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Research Article

Evaluation and Comparison of Curve Numbers Based on Dynamic Land Use and Land Cover Changes

Menuka Gautam[1]*, Nishan Bhattarai[2], Binod Ale Magar[3], Dewasis Dahal[3], Sujan Shrestha[3], Bishal Poudel[3] and Arif Hasnat[3]

[1]*Department of Geology, Tribhuvan University, Nepal*

[2]*Department of Geomatics Engineering, Kathmandu University, Nepal*

[3]*Department of Civil, Environmental, and Infrastructure Engineering, Southern Illinois University Carbondale, United States*

***Corresponding author:** Menuka Gautam, Department of Geology, Tribhuvan University, Nepal

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Abstract

The NRCS, which is widely used in hydrological modeling, aids in assessing runoff by considering vegetation, land use, and soil characteristics. Using the Curve Number (CN) model created by the Natural Resources Conservation Service (NRCS), this study examines water dynamics in Lewis County, New York. The study investigates the connection between hydrological processes and changes in land use, with a particular focus on CN grades for 2001, 2011, and 2021. ArcGIS was utilized for mapping and land use and land cover (LULC) classification, while Arc Hydro was employed to generate the CN numbers. These CN grades, which vary from 0 to 100, show a range of hydrological features that impact possible infiltration and runoff. Substance infiltration is significant in areas with CN classes 0–30, which lowers surface runoff. The varied effects of land cover are reflected in CN classes 30-58, which indicate moderate infiltration and runoff capacity. Increased runoff potential due to urbanization and changes in land use is indicated by CN classes 58–82. CN Classes 74.5–79 designate regions with increased potential for runoff, highlighting the necessity of proactive land management to lower the danger of flooding. The study recognizes the limits of the data, especially about land usage and coverage, which emphasizes the need for future research endeavors to improve the accuracy and accessibility of the data.

Keywords: Land Use Land Cover (LULC); Natural Resources Conservation Service (NRCS); CN grade

Introduction

The Curve Number model, established by the United States Soil Conservation Service, now known as the Natural Resources Conservation Service (NRCS), has long been a cornerstone of hydrological modeling [1]. It is frequently used to estimate surface runoff in watersheds, making it one of the most complex and reliable techniques in applied hydrology for over 60 years [2]. This model, with its simplicity and practicality, has been instrumental in flood predictions and actual watershed management. Despite its popularity, the model's widespread implementation in many geographical regions presents challenges, mainly when land use and hydrological regimes differ significantly from the originally modeled United States. Since it incorporates important watershed factors such as vegetation cover, soil type, land use, and antecedent moisture conditions, it can be regarded as an estimate of direct runoff [3]. Like other event-based rainfall-runoff models, the CN technique is incredibly effective at estimating dynamic changes in runoff volume and distribution over time. These models are indispensable when it comes to predicting hydrological events, planning flood defense strategies, and managing erosion in specific landscapes [4]. Achieving sustainable water management and urban planning requires an awareness of the impact of global land use changes and rising urbanization on runoff. The growth of impermeable surfaces due to urbanization is one of the most significant causes of contemporary hydrological change. The worldwide urban land area increased by 346,400 km^2 between 1992 and 2016, and by 2030, an additional 1.2 million km^2 of urban land expansion is expected [5]. Rapid urbanization significantly impacts the overall health of watersheds by affecting surface runoff and infiltration. Roads, buildings, and pavements impermeable to light lower an area's natural infiltration capacity and increase surface runoff, lowering groundwater recharge and raising the risk of flooding. Research has demonstrated that urbanization disrupts naturally occurring hydrologic cycles; urban watersheds frequently generate higher peak flow rates, and flood events occur more frequently than they would normally [6]. The hydrological equilibrium between runoff and infiltration is altered by deforestation, agriculture, and urban sprawl, which exacerbates land use and cover disturbance. This may lead to higher surface runoff, soil erosion, and sedimentation in water bodies, which may affect water quality. Watershed management is made more difficult by poor land use management, which leads to soil degradation and increased runoff volume [7]. An example of this would be the spread of agriculture without proper erosion control techniques. This is explained by the growing necessity for LULC data to be included in hydrological models, such as the CN technique, to improve runoff predictions and offer information that guides land management strategies [8].

Even though the NRCS-CN approach is widely used, its accuracy varies greatly depending on the location. The model was initially created for small agricultural watersheds in the US and makes assumptions about the type of soil and land use that may not apply to other nations or areas [9]. A few studies' descriptions of the applications of the CN approach point to the necessity of changing and adapting it to be used in a variety of hydrological circumstances. For instance, research by Moon et al. (2016) revealed that locations with steep slopes or varying vegetation types may have their runoff potential overestimated or underestimated by the standard CN [10]. This highlights the need to adapt the CN model to local circumstances by accounting for variances. The study established a connection between Lewis County, New York's hydrological processes and dynamic land use. In this work, land use and cover data are used to compute the CN classes corresponding to the years 2001, 2011, and 2021 in order to examine the effects of land cover change on runoff potential within the region. Therefore, Lewis County includes forest, agricultural, urbanized, and water body regions that collectively form an excellent area for studying the interplay between land use and hydrology in both static and dynamic terms [11]. The results of this study will be crucial in developing land management strategies that strike a balance between environmental sustainability and development, given that the amount of urban land will at least double over the next several decades. Deeper integrations of CN modeling with LULC data will be necessary in the future due to the acceleration of land-use changes in order to make well-informed decisions on urban planning, flood mitigation, and water resource management [12].

The comparative study of CN grades throughout Lewis County provides a critical viewpoint on how vegetation, land use, and urbanization impact hydrological processes. These results have implications for other areas experiencing comparable land-use changes in addition to the local context. The study's conclusions offer legislators and land use planners practical recommendations for optimizing hydrological systems to lessen the dangers associated with higher surface runoff and lower infiltration brought on by altered land use [13]. With a focus on watershed management and urbanization, this research will advance our understanding of how catchment-wise dynamics in land cover affect hydrological responses. The focus on Lewis County, an area with various land uses and a changing environment, provides a microcosm of the difficulties associated with land use change and how it affects hydrologic systems on a broader scale [14]. Thus, for improved forecasting and sustainable land management, this study emphasizes the significance of modifying standard hydrological models, such as the NRCS-CN, in line with changes in land use.

Materials and Methods

Study Area

The study focuses on Lewis County, located in the northern section of New York State, within the Mid-Atlantic Census Bureau division in the northeastern United States [15]. New York has roughly 54,556 square miles, ranking as the 27th largest state in the country [16]. Our study, however, focuses on a smaller area, 97.2 square miles in Lewis County, which was chosen for its unique hydrological and land cover features. This particular subgroup makes a thorough examination of land cover dynamics and their impact on surface runoff and infiltration patterns possible. One of the key features of the region is the presence of two significant water stations. These stations, Deer River at Copenhagen, New York (station ID 04258500), and Deer River at Deer River, New York (station ID 04258700), provide crucial data on precipitation and rainfall patterns [17]. This data is indispensable for evaluating the hydrological behavior of the area, determining Curve Numbers (CN), and understanding runoff potential across various land cover types. The land cover in Lewis County is divided into four basic classes: water bodies, medium-density residential areas, woods, and agricultural lands. These classifications are similar over the study period, with land cover data collected from the National Land Cover Database (NLCD) for the years 2001, 2011, and 2021, as demonstrated in Figures 1 (2001 NLCD Land Cover), 2 (2011 NLCD Land Cover), and 3 (2021 NLCD Land Cover). These pictures give a clear picture of how land cover has changed over time, shedding light on how the hydrological dynamics of the area have changed. A more detailed understanding of regional hydrological processes can be gained by concentrating on Lewis County, as opposed to the more general features of New York State, which are characterized by a variety of topography, including mountains, lakes, and extensive woods. An in-depth investigation of how changes in land cover, especially urbanization and agricultural growth, affect runoff and infiltration in the area is made possible by the targeted method, which improves the accuracy of hydrological evaluations [18]. Gaining an understanding of the broader ramifications for New York's water resource management as well as for enhancing land management techniques requires this localized perspective

Curve Number derived from land use and land cover (LULC) and soil characteristics: [CNLU]

The study's methodology involved the use of the Curve Number Land Use (CNLU), a dimensionless runoff indicator that considers antecedent moisture condition (AMC), hydrologic conditions, land use, land treatment, and hydrologic soil group (HSG) [19]. The creation of land use and land cover maps for 2001, 2011, and 2021 was a painstaking process, utilizing soil and watershed data from the Geospatial Data Gateway (GDG) and US Geological Survey (USGS) websites. Detailed land use and land cover data can be found on the Multi-Resolution Land Characteristics (MRLC) website. Accessible datasets from the MRLC, National Land Cover Database (NLCD), and Digital Elevation Model (DEM) for 2001, 2011, 2011, and 2021 were clipped and projected into a consistent method to streamline data for the Lewis County research region. The NLCD data comprised several classifications and was divided into smaller groups based on the Merwade, V. (2019) study: agriculture, forest land, settlement, and water body divisions [20]. After that, the raster file was converted into a polygon. Using soil categorization information from the study, the NLCD polygon and soil files were integrated [21]. Arc Hydro and ArcGIS Pro assisted in establishing a CN grade table and developing CN grades. This all-encompassing method of land use mapping and classification creates a fundamental understanding of the dynamic landscape, offering crucial information for assessing hydrological consequences and directing successful land management plans.

Comparative Analysis Approach

For comparative analysis, CN grade values for each of the ensuing years (2001, 2011, and 2021) were divided into ten intervals ranging from 0 to 100. Every CN grade class's geographic coverage was established for the years prior. Subsequently, data was analyzed using Microsoft Excel to create a comparison chart showing the variation in a covered area for specific CN grade classes in 2001, 2011, and 2021. This analytical approach methodically examines dynamic changes in CN grade distributions over the designated periods.

Results and Discussions

Land Cover Dynamics and Curve Number Distributions in Lewis County

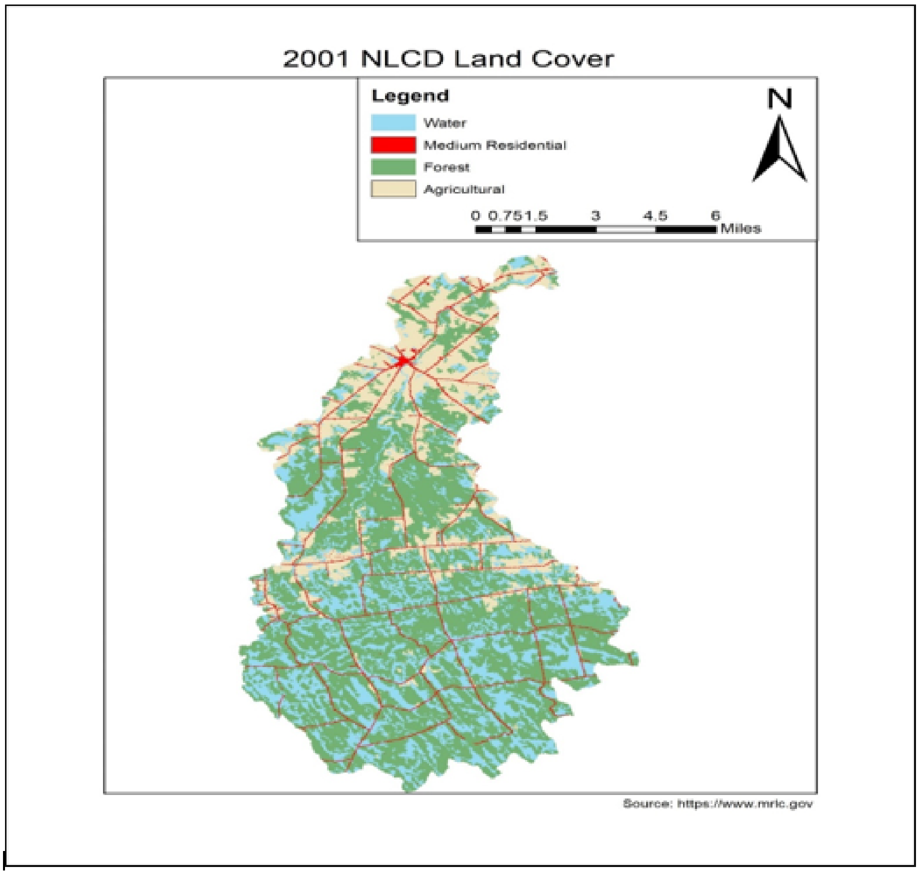

Figure 1: 2001 NLCD Land Cover, Lewis County.

The land dynamics in Lewis County, New York, which include woody wetlands, emergent herbaceous wetlands, developed areas of varying intensity, deciduous and evergreen forests, mixed forests, barren lands, shrub/scrub, grasslands/herbaceous zones, pasture/hay, and cultivated crops, are thus presented in this paper. Notably, these changes were mapped from the analyzed multi-date Landsat data scenes. As observed in Figures 1 (2001), 2 (2011), and 3 (2021), land cover type data were divided into four divisions to aid in the analysis: water bodies, medium-density residential areas, woods, and agricultural land. This makes it possible to examine how land-use modifications affect hydrological processes-particularly surface runoff and infiltration potential. The geographic distribution of CN grade was investigated in 2001, 2011, and 2021. The range of the CN grade is between 1 and 100. Whereas CN grade 100 showed near-total imperviousness with an enhanced tendency for runoff, CN grade 1 indicated good infiltration and low runoff. Table 1 shows the land distribution for each of these three years across the different CN grades.

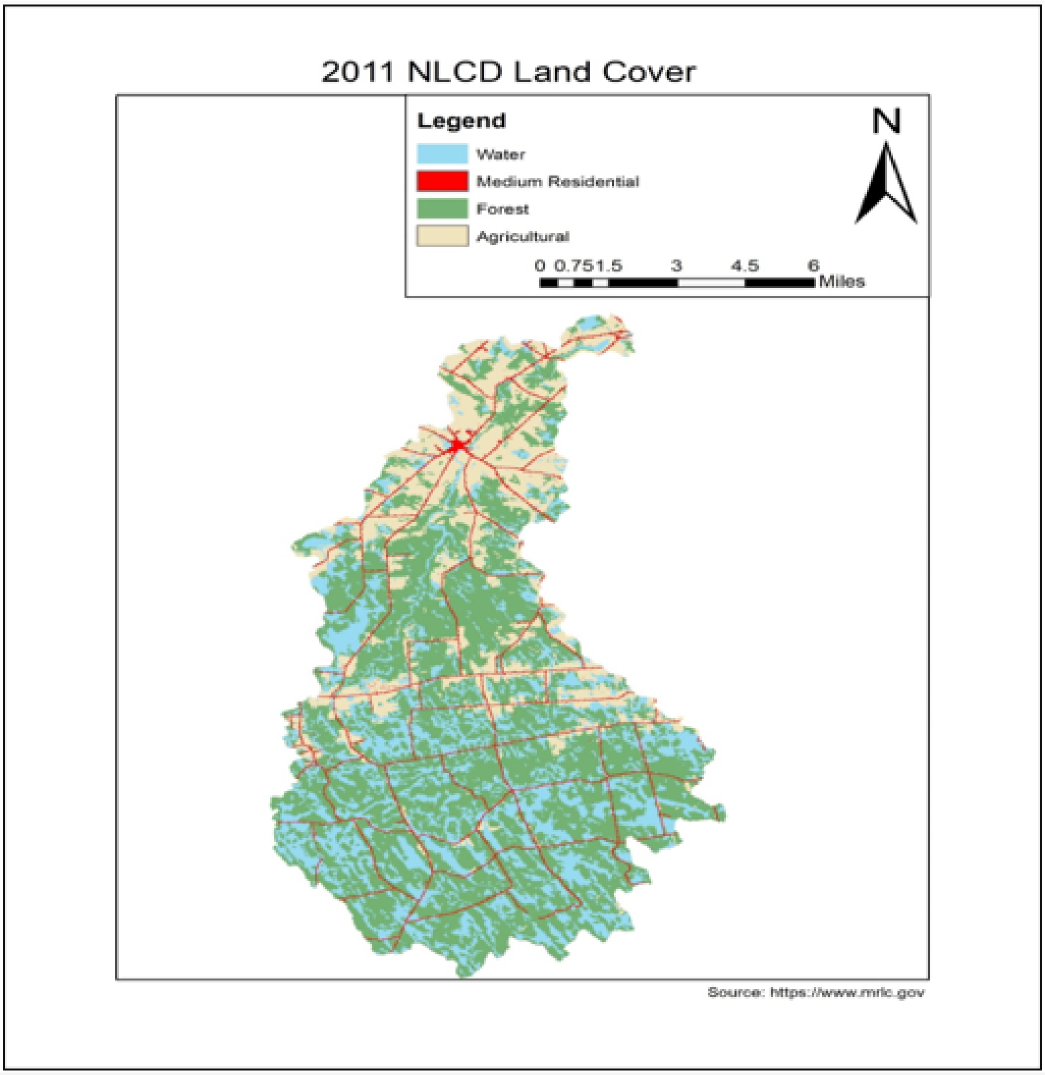

Figure 2: 2011 NLCD Land Cover, Lewis County.

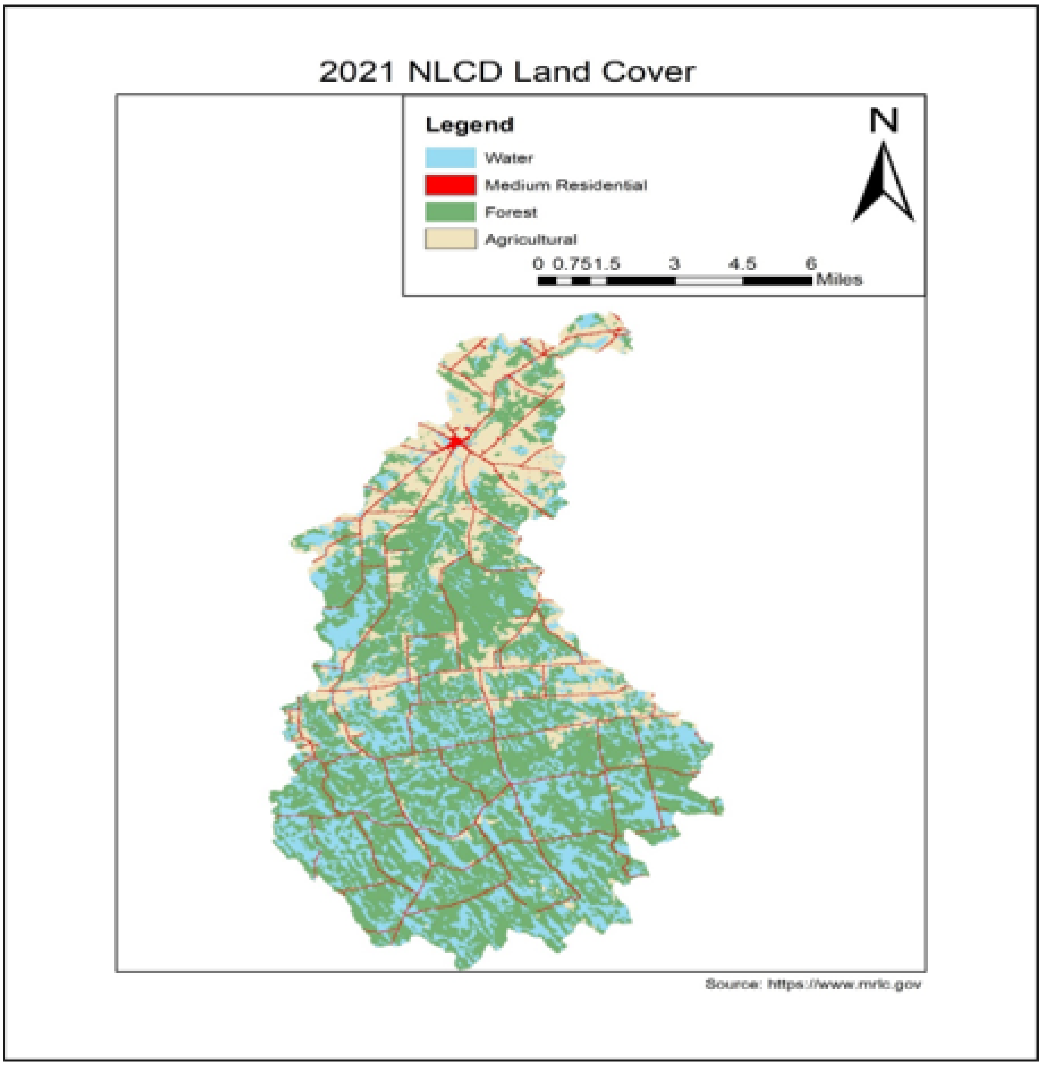

Figure 3: 2021 NLCD Land Cover, Lewis County.

The range of CN grade groups 79 to 92, which saw an increase in area from 2001 to 2021, had the most significant changes in land area coverage. As shown in Table 1, this CN grade range encompasses an enhanced impervious surface that typically arises from urban expansion and raises the risk for runoff. The CN grade group of 83.5 to 87 was likewise affected by the noteworthy shift in land area coverage; during that time, it was the second most affected group. The CN grade range of 82 to 83.5 displayed the next more significant rate of change in the area coverage, indicating additional changes in land use over the study period. In all three-year investigations, the CN group between 87 and 100 covered the most area, measuring 65,148,317.1 km^2 in 2001, 64,947,889.48 km^2 in 2011, and 65,165,642.98 km^2 in 2021. This group, which reflects nearly 100% imperviousness and considerable potential for runoff, indicates high levels of urbanization and infrastructure growth throughout Lewis County throughout the research period. The areal distribution for CN grade ranging from 74.5 to 70 was the second highest, closely followed by the range of 68-72. The results have indicated a constant increase in surface runoff potential, particularly in areas undergoing urban growth and changes in land use. The historical fluctuations in CN grade distributions also show this pattern, with movements towards higher CN values being driven by urbanization. Such changes have a direct impact on hydrological processes, particularly those about surface runoff, infiltration, and flood potential. Figure 4 compares geographic coverage based on changes in CN grade classification over the course of three years. Furthermore, the land area distribution based on CN grades will provide useful information regarding the effects of changes in land use and land cover on the region's hydrological characteristics.

Table 1: Variation in Land Area Coverage Relative to CN Grade for 2001, 2011, and 2021.

	Temporal Variation in Land Area Coverage		
	2001	**2011**	**2021**
CN Grid Values	Area (m^2)	Area (m^2)	Area (m^2)
0-30	22244045	22286749	22078106
30-58	5102281	5083247	5116272
58-68	8159046	8023855	8272681
68-72	31757685	31292488	31466560
72-74.5	9645496	9555043	9616050
74.5-79	59011443	58876170	58703399
79-82	4299350	4440642	4395009
82-83.5	24909797	25379874	25145852
83.5-87	21399792	21825701	21717028
87-100	65148317	64947889	65165643

Comparative Analysis of CN Distributions and Hydrological Responses

In this section, Figures 5, 6, and 7 compare the Curve Number grade geographical distribution in Lewis County, New York, for 2001, 2011, and 2021. Land use patterns and hydrological processes in this county have changed significantly in terms of spatial variation over these three times in time. Class 79–82 has the biggest increment; obvious adjustments are presented for it, and classes 83.5–87 come next. These variations suggest that significant alterations have occurred to this topography, which may impact the rates of infiltration and surface runoff. The apparent rise in CN classes 79–82 indicates an increase in runoff potential, which may result from land use changes, urbanization, or alterations to soil qualities that reduce infiltration capacity. The CN often rises due to more impermeable surfaces, such as buildings and roads, lowering the infiltration rate and raising surface runoff. For instance, Deshmukh et al. (2013) observed that the rise in CN values brought on by urbanization was consistent with a worldwide pattern in which fast urbanization changed hydrological processes naturally, increasing the risk of floods and decreasing the ability for groundwater recharge [22]. Global trends indicate that fast urban growth has changed natural hydrological regimes, increased the risk of flooding and decreased the potential for groundwater recharge. This is consistent with the increase in CN values.

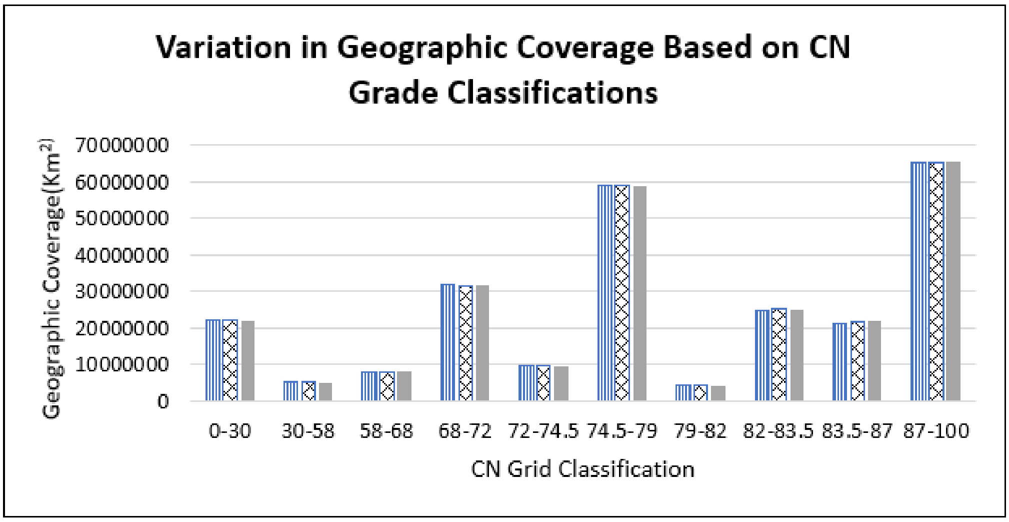

Figure 4: Variation in Geographic Coverage Based on CN Grade Classifications.

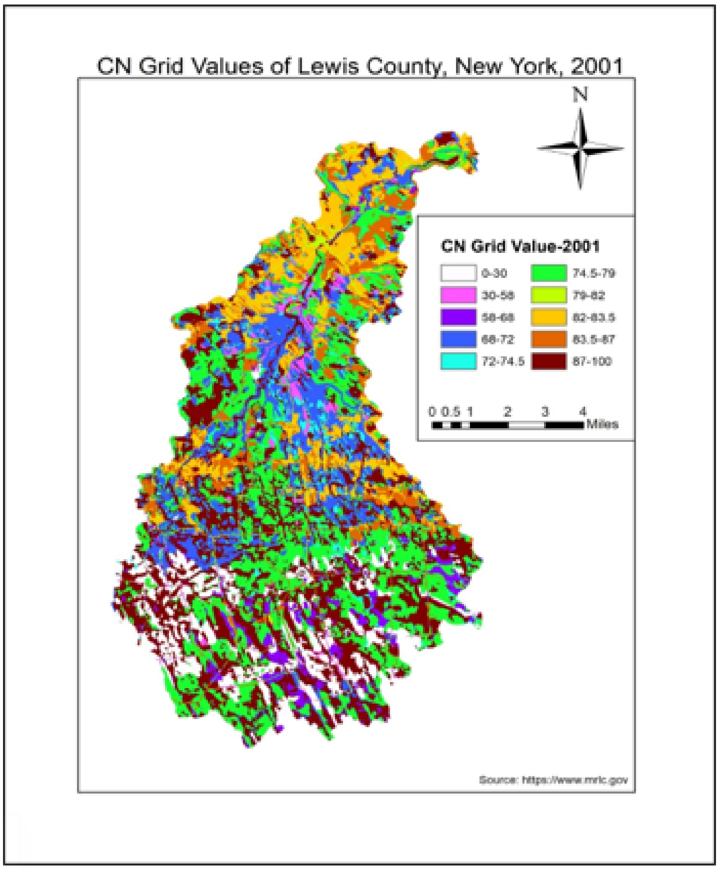

Figure 5: Spatial Distribution of Curve Number (CN) Grades in Lewis County, New York, for the Year 2001.

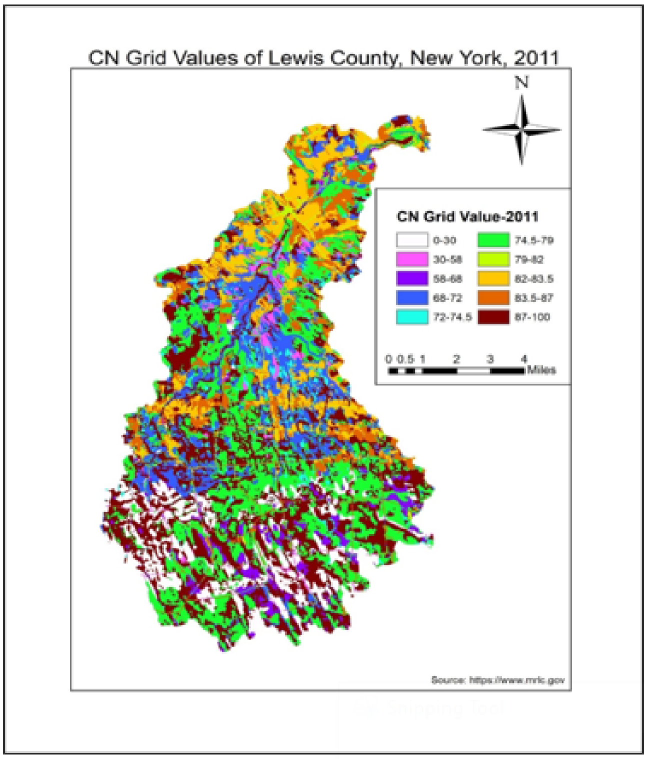

Figure 6: Spatial Distribution of Curve Number (CN) Grades in Lewis County, New York, for the Year 2011.

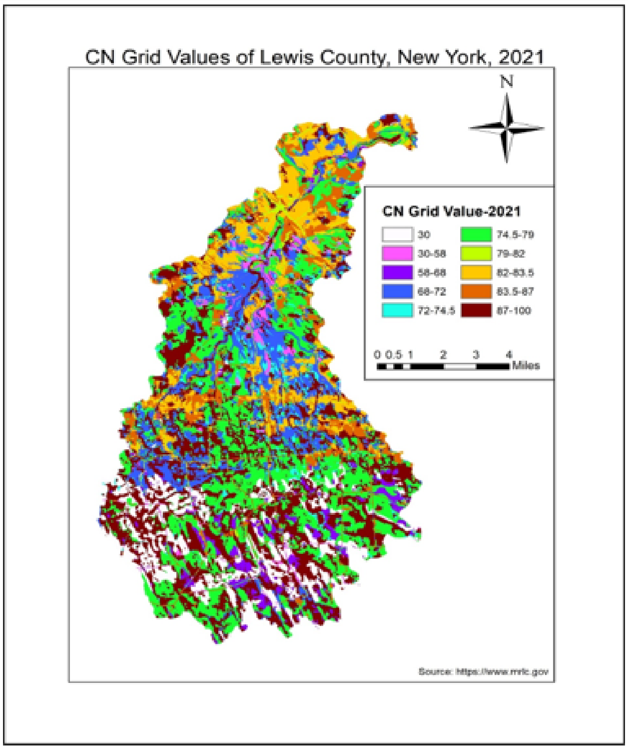

Figure 7: Spatial Distribution of Curve Number (CN) Grades in Lewis County, New York, for the Year 2021.

The second most notable change in land area, however, was represented by the CN class 83.5–87. While this class's rise in runoff potential was less than that of the range 79–82, it nevertheless represents significant changes in land features that may impact hydrological processes. These alterations are most likely the result of natural and artificial changes in the land cover, such as the growth of agriculture or deforestation, which alter the soil's structural properties and may affect its capacity to retain water. Furthermore, this emphasizes the significance of adequately monitoring land-use changes because even a tiny shift in the CN value dramatically impacts the local hydrology regarding water storage and drainage patterns. These classes of CN do have significant implications for the local water management systems due to high potential runoff. Increased runoff can overrun current drainage systems, alter river and stream flow dynamics, and even increase the likelihood of flooding in downstream regions. The findings would thus necessitate reevaluating how land is now managed in light of the growing urbanization of the area, particularly in Lewis County. According to Moon et al. (2016), this necessitates the deployment of sustainable land-use policies and intelligent urban design to lessen the adverse effects caused by increased surface runoff [10].

The hydrological significance of the identified modifications, particularly in terms of catchment management, is further highlighted by spatial analysis. The expansion of regions with higher CN grades indicates a decrease in infiltration capacity, which could impact river baseflow and groundwater recharge. These hydrological alterations, particularly during heavy rainfall, may encourage greater seasonal variability in water availability. This underscores the need for integrated catchment management strategies that consider shifting land cover conditions, providing a comprehensive approach to managing these hydrological alterations. The land-area change list for all CN grade classes from 2001 to 2021 is displayed in detail in Table 1. Throughout the research period, the CN group occupied the most significant area because, within a range of 87-100, it represented the area with the highest potential for runoff and imperviousness. Later, in 2011, this area declined slightly before hiking again in 2021. This fluctuation suggests that, despite a possible brief stability of land use intensity, the runoff potential in this area has continued to rise due to subsequent development and urbanization trends. The comparative analysis of CN grades in Lewis County, which highlights a proactive approach to land management in light of challenges related to urbanization and land-use change, also reveals dramatic changes in hydrological perspectives over two decades characterized by high runoff potential, particularly from CN classes 79–82 and 83.5–87. In order to make county water management resilient, it is necessary to manage lands sustainably by maintaining their permeable surfaces and creating green infrastructure that may lessen the effects of this increasing runoff.

Discussion

In order to develop suitable land management practices in Lewis County, New York, understanding hydrological responses is contingent upon understanding both the geographical distribution of Curve Number grades and the dynamics of land cover. One of the well-established techniques for calculating surface runoff is the CN model, which is particularly helpful in areas with noticeable changes in the land cover. The study's results have demonstrated the intricate linkages between different forms of land cover and hydrological processes, underscoring the necessity of appropriate land management—particularly in places undergoing significant land-use change due to urbanization.

Hydrological Implication of CN Grade Distribution

The distribution of CN classes in Lewis County shows a variety of infiltration potential and runoff capacity, which range from 0 to 82. In order to understand the hydrological dynamics of a region, these grades are crucial for classifying the land based on its capacity to absorb water or generate surface runoff. In this work, low runoff potential and high infiltration capacity are represented by CN classes 0 through 30. These classes covered a good deal of the study space. Permeable land cover types, such as wetlands and forests, which help replenish groundwater reserves and lessen surface runoff, most likely make up most of these classifications. This is consistent with research by Deshmukh et al. (2013), who found that regions with high infiltration were critical to preserving the regional water balance and achieving hydrological stability [22].

Furthermore, the nearly constant distribution of CN grades between 30 and 58, which suggests a moderate class of infiltration and runoff potential, might suggest that a range of land cover types with intermediate degrees of imperviousness influence the hydrological dynamics in the area. These would include classes of agricultural lands, open spaces, and regions with sparser developments where runoff generation is minimal, thus permitting both infiltration and some degree of surface runoff. Moreover, research studies like the one conducted by Ajmal et al. (2016) provide evidence that, due to the intensities and lateral extents of development or agriculture, areas with moderate CN values typically contain mixed uses that can influence hydrological responses in interactionally complex ways [23].

The classes with a CN value between 58 and 82, where the land surface is becoming more impermeable and the possibility for runoff is rising, are more concerning. That indicates that due to urbanization or other changes in land use that lower the earth's ability to allow for infiltration, the ground may become more and more impervious. These impermeable surfaces, including roads and buildings, do not allow infiltration and consequently boost the volume of surface runoff, elevating the flood threat proportionally. This is particularly clear in CN classes 74.5–79, where the high geographical distribution supports the idea that impermeable surfaces occupy significant portions of the terrain. Moon et al. (2016) noted that expanding urban areas is a well-documented cause of hydrological disruption [24]. Expanding urban areas results in altered runoff patterns, decreased groundwater recharge, and increased vulnerability to flood events.

Implications for Water Management and Land Planning

Elevations in the aforementioned classes of CN indicate a shift in land use, which has significant consequences for water management and land use planning. Increasing surface runoff and declining natural water-absorbing capacity are typically linked to urbanization, intensifying flooding and modifying the water flow pattern. As evidenced by this pattern, research worldwide shows that urban growth significantly affects regional hydrology by raising peak flow rates and reducing the time lag between precipitation and runoff [25]. The CN classes 79–82 in Lewis County is associated with regions with a significant potential for runoff. Thus, proactive land management techniques are required. Urban planners and environmental managers will, therefore, need to implement more permeable pavements, green roofs, and artificial wetlands as sustainable drainage methods to mitigate the negative effects of increasing impermeable surfaces. These actions, particularly in places where urbanization is occurring quickly, lessen runoff, boost infiltration, and establish more sustainable hydrological cycles. The CN grade distribution's temporal changes—particularly the rise in impermeable areas—show that land-use regulations must be flexible to deal with newly emerging hydrologic problems. Land-use practices need to be controlled to support infiltration processes essential to the regional hydrologic balance, with a restricted increase in impervious surface area and an optimized amount of green space. Therefore, using green infrastructure could help reduce runoff, improve the quality of the water, and increase resistance to climate-related effects such as extreme rainfall events.

Limits and Future Research

Although the study that is being presented offers some insightful information about the dynamics of land cover and hydrological processes in Lewis County, there are certain limitations that should be considered. These compound the main problem of accurate and readily available land-use and land-cover data at a given categorization. Furthermore, it was discovered that several high-resolution classes were absent, which could have contributed to the observed differences in the CN grade computation. This is also consistent with previous research on hydrological modeling, which found that accurately capturing land-use changes needs to be improved by data gaps and classification issues [26]. Future research will be susceptible to considerably more accessible access to data, especially with high-resolution remote-sensing technologies, like satellite images and LiDAR, which enable far more accurate mapping of land cover change [27]. Second, the research should have accounted for future land-use changes that might occur, such as the growth of metropolitan areas and/or changes in land cover brought on by climate change. Including more predictive models—which can forecast future land-use scenarios and their effects on hydrology—in the quest to better comprehend long-term hydrological concerns would also be instructive. To ensure that water management policies remain effective in the face of urbanization and environmental change shows how future land-use planning must incorporate hydrological modeling [28].

Conclusion

The significant connection between land cover dynamics and hydrologic processes in Lewis County, New York, can be realized through the Curve Number grades. Most of the infiltration and runoff characteristics of the area can be summed up by the 0 to 82 CN values. Lower CN values (0–30) show better groundwater recharge and less surface discharge. These regions also have a high invasion rate. However, CN values between 58 and 82 show that urbanization has increased impermeable surfaces, increasing the risk of flooding and runoff. Such regions need to be planned for development using sustainable techniques, such as permeable surface areas and green infrastructure, to reduce the consequences of land-use change on regional hydrology. Despite the information deemed significant as gathered from the study, there was the inclusion of various restrictions that, for the most part, were related to data availability and accuracy in land-use classification and cover. The hydrological projections may have been less accurate due to a lack of comprehensive and high-resolution resources. It consequently emphasizes the need for better data collection techniques, such as remote sensing and sophisticated geographic information systems, to obtain more precise and in-depth data on land cover for upcoming research. It also highlights the possibility of looking into forecast models to consider probable future land-use scenarios. These models have the potential to offer valuable insights into long-term planning for flood protection and water resource management by forecasting the outcomes of additional urbanization or agricultural growth. This will provide comfort or assurance when making plans. In brief, the study offers a solid foundation for comprehending the interactions between hydrology and changing land cover in Lewis County. It will also help the lawmakers and land-use planners in charge of regulating the environmental repercussions of development by providing them with relevant guidance; it will further underline the importance of their function within the research process. In order to more effectively assess and manage the modified hydrological regime in regions that face or are undergoing significant land-use changes, more research should be directed toward improving data accuracy and incorporating additional forecasting models.

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Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

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