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Review Article

GIS Application in Environmental Management: A Review

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Abstract: The role of environmental management is extremely important in human life because of its contribution to environmental protection and strategies. In modern society, nevertheless, facing the challenges in land, water, and air quality management in reality is unavoidable. Understanding the information on variability and features of environmental issues is necessary to support decision-makers in establishing environmental management planning. Spatial information and data should be considered as basic initial knowledge of environmental management. Among various technologies, Geographic Information Systems (GIS) is known as one of the most popular tools to store, analyze, and visualize data relating to geographically referenced information which can mitigate these challenges more effectively and accurately. The main purpose of this paper is to emphasize how GIS applications in environmental management, discuss the challenges of GIS technology in environmental management, and provide recommendations for future research directions. Many articles over the last decades were reviewed to highlight the application of GIS in environmental management. These results indicated GIS applications support land, water, air quality, and waste management. Moreover, it is a useful tool to monitor and assess environmental quality and in environmental planning and decision-making. For the limitation of GIS application, it is obvious that accuracy assessment and sensitivity analysis should be noticed and assessed although GIS application may strongly support decision-making in environmental management. Emerging GIS technologies and tendencies could help address these challenges. In future, GIS should be integrated along with new technologies and different decision-making algorithms in further steps for developing and supporting spatial decision-support systems more efficiently.

Keywords: GIS application, Environmental management, Land management, Water management.

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1. Introduction

Environmental management plays an important role in improving the protection and planning of our environment, and ensuring the earth remains sustainable development [1]. Effective environmental management requires the combination of different industries, companies, and individuals to undertake the essential rules and activities to regulate and protect the health of the natural world [2]. Specifically, it helps us identify environmental degradation factors [3, 4] and perform plans to mitigate them [5]. Environmental management also includes prediction impacts of environmental degradation and processes for minimizing the effects [6]. Moreover, environmental management is very wide and complicated, which involves not only environmental protection and sustainability but also each environmental aspect such as wildlife management, forest management, soil management, human resource management, water resource management, natural resource management, etc. [7]. In many countries especially developing countries, however, under several pressures (e.g., expansion in population, technology, and economic development activities) the environment of the countries has been faced with many issues (e.g., global warming and climate change; air and water pollution, and loss of biodiversity [8]. The severe degradation, especially the land cover, will be leading to a diminishing in soil erosion and soil fertility [9]. These problems provoked by erosion result in economic loss in the agricultural and forestry sectors and many directly or indirectly pose hazards to human and natural populations due to such events as floods, droughts, landslides, etc. [10]. The severe degradation of the environment in these countries has occurred and can be continued to experience in the future. The spatiality of environmental management seems to be the development landscape that is suggested for application with the potential pathway's changes [11, 12]. These outcomes perform the information on variability and characteristics of environmental problems that are much needed to enhance decision-making in environmental management [13]. On the whole, spatial information has been a significant fundamental understanding of environmental management.

Geographic Information Systems (GIS) are computer-based information systems, which are used to store, analyze, and visualize data related to geographically referenced information. GIS can incorporate many different data forms (spatial and non-spatial), and can be applied in many areas [6, 14, 15]. Since GIS can be an effective tool for environmental and natural resources management (such as land, water resources, air quality, forests, soil, mining; and in pollution monitoring and mitigation strategies and natural disasters management), application of GIS in environmental management has been rapidly increasing since the 1990s [16]. With applying GIS, spatial diversity of the environment can have better observation and visualization, data from various sources can possibly analyze and integrate, and different impacts on the environment can be assessed. Specifically, GIS provides an effective graphical and intensive numerical observation of environmental problems [14]. GIS has been heavily depended upon for environmental observation [17] e.g., air and water quality observation [18] and observation of land degradation and soil loss [14, 19]. Hence, GIS can monitor and overall map the characteristics of environment. In addition, since GIS has capabilities for geo-database management, spatial analysis, mapping, and modelling, it can enhance the ability to address and evaluate environmental issues (e.g., deforestation, soil erosion, water quality). Moreover, through using spatial and statistical analytical techniques of GIS, attribute and geographic data layers can provide deeper information regarding environmental issues [20]. Thus, GIS can help to understand the processes and procedures of environmental issues. Furthermore, GIS aids decision making process for environmental managers by incorporating into a wide range of management practices and integrating and displaying data in an understandable form. Therefore, GIS has become an effective tool for helping and supporting in environmental management.

Over the last decade, much research has applied GIS and achievements of GIS applications have been made in environmental management. However, environmental degradation is still a severe concern in many countries especially in developing countries [19]. The main issues in environmental management such as water quality are remaining [21-23]. Recently, advances in geospatial technologies, as well as the increasing availability of spatial data, have renewed interest in using GIS in order to address a wide range of environmental problems and questions [7, 18]. Thus, it may be a time to examine what and how GIS applications have been done as well as challengers and future directions under its applications in environmental management.

Under the aforementioned perspectives, therefore, this review article aims to summarize the applications of GIS in environmental management over the last decade.

2. Overview of GIS Technology

GIS is the instrument or method used to develop the efficiency of data collecting and its analysis including the data results from the fact. Geo-reference or Coordinating System to match the objectives may be made different under the same coordinate and GIS may be used the descriptive data or picture and connected to the system [24]. The term GIS is used in many different fields such as: geography, information technology, environmental and resource management, spatial data processing science, etc. Diversity in fields, the application leads to many definitions of GIS. Some typical definitions of GIS can be mentioned as Tomlinson [25] gave the meaning of GIS as the information and filled in the map for decision making. GIS is the hardware and software including the system design and collecting data, analysis, results of data in different positions on earth and helping with the complicated planning and eliminating the problem.

GIS is gaining importance and widespread acceptance as a tool for decision support in land, infrastructure, resources, environmental management and spatial analysis, and in urban and regional development planning. With the development of GIS, environmental and natural resource managers increasingly have at their disposal information systems in which data are more readily accessible, more easily combined and more flexibly modified to meet the needs of environmental and natural resource decision making. It is thus reasonable to expect a better informed, more explicitly reasoned, decision-making process. But despite the proliferation of GIS software systems and the surge of public interest in the application of the system to resolve the real-world problems, the technology has commonly been seen as complex, inaccessible, and alienating to the decision makers [26, 27].

The reasons for this estrangement are varied. In part the early development and commercial success of GIS were fueled more by the need for efficient spatial inventory rather than decision support systems. As a result, few systems yet provide any explicit decision analysis tools. In addition, the technology is built upon a very broad base of scientific disciplines, ranging from cartography, to remote sensing, to computer science, to statistics and the like. This implies that to become broadly involved in GIS use, an extensive background in the digital data management, mapping sciences and information technology are required. Furthermore, the technology has strong elements of modernity and scientific rigor that is strongly cultivated by vendors, consultants, and other advocates. As a result, GIS has become a field requiring a host of intermediaries between the end user and the data provider: technicians, system managers, analysts, user interfaces, query languages and so on. Added to this are the institutional and organizational issues of the technology transfer.

Although, recent development in GIS software`s and Web Technology has made GIS more user-friendly, therefore useable and accessible to more users [27]. Information technology may either democratize information by making it more equitably accessible, or it may have the opposite effects of disproportionately empowering a selected sector of society. The lack of analytical tools to efficiently aid decision evaluation and policy formulation and the continuing mystification of the field have unfortunately often led to the latter in GIS [27, 28]. In many cases GIS has become a rifting technology, tending to divert the process of decision making away from decision makers and into the hands of GIS analysts and host of other highly trained technological intercessors [29]. To alleviate the above problems GIS should be upgraded by decision support system (DSS) functionality in a user friendly and easy to use environment. However, there is a trade-off between the efficiency and ease of use, and the flexibility of the system. The more options are predetermined and available from the menu of choices, the more defaults are provided, the easier it becomes to use a system for an increasingly small sets of tasks. There is also trade-off between the ease of understanding and the precision of the results. Providing a visual or symbolic presentation changes the quality of the information in the course of transformation from quantitative to qualitative data sets. Finally, the easier the system the harder is to make and maintain.

3. GIS Applications in Environmental Management

In April 2023 a search of the terms “GIS application” and “Environmental management” was conducted on the Google scholar literature database (https://scholar.google.com/) and a total of over 2,820 articles were shown. The number of papers was narrowed down to 176 after selecting and downloading the articles that were considered for specific topics and detailed keywords regarding land, water, air quality and waste management of the search result (Figure 1a) (Appendix A). The papers reviewed were in the last decade which is from the years 2012 to 2022. The years with the highest numbers of papers in this review were 2012 and 2015, with 24 papers each (Figure 1b). The papers reviewed extensively covered many countries around the world. The top three countries with the highest numbers of papers in this review were India, China, and Iran with 41, 19 and 10 papers respectively (Figure 2). From this review, 17% were large scale (region or country) studies and 83% were smaller scale such as country’s state, province, regional and city studies. Among the reviewed papers, only 11% of the studies’ results were evaluated accurately based on several statistical indicators such as RMSE, MSE and/or sensitivity analysis. The more detailed can be referred to Appendix A.

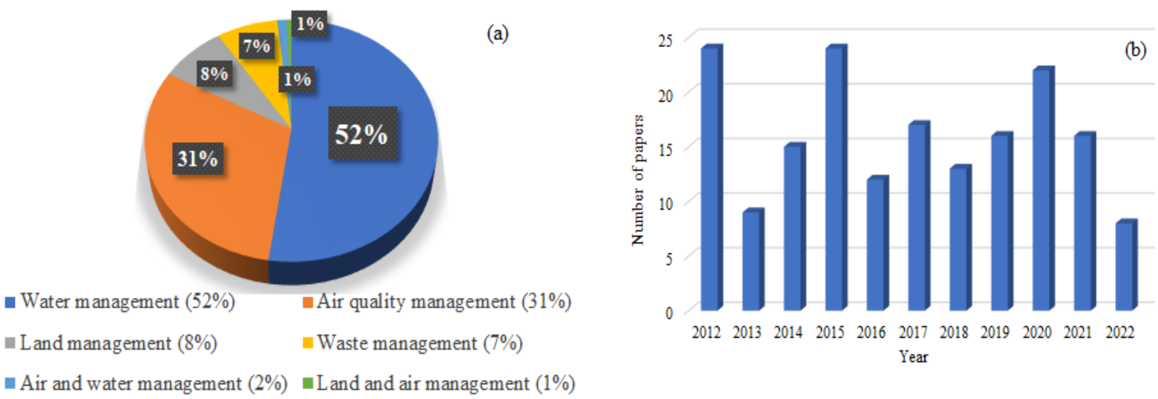

Figure 1. Relative number of papers by specific topics (a) and publication year (b).

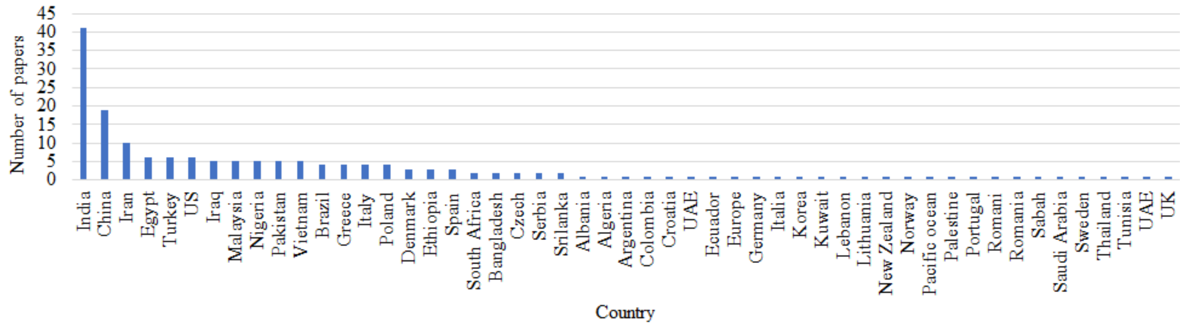

Figure 2. Relative distribution of reviewed papers by countries.

3.1. Land Management

Compared to the traditional approach, GIS applications seem to be modern with a variety of sufficient methods, especially in land management. GIS was applied to manage land for a long time through exceptional features for data storage, visualization, analysis, and modeling [30-32]. Among the different components in land management, GIS is known as an important factor based on the rapid conversion and considering the optimal land use options. Integrating GIS and remote sensing is increasing the accuracy and effectiveness in evaluating land use and land cover changes [32, 33]. These results indicated that the cost-effective multi-spectral and multi-temporal data were provided as the necessary information for analyzing and monitoring the land development systems. Especially, spatial data was managed by GIS which is extremely important in detecting the change in land use/land cover and expanding database development. Variables in land management can be changed easily by using GIS tools to visualize these changes immediately [34]. By using GIS platforms, the prospective utility was emphasized obviously to conduct real-time assessments of the soil moisture monitoring [35]. In the modern world, agriculture is considered carefully by using modern technologies such as GIS, remote sensing, WebGIS and monitoring devices, AHP algorithm, sensors, and so on [30, 33, 35]. Meanwhile, satellite imagery is used to assess the environment based on ecological characteristics or evaluate the effective management of ecological space [36]. The management of spatial databases in GIS had a significant contribution to the integration and wide application of land management. Based on the support of GIS, cadastral information in the digital era should be managed systematically including ID, location, aim, ownership, and data quality which is better than the traditional way in the past.

Some examples of GIS applications in land management are described in detail below. In 2018, the GIS application along with remote sensing satellite imagery was used to determine and classify the land use/ land cover types of an environment and how to manage and plan for environmental protection in Nigeria [33]. Local data and satellite data were used to support the analysis of the impacts of human activities as well as the interaction between human activities and environmental impacts more effectively. From these results, the new map showing the conversion of the categories of land use/land cover types was conducted by local farmers, private companies, or local government to support regional landscape planning and resource management of our environment. The law should be enforced by the government to guide the way how human activities adapt to the environment. Another typical illustration was found in Yunnan province, China in 2021 [37]. The web geographic information systems were utilized to establish a set of soil monitoring and analysis platforms according to the provincial scale. Based on the soil information and local data, evidence reveals that its application had a variety of benefits in integrating with the environmental pollution GIS systems. Focused on the advantages of this WebGIS platform, one of the main benefits is the lower cost of information construction and operation leading to the efficiency of economic aspect compared to the traditional way. Furthermore, it is no doubt that upgrading the quality of management efficiency and level of the local department as well as the comprehensive data to support the scientists and decision-makers in the future, especially in the ecological environment. In the same way, this approach was also applied in the Basilicata region, southern Italy [32]. To analyze the spatial land cover changes, using the GIS approach on the regional scale with the support of remote sensing data was conducted with higher accuracy. Its application can be widely applied in other countries as an initial approach to a sustainable development model. The results indicated that the land conversion had negative effects on the environmental components. It is necessary to consider tools that can integrate decision support systems to assess past local policies or develop future plan/strategies.

3.2. Water Management

With the role and importance of water resources, there is an urgent requirement for monitoring and assessment to obtain a better understanding of water management. GIS can provide tools which can assist towards the development of an effective water management [38]. It has the capabilities of water resource management and conservation tools [39]. With GIS, water bodies such as rivers, lakes, dams and reservoirs can be mapped [40]. The spatial water availability maps can be generated [41]. GIS analysis can show where water resources are available [42]. Using this information, managers can identify areas where there is potential for development of new water resources [43]; where water can be reallocated from one use or one basin to another [44]; and identify potential areas of water scarcity before water shortages occur [45]. GIS helps in generation of irrigation water demand map by modeling of water demand considering variation in crop, soil and climate [6, 34, 41, 12]. The GIS technique helps in integration to evaluate the system performance and to diagnose the inequality in the performance to aid in improving agricultural water management. Water quality should be regularly monitored in order to manage and improve the quality [3, 38]. GIS, remote sensing and IoT technology can be used to monitor water quality indicators (e.g., suspended sediments, and chlorophyll) [5]. GIS and hydrological models are generally used for water management purposes. Approaches for modeling under GIS could follow two directions. First direction, a decision support system based on rule formation for individual layers or integrating the layers by a series of equations, which expresses the relationship among the parameters and finally provides an output. The second direction of modeling is also called lumped parameter model. If under GIS environment all the basic functions (data input, management, analysis, and output generations) are integrated with the rule-based or other necessary tools for the modeling under one graphical users' interface (GUI), then it is called the GIS-based modeling or decision-support system. In general, for water management GIS has been applied in several classified areas including water resources monitoring [46]; water quality/pollution assessment [47, 48]; and groundwater assessment [48].

3.3. Air Quality Management

In general, GIS has been mainly applied to air quality monitoring and assessment. Comparative analysis of works carried out by previous studies revealed the importance of geospatial analysis for air quality monitoring. GIS techniques such as interpolation and overlay were not only performed for identifying and optimizing suitable locations for air quality monitoring stations [49-51], but also assessed spatial representativeness of the monitoring stations in urban regions [52]. GIS was applied to consider on several factors such as point, area, and line sources; high-traffic areas; spatial proximity to roads; population density; wind direction; sensitive receptors; industries, distance from current air quality stations; prediction error; and spatial distribution of air pollutants [51]. For example, Pope and Wu [50] created a comprehensive set of indicators (e.g., measured concentration, deviation from U.S. National Ambient Air Quality Standards, area served, emissions inventory, traffic counts) for evaluating differing aspects of the air quality monitoring networks' purposes, and weights were employed to emphasize important indicators. GIS was used to build the spatial layer of each indicator with raster data type. These raster data were reclassified so that the data distribution of each indicator was scored. The reclassified raster data were then the weighted spatial overlay tool was used to calculate spatially averaged with weights, giving each indicator a weighted-average score. A higher score indicated a greater likelihood that a spatial location would benefit from additional monitoring representation. Thus, appropriate numbers and locations of air quality monitoring stations have been identified and recommended.

For air quality assessment, GIS has also been used to create concentration and spatial distribution maps of air quality index or pollutants for an area [53-55]. Two interpolation algorithms (Inverse distance weighted (IDW) and Kriging) have been widely used for generating the map of air quality index or pollutants. For instance, IDW and Kriging showed good interpolation results for three air pollutants including sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and suspended particulate matter (SPM) in Mumbai City, India. They have provided a feasible method using GIS that examined spatial point pattern of air pollutants and identifies the relationship between air quality and health risk and gives better visualization and analysis possibilities. Then, that could help to estimate the valuation of health damage due to air pollution [55]. In recent years, since GIS can provide an advanced modeling and analysis system, researchers have come up with air quality modelling which is an alternative approach for air quality assessment. Spatial mathematical modelling and artificial intelligence for air quality are applicable for mapping air quality index or pollutants, analysis of association between air pollution and health risk, focused on the contributions of air pollutant emissions from point sources to the surrounding air environment and their impact on human health [4, 56-58]. Traditional studies are costly and time consuming, so modeling is used to produce predictions for the unsampled locations [58]. The air pollution problem can be originated from the various sources by using the modeling they can be all considered [56]. Air quality modeling can be used to estimate pollutant levels for evaluating environmental contaminant levels, health risk and their relation to the incidence rates of disease [58]. The modeling can provide information on how much pollution exposed how many populations affected and estimate environmental impacts from present and future developments so establish strategies that reduce pollution [58]. As an example, a dispersion model was applied for an urban agglomeration located in South-West Romania [56]. The model not only can account for different types of pollutant sources in the study area, but also can simulate concentration and spatial distribution of the air pollutants (SO_2, NO_2, PM10) [56]. The accuracy evaluation indicated that the model showed a good behavior for the NO_2 and PM10 pollutants and an unsatisfactory behavior for the SO_2 [56]. In conclusion, this study had written that usage of pollutant dispersion modeling has advantages such as assuring a continuous pollution representation, lower costs and input of high-quality data [56].

Meanwhile, GIS's visualization capability is widely used and conventional technologies in the GIS and statistical map making skills are often utilized to manage, analyze, and visualize air quality index or pollutant data. In these studies, however, the visualization techniques are limited to conventional methods. With the development of web technologies, open-source GIS standards and web mapping tools are adopted in the analysis and presentation of environmental data-related studies not only for experts and managers, but also for the public in general [59]. Currently, as urban air quality is an urgent societal problem for many policy-makers and a study topic for scholars, air quality data are gaining more attention [59]. Therefore, more effective visualization tools like WebGIS need to be developed for visualization of the increasing accumulated multi-dimensional air quality and pollutant data.

3.4. Waste Management

The application of GIS in waste management has been widely adopted in many cities in developed as well as developing countries around the world [60]. In waste management, the collection, transportation, treatment, and disposal of diverse types of waste in a manner that does not damage the environment, human health, or future generations is referred to as sustainable waste management. The primary objective for the application of GIS is to reduce cost and time and help planners make better decisions in waste management [60]. GIS, remote sensing, Artificial Neural Network (ANN) and WebGIS can be used to improve and optimize the practice efficiency of waste management (i.e., waste collection and transportation) [61, 62]. In many studies, efforts have been undertaken to shorten the distance between waste collection stations and landfills, hence reducing the number of trucks involved in waste collection and disposal [60, 63-65]. Many elements influence route optimization, including the location of waste bins, collection details, vehicle kinds, trip impedances, and the road network's integrity which can be analyzed by GIS [66, 67]. Another key application of GIS in waste management is the selection of disposal and landfill sites [68-70]. Multi-criteria coupled with GIS have recently become popular in waste management for assessing the criteria. In most cases, GIS is used with the integration of remote sensing and/or multicriteria decision-making analysis (MCDA) [67, 71]. In spatial multicriteria analysis, the combination of GIS and MCDA capabilities is crucial. GIS allows for the acquisition, storage, retrieval, manipulation, and analysis of data to obtain information for decision-making. Whereas MCDA techniques provide tools for aggregating geographic data and decision-maker preferences into a single-dimensional value or utility of alternative decisions [68, 71]. GIS in combination with the multicriteria decision-making method and the analytical hierarchy process to find the best landfill location by balancing competing environmental and socioeconomic concerns [72-74]. For example, Araiza Aguilar [75] identified the feasible areas for the emplacement of the Municipal Solid Waste management infrastructure in Chiapas by applying spatial analysis tools contained in the GIS software. The study highlighted that the GIS tool is a noteworthy methodology that should always be considered in waste management programs because it permits weighing and relating several environmental parameters [75]. Singh [67] provided an assessment of remote sensing and GIS techniques used for managing the environmental problems of waste disposal. The results revealed that these technologies could also be efficient use for waste management systems to decrease the driver's workload and authenticate the real-time location of the waste management [67].

4. Challenges and Future Directions

The review presented here underscores that GIS has proven to be a robust research and support tool for many types of environmental management applications around the world. However, it is also clear that there remain many challenges and research gaps that impede the routine use of GIS. Through the review, the lack of data, specialist knowledge and accuracy assessments present current and further challenges regarding more widespread and reliable application of GIS. Specifically, previous studies had concluded that they couldn't achieve more results and detailed assessments due to data availability and quality as well as resources limitation [46, 54, 76-78]. While several studies were successful, the duplicate future studies for other places with similar methodology may not produce because of requirements of specialist knowledge regarding research topics [52, 58, 76, 79-81]. Although the application of GIS may strongly support decision-making, accuracy assessment and sensitivity analysis of the analyzed results in several case studies were neglected [70, 82-85]. Thus, the evaluations and analysis should be noticed and performed.

GIS has seen a fast development from traditional practices involving land use planning to variety applications since 1960s. Remote sensing has been the most common provider input data for GIS analysis. In order to full fill demand of GIS analysis, it has speedily developed. Several new products (e.g., land use land cover, precipitation) of RS have been inputted to GIS analysis which can produce better results or have ever done before [86, 87]. Meanwhile, Artificial Intelligence (AI), Big data, the Internet of Things (IoT), Unmanned Aerial Vehicles (UAVs) and other technological advancements have spread out over the world with their potential and reliability [88]. These technologies are expected to play a significant role in shaping up the modern environmental management meeting the application of GIS. Therefore, the future research directions are proposed as following:

i) Site-specific selection technique in GIS has been found to contribute for identifying environmental monitoring station position and network [50, 57, 89, 90]. Future studies should focus on developing new site-specific selection techniques satisfying the applicant requirements and meeting the challenges posed by the increased data size and social-economic conditions. It is recommended to use modern technologies to optimize the results and combine them with the existing models for gaining meaningful insights in real time [88]. Remote sensing and UAVs may be used to increase the outreach to enhance the effectiveness of environmental monitoring [91]. There is also considerable potential for integrating GIS with new technologies such as AI for improving site search and selection. Such integration of analytical techniques will help in improved monitoring, resulting in identifying future risks based on past and current trends of environmental quality;

ii) Modeling and software can be effective tools for supporting environmental management. This has been well proven by the previous study [49, 84, 92-94]. The use of advanced algorithms can help to enhance output and increase accuracy. Hence, researchers should develop advanced algorithms and carry out studies involving new GIS techniques for applying in environmental management. Besides, future studies should focus on combining modeling with other methods for assessing environmental impact. In addition, environmental modeling may be fast development with the exponential rise in the data [95, 96]. Then, GIS program will be required to process and manage the big spatial data regarding environmental modeling performances. Windows-based GIS application with the artificial neural network (ANN) approach will be required to be adopted in future studies in the context of environmental modeling with a specific focus on managing big spatial datasets and integrating different decision-making algorithms for efficient analysis [97];

iii) Previous studies have used Multi-Criteria Decision Analysis (MCDA) techniques for supporting decision-making in environmental management [76, 81, 98]. However, many substantial attributes (e.g., the socio-economic factors) have not been involved in the MCDA process [99]. Integration of GIS and MCDA techniques can incorporate a substantial number of environmental criteria for the evaluation of environmental management [99]. More developments to integrate GIS, computer modeling, and MCDA techniques should be initiated to deliver better insights [88]. This approach should be studied and demonstrated in the future for developing intelligent and/or web-based spatial decision support systems.

5. Conclusion

This review paper emphasized the important role of GIS technology in environmental management. Also, the limitation of GIS application in environmental management was discussed along with considering future development directions. It seems to be a detailed review of GIS applications in environmental management based on summarizing many articles over the last decades. The main points were highlighted as follows:

i) GIS application plays a key role in land, water, air quality and waste management;

ii) GIS is known as a useful tool to monitor and assess environmental quality and pollution;

iii) The accuracy of GIS in environmental planning and decision-making is unavoidable;

iv) Emerging GIS technologies and trends could help address these challenges;

v) Although the application of GIS may strongly support decision-making, accuracy assessment and sensitivity analysis should be noticed and performed.

In conclusion, GIS is one of the most popular tools to store, analyze, and visualize data relating to geographically referenced information which can mitigate these challenges more effectively and accurately. In the future, integrating GIS with new technologies (such as AI, Big data, ANN, computer modeling, or MCDA techniques) and different decision-making algorithms should be conducted in further analyses for developing intelligent and/or web-based spatial decision support systems.

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