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EDITORIAL

Navigating the Complexities of Land Management and Utilization for Sustainable Development

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As the inaugural Editor-in-Chief of the "Land Management and Utilization" journal, I, on behalf of our editorial board members, would like to introduce to you the inaugural editorial of our publication. Land Management and Utilization aims to publish the latest research findings and innovative research that explores the complex dynamics of land use and its impacts on environmental, social, and economic systems. As pointed out in the journal's aims and scope, we call for papers encompassing a wide array of geoscience and planetary science disciplines, including, but not limited to: 1) theory and policy of land management, 2) land resource survey and evaluation, 3) land protection and ecological restoration, 4) land informatization and remote sensing technology, 5) rural land system reform and rural revitalization.

Land is the material basis upon which humanity relies for survival and development, providing living space, natural resources, and ecosystem services. It is a crucial factor in social production, and an essential element for economic and social development, which is related to national security, ethnic survival, and the well-being of the people. Land management and utilization face multiple challenges, including intensifying resource constraints, rapid ecological degradation, there is an urgent need to optimize land spatial development patterns, and to improve land development quality [1]. Studies have shown that approximately 24% of the terrestrial area is affected by land degradation [2]. Overdevelopment and utilization of land resources have led to severe damage to land ecosystems, resulting in issues such as soil erosion, soil

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nutrient imbalance, soil fertility decrease, and soil contamination, posing threats to ecosystems and ecological security [3]. Additionally, due to urbanization and industrial development, the area of arable land is continuously decreasing, and food security cannot be guaranteed. The protection of land resources and the contradiction between land supply and demand are increasingly prominent, and land utilization faces severe challenges [4]. At the same time, in some regions, abandoned farmland has expanded due to issues such as population aging and labor force transfer [5]. Also, the needs of humanity and the development of the socio-economy lead to more diversified land uses, such as the development of wind and solar energy in desert areas [6]. There are also land use conflicts, leading to disharmony in land use, which restricts sustainable development [7]. Therefore, how to implement optimized land resource strategies, optimize land resource allocation, reduce land resource vacancy, repair land resources, protect the ecological environment, ensure food security and ecological security, and achieve carbon neutrality and sustainable development at the national and regional levels requires in-depth research [8].

Research related to land management and utilization represents a sophisticated interdisciplinary exploration that applies theoretical frameworks and methodological approaches from land sciences and related disciplines to practical applications. Land management and utilization encompass the interplay between land resources and ecosystems, economic systems, and social systems (**Figure 1**). Land resources and ecosystems constitute the fundamental research domain, while contemporary land systems are subject to multifaceted pressures, including accelerating urbanization, increasing land use transformations, rural structural reconfiguration, and emergent environmental challenges [9]. These pressures impact land resources and ecosystems, and land management and utilization respond to these challenges through land use pattern optimization, land use evaluation, and land use allocation. The supply and demand of land resources are influenced by various factors. On the land resource supply side, measures such as ecological restoration, land integration, land improvement, and ecological protection are needed, and these measures are crucial for increasing the area, quality, and productivity [10]. On the other hand, land demand is intricately related to population growth, urban expansion, food requirements, regional spatial coordination, and infrastructure construction. Land management strategies must strategically address these multifaceted needs while simultaneously enhancing soil quality and ecosystem integrity [11]. Therefore, comprehensive research is imperative to elucidate land use patterns, understand land use processes, and predict land use dynamics. Furthermore, an in-depth investigation of land use patterns, ecological processes, and land use dynamics is crucial. Advanced methodological approaches, including precision agriculture, remote sensing (RS) technologies, and Geographic Information Systems (GIS), offer innovative strategies to optimize land management efficiency. On this basis, optimizing, evaluating, and allocating land management are key to achieving sustainable development [12]. Through systematic and interdisciplinary research, land resources can be more effectively planned and managed to address both contemporary and prospective societal requirements.

Figure 1. The socio-economic and ecosystem interaction mechanism in land management and utilization.

Economic and social systems constitute pivotal determinants in land management and utilization. The two systems are inseparable, involving products and values, resource allocation, property rights, ecosystem services, and human well-being. Relevant research also emphasizes the importance of sustainable land management for economic growth and how to achieve sustainable ecosystem goals through market mechanisms and policy incentives [13]. Socio-economic interactions are key to the success of land management strategies, involving land use policies and innovations, land management systems, and the behavior of land use entities [14]. Researchers systematically incorporate socio-economic factors to enhance the effectiveness and fairness of land management policies. Therefore, strategic public engagement and comprehensive educational initiatives are crucial for improving the acceptance and effectiveness of land management policies.

In terms of the economic system, attention needs to be directed toward product and value generation, resource allocation efficiency, and land carrying capacity. These elements are essential for ensuring the economic benefits and environmental sustainability of land use. Consequently, it is necessary to consider the role of labor, capital, and technology in land use, which are key factors in driving land management innovation and improving land use efficiency [15]. In terms of the social system, the clarification of property rights, the protection of ecosystem services, the improvement of human well-being, and the achievement of Sustainable Development Goals (SDGs) [16] are current issues that need to be emphasized. The achievement of these goals requires guiding and regulating land use behavior through policies and regulations, while elevating public consciousness of the importance of land management [17]. In the development of the new era, land management and utilization need innovation in terms of laws and regulations, resource allocation, market reform, ecological governance, informatization, and supervision. Only by continuously improving the land management system, promoting the increase of farmers' income, and promoting the integrated development of urban and rural areas, can the efficient use of land resources be achieved. Scientific land utilization is critical for ensuring national food security, maintaining ecological environment security, reducing carbon emissions, and promoting the construction of ecological civilization [18].

We are dedicated to establishing a comprehensive scholarly platform that facilitates interdisciplinary dialogue and knowledge exchange among researchers, practitioners, and policymakers across diverse domains. Our primary objective is to catalyze collaborative advancement in the field of land management and utilization through rigorous academic discourse and innovative research methodologies. We encourage scholarly submissions that reflect interdisciplinary approaches, integrating perspectives from ecology, economics, sociology, and policy analysis, to address the complex challenges of land use. Such holistic research frameworks are essential for comprehensively addressing the multifaceted challenges inherent in contemporary land use systems. Through interdisciplinary research and innovation, contributions can be made to the sustainable use and protection of land resources. We look forward to your participation and contribution. Together, we can advance knowledge, develop innovative solutions, and promote the sustainable utilization and conservation of land resources.

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Conflicts of Interest

The authors declare no conflict of interest.

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RESEARCH ARTICLE

The Factors and Actors Engaged in African Land Commoditization and How They Affect Communities in Northern Ghana

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ABSTRACT

Increase in multiple demands for land in Africa has been affected by increased global food and energy requirements together with population growth. This has in turn led to large-scale acquisition of lands for agriculture by foreigners and wealthy local investors. Small holder farmers are at risk of losing their lands to the investors even if they receive government support. This often marginalizes the local people, undermines their livelihood and collides with the African indigenous tradition which sees land as a gift of God. Asinformation on the factors and actors in land commoditization is inadequate and often withheld, one purpose of this paper is to identify these actors and factors. The Bolga Municipality is used as an example because it carries all the characteristics that can be found throughout most of Africa. Data was gathered using key informant interviews, focus discussion and secondary sources. The findings of the study reveal that people sell their lands because they need to pay school fees, to build and live in decent houses, to expense money for upholding the tradition of resplendently celebrating funerals, to raise funds for the dowry of a bride, and because owners of small land parcels are often unemployed. To solve all this, better information is needed as well as purposeful job-creation to decrease unemployment and socially adequate mortgages. As social cohesion depends on full inclusivity and accessibility for all who are affected by land deals, the government must take up the problem in a holistic manner.

Keywords: Commoditization; Africa; Indigenous Tradition; Land Transaction

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1. Introduction

Land means a lot to people in terms of their agricultural, economic, social, cultural, and religious activities. Whether in developed or in developing countries, people's livelihoods depend directly or indirectly on land. However, Muir, Smith, and Agrawal [1] state that access to arable productive land in Africa is on the decline due to the pressure of growing population trends and worsening land degradation which is caused by climate change. And population growth has led to the rush and conversion of small subsistence farmlands to large scale farms or to non-agriculture use by both local and foreign investors. The land which was initially held as a sacred inheritance is now a commodity that is exchanged for money. In the peri-urban areas where there is greater potential for high value crops, land acquisitions are characterized by many informal sales which exceed large scale acquisitions. In quite a few cases, the rich "elite" have taken advantage of the poor rural farmers and taken over their farms which denies them their sources of livelihoods. The farmers are enticed to enter ventures which make them lose ownership of their land: They are offered what they believe are short- or long-term financial gains. There are even instances, as Yaro [2] puts it, where the chiefs and earth priests claim that the traditional rights of land tenure entitle them to conclude land deals (a newfound elucidation of their competences which they use to "re-invent" custom). They sell off the lands to outsiders leaving the farmers without their sources of income. This is a provocative change in customary land tenure systems which has generated uncertainty and tension. The titleholders feel that their title and their responsibilities have become subject to interpretation by the elders who administer custom..

Another issue is purchase of land by foreigners. Large tracts of land in Africa as well as land rights of local people were taken over by foreigners who mainly exploit the produce - food and crops to be used as a source for energy - for sending it back to their home countries [3, 4]. But access to land and other natural resources are particularly very essential to the people of Africa [5, 6].

Two thirds of agricultural land deals by foreign investors are in countries with serious hunger problems. Yet perversely, precious little of this land is being used to feed people in those countries or go into local markets where it is desperately needed. Instead, the land is either being left idle, as speculators wait for its value to increase and then sell it at a profit, or it is predominantly used to grow crops for export, often for use as biofuels in Europe ([7] – a sheer perversity of European environmentalists whose narrow perspective seems to only focus on decarbonization in their homelands.

Foreign investors, from 2008 on, expressed interest in approximately 56 million ha of land with agricultural potential worldwide [8]. However, what truly differentiates the newer trend of large-scale land acquisitions from those of the past is its connection to three major crises of the present decade: the global financial crisis, the food crisis, and the energy crisis [9]. According to Oxfam [7], Africa has borne the brunt of this, with an area the size of Kenya acquired for agriculture by foreign investors in just ten years. The experience on other continents is similar. World Bank and IMF research has shown that most of the land being sold off is in the poorest countries with the weakest protection of people's land rights. Secure access to land and other natural resources is crucial for the achievement of what the World Food Summit Declaration and the Millennium Development Goals have postulated, and for the eradication of food insecurity and rural poverty because land is disproportionally valuable to poor households. The same goes for in situations where the offer of off-farm employment is insufficient [10].

Holden [11] states that improved access to land can increase household food consumption and produce a surplus for sale in the market which helps to ensure household income and may improve the ability of a household to access credit. Secure access to land often provides a valuable safety net as a source of shelter, food, and income in times of hardship, and a family's land can be the last available resort in the instance of disaster. Apart from being important for food, the social and cultural identity of a people are tired to their land [12].

There are two opposing opinions regarding the relationship between commoditization and living standards of people. One school of thought thinks commoditization can contribute to poverty alleviation, better livelihoods and food security [13], while the overwhelming opinion of others says it has deleterious implications on livelihoods and food security deepening rural poverty [14–17].

2. Literature Review

2.1. Commoditization of Land

Governments of Africa have been encouraged to promote private sector participation in investment in land as a way of generating an increase in revenue from the sector in aid of plans aimed at rural development. Investors, in taking advantage of this development, have acquired huge tracts of land. And this is what can be assumed from many publications [16, 18, 19].

The acquisition of lands on large-scale for agriculture by foreigners is attributed to growing economic relations between Africa and other nations of the world. The last decade witnessed the liberalization of economies, the globalization of transport and communications, and an increase in the requirement levels of the world's food, energy, and commodities and this has led to foreign countries investing in many African countries especially in the extractive industries and in agriculture for food and fuel [17, 18, 20]. This new development creates opportunities, challenges, and risks. The benefits may include GDP growth and an increase in government revenues, and the creation of opportunities for raising the living standards of the local people. Also, the presence of investors in poor countries that have relatively a lot of land, is likely to bring it capital, technology, know-how and market access and in a way cause economic development in rural areas. However, large-scale acquisition of land can lead to loss of local people' access to resources with implications on their food and livelihood security since these depend on their access to natural resource. As the land becomes commercialized, the other effects on natives may include the loss of land and heritage, loss of access to seasonal resources by non-resident groups such pastoralists [21]. As the market value land increases, women and the other individuals in the communities who have no money to purchase land are marginalised. In the case where land acquisitions go with policy reforms, the effect might be more severe and might include contestations, strife, and struggles among different parties [22].

The problem of land grabbing is not peculiar to Ghana alone. Included in the list are countries such as Cameroon, Ethiopia, the Democratic Republic of Congo, Madagascar, Mali, Somalia, Sudan, Tanzania, and Zambia. It is believed that developing countries in general, and Sub-Saharan Africa in particular, are targeted because of the perception that there is plenty of land available, a favourable climate for crop production, cheap local labour, and that the land is still relatively cheap [23–25].

The past decade has recorded over 50 million hectares have leased or bought from individuals, communities, and governments to produce biofuels, food, forests resources, industrial goods, infrastructure, tourism, and livestock. The case is a global one, but Africa is very significant among the areas targeted as there are so many countries across the continent in which land deals have been carried out [26]. 422 concluded agricultural land deals (42% of all deals) and 10 million hectares, amounting to 37% of the deals have occurred on the African continent [26]. The overall situation requires that land acquisition, at least when reaching larger scales, should not be left to market forces alone. Protecting the interests of the poor must become a task for national governments, regional associations, and the international community. One starting point was the Principles on Responsible Agricultural Investment that were developed by FAO (https://www.fao.org/3/ml291e/ml291e.pdf) together with several international organizations. They were adopted in 2014, but progress of implementation has been very slow [27]. There are a few governments that deploy active land policies, with the main motivation being food security. Even though their main objective is directed towards the population in the investors' countries, there are some signs which show a certain degree of responsibility towards the target countries. For example, Gulf States, with scarce water and soil resources on which to grow food, but vast oil and cash reserves, have watched their dependence on food imports become increasingly uncertain and ever more expensive, their total food import bill ballooning from US$ 8 billion to US$ 20 billion from 2002 to 2007. So, they have moved quickly to extend control over food-producing lands abroad [28].

Qatar, with only 1% of its land suitable for farming, has purchased 40,000 ha in Kenya for crop production and recently acquired holdings in Vietnam and Cambodia for rice production, and in Sudan for oils, wheat, and corn production. The United Arab Emirates (UAE), which imports 85% of its food, purchased 324,000 ha of farmland in the Punjab and Sindh provinces of Pakistan in June 2008. Daniel observed that other emerging nations such as China, Japan, and South Korea are also seeking to acquire land as part of a long-term strategy for food security [28]. A 2009 study titled "Land grab or development opportunity?" jointly produced by the Food and Agriculture Organization of the United Nations (FAO), the International Fund for Agricultural Development (IFAD) and the International Institute for Environment and Development (IIED), has analysed land acquisitions of 1000 hectares or more between 2004 and 2009 from four countries: Ethiopia, Ghana, Madagascar, and Mali. It documented an overall total of 2,492,684 ha of approved land allocations since 2004 in the five study countries, excluding allocations below 1000 ha [29].

2.2. Factors and Actors in Land Commoditization

Land commoditization is an inevitable reality the world over, and Ghana is no exception. The phenomenon of land grabbing has been increasingly described by the media as a growing trend across all continents, most notably in Africa [30]. However, De Schutter [30] and Cotula et al. [29] declare that land deals reported in the international press and which enter statistics, only constitute a tip of the iceberg. The factors affecting the commercialization of land are said to be rapid growth of economies in both the developing and developed countries, introduction of new technologies, market expansion, market liberalization, urbanization, rapid increase of demand for food, decreasing of farming population, liberalized and open economic policies, bilateral and multilateral economic agreements, developed infrastructure facilities in farming areas and government agricultural policies [13, 22, 31].

But land has never been a mere commodity throughout the history of mankind. Land is considered a primary source of wealth as well as the foundation for shelter, food, and other economic activities. Particularly, land is the most significant provider of employment opportunities in rural areas. Given that in northern Ghana like many communities in Sub-Saharan African, much of the population live in rural areas countries, access to land for rural livelihoods is very crucial [32]. In Ghana the poor rural inhabitants derive their livelihoods from a number of diverse on-farm sources. These on-farm sources of income include income earned from the sale of farm crops, livestock, and other natural resources. These land-based livelihoods are critical to the survival and health of most rural households, particularly the very poor [17, 33]. The UN in 1976, realizing the importance of land to development, reiterates that land cannot be treated as an ordinary asset, controlled by individuals and subject to the pressures and inefficiencies of the market. Private land ownership is also a principal instrument of accumulation and concentration of wealth and therefore contributes to social injustice; if unchecked, it may become a major obstacle in the planning and implementation of development schemes. The provision of decent dwellings and healthy conditions for the people can only be achieved if land is used in the interests of all of society. Public control of land use is therefore indispensable [34]. But all along, land dispossession of smallholder farmers, pastoralists, indigenous peoples, and other rural communities, has been a continuous process over centuries of foreign and internal colonization, as well as post-independence 'land grabbing'. Abebe adds [28] that the various political and economic factors peculiar to Sub-Saharan Africa have compounded the implications of land grabs in the region. Apart from increase in population and the growing desire of people to own land a surging demand was built up for agrofuels (biofuel produced from ethanol and sugarcane as well as biodiesel). This together with the quest for new raw materials from which to manufacture various goods is a new driver of land purchases. With biofuels, for example, the US Renewable Fuel Standard aims to increase ethanol use by 3.5 billion gallons between 2005 and 2012, and the European Union's aim was to increase the proportion of biofuels used in land transport to 10% by 2020 [28]. The source further argues that another factor fuelling land grab is the hunger of investors who have identified farmland as an important investment which is posed to produce significant returns. He asserts that many Western investors including Wall Street banks and wealthy individuals have, since 2008, turned their attention to agricultural acquisitions.

Land commoditization is also driven urbanization and the demand for residential facilities [35]. The population of towns and cities have greatly increased leading to their expansion into adjoining rural areas which caused sharp declines in farming businesses. Development agencies and think tanks such as the International Food Policy Research Institute (IFPRI), the World Bank, the Food and Agriculture Organization of the United Nations (FAO), the International Fund for Agricultural Development (IFAD), and the United Nations Conference on Trade and Development (UNCTAD) realize that there have been extremely negative consequences associated with the recent surge of land grabbing: the displacement of local populations; a reduction in food security; environmental damage; loss of livelihoods; social polarization and political instability. These agencies have also identified the secretive manner land deals are often conducted as the investors chose to target countries with weak land tenure rights [13, 36, 37]. Land grabbing directly interferes with the right to feed oneself. Land grabbing forecloses the lands taken from landless or land-scarce communities who could make alternative and better use of the resource. In the future, national policy decisions will be needed to make land available (again) for local food production by and for the local communities and for the nearby urban areas. This will have to face the well-known difficulties of expropriating large-scale lands for the benefit of landless communities – especially where these lands are not used productively. But there is the danger that the foreign owners will seek recourse from bilateral investment treaties or trade regulations that prevent national government from implementing such policies. The question is how to balance this with governments' obligations to facilitate people's access to food resources [38].

The World Bank believes that privatisation of land rights has the potential to contribute to poverty alleviation through three mechanisms: payments for the lease and purchase of land; generating employment for wage-workers; and new opportunities for contract farmers [13]. But on the contrary, what is reported in many communities in countries of Africa is not what the World Bank envisioned. We see displacement of farmers, and pastoralists, depletion of rural livelihoods, changes in institutions as well as in gender and power relations, food insecurity and increase in conflicts [4, 39–41].

Speculation is said to be the greatest challenge of the global land grab. Whether it is a large-scale land transaction by foreign investors for agricultural production, or '(trans) national commercial land transactions', the purely commercial motive mostly overrides any other consideration, irrespective of scale and markets [4, 42]. Land grabbing or commercialization land acquisitions referred to as commoditization of land in the context of this paper means taking custody of and/or controlling a scale of land which is disproportionate in size in comparison to average land holdings. The lease/purchase of the land could be for any purpose, but in all cases, there are implications for livelihood security. The Upper East Region of Ghana has suffered significantly from all these features.

The perpetuation of land commoditization by foreign investors is now a known fact. But what is new, is that illegitimate, or at least improper, foreign land deals may only be a small part of the 'commercialization of land'. More significantly, in many cases, land commercialization is carried out by a national and local upper class, which competes with land users (pastoralists, crop farmers), and which incites land grabs within families, where men take over lands from women, in a lot of cases from poor widows and their children. Hence, focusing only on large-scale land acquisitions by foreigners can divert attention from more serious 'land grabbing' in some societies.

If the land has both cultural and social significance and the lives of people depend so much on it, the question must be asked why they part with such an important resource. Who are the faces behind the transactions? And why is it that the direct dependence on agriculture for the livelihood of a majority in rural Africa (three out of every four poor people as per the 2008 World Development Report) [43] is overlooked in national and international policymaking? If this continues, the large population of unemployed rural and urban youth in all Africa (of which the Upper East Region of Ghana is an exemplary case) will lose their livelihoods and all prospects of personal development as the days go by. It is against this background that our paper contributes to new strives for better and more holistic policies.

Our paper, by investigating the key factors and actors in land transaction and commoditization in the Upper East Region would reveal the root cause of the problem: What accounts for the inadequate information on factors and unclear identification of actors in the transaction and commoditization of land in the Upper East Region of Ghana?

3. The Study Area – Bolgatanga Municipality

The Bolgatanga Municipal Assembly with its capital Bolgatanga was established by a Legislative Instrument (LI) 1797 of 2004. Bolgatanga is also the capital town of the Upper East Region. The Municipality, which is the largest urban centre of the region forms part of the fifteen (15) districts and municipalities in the region. The Municipality is bordered to the North by the Bongo District, to the East by the Nabdam District, to the South by the Talensi District and to the West by the Kassena Nankana East District. The Administrative capital is Bolgatanga. The municipality has a total land area of 729 sq km. Bolgatanga Township consists of suburbs such as Daporetidongo, Tanzui, Atulbabisi, Bolga-Soe, and Zaare. Others include Yikene, Dulugu, Kumbosco, and Tindonmoligo, which are all peri-urban in nature. Bolgatanga is the biggest settlement. The Municipal Assembly Area has about 182 towns and villages, and the settlement pattern is predominantly rural (about 95 percent) with dispersed buildings, which render service location extremely difficult.

In the last Population and Housing Census, the population of the Municipality stood at 131,550 with a population growth rate of 1.2% and a population density of 142.2 persons per square kilometre. The population was comprised of 62,783 males (47.7%) and 68,767 females (52.3%). But it increased much faster: to 139,864 with 66, 607 males and 73,257 females[44]. Ethnically, the largest group is the Gurune people.

According to the 2020 ministry of finance composite budget of the municipality, agriculture is the main economic activity in the Municipality. This is done on a subsistence basis and employs about 57% of the people. The major crops that are cultivated by the people of the municipality are millet, sorghum, maize, rice, groundnuts, cowpea, sweet potato, and soya beans. Also, tomatoes, pepper and onions are cultivated on a large scale. The animals that are reared include cattle, goats, sheep, poultry, donkey, and pigs but on a subsistence level (See: https://mofep.gov.gh/sites/default/files/composite-budget/2020/UE/Bolgatanga.pdf (Accessed 14 February 2025).

Below is a map of Bolgatanga municipality showing its communities or subsections (**Figure 1**).

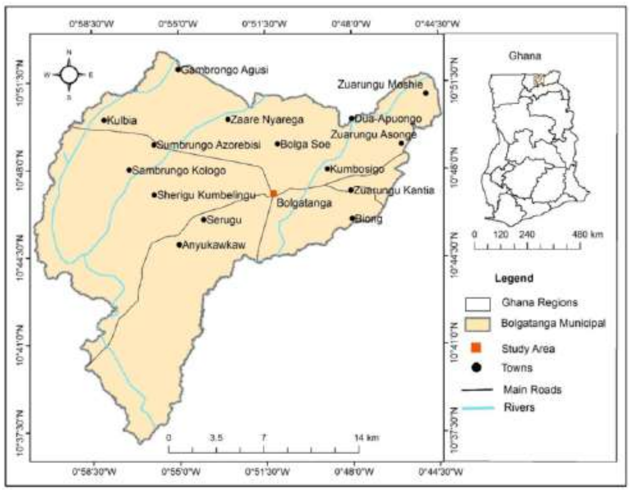

Figure 1. Map of Bolgatanga municipality in the Upper East region of Ghana.

3.1. Land Tenure and Governance in the Bolgatanga Municipality

In line with the rest of the country, the Bolgatanga Municipality practices a dual land governance system, statutory and customary. Customarily, the Tindaana (Earth Priest) is recognized as the custodian and the allodial title holder of land in Bolgatanga. He is said to be the descendant of the first settler on the land and by custom has right of ownership over the land[45–47]. Tribal chiefs, because of their social and political status and the recognition which they receive from the public from long before the colonial era, also have authority on land, but this is limited [48, 49].

The various recognised interests in land in the municipality like other parts of the country include the allodial title, common law freehold or customary law freehold, usufructuary interests, leasehold interest, and customary tenancy. As per the Land Act of 2020, the allodial title is the highest interest [50]. In the Upper East region, the chief, Tindaana, clan head, family head are authorities in charge of the management of skin-, or clan- or family-land. They are fiduciaries charged with the obligation to discharge the management function for the benefit of the skin, or clan or family concerned, and are accountable as fiduciaries [50].

Customarily land is owned by male members of the family, but women can access land through their relationship the men – father, brother, uncle, and husband [51, 52]. They have access but not ownership. What this means is that women are allowed to use the land, but they tend to sell this right or to enter into contract with another party on the usage of the land since they do not control the land. The other parties often dictate their terms. So, ownership and control of land is a preserve of men [53]. The explanation for the exclusion of women is that they do not sacrifice to the Earth God [51], and even though they belong to their husband's family, the family regards them as strangers who cannot be trusted with their land [54].

3.2. Research Methodology

A qualitative research approach was employed in this study. Qualitative research allows a researcher to explore and understand the "meanings individuals or groups ascribe to a social or human problem" [18, 55]. Since the study needed to capture the meaning that people ascribe to commoditization, a qualitative approach was the best fit.

The research mainly relied primary data, but a review of books, journal articles, magazines and internet sources that had information on the subject matter was also carried out. Secondary data from census reports were reviewed to for an initial picture of the situation of the target group. The best format for enabling local people to analyse their living conditions and to share the outcomes is Participatory Rural Appraisal [56].4This tool was used in conjunction with key informant interviews and Focus Group Discussions.

Purposive sampling was employed in the selection of research participants. The sampling technique was used because of the nature of the study and the need for people who knew the subject matter and who could answer the research questions [55]. The sampling technique was employed in two communities, Atulbabiisi (urban) and Zaare (peri-urban). The locations, presence of land sales and the evidence of the effects on the community were the criteria used for the sampling. Two communities, one urban and the other peri-urban were purposively selected. Three key informants (chiefs, Earth Priests and community members of the assembly) from each of the selected communities, and participants of the focus group discussion numbering twelve (eight men and four women) were also purposively interviewed. The members of the focus group discussion consisted of land agents, landowners and people who had sold land. The discussion allowed each of these actors to share their perspectives on the subject matter. They discussed the actors, factors, and implications of land sales on communities and their people.

Data were analysed concurrently with data collection as respondents were asked to scrutinise the situation during the interviews. The involvement of participants in the subsequent analysis of data leads to community control and ownership of information [55].

4. Findings and Discussions from the Study

This section has two parts: A first part presents the outcomes of the key informants' interviews as well as the feedback from the focus groups. In the second part, the authors will mirror this in the socio-political environment of the topic.

4.1. Analysis of the Informants' Statements

(a) Understanding of land commoditization

According to the respondents, land was free, historically, but the infiltration of 'foreigners' or non-natives seeking land for residential and commercial purposes makes indigenes see this as an opportunity to make money, resulting in the sale of lands. Land sales are so rampant in local communities that their outcomes are obvious to members. Responses from participants on their understanding of land commoditization included '*land having a monetary value; land becoming an item for sale just like items on the market; land becoming something we can sell when we want to, and making the land which initially was free and an important resource an item for sale just like salt or pepper in the market*'. It is assumed among the Gurune people that salt and pepper are the commonest and cheapest commodity in the market. This comparison goes to show how common and rampant the sales are. One respondent lamented: "*The sales are now too serious. Some for good reasons but others are not. Can you imagine selling a piece of land to someone to build a 'block house' when you cannot even get a common laterite house for yourself after the sales? That is not good enough. Some people use the proceeds from the sale of the land on alcohol and women".*

One of the communities that was chosen for the interviews, Atulbabiisi, is in the heart of Bolgatanga town. It houses one of Bolga's major markets, business stores, businesses, offices including the Post office, some schools, banks, hotels, the catholic church, a big mosque, as well as residences of both locals and non-locals are on the land. The other community, Zaare, has the regional hospital, nursing and doctors' residences, some basic schools, the girls' senior high school and some government office buildings and most of this land was compulsorily acquired by the government. The land seems to have so many buildings on it that not much land is left. But because of its location, the few lands left is in high demand and so land is moving from agriculture to non-agriculture purposes. The rate of commoditization of land varies from place to place, depending on location, urban or rural or its nearness to certain important facilities. And that is the fate of this urban community. As earlier stated, within the culture of the Gurune people, land is not sold, and there are many who still hold to this value in the face of modernity and commoditization. It is expected that people will only make money from a piece of land under urgent and very important situations when it is considered that there is no other remedy. However, from the responses it does not appear that people follow the culture and the expectations of society with regards on when to put a piece of land on the market. There are cases of people giving the land to persons who they think will put it to a profitable use such as a residential home/a business, or to a bank who will use it for higher gains in the future. In their own view, the old landowners waste their property on what the community terms as unimportant. They are made to believe this, as Yaro alluded to (see: [2]), and are lured into ventures where they lose their lands and livelihoods because of the short term benefits they gain through the disposal. The proceeds when it is not put to good use or a good investment, soon finishes and they are worse off than before.

(b) Factors that drive the commoditization of land

There was a chieftaincy (political) conflict in neighbouring Bawku which caused many people from that area to migrate to settle in Bolga. From there, the demand for land for residential and business purposes rose, and this has led to an increase in the cost of land within the municipality and in Bolga Township in particular. A plot of land was sold for about ten thousand Ghana cedis (roughly 850 USD at the time), according to one respondent, which was meant to be a good bargain. The land could even be more expensive than that in places where there are pipelines and electricity.

The findings have it that the factors that drive the sale of land in the municipality vary but include the need for families to pay school fees of children, especially when they get to levels in education where the fees are high; then there is people's desire to build and live in decent houses and roofing them with iron roofing sheets or replacing their thatch roofs with iron roof sheets. It is seen as unfashionable to still have a thatch roof on one's house. An individual or family with such a roof is seen in the community as being among the poorest and suffers some mockery. Other identified factors driving commoditization of land include population growth, poverty, the need to acquire property such as a motor bike (mostly by the youth) or to perform 'befitting' funerals, to finance the dowry of a wife, or to solve conflicts. And there are 'forced' sales. Among the indigenous people of Bolgatanga, grooms and their families are expected to give the bride's family some cattle (could be 2 or 3) and some small ruminants as dowry during marriages. Usually, the bride joins her husband before this is demanded. In some instances, failure to meet the demands of the in-laws could make them take the bride back home until the request is granted. Families may resort to selling the land to meet this demand as it is considered a shame to allow one's wife to be taken away due to nonpayment of the dowry.

It was pointed out in the interviews that degraded lands were likely to be disposed of since farming them would not bring the desired yields. The farmers usually do not have the resources to improve the fertility of the lands. The lands are disposed of, and according to the respondents, the proceeds are put into a more viable venture. A respondent from Atulbabiisi had this to say, *"You see where the Bolga new market is? Some of our people had their farms there. They used to get a lot of yields but after a while, they had to abandon the lands because the yields were now too low. So, when the assembly came asking for the land to put up a new market, they saw it as an opportunity to dispose of it".*

During discussions participants explained that sometimes the lands that are given out for 'free' as required by custom are later sold by the second "owner" after the death of the giver (actual owner). In this case the children of the original owner, in order to enjoy any benefit, are forced to agree to the sale so that they do not entirely lose. Also lands that were seen as source of conflict are sold out to avoid further conflicts.

It was also explained that lands were given free for farming purposes, but people now want the land for other uses such as siting of businesses and construction of buildings which are more permanent. Since it is not possible to get the land back it is only right to take money in exchange for it. A respondent in the group said, "We have realized that when our fathers gave the land for free to their friends, these friends later sold the land and are wealthier now, so we will not give out lands for free again, we have to get money for it".

From the findings, the main underlying causes of land sales in the municipality are poverty and unemployment. The municipality is in the Northern part of the country, and unlike southern Ghana which has two raining seasons, it has one short raining season which is May/June – September/October, with 800 mm and 1,100 mm of rain, and long spell of dry season, which is November – mid February [44]. The soil is degraded and requires a lot of input to get good produce or yields. Apart from the economically endowed farmers, many of whom are commercial farmers, most dwellers are unable to make the needed investment for good yield. Thus, the land is not fertile enough to feed the family all year round let alone sell part of the produce to acquire other family needs. Many individuals therefore resort to selling portions of their lands to take care of their pressing needs, although our findings also show that some might sell the land for insignificant reasons.

(c) The actors involved in land transactions and commoditization

It was revealed that the actors in land transactions and commoditization include the landowner who is selling the land, the family head, the Tindaana (Earth Priest) and the buyers. Some land belongs to the clan and the clan heads have oversight authority over them. There are also lands belonging to individuals (individual landowners). If the land to be bought belongs to a clan, then the buyers will need to see the head who will in turn inform his younger brothers about it. He also shares the proceeds with them.

It was also revealed that the Tindaana is an important actor or player in the land transaction. He is the spiritual head of the land, and all land directly or indirectly belongs to him. The Tindaama (plural) within the Bolga area sign the land documents when lands are sold. The respondent however revealed that some areas within the Bolga Municipality have no Tindaama (Zaare, Yorogo, Sumburungu) and so the chiefs do the signing.

When asked about the position of the chief in land issues, a respondent had this to say, "*chiefs are for the people not the land",* and they should not be considered as actors in the transaction. Most local communities of the Gurune people have two key traditional leaders, the Tindaana and the chief. This has to do with a cultural position where the Tindana in many cases is the descendant of the first settler and is considered the owner of the land, whereas the chief is not considered to own the land. He is supposed to administer to the people. There are some instances where the chief is an overall landowner, but he mostly owns just his family land. The chief at times is said to be a stranger who was asked by the Tindana to take care of the people while he attends to the spiritual matters of the land. This often happened in colonial times; the imposition of chief in these non-centralised or acephalous communities is to blame for a lot of the confusion that was created [49]. In the face of commoditization, the issue of who owns the land or who among them should be considered the actor in the transaction process has become a source of conflict in recent times in many communities.

There are land agents within the Bolga Zone who are very important in the land transaction process. They form the link between the landowners and the buyers. Landowners do not know where the buyers are, neither do the buyers know where the lands are. The agent's responsibility is to link them. He is sometimes the first point of contact for buyers. Agents are contacted by landowners to help them advertise and sell their lands. The agents sell the land at a higher price than what the owner is seeking for, thus making some money for themselves. Another important actor in land transaction according to the respondents is the Government. The government is an active player in land transactions since a lot of lands are acquired by government for development projects.

4.2. Positioning the Respondents' Opinions into the Socio-Political Environment

From the findings, respondents did not have a clear stand or position about commoditization of land or the sale of land. The results have it that commoditization could be beneficial or detrimental depending on what happens to the money that accrued from the sale of land. "It will in a particular situation be beneficial if the money is put into a venture that is profitable. Otherwise, the individual has lost it all." Apart from the proceeds not being used for beneficial purposes, the effects land sales and takeover of lands by strangers and migrants on their culture also came up.

> *"You sell land to a stranger and when he settles near you, he now wants to dictate to you how you should live your life. For instance, some want to change our culture; they do not want us to drum during funerals – that we are disturbing them. Is that good?"* – (A man from the group discussion).

> *"If a landlord sells all the land around his own house, when he dies, how will his body be taken round the house as tradition demands?"* – (A woman from the group discussion).

The second group held the opinion that land sales promote development as it encourages 'strangers' to settle on their lands and to help build them their community. The group held the view that commoditization had the ability to reduce poverty leading to the building of better houses and ownership of other forms of property.

> "*Commoditization is not entirely bad; it creates development and expands the town. But when the money is finished the landowners have nowhere to turn to. Land is leased for 99 years for residential and 50 years for commercial purposes, and that is so much time*."

The view of the research participants reflects that of the scholars whose opinion on commoditization of land is divided (see the Literature Review above). However, unlike the academics who have fixed positions, the respondents did not. They acknowledged that commoditization of land is detrimental to landowners but in situations where they are compelled to dispose of the land for money to solve some very important or serious problems such as treatment of illness, payment of school fees etc., it could be of benefit to the family or individuals if the proceeds from the sale is used for that purpose.

The findings revealed that farming is seen as unattractive and less profitable by the youth. And so, some tend to sell off the land to put the money into ventures they deem more profitable. This will have implications not only for food security, but for the availability of land for future generations. But land should be considered a property owned by those dead, by the living and by those yet to be born (Ollenu, 1962). If the living sells it to meet their needs of today, those yet to be born will be deprived of the ability to own the land.

Strategies to ensure synergy between land-security and commoditization for enhanced livelihood security

Some respondents wanted the lease period of land to be reduced from 99 years to 15 or 10 years while others felt a 50-year lease period was more realistic. The group was of the view that after the 50-year period there should be a re-negotiation between the landowner and buyer to fix a new price. This, they believe, will better benefit landowners than the 99-year lease period, which in their opinion is almost a permanent purchase. And, to them, land should be rented out and not sold out right.

Respondents suggested that owners of land should be allowed to lease lands in their own names with conditions that will favour them. For example, if the land is acquired for a commercial purpose building a bank, the landowner could have an agreement with the bank so that some jobs could be given to members of their family so that their livelihoods are not totally lost when the land is sold.

Another suggestion was that the traditional leaders who administer the land should set up a committee to deal with issues regarding the sale of land. This committee should always interview a seller (landowner) to ensure that the sale is necessary and legal. The leaders should ensure that the reason for which the landowner is selling the land is well investigated and established before signing any of the documents relating to that land. The respondents hold the opinion that land should be given out for beneficial purposes such as farming and not for quarrying.

Respondents gave the following as the profile of the actors in land transactions and the driving force towards commoditization of land in the research area (**Tables 1** and **2**).

Profile of Actors

Respondents blame communities' engagement in land sales on the lack of employment opportunities and poverty. They stated that there are some instances that due to poverty, some individuals are compelled to dispose of the land as a last resort for the payment of school fees, medical bills, and dowries. They feel if farming is more productive, farmers will be able to meet these needs without having to sell their lands. They therefore called on government and non-governmental organisations to help farming communities to improve yields, make farming a viable business that gives farmers a decent living. Others believed the land is now small, and population is large, government should therefore create jobs to employ people so that they do not continue to solely depend on the land.

What can be gleaned from the interviews exhibits some type of disproportion between what the community people express and the factual circumstances: The current trajectories of development in Africa with modernization of many sectors in the economy and not the least in agribusiness would point to (forced) land commodification becoming a concept that is losing relevance. Land commodification is not entirely 'evil' as it can be reconciled, in several ways, with the resilience of custom on land. One example is the chieftaincy conflict in Bawku community where the influx of migrants caused land dispositions – but, in the end, one might say that what was seen as unwelcome intrusion and acts by external players turned into changes of land use from which all parties benefitted.

5. Conclusion and Recommendations

Commoditization of land has caused a lot of harm to Northern Ghana in particular, and to Ghana as a whole. The study however reveals that land commoditization is not entirely 'evil'. "*Commoditization is not entirely bad; it creates development and expands the town. But when the money is finished the landowners have nowhere to turn to. Land is leased for 99 years for residential purposes and 50 years for commercial purposes and that is so much time*" (Opinion leader, Atulibabiisi).

The paper has contributed to the existing literature by revealing on-the-ground opinion regarding the actors and factors. While the issue of land-commoditization is a very important one, there is very little research on the topic that would reveal the background and the outcomes in a specific region like in the Upper East Region of Ghana. We hope that our analysis can serve as a model

Table 1. Actors in the land transaction process in Bolgatanga Municipality.

ACTOR	ROLE(S)
Landowners	They have the lands for sale.
Clan heads	They oversee clan lands and sometimes sell them
Tindaana	He is the owner of the entire land. He signs the land documents.
Chief	He is the leader of the people. Owns the land in some cultures and signs the land documents. Leases large tracts of land for developmental projects.
Land Agents	They link landowners to buyer.
Family heads	Members of the family informed of land sales and may sometimes intervene if sale is not thought to be beneficial.

Table 2. Actors and the driving forces towards land commoditization.

ACTOR	DRIVING FACTOR (S)
Chief	Prevents conflicts in their communities, including land related conflicts. Financial benefit from sales.
Tindaana (land priest)	Ensures spiritual links with the ancestors are maintained. Financial benefit from sales.
Family head	Desires to prevent conflict. Ensure that land transactions carried out by family is legal and beneficial.
Agent	Financial benefit
Witness	Desire to prevent future conflict
Government	Ensure that contracts entered into by the parties are kept. To prevent conflicts To ensure security of citizens Financial benefit

for more research in this area.

We are not aware that the governmental policies on land issues are interlinked with labour policies. But creating jobs to reduce poverty can certainly minimize the sale of land for the purpose of just gaining money.

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Conflict of interest

The authors declare no conflict of interest.

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ARTICLE

Exploring Hydrological Processes and Land Management Impacts in the Hamp River Basin—A SWAT Model Approach

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ABSTRACT

Rainfall-runoff modeling is a critical component of hydrological studies, aiding in analyzing river basin responses to climatic variations. This paper examines the rainfall-runoff behaviour of the Hamp River Basin, part of the Mahanadi River System, using the Soil and Water Assessment Tool (SWAT). SWAT, a physically based, continuous-time model, predicts land management effects on water, sediment and agricultural yields in large watersheds. This study calibrates and validates SWAT for the Hamp River Basin to assess its effectiveness in simulating stream flow. Additionally, it explores the implications of land management policies on hydrological processes, examining policy-model interactions to understand regulatory impacts on runoff and sediment yield. Simulated policy scenarios predict hydrological changes under different land management strategies. By integrating socio-economic characteristics, the study analyses hydrological changes affecting local communities, particularly regarding land use and agricultural sustainability. Soil conservation strategies are evaluated to recommend measures for mitigating sediment loss and enhancing resource conservation. The Hamp River watershed, within the Seonath sub-basin of the upper Mahanadi basin, was studied to estimate sediment yield and nutrient loss. Critical agricultural sub-watersheds

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and associated Hydrological Response Units (HRUs) were identified using ArcSWAT. The area was divided into 16 sub-watersheds based on topographical features from a Digital Elevation Model (DEM) and drainage networks. Land cover, soil and DEM data were used to create HRUs, enabling annual runoff analysis across calibration and validation periods (2017–2023).

Keywords: Rainfall-Runoff Modelling; Mahanadi River System; SWAT Model; Hydrology; Stream Flow Simulation; Sediment Yield; Nutrient Loss

1. Introduction

Hydrological modelling plays a dynamic role in effective water resource management, flood forecasting and assessing the impacts of climate change on river systems [1, 2]. The Hamp River Basin, a part of the Mahanadi river system in India, holds significant agricultural and socio-economic importance, making precise rainfall-runoff modelling crucial for sustainable water management [3, 4]. The Mahanadi River, one of India's major peninsular rivers, is divided into Upper, Middle and Lower sub-basins, with this study focused on its left tributary, the Hamp watershed.

Accurate modelling of rainfall-runoff interactions in this basin is critical, as water resources are among the most precious assets essential for ecological and human sustenance [5]. Uncontrolled water flow, however, can lead to catastrophic events such as floods and mudslides, underscoring the need for reliable runoff estimation. This process is influenced by factors such as local topography, vegetation and climatic conditions, which are essential to minimising risks and enhancing water resource planning [6, 7].

The Soil and Water Assessment Tool (SWAT) is recognised as a robust and tangible model for simulating the effects of land management on water, sediment and agricultural yield across diverse landscapes [8]. Initially developed by Arnold for the USDA, SWAT has gained global prominence as a distributed-parameter model for both small and large basin studies [9, 10]. It integrates weather data, topography, vegetation and land use practices, providing comprehensive insights into watershed dynamics over extended periods.

To apply SWAT effectively, watersheds are divided into sub-watersheds and further segmented into Hydrological Response Units (HRUs), representing unique combinations of land use, soil type and slope [11]. SWAT provides two primary methods for watershed delineation, i.e., a Digital Elevation Model (DEM)-based approach, which uses the area's topography and a predefined method, which is tailored manually. The DEM-based approach is often favoured due to its precision in delineating complex terrain features, which aids in analysing sediment and runoff yields within river basins [12].

In this study, SWAT's capabilities are harnessed to model the hydrological responses of the Hamp watershed, aiming to generate actionable insights for sustainable management while identifying high-risk zones for sediment yield and nutrient loss. Through GIS integration, ArcSWAT is used in this research to establish a framework for optimised water management strategies in the Hamp River Basin [10].

This study also considers the impact of land management policies on hydrological behaviour and appraises potential strategies for improving watershed sustainability. It considers the socio-economic trepidations to bridge the gap between veracity and implications of land management.

2. Study Area

The Hamp River Basin, part of India's Mahanadi River System, exhibits diverse topography that spans from hilly terrains to expansive plains, and it experiences a tropical monsoon climate with distinct wet and dry seasons. The primary land use includes agriculture, forest cover, and urban areas, underscoring the region's socio-economic and environmental significance. For this study, the Hamp watershed, situated in the Seonath sub-basin of the upper Mahanadi basin, was selected, with the Andhiyarkhore gauging station of the Central Water

Commission (CWC) as its outlet.

The Hamp River, originating in the Kawardha district, flows through the newly formed Bemetara district and merges with the Seonath River in Raipur district, Chhattisgarh. Geographically, the study area extends from 81°01’ E to 81°36’ E longitude and 21°45’ N to 22°30’ N latitude, covering an altitude range from 267 to 1,193 meters above mean sea level (MSL) and a total area of approximately 2,210 km^2.

Positioned at the uppermost boundary of the Mahanadi basin, the Hamp River region is dominated by upland farming, which often results in significant soil erosion and decreased crop productivity. The socio-economic impacts of these hydrological processes on local communities are substantial, particularly in terms of land use changes. Agricultural practices and water availability directly affect livelihoods, necessitating an integrated approach that considers both hydrological dynamics and community well-being. The agricultural landscape in the Chhattisgarh agro-climatic zone is distinguished by four soil types: Bhata (Entisols), Matasi (Inceptisols), Dorsa (Alfisols), and Kanhar (Vertisols). Bhata lands, prevalent in the uplands, have slopes exceeding 5%, shallow soil depths (less than 30 cm), and loamy fine sand to silt loam textures, making them particularly vulnerable to erosion. The area faces increasing gully erosion, which has become a notable source of soil loss, further exacerbated by low infiltration capacities in these soils [13, 14].

The Hamp watershed was chosen specifically to assess soil loss and prioritise critical sub-watersheds and HRUs to improve sediment and nutrient management strategies. This study area, as shown in **Figure 1**, provides a representative setting for evaluating sustainable watershed management practices in a region facing complex hydrological and land-use challenges.

3. Data and Materials

In this study, various datasets were collected to set up the SWAT model for the Hamp River Basin. The primary data sources include DEM, Land Use and Land Cover (LULC), Soil Properties Data, Meteorological Data and Hydrological Data.

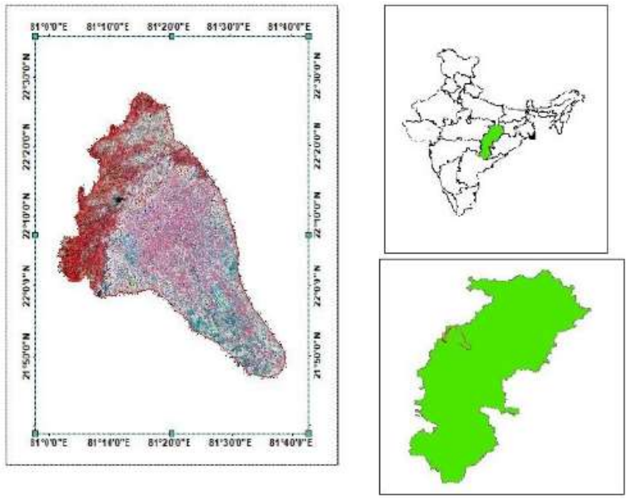

Figure 1. Location map of the study area.

The DEM, sourced from the Shuttle Radar Topographic Mission (SRTM) provided by the US Geological Survey (USGS), was used to represent the topography of the basin. This DEM data, at a 1 arc-second (30 meters) resolution, was reprojected to the Universal Transverse Mercator (UTM) coordinate system, Datum WGS 1984 (Zone-44), to ensure consistency in spatial data. A visual representation of the DEM for the Hamp River Basin is shown in **Figure 2**.

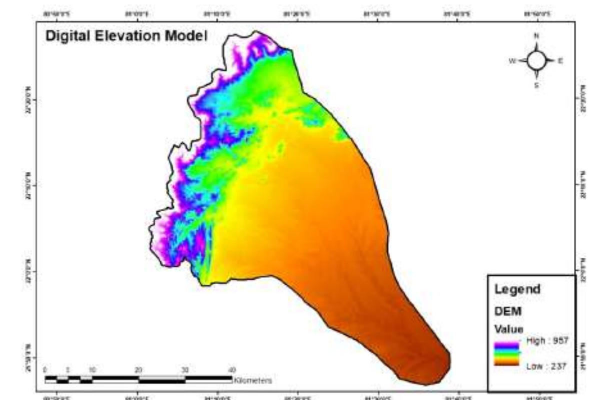

Figure 2. DEM Map of the Hamp River Basin.

To capture the spatial distribution of land cover, Land Use and Land Cover (LULC) data was derived from Landsat 8 satellite imagery, using bands 5, 4, and 3 at a 30-meter resolution. This data was classified into seven distinct LULC categories: Built-up Area, Water Body, Range Land, Trees, Crop Land, and Barren Land. These classifications were essential for assigning accurate hydrological parameters within the SWAT model. The pro-

Table 1. Major LULC Classes in the Hamp River Basin.

S. No	Field Name	Area in Sq.km.	Area in Percentage
1	Range Land	289.86	12.84
2	Trees	428.97	19
3	Crop	1,430.38	63.36
4	Water	16.87	0.74
5	Built up Area	91.09	4.03
6	Barren Land	0.01	0.03
7	Total Area	2,257.20	100

portions of each LULC class in the study area are summarised in **Table 1**, with a detailed LULC map shown in **Figure 3**.

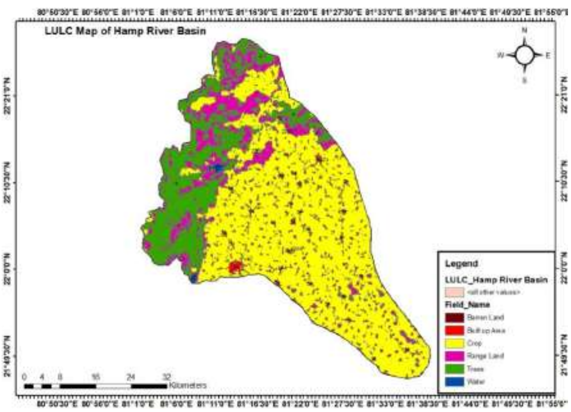

Figure 3. Land Use and Land Cover (LULC) Map.

Soil Properties Data was obtained from the Soil Texture Map for Chhattisgarh, developed by the National Bureau of Soil Survey and Land Use Planning (NBSSLUP). For increased precision, soil classifications were further refined based on soil health card data. The dominant soil textures include clay, gravelly sandy loam, clay loam, among others. The spatial distribution of these soil types is displayed in **Figure 4**, while **Table 2** outlines the specific properties and SWAT codes of these soils.

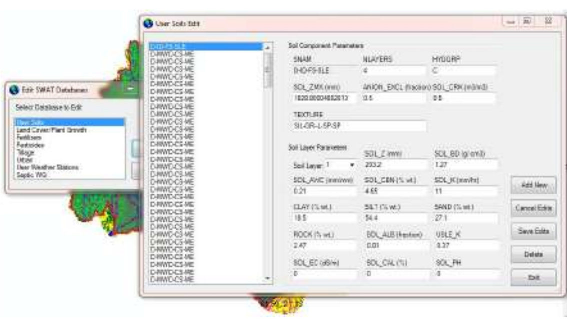

Figure 4. Soil Properties in the Study Area.

Meteorological Data used in this study consisted of rainfall, temperature, humidity, wind speed, and solar radiation records, essential for SWAT model simulation of hydrological processes. Furthermore, Hydrological Data was obtained in the form of daily river discharge measurements from 2017 to 2023, recorded at the Andhiyarkhore gauging station at the watershed outlet of the Hamp River Basin. This data, provided by the CWC Regional Office, Mahanadi & Eastern Rivers Organization in Bhubaneswar, served as the baseline for model calibration and validation efforts. Each dataset contributed to the spatial and temporal accuracy required for effective SWAT model implementation, with tables and figures providing an overview of the model's inputs.

4. Methodology

This section details the methods employed to set up, calibrate and evaluate the SWAT model for the Hamp River Basin. The methodology framework engaged in the study is shown as a flowchart in **Figure 5**.

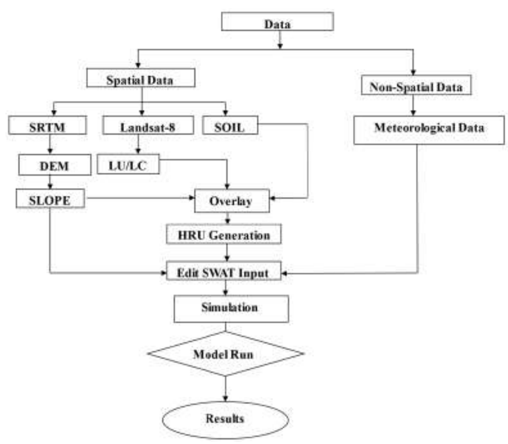

Figure 5. Methodology flow chart of the study.

Table 2. Properties of Soil with SWAT Codes.

S.No.	Soil Numbers	Soil Description	SWAT CODE
1	9	Moderately Shallow, Somewhat Excessively Drained, Fine-Loamy soils, severe erosion.	MS-SED-FLS-SE
2	10	Deep poorly drained fine cracking soil with clayey surface with slight erosion	D-PD-FCS-SLE
3	70	Deep, moderately well drained, fine soils, severe erosion	D-MWD-FS-SE
4	72	Deep, moderately well drained, fine loamy soils, moderate erosion	D-MWD-FLS-ME
5	95	Extremely shallow, somewhat excessively drained, loamy soils, severe erosion	ES-SED-LS-SE
6	96	Very shallow excessively drained, loamy skeletal soils, severe erosion.	VS-ED-LS-SE
7	99	Deep, very poorly drained, very fine cracking soils, slight erosion	D-VPD-VFCS-SLE
8	101	Deep, well drained, Loamy soils, moderate erosion	D-WD-LS-ME
9	103	Shallow, somewhat excessively drained, loamy soils, moderate erosion	S-SED-LS-ME
10	114	Deep, moderately well drained, clayey soils, moderate erosion	D-MWD-CS-ME
11	668	Deep, well drained, Loamy soils, moderate erosion	D-WD-LS-ME
12	687	Deep, moderately well drained, clayey soils, moderate erosion	D-MWD-CS-ME
13	688	Deep, well drained clayey soils, moderate erosion	D-WD-CS-ME
14	691	Deep, Moderately Well Drained, Clayey Soils, Moderate Erosion	D-MWD-CS-ME
15	692	Deep, Moderately Well Drained, Clayey Soils, Moderate Erosion	D-MWD-CS-ME
16	699	Deep, Moderately Well Drained, Clayey Soils, Moderate Erosion	D-MWD-CS-ME
17	707	Deep, moderately well drained, clayey soils, moderate erosion	D-MWD-CS-ME

4.1. Soil

The soil texture map of Chhattisgarh, prepared by the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Nagpur, using a 10 km^2 grid sampling, was utilised in this study. The map was further refined and reclassified based on soil sample analysis and point data from soil health cards provided by the Department of Agriculture, Government of Chhattisgarh. The identified soil textures in the study area included clay, gravelly sandy loam, clay loam, silty clay, gravelly sandy clay loam, sandy clay loam and sandy loam as shown in **Figure 6**.

4.2. Watershed and Sub-Watershed Delineation

Watershed subdivision is a critical step in hydrological modelling, as it allows for a more precise representation of hydrological processes. In this study, the watershed delineation tool within Arc SWAT was utilised to define the boundaries of the Hamp River Basin. Employing the eight-pour point algorithm [15], streams were extracted from the DEM, as depicted in **Figure 7**. This figure illustrates the delineated stream network and the identified watershed boundaries.

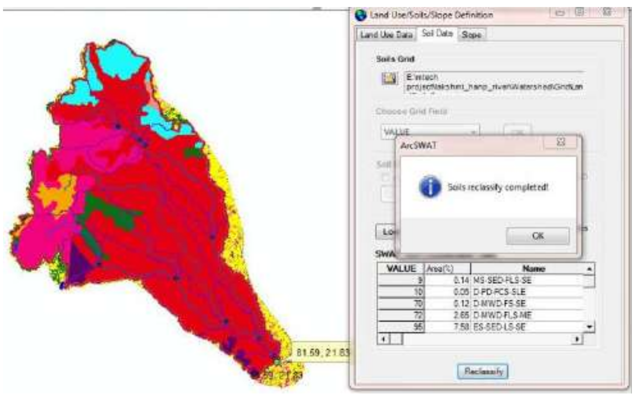

Figure 6. Map showing the distribution of different Soil categories in Hamp basin.

To define HRUs, a combination of land use, soil types, and slopes was analysed. HRUs were categorised based on these criteria to represent unique hydrological characteristics across the basin. Any land use, soil, or slope classes that covered less than the specified threshold were merged with adjacent classes, ensuring complete land area modelling for the entire watershed [8].

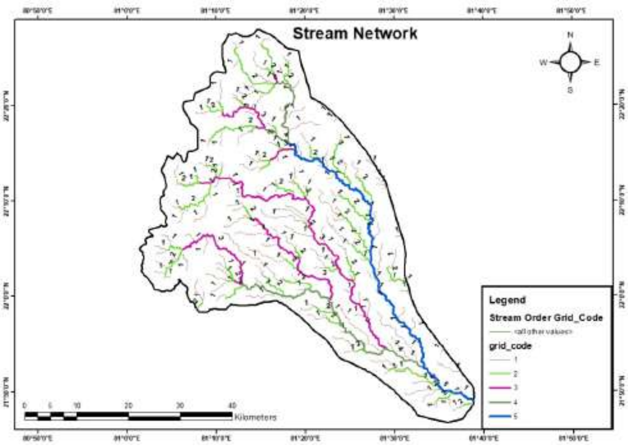

Figure 7. Hamp River Basin drainage with sub-watersheds.

4.3. Model Setup

The setup of the SWAT model for the Hamp River Basin was carried out using the Arc SWAT GIS interface. The delineated watershed was divided into multiple subbasins, each characterised by distinct hydrological features. The HRUs were defined based on the distribution of land use, soil types, and slope gradients, which is illustrated in **Figure 8**. This figure provides a visual representation of the defined HRUs within the basin, highlighting the diversity of land cover and soil characteristics critical for accurate hydrological simulation [16].

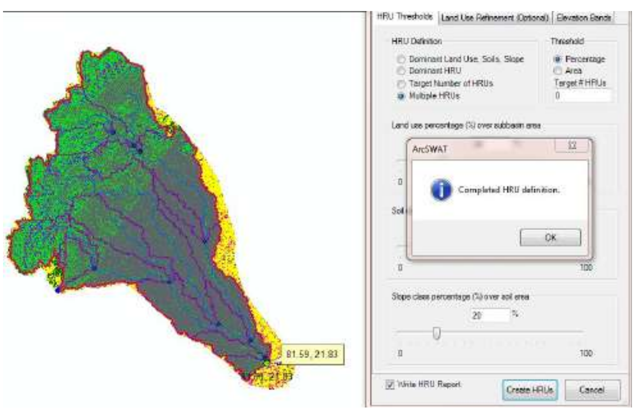

Figure 8. HRU Definition for Sub-watershed Delineation.

4.4. Calibration and Validation

Model calibration was performed using observed streamflow data collected from the Andhiyarkhore gauging station. The Sequential Uncertainty Fitting (SUFI-2) algorithm was employed to adjust the model parameters systematically, aiming to minimise the discrepancies between the observed and simulated stream flow data [17]. This calibration process is essential to ensure that the model accurately reflects the hydrological dynamics of the basin.

Once calibrated, the model underwent validation to assess its predictive accuracy. This involved comparing the SWAT model outputs against independent datasets not used in the calibration process [17]. This step is critical for verifying that the model can generalise well to different conditions and time periods.

4.5. Performance Evaluation

The performance of the SWAT model was assessed using three key statistical indicators: Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), and Percent Bias (PBIAS). The details of these performance evaluation criteria, including their acceptable ranges and categories for model accuracy, are summarised in **Table 3**. This table provides a clear overview of how model performance is categorised based on the values obtained for NSE and PBIAS, enabling a comprehensive understanding of the model's reliability in simulating stream flow within the Hamp River Basin [18].

By following these systematic methods for watershed delineation, model setup, calibration, validation, and performance evaluation, this study ensures a robust framework for accurately simulating hydrological processes in the Hamp River Basin using the SWAT model.

5. Results and Discussion

The hydrological analysis of the Hamp River basin from 2017 to 2023 reveals considerable insights into spatial runoff variability, seasonal trends, and the effects of local terrain and rainfall patterns on water flow. This study investigates how existing land management policies influence hydrological processes in the Hamp River Basin. By analysing runoff, sediment yield and nutrient transport, it is evident from the outcomes that regulatory measures play a crucial role in shaping basin hydrodynamics of Hamp basin. The findings underscore the

Table 3. Performance Evaluation Categories and Criteria.

Performance Rating	ENS	PBIAS (%)	PBIAS (%)
Unsatisfactory	ENS < 0.50	PBIAS > ± 25	PBIAS > ± 55
Satisfactory	0.50 < ENS < 0.65	± 15 < PBIAS < ± 25	± 30 < PBIAS < ± 55
Good	0.65 < ENS < 0.75	± 10 < PBIAS < ± 15	± 15 < PBIAS < ± 30

necessity for integrating policy frameworks with hydrological modelling to ensure sustainable watershed management. An in-depth examination of the region's existing policies reveals gaps in enforcement and effectiveness, necessitating new frameworks that better incorporate hydrological data and environmental sustainability principles.

Figure 9 illustrates the relationship between rainfall and runoff across the Hamp River basin, showing a pronounced correlation, particularly during the monsoon season. Here, rainfall peaks from July to October lead to corresponding surges in runoff, with nearly 75% of the annual runoff occurring within these months. This observation aligns with other monsoon-driven basins in India, highlighting a dependency on monsoon rains for water availability [19].

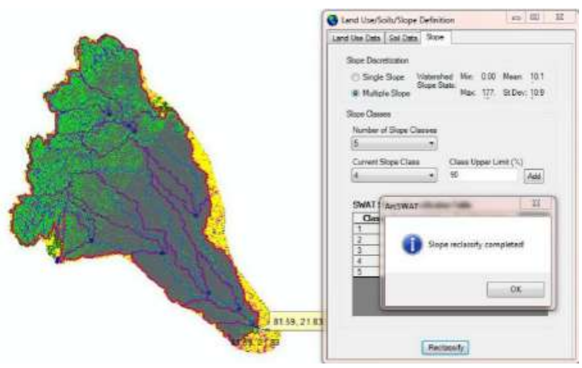

Figure 9. Spatial Variability of Runoff across Watersheds in the Hamp River Basin.

Spatially, the basin demonstrates significant variability in runoff production across its watersheds, as shown in **Figure 9**. Watersheds 12, 13, and 18 generate notably higher runoff, which can be attributed to steeper slopes, reduced vegetation, and impervious soils. These factors contribute to rapid surface flow, especially during heavy rains. In contrast, Watersheds 1 and 2 exhibit relatively low runoff due to flatter terrain and more permeable soils, which promote groundwater recharge instead of direct surface runoff. This variability underscores the need for tailored water management strategies: high-runoff areas could benefit from water storage structures, whereas low-runoff areas may be better suited for techniques such as contour bunding to enhance groundwater retention.

Monthly runoff patterns (**Figure 10**) across the watersheds, as visualised in **Figures 11**, **12** and **13**, further demonstrate the monsoon's influence. Watershed-specific responses to rainfall illustrate differences in hydrological behaviour across the basin. For instance, Watershed 3 shows a pronounced peak in October, with runoff reaching 7,232.55 cubic meters, while Watershed 4 peaks slightly later in November at 7,808.79 cubic meters. This delayed response suggests that local topographic and soil characteristics in Watershed 4 may retain water longer before releasing it as surface runoff. These patterns support findings in hydrology research, where flatter or permeable terrains are known to delay runoff peaks [20].

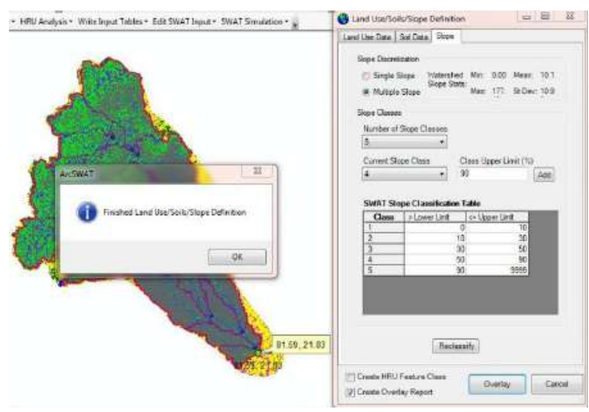

Figure 10. Monthly Runoff Patterns in the Hamp River Basin by Watershed.

The analysis of extreme runoff events is presented in **Figures 14** and **15**, highlighting watersheds with particularly high runoff rates, such as Watersheds 12, 13, and 18. These figures illustrate how localised rainstorms can significantly amplify surface flows in these areas. For example, Watershed 18 experiences a remarkable peak runoff of 29,288.9 cubic meters in May, indicating the potential for severe hydrological responses during extreme weather conditions. The extreme runoff observed in these steep and sparsely vegetated watersheds suggests an elevated risk of soil erosion and sedimentation downstream. This observation underscores the urgent need for implementing erosion control strategies, including checking dams and riparian buffers, to mitigate sediment loss and enhance water quality in downstream ecosystems.

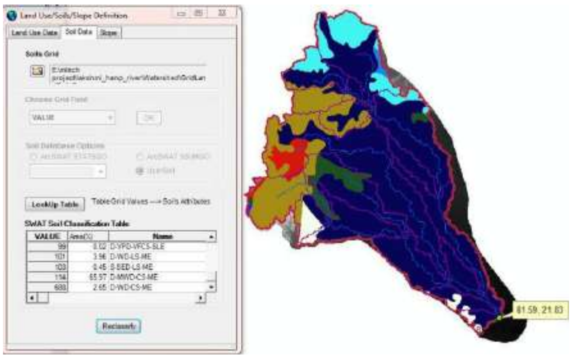

Figure 11. Comparison of Peak Runoff Events across Different Watersheds.

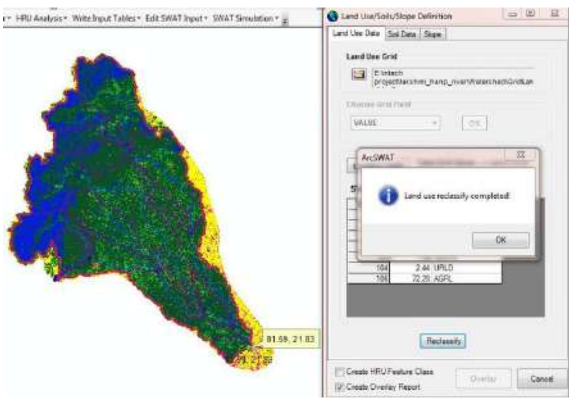

Figure 12. Temporal Distribution of Runoff across Watersheds during the Monsoon Season.

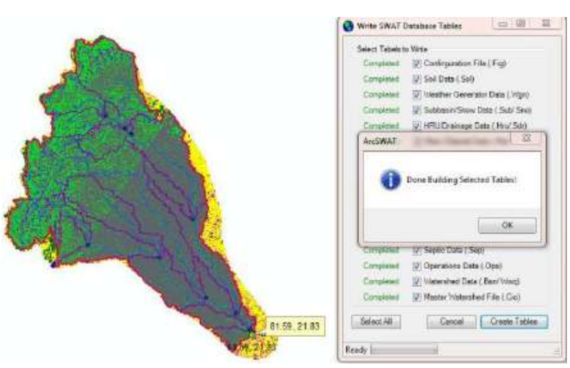

Figure 13. Extreme Runoff Events in High-Runoff Watersheds of the Hamp River Basin.

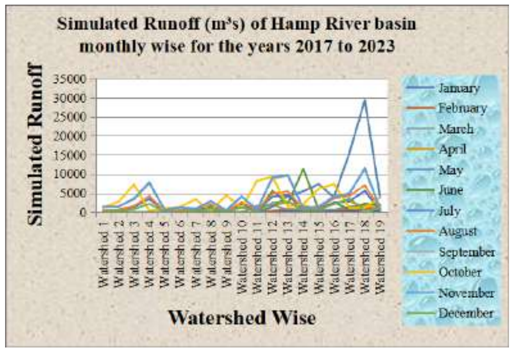

Figure 14. Impact of Localised Rainstorms on Runoff in Selected Watersheds.

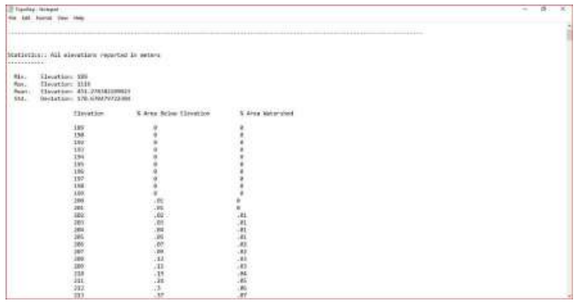

Figure 15. Seasonal Contribution of Monthly Runoff to Total Annual Runoff in the Hamp River.

An integrated view of seasonal and cumulative runoff patterns in **Figures 16** further underscores the monsoon season's dominance in the basin's hydrology. **Figure 16** reveals that monsoon months contribute approximately 85% of the total annual runoff and demonstrates how average monthly runoff significantly declines from January to June. These observations suggest that effective water management in the Hamp River basin would benefit from strategies aimed at capturing and storing excess runoff during monsoon months, thus ensuring a more stable water supply throughout the dry season.

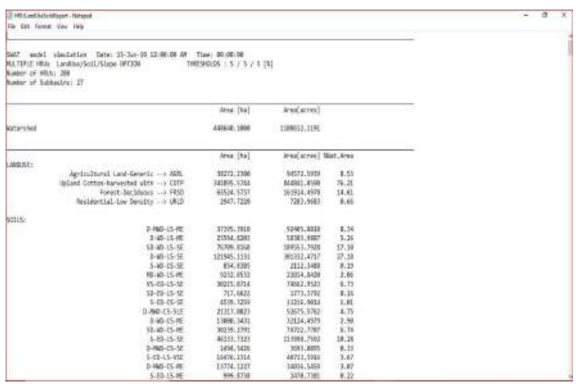

Figure 16. Average Monthly Runoff Decline from January to June in the Hamp River Basin.

The synthesised findings from these figures, along with **Table 4** data on monthly runoff, highlight critical implications for water management in the Hamp River basin. High-runoff watersheds, particularly those with steep terrain and reduced vegetation cover, should prioritise water storage infrastructure such as reservoirs or check dams to capture monsoon flows and mitigate downstream erosion risks [21]. Low-runoff watersheds, which generally have flatter, permeable soils, are ideal candidates for soil conservation techniques and groundwater recharge initiatives that allow for gradual release and sustained water availability. In erosion-prone areas, particularly in high-runoff regions, implementing vegetative barriers and soil stabilisation measures would mitigate sediment loss and improve water quality downstream.

Table 4. Monthly Runoff Data of Hamp River Basin by Watershed (2017–2023).

Watershed No	January	February	March	April	May	June	July	August	September	October	November	December
Watershed 1	29.41	19.18	0.511	0	0	0	433.96	577.12	1276.69	1203.75	1432.09	351.33
Watershed 2	7.33	0	0	0	0	0	663.27	734.3	1489.03	2787.44	1542.47	333.15
Watershed 3	0.04	0	0	0	0	0	1376.77	1601.53	3383.06	7232.55	3618.93	845.2
Watershed 4	29.52	13.11	0	0	0	4.68	3463.62	4232.24	7518.56	477.79	7808.79	2176.17
Watershed 5	74.98	44.59	7.402	0	0	23.16	280.05	283.42	613.24	1031.27	625.76	158.32
Watershed 6	48.56	41.12	10.539	1.545	0	103.69	536.63	601.69	1272.13	1400.28	1346.88	354.44
Watershed 7	81.13	86.12	66.539	18.106	9.182	9.76	573.66	834.28	953.31	3402.24	901.71	378.37
Watershed 8	94.63	75.18	34.658	18.621	7.404	158.29	1500.52	2008.81	2881	390.32	2875.53	995.5
Watershed 9	23	4.19	1.283	0	0	62.01	233.49	240.32	500.21	4432.16	509.18	132.97
Watershed 10	32.92	15.36	0	0	0	1.85	2080.58	2623.65	4120.65	996.03	4173.68	1327.28
Watershed 11	142.96	0	1640.34	0	0	133.53	407.13	591.88	678.12	8257.3	637.78	267.95
Watershed 12	0	451.98	1857.58	1498.67	1432.07	5569.62	4081.21	4853.75	8814.18	9264.6	9126.1	2504.67
Watershed 13	296.43	789.29	600.29	2680.57	4173.68	2291.88	4493.25	5452.81	9498.68	1458.95	9771.4	2775.71
Watershed 14	133.08	884.42	702.39	1619.69	5452.81	11318.3	611.53	869.62	1017.45	2134.05	978.09	444.46
Watershed 15	0	679.8	679.32	1094.53	7318.24	806.377	848.26	1265.45	1504.98	6097.58	1485.25	702.07
Watershed 16	285.67	631.13	633.82	2369.89	3894.68	2572.91	2453.46	3598.06	4124.72	7318.24	3996.29	2134.78
Watershed 17	148.87	723.37	1433.75	2853.37	15559.1	735.12	2912.07	4301.37	4955.84	1188.78	4833.47	3575.14
Watershed 18	543.96	966.8	1966.08	1421.09	29288.9	2281.73	5569.62	7007.09	11318.3	1184.25	11534.6	386.93
Watershed 19	262.25	697.8	1780.9	1255.7	3698.62	1876.29	444.28	681.94	806.377	3894.68	813.28	1016.07

These targeted recommendations align with the basin's variable hydrology, highlighting the need for adaptive, site-specific approaches to water management. By integrating findings across multiple figures and monthly runoff data, this analysis underscores the importance of strategic planning to optimise water availability and ecosystem health across the Hamp River basin's diverse landscapes and seasonal conditions. This study also highlights the need for targeted land resource conservation measures. Specific soil conservation techniques, such as contour bunding, afforestation, and check dam installations, are recommended to reduce erosion and mitigate sediment loss. The sediment yield analysis further informs potential conservation strategies that align with the identified land-use patterns.

The calibrated SWAT model is employed to simulate potential future land management policies. Various scenarios, including afforestation programs, soil conservation techniques, and agricultural land-use modifications, are assessed to determine their impact on stream flow and sediment transport. The model outcomes provide actionable insights for policymakers to optimise land-use strategies that mitigate environmental degradation while enhancing water availability. By forecasting hydrological shifts under different land-use policies, the study offers predictive insights that can aid in proactive decision-making and adaptive land management planning.

The study has noted that changes in stream flow patterns are due to deforestation, urbanisation and agricultural expansion in the basin influencing water availability which is being used for domestic, agricultural and industrial use. Examination of socio-economic conditions revealed an altered hydrological scenario, emphasising the need for community-centric land management practices. Agricultural productivity varies under different hydrological conditions highlighting the pressing need for adaptive policies that balance economic development with environmental conservation.

Various soil conservation measures are recommended for maintaining stability of Hamp watershed. Sediment yield patterns helped in suggesting specific soil conservation measures such as contour bunding, afforestation and checking dams in various locations of the basin area. These conservation strategies are suggested in line with existing land-use patterns, which ensure long-term soil fertility and minimise erosion. This is critical in maintaining land productivity and mitigating the adverse effects of excessive sediment transport on aquatic ecosystems.

6. Conclusions

This study successfully calibrated and validated the SWAT model to analyse the rainfall-runoff dynamics of the Hamp River Basin within the Mahanadi River System. The integration of various datasets, including DEM, Land Use and Land Cover (LULC) information, soil properties, and meteorological data, facilitated a comprehensive representation of the watershed's hydrological characteristics. The delineation of the basin into sub-watersheds and the identification of HRUs were pivotal in enhancing the precision of hydrological simulations. The calibration and validation phases revealed that the SWAT model effectively mimicked observed stream flow, as evidenced by satisfactory performance metrics, including Nash-Sutcliffe Efficiency and Percent Bias. The outcomes of this research provide valuable insights into the hydrological behaviour of the Hamp River Basin, identifying critical areas prone to sediment yield and nutrient loss. Beyond hydrological assessment, this study underscores the broader implications for land management policy. Findings from the SWAT simulations can guide policymakers in refining conservation strategies, ensuring that both ecological and socio-economic factors are considered. Moreover, the simulation of future land management policy scenarios provides a proactive framework for sustainable watershed management. These findings are crucial for formulating sustainable water resource management strategies, particularly in agricultural settings where erosion and nutrient runoff pose significant challenges. The application of SWAT in this context demonstrates its potential as a robust tool for hydrological modelling, offering a framework that can be adapted for similar studies in diverse river basins, ultimately contributing to improved water management practices and environmental sustainability. The study also highlights the necessity of land conservation efforts, particularly in erosion-prone areas, to ensure long-term watershed stability and agricultural productivity. The study contributes to ongoing efforts in integrating hydrological processes with land management policies and ensures optimal utilisation of water and land resources for a sustainable future.

Author Contributions

Conceptualization, M.R. and M.K.G.; methodology, M.R.; software, M.R.; validation, M.R., M.K.G. and B.V.S.; formal analysis, M.R.; investigation, M.R.; resources, M.K.G.; data curation, M.R.; writing—original draft preparation, M.R.; writing—review and editing, M.K.G.; visualization, M.R.; supervision, M.K.G.; project administration, M.K.G.; funding acquisition, N.B.R. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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ARTICLE

Geospatial Assessment of Groundwater Hydrochemistry and Land Sustainability—A Case Study of Paderu Mandal, Andhra Pradesh, India

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ABSTRACT

This study rigorously investigates the hydrochemical characteristics of groundwater in Paderu Mandal, an enclave of tribal life in Andhra Pradesh, India, through a comprehensive GIS-based analysis of 83 water samples collected from open wells and bore wells. The study examines key parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), Turbidity, Chloride (Cl_2^-), Sulphate (SO_4^{2-}), Fluoride (F^-), Nitrate (NO_3^-), and Iron (Fe). Standardized methodologies are employed to evaluate these samples against the World Health Organization (WHO) and Bureau of Indian Standards (BIS) benchmarks, assessing water safety and suitability. Spatial distribution mapping reveals contamination hotspots and zones adhering to water quality norms, offering insights into potential contamination sources. The study further explores groundwater quality implications on land productivity, irrigation potential, and sustainable land use, linking contamination risks to

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soil degradation and agricultural viability. Correlation matrices, Hill-Piper diagrams, and irrigation suitability indices provide deeper insights into the intricate interactions between groundwater constituents and land resource management. The findings serve as a critical foundation for groundwater protection policies, land conservation strategies, and sustainable resource management in Paderu Mandal. The study underscores the need for targeted interventions to mitigate water quality deterioration and ensure long-term environmental and agricultural sustainability.

Keywords: Spatial Distribution; Groundwater Quality; Physiochemical Parameters; Geospatial Techniques

1. Introduction

India, home to the world's second-largest tribal population, faces critical challenges in providing safe drinking water, especially in tribal-dominant regions like Paderu, Andhra Pradesh, where 95% of the population belongs to tribal communities [1]. The pervasive issue of contaminated water serves as a root cause for numerous health ailments, impacting thousands annually. The urgency of addressing this challenge is underscored by the United Nations' guidelines, advocating a minimum of 50 liters of water daily for essential needs, including drinking, sanitation, culinary purposes, and hygiene [2]. The scarcity and contamination of water have become pivotal challenges in the 21st century [3].

This research aims to assess groundwater quality in the tribal expanse of Paderu Mandal, situated in the Visakhapatnam district of Andhra Pradesh, utilizing advanced geospatial methodologies. Several scholarly articles have delved into groundwater quality analysis within GIS frameworks, consistently emphasizing that water pollution primarily emanates from human activities [4]. While groundwater serves as a primary source of drinking water across most parts of the country, issues such as arsenic and fluoride contamination, stemming from both natural and human-induced factors, persist in several regions of India [5, 6]. The excessive utilization of nitrates in agricultural practices emerges as a pivotal contributor to groundwater pollution [7], as these nitrates permeate the soil and accumulate in groundwater, instigating chemical and biological transformations [8, 9].

Mineral ions naturally permeate groundwater, gradually dissolving from soil, sediments, and rocks during the water's passage through aquifers and unsaturated zones [10]. Geohydrological assessments of springs and stream water within the watershed have been scrutinized, facilitating the development of spatial distribution maps tailored for agricultural, livestock, and poultry requisites [11, 12]. The Hill-Piper trilinear plot has proven instrumental in formulating these maps alongside their corresponding areal statistics [13, 14]. The contamination of groundwater in rural regions often arises from agricultural pursuits, specifically the excessive application of nitrate-based fertilizers. Safeguarding potable water from pollution and biological impurities remains imperative. The quality of water bodies in the region displays substantial variations contingent upon their geographical placement and surrounding environmental influences [15]. It is noticed that, the health of numerous individuals within the study area suffers due to water-related challenges. In view of this, this study also focuses on find out the impact of land use practices on groundwater quality such as, unregulated agricultural practices, deforestation and urbanization, which can lead to contamination and depletion of groundwater resources. Incidentally, the research also endeavors to explore the interrelation between groundwater quality and land management policies, emphasizing the need for sustainable groundwater conservation measures, protection of recharge areas and informed land-use planning.

2. Study Area

The study area nestled within the confines of Paderu Mandal in Andhra Pradesh, India, forms a fragment of the Eastern Ghats. Spanning the coordinates of 18°04'39" in Northern Latitudes and 82°39'38" in Eastern Longitudes, this area encompasses 435 square kilometers of diverse terrain. Paderu Mandal, situated at an altitude exceeding 900 meters above sea level, boasts a captivating and lush valley landscape shown in **Figure 1** along with the sample locations.

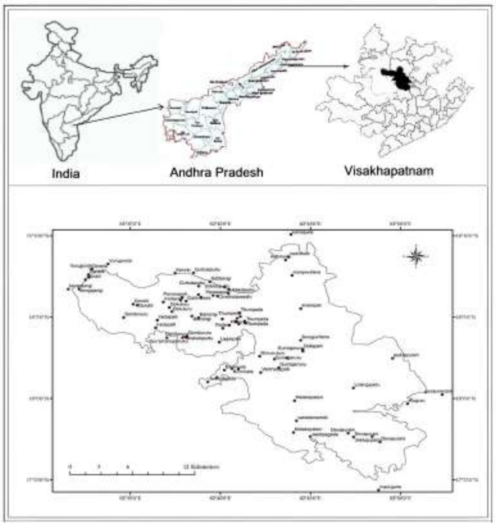

Figure 1. Location Map of the Study Area with sample locations.

Inhabited entirely by scheduled tribes belonging to various sects, this region is encircled by an abundance of hill streams. Annual precipitation averages 1252 mm, benefiting from both the southwest and northeast monsoons, which results in the proliferation of numerous streams, open wells, and bore wells across the area.

The climate in these hills contrasts starkly with the plains, experiencing higher precipitation rates, leading to a cooler atmosphere. Mean annual temperatures fluctuate between 24 °C to 35 °C. May emerges as the hottest month, while January stands as the coldest in this picturesque enclave [16]. The region's unique topography and hydrological conditions significantly influence groundwater recharge and quality. The presence of lateritic and weathered rock formations impacts groundwater movement and storage, making it crucial to assess the hydrogeological dynamics for effective water resource management. On the other hand, land use in the study area is predominantly agricultural, with shifting cultivation practices affecting soil permeability and groundwater infiltration. Understanding these interrelations between geology, climate and human activities is essential for formulating sustainable groundwater management strategies suitable to the region's ecological and socio-economic background.

3. Methodology

About 83 water samples were collected for the study from open wells and bore wells from selected locations in the Paderu Mandal (**Figure 1**). Various physical and chemical parameters of water samples were analysed and the results were compared with the values of various water quality standards such as World Health Organization (WHO) and Bureau of Indian Standards (BIS) (**Table 1**). The parameters analyzed were pH, EC, TDS, TH, Turbidity, Chloride, Sulphate, Fluoride, Nitrate, and Iron. Standard methods were used for the determination of the chemistry of the water samples. The selection of these parameters for analysis in this study is guided by a comprehensive approach to water quality assessment, tailored to the address the explicit conditions of the Paderu Mandal region. These quality parameters were chosen based on their relevance to drinking water and irrigation suitability. These parameters align with global and national water quality standards, ensuring a comprehensive evaluation. The study aims to provide valuable insights into the unique challenges of the region, addressing both natural and anthropogenic sources of potential contaminants and offering a holistic understanding of groundwater quality for sustainable resource management and community welfare.

The collected water samples were subjected to laboratory analysis using spectrophotometry, titration, and ion-selective electrodes, ensuring precise quantification of each parameter. All the chemical constituents are expressed in mg/L (milligrams/liter) except pH, which is represented in standard pH units, which refers to the measurement of pH using the standard pH scale, which ranges from 0 to 14. On this scale, a pH value of 7 is considered neutral, values below 7 are acidic, and values above 7 are alkaline or basic. Standard pH units, provides a clear and consistent representation of the measurement units for pH throughout the water quality assessment.

Water quality limits and parameters mentioned in **Table 1** succinctly cover the various factors measured in water quality assessment, like pH, conductivity, TDS, and mineral concentrations such as sodium, potassium, calcium, and others. It highlights the acceptable, permissible, and unacceptable limits for each parameter, de-

Table 1. Water Quality Parameters and Permissible Limits.

S#	Parameter	Not Acceptable Limit	Acceptable Limit	Permissible Limit	Not Permissible Limit	WHO	BIS 10500-2012	Methods of Determination
1	pH	<6.5	=6.5	6.5–8.5	>8.5	6.5–8.5	6.5–8.5	pH meter
2	EC (μS/cm)	<200	=200	200–300	>300	250	<1000	Conductivity
3	TDS (mg/L)	<500	=500	500–2000	>2000	1000	500–2000	Conductivity
4	Sodium-Na (mg/L)	<100	100	100	>100		100	Flame photometry
5	Potassium-K (mg/L)	<10	10	10	>10		10	Flame photometry
6	Total Hardness-TD (mg/L)	<200	=200	200–600	>600	500	300–600	EDTA-Titrimetry
7	Magnesium-Mg (mg/L)	<30	30	30–100	>100		30–100	EDTA-Titrimetry
8	Calcium-Ca (mg/L)	<75	75	75–200	>200	75	75–200	EDTA-Titrimetry
9	Iron-Fe (mg/L)	<0.3	=0.3	No relaxation		0.3	250–1000	ICPMS
10	Fluoride-F (mg/L)	<1	=1	1–1.5	>1.5	1.5	1–1.5	Spectrophotometry
11	Chloride-Cl (mg/L)	<250	=250	250–1000	>1000	250	250–1000	Titrimetry
12	Sulphate-SO_4 (mg/L)	<200	=200	200–400	>400	250	200–400	Turbidimetric
13	Bicarbonate-HCO_3 (mEq/L)	1.0	=1	1–1000	1000		1– 1000	Titrimetric
14	Carbonate Ion-CO_3 (g/mol)	0.1	=0.1	0.1–10	10		0.1– 10	Titrimetric
15	Nitrate-NO_3 (mg/L)	<45	=45	45–100	>100	50	45–100	Spectrophotometry
16	Alkalinity (mg/L)	<200	=200	200–600	>600		200–600	Titrimetric

tailing the methods used for measurement. This table serves as a comprehensive guide for evaluating water quality based on multiple parameters and their respective thresholds.

Geospatial techniques were employed to visualize and interpret spatial distribution trends, highlighting contamination hotspots and safe zones within the study area. The methodology employs diverse analytical techniques which leverages spatial analysis tools like Inverse Distance Weightage (IDW) to map water quality distribution across the region. Specific statistical tests, such as Analysis of Variance (ANOVA) and Pearson correlation, were employed to identify trends and variations in the dataset. ANOVA was applied to assess differences in water quality parameters among various sample locations, helping discern spatial variations. Pearson correlation, on the other hand, was employed to explore relationships between different water quality variables, aiding in identifying potential interdependencies. These tests were intended to produce outcomes that enhance our understanding of spatial patterns in water quality across the Paderu Mandal region. ANOVA helps identify if there are significant differences in water quality metrics among various locations, contributing to spatial mapping accuracy. Pearson correlation, on the other hand, provides insights into potential associations between different parameters, aiding in the identification of complex relationships within the dataset. In addition to these tests, land-use patterns were examined to establish correlations between groundwater quality and human activities such as farming, deforestation, and settlement expansion.

Statistical methods such as correlation matrices and regression analysis were utilized to identify relationships among the water quality parameters, offering insights into potential contamination sources. The Hill Piper analysis, a key element in our methodology, plays a crucial role in evaluating water chemistry and its applicability for irrigation in the Paderu Mandal region. Utilizing a trilinear diagram, this analysis visually represents the proportions of major cations and anions in water samples, offering insights into the prevailing hydrochemical processes and the types of water present. By identifying potential sources of contamination and assessing groundwater quality dynamics, the Hill Piper analysis contributes significantly to our understanding of groundwater composition. Additionally, it aids in determining the suitability of groundwater for irrigation, guiding sustainable agricultural practices in the region. Irrigation suitability was assessed using key indices like the Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Permeability Index (PI), ensuring a comprehensive evaluation of water usability for agricultural practices. By integrating spatial mapping, statistical evaluation, and chemical analysis, this holistic approach provides a comprehensive assessment of both drinking water quality and irrigation potential, informing sustainable water management in the region.

4. Results and Discussion

This investigation uncovers a tapestry of insights and revelations stemming from the comprehensive analysis of collected data. This segment serves as the juncture where it delves into the implications, correlations, and significance of the results obtained through our meticulous study of the physical and chemical aspects of groundwater in Paderu Mandal in the state of Andhra Pradesh, India.

4.1. Spatial Distribution of Groundwater Quality

A comprehensive analysis of various physical and chemical parameters present in water samples was carried out to compare them against established water quality standards set forth by the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). Employing standardized procedures, we meticulously analyzed the collected samples for key parameters encompassing Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), Chloride (Cl_2^-), Fluoride (F), Nitrate (NO_3^-), Sulphate (SO_4^{2-}), Iron (Fe), and alkalinity. The measurements for these chemical constituents are reported in milligrams per liter (mg/L), except EC (measured in μS/cm).

pH stands as a pivotal parameter in evaluating water quality within an aquatic environment, signifying the acidity or alkalinity of a solution. Low pH levels can lead to gastrointestinal disorders such as hyperacidity, ulcers, stomach pain, and a burning sensation [17]. Additionally, climatological and vegetation factors exert influence on the pH levels within a system.

The results revealed that the groundwater pH values within the study area ranged from 6.37 to 8.27, with an average value of 7.46 and a standard deviation of 0.20. This signifies a moderate level of acidity or alkalinity across the sampled groundwater. Spatially, the distribution of groundwater pH fell within the permissible limit across 408.5 square kilometers and within the acceptable limit within 26.5 square kilometers, as illustrated in **Figure 2**. The observed spatial variability in pH within the Paderu region may be attributed to various factors. Potential causes include geological variations, land use practices, and anthropogenic activities in the vicinity.

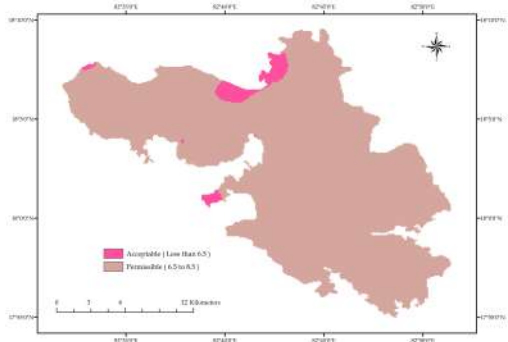

Figure 2. Spatial distribution of pH.

Electrical Conductivity (EC) serves as a metric for the water sample's ability to conduct electric current, reflecting the proportional ionic strength of the water. The conductivity is influenced by inorganic dissolved solids, including chloride, nitrate, sulfate, and phosphate ions, each carrying a positive charge. The actual relative concentrations of these substances and the temperature collectively determine water conductivity. Notably, the observed EC values exhibited significant variance across samples, ranging from 53 to 1864 μS/cm, with a mean value of 1382.3 μS/cm and a standard deviation of 622.017. This surpasses the WHO's recommended limit of 250 μS/cm, except for specific locations like Thumpada, which recorded the lowest EC level at 53 μS/cm.

The deviation from recommended EC values suggests a notable presence of Total Dissolved Solids (TDS) in the water (**Figure 3**), contributing significantly to elevated EC values. Inorganic ions such as chloride, nitrate, sulfate, and phosphate play a pivotal role in the overall conductivity of water, contributing to the observed disparities across different locations.

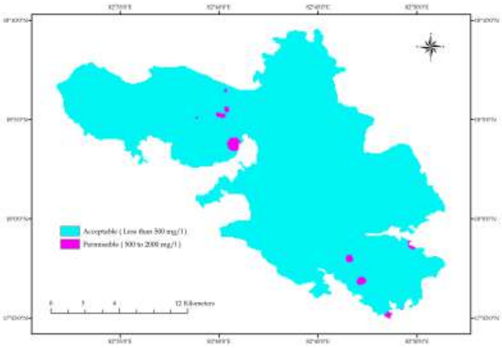

Figure 3. Spatial distribution of TDS.

Furthermore, variations in other parameters like Chloride, Nitrate, Sulphate, and Iron underscore the diverse composition and potential contamination sources within the groundwater across the study area. This highlights the necessity for further investigation and the implementation of remediation strategies to ensure the quality and safety of groundwater in these regions.

Total Dissolved Solids (TDS), encompassing mineral constituents dissolved in water, significantly impact water usability. Concentrations exceeding 500 mg/L are undesirable for drinking and many industrial purposes, while levels below 300 mg/L are preferable for specific manufacturing processes. In our study, TDS values in sampled groundwater ranged from 34 to 1211 mg/L, with an average of 968 mg/L and a standard deviation of 436.15. Notably, Thumpada and Dokuluru locations exhibited remarkably low concentrations of 34 mg/L.

Adhering to Bureau of Indian Standards (BIS) specifications, our study area's TDS values fall within the desirable limit of 500–2000 mg/L, as depicted in **Figure 3**, emphasizing the overall compliance and distribution pattern across different locations. This suggests that, despite variations in EC values, the TDS concentrations in the sampled groundwater generally meet established standards.

The Total Hardness of water denotes the cumulative concentration of alkaline earth metals within it. Predominantly attributed to calcium and magnesium in freshwater, the hardness can also be influenced by other metals like iron, strontium, and manganese, particularly in appreciable concentrations. The impact of hardness on health has been a subject of study, with reports suggesting a correlation between cardiovascular diseases and the water's hardness level, showing higher prevalence in areas with soft water [15].

In our study, Total Hardness (TH) values ranged from 20 to 310 mg/L within the sampled groundwater, with an average value of 329.29 mg/L and a standard deviation of 121.17. This variance in hardness reflects the geological composition of the areas from which the water samples were obtained. While the Bureau of Indian Standards (BIS) specifies a desirable limit for Total Hardness (TH) in drinking water at 300 mg/L and a maximum permissible limit of 600 mg/L, all samples from our study area adhere to the standard limits set by BIS, as depicted in **Figure 4**, showcasing the distribution pattern across various sampling locations. This suggests that the groundwater within the study area is within acceptable ranges of hardness as per regulatory guidelines, ensuring its suitability for drinking purposes. However, it is essential to note that despite meeting hardness standards, further investigations into the specific mineral composition are necessary to comprehensively assess potential health implications, particularly in relation to cardiovascular diseases, as studies have indicated that excessive hardness in water may contribute to an increased risk of such issues.

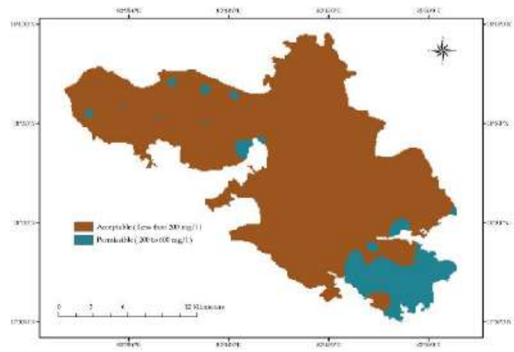

Figure 4. Spatial distribution of Total Hardness.

In addition to hardness, turbidity, indicating the cloudiness or haziness of a liquid due to numerous invisible particles, is crucial in assessing water quality. In the present study area, observations of turbidity ranged from 0.0 to 190 mg/bl, with an average value of 2.51 mg/bl and a standard deviation of 0.59. This variation signifies the presence of particles affecting water clarity. Specific locations like Arada, Relimamidi, and Vantaamamidi recorded turbidity levels exceeding the BIS specified standard limit. For instance, readings reached

140 mg/bl at Arada, 76 mg/bl at Relimamidi, and a significant 190 mg/bl at Vantaamamidi, among other areas. The spatial distribution of acceptable, permissible, and impermissible turbidity levels spans different areas. The distribution pattern shows an area of about 23 km^2 within acceptable limits, while the permissible limit covers 204 km^2, and the impermissible limit extends to 208 km^2, as depicted in **Figure 5**. This distribution highlights areas where turbidity levels comply with or exceed the specified standards, delineating zones where water clarity meets or falls short of regulatory thresholds. Considering the impact of turbidity on water quality, it is essential to acknowledge that elevated turbidity levels can potentially have health consequences, as the presence of suspended particles may facilitate the growth of harmful microorganisms and compromise the effectiveness of water treatment processes. Further research is warranted to comprehensively assess the potential health risks associated with turbidity in the studied areas.

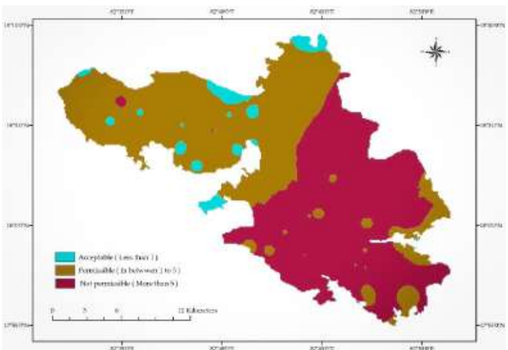

Figure 5. Spatial distribution of turbidity.

Considering chloride's impact on water quality, it is noteworthy that Chloride (Cl_2^-) primarily originates from sedimentary rock (Evaporates) as a major natural source, with minor contributions from igneous rocks. In natural water, chloride concentrations typically range below 10 mg/L in humid regions but can surge to 1,000 mg/L in arid areas. Seawater, rich in chloride, registers around 19,300 mg/L, escalating up to 200,000 mg/L in brines. Excessive chloride levels exceeding 100 mg/L can impart a salty taste, and concentrations significantly surpassing this mark may lead to physiological harm. Various industries, including food processing, textile, paper manufacturing, and synthetic rubber production, necessitate chloride concentrations lower than specific thresholds, typically below 250 mg/L or even 100 mg/L for select sectors. Chloride ion concentrations varied between 10 and 230 mg/L across the sampled groundwater. Importantly, none of the samples exceeded the permissible limits outlined by the Bureau of Indian Standards (BIS). A remarkably low concentration of 10 mg/L was observed at Thumpada (BW1), as depicted in **Figure 6**, highlighting an area with exceptionally low chloride levels, ensuring adherence to regulatory standards for water usability.

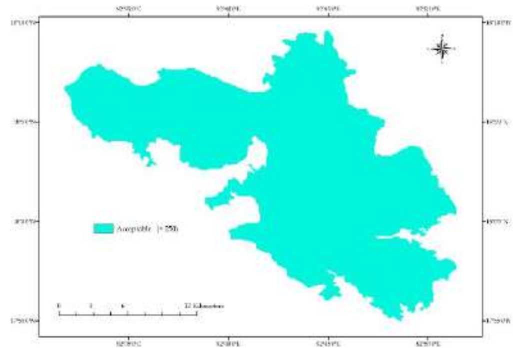

Figure 6. Spatial distribution of Chloride (Cl_2^-).

Sulphate (SO_4^{2-}) primarily originates from the oxidation of sulphide ores, gypsum and anhydrite. In natural water, sulphate concentrations commonly remain below 300 mg/L, except in wells affected by acid mine drainage, where higher levels might be present, sometimes reaching as much as 200,000 mg/L in brines. Its impact on water usability involves the formation of a heat-retarding scale when combined with calcium. Levels exceeding 250 mg/L can be objectionable in certain industries, and at around 500 mg/L, water might taste bitter, while concentrations around 1,000 mg/L could have a cathartic effect. Sulphate values in the Paderu region (**Figure 7**) ranged from 0 to 48 mg/L, all falling within the desirable limits prescribed by both the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). This aligns with recommended standards, indicating that all samples maintain sulphate concentrations within the acceptable range, ensuring water suitability for various purposes as outlined by regulatory guidelines.

Fluoride finds its major natural sources in substances like amphiboles (hornblende), apatite, fluorite, and mica. Typically, concentrations in natural water remain below 10 mg/L, although in brines, levels might escalate to as high as 1,600 mg/L. The impact of fluoride on water usability manifests in its effects on dental health. Concentrations between 0.6 and 1.7 mg/L in drinking water are beneficial for the structure and decay resistance of children's teeth. However, in some areas, concentrations surpassing 1.5 mg/L can lead to "mottled enamel," and at levels exceeding 6.0 mg/L, pronounced mottling and disfiguration of teeth can occur. Fluoride concentrations were found (**Figure 8**) to range from 0.1 to 0.80 mg/L across the sampled groundwater. Notably, none of the samples exceeded the permissible limits outlined by regulatory standards. However, it's worth noting that potential factors like damp rubbish materials or sewer line conditions might contribute to local variations in fluoride levels, possibly leading to the formation of stagnant water.

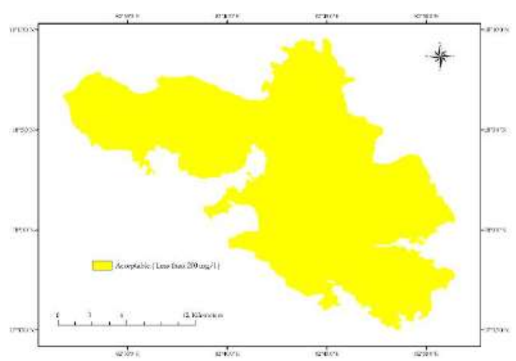

Figure 7. Spatial distribution of Sulphate ($SO_4{}^{2-}$).

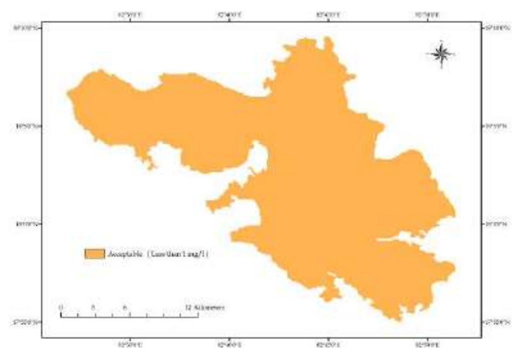

Figure 8. Spatial distributions of Fluoride (F^-).

Nitrate ($NO_3{}^-$) derives primarily from natural sources such as the atmosphere, legumes, plant debris, and animal excrement, with concentrations in natural water typically remaining below 10 mg/L. The impact of nitrate on water usability manifests in its taste and potential physiological effects. Water with elevated nitrate levels, exceeding 100 mg/L, may taste bitter and cause physiological distress. In infants, water from shallow wells with more than 45 mg/L has been associated with methemoglobinemia. Interestingly, small nitrate amounts aid in reducing the cracking of high-pressure boiler steel. Nitrate concentrations found (**Figure 9**) spanned from 4.2 to 68.8 mg/L across the sampled groundwater, with an average of 24.905 mg/L and a standard deviation of 14.616 mg/L. Notably, only one sample at Vantalamamidi exceeded the permissible limits. This outlier could potentially be attributed to agricultural activities surrounding the well, possibly involving the use of nitrate fertilizers, leading to elevated nitrate levels in the water. This emphasizes the need for monitoring and managing fertilizer use in these areas to maintain safe nitrate levels in groundwater. The potential health consequences of elevated nitrate levels underscore the importance of continuous water quality monitoring to safeguard public health.

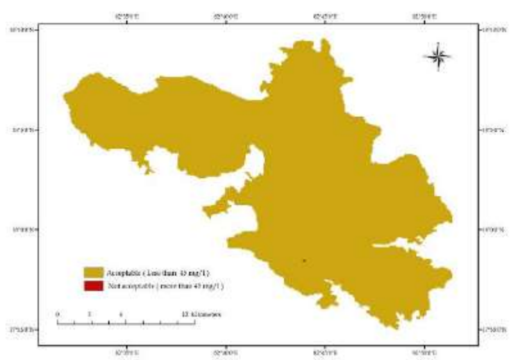

Figure 9. Spatial distribution of Nitrate ($NO_3{}^-$).

Iron (Fe) arises primarily from natural sources such as igneous rocks, amphiboles, ferromagnesian micas, iron sulphide compounds like FeS and FeS_2, and magnetite (Fe_3O_4), alongside various minerals in sandstone rocks and clay minerals rich in iron oxides, carbonates and sulphides. In fully aerated water, iron concentrations in natural water sources usually remain below 0.50 mg/L. Groundwater with a pH below 8.0 might occasionally contain up to 10 mg/L, and rarely as much as 50 mg/L. Acidic water from thermal springs, mine wastes, and industrial effluents might exhibit exceedingly high levels, surpassing 6,000 mg/L. The impact of iron on water usability becomes apparent when concen-

Table 2. Statistical analysis of the Groundwater Quality.

Observed Concentration	Groundwater Parameters														
	pH	Cond	TDS	Na^+	K^+	TH	Mg^{2+}	Ca^{2+}	Fe	F	$Cl_2{}^-$	$SO_4{}^{2-}$	$HCO_3{}^{2-}$	$CO_3{}^{2-}$	$NO_3{}^-$
Mean	7.1	497.4	319.1	42.1	21.1	140.4	8.5	43.7	0.2	0.1	69.0	18.3	128.6	38.8	13.2
Max.	8.3	987.0	641.6	145.0	108.0	320.3	18.5	104.7	0.9	0.8	230.0	48.0	300.0	300.0	60.5
Mini.	6.2	53.0	34.5	2.6	0.5	19.0	1.2	5.8	0.0	0.0	10.0	0.0	0.0	0.0	0.0
Range	2.1	934.0	607.1	142.4	107.5	301.3	17.3	98.9	0.9	0.8	220.0	48.0	300.0	300.0	60.5
Median	7.1	521.0	338.7	28.9	9.4	110.0	7.7	34.4	0.2	0.1	68.0	13.0	130.0	23.9	11.5
Mode	7.5	687.0	446.6	105.0	23.8	195.3	3.0	59.5	0.3	0.1	30.0	38.0	150.0	0.0	20.0
Std. Dev.	0.4	277.1	178.6	33.3	26.1	87.6	5.1	27.7	0.1	0.1	35.1	13.4	61.6	58.3	10.7
Skew	0.0	0.0	0.1	1.1	1.7	0.4	0.4	0.5	2.7	2.7	1.3	0.6	0.2	2.3	1.7
Kurtosis	0.5	−1.4	−1.3	0.1	2.0	−1.1	−1.2	−1.0	17.7	9.0	4.4	−1.1	−0.2	6.4	4.1
C.V.	5.7	55.7	56.0	79.1	123.8	62.4	60.1	63.5	54.1	113.5	50.9	73.3	47.9	150.3	81.2

and minerals. While some minerals are essential, elevated levels could imply contamination or water unsuitability for drinking, irrigation, or industrial use.

Metal Ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Fe): Presence of metal ions like Sodium, Potassium, Magnesium, Calcium and Iron beyond permissible limits can affect taste, health and the suitability of water for specific uses. For instance, high iron content may cause discoloration or affect taste.

Anions ($Cl_2{}^-$, $SO_4{}^{2-}$, F^-, $NO_3{}^-$): Chloride, Sulphate, Fluoride, and Nitrate concentrations beyond recommended levels can impact taste and health. High levels of nitrate and fluoride may pose health risks, particularly for vulnerable populations like infants or those with specific health conditions.

Turbidity: Elevated turbidity signifies suspended particles in water. While not directly harmful, it can indicate the presence of pathogens, affecting water aesthetics and potentially signalling contamination.

The relationships observed in these parameters offer insights into potential water quality concerns. Elevated levels or significant deviations from standard values might indicate contamination, natural geological influences, or human activities affecting groundwater quality. Understanding these relationships helps in pinpointing potential sources of contamination, identifying water treatment needs and ensuring water meets acceptable quality standards for various purposes like drinking, agriculture and industrial use.

4.3. Correlation Matrix for Groundwater Quality

A correlation matrix was generated (**Table 3**) to illustrate the relationships between various parameters present in the water quality dataset. Many of the parameters demonstrate significant correlations, indicating substantial interactions among the chemical constituents within the water samples. Notably, there is a consistently strong positive correlation among most parameters with the measured cations and anions. However, Turbidity exhibits a consistent negative correlation with other parameters. This suggests that as the values of one parameter increase, the values of Turbidity tend to decrease, and vice versa. Moreover, a significant positive correlation is evident between Total Hardness (TH) and several other parameters, signifying a mutually influential relationship between Total Hardness and these specific chemical constituents. Overall, these correlations provide valuable insights into how different elements within the groundwater interact and influence each other. They offer a clearer understanding of the interdependencies among various chemical components, aiding in assessing water quality and potential relationships between different constituents.

4.4. Hill Piper Diagram for Groundwater Quality

In pursuit of comprehending the predominant groundwater anions and cations, the study integrates a Hill Piper diagram shown in **Figure 11**. This analytical tool helps delineate the composition and types of water present within the aquifers. Various factors, including lithological characteristics of aquifers, groundwater flow patterns, and retention time, alongside anthropogenic influences, collectively contribute to determining the water types within the aquifer system [18].

Table 3. Correlation Matrix for the groundwater quality data.

Parameters	pH	EC	TDS	TH	Tur	Cl	SO_4	F	NO_3	Fe
pH	**1.00**	0.15	0.16	0.17	−0.09	0.01	0.27	0.14	0.12	0.46
EC		**1.00**	0.98	0.95	−0.17	0.66	0.56	0.38	0.33	0.21
TDS			**1.00**	0.94	−0.17	0.64	0.57	0.40	0.35	0.21
TH				**1.00**	−0.18	0.63	0.59	0.44	0.36	0.25
Tur					**1.00**	−0.07	−0.02	−0.10	0.27	−0.08
Cl						**1.00**	0.27	0.16	0.24	0.19
SO_4							**1.00**	0.66	0.52	0.30
F								**1.00**	0.25	0.24
NO_3									**1.00**	0.16
Fe										**1.00**

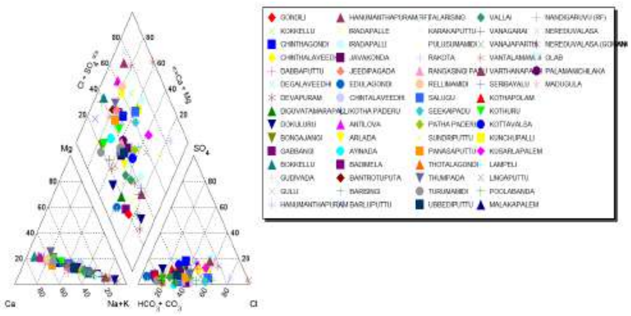

Figure 11. Hill Piper diagram.

Typically, sulfate and chloride serve as prominent anions, while no singular cation necessarily dominates the water composition. The Piper diagram illustrates a relatively even distribution of water types, encompassing Ca^{2+}-Mg^{+2}-Cl_2^{-}, Ca^{2+}+HCO_3^{-}, Ca^{2+}-Na^{+}-HCO_3^{-}, Ca^{2+}, Na^{+}/K^{+}, and HCO_3^{-} across all samples. This observation leads to a classification of the water type as SO_4^{2-}+ Cl_2^{-}/Na^{+}+K^{+}, a classification uncommon in typical domestic groundwater scenarios [19].

The detection of calcium and magnesium ions might be attributed to water-rock interactions stemming from geogenic sources, aligning with the geological composition of the study area [20]. Conversely, the presence of Na^{+}, SO_4^{2-}, and Cl_2^{-} might indicate anthropogenic sources influencing the water composition.

This analysis aids in understanding the complex interplay between natural geological elements and human-induced factors, shedding light on the atypical classification of groundwater types within the study area, which diverges from conventional patterns found in domestic groundwater settings.

4.5. Irrigation Suitability and Land Resource Management

The US Salinity Laboratory's classification (**Figure 12**) categorizes the collected groundwater samples into salinity and alkalinity hazard classes: C3–S1 (15%), C2–S1 (60%), and C1–S1 (25%). This distribution suggests that a significant portion of the groundwater in Paderu Mandal exhibits moderate salinity with a low sodium hazard (C2–S1), making it suitable for irrigation with proper management.

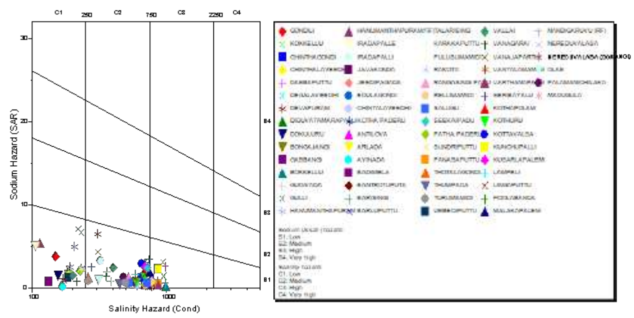

Figure 12. Sodium Hazard.

Salinity is a critical determinant of soil health and agricultural productivity, as high salt concentrations can impair plant growth through osmotic stress, nutrient imbalance, and ion toxicity [21]. The presence of elevated salinity in some samples suggests that long-term irrigation without appropriate mitigation strategies, such as leaching requirements or the adoption of salt-tolerant crops, could lead to soil degradation. If a sample falls under C4–S4, prolonged use can significantly impact land productivity by inducing salinity stress, altering soil texture, and reducing water infiltration capacity, ultimately threatening sustainable agricultural practices.

4.5.1. Land-Water Interactions and Implications for Sustainable Management

The analysis of groundwater samples in Paderu Mandal reveals that the majority exhibit moderate salinity (C2–S1) with a low sodium hazard, making them generally suitable for irrigation. However, localized elevations in Total Dissolved Solids (TDS) and nitrate concentrations—particularly in agricultural zones—indicate anthropogenic influences such as fertilizer and pesticide leaching. The spatial variability in these contaminants underscores the necessity for hydrogeochemical assessments to monitor water quality fluctuations and their impact on land productivity.

Salinity-induced soil degradation poses a significant challenge to sustainable agriculture in the region. Prolonged irrigation with high TDS water accelerates soil salinization, reducing crop yield and soil permeability. GIS analysis of soil moisture and salinity in the Paderu region provided critical insights for optimizing irrigation planning by identifying high-risk zones and facilitating the implementation of site-specific water management strategies, such as precision irrigation, controlled drainage, and adaptive cropping patterns to mitigate salinity-induced land degradation. Groundwater regulatory frameworks play a critical role in mitigating pollution risks. The enforcement of water quality thresholds in agricultural zones is essential to control nitrate leaching and excessive groundwater withdrawals. Moreover, the integration of spatiotemporal groundwater monitoring with land-use planning can optimize resource allocation, ensuring agricultural viability without compromising hydrological balance.

The study underscores the critical need for ecological restoration to mitigate groundwater depletion and land degradation in the Paderu region, where unregulated extraction has disrupted aquifer recharge dynamics, leading to progressive soil salinization and declining agricultural productivity. Hydrochemical analysis reveals elevated TDS concentrations in intensively irrigated zones, suggesting a direct link between excessive groundwater use and soil degradation. To counter these effects, precision irrigation techniques, informed by soil moisture analytics, can optimize water application and minimize salinity build-up. Additionally, the adoption of salt-tolerant crops, crop rotation strategies, and conservation tillage can enhance soil resilience and sustain long-term productivity. Implementing integrated land-use policies, including watershed management and agroforestry, is essential to balancing agricultural demands with ecological conservation. These measures are crucial for ensuring the long-term sustainability of groundwater and land resources in Paderu Mandal while mitigating the adverse impacts of intensive land use on regional hydrology and soil health.

4.5.2. Groundwater Quality and Sustainable Land Utilization

Heavy metal analysis indicates elevated iron and manganese concentrations in certain groundwater samples, primarily influenced by regional lithology and geogenic processes. These metals pose potential risks for both human consumption and agricultural irrigation, necessitating targeted water treatment strategies to ensure safe usage. Moreover, land-use alterations, including deforestation and unregulated urban expansion, may further impact groundwater recharge and quality by altering natural infiltration dynamics. To mitigate these risks, a sustainable land management framework that integrates groundwater conservation policies is imperative for maintaining agricultural viability and ecological stability in Paderu Mandal. This study establishes a scientific basis for land and water resource policy formulation, aligning with the broader goals of sustainable land utilization and environmental conservation.

5. Conclusions

The investigation of groundwater quality in Paderu Mandal, Andhra Pradesh, traversed a multitude of areas including Chintalaveedhi, Gondali, Vanagarai, Kothapalem, Jeedipagada, Kothuru, Bongajangi, Bontrotuputa, Thumpada, Dokuluru, Arada, Relimamidi, Vantaamamidi and in other areas. Unveiling substantial variations in pH, TDS, TH, Chloride, Sulfate, Fluoride, Nitrate and Iron across these locations, the study highlighted adherence to recommended WHO and BIS standards in most areas. However, specific regions such as Arada, Relimamidi, Vantaamamidi and other areas showcased deviations, hinting at potential contamination sources or geological influences. This emphasizes the continual need for monitoring, further investigations, and tailored remediation strategies to uphold water quality and safety across these diverse regions. Integrating techniques like GIS, spatial analysis, statistical analysis and Hill Piper analysis, the study mapped variations, discerned parameter relationships and identified potential contamination sources within these locations, forming the foundation for informed groundwater management decisions and targeted remediation efforts aimed at sustaining water quality in this diverse region. The study further emphasizes on implementing strategic land-water interaction policies and groundwater-related land-management regulations, so that stakeholders can ensure sustainable water resources while minimizing contamination risks.

Author Contributions

Conceptualization, R.N.D.; methodology, M.K.G.; validation, A.R.N.; formal analysis, R.N.D.; investigation, R.N.D.; data curation, R.N.D.; writing—original draft preparation, M.K.G.; writing—review and editing, A.R.N. and N.R.K.; supervision, M.K.G.; project administration, N.R.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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REVIEW

Challenges and Pathways for Sustainable Development in Global Land Use Systems: A Narrative Review

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ABSTRACT

Land is essential for the flourishing of human civilizations. It is a complex interplay of natural processes, socio-economic dynamics, and environmental sustainability. Hence, it influences policy, research, and practice. This study critically reviews the literature about the challenges and issues currently explored for sustainable development in global land use systems based on an extensive bibliographic database from the Web of Science. It explores the complex world of global land use system development, examining research trends, tools, and future directions. This study's findings indicate that current research trends emphasize the use of emerging digital

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technologies, including geospatial and informatics techniques, Geo-detectors, regression models, artificial intelligence, and socio-economic models. These tools are instrumental in addressing the challenges posed by land use change at various scales. They enable us to effectively identify, track, and enhance our understanding of the sustainability, science, and management of land use systems. The studies reviewed offer valuable support for initiatives aimed at adopting innovative theories, methods, instruments, and procedures to tackle land use and sustainability issues related to natural resources globally. Furthermore, new fields within land use systems are increasingly recognized for their potential to transform traditional practices, strengthen urban-rural linkages, and contribute to the realization of the 17 UN Sustainable Development Goals. This recognition stems from the multidisciplinary nature of the discipline.

Keywords: Current Issues; Global; Land Cover; Land Management; Land Use; Sustainable Development

1. Introduction

The canvas of human history bears the marks of humans' relationship with the land. Over the centuries, agricultural practices, settlements, and use of resources have shaped landscapes and societies. The agrarian roots of civilization laid the groundwork for evolving land use systems that responded to the needs of growing populations [1]. From the agricultural revolution to the industrial age, these systems evolved and encountered challenges, leading to the complex mosaic of land use observed today. A major turning point came with the introduction of mechanization and rapid urbanization in the 19th and 20th centuries. Technological advancements and the rise of industrial economies spurred changes in land use patterns [2,3]. Expansive agricultural fields coexisted with sprawling urban landscapes, each competing for their share of this limited resource in most developing countries. Concurrently, concerns about environmental sustainability began to emerge, leading to a shift towards sustainable land use.

The evolution of sustainable land use systems worldwide has attracted interest from various academic and industrial circles. As a result, there have been increasing calls for more research and scientific progress in Land System Science (LSS) discipline. This has influenced global discourse, policy directives, and state-of-the-art initiatives. Worldwide socio-political, economic, and environmental investments and development have led to transformations of previous environments into various land use forms. However, these desired changes have had unintended consequences, including land degradation, air pollution, concerns about food and water scarcity, infiltration of cultural systems, climate stressors, and disturbances. **Figure 1** depicts the changes in global land use systems between 1993 and 2023. The spatial distribution shown in the figure was derived from Landsat datasets stored in Google Earth Engine (GEE) (https://code.earthengine.google.com/) and analyzed using ArcGIS 10.8 software.

The global LULCC (**Figure 1**) spatial distribution based on the change detection analysis performed in this study illustrates the increasing areas of grasslands, built environments, and water bodies over the past 30 years (1993–2023) (**Supplementary Table S1**). Specifically, cultivated lands, built environments, grasslands and water bodies have expanded globally at annual rates of 0.38%, 0.16%, 0.41% and 0.001%, respectively. On the other hand, unused land and natural vegetation have seen a decrease in their areas at annual rates of 0.02% and 0.36%, respectively, over the same period. These changes based on the spatial distribution of land use systems between 1993 and 2023, largely driven by human-induced and biophysical factors across different eras, underscore the relevance of studying and understanding shifts in global land use systems. Additonal information related to accuracy assessment results are captured in Supplementary Figure S1. According to Sarfo et al., the Global Land Project (GLP) that began in 2006, through a group of land system scientists from various academic and research institutes worldwide, has played a significant role in shaping discussions on LSS [4]. Combining the efforts of the International Geosphere-Biosphere Programme (IGBP) and the Inter-

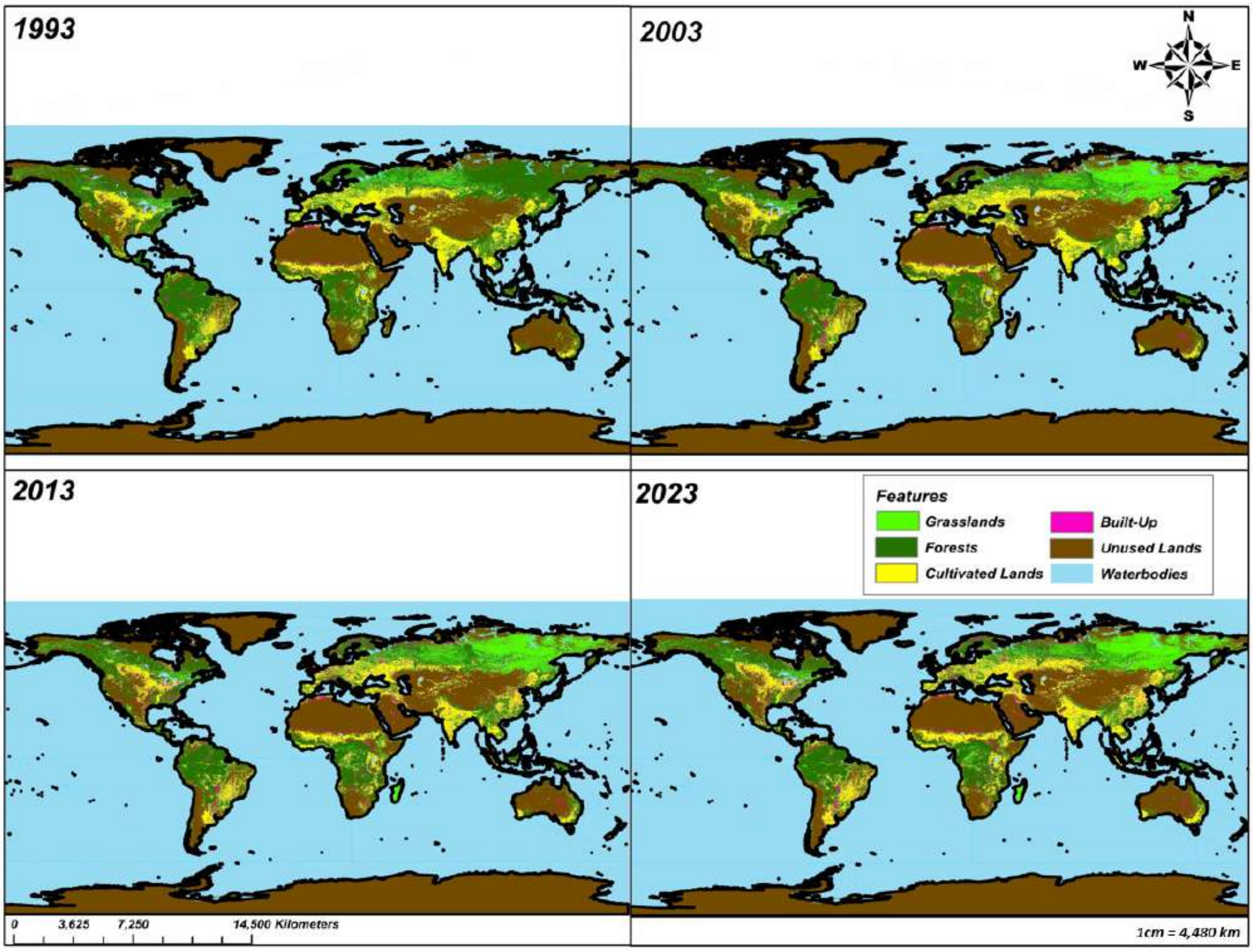

Figure 1. Spatial Distribution of Land Use and Land Cover Change (LULCC) Across the Globe (1993–2023).

national Human Dimensions Programme on Global Environmental Change (IHDP), GLP serves as an essential platform for synthesizing information, methodologies, and knowledge within the LSS community. Subsequent to the 1994–2005 LULCC project and the Global Change and Terrestrial Ecosystems project, GLP tackles the evolving challenges of understanding and managing land use systems worldwide. In line with the objectives of the GLP, this narrative review sought to identify key issues that engulf the tools and practices used in facilitating land management, informatization, and sustainability of land use systems worldwide using recent studies spanning from 2004 to 2023.

Land Use Management (LUM) innovations are essential for tackling the contemporary challenges in LSS and LULCC [5]. Technological advancements, including Geographic Information Systems (GIS), remote sensing, and drone technology, have transformed planning and monitoring of the subject. According to Kumar et al., these innovations allow for more precise and efficient management of land resources [6]. By providing detailed, real-time data on land use patterns, environmental conditions, and resource availability, these technologies support improved decision-making [7]. According to Dinesha et al., sustainable farming techniques such as permaculture, agroforestry, and organic farming are currently utlized to enhance farming outputs while maintaining ecological balance [8]. In cities, urban greenery and architecture, urban agriculture, and vertical farming are presently being institutionalized to promote urban resilience and transform cities [9]. For further details, please refer to **Supplementary Table S2**, which details the research progress in relation to the subject worldwide. Over the years, there have been significant advancements at various levels—global, regional, national, and local—that have enhanced scientific productivity and improved the identification, monitoring, and response of land use systems to environmental challenges. This narrative review aims to enrich existing literature and explore various concepts related to land use systems, land management, and sustainability worldwide that influence policy, research, and practice. Specifically, the present study will analyze current trends, smart tools, and practices in the sustainability of LSS land use systems worldwide.

2. Methodology

Source of Data, Search, Screening and Analysis Procedures

This narrative review examined land use studies conducted worldwide. Data from the core database collection of Web of Science (WoS) between 2004 and 2023 were used. The WoS is renowned for its standardized and widely recognized bibliographic and citation database, which is organized in a well-structured format. This study specifically focused on significant studies published between 2004 and 2023 because they offer valid and reliable information on advancements, tools, and scientific production in the field of land use [10]. Overall, four stages were utilized in generating and screening the datasets used for the analysis. In the initial stage marks data search in WoS (**Figure 2**), based on the search terms "global land use system*" (Topic) or "land use management" (Topic) or "land use science" (Topic) or "land use" (Topic) and " land cover change" (Topic) and "sustainable development" or "global sustainability" (Topic) were utilized. The first step generated an overall output of 2,221 documents. The overall output was further refined to constitute book chapters, reviews and original research articles during the second stage of the screening process. This resulted in the overall output, being reduced to 2,204 documents. The third stage included limiting the search to some disciplines interlinked to the study's rationale, based on WoS database core collection, as well as some specific indexing. This further shrunk the total output to 1,829 documents. The final step further limited the resultant outcome by excluding papers not published in English medium. This brought the total to 1,814 documents, which were utilized for the comprehensive analysis conducted in this study.

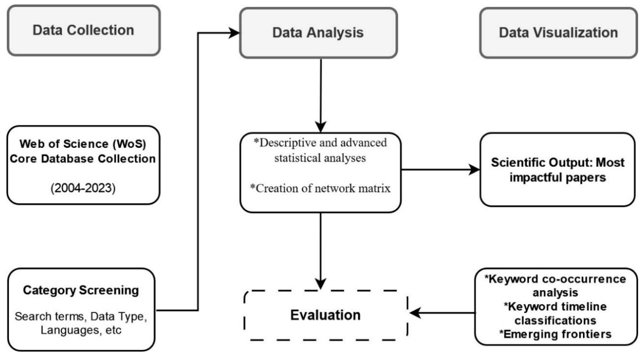

Figure 2. Search, Screening and Analysis Procedures Utilized in This Study.

This narrative review study focused on recent years considering the ever-evolving landscape of land use science. As new information is constantly being generated, it is crucial to stay current with latest advancements; hence, this study focuses on recent years. Also, focusing on recent years facilitated the identification of knowledge gaps, trends and developments that require further investigation to drive innovation in the field. The data gathered through this study shows that as we go back in time, scientific studies in relation to land use science become increasingly sparse. Additionally, there is a scarcity or absence of comprehensive review studies on global land use systems. This study includes recent developments in the field that may have been ignored/overlooked in earlier reviews. It is important to note that this study only utilized articles published in English to maintain consistency and prevent any over- or under-representation of studies published in other languages. The following parameters, were used for the selection process [10,11] :

The primary goal was to review papers that primarily focused on providing in-depth information about 'land use', 'land cover change', 'land management', and sustainable development.

Papers that had 'land use' and 'land cover' in their title or keywords but were published in languages other than English were excluded.

Furthermore, studies conducted multiple times in the same area that employed similar techniques or approaches and had nearly identical viewpoints or contributions, were also excluded.

The 'Analysis and Discussions' section primarily includes representative works from the 1814 articles obtained from the said database. It is worth mentioning that the study's discussions were not solely subjected to content analysis of the 5 most cited papers among the 1814 articles generated from the WoS core database collection, but also included other relevant studies, information about policy frameworks, and sectoral reports that demonstrate LSS's impact on development practices and science.

Indicatively, this research employed R's biblioshiny package to conduct its analysis. Aria and Cuccurullo assert that this software integrates bibliometrix package functions and facilitates the creation of web-based applications [12]. This narrative review identified and quantified the co-occurrence of keywords based on the articles generated in line with the search terms and information titles, abstracts, and years that the given output or papers were published using R's biblioshiny. **Figure 2** presents a flowchart of data search, screening and analysis procedures based on this standardized approach.

3. Analysis and Discussions

This section presents findings on the current trends, smart tools, and practices associated with the challenges and pathways of promoting sustainable land use systems worldwide. **Table 1** includes the 5 most influential papers from 2004 to 2023, as determined by the WoS core database collection, which has substantially contributed to the progress of the field worldwide [13–17].

3.1. Analysis of Keyword Co-Occurrence and Classification of Trending Topics (2004–2023)

The analysis of keyword co-occurrence in the sustenance of the subject demonstrates the strong and

Table 1. The Most Cited Studies Given the Search Terms or Scope (2004–2023).

No.	Paper	Author/Publication Year/ Journal	DOI	Total citations	Annual total citations
1	Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management	[13] ECOL LETT	10.1111/j.1461-0248.2005. 00782.x	2829	141.45
2	Soil structure and management: a review	[14] GEODERMA	10.1016/j.geoderma.2004.03.005	2611	130.55
3	China and India lead in greening of the world through land-use management	[15] NAT SUSTAIN	10.1038/s41893-019-0220-7	1391	231.83
4	Defining place attachment: A tripartite organizing framework	[16] J ENVIRON PSYCHOL	10.1016/j.jenvp.2009.09.006	1278	85.20
5	Effects of landscape structure and land-use intensity on similarity of plant and animal communities	[17] GLOBAL ECOL BIOGEOGR	10.1111/j.1466-8238.2007. 00344.x	1104	61.33

interdependent relationship between the keywords used in the study sample (i.e., 1814 articles used). In **Figure 3**, the width of the connecting lines indicates the degree of co-occurrence based on the study sample. **Figure 3** shows the top ten concept/keyword pairs in the field, which include *'Land Use – Land Cover', 'Land Use – Climate Change', 'Land Use – Ecosystem Services', 'GIS – Spatial Planning', 'GIS – Remote Sensing', 'Land Use – Remote Sensing', 'Land Use – Urbanization', 'Land Use – Water Quality', 'Ecosystem Services – Sustainable Development', and 'Land Use – Land Use Management'.* These pairs analyze a range of environmental, political, cultural, social, technological, and economic parameters that drive progress in the field. Furthermore, they emphasize the intricate and dynamic characteristics of land use systems.

A wide range of topics have garnered noticeable attention over time. Based on the results presented in **Figure 4**, the classification of keywords provides a timeline view of trending topics and emerging areas of focus in this field. In **Figure 3**, the node sizes indicate the number of times the trending topics appeared in various studies. The lines embedded with the nodes mark the density and centrality of each given term over a given period. When examining the scientific research productivity relevant to this study, it is clear that the importance of land use topics has significantly increased since the late 2000s, especially in 2010. From 2010 to 2020, several topics have gained prominence. These topics include *'Sustainability', 'Biodiversity', 'Land Use Management', 'Watershed Management', 'Land Use Planning', 'Modelling', 'Soil Organic Carbon', 'Impact Assessments', 'Sensitivity Analysis', 'Land Use Change', 'Global Change', 'Landscape Ecology', and many others. In the post-2020 era, topics such as 'Land use', 'Ecological Services', 'Climate Change', 'Ecological Service Value (ESV)',*

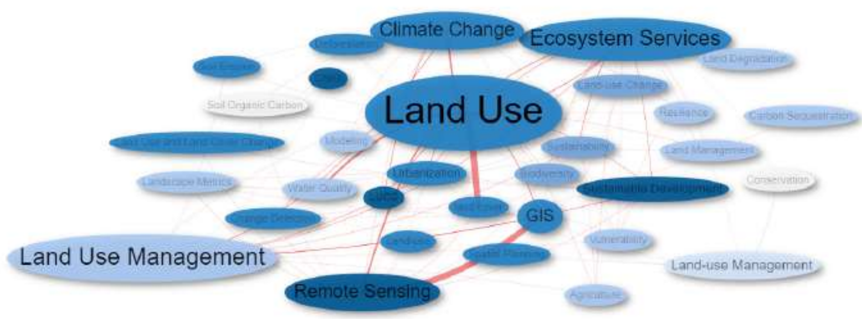

Figure 3. Keyword Co-Occurrence Analysis in Land Use Systems and Sustainability Studies Wordwide (2004–2023).

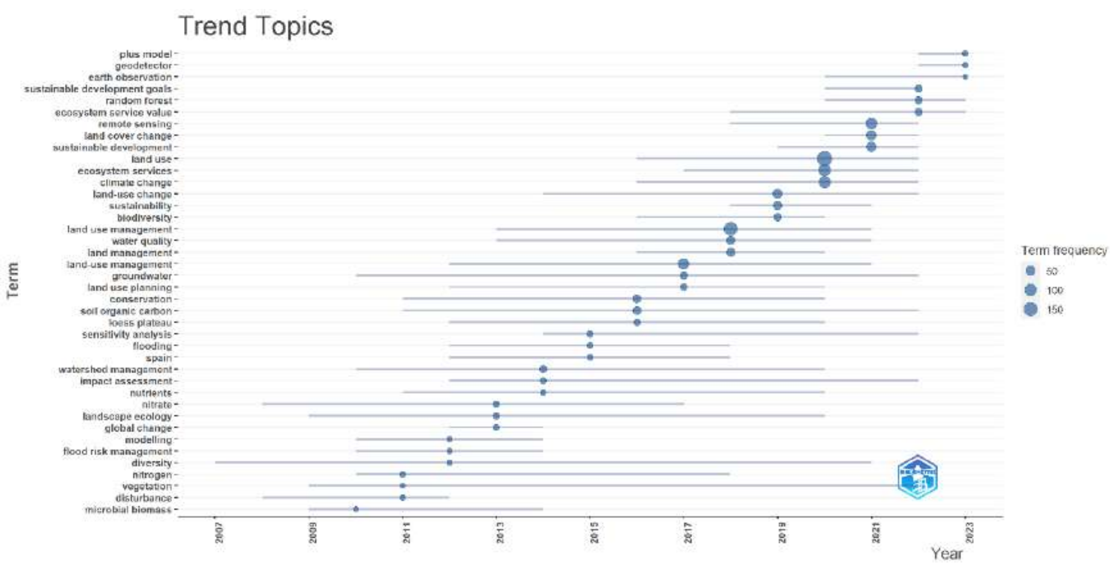

Figure 4. Timeline Classification of Keywords Related to the Scope of This Study (2004–2023).

'Remote Sensing', 'Sustainable Development Goals (SDGs)', 'Land Cover Change (LCC)', 'Random Forest (RF)', 'Earth observation', 'Geodetector', and 'PLUS Model' have become more popular. It is worth noting that the periods (i.e., between 2004–2007) were not captured in **Figure 4** mainly as a result of their frequencies of occurrence being less than 50, coupled with scientific studies in the field becoming increasingly sparse as we go back to these years.

3.2. Evaluating Major Studies and Trends in Land Use Systems Development

Given the findings presented in **Table 1**, it is evident that the top five most cited papers have had a significant impact on diverse studies in different disciplines, nations, and sectors. This underscores the complexity and comprehensive nature of land use systems. A detailed analysis of the top five influential papers, based on their citation count and influence in the field, further emphasizes the multidisciplinary nature of the subject in scope. In their 2005 study, Tscharntke et al. emphasized the importance of understanding the bottlenecks and principles of agricultural land use to maintain biodiversity, ecosystem functions, and endpoints [13]. They highlighted how agriculture influences land management and identified research gaps and opportunities across various scales. Moreover, they stressed the need for further investigation into the relative significance of local versus landscape management concerning biodiversity and ecosystem services. Their calls for research have inspired numerous studies exploring the interplay between different land use systems and ecosystem services, as illustrated in **Figures 3** and **4**. Bronick and Lal in their review study examined how management practices and environmental changes can modify soil structure [14]. They highlighted its importance for sustainable food production and societal well-being. In their conclusion, they advocated for a holistic approach to LUM to address the various practices that place pressure on soil resources. Given the significant impact of soil structure on multiple fronts, pedology is crucial for the sustenance and effective management of land use systems.

Currently, many industrialized nations in both the Global North and Global South are actively working towards regenerating and greening urban and peri-urban areas within their territories. These efforts, which involve significant investments, political commitment, and scientific productivity, aim to transform landscapes and bring various direct and indirect benefits. These benefits include enhancing urban resilience, improving air quality, preventing land degradation, and supporting mitigation and adaptation measures. In a study conducted by Dormann et al. investigated land management strategies for nature conservation in Europe using ecological models to analyze the composition, configuration, and intensity of land use, along with their effects on plant and animal species and communities [15]. Their research demonstrated how these parameters influence ecological processes and contribute to overall diversification and productivity. Several researchers have reported some progress and observations in China and India [16,17]. By analyzing satellite data, these researchers identified significant greening patterns in both countries. As the largest developing country, China has made substantial efforts to preserve and expand its forests and croplands in alignment with the SDGs. These initiatives address key issues related to poverty (SDG 1), hunger (SDG 2), child health (SDG 3), safe cities (SDG 11), climate action (SDG 13), and preserving life on land and biodiversity (SDG 15) [17]. The authors concluded by emphasizing the importance of accurately representing human land use practices through advanced observation models.

3.3. Theories, Tools, Practices, and the Future of Land Use Science

3.3.1. Land Cover Transition Theory (LCTT)

According to Coral et al., the LCTT originated from observations in agriculture and rural development in the late nineteenth and early twentieth centuries [18]. Unlike being associated with a specific individual, this theory represents a conceptual framework that researchers in the geography, environmental science, and land-use planning disciplines have collectively developed. Noteworthy contributions to this theory were made by Halford Mackinder, who enhanced our understanding of how geographical factors, such as land utilization, can significantly shape the fate of nations and societies [19]. Pulver et al., on the other hand, laid the foundation for comprehending the dynamics of societies within their landscapes by emphasizing the impact of geographical factors on human behavior [20]. The LCTT examines the progression of land use patterns over a specific timeframe, largely dwelling on the transition from traditional agricultural practices to more diverse and multifunctional land uses [21]. It analyzes the socio-economic, technological, and policy-driven factors that contribute to these shifts and investigates their global impact [22]. For instance, the timeline classification of key land use terms (**Figure 4**) captured in the 1814 articles show the encompassing nature of land use science, the transitions and management approaches involved.

The theory has been criticized by Petroni et al. for oversimplifying the complex processes of land-use change [23]. Similarly, Long et al. pointed out that the theory fails to adequately consider the political and power dynamics that affect land-use decisions [24]. However, despite these limitations, the theory has several strengths that contribute to its prominence in exploring land-use dynamics. It provides a historical framework for understanding changes in land utilization [25]. The theory emphasizes the importance of societal transitions and recognizes that changes in land use are often linked to broader economic, demographic, and cultural trends [26]. Moreover, it provides valuable insights into the relationship between cultures and land use by examining historical transitions. This approach helps us understand how socio-economic, technological, and cultural changes influence global patterns of land utilization. By utilizing this theory, understanding the complex dynamics that shape modern land-use systems and guide sustainable development and resource management policies worldwide is enhanced.

3.3.2. Land Use and Sustainable Development

The term "sustainable development" was introduced in the 1987 report by the World Commission on Environment and Development (WCED), also known as the Brundtland Commission [27]. Abera significantly contributed to this theory by highlighting the necessity of integrating social, economic, and environmental factors to achieve sustainable outcomes [28]. Sustainable development advocates for the responsible and equitable use of resources to ensure both long-term environmental sustainability and societal well-being [29]. However, the theory has often been criticized for its broad scope and lack of a precise, actionable definition [30]. Striking a balance between economic growth and environmental preservation within sustainable development can also present challenges [31]. Despite these criticisms, sustainable development remains a vital component in the evolution of land use systems [32].

Sustainable development is globally relevant because it helps to address common challenges, promote global collaborations, and emphasizes the importance of addressing issues such as LULCC, climate change, biodiversity loss, and poverty [33]. There have been numerous calls for sustainable land use through the Sustainable Development Goals (SDGs) 11 and 15, considering that all activities take place on land. SDG 11 focuses on sustainable cities and the quality of life, while SDG 15 addresses land use issues. By prioritizing resilience and equity, this approach encourages the exploration of emerging areas (see **Figures 3** and **4**) such as *'land metrics and transitions', 'land use dynamics degree (LUDD)', 'causality/spatial and temporal inference causality', 'land and habitat fragmentation', 'ecological security patterns (ESP) and ecosystem services value (ESV)', and 'urban-rural linkages/transformations.'* This ensures the adoption of sustainable practices that meet current needs while safeguarding the well-being of future generations in the ever-evolving field of land use systems. Hence, there is a need to support calls for 'adaptation justice', 'social justice', *and 'empathy'* among key players who influence or are influenced by policies/decision-making processes.

3.3.3. Urbanization and Land Use Change

Urbanization is extensively influenced by rural-to-urban migration, presence of economic opportunities, and the process of industrialization [34]. As populations increase, urban areas need to develop infrastructure, services, and facilities, resulting in the construction of residential, commercial, and industrial buildings. This, in turn, has an impact on consumerism and social structures through population fluctuations, cultural dynamics, and lifestyle changes [26]. The rapid pace of urbanization also leads to LULCC, environmental degradation, resource depletion, and social inequalities. To ensure sustainable urban development, it is essential to create inclusive and resilient cities for future generations. This requires effective urban planning, infrastructure development, and governance mechanisms [35].

LULCC and land management techniques vary over time because of natural and human-induced factors [36]. These changes affect agricultural land, forests, grasslands, wetlands, urban areas, and infrastructure development. Agricultural growth, urbanization, industrialization, and infrastructure projects all have an impact on land use and geographical distribution [37,38]. Changes in land use have significant effects on the environment, biodiversity, socio-economic systems, habitat suitability, ecosystem services, and livelihoods. In a rapidly changing world, it is crucial to have land use regulations, sustainable management methods, and integrated approaches to balance conflicting land use demands, conserve natural resources, and promote resilient socio-ecological systems [39].

3.3.4. Land Use, Carbon Neutrality and Climate Mitigation/Adaptation

Climate adaptation involves actively modifying societal structures and ecosystems to limit harm and increase advantages [40]. It encompasses various approaches aimed at reducing vulnerability, enhancing resilience, and promoting sustainable development in the face of changing conditions. These approaches range from small community-based adaptations to major infrastructure and policy changes. The goals of climate adaptation include protecting human health, livelihoods, ecosystems, and vulnerable sectors from extreme weather conditions, sea-level rise in coastal regions, variations in precipitation patterns and temperature [41]. To achieve these goals, adaptation strategies encompass a wide range of measures such as digital or critical infrastructure, sustainable land and water management, early warning systems using Digital Technologies (DTs), livelihood diversification, adaptation justice and social capital, social safety nets, and incorporating climatic concerns into development planning and decision-making processes. Despite resource constraints, uncertainties, and socio-political barriers, successful climate adaptation requires collaborative governance, stakeholder engagement, capacity building, and the utilization of local knowledge and skills [42].

Climate mitigation and adaptation involve various strategies aimed at reducing greenhouse gas emissions, managing the Earth's energy balance, and tackling the core and potential drivers driving global warming to lessen its impacts [43]. These efforts include implementing carbon capture and storage techniques (carbon sequestration), transitioning to renewable energy sources, enhancing energy efficiency, reducing deforestation, and promoting sustainable land management. To achieve the objectives of mitigation and adaptation, Saraji and Streimikiene opines that concerted efforts, international exchanges, and robust policy actions are essential for accelerating the transition to a low-carbon economy and meeting climate targets [44].

3.4. Tools: Utilization of Artificial Intelligence and Digital Technologies in Land Use Management

Innovative approaches or tools are needed for monitoring, managing, and utilizing land resources [45]. Digital technologies such as remote sensing and GIS offer precise mapping of land cover changes, aiding in planning and decision-making (**Figure 3**). In precision agriculture, for example, sensors and data analytics using machine and deep learning techniques can enhance crop management, resource efficiency, and production while minimizing environmental impact [46]. Land information systems integrate various datasets to facilitate land management, ensure land tenure, and enhance government transparency. Blockchain technology can enhance the credibility and efficiency of the land tenure system by ensuring secure and transparent land transactions. Digital soil mapping can contribute to conservation and restoration efforts by providing information on soil health and characteristics. Internet of Things

(IoT) applications can improve farming resilience and sustainability by enabling real-time monitoring and management of operations [47]. Lastly, land restoration technologies based on ecological principles and innovative approaches can restore ecosystem services, biodiversity, and promote sustainable land use. These technological advancements have the potential to address complex land issues, support sustainable development, and enhance global land management [48].

Spangler et al. analyzed agricultural land use and policy data comprehensively [5]. They visualized land modifications like farmland transformation, crop production, and crop composition throughout the United States in recent decades. They further identified significant policy changes in the U.S. Farm Bills between 1933 and 2018, which are linked to the understudied land use trends. They reported that the agricultural sector in the United States has progressively shifted into a highly regulated and specialized structure. Agricultural cultivation is predominantly focused on specific regions, with the expansion of larger farms and a decline in the number of smaller ones resulting in a reduction in crop variety. Simultaneously, the scope and influence of federal agriculture policy are expanding. These data-driven findings indicate that both gradual and radical approaches to change are essential for promoting alternative production techniques, encouraging diverse landscapes, and fostering innovation in sustainable agricultural systems at all levels.

The study by Mohamed and Worku modeled changes in LULC and created future scenarios of LULC based on induced trends/activities [49]. Land use predictions are essential for promoting sustainable growth planning and management in both rural and urban areas of Addis Ababa and its surroundings. This study utilized Cellular Automata, Markov Chain (CA-Markov), and Multi-criteria Analytical Hierarchy Process (AHP) modeling methods. The findings indicate a consistent increase in built-up areas, often at the expense of ecologically beneficial land features. Quantitative landscape measurements demonstrate that the Ecologically Sensitive Scenario (ESS) modeling offers significant advantages over the Business-as-Usual Scenario (BAUS), particularly in ensuring the long-term sustainability of urban spaces. ESS modeling aids in enhancing urban systems by limiting built-up expansion and managing the loss of water bodies, forests, and agricultural land. Additionally, scenario-based simulations of LULC dynamics provide valuable decision-making alternatives for long-term urban growth planning and management, applicable not only to the study region but also to other similar cities and regions.

3.5. Optimization of LULC Analysis Within the Context of Geo-Visualization

LULCC analysis is essential for understanding the dynamics of land use changes over time, particularly in the context of rapid urbanization and environmental degradation. As shown in **Figure 3**, geo-visualization methods have become increasingly important for optimizing LULCC analysis. These methods serve as powerful tools for visualizing spatial data and analyzing patterns and trends in land use changes [47]. The optimization of LULCC analysis through geo-visualization provides key insights, highlighting the integration of advanced visualization techniques in this field.

By employing geo-visualization techniques, we can significantly enhance our understanding and interpretation of complex land use change patterns. Tools such as maps, 3D models, and interactive visualizations allow researchers to gain valuable insights into the drivers of LULCC and identify areas at high risk for environmental degradation or resource depletion [49]. Advanced techniques like remote sensing and GIS enable the analysis of large datasets, revealing patterns that may not be apparent through traditional analytical methods. This approach facilitates the clear and intuitive communication of complex spatial information. By presenting data visually, researchers can effectively share their findings with diverse stakeholders, including policymakers, land managers, and the general public [50,51]. Ultimately, this can promote informed decision-making and raise awareness about the impacts of land use changes on the environment and society.

Optimizing LULCC analysis through geo-visualization enhances the accuracy and reliability of research findings. By integrating spatial data from various sources and presenting it in a coherent and interactive format, researchers can achieve a deeper understanding of the dynamics of land use changes and their implications for environmental sustainability. This improved understanding can inform more effective conservation and land management strategies based on data-driven insights across different sectors of the economy.

3.5.1. Validating and Estimating the Accuracy of Global Land Use/Land Cover (LULC) Over the Years

The validation of LULC data and the estimation of accuracy are crucial for ensuring the reliability and credibility of land cover change detection studies. Advancements in remote sensing technology and spatial analysis techniques have enhanced the accuracy of these detections over the years. However, challenges remain in accurately validating LULC data and estimating the accuracy of change detection algorithms. These challenges arise from issues such as class definitions, spatial heterogeneity, temporal consistency, and scale mismatches. Variations in classification schemes, spatial resolution, and validation methods also contribute to these difficulties. Validation methods include ground truthing data from field surveys and photo interpretation, cross-validation with other datasets, confusion matrices, error metrics, and independent benchmark datasets [52–56]. **Table 2** presents an overview of accuracy trends for widely used global LULC products, along with their validation approaches.

Table 2 illustrates the estimated accuracy rates of global LULC trends over time. Early datasets from the pre-2000 era, such as IGBP and UMD, had accuracy rates of around 65–75%. These limitations were primarily due to their coarse resolution of 1 km and a smaller number of validation samples. In the 2000s, the MODIS and GlobCover datasets improved their accuracy to 75–85%, although they still exhibited some regional inconsistencies. By 2010, datasets like FROM-GLC and CCI achieved higher resolutions (75–85%), but this came with trade-offs between resolution and global consistency. In the 2020 era, the ESA WorldCover (10 m) and Dynamic World (AI-based) datasets surpassed 80% accuracy, benefiting from advancements in Sentinel-2 technology and deep learning techniques.

Table 2. Overview of Global Land Use and Land Cover Accuracy Trends and Validation Efforts.

Dataset	Period (s)	Reported Accuracy	Resolution	Remarks
IGBP DISCover – 17-class land cover dataset	1992–1993	~65–75%	1 km	*Early global product, moderate accuracy
University of Maryland (UMD) Land Cover	1992–1993	~70–75%	1 km	*Improved over IGBP
MODIS Land Cover (MCD12Q1)	2001–2020	~75–85% (with variations in features/classes)	500 m	*Yearly updates, commonly used
GlobCover (ESA)	2005, 2009	~70–80%	300 m	*MERIS sensor, regional variations
Climate Change Initiative (CCI) Land Cover (ESA)	1992–2020	~75–85%	300 m	*Merges MERIS and PROBA-V
FROM-GLC (Tsinghua)	2010, 2015, 2017	~65–80%	10–20 m	*Higher resolution but lower global consistency
WorldCover (ESA)	2020	~75–85%	10 m	*Sentinel-1/2, high-resolution
Dynamic World (Google)	2015–2023	~80–90% (near-real-time)	10 m	*AI-based, frequent updates

3.6. Policy-Regulatory Frameworks, Stakeholder Involvement and Public-Private Partnerships

Monkkonen et al. used novel data to investigate the relationship between urban land policy, urban form, and greenhouse gas emissions from transportation [57]. The study used property registration administration as a substitute measure to examine the correlation across 431 metropolitan areas in approximately 40 countries. The results of the study validate that highly populated metropolitan regions, characterized by concentrated city centers and shorter road sections, exhibit reduced carbon emissions per person. Regions with more laborious property administration have higher population density and lower levels of emissions. This discovery diverges from the typical correlation between rules and urban expansion, emphasizing the need for a more refined awareness of the effect of laws on urban structure and sustainability.

Spangler et al. also examined previous and present U.S. agricultural landscapes using national open-source datasets from various decades in the National Research Council's (NRC) Sustainable Agricultural Systems Framework [5,58]. Their study analyzed policy data as well as agricultural land use and cover datasets. Their study sought to (1) record and visualize changes in cropland conversion, agricultural productivity, and crop mix throughout the United States during recent decades and (2) identify general policy changes in the 1933–2018 Farm Bills related to these land use patterns. The study demonstrates that United States agriculture has become highly regulated and specialized. Larger farms are growing, smaller farms are shrinking, and agricultural variety is dwindling. These data-driven insights provide incremental and revolutionary change routes to encourage different production techniques, incentivize varied landscapes, and encourage innovation toward more sustainable agricultural systems at various scales.

Hasnat and Hossain argue that studying international land use policies, changes, and conflicts provides the latest research on LULCC worldwide [59]. This research can help develop land use policies aimed at protecting the Earth for both present and future generations. The study investigates land tenure systems in various nations and the causes behind policy changes. It provides guidance on sustaining land management, using landscape models to predict future land use, implementing best architectural practices, and utilizing urban forestry to enhance environmental management and climate adaptation. Studies of this nature relevant stakeholders or proponents to optimizefuture land use systems. To this end, it is worth noting that several planning models or approaches that draw on the tenets of 'bottom-up,' 'transformative governance' and 'top-down' paradigms could be utilized to examine land use systems at all levels.

In line with SDG 17, community-based land use planning and public-private partnerships are two widely used approaches for managing and developing land. Both methods involve collaboration between various stakeholders to ensure a sustainable and equitable use of land resources. According to Li et al., community-based land use planning involves engaging key project proponents to circumvent or make informed decisions regarding land use [60]. This approach allows for greater participation and input from those who will be directly impacted by development projects. By engaging the community in the planning process, it ensures that their needs and preferences are taken into account, leading to more sustainable and socially responsible development outcomes. In the United States, these approaches are often conducted at the local level, with cities and counties responsible for zoning regulations and development decisions [61]. Here, one common approach is the use of comprehensive land use plans, which outline long-term goals and strategies for land use within a community. These plans are typically developed with input from residents, businesses, and other stakeholders to ensure that they reflect the collective vision for the community's future. In addition, tools such as community workshops, surveys, and public hearings are used to gather input from a diverse range of stakeholders, helping to ensure that the planning process is inclusive and transparent.

In developing countries like Kenya, community-based land use planning is essential for promoting sustainable development and addressing land tenure issues [62]. With a majority of the population relying on agriculture for their livelihoods, proper land use planning is crucial for ensuring food security, reducing conflicts over land, and promoting economic development. One example of successful community-based land use planning initiatives in Kenya is the establishment of community conservancies, where local communities manage and conserve their natural resources in a sustainable manner. By involving communities in the management of their natural resources, these conservancies have helped to protect biodiversity, promote sustainable land use practices, and improve livelihoods for local residents [63].

In Australia, community-based land use planning is often integrated with indigenous land management practices, recognizing the long-standing connection between indigenous peoples and the land. Indigenous land use planning involves engaging indigenous communities in decisions about how their traditional lands are managed and developed, ensuring that their cultural practices and environmental knowledge are taken into account [64]. One successful scenario of indigenous land use planning in Australia is the Working on Country program, which provides funding and support for indigenous land management initiatives. By involving indigenous communities in land use planning, Australia is able to promote sustainable development while respecting the rights and traditions of indigenous peoples [65].

3.7. Economic Viability of Emerging Land Use Practices

Bibri et al. explored the implementation and rationale of the compact city model in urban planning and development, with a focus on its three dimensions of sustainability and an evaluation of progress [66]. They employed a descriptive case study as a qualitative research method to investigate this urban phenomenon. The empirical foundation of the study included official plans and documents from two Swedish cities, Gothenburg and Helsingborg, along with qualitative interviews and secondary data.

In their study, they identified key design strategies for creating compact cities, which encompass compactness, density, diversity, mixed land use, sustainable transportation, and green spaces. It also highlighted the concept of green structure, an institutional framework that governs the operations of both cities and is closely linked to the notion of green space. Furthermore, the compact city model relies on strong collaboration among its underlying strategies, which work together to produce synergistic effects greater than the sum of their individual impacts. This collaboration aims to maximize the sustainability benefits of the model, which consists of three interconnected components. Moreso, the study demonstrated that the compact city model, as implemented by the governments of the two cities, was effective in contributing to the economic, environmental, and social objectives of sustainability. However, it noted that economic objectives tend to take precedence over environmental and social ones, despite the theoretical assertion that all three components of sustainability hold equal significance.

Xie et al. examined the patterns, distribution of research influence, focal areas, popular research topics, and global collaboration in sustainable land use research in recent years [67]. The work employed the Bibliometrix and Biblioshiny software packages to conduct a comprehensive bibliometric analysis and visually present the research papers on sustainable land use (1990–2019). The results indicated that the impact of industrialized nations in the domain of sustainable land utilization is considerably higher than that of emerging nations. The concepts that engulf sustainable land use have undergone significant transformations throughout different periods (**Figure 4**); however, a strong sense of continuity can be observed in some key themes (**Figure 4**). Their study further suggests that to advance the progress of sustainable land use, it is crucial to incorporate robust sustainability, landscape ecological theories, and geographical design principles into LSS.

Liu et al. devised a novel framework for measuring Land Use Efficiency (LUE) that takes into account the anticipated land use outcomes and the interplay between three key aspects: production of food, economic viability, and environmental sustainability [68]. They employed the coupling coordination degree model to assess the spatial variations and coordination relationships among these sub-categories. The evaluation focused on Jiangsu Province in eastern China, utilizing multivariable linear regression and geographical detectors. A total of ten indicators were considered, including cultivated land quality, grain output, multiple cropping index, average Gross Domestic Product (GDP) per km^2, population density, proportion of industry and service sector, vegetation cover index, water conservation index, soil retention index, and carbon concentration. Jiangsu's LUE for food production, economic development, and environmental conservation was estimated at 54.15%, 85.56%, and 54.95%, respectively, exceeding expectations. This suggests that Jiangsu province has high prospects for the sustenance of its land use systems. The degree of coupling typically corresponds to the level of coordination between land use activities, which accounts for 65.34% of the province's land area.

3.8. Future Scenarios and Uncertainties

The future of land use science and systems development is uncertain due to factors such as population growth, urbanization, climate hazards, technological advances, governmental interventions, and global market dynamics [69]. Urban growth, climate hazards, technological adoption, regulatory frameworks, governance frameworks, global demand for land-based commodities, and conservation objectives all have elements of uncertainty [70]. Therefore, it is necessary to utilize multiple tools to comprehensively model or simulate trends. This can be achieved by using big data platforms and machine and deep learning techniques to provide more information on environmental and sustainability challenges. Integrated methods/models, evidence-based decision-making, stakeholder involvement, and transformative governance are also essential to address these challenges. Scenario planning, risk assessments, and participatory procedures can be used to develop alternative futures that provide effective solutions to uncertainties, build resilience, and achieve sustainable land use outcomes in a rapidly changing world [71]. It is also important to empower youth through innovative schemes that allow them to contribute to global discussions and debates, as well as to promote scientific research collaborations and investments between industrialized nations with high scientific productivity and emerging or less productive nations.

3.9. Limitations and Future Research Perspectives

In spite of these developments, the current study is not devoid of some limitations and opportunities that could drive further studies. To begin with, one of the main limitations of this narrative review is linked to the potential for bias as this study may unconsiciously select studies that align with the authors' beliefs. This may result in skewed representation of existing literature and failure to cover the full range of perspectives and findings on a particular topic. Hence, further studies could be conducted to cover each theme or subject presented in the analysis and discussion section. Another limitation of this narrative review is linked to the lack of systematic methodology. Unlike systematic reviews that adhere to strict protocols for selecting and analyzing studies, this research acknowledges the element of subjectivity and inconsistencies that may occur during data extraction and analysis processes, further making it challenging to make evidence-based recommendations for policy and practice.

Furthermore, this review may also be limited by the quality of the studies included. In land use studies, where research methods and data sources can vary widely, it can be difficult to assess the reliability and validity of the findings in each study. This can undermine the credibility of the review and its utility for informing decision-making in the field of land use planning and management. In addition, while this narrative review may serve as a valuable tool for synthesizing existing studies in this field, it may not always reflect the most current research on this topic as land use studies/land system science is constantly evolving. New studies published regularly may contradict or build upon existing studies. Future studies could investigate automated validation methods using crowdsourcing, multi-sensor fusion, and machine learning to achieve scalable validation. Additionally, employing standardized protocols like CEOS Land Product Validation (LPV) could improve consistency in the validation process.

4. Conclusions

Global land use systems have changed significantly over time due to technological advancements, socioeconomic transformations, and environmental challenges. To manage modern land use effectively, a multidisciplinary approach that integrates technology, policy, and economics is essential. As technology advances, the need for sustainable and equitable land management practices grows. It is crucial to adapt to these changes to strike a balance between competing demands on land resources in order to secure a sustainable future for both human societies and the environment. In this study, we critically reviewed existing literature on the development and sustainability of global land use systems. Using an extensive bibliographic database from Web of Science, we explored the complex realm of global land use systems, including their historical trajectories, contemporary issues, and future outlook.

Evidence shows that current research trends in land use science, management, and sustainability involve the use of emerging DTs such as geoinformatics, Geo-detectors, regression models, artificial intelligence (including machine and deep learning models), as well as social and economic models. The integration of remote sensing and geospatial techniques with transformative governance models that incorporate economic, social, and environmental factors is crucial for addressing land use issues and promoting sustainability. This review study emphasizes the importance of thoroughly examining the different aspects of this subject to establish a comprehensive understanding of the historical, current, and future developments in global land use systems. Therefore, this study's outcome suggest fostering strong collaborations among researchers, government agencies, private organizations, international donors, policy-makers, and other stakeholders to collectively advance knowledge in this field. Enhancing the theoretical and practical foundations of land use sustainability requires the combination of various techniques and models, the integration of policy approaches, and the utilization of big data platforms.

Supplementary Materials

The following supporting information can be downloaded at https://journals.nasspublishing.com/files/lmu-1836_Supplementary-Materials.docx

Author Contributions

Conceptualization, I.S. and N.A.A.E.; methodology, I.S., N.A.A.E., E.Y., and D.B.A.; validation, I.S., N.A.A.E., M.A.D., M.K.A., E.Y., D.B.A., A.B., P.A.D., and G.H.X.; formal analysis, I.S., N.A.A.E., M.A.D., M.K.A., D.B.A., M.B., A.B., P.A.D., and G.H.X.; resources, N.A.A.E.; data curation, I.S., N.A.A.E., and E.Y.; writing—original draft preparation, I.S.; writing—review and editing, N.A.A.E., M.A.D., M.K.A., D.B.A., M.B., A.B., P.A.D., and G.H.X.; visualization, N.A.A.E. and E.Y. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interests

The authors declare no conflict of interest.

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