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Review

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Special Issue
Constructed Green Areas as a Challenge for Spatial Planning at the Local and Regional Levels

Edited by
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https://doi.org/10.3390/land12030612

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Calculating the Environmental Impacts of Low-Impact Development Using Long-Term Hydrologic Impact Assessment: A Review of Model Applications

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Abstract: Low-impact development (LID) is a planning and design strategy that addresses water quality and quantity while providing co-benefits in the urban and suburban landscape. The Long-Term Hydrologic Impact Assessment (L-THIA) model estimates runoff and pollutant loadings using simple inputs of land use, soil type, and climatic data for the watershed-scale analysis of average annual runoff based on curve number analysis. Using Scopus, Web of Science, and Google Scholar, we screened 303 articles that included the search term "L-THIA", identifying 47 where L-THIA was used as the primary research method. After review, articles were categorized on the basis of the primary purpose of the use of L-THIA, including site screening, future scenarios and long-term impacts, site planning and design, economic impacts, model verification and calibration, and broader applications including policy development or flood mitigation. A growing body of research documents the use of L-THIA models across landscapes in applications such as the simulations of pollutant loadings for land use change scenarios and the evaluation of designs and cost-effectiveness. While the existing literature demonstrates that L-THIA models are a useful tool, future directions should include more innovative applications such as intentional community engagement and a focus on equity, climate change impacts, and the return on investment and performance of LID practices to address gaps in knowledge.

Keywords: L-THIA; low-impact development; performance modeling; green infrastructure; urbanization; runoff; pollutant loading

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Citation: Cai, Z.; Zhu, R.; Ruggiero, E.; Newman, G.; Horney, J.A. Calculating the Environmental Impacts of Low-Impact Development Using Long-Term Hydrologic Impact Assessment: A Review of Model Applications. *Land* **2023**, *12*, 612. https://doi.org/10.3390/land12030612

Academic Editors: Andrzej Greinert, Anna Bazan-Krzywoszańska, Katarzyna Tokarczyk-Dorociak, Sinan Tankut Gülhan and Eduarda Marques da Costa

Received: 20 January 2023
Revised: 2 March 2023
Accepted: 3 March 2023
Published: 4 March 2023

1. Introduction

Low-impact development (LID) has become the best practice in sustainable urban planning and design, as it reduces negative environmental impacts of development in growing cities. Strategies and techniques that increase the infiltration of stormwater, limit runoff, and protect water quality are particularly relevant for urbanized areas. However, limited space and altered hydrology require thoughtful planning and landscape designs to mitigate water quality and quantity impacts. Greening, green infrastructure (GI), and green stormwater management or, broadly, LID are design solutions that address water quality degradation and associated environmental impacts on a watershed scale while also addressing flood volumes on site. LID includes a variety of sustainable and nature-based solutions for stormwater management that are necessary to meet sustainable development goals and can be compared to conventional urban drainage systems to assess benefits ranging from environmental pollution to climate change reduction [1–3]. LID strategies include interventions such as street and parking area bioswales, pervious pavements and asphalts, stormwater retention and detention, green roofs, rainwater harvesting, and other methods of treating runoff at its source.

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The benefits of LID, including infiltration and evapotranspiration capability, have been well-documented [4], yet quantifying the impact on the site and watershed levels can be challenging. For example, planners might question the scale of LID implementation needed to reduce runoff volumes and pollutant loads to water bodies. Planners may also be required to show how a proposed design would demonstrate a return on investment. In new developments, where runoff reduction is necessary, planners also need to be able to quantify whether or not the performance of proposed LID would be adequate for stormwater management. Regardless of these challenges, the use of LID is recommended as a strategy for stormwater management that can improve water quality while adding ecological, economic, and social values [5]. Accordingly, there is an increasing need to demonstrate LID's efficacy and cost-effectiveness in various landscapes.

2. Model Presentation

One way to demonstrate the potential stormwater impacts associated with a design or plan is through the modeling of rainfall and runoff. The Long-Term Hydrologic Impact Assessment (L-THIA) model was developed in 1999 [6,7] to more easily calculate pollutant load with runoff during a simulated period. The L-THIA and Long-Term Hydrologic Impact Analysis–Low-Impact Development (L-THIA-LID) models, the latter of which is an enhanced version of the L-THIA model, are user-friendly and accessible online resources that characterize the impacts of LID practices on runoff, recharge, and pollutant loading [8]. The models calculate the average annual estimates on the basis of modified curve-number (CN) values for the type and size of land use change, soil type, and long-term climatic data. Equation 1 shows how these calculations are carried out.

Equation (1). Function of the Curve Number (CN) is calculated as:

$$\mathrm{S} = \frac{25{,}400}{CN} - 254 \tag{1}$$

Under the condition that precipitation, P(mm) > 0.2S, direct runoff depth, Q_h (mm) is estimated as:

$$Q_h = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2}$$

$$Q_h = 0 \; when \; P \; \leq 0.2S \tag{3}$$

The volume of runoff from an area is determined by:

$$Q_v = Q_h \times A \tag{4}$$

where Q_v is the volume of water; and the A is the area of interest.

Figure 1 demonstrates how the L-THIA and L-THIA-LID models estimate changes in recharge, runoff, and nonpoint-source pollution from past or proposed development. Outputs include runoff volume, runoff depth, and pollutant load. The calculators can also be used to assess the current runoff and pollutant conditions, to determine the impacts of recent development or urbanization, or to demonstrate the viability of a proposed design [9].

Although there are many published studies using the L-THIA and L-THIA-LID models to evaluate the performance of LID practices in reducing runoff and nonpoint-source (NPS) pollutants, the reason for this review is that we still lack a systematic understanding about their research methods, tools, and site-specific outcomes of the strategy in practice. There are reviews about storm runoff models, but these papers only mentioned the advantages and disadvantages of the L-THIA [10–14]. Further, these studies did not focus on the L-THIA model to examine its mechanism and application in the research, nor did they perform comparisons across studies, sites, and time. Therefore, our study aims to bridge these two knowledge gaps by conducting a review to identify articles where the main research method is the L-THIA model, synthesizing the findings and discussing potential extensions of the L-THIA model that are needed in light of increased risks from climate-mediated hazards and the inequitable distribution of physical and social vulnerability. This research also contributes to the existing literature around LID practice impact evaluation, stormwater runoff modeling, and environmental planning.

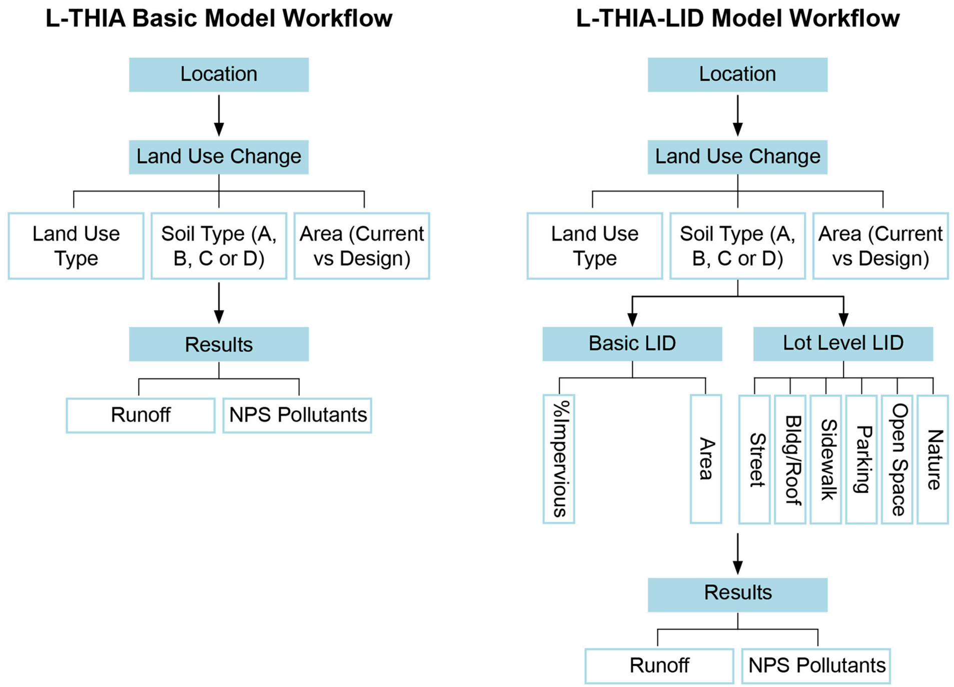

Figure 1. L-THIA and L-THIA-LID models.

3. Materials and Methods

The L-THIA model has been widely used by academic researchers to calculate runoff and NPS pollutants in various individual settings. The goal of this project was to categorize these papers into thematic areas in order to identify potential gaps and areas for future research and application. To document the ways in which researchers have globally applied the L-THIA model to LID practices, we conducted a systematic literature review across four phases: identification, screening, eligibility, and inclusion. First, we searched Scopus, Web of Science, and Google Scholar using the term "L-THIA", which returned 303 total records (Figure 2). Compared to the more traditional online academic databases, Google Scholar covers more types of documents (published peer-reviewed articles, gray literature including conference paper and dissertations), and thereby includes more articles compared to Scopus and Web of Science when using the same search criteria [15]. All articles were screened to remove duplicates, leaving 235 records. These 235 publications were screened by a trained graduate student for inclusion on the basis of containing the term "L-THIA" in the abstract, keywords, or full text, which resulted in 150 records. Lastly, we limited the remaining records to those using L-THIA as the major research method, which resulted in a total of 47 records, 20 from Scopus, 15 from Web of Science, and 12 from Google Scholar.

All 47 articles that used L-THIA as a major research method were annotated and inductively coded (i.e., themes emerge from the data and are not predetermined) using Microsoft Excel. Six themes emerged from the review and were used to create a framework to which descriptions of the papers were added. On the basis of these descriptions, papers were categorized according to their primary research question, including papers that focused on either water quantity (runoff depth and volume) or water quality, papers that simulated or processed future land use scenarios using either primary or secondary data prior to being input into the L-THIA model, papers that used L-THIA to evaluate LID practices across multiple sites, papers that focused on economic considerations such as cost and return on investment, papers that focused on two major model verification methods, their indicators, and the model's accuracy, and finally, papers that focused on broader impacts to urban planning policy and the integration potential on flood mitigation.

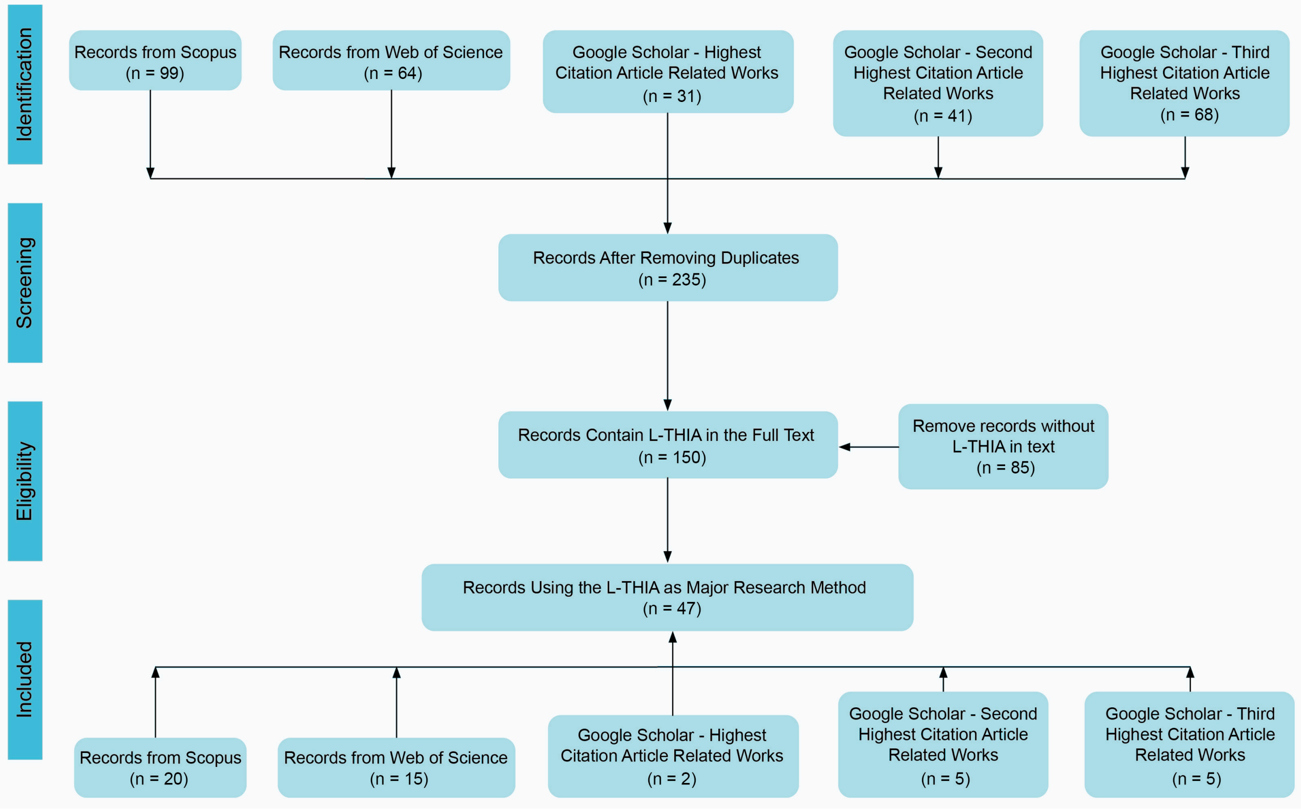

Figure 2. Process for reviewing published applications of the L-THIA and L-THIA-LID models.

4. Results

The 47 articles were reviewed and annotated for 15 categories of information: publication type, author names, year of publication, title, category of focus, journal name, Google Scholar citation total as of December 2022, impact factor from Web of Science as of 2021, impact factor from Scopus as of 2021, study location, site area in km^2, research questions, methodology (e.g., how the research used L-THIA, main findings, and limitations (Figure 3; Supplementary Table S1). Figure 2 shows detailed statistics for the recent studies used in the review. Papers were most frequently published in the journals *Water* (5 articles), *Environmental Management* (n = 5), *Journal of Environmental Management* (n = 5), and *Science of Total Environment* (n = 3), with Web of Science Impact Factors ranging from 1.188 (*Transactions of the ASABE*) to 8.071 (*Environmental and Pollution*). Scopus Impact Factors ranged from 0.083 (*Landscape Journal*) to 10.147 (*Science of the Total Environment*). Most of the study sites were located in the United States (23 of 44; 52.3%) and China (11 of 44; 25.0%). Papers were categorized into six research foci: site screening, future scenarios and long-term impact, site planning and design, economic impacts, model verification and calibration, and broader applications. Each category is discussed in detail below.

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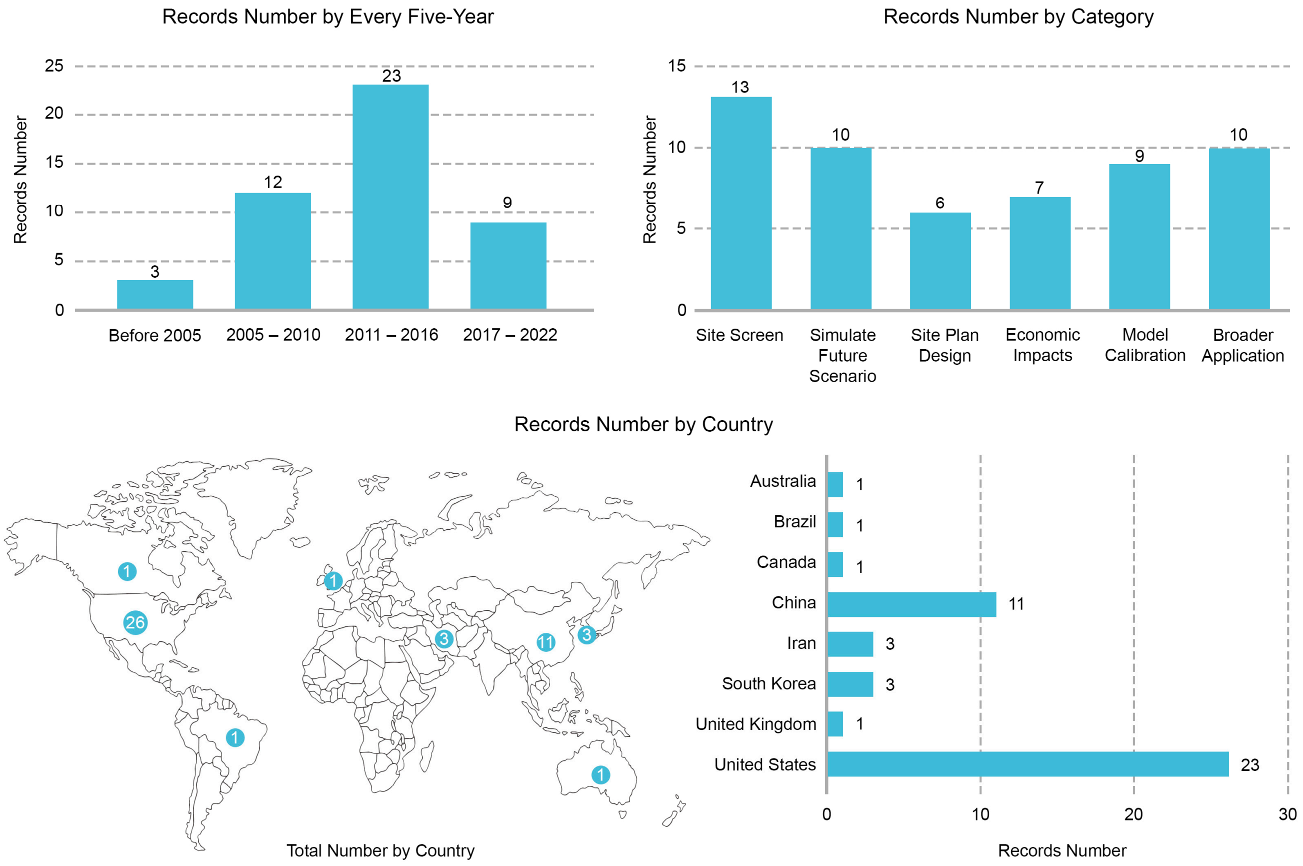

Figure 3. Descriptive results of 47 selected articles.

4.1. Site Screening for Urbanization and Watershed Impact

Of the 47 included articles, 13 (27.7%) focused on site screening [16,17]. Most contained similar background information, including the observation that increasing numbers of watersheds were experiencing less regulated impacts of urbanization attributable to global industrialization and rapid population growth. These papers all addressed the general research question of how land use change would impact runoff volume and NPS pollutant loads using the L-THIA model.

Although similar in approach, these site screening-focused papers were diverse in both geographic location and scale, with 6 of 13 located in China, 5 of 13 in the United States, and 1 each in Canada and Iran. Site areas ranged from 20 to 41,500 km^2 on the basis of the number of hydrological units but all were located in urbanized watersheds. The main methodology across all 13 articles was using the L-THIA model to examine the impacts of land use change on water quantity and quality. Similar types of data were processed as input parameters into the L-THIA model, including (1) 20-year land use change data from remote-sensing imagery, (2) soil types from the U.S. Geological Survey (USGS), and (3) historical precipitation data.

This research quantified the impacts of land use change on the environment in two ways: water quantity (e.g., annual runoff volume/depth) and water quality (e.g., total nitrogen (TN), total phosphorus (TP), and other NPS). In general, findings demonstrated that increases in imperviousness, such as residential or commercial development and loss of forest or agriculture land were the main reasons for water quantity increase and water quality decrease. Specifically, of the 5 articles that examined water quantity as a primary outcome, all found that urbanization increased the annual runoff volume/depth, but there was not a linear relationship between urbanization rates and runoff volume. For example, Bhaduri et al. found that the Little Eagle Creek watershed in Indiana experienced an 80% annual runoff volume increase with an 18% impervious area increase [18]. Yang et al.

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reported a 94% runoff increase with a 30.4% increase in imperviousness in Hanyang, Hubei, China [19], while Li and Wang reported a 70% runoff increase with a 27.3% increase in imperviousness in Dardenne Creek watershed in Missouri [20]. Zhang et al. reported a 58% runoff increase with a 52% increase in imperviousness in Dongguan, Guangdong, China [21]. Engel et al. reported increased water levels in Lake Maxinkuckee, Indiana of 0.01, 0.02, and 0.04 m linked to urbanization of 3%, 7%, and 15%, respectively [22].

The 9 articles that reported water quality analysis also observed nonlinear relationships between urbanization rates and NPS pollutant loads that were attributed to spatial–temporal changes in TN and TP associated with land use type, slope, and rainfall intensity. Most studies estimated the TN and TP loads in NPS since they are major elements produced by fertilizer, which could reflect agriculture land change [23]. For instance, Bhaduri et al. found a 15% decrease in nutrient loads due to the loss of agriculture land in Little Eagle Creek watershed in Indiana [18]. Similarly, Bai et al. reported a more than 50% decrease in TN and TP due to 44.9% agricultural land loss in Lugu Lake, Hubei, China [24]. Other studies linked changes in TN, TP, and NPS to imperviousness, industrialization, or residential development. Lim et al. reported 24% and 22% increase in TN and TP, respectively, with a 15% imperviousness increase in the Little Eagle Creek watershed in Indiana [25]. Yang et al. reported 40% and 43% increases in TN and TP due to increasing industrial land in Hanyang, Hubei, China [17], while Wilson and Weng reported that the combination of commercial, industrial, and transportation land uses generated the highest concentration of NPS in Lake Calumet watershed in the Greater Chicago area [26]. Zhang et al. determined that increases in residential land use generated the largest amounts of dissolved phosphorus, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) in Qingdao, Shandong, China [27]. Similarly, Li et al. reported increases in COD, suspended solids, and TP of 132%, 32.5%, and 38%, respectively, due to high population immigration rates in Shenzhen, China [28].

4.2. Simulating Future Scenarios and Long-Term Impact

Of the 47 articles (21.3%), 10 focused on how to use the L-THIA or L-THIA-LID model to estimate the impact of future land use and development through scenarios. These studies used similar data to those included in the site screening papers. However, the major difference in these studies were the types and sources of land use data. Compared to the site screening studies that used data on land use extracted from historical remote-sensing imagery, the future scenario simulation studies obtained predicted land use maps from either secondary data sources (e.g., government) or primary data sources. Primary data sources were predicted by land use change models, such as the Land Transformation Model (LTM), the Land Use Evolution and Impact Assessment Model (LEAM), or the Conversion of Land Use and its Effects (CLUE-S).

Of the 10 studies, 5 obtained future land use data from secondary data sources, including urban planning land use maps. All studies determined that future runoff volumes and NPS loads would increase if development followed these land use maps without sufficient LID practices regardless of the site scale. For example, Aprigio and Brandao found that expanding residential areas was the major cause for increasing runoff and pollutants, and by 2025, the study area in Sao Paulo, Brazil would experience 67%, 4.47%, and 10.86% more in runoff volume, TN, and TP, respectively [29]. Zhu et al. predicted that, by 2045, Houston, Texas super neighborhoods would experience 58.68% more runoff and 55% more NPS pollutant loads due to rapid industrialization [30]. In a scenario based in the Qinhuai River watershed in Jangsu, China, Du and Hu showed that, as imperviousness increased, annual runoff also increased. This increase would be linear as long the imperviousness growth rate was below 9%; otherwise, annual runoff would increase at greater rates [31]. LID could change the outcome of these scenarios. Eaton combined planned development with LID practices, predicting a runoff reduction in single land use of 35–55% and a runoff reduction of 23–42% for the entire Alley Creek watershed in New York City [32]. Similarly, Newman et al. predicted that by the year 2028, the Wilmington, Delaware area would

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experience 9.66% reductions in runoff volume and 29.93% reductions in NPS pollutants loads due to the planned use of LID practices [33].

The 5 studies using primary data to simulate future land use utilized LTM (n = 1), LEAM (n = 2), and CLUE-S (n = 2). All confirmed the direction of findings from studies using municipal land use maps. Tang et al. employed LTM in land use prediction for the Muskegon River watershed in Lake Michigan, forecasting land use change over a large region relying on Geographic Information System (GIS) and artificial neural networks routines (ANNs). They found that urbanization would significantly increase runoff volume, TN, and TP; all were highly correlated with development rates [34]. Wang et al. used LEAM to simulate 2030 land use maps in base, low, and high economic growth scenarios. They found that the mean annual TN would increase 0.21%, 0.13%, and 0.14%, respectively, and the runoff volume would increase most in the high-economic growth scenario [35]. Choi also adopted LEAM to simulate a 2030 land use map in base and high population growth scenario in Richland Creek Basin, Texas, showing annual runoff volumes would increase 7% and 4% respectively, while TN and TP would show little change [36]. Since 2016, several papers have used the CLUE-S prediction model, since it includes more variables for land use prediction, with the maximum at 13, than those of LTM or LEAM. Zare et al. used land use maps from 1986, 2000, and 2011 to predict the 2030 land use map in CLUE-S, observing a 54% increase in runoff volume in the Kasilian watershed, Iran [37]. In a 2020 study by Ju et al. LID scenarios were included in CLUE-S before input into the L-THIA-LID model, which suggested runoff volume could be reduced by 78 million cubic meters compared to baseline [38]. While not included here, machine learning combined with hydraulic and other data can also be used to predict future scenarios of pollution and sedimentation change [39]. However, we focused on the L-THIA model since it requires relatively more basic primary and secondary data to estimate runoff.

4.3. Modeling of LID in Site Planning and Design

Of the 47 articles, 6 examined how to use the L-THIA-LID model to evaluate the performance of LID practices as related to runoff and NPS pollutants reduction [40]. From a data preparation perspective, these papers added an additional dataset to the three used in the papers discussed above, which is the percentage of LID practices in a given land use type. All of these studies confirmed that LID practice was effective in reducing runoff and NPS pollutant loads, but the number or percentage of LID practices was not statistically related to overall effectiveness. Moreover, these papers did not agree on which LID or which combination of LID practices performed best due to location sensitivity and budget limitations.

Tang et al. found that minimizing imperviousness between 1978 and 2040 would reduce runoff by 12.3% in a non-sprawl scenario and by 20.5% in a sprawl scenario [41]. More specifically, Ahiablame et al. reported the most effective LID practice for reducing runoff volume was porous pavement (52% reduction), green roofs (11% reduction), permeable patios (10% reduction), rain barrels and cisterns (6% reduction), and bioretention systems (2% reduction) [41]. Overall, the most effective and lowest cost combinations of LID practices for reducing both runoff and pollutants were a 50% rain barrel/cistern scenario and a 50% porous pavement scenario [42]. Across 13 LID scenarios, Martin et al. reported reductions in runoff volume of 2 to 24%, with 50% porous pavement being the most effective scenario [43]. In terms of cost-effectiveness, Li et al. found that grass swales, rain barrels, dry ponds, and porous pavement would be the most cost-effective solutions in runoff reduction, while additional wet ponds would be the most cost-effective for NPS pollution reduction [44]. In a later study, Li et al. also found grass swales to be a highly cost-effective practice. However, implementation efficiency was limited due to the small area of suitability [45]. This same study found that annual runoff volumes could be decreased by 47% with the combination of rain cisterns and permeable pavements [45].

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4.4. Economic Considerations

Six of the studies discussed above integrated economic considerations into site planning and design. When assessing the cost of LID practices, they included (1) initial construction cost, (2) maintenance cost, (3) interest rates, and (4) LID practice design life across 20-years in all studies [45]. The most cost-effective LID practices varied from place to place. The shortest return on investment period was 3 years.

For example, in the Crooked Creek watershed in Indiana, Liu, Bralts, and Engel found that a 25% grass strip was the most cost-effective LID practice [46]. Depending on the types of LID practices implemented and the level of adoption, Lafayette, Indiana neighborhoods could realize a 10 to 70% reduction in annual runoff volumes over return periods as low as 3 years with investments ranging from just USD 3 to USD 600 [47]. The most cost-effective practices were rain barrels, followed by cisterns, bioretention, permeable pavement, and green roofs [47]. Other reductions require much larger investments. For example, a study by Liu et al. focused on the Trail Creek watershed in Indiana, a USD 2.1 million investment in green infrastructure would be needed to reduce NPS by 10.8% by 2050 [48]. Lastly, a study by Chen et al. in the Darst sewershed in Illinois showed that combined LID practices tended to be more cost-effective than individual ones. However, simply adding more LID practices did not necessarily increase cost-effectiveness [49].

4.5. Model Verification and Methods for Calibration

Of the 47 studies, 10 included ways to verify or calibrate the L-THIA model to enhance the credibility of model outputs [50–53]. For example, verification studies compared outputs from the L-THIA model to water samples collected in the field to verify TN and TP concentrations. For calibration, studies adjusted the CN rather than using the default CN from the USGS soil types. On the basis of these studies' findings, the L-THIA model demonstrated good credibility in water quality (TN and TP concentration) and water quantity (runoff depth/volume), with all reported R^2 greater than 0.75, and Nash–Sutcliffe efficiency (NSE) greater than 0.65. For example, Jeon, Lim, and Engel tested multiple methods of regional calibration for the soil conservation service curve number (SCS-CN) parameters used in L-THIA after determining that the parameters lacked regional specificity, which could lead to errors [54]. Calibration methods for parameters included average; average weighted by land use, hydrologic soil group, or a combination of the two; spatial nearest neighbor; inverse distance weighted average; and global calibration. All methods produced statistically different results from those of the default SCS-CN, and ultimately, the global calibration method was recommended.

Ryu et al. enhanced the L-THIA model's ability to estimate runoff during low flows by including precipitation data and a lag time of the direct runoff component in the L-THIA asymptotic curve number (ACN) model [55]. By pairing the L-THIA model with water quality simulation model QUAL2E, stream water quality can be predicted at the watershed scale to enhance pollutant load estimation. This combined model was applied to two watersheds in South Korea where simulated data were compared to the observed data for water quality. Results showed that the model accurately reflected water quality, streamflow, and pollutant loads, though the authors called for more input values to be included in future models [56]. In a simulation of hydrologic and water quality impacts of land use changes in an Indiana watershed, Lim et al. calibrated the L-THIA model through an automated program with millions of combinations of land use and hydrologic soil group [25]. This calibration of input parameters improved model accuracy for both direct runoff and pollutant estimation. Therefore, the authors recommend that the L-THIA model be calibrated and validated prior to its use in any project to produce more accurate results.

Liu et al. modeled sensitivity and uncertainty to identify key variables impacting model performance (sensitivity) and to gain an understanding of the model's precision (uncertainty) using L-THIA-LID 2.1 [57]. The methods employed include Sobol's global sensitivity analysis method (for sensitivity) and the bootstrap method (for uncertainty). In cases where sites were evaluated without LID implementation, CN was the most sensitive variable requiring calibration before model use. In cases where LID was implemented, Ratio_r (practice outflow runoff volume/inflow runoff volume) was the most sensitive variable requiring calibration. Bounds for output uncertainty were larger without LID; observed data were well within bounds for example projects, indicating good precision [57].

A study in the Zayandehrud Basin, Iran utilized the L-THIA model to assess the impacts of land use change over 18 years with 30 years of precipitation data [58]. Runoff volumes and depth increased with a conversion of pasture and forest to residential areas, bare land, and agricultural land. Model estimates for average annual direct runoff were +154%, while observed annual runoff was +147%, showing that the model produced results close to field data. This study supports the accuracy of model data when data are not available. The verification of the L-THIA model with field data could indicate the accuracy of the results, while calibration can increase accuracy, and both increase the reliability of modeled results. This can be particularly helpful for planning future scenarios.

4.6. Broader Applications

Of the 47 studies, 10 discussed the potential for L-THIA results to be combined with LID performance evaluation to support urban planning policy and flood mitigation globally. These studies, published between 2002 and 2021, are at multiple scales, from community to regional watershed. For example, some research used the L-THIA model to justify environmental protection policies related to coastal development and ecological planning. Baginska et al. adopted the L-THIA model to compare runoff volume and NPS change before and after coastal area development in Tweed Catchment, Australia, and integrated the outputs with the Coastal Eutrophication Risk Assessment Tool (CERAT) to support the coastal development regulations [59]. Similarly, Ju et al. evaluated the performance of an ecological redline policy across three scenarios to promote the implementation of the ecological planning in the Beijing–Tianjin–Hebei region, China [38].

L-THIA results were used for assessing runoff intensity, predicting flood vulnerability, and supporting investments in flood mitigation during different rainfall intensity scenarios by using rainfall events of 1-, 5-, 10-, 50-, and 100-year return periods for CN in the Lagoon watershed in Indiana [60]. In addition to setting up scenarios regarding rainfall events in the L-THIA, Liu et al. also modeled with NPS levels in the future land use development impact analysis, simulating the NPS reduction in 2050 at the levels of 0%, 10%, 15%, 25%, and 50% to 2001 [46]. By combining the runoff volumes generated by the L-THIA with digital elevation models (DEMs), You et al. calculated the runoff direction [61]. Using L-THIA, Perry and Nawaz found that more flood-vulnerable communities would experience 12% more runoff volume in Leeds, United Kingdom [62]. Similarly, in Houston, Texas, Zhu et al. found that the most flood-vulnerable communities would experience more runoff volume and NPS loads in flooding events [9]. In addition to runoff, Conrad used the L-THIA to identify the influence of rainfall intensity on flood events. As rainfall intensity increased from 1 inch to 6 inches, there would be more, and more vulnerable, people impacted by flooding, more inundated households, and more impacted businesses and employees. However, as rainfall intensity would increase, the median household income of those affected would decrease from USD 64,000 to USD 43,000, suggesting that people with less income may be increasingly vulnerable to flooding as precipitation events intensify [63].

5. Conclusions

The L-THIA and related models reviewed here have been used for several decades in a wide range of applications including site screening, future scenarios and long-term impact, site planning and design, economic impacts, model verification and calibration, and broader applications such as policy development or flood mitigation. Findings generated from the use of L-THIA and L-THIA-LID can be used for decision analysis or synthesis of planned or potential development impacts. In addition, findings generated through research and application of L-THIA have been utilized by policymakers and planners

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globally to raise awareness of the potential long-term impacts of urbanization and land use change that can occur due to urban sprawl [41,61,64]. L-THIA was also used to inform planning by quantifying the environmental harms of land use change, particularly as they relate to water quality and quantity impacts [26,46,49].

L-THIA models have not adequately engaged communities and vulnerable populations subject to the greatest negative impacts of land use change, which are currently being compounded by climate change and natural hazard vulnerability. Community engagement is one essential element of building authentic partnerships to hear from socially and physically vulnerable populations who have borne the brunt of the impacts for many years from more frequent and severe disasters due to disinvestment in gray infrastructure and a lack of power that have made it impossible for sustainable development and environmental justice to coexist. The broader implications of these oversights include greater inequities in exposure and long-term health impacts associated with exposure to flooding and other hazards. However, there is little indication that this type of engagement and research translation can be achieved until more evidence is generated through the application of L-THIA model data in future development.

There are potentially under-recognized benefits of the use of the L-THIA model, the importance of which should be highlighted as part of future research going forward. There is potential to use the model to increase community engagement in siting, design, and investment decisions. The basic L-THIA model can generate recharge, runoff, and NPS pollution data on the impact of past or future land use changes using relatively simple inputs such as current land use, size, and soil type. These results can also be combined with case studies and other data to inform urban planning decisions, gain support for investments in urban renewal, and increase the transparency of planned changes [65,66]. Building on a long tradition of focusing on the benefits of community engagement to more traditional hazard planning [67], a stronger focus on the use of L-THIA as a tool for community-informed planning and citizen-science is needed, along with new avenues for research translation of L-THIA generated data to both local governments and community residents [63,68]. This type of engagement is critical in the face of greatly increased risks from urban flooding resulting from urbanization, increases in impervious surfaces and soil compaction, impacts from more frequent and severe hydrological disasters like tropical storms and hurricanes, and climate change [33,69,70].

Another potential benefit of the implementation of the L-THIA is the ability to identify physically and socially vulnerable sub-populations where targeted resilience interventions are needed [63,71,72]. Both exposures to pollutants and access to protective factors like LID are inequitably distributed across race, ethnicity, socioeconomic status, and other vital conditions that provide the framework for planning as well as for equitable recovery and resilience [73]. Vacancy, environmental degradation, legacy contamination, and long-term disinvestment in the stormwater and other infrastructures of majority–minority and environmental justice communities mean that these communities have the potential to realize substantial reductions in both runoff volume and pollution with relatively modest investments in LID and other greening interventions [72]. In the future, as these communities face the disproportionate impacts of climate change, L-THIA could also account for these types of dynamic land use changes for better understanding of hydrologic processes [74]. However, these potentials must be carefully balanced through engagement with community concerns about green gentrification that can result when environmental clean-up leads to high-end residential and commercial development while pushing out established communities, continued industrial uses, and blue-collar employment [74].

As a tool for modeling runoff and pollutant loading, the L-THIA simulated accurate results, as verified in testing against field observations and data. Through applications to site screening, site design, future land use planning, and determining optimal LID solutions on the basis of costs and efficiency, researchers have demonstrated the L-THIA model's applicability for the design of developing urban and suburban areas. In the future, there is an opportunity to expand upon the broader applications of modeling climate change

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impacts and flood mitigation scenarios and to expand the application of the model to new geographic locations such as Russia and Africa, where we identified no prior studies. The model's inability to capture granularity is a limitation, especially when assessing a variety of performance outcomes of LID practices. However, future directions could include modeling LID under different scenarios that account for relevant changes in the landscape such as climate-mediated hazards (e.g., sea level rise or increased precipitation and storm events) as well as differing levels of installation success and maintenance over time.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12030612/s1, Table S1. Annotated bibliography of 47 selected L-THIA articles.

Author Contributions: Conceptualization, G.N. and J.A.H.; methodology, G.N., Z.C. and R.Z.; formal analysis, Z.C. and R.Z.; resources, G.N. and J.A.H.; writing—original draft preparation, Z.C., R.Z. and E.R.; writing—review and editing, G.N. and J.A.H.; supervision, G.N. and J.A.H.; project administration, G.N. and J.A.H.; funding acquisition, G.N. and J.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Fish and Wildlife Foundation under Grant 65335.

Data Availability Statement: All data related to the articles reviewed are available in Supplementary Table S1.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

LID	Low-impact development
L-THIA	Long-Term Hydrologic Impact Assessment
GI	green infrastructure
L-THIA-LID	Long-Term Hydrologic Impact Analysis–Low-Impact Development
CN	curve-number
NPS	nonpoint-source
TN	total nitrogen
TP	total phosphorus
BOD	biochemical oxygen demand
COD	chemical oxygen demand
LTM	Land Transformation Model
LEAM	Land Use Evolution and Impact Assessment Model
CLUE-S	Conversion of Land Use and its Effects
GIS	Geographic Information System
ANN	artificial neural networks
USD	U.S. Dollars
NSE	Nash–Sutcliffe efficiency
SCS-CN	soil conservation service curve number
CAN	asymptotic curve number
CERAT	Coastal Eutrophication Risk Assessment Tool
DEM	digital elevation model

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