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The Synergy of Remote Sensing and GIS for Enhanced Irrigation Management: A Comprehensive Review

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Abstract

The use of Geographic Information Systems (GIS) has played a crucial role in transforming irrigation management methods via the facilitation of spatial analysis and the enhancement of informed decision-making processes. This study offers a comprehensive analysis of the diverse scholarly literature, case studies, and reports to provide a comprehensive perspective on the multidimensional impact of Geographic Information Systems (GIS) on the transformation of irrigation methods. In order to demonstrate the variety of GIS applications in irrigation management, many case studies are investigated (Irrigation water management, decision support systems, site suitability analysis and Web-GIS), each of which comes from a different geographical setting. It examines GIS application advancements such cloud-based platforms, smartphone apps, and sensor networks. These technological developments make real-time data collecting and analysis possible, which, in the end, improves the precision and timeliness of choices about irrigation. The findings of this analysis provide a foundation for future research in this rapidly evolving topic and enhance our understanding of GIS applications in irrigation management.

Introduction

The emergence of Geographic Information Systems (GIS) and Remote Sensing (RS) in recent decades has significantly impacted various industries [1]. These tools have revolutionized the way spatial analysis is conducted, enabling advanced data visualization and decision-making capabilities. The irrigation industry stands out as one of the most prominent businesses that stands to benefit significantly from GIS and Remote Sensing technology[2]. The incorporation of these cutting-edge technologies into irrigation methodologies has ushered in an era of unparalleled accuracy, efficacy, and sustainability in the realm of water resource administration, revolutionizing the allocation, surveillance, and utilization of water in agricultural environments. The global population is experiencing a steady increase, thereby exerting mounting pressures on agricultural systems to meet the escalating demands for food and ensure the long-term sustenance of communities. In this context, the prudent and effective governance of water resources assumes utmost significance. The irrigation sector, a vital component of worldwide food production, confronts the intertwined task of enhancing water efficiency while mitigating ecological repercussions. Remote sensing and GIS have become crucial in this regard, providing cutting-edge strategies for improving irrigation methods.

Geographic Information Systems (GIS) is a fundamental framework within contemporary geospatial technology. It serves as a versatile tool for the acquisition, administration, examination, and visualization of spatial data. Geographic Information Systems (GIS) seamlessly merge spatial components with corresponding attributes, enabling a comprehensive and dynamic comprehension of real-world situations. Within the domain of irrigation, Geographic Information System (GIS) facilitates the generation of stratified maps that amalgamate data pertaining to topography, soil classifications, land utilization, hydrological patterns, and infrastructure. Using spatial intelligence in irrigation enables professionals to make well-informed decisions by discerning and analyzing trends, patterns, and interconnections within the data.

In addition to Geographic Information Systems (GIS), the scientific realm of Remote Sensing emerges as a groundbreaking discipline that utilizes a diverse array of sensors and imaging apparatuses to acquire valuable data pertaining to the Earth's surface, all from a considerable distance. Images in the visible and infrared spectrums, thermal data, elevation models, and other forms of data may be obtained from space using satellites, Unmanned Aerial Vehicles (UAVs), and airplanes fitted with specialized sensors. The use of remote sensing offers a more complete picture of landscapes, illuminating previously hidden information on the state of the plants, the amount of moisture in the soil, and the distribution of water. This technique, rich in data, may be used with GIS to provide irrigation professionals with instantaneous information and a full knowledge of the many patterns of dynamic water utilization.

In the epoch of water scarcity, the pursuit of precision water management has emerged as a fundamental imperative for the promotion of sustainable agriculture. The integration of Geographic Information Systems (GIS) and Remote Sensing techniques plays a crucial role in conserving soil. This powerful combination allows us to access precise and current data regarding soil moisture levels, meteorological patterns, and the water requirements of our land. Through the integration of this valuable data, it becomes possible to refine irrigation systems to accurately allocate water resources to the specific areas and times where they are most needed. This not only helps to minimize water wastage but also maximizes the potential for optimal crop growth and development. The outcome is a well-optimized irrigation system that efficiently utilizes water resources to achieve maximum crop yields.

Historically, the determination of irrigation strategies has frequently relied upon generalized methodologies that failed to account for the unique variability present within individual fields. Through the utilization of Geographic Information Systems (GIS) and Remote Sensing technologies, the field of precision agriculture experiences a significant advancement. Within a single field, farmers may distinguish different zones with variable degrees of soil richness and moisture content. By designating these zones, it becomes possible to strategically distribute resources, therefore customizing irrigation and fertilization procedures to meet the needs of each zone. The utilization of a data-driven methodology in this context serves to optimize resource allocation, thereby reducing the expenditure associated with inputs. Furthermore, it facilitates the augmentation of productivity levels, while concurrently mitigating the adverse effects on the environment.

The optimal irrigation requirements are contingent upon the robustness and vitality of the crops. Remote sensing technologies, such as multispectral and thermal images, have the capability to detect stressed vegetation even prior to the appearance of apparent signs. Geographic Information System (GIS) platforms have the capability to integrate remote sensing data, thereby enabling the creation of cartographic representations that emphasize regions exhibiting suboptimal agricultural productivity. By precisely identifying these specific regions, strategic irrigation measures can be directed, mitigating the risks of inadequate or excessive irrigation, and guaranteeing the utmost efficiency in crop yield.

Efficient irrigation systems are contingent upon meticulously engineered infrastructure. Geographic Information Systems (GIS) play a pivotal role in facilitating the strategic development, meticulous design, and efficient administration of irrigation networks. Through the examination of topography, soil classifications, and land use, Geographic Information Systems (GIS) possess the capability to enhance the positioning of canals, pipelines, and distribution stations. The utilization of Remote Sensing technology facilitates the systematic observation and evaluation of the state of these crucial infrastructure components throughout a designated period. This enables the timely identification of potential leakages, obstructions, or any other complications that may impede the optimal functioning of the irrigation system.

The integration of Geographic Information Systems (GIS) and Remote Sensing (RS) has brought about a transformative period for the irrigation sector. The present study provides a comprehensive and all-encompassing review of the various applications, advantages, obstacles, and potential future developments of Geographic Information Systems (GIS) and Remote Sensing across the irrigation domain.

Irrigation Water Management

GIS and remote sensing are excellent irrigation water management technologies. These sources provide crucial data and perspectives that contribute to the optimization of water use, the enhancement of agricultural output, and the general improvement of water resource management. Geographic Information Systems (GIS) enable the generation of precise and comprehensive cartographic representations of the agricultural terrain, including various elements such as fields, water resources, infrastructure, and topographical features. The utilization of these cartographic representations enables the identification of optimal regions for irrigation, examination of soil compositions and land attributes, and evaluation of potential water resources and their proximity to agricultural plots. The successful implementation of the GIS Based Water Resources and Agricultural Permitting and Planning System (GWRAPPS) has been accomplished through the integration of the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS), Geographic Information System (GIS), and a robust database management system. This integration has been achieved within the ArcGIS framework, enabling efficient and effective management of water resources and agricultural permitting and planning processes. The GWRAPPS system has effectively expanded the scope of the AFSIRS application, transitioning it from a farm-level analysis to a regional-level analysis. By incorporating spatially distributed data, GWRAPPS can accurately estimate the irrigation needs across the entire region.[3]

The investigation focused on the expansion of irrigation in the Lake Tana Basin of Ethiopia between the years 1986 and 2016. This analysis was conducted by employing image classification techniques on thematic maps and Landsat5-8 TM/ETM+ and OLI sensors. The Soil-adjusted Vegetation Index (SAVI) applied on the multispectral imagery has been utilized to effectively identify irrigated cropland by assessing the level of greenness. Irrigation water consumption was assessed by evaluating the irrigation water needs of the predominant crops cultivated with irrigation and considering the estimated area of irrigated land in the basin. Landsat imaging proves to be valuable for monitoring the spatial and temporal distribution of irrigated agricultural fields, particularly in regions with limited data availability and a scattered presence of small-scale irrigated farms. This information is crucial for effective water management strategies [4].

Due to a lack of available surface water, groundwater irrigation is crucial to the region's agricultural economy. The utilization of the Analytic Hierarchy Process (AHP) in conjunction with Geographic Information Systems (GIS) allows for the evaluation of irrigation water quality within aquifers. The combination of the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) is utilized to evaluate and analyze the irrigation water quality within the aquifers [5].

Zonation, when combined with Geographic Information Systems (GIS) and standard tables, is a valuable tool for analyzing the utilization of groundwater in both drip and sprinkler irrigation systems. Based on the findings of the water quality zoning analysis in the agricultural sector, it has been determined that the water quality can be categorized into three groups: good, moderate, and unsuitable. This classification is based on the Wilcox classification system.[6]

Data from the multi-temporal remote sensing instruments Landsat TM and ETM+ were collected and processed to determine changes in land cover, agricultural activities, and the existence of seepage channels and water ponds. The SRTM Digital Elevation Model (DEM) has undergone extensive processing to elucidate the morphometric characteristics of catchments and investigate the spatial arrangement of cultivated fields in relation to the retrieved drainage networks. In the context of devising strategies for the development of dry land areas of catchment, it is crucial to consider the geomorphological characteristics of confined drainage basins to efficiently address the potential issue of waterlogging [7]. The use of hydrological computer software packages that are designed to be user-friendly has shown their efficacy as valuable instruments in the effective management of valuable water resources. Watershed models have proven effective in conducting intricate analyses and making well-informed predictions regarding the potential outcomes of proposed actions [8]

Remote sensing and geographic information system (RS/GIS) analysis may provide insights into the inflow and outflow dynamics of water within a given system. Specifically, it can identify the locations where water enters the system and elucidate the processes through which it exists, namely evapotranspiration and runoff. Based on this information, planners may determine potential areas for new water resource development, reallocating water between uses or basins, and anticipate areas at risk of water scarcity before experiencing water shortages. Supervised and unsupervised classification techniques, along with spectral mixture analysis, were employed to accurately identify different crop types in the region. Subsequently, satellite images were used to calculate precise areas for each classified crop [9]. The CROPWAT model was used to determine Evapo-transpiration (ET) at several different development phases for the crop. After that, the amount of water needed for each specific crop was determined. Figure 1 shows the parameters involved in the remote sensing and GIS for irrigation water management.

The implementation of water-saving techniques, also known as Water Safety Plans (WSPs), is necessary for the growth of agriculture in a sustainable manner. Human activities, such as Water Safety Plans (WSPs) and increased groundwater abstraction, can potentially decrease the groundwater table. This decrease in the groundwater table can be beneficial for controlling salinity. On the other hand, a groundwater table depth that is significantly higher than optimal levels may potentially have adverse effects on crop growth and the delicate ecological environment.

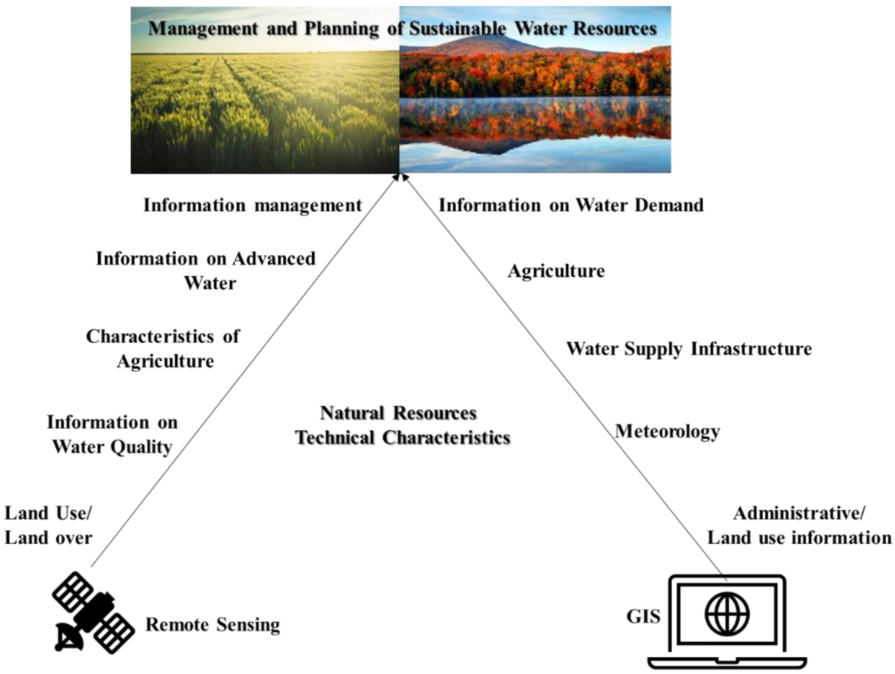

Figure 1: Satellite remote sensing and GIS for better water management [10].

The combination of GIS and remote sensing methodologies offers a promising opportunity to significantly enhance irrigation water management practices. The literature examined highlights the effectiveness of these methods in enhancing irrigation techniques, preserving water resources, and promoting sustainable agricultural methodologies. The ongoing evolution of technology is expected to drive future breakthroughs in irrigation water management, hence positively influencing the landscape.

Decision Support Systems

The utilization of a Decision Support System (DSS) within the agricultural sector, specifically in the domain of irrigation, through the integration of Geographic Information Systems (GIS), holds immense potential to significantly augment the efficacy and proficiency of water resource management and irrigation methodologies. The hydraulic performance evaluation of an irrigation distribution network involves the calculation of two key performance indicators at the hydrant level. These indicators are the reliability and relative pressure deficit. To facilitate the analysis and decision-making process, the outputs of this evaluation are integrated within a Geographic Information Systems (GIS) environment. This integration provides a comprehensive framework for a Decision Support System (DSS) tailored to the agricultural engineering needs of the irrigation system. The user interface, crafted with a focus on enhancing user experience, provides a wealth of comprehensive and readily comprehensible agricultural information. The provided data is of utmost importance for conducting a comprehensive analysis of the present state and making accurate projections regarding the future advancements within the agricultural domain. Additionally, it serves as a crucial catalyst for promoting collaboration among agricultural researchers. The objective of this collaborative effort is to optimize the effectiveness of various operational, maintenance, and management activities within the agricultural sector [11]

Soil salinization primarily manifests as a challenge within arid zones, ultimately resulting in the undesirable outcome of land desertification. The degradation of soil quality poses significant constraints on agricultural productivity, thereby impeding the optimal growth and development of crops. The development of the irrigation Decision Support System (DSS) is rooted in the management scenario of irrigation schemes on the identification of degradation of soil quality. This system effectively addresses the complexities of multi-objective models and leverages the capabilities of Geographic Information Systems (GIS) to facilitate spatial management. The investigation and analysis of irrigation Decision Support Systems (DSS) in an irrigation area will yield valuable scientific insights and design strategies. These findings will serve as a foundation for accurately determining the appropriate irrigation area type, implementing scientifically sound management practices, and optimizing the allocation of agricultural water resources in arid regions [12].

In precision agriculture, the methods for acquiring data undergo a gradual transition from traditional field surveys to the utilization of sensor-based acquisition techniques. The Central Neural Control System (CNCS) is a valuable tool designed specifically for farmers seeking guidance on optimal cultivation strategies. It assists in determining the appropriate timing, location, and quantity of irrigation, fertilizer, and pesticide application for each individual [13].

A comprehensive irrigation management system has been developed, incorporating a user-friendly graphical interface. This system has been enhanced with the integration of a Geographic Information Systems (GIS) for customized analysis. The implementation of Visual Basic for Application (VBA) further enhances the functionality of this system. The utilization of the Inverse Distance Weighted (IDW) method is implemented for the purpose of interpolating spatial inputs within a given environment facilitated by the Geographic Information System (GIS) for customization using the Visual Basic for Applications (VBA) technique. The application enables the display of the geographical distribution of water needs within a designated area and aids in identifying any disparities in water management, hence showing the need for action. The use of an interface was ultimately employed to calculate the spatial irrigation water demand, resulting in the generation of various outputs such as spatial maps depicting rainfall, effective rainfall, daily evapotranspiration (ETo), daily crop evapotranspiration (ETc), and net irrigation requirement (NIR) [14]

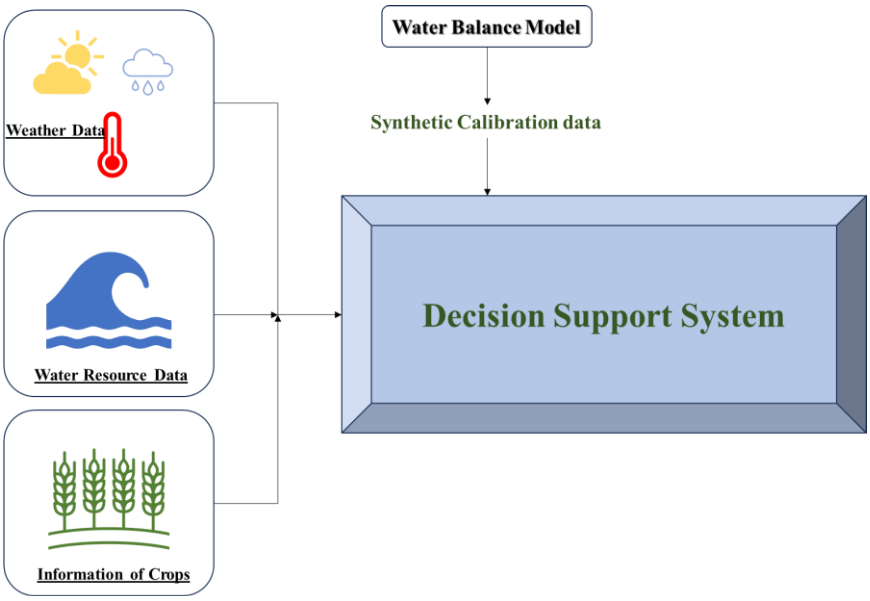

Figure 2: Decision Support System Module

The decision support system created to predict the environmental performance index to show the effectiveness of the soil for the crop modeling by utilizing the climate, water resources and crop dataset (Figure 2) [15].

The two-order analysis mode, known as a method for Geographic Information Systems (GIS) database design, has been thoroughly examined and implemented. This approach involves two key steps. Firstly, the bottom spatial data model of the GIS database is constructed using the object-oriented integrity data model. Secondly, the applied database structure is designed using the semantic object model. The paper introduces a technique for representing the object-oriented integrity data model using Unified Modeling Language (UML) and pictograms. Additionally, a semantic object model is constructed using Unified Modeling Language (UML) to ensure consistency with the Object-Based integrity data model [16].

Site Suitability Analysis

The process of selecting appropriate sites for various irrigation systems has the potential to enhance water production during periods of drought. Utilizing the capabilities of Geographic Information Systems (GIS), a comprehensive multi-criteria analysis can be effectively employed to delineate and visualize regions exhibiting significant irrigation potential. The multi-criteria analysis will consider all the numerous factors, such as the types of rivers that are perennial, the land cover, the geography, and the dams. The data that has been gathered may be subjected to analysis via the use of multi-criteria analysis inside the Arc GIS 10.2.2 software, using the Multiple Integral Function (MIF) approach [Identification of irrigation potential areas, using multi-criteria analysis in Khyber District, Pakistan]. The weighted overlay model was used to show the land suitability for irrigation. The parameters such as slope, soil, drainage, texture and depth, proximity zone and land use were used in the different process of suitability analysis **[**[17]**,** [18]**[** [19]**]**.

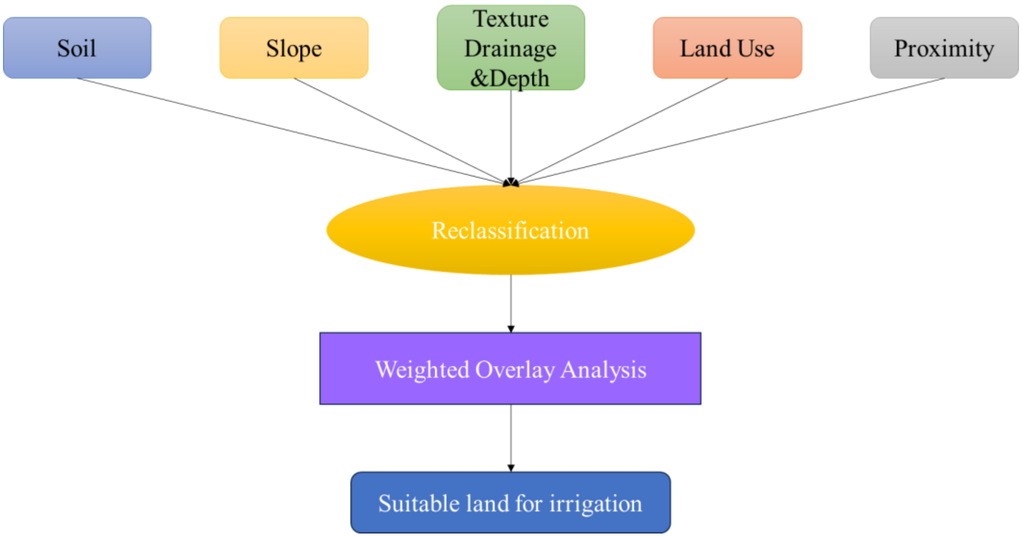

Figure 3: Methodology for Land Suitability Analysis [20]

The utilization of a Geographic Information Systems (GIS) in conjunction with the Analytical Hierarchy Process (AHP) is employed for the purpose of evaluating the appropriateness of soil conditions for the sustainable implementation of intensive agricultural practices. The Analytic Hierarchy Process (AHP) methodology was used to determine the relative importance or weight of each indication based on the pairwise

comparison matrix. The process of generating the soil quality map in a GIS environment involved utilizing the weighted sum overlay analysis. This analysis involved overlaying both indicator weights and sub-indicator weights to determine the overall soil quality (Figure 3) [21] [22].
The GIS data set was combined with the locations of the significant lands and unsuitable paddy fields using a specifically designed point system for analysis [23]. The integration of ArcGIS with multicriteria analysis methods in this scenario involves exploring the potential synergies and benefits derived from the combination of these two systems. By leveraging the spatial analysis capabilities of ArcGIS and the decision-making frameworks offered by multicriteria analysis methods, a comprehensive and robust approach can be developed to address the complexities and challenges inherent in this case [24]**.** This integration allows for the examination and evaluation of multiple criteria simultaneously, enabling a more holistic understanding of the problem at hand. The implementation of ELECTRE TRI, a decision-making method, and a variant of the simple additive weighting method for the vector data model. These methods will be utilized to identify appropriate land for irrigation purposes [25]**.** Land suitability parameters coupled with fuzzy overlay analysis by assigning fuzzy membership values for each thematic layers, the land suitability map may be created for irrigation [26].

Web GIS

Incorporating Geographic Information Systems (GIS) technology with online technologies has allowed for the development of a platform known as WebGIS (online Geographic Information System), which plays an important part in irrigation. It makes it possible to use web browsers for the viewing, analysis, and administration of geographical data connected to irrigation systems. WebGIS, also known as Web Geographic Information System, plays a pivotal role in enhancing water resource management, planning, and decision-making within the realm of agricultural practices. By leveraging the power of geospatial data and web technologies, WebGIS empowers stakeholders in the irrigation domain to achieve optimal efficiency and effectiveness. One of the key advantages of WebGIS in irrigation is its ability to provide a comprehensive view of the water resource landscape. By integrating various data sources such as satellite imagery, weather data, and soil moisture levels, WebGIS enables users to gain valuable insights into the current state of water resources (Figure 4). This holistic perspective facilitates informed decision-making and allows for proactive measures to be taken in managing water allocation and distribution. Furthermore, WebGIS offers advanced analytical capabilities.
One of the goals of the agricultural sector is to improve the amount as well as the quality of the goods that are produced while simultaneously maximizing the efficiency with which the available natural and energy resources are used. The connectivity of sensors, actuators, and other agricultural equipment over the Internet offers the opportunity to create interoperable systems that adhere to standards, therefore addressing the monitoring and control needs of many scenarios. The use of a 3-layer architecture, in conjunction with the integration of the water management model advocated by the TRAGSA Group using NGSI-LD, as well as the integration with Geographic

Information Systems (GIS), and the subsequent implementation of these systems in collaboration with the agricultural sector, have resulted in several advantages [27].
To facilitate the deployment of an interactive map within a web environment, it is imperative to undergo a sequence of map preparation stages utilizing various Geographic Information System (GIS) software tools. These tools include ArcGIS, Quantum GIS, PostgreSQL, PostGIS, GeoServer, and OpenLayers. The resultant cartographic representation is subsequently partitioned into three primary strata, predicated upon the categorical object to be exhibited. These strata encompass the principal irrigation conduit, the secondary conduit, and the structures employed for tapping purposes. The location and status of each item may be visually seen by users via the use of distinct colours. Specifically, green is employed to represent objects in excellent condition, yellow denotes objects with mild damage, and red signifies objects with significant damage. The purpose of this application is to facilitate the acquisition of a comprehensive and precise understanding of irrigation in specific regions for the relevant entities concerned [28]. The use of GIS web services is well-suited for the development of geographic decision support systems in the field of precision farming. Applications based on GIS web services provide clear benefits in addressing challenges related to the sharing of spatial data, the reuse of software, and the reduction of system integration costs [29].

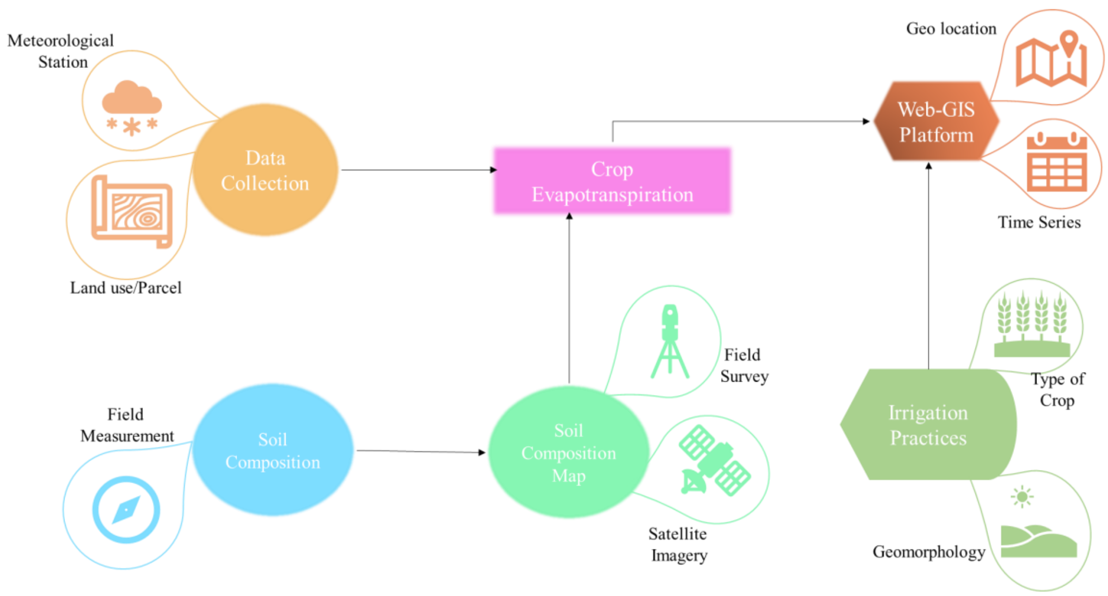

Figure 4: Web based GIS platform for irrigation management [30]

The agricultural research system incorporates the knowledge gained from the previous irrigation management system that utilized Geographic Information System (GIS). It leverages the MapX module of GIS on the Visual C++.NET platform and employs a client-server (C/S) structure on mobile devices. This enables the system to effectively execute irrigation decision-making processes and facilitate data sharing using MapX

Mobile and GPS technologies. Consequently, the system efficiently collects environmental data from the field and promptly delivers it to the server with precision. Additionally, it utilizes GIS techniques to display crop position information and associated attributes on a map [31].

A cutting-edge solution has been devised to effectively distribute and share valuable soil information obtained from comprehensive soil surveys. This innovative approach empowers decision-makers, policy formulators, land use planners, and agriculturalists to optimally manage and utilize our precious soil resources. The UAE Soil Information System (UAESIS, www.uaesis.ae) serves as a valuable online repository for soil data, offering a comprehensive collection of information with geographical representation. This platform facilitates access to descriptive, quantitative, and geographical data through a user-friendly interface. The agricultural system comprises several integral components, namely a geospatial soil database, a field operating system, and a web-based secure application with exceptional user-friendliness [32].

The use of remote sensing and Geographic Information System (GIS) technologies in the field of irrigation management presents a range of benefits and drawbacks.

Remote sensing plays a crucial role in acquiring significant information pertaining to soil moisture, crop vitality, meteorological patterns, and land surface characteristics. Geographic Information Systems (GIS) play a crucial role in facilitating the spatial visualization of agricultural data. By leveraging GIS technology, researchers can effectively comprehend and analyze patterns, trends, and relationships within the data. The other uses of remote sensing and GIS in irrigation management observed from the literature review are, precise monitoring of large irrigation areas, data integration, efficient resource allocation, simulation, and modeling of irrigation scenarios, early warning systems for drought, excessive rainfall, and decision support systems for irrigation planning.

Cost and infrastructure for establishing and maintaining GIS and Remote sensing hardware and software may be expensive. Technical expertise is required to use the software. Data integration, spatial and temporal resolution of the data. To strike the right balance between these positive and negative aspects, careful planning, adequate training, close cooperation with subject matter experts, and the integration of remote sensing and GIS technology with time-honored, on-the-ground observations and intimate familiarity with the area are required.

Conclusion

In summary, the comprehensive literature review analysis of remote sensing and Geographic Information Systems (GIS) in irrigation management unveils many promising advantages and associated complexities. These emerging technologies have surfaced as robust instruments that bear the potential to revolutionize the methodologies employed in the planning, monitoring, and management of irrigation systems. Remote sensing and GIS have a lot of benefits for irrigation, such as making it easier to get data, doing spatial analysis, making the best use of resources, and making smart decisions (Water management, DSS, Site Suitability Analysis and web-GIS). The capacity to effectively observe the well-being of crops, identify irregularities, and incorporate diverse data sources offers a holistic viewpoint that can facilitate optimal water distribution and foster environmentally friendly agricultural methodologies.

Nevertheless, this literature review highlights several significant drawbacks that necessitate recognition and resolution. The considerable expenses linked to the establishment of infrastructure, the necessity for specialized knowledge, and the potential constraints on data availability present formidable obstacles to achieving widespread implementation. To optimize the advantages and address the obstacles, it is advisable to adopt a comprehensive approach. This involves synergizing the capabilities of Remote Sensing (RS) and Geographic Information Systems (GIS) with conventional ground-based observations and indigenous expertise. With the continuous advancement of technology and the increasing accessibility of expertise, it is expected that the utilization of remote sensing and Geographic Information Systems (GIS) will have a growing significance in the realm of agriculture. These tools will play a crucial role in enhancing sustainable irrigation practices, optimizing the utilization of water resources, and ultimately contributing to global food security efforts.

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