patterns may result in drastic alterations of the seasonal cycle of rivers, with early melting of snows leading to a surge of water in

spring, and then decreased flow in summer. Such changes may have adverse effects on agriculture, the generation of hydropower, and systems that need a year-long water supply^[24,25].

Lastly, the vegetation health and land use changes also give crucial information on how climate change affects water availability and ecosystems. Vegetation stress is monitored using remote sensing data that includes vegetation indices such as the Normalized Difference Vegetation Index (NDVI), which are highly correlated with water availability and climate conditions. Vegetation health changes may predict water scarcity or water availability change, especially in areas that are reliant on rainfall. Also, hydrology systems may be altered by human activities like land use (deforestation or urbanization), which affect the infiltration of water, the rate of evapotranspiration, and the total water balance within an area.

3. Remote Sensing Technology for Hydrological Monitoring

Remote sensing technologies are now considered important tools to monitor the dynamics of the hydrological systems affected by climate change. Such technologies offer useful information on hydrological variables like precipitation, soil moisture, streamflow, snow cover, and groundwater that are of great importance in explaining the effects of climate change on water resources. Remote sensing will be useful in tracking these variables over spatial and temporal scales that otherwise cannot be tracked using the conventional ground-based approaches. This section discusses the various remote sensing platforms: satellite-based and ground-based platforms, and high-resolution platforms, which are employed in hydrological monitoring and in monitoring and understanding of the hydrological changes^[26–29]. **Figure 1a** gives an overview of the components in the dynamics of hydrological systems that highlight the key factors that affect them. The complexity of the study of the processes of climate is emphasized in **Figure 1b** as it indicates the need to have an integrated observation system that integrates ground-based, airborne, and space platforms to obtain a wide spectrum of environmental data.

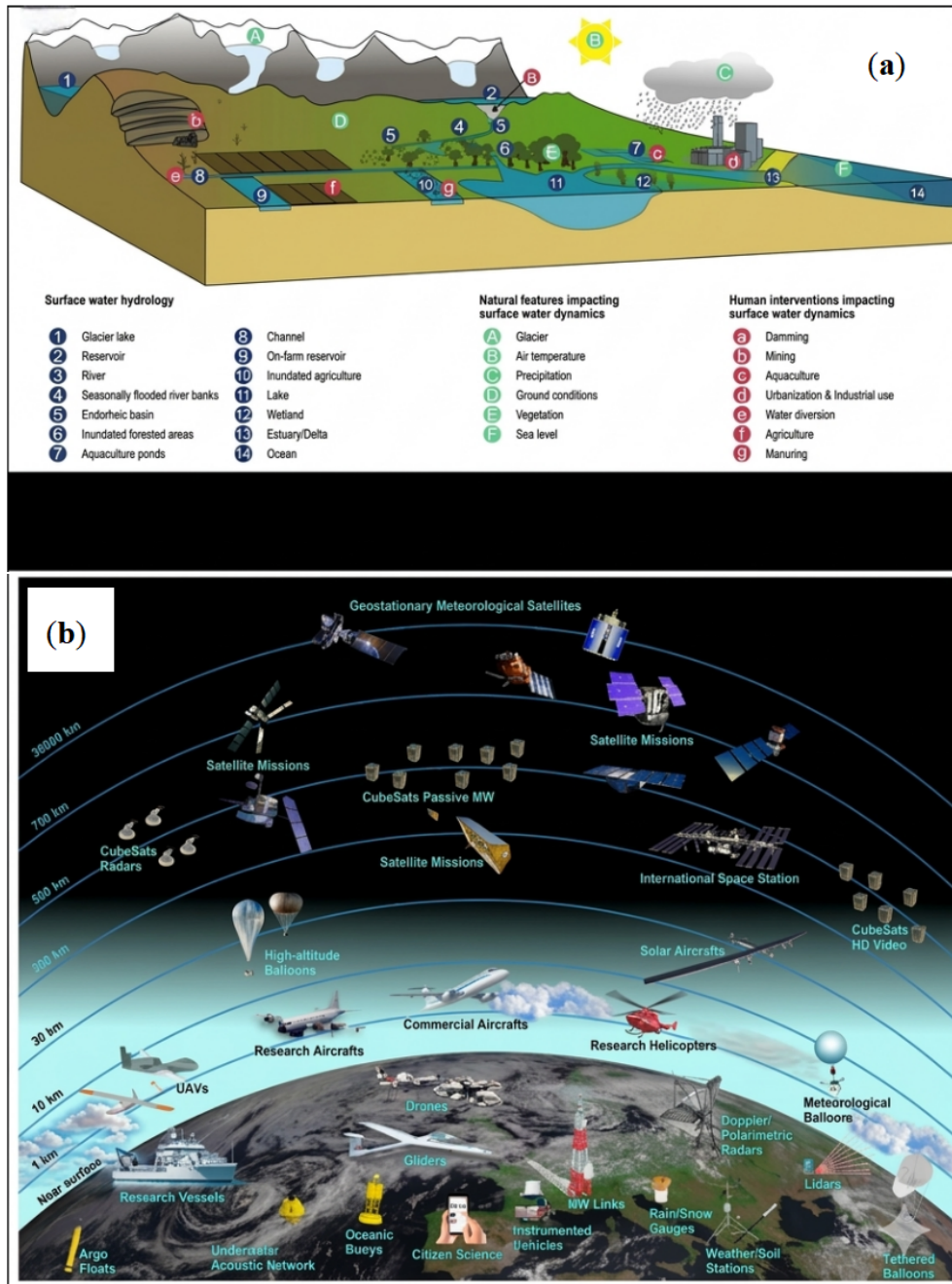


Figure 1. (a) Summary of the elements and variables that affect the dynamics of hydrological systems^[27]; (b) A case of the integrated observation system, which involves ground, air, and spaceborne systems, is necessary in the analysis of complicated climate processes^[29].

3.1. Satellite-Based Remote Sensing Platforms

Among the most essential tools for tracking the large-scale changes in hydrology is satellite-based remote sensing. The satellites provide the capability of recording global data about the hydrological systems, which gives valuable information on the precipitation, surface water, soil moisture content, and snow cover over expansive areas. The most sig-

nificant benefit of remote sensing via satellite is that it can provide constant and extensive observation of hard-to-access or inaccessible areas. Several satellite platforms have been designed specifically to monitor different aspects of hydrology^[30]. **Table 1** provides an overview of satellite missions, including Landsat, Sentinel, and GPM, which are utilized in hydrological monitoring, their sensors, spatial resolution, and the most important applications.

Table 1. Remote Sensing Satellite Missions for Hydrological Monitoring.

Satellite Mission	Launch Year	Primary Sensors	Spatial Resolution	Temporal Resolution	Key Hydrological Applications
Landsat	1972	Multispectral (OLI)	30 m	16 days	Surface water, land use, vegetation health
Sentinel-1	2014	Synthetic Aperture Radar (SAR)	10 m (SAR)	6–12 days	Surface water, flood monitoring, land subsidence
GPM	2014	Dual-frequency Precipitation Radar (DPR)	5–50 km	3 h	Precipitation estimation
MODIS	1999	Moderate Resolution Imaging Spectroradiometer	250 m to 1 km	1–2 days	Snow cover, vegetation health, surface temperature

One of the oldest and most popular sources of satellite imagery is the Landsat program, which has been in use since 1972. The Landsat satellites have multispectral sensors that are designed to record visible and infrared light, which enables them to monitor the surface features of the land in great detail, such as vegetation, water bodies, topographical features, moisture, and soil. The temporal resolution of Landsat, which is at the order of 16 days, offers useful data to be used in the analysis of long-term variations in surface water, vegetation health, and changes in land use. These satellites especially come in handy during the monitoring of changes occurring in surface water bodies, as well as in the detection of floods or droughts and effects of land use changes on hydrological systems, including urbanization and deforestation. The Landsat long-term archive will be invaluable in getting an insight into how the hydrological situations have changed over the past few decades^[31].

The Sentinel missions, which are the Copernicus program of the European Space Agency, offer high-resolution and high-frequency data, which are essential in hydrological monitoring. An example of this is Sentinel-1, which has Synthetic Aperture Radar (SAR), is quite useful in the dynamics of surface water. SAR is not limited to optical imagery, like the cloud cover, and is also useful in all weather conditions, unlike optical remote sensing, which may not be efficient in such areas due to the frequent cloud cover. Sentinel-1 is utilized to observe the changes in surface water through floods and alterations in river or lake extents. It is also used in monitoring the subsidence as a result of groundwater extraction or variation in water levels. In the meantime, the Sentinel-2, an optical sensor with multispectral data, is applied in land surface properties, vegetation health, and soil moisture monitoring. The Sentinel satellites undertake near-real-time data,

meaning that there are fast updates to the changes in hydrology, which is especially relevant in disaster management and early warning of floods and droughts^[32,33].

The instruments on the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites, known as the MODIS (Moderate Resolution Imaging Spectroradiometer), offer constant measurements of the surface of the Earth, although the instruments are concerned with extensive environmental surveys. MODIS is a medium-resolution (around 250 meters to 1 kilometer) data source that offers vital data regarding snow cover, vegetation, surface temperature, and water availability. There is a global coverage of the MODIS, and it has been extensively applied in monitoring the changes in the snow cover and the magnitude of snowmelt over time, which has a direct effect on streamflow in snow-dependent areas. The MODIS data come in especially handy in tracking the vegetation health changes that may be indicative of water stress in the agricultural areas and monitoring the large-scale precipitations and their impact on the hydrology^[33,34].

The other valuable satellite in hydrological monitoring is the Global Precipitation Measurement (GPM) satellite, which measures the precise rainfall data worldwide. GPM Core Observatory, which was opened in 2014, utilizes state-of-the-art radar and microwave sensors to estimate the rainfall in near real-time. The GPM information would prove especially useful in the monitoring of the intensity of rainfall that plays a key role in hydrological modelling, flood prediction, and drought monitoring. With the change in the patterns of precipitation as a result of climate change, the capability to measure the rainfall at global scales and very accurately is crucial in tracking and predicting the hydrological patterns, especially in areas that are susceptible to adverse weather conditions^[35,36].

3.2. Ground-Based Remote Sensing Approaches

Although satellite-based remote sensing can be important in terms of broad-scale data, rain-based remote sensing methods can offer high-resolution data, which forms the basis of localized hydrological observations. Such techniques are quite handy to monitor the variation in certain hydrological features and validate and calibrate satellite data. On-ground sensors, e.g., those in soil moisture networks or groundwater monitoring systems, may provide on-the-ground information on the hydrological situation in particular locations.

Unmanned Aerial Vehicles (UAVs), also known as drones, have gained popularity in hydrological surveillance because of their high-resolution data at relatively affordable prices. Many types of sensors can be installed on UAVs, such as multispectral cameras, LiDAR (Light Detection and Ranging), and thermal infrared sensors. Such sensors enable UAVs to obtain finer images of coverage of surface water, health of the vegetation, and the soil moisture level. Unmanned aerial vehicles are especially applicable in the survey of small-scale hydrological regions, including temporary streams, ponds, or small wetlands, that could be challenging to identify using satellite imagery. Furthermore, in the case of extreme weather conditions, like flooding, UAVs can be activated quickly enough to gather data, which will allow monitoring the situation and estimation of damage. They can fly low and capture high-resolution images, which means that they can make more detailed measurements than satellites can, especially in regions where fine-scale changes are to be monitored^[37,38].

Ground-based sensor networks are the other significant element of the hydrological monitor. These networks involve several different sensors that are used to measure various parameters of the hydrological cycle. The application of water in the soil is done through soil moisture sensors that are commonly used to know the water content of the soil, which is vital in determining the drought condition, the availability of water to be used by crops, and the general balance of water in an area. Piezometers are groundwater sensors that are employed to track any changes in the groundwater levels, which are important in the storage of the groundwater aquifer as well as the effects of groundwater extraction. Such sensors can be commonly installed in places where groundwater is an important source of agricultural or drinking water. The water

levels of rivers, lakes, and reservoirs are measured using surface water sensors, and this is necessary to check flood occurrences, water availability, and water storage changes. Ground sensor measurements can be combined with satellite remote sensing data to provide a more complete picture of the situation in terms of hydrology^[39,40].

3.3. High-Resolution and Large-Scale Monitoring

High-resolution monitoring is an important part of hydrological research, especially to monitor items of small scale which may cause an important local or regional effect. This is because, although satellite data gives broad-scale measurements, small-scale measurements are required to track local hydrological processes like temporary rivers, small-scale flooding, and small reservoirs. Also, the detailed high-resolution information is essential to examine the fine-scale interactions between land cover, water resources, and human activities^[41].

Both commercial and government satellite imagery have become more and more available in high resolution. There are also platforms like WorldView and GeoEye run by companies like DigitalGlobe that have spatial resolutions as small as 30 cm. Such a detailed level can be able to identify minor hydrological alterations that could not otherwise be identified, e.g., small-scale alterations in small water bodies, wetland areas, or irrigation infrastructure status. These satellites come in handy, especially in keeping track of the water management systems in the cities, the extent of risk of floods, and also monitoring the quality of water in the smaller water bodies^[42].

Data fusion methods, which involve integrating the data of various remote sensing platforms, allow integration of high-resolution imagery with lower-resolution yet more frequent data. This can be used to monitor both the fine-scale and the large-scale observations in order to increase the capacity to examine hydrological changes in the course of time. As an example, the integration of high-resolution optical data collected by UAVs and SAR by Sentinel-1 can be conducted to offer a more comprehensive insight into the dynamics of surface water as well as the dynamics of soil moisture. In the same vein, the combination of the ground sensors data and the satellite records can enable more precise monitoring of the hydrological indicators both locally and

globally^[43,44].

Besides high-resolution images, real-time and near-real-time monitoring is needed to respond to the rapid processes in hydrological systems, e.g., in floods or droughts. Platforms like Sentinel-1, which are remote sensors, will give near continuous data, which is gathered at a frequency, though it is frequent, giving the opportunity to monitor hydrological changes as they happen. The SAR ability of Sentinel-1 is more practical in flood monitoring because the camera can observe the flux of water even when it is cloudy. This real or near-real-time provision of data is essential in disaster management, early warning, and quick reaction to extreme hydrological phenomena^[45].

To sum up, remote sensing technologies, whether it is satellites, such as Landsat, Sentinel, and GPM, or ground-based sensors and UAVs, are invaluable in hydrological systems remotely, under the conditions of climate change. These technologies offer useful information, which advances our perception of hydrological variations, assist in monitoring important hydrological signals, and shape water management policies. Integrating high-resolution information and extensive scale surveillance, remote sensing provides an opportunity to conduct a complete measurement of the local and global hydrological processes and represents essential materials to adjust and adapt to the impact of climate change on water resources. In the following part, the discussion

will focus on the particular remote sensing methods to detect the main hydrological parameters like precipitation, soil moisture, snow cover, and surface water^[46].

4. Key Remote Sensing Techniques for Tracking Climate-Induced Hydrological Changes

Remote sensing technology is invaluable in monitoring the hydrological systems that are affected by changes in climate. Remote sensing has made important contributions to our knowledge about the impacts of climate change on water resources in terms of the critical hydrological variables. The critical hydrological indicators, including precipitation, soil moisture, and snow cover, together with the most appropriate remote sensing methods to monitor these values, are described in **Figure 2**. In this section, the most important methods of remote sensing will be examined to monitor the hydrology changes brought about by climatic conditions. In particular, it will touch upon the application of remote sensing to track the processes of precipitation, soil moisture, snow cover, surface water, and groundwater, which all depend directly on the changing climatic patterns. These methods offer important information to make decisions on water management, climate adaptation, and the reduction of risk of disasters^[47,48].

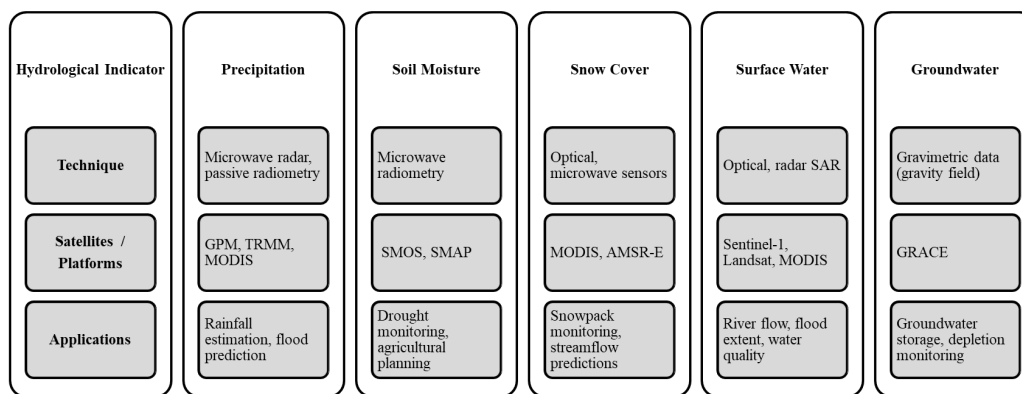


Figure 2. Flowchart of Remote Sensing Applications in Hydrological Monitoring.

4.1. Precipitation Estimation and Extreme Events

Hydrological processes are mainly caused by precipitation, and any changes in precipitation patterns as a result of climate change are significantly affecting water availabil-

ity, flood risk, and drought. Surveillance of precipitation is very important in order to understand such transformations and forecast extreme weather patterns. Remote sensing has been a key element in the estimation of precipitation on a global scale, as well as in near-real time, which is critical for effective water resource management and early warning

systems^[49,50].

The satellites like Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Measurement (GPM), and others have enabled very precise and frequent measurements of rainfall. These satellites have sophisticated radar and microwave detectors that determine the rate and volume of precipitation, which gives a worldwide outlook on the pattern of precipitation. The GPM Core Observatory, which has the Dual-frequency Precipitation Radar (DPR) and a Microwave Imager (GMI), gives high-resolution data on the intensity of the rainfall and is a very useful tool in monitoring extreme precipitation events. Following the changes in precipitation trends, GPM data is used to determine the extremeness of the flooding and droughts, as well as to serve as an input to the hydrological models that model the flow and availability of water in river basins^[51].

The data provided by GPM can be especially beneficial to areas with high rainfall and flood risks, because the data provided by this service is almost real-time, and as a result, it may be integrated into the systems that forecast floods. Monitoring the precipitation with this precision is important to evaluate the effects of climate change on the water resources because some of the most immediate effects of a changing climate are the alteration in the intensity, frequency, and distribution of rainfall. Such remote sensing tools are also important in the knowledge of the changing precipitation pattern due to climate change, which is vital to water managers and policy makers who may be charged with the role of planning future water supply^[52,53].

4.2. Soil Moisture Monitoring

One of the most crucial hydrological variables is soil moisture, which has a direct impact on the availability of water to the ecosystem, agriculture, and human consumption. It is very important in controlling the flow of water via the hydrological cycle, including impacting infiltration, evaporation, and groundwater recharge. Due to the intensified frequency and duration of droughts in some areas due to climate change, the soil moisture has gained more importance in terms of measuring the severity of droughts, controlling irrigation systems, as well as food and water security^[54].

Microwave-based sensors are the key to soil moisture monitoring methods of remote sensing. The European Space Agency launched the Soil Moisture and Ocean Salin-

ity (SMOS) mission, and NASA launched the Soil Moisture Active Passive (SMAP) mission, which is based on passive microwave radiometry to collect soil moisture at the global level. These satellites intercept the natural microwave radiation on the surface of the earth, and this is sensitive to the moisture content in the soil. Both SMOS and SMAP are sources of data on surface soil moisture at a resolution that can be used to support large-scale hydrological surveillance, allowing detection of drought states and hence early warning systems of water stress^[55,56].

The gathered soil moisture data can be used in conjunction with the other hydrological data, using these satellites to increase the precision of drought forecasting and other aspects of water management. The information can be used to monitor soil conditions in real-time, and this will give important insights into the temporal and spatial variation of the availability of water, particularly in areas where ground-based monitoring is either sparse or inaccessible. This is also capable of supporting agricultural planning by predicting the potential yield of crops and also the areas that are likely to face water shortages due to the ability to monitor the soil moisture of large areas^[57].

4.3. Snow and Ice Monitoring

The snow and ice are very crucial in global hydrology, especially in areas that use snowmelt to deliver water during the dry season. Glaciers and snowpacks in most mountainous areas serve as natural reservoirs, where water is stored in the form of ice and is released through processes of snowmelt, which is added to the flow of rivers. Climate change is, however, increasing the rate of melting glaciers and changing the amount and time of snow melt. It is imperative to monitor the snow cover, snow depth, and the ice mass to be able to predict the nature of the changes on the water resources in particular areas where these variations will impact the availability of water in terms of agriculture and hydropower, as well as drinking water (regions that are dependent on the melting of the ice caps)^[58].

Remote sensors provide an effective tool for observing the state of the snow and ice on large scales. The instrument known as the MODIS is the measurement instrument onboard the Terra and Aqua satellites of NASA, which measures the daily and detailed images of the snow cover and the dynamics of the snowmelt. MODIS data is employed to

monitor the extent of the snow, the time of its melting, and the variation of snow albedo (reflectivity), which is essential in determining how the snowpacks are reacting to the warming of the climate. Spatial resolution of MODIS is adequate in tracking the snow cover over large areas and hence is an invaluable tool in the study of seasonal and long-term transformation in the snow and ice dynamics^[34,59,60].

Besides MODIS, other NASA satellites such as the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), located in the Aqua satellite, also use microwave sensors to record data on snow water equivalent (SWE), which is a direct indication of the amount of water in the snowpack. Microwave sensors are also useful since they do not suffer the impact of cloud cover, which means that the snow and ice conditions can be continuously checked even in areas where the cloud cover is frequent enough to affect optical measurements. Changes in the SWE may be monitored to forecast the trend in the streamflow, especially in areas where snowmelt forms a major part of the river flow^[24].

High-resolution satellite imagery (as in the Landsat series) is also being used to closely observe the detachment of glaciers. Landsat gives a detailed optical and infrared view, which enables the researcher to monitor glacier areas, thickness, and dynamics. The optical image, coupled with radar-based data of Sentinel-1, contributes to the additional power of tracking ice movement, ice shelves, and the variation of glaciers in mass over time. The information is important to unveil the long-term effects of climate change on water supply in glacial areas^[61,62].

4.4. Surface Water Monitoring

Climate change directly impacts the surface water bodies, such as rivers, lakes, reservoirs, and wetlands. Changes in precipitation, higher evaporation as temperatures rise, and a more dynamic snowmelt all have an effect on the surface water availability and extent. Remote sensing techniques are necessary to monitor surface water bodies on large scales and hence determine the change in water extent, quality, and seasonal variations^[63,64].

Synthetic Aperture Radar (SAR) is one of the most popular methods of remote sensing used in monitoring surface water, especially in spotting the variation of water bodies, even in the presence of clouds. SAR is used in the Sentinel-1 operation by the European Space Agency to provide a regular,

high-resolution dataset on the extent and dynamics of surface water. The flood management and flood risk monitoring capacity of Sentinel-1, which allows monitoring small shifts in the water level and detecting flooded territories, renders it invaluable in flood management. Comparative analysis of SAR images made at various times allows the researchers to determine the magnitude of floods, observe seasonal variations in the water bodies, and observe changes in surface water caused by varying precipitation and evaporation patterns^[65].

Besides SAR, optical remote sensing is employed to keep track of surface water bodies. Landsat and Sentinel-2 satellites (that are capable of capturing multispectral data) are often used to monitor the fluctuations in surface water area and the water quality and health of vegetation in wetlands and lakes. These satellites are able to sense the alteration of the colour and turbidity of water, and this information will be vital in the determination of the water quality, which is influenced by the runoff, pollution, and changes in hydrological factors^[66–68].

Specifically, Landsat has played a major role in monitoring the dynamics of large water bodies over time. Through the historical record of the Landsat image, the researchers can evaluate the long-term changes in water surface area, the effects of drought on the reservoir, and observe the increase in water body size through flooding or melting glaciers.

4.5. Groundwater and Surface Water Flow

Surveillance of groundwater and surface water movement is essential in the realization of water availability, especially in areas whose livelihood is dependent on the availability of groundwater used in irrigation and drinking water. The effects of climate change particularly affect groundwater; long droughts may decrease the recharge rates, and the effects of evaporation may empty the surface water sources. Remote sensing has a significant role in measuring the alterations in the groundwater levels, and also in measuring the surface water flow and storage^[69].

Another good option to use in monitoring groundwater storage is satellite altimetry, like the one in the Gravity Recovery and Climate Experiment (GRACE) mission. GRACE records the alteration in the gravity field of the Earth, and this parameter is representative of the alteration in water mass, such as groundwater. This is a method by which, by monitoring the variation in gravitational anomalies over time, one

can trace the variation in groundwater storage within a large area. GRACE data is particularly valuable in the observation of the depletion of groundwater in regions where the groundwater is being over pumped due to excessive agricultural or urban activity^[21].

Besides GRACE, Sentinel-1 SAR data are also utilized in surface water movement and land subsidence associated with groundwater. Where massive groundwater pumping is taking place, the land subsidence can be realized through SAR data, which has direct evidence regarding the depletion of groundwater. It is my capacity to monitor the alterations both in the surface water and ground water that is critical in managing the water resources and the sustainability of water use, considering the changing climate^[70].

5. Case Studies: Remote Sensing Applications in Climate-Driven Hydrological Changes

Remote sensing has been successfully applied in monitoring climate-induced hydrological systems changes in different case studies across the world. These papers demonstrate the application of remote sensing technologies to monitor and deal with the issues of climate change, including the

altered patterns of precipitation, the shifts in the processes of snow melting, water stress, and the rising number of extreme events, including floods and droughts. In this section, some case studies will be discussed on the importance of remote sensing in monitoring hydrological alterations and guiding the management of water resources, disaster management, and climate adaptation plans^[1,71]. **Table 2** gives a summary of the remote sensing applications in the case study items, which shows that there is some variation in the application of satellite and sensor data by the various regions to monitor the hydrological changes due to climatic changes.

5.1. Case Study 1: Drought Monitoring and Water Stress in the Horn of Africa

The Horn of Africa is amongst the areas that are most susceptible to the droughts caused by the climate, and water scarcity is already a major problem for agriculture, food security, and human health. Over the past few decades, droughts have become more and more intense and frequent in the region, causing catastrophic effects on water resources, livestock, and crops. Remote sensing plays a role in observing soil moisture, precipitation, and vegetation health, which are important factors that identify the level of drought and water stress^[72].

Table 2. Remote Sensing Applications in Climate Change-Related Hydrological Case Studies.

Case Study Region	Hydrological Change Monitored	Remote Sensing Techniques Used	Key Findings and Insights
Horn of Africa	Drought, soil moisture, vegetation stress	SMOS, SMAP, MODIS	Soil moisture monitoring for drought early warning
Himalayas	Glacier retreat, river flow changes	Landsat, Sentinel-2, MODIS	Monitoring glacier melt and predicting seasonal river flow
Coastal Southeast Asia	Saltwater intrusion in groundwater	Sentinel-1 (SAR), GRACE	Land subsidence and saltwater intrusion monitoring
Arctic Wetlands	Wetland water level, vegetation health	Landsat, MODIS, Sentinel-2	Monitoring wetland changes and vegetation stress

Remote sensing technologies via satellite, like the SMOS (Soil Moisture and Ocean Salinity) and SMAP (Soil Moisture Active Passive) missions, have helped in monitoring the amount of soil moisture in the region. These satellites can give near-real-time information on soil moisture, which is a direct prediction of drought and water availability. Monitoring soil moisture on a regional scale enables early warning systems whereby the local authorities and communities detect any impending droughts to make preparations and take water-saving measures.

Besides the soil moisture measurements, the satellite

obtained vegetation indices, such as the MODIS and Sentinel-2, have also been employed to track vegetation health. Such alterations as in the Normalized Difference Vegetation Index (NDVI) give information on vegetation stress due to water scarcity. Through time comparison, the satellite data can help researchers determine localities where vegetation is under severe stress, which is usually associated with the lack of water.

The changes in the availability of surface water in the Horn of Africa have also been monitored using remote sensing data, especially with regard to seasonal changes in rainfall

and the effects of drought. These lessons can be used in water distribution planning, water resources management, and enhancing drought response measures^[23,73].

5.2. Case Study 2: Glacier Retreat and River Flow Changes in the Himalayas

The Himalayan Mountain range has been home to some of the largest glaciers in the world, which are very important sources of water to the people living downstream. These

glaciers supply freshwater to the surface as a result of snow melting, especially during the dry season when levels are generally low in rivers. Nevertheless, the Himalayan glaciers are receding due to an increase in temperature, and this event has severe consequences regarding the availability of water in the area^[74–76]. **Figure 3** illustrates the effects of glacier shrinkage on increasing glacial lakes in the Himalayas by way of satellite imaging to show the correlation between the size of the glacier and the river discharge with time.

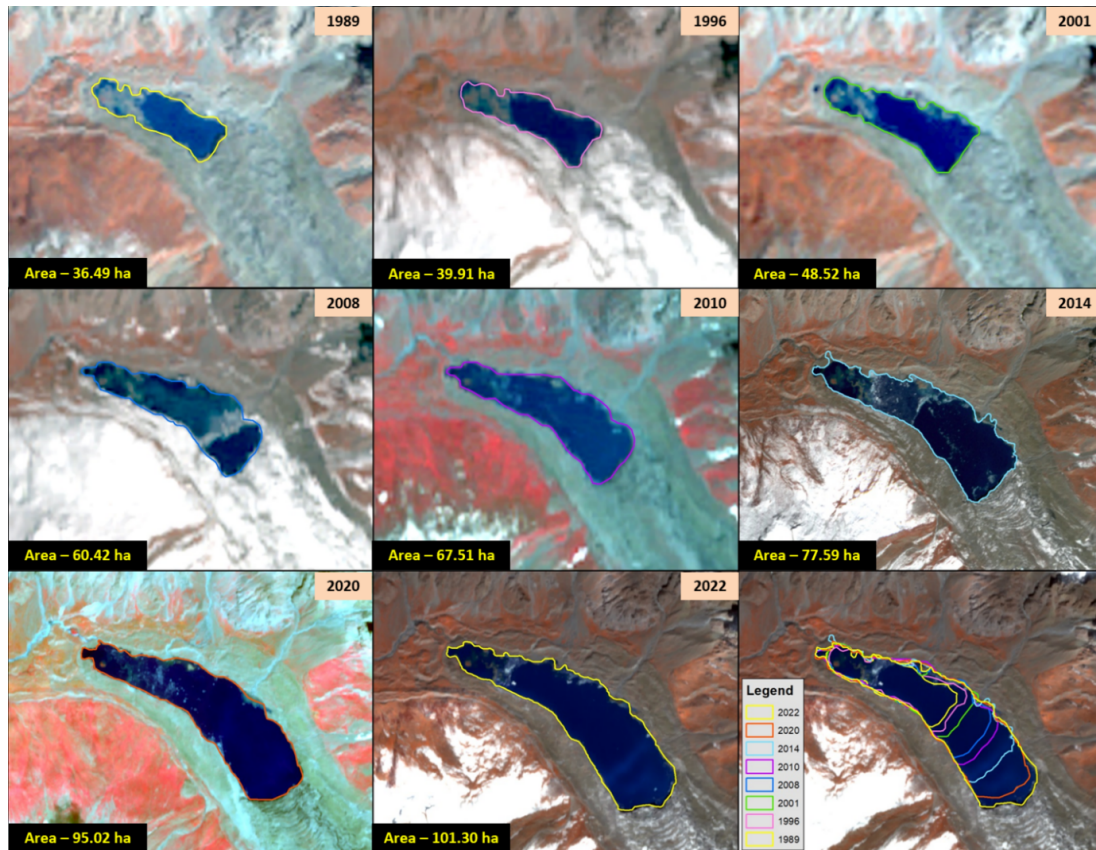


Figure 3. Glacier Lag and Effect on Swelling Glacier Lakes within the Himalayas: Satellite Observations^[76].

The remote sensing instruments have been critical in tracking the changes in the size and quantity of glaciers in the Himalayan Region. The satellites have been used to estimate the extent of glacial surface area and determine their retreating progression on a time scale using the Landsat and Sentinel-2 satellites, which have multispectral sensors. The long-term archive of Landsat, which is several decades old, offers data of invaluable value in terms of learning the historical changes in the mass and area of glaciers. Through comparison of photographs of glaciers at various periods, the scientists can measure the pace at which the glaciers are

melting, as well as be able to predict the future effects of the changes that would be experienced on the river flows^[77].

Besides glacier observation, MODIS and AMSR-E have been applied in monitoring the snow cover and snowmelt timing, both of which affect the river discharge in the area. The time and amount of the snowmelt are becoming increasingly unpredictable as glaciers are shrinking. Satellite data have shown that the earlier snow melts, the more likely it is that a seasonal water shortage will occur during the summer season when water is mostly needed. Remote sensing information can be used to give vital information on

these changes, which is vital in the management of water resources, especially in hydropower generation and irrigation in nations such as India, Nepal, and China [78,79].

The effects of glacier melting on the flow of rivers can be traced by satellite altimetry and other devices of remote sensing, which trace the alterations of the water level and discharge of the rivers fed by glacial melting. These gauges are useful to know the impact of losing glaciers on the long-term sustainability of the water resources in the area, and the possibility of having more flooding due to glacial lake outburst floods (GLOFs) [80].

5.3. Case Study 3: Coastal Groundwater Salinization Due to Sea-Level Rise

Rising sea levels are also causing saltwater intrusion into freshwater aquifers in the coastal areas of the world, beyond which the quality of groundwater is changing signif-

icantly. Groundwater sources are very susceptible to salinity changes and, therefore, in most coastal regions, groundwater depends greatly on freshwater. Over time, with increased sea levels, freshwater supplies are contaminated with saltwater that enters freshwater aquifers, and the consequent result is that there is a decrease in freshwater available to use in agriculture and industrial purposes [81,82]. **Figure 4** shows the fast growth of the suburb of Quinns Rocks between 1984 and 2016, and the IWSS groundwater abstraction between the same years, and the site of the shallow wellfield and the monitoring wells that were developed in 1998. It also indicates higher local abstraction of to the tune of 14 GL/year in 2002, which is indicative of pumping being an added catalyst of seawater intrusion. Remote sensing data has the potential to monitor saltwater intrusion and land subsidence in coastal zones, as demonstrated in **Figure 4**, and can provide important information regarding the consequences of the rising sea level on groundwater resources.

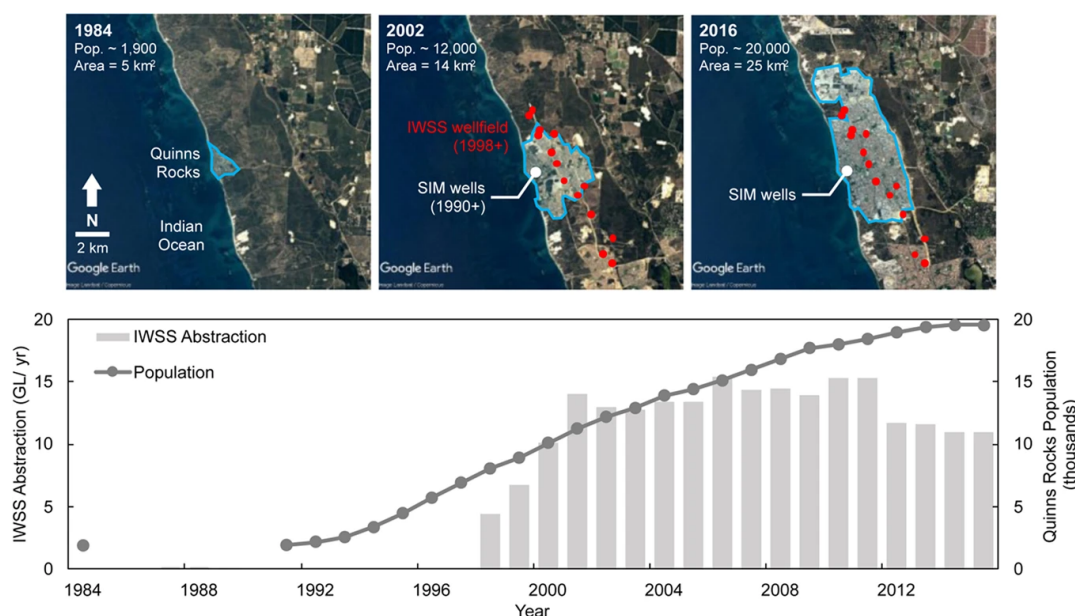


Figure 4. Satellite image of the growth of the Quinns Rocks suburb (1984–2016) (top row) and groundwater removal by the Integrated Water Supply Scheme (IWSS) bore field (bottom row) between the years 1984 and 2016.

Note: The central picture (top row) shows the whereabouts of the shallow regional wellfield, which was built in 1998, and seawater intrusion monitoring (SIM) wells. It was found that the maximum groundwater withdrawal in the local wellfield in 2002 was about 14 GL/year. The rise in the extraction of groundwater during this time is a possible factor in seawater encroachment at the reference site.
Source: Google Earth, Maxar Technologies, 2019 [82].

Saltwater intrusion into coastal aquifers has been monitored and measured by remote sensing. The subsidence of the land along the coast has been observed using the data of Sentinel-1 Synthetic Aperture Radar (SAR), and in most cases, these processes take place due to excessive use of groundwater tables and saltwater intrusion. Using SAR data

and other remote sensing applications, e.g., Landsat and MODIS, a scientist may monitor the changes in land elevation and groundwater storage, which could represent the early warning signs of saltwater intrusion.

Also, changes in groundwater storage in coastal areas have been measured by GRACE (Gravity Recovery and Cli-

mate Experiment) satellite data. GRACE can be used to track the fluctuations in the Earth's gravity field, and therefore, groundwater can be measured as depleting, which is usually made worse by saltwater intrusion. This information is important to know the degree of groundwater salinization as well as its effect on the water supply of coastal communities.

Combining both remote sensing data and hydrological models can assist researchers to forecast the future effects of sea-level rise on coastal aquifers, assist in the development of water management plans, and help policy-makers to make decisions in an effort to reduce the impacts of saltwater intrusion. Such understandings are crucial to coastal areas that use groundwater as drinking and agricultural water resources, particularly given the occurrence of climate change^[82].

5.4. Case Study 4: Monitoring Wetland Hydrology and Climate Change Impacts

Wetlands are very critical in the hydrological cycle because they act as natural filters for water, biodiversity, and water storage. The wetland hydrology has been greatly affected by climate change through the changes in water levels, vegetation, and general ecosystem health. Alterations in the pattern of precipitation, greater evaporation, and a rise in temperature are all causing changes in the wetland ecologies, which cause both the disappearance of wetlands and the deterioration of the available wetlands.

Remote sensing technologies have been exploited a lot to keep a check on wetland hydrology and determine the effects of climate change on wetland ecosystems. The changes in the extent and the health of vegetation have been monitored by using Landsat and Sentinel-2 satellites that have high spatial and temporal resolution. Through the multispectral images, scientists can measure the seasonal changes in water levels within the wetlands, which are usually caused by rainfall, the melting snow, and groundwater levels^[83].

The use of MODIS and SMOS (Soil Moisture and Ocean Salinity) also involves monitoring the content of soil moisture in wetlands, which is an important indicator of the health of wetlands. Wetland drying associated with reduced soil moisture due to variation in precipitation and temperature poses a threat to biodiversity and has negative impacts on the capacity of wetlands to fulfil ecosystem functions such as carbon storage and water filtration.

Other than measuring the wetland area and vegetation

well-being, remote sensing data have also been deployed to determine the effects of climate change on wetland water quality. Optical imagery analysis can be used to identify changes in the quality of water at the surface (e.g., turbidity, nutrient load) that can give useful data on the impacts of climate change on wetland ecosystems^[84].

5.5. Critical Overview of Case Studies and Remote Sensing Technologies

The case studies presented in this section show how remote sensing is increasingly being used to help track climate-related alterations in hydrological systems in a wide geographic setting. The use of satellite observations to identify droughts, glacier melting, and groundwater contamination can be used in other areas like the Horn of Africa, the Himalayas and coastal Southeast Asia. These are just some examples of how remote sensing technologies can offer uniform measurements across a wide area of space and where traditional monitoring networks are inaccessible or do not exist. Yet, since these studies prove significant use, many methodological and technological aspects ought to be taken into serious consideration^[85].

Among the observations made in the reviewed case studies is that multi-sensor satellite datasets were relied on to monitor various hydrological variables. Land sensors like Landsat and Sentinel-2 are generally utilized in the monitoring of surface water, glacier limits, and the stress of vegetation. Conversely, microwave and radar sensors such as Sentinel-1 SAR, SMAP, and SMOS are useful in the determination of soil moisture and flood levels since they are able to work during the cloud-covered days and even during the dark hours. Moreover, missions that use gravity like GRACE allow large-scale observation of the change in groundwater storage. These complementary datasets have enhanced the knowledge of hydrological activities, especially where data is limited.

Regardless of such benefits, there are a number of limitations that are still quite obvious in the discussed case studies. To begin with, the spatial resolution of certain datasets provided by satellites, especially gravimetric satellites like GRACE, is quite coarse, thus limiting their use in localized hydrological evaluations. Second, numerous articles are based on remote sensing data, which is not validated adequately by ground-based measurements, and this may im-

impact the usefulness of the estimated hydrological data. Third, variations in the spatial resolution, frequency of revisit, and data processing methodology may also create uncertainties in the combination of different datasets in a single analysis system.

The other problem, as indicated in the case studies, is the inability to directly relate satellite observations to local-level hydrological processes. Whereas satellite data can be used to identify surface-scale variability, e.g., vegetation distress or water surface area, it is commonly necessary to use further modeling methods to transform observations into measurable indicators of groundwater depletion, river discharge, or ground soil moisture dynamics. The use of models also adds additional uncertainties concerning the choice of parameters and the process of their calibration, as well as the quality of data.

Still, the analyzed articles taken altogether indicate that remote sensing technologies are of great benefit in long-term environmental monitoring and climate change evaluation. Satellite images together with hydrological models and ground-based observations offer a strong platform for comprehending the great deal of hydrological variability and enhancing early warning against droughts, floods, and stress on water resources^[86].

Future studies need to aim at enhancing data integration between multiple sensors, improving ground observations as a reference, and creating better methods of analysis, such as machine learning, to analyze large-scale hydrological data. Moreover, new satellite missions that are of better spatial and temporal resolution will keep on enhancing the accuracy and usability of remote sensing in monitoring hydrological changes caused by climate. Under these circumstances, remote sensing can become more significant to assist in the process of sustainable water resources management in the changing climate conditions.

6. Challenges, Limitations, and Future Directions

Although remote sensing is a powerful tool in the monitoring of change in the hydrological systems caused by climate, it has its challenges and limitations. All these are due to sensor constraints, data resolution, and integration challenges. Moreover, although the development of remote

sensing technologies has been moving at a high pace, the capability to incorporate remote sensing information within efficient hydrological models and decision-making is one of the main areas under continuous development. The section will explore the key issues and constraints involved in remote sensing applications to hydrological monitoring, the solutions to these problems, which are being developed, and where the remote sensing technologies are headed in light of climate change and hydrology^[87].

6.1. Technical Challenges in Remote Sensing for Hydrology

The spatial and temporal resolution of the data is one of the major technical problems of remote sensing applications in hydrological monitoring. Although satellite-based remote sensing systems like Landsat, Sentinel, and MODIS can be useful at the global scale, they are not always adequate to monitor small-scale hydrological units like small streams, wetlands, or localized flooding events. Indicatively, commercial satellites such as the WorldView or GeoEye, which offer high-resolution imagery with sub-meter resolutions, are very expensive and not thorough enough to cover every area. Conversely, the coarser spatial resolution of most free satellite missions (e.g., Landsat at 30 m) might not be appropriate in observing finer-scale hydrological processes, such as small-scale surface water variations or local 3D groundwater variations.

The other technical issue is that of data availability and continuity. The cloud cover sometimes hides the remote sensing data, and optical sensors are unable to detect the data in a tropical area. Although other radar-based systems, such as synthetic aperture radar (SAR) and the Sentinel-1, have the capacity to lift the cloud cover, not all remote sensing platforms have this functionality, and thus, it is difficult to capture consistent data when the weather is extreme. Also, the temporal resolution of the data may occasionally act as a barrier to the usefulness of remote sensing in tracking fast-changing hydrological events, including flash floods or the development of drought. Even though satellites such as Sentinel-1 have a high revisit rate (6–12 days), hydrological events might need to be monitored in real-time at high frequencies, making it not always possible to perform continuous data collection.

Moreover, the accuracy of data and the sensor calibra-

tion are still the persistent issues of remote sensing in hydrology. Although the sensors have evolved over the years, they still need proper calibration when it comes to proper measurements of the hydrological variables, especially the soil moisture, the amount of snow on the ground, and the amount of precipitation. Data mismatch of sensor data, particularly amongst various platforms, can result in discrepancies in hydrological modelling and analysis. Hence, to combine information of various sources, i.e., satellites, UAVs, and ground-based sensors, and to ensure the accuracy of data, it is technically difficult to combine and verify the information^[88,89].

6.2. Data Integration and Modelling Challenges

Remote sensing data proves to be best when integrated with other types of data, including ground-based data, meteorological data, and hydrological models. Nevertheless, there are difficulties in ensuring that these divergent pieces of data come together in a unified system. A significant problem is the spatial and temporal discrepancy of various datasets. As an example, ground-based sensors are usually distributed sparsely and measured at particular stations, whereas satellite data has a global coverage at different resolutions and revisiting frequency. The process of harmonization of these datasets to achieve consistency and accuracy presents a serious challenge to hydrologists and remote sensing scientists^[90].

Besides that, data fusion, which can be viewed as a combination of information collected by various remote sensing systems (e.g., optical, radar, thermal infrared) to achieve more precise or complete datasets, is not only a challenge in the field of technical implementation, but also in the interpretation of findings. The data fusion methods entail advanced algorithms and computational models to combine various types of data, which can possess different spatial resolutions, time frequencies, and units of measurement. The resulting combined information should then be digested and deciphered in a manner that can be useful in hydrological models, which is usually complicated and involves the combination of several hydrological variables.

Another area where challenges are experienced is in hydrological modelling, which is usually applied alongside remote sensing data. These models work on the basis of precise input information to model water flow, the dynamics

of soil moisture, streamflow, and recharge of groundwater. Remote sensing information can be useful in inputting these models, though the quality of the remote sensing information and its combination with other environmental variables, including land use, vegetation cover, and atmospheric conditions, can be very important in terms of the accuracy and performance of the model. Numerous hydrological models are extremely sensitive to the input data, requiring the slightest errors in remote sensing data to cause prodigious inaccuracies in predictions. Moreover, the integration of remote sensing data into hydrological models may be computationally intensive and time-consuming, especially when executing the simulation on a global or regional scale^[11,47,91].

6.3. Limitations in Data Accessibility and Cost

Although remote sensing technology has been developed to a large extent, the availability of quality remote sensing data cannot always be assured, particularly in low-income nations or regions that are under-resourced. Most of the more sophisticated remote sensing systems, including high-resolution commercial satellites (e.g., WorldView and GeoEye), provide high-resolution imagery but are costly, and therefore are challenging to obtain by many institutions or even governments. Conversely, publicly available satellite data, including Landsat or Sentinel, is priceless and yet might be lower in resolution and may not be suitable for the requirements of scale-intensive hydrological study, at least of small-scale objects.

The availability of data may also be a problem in terms of technical infrastructure to be able to process and interpret the remote sensing data. The amount of data produced by remote sensing missions is huge, and the processing, storage, as well as analysis of such data demands huge computing capabilities. Although cloud computing and data platforms such as Google Earth Engine are making remote sensing data more democratic, the ability of most institutions in developing countries to process and utilize such datasets remains a gap^[92].

Besides the cost of data, licensing, and complexity of accessing proprietary data can also be a limitation to the popularization of remote sensing data. Although open-access projects, including Copernicus Sentinel-1 and Sentinel-2, offer free-of-charge data, certain commercial satellite systems have strict licensing protocols, limiting access to them

or making them very expensive. Such inequitable access may impede research and decision-making, especially in places where the monitoring is most required but resources are scarce.

6.4. Future Directions: Technological Advancements and Emerging Solutions

Remote sensing is a rapidly developing field, and it is pursued in terms of sensor technology, satellite missions, and data processing methods, which promise to address most of the existing challenges. The next important development that has been made is the impending Surface Water and Ocean Topography (SWOT) mission, planned to be launched in the near future. SWOT shall offer high-resolution data of the surface water bodies, such as rivers, lakes, and wetlands, on water height and water volume. This mission will improve our capability to observe the level of water availability and the pattern of water flow on the global scale, which will be important in flood forecasting and in managing water resources, as well as adapting to climate change^[8,93].

Along with new missions, artificial intelligence (AI) and machine learning (ML) have provided new prospects for enhancing remote sensing data processing and interpretation. AI and ML algorithms have the potential to be used to detect trends in large datasets, to enhance data fusion methodologies, and to increase the quality of hydrological models. As an illustration, monitoring the water body extent or vegetation stress can be conducted automatically through AI, which will provide near-real-time information about hydrological conditions. Such technologies may also be used to enhance the prediction of extreme weather conditions, including floods and droughts, based on the analysis of trends in large volumes of data and finding early warning signals^[94].

The other area of promise is the enhanced application of unmanned aerial vehicles (UAVs) and drone-based remote sensing. UAVs are also at a significantly lower cost in terms of high-resolution imagery than conventional satellite platforms, and can deliver real-time information on local hydrological aspects, including small streams, wetlands, and flood-prone zones. With the further advancement of UAV technology, it is likely to have a more significant impact on hydrological monitoring in the future, especially in areas with fewer facilities on the ground. On the last note, international agencies, governments, and research institu-

tions' partnership and data sharing will play an essential role in dealing with the challenges of accessing data discussed above. With the increasing availability of remote sensing data in more open-source forms, such as Google Earth Engine, the capacity-building process, especially in low-income communities, will also aid in making sure the fruits of those developments are distributed worldwide^[95].

Remote sensing in the monitoring of climate-induced alterations in hydrological systems has transformed the manner in which we evaluate and manage water resources. Although the problem of data resolution, integration, and accessibility is huge, new technologies, including SWOT, AI, and UAVs, have immense potential to solve the problem. With the ever-increasing advancement of remote sensing technology, it will become an increasingly important resource when it comes to assisting in the management of water resources, especially in the adaptation strategy to climate change and in reducing the risks associated with disasters. The combination of remote sensing data and hydrological models with real-time decision-making applications will be more efficient in responding to the challenges of climate change in the future and make the water resources in a fast-changing world sustainable.

7. Conclusions

Due to climate change, hydrological processes are changing because of the changes in the precipitation process, glacier melting, declining snowpack, and an increased strain on groundwater supplies. These transformations underscore the importance of having good monitoring systems that can record hydrological processes on the huge spatial and temporal scales. In this review, we have discussed how remote sensing tools are vital in tracking climate induced variations in terms of precipitation, soil moisture, snow cover, surface water, and groundwater storage among several important elements of the hydrological cycle.

This review of literature shows that remote sensing has greatly enhanced the capacity of monitoring hydrological processes in areas where traditional monitoring systems are scanty or non-existent. Landsat, Sentinel, MODIS, GPM, and GRACE are some of the satellite missions that offer useful multi-scale measurements, which are used to monitor floods, assess droughts, detect glacier changes, and analyse groundwater variations. Nonetheless, the review also

points out various limitations that limit the full potential of remote sensing for hydrological uses. These are the inconsistencies in spatial and temporal resolving of satellite data, the uncertainties of data processing and retrieval algorithms, and the use of ground-based observations in calibration and validation.

Moreover, most of the available literature considers individual hydrological variables or individual sensor systems and can thus restrict the possibility of considering interactions in the wider hydrological cycle. To overcome this shortcoming, there is a need to better integrate multi-sensor data and to better couple remote sensing observations and hydrological models. Enhancement of the integration of multi-source data, improved validation systems, and the use of more sophisticated analytical techniques like machine learning should be emphasized in future studies in order to enhance the accuracy of satellite-based hydrological estimates. It will be of great importance to strengthen these methodological strategies to maximise the role of remote sensing in climate-resilient water management.

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Conflicts of Interest

The authors declare no conflict of interest.

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