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RESEARCH ARTICLE

Effects of Future Land Use Variability on Nutrient Loads in a Fast-Urbanizing Landscape

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ABSTRACT

Urbanization, driven by population growth, alters watershed hydrology and nutrient runoff. However, the complex interplay between urbanization and nutrients in regional watersheds remains an open question. This study assessed how urbanization affects streamflow, total nitrogen (TN), and total phosphorus (TP) loads in six diverse Florida watersheds covering an area of 10,600 km^2. This was carried out by introducing 2070 land use/land cover (LULC) projections to a watershed hydrology/water quality model. We investigated how different levels of urban density, as a proxy for urbanization patterns, affect streamflow and nutrient variability. Results indicate that urban land could increase from 14% to 27% in 2070. This expansion could lead to monthly streamflow increases of 0%–36%, based on watershed and urbanization patterns. Future TP loads could change by −8% to +140%, with decreases attributed to LULC transitions from high-use fertilizer agriculture to low/medium density residential classes. Projected TN loads are more consistent, with simulated changes of −1% to +26%. Among LULC transitions, the largest increases in TP and TN are caused by potential urbanization of freshwater wetlands. This study provides knowledge relevant to regions undergoing similar urbanization trends, enabling managers to make better land development plans with water quality considerations. It also contributes a detailed modeling framework that can be adopted even with the use of different LULC datasets and software.

1 | Introduction

The global population is expected to continue increasing for the foreseeable future, leading to a transition from natural and agricultural lands to urban centers and sprawl as the demand for housing increases (The World Bank 2022). Gao and O'Neill (2020) projected that the amount of global urban land could increase by 1.8–5.9 times by 2100 in comparison to 2000, with these increases distributed across all world regions, not only developing countries. As these global trends in urbanization unfold, the State of Florida in the United States serves as a prominent example of this shift. With a 10-fold population increase in less than 80 years (from 2.4 million in 1946 to over 22 million in 2022; US Census Bureau 2022), Florida exemplifies the rapid urban growth seen worldwide. Though Florida is already the US's third most populous state, urbanization trends are expected to continue, with a population projection of 27 million people by 2045 and a projected increase in developed land from 18% in the present to 34% in 2070 (the Florida Department of Agriculture and Consumer Services (FDACS) et al. 2016). This land use/

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Summary

- Urbanization in Central Florida could significantly alter phosphorus and nitrogen loads by 2070.

land cover (LULC) transition is expected to have a significant impact on the state's water resources, which have already experienced a rapid transition from a predominantly natural system to a hydrologically managed system over the past century (Lecher 2021; Rains et al. 2023). These landscape transitions—in addition to changes in the use of fertilizers, septic tanks, and several other practices affecting water nutrients—have caused significant contemporary alterations to the natural transport of nitrogen and phosphorus through the Florida landscape (Carey et al. 2011; Nagy et al. 2012; Khare et al. 2012; Tarabih and Arias 2021).

Florida is not an isolated case, as research in other regions globally has demonstrated that urbanization alters surface water discharge and nutrient loads as more impervious surfaces are added (McGrane 2016). For instance, Wickham et al. (2008) compiled published data on total phosphorus (TP) and total nitrogen (TN) yields from various watersheds, concluding that TN loads tended to decrease, while TP loads tended to increase in most of the watersheds. Moreover, a study in South Australia found that flows increased by 26.9% compared to the baseline scenario, with a corresponding 20% increase in impervious area, resulting in a TP load increase of 44%, while TN load decreased annually but was higher in the wet season (Nguyen et al. 2019). Another study suggested that urbanization in Southern Alabama was expected to decrease TN loads due to reduced croplands, while TP was expected to increase in fall and winter (Wang and Kalin 2018). A larger scope study, looking at multiple watersheds in Europe, also found reductions in both nitrate-nitrogen and TP caused by urbanization of croplands (Wade et al. 2022). Studies have also found that urban areas tend to have higher concentrations of TP compared to rural areas, attributed to increased phosphorus deposition in developed areas due to pesticides, detergents, etc. (Fang et al. 2019; Zhao and Xia 2012). For instance, using a hydrological/nutrient transport model in Southeast Asia's Mekong Basin, urbanization of vegetated land led to a sixfold increase in TP and TN loads compared to transitions into cropland (Yoshimura et al. 2009). Studies on the combined effects of LULC and climate change have revealed that, while climate predominantly influences TN and TP load changes, LULC changes also play a significant role (Alamdari et al. 2022; Li et al. 2022). In fact, research across multiple watersheds documented that the effect of urbanization on nutrients could be larger than the effect of climate change (Wade et al. 2022).

Although previous studies have investigated the impacts of LULC change on water resources, there is limited research exploring the variability in predicted streamflow and nutrient loads resulting from LULC change. For instance, a study in the Brazilian Amazon examined the uncertainty caused by LULC change and global circulation models, with three different LULC scenarios based on possible deforestation rates (Farinosi et al. 2019). Moreover, Shrestha et al. (2017) demonstrated the vast uncertainty in streamflow and sediment projections resulting from the transition from forest to agriculture in Southeast Asia. In Florida, recent research found that increased rainfall magnitudes could result in climate change augmenting watershed nutrient loads into Lake Okeechobee (Song et al. 2023). Other research conducted elsewhere in Florida found that LULC change could lead to an increase in nutrient concentrations and loads, sediment, and bacterial concentrations (Nagy et al. 2012). Yet, a study that examined the effects of land use changes in the Alafia and Hillsborough River watersheds in Florida suggested that regulatory efforts, such as the Clean Water Act and improvements in phosphate mining practices, may mitigate the impacts of land use changes on water quality (Khare et al. 2012). Despite these past studies, there is still a need for research linking the effects of future urbanization on water quality and how differences in urbanization projections may lead to variability in future water quantity and quality estimates.

In this study, we aim to fill this scientific gap by investigating the potential effects of plausible future LULC transitions on the magnitude and variability of streamflow and nutrient loads across six diverse watersheds. Each watershed was analyzed independently, using a calibrated/validated surface water quantity/quality model representing daily climatological drivers for over two contemporary decades. This study focused on the effects of LULC change only, so that future climate change as affected by global warming was not evaluated. We simulated two LULC scenarios: a contemporary scenario (circa 2016) and a plausible future scenario (2070). We also investigated how different levels of future urban density could affect the variability in streamflow and nutrient load predictions, and how transitions from specific LULC classes to urban lands contributed to overall nutrient load changes. The findings from this study provide critical, actionable insights for water resource managers and policymakers in Florida and similar regions. By detailing the implications of alternative urbanization patterns, our research informs strategies to mitigate nutrient pollution, improve water quality, and sustainably manage water resources amid anticipated LULC transitions. These insights can guide proactive decision-making to ensure long-term ecological and hydrological resilience.

2 | Methodology

2.1 | Study Area

The study area is in South-Central Florida (United States), covering an area of 10,600 km^2 in 11 counties and consisting of six watersheds: Fisheating Creek, Indian Prairie, Upper Kissimmee, Lower Kissimmee, Lake Istokpoga, and Taylor Creek–Nubbin Slough (herein referred as Taylor Creek; Figure 1). These watersheds, characterized by a relative combination of LULC that varies by each watershed (Tarabih et al. 2024), drain into Lake Okeechobee, Florida's largest, playing a crucial role in the regional water system. Plots depicting streamflow, hydrology, nutrient loads, and climatic conditions of each watershed are provided in Figures S1–S5. This region has experienced considerable LULC transitions recently—primarily due to residential development—and further urbanization is expected in coming decades, as illustrated in Figure 1. Historical TP load generation in this region has been primarily linked to agricultural activities

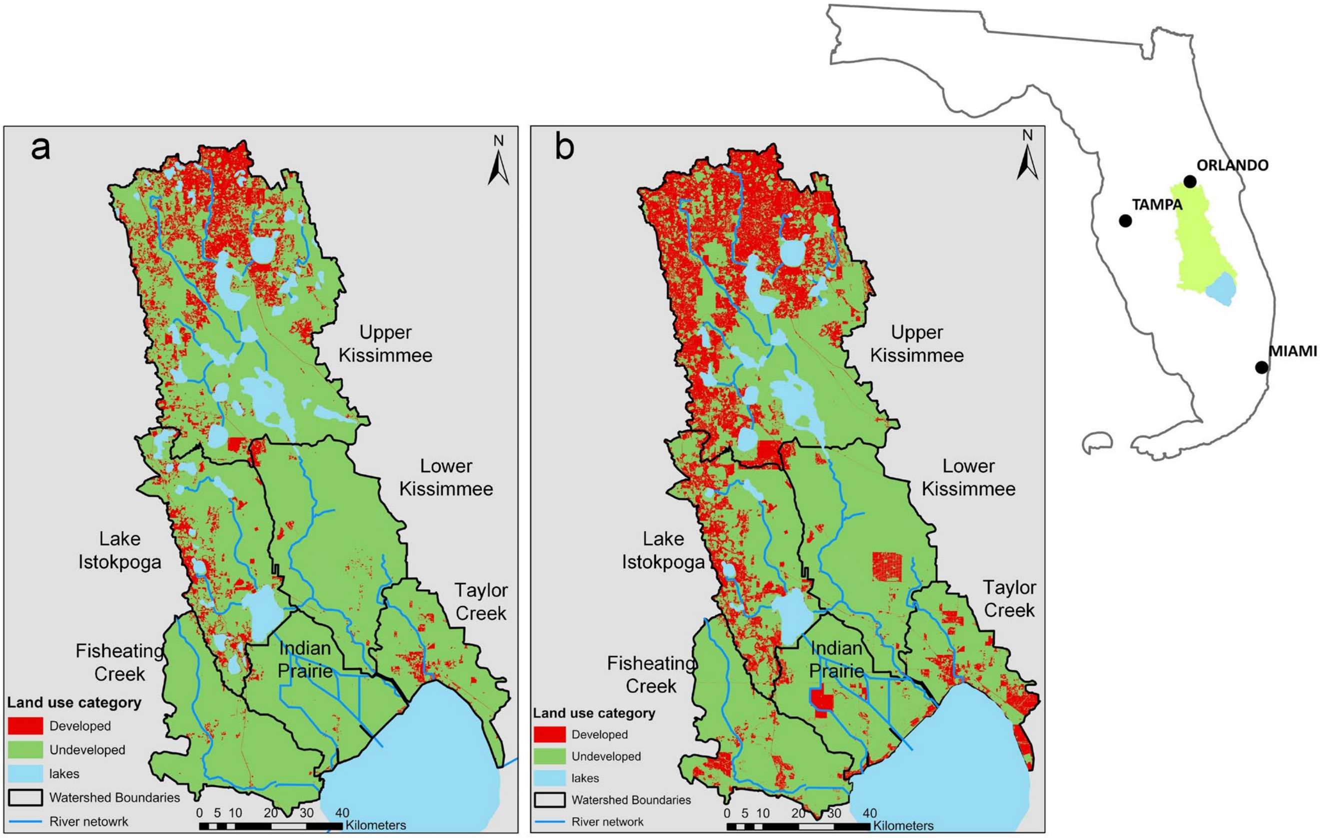

FIGURE 1 | Map of the study watersheds illustrating (a) existing developed and undeveloped Land Use/Land Cover (LULC) vs. (b) 2070 developed and undeveloped LULC.

(Boggess et al. 1995). TN loads have also been primarily linked to agricultural activities, though atmospheric deposition may also play an important role (Ma et al. 2020). TP net imports from different residential land uses were estimated to range between 8.2 and 22.7 kg/ha compared to a range of 3.4–12.8 for dominant agricultural lands (He et al. 2014).

2.2 | Hydrological and Water Quality Modeling

The Watershed Assessment Model (WAM; Soil and Water Engineering Technology, Gainesville, Florida) was selected as the primary modeling tool for this study due to its superior ability to accurately characterize the unique surface and shallow groundwater hydrologic characteristics of Florida, as well as its long history of development and publications in the region (Chebud et al. 2011; Corrales et al. 2014, 2017; He et al. 2014; Khare et al. 2019, 2021; Song et al. 2023; Tarabih et al. 2024). WAM simulates water and constituents in three phases: (1) Source cell simulation where land use, soil, rainfall, and wastewater service areas for each cell in the watershed are overlayed to create multiple combinations among these inputs. (2) Simulation of daily surface and groundwater flows and constituent concentrations leaving every grid cell, where runoff flow and constituents are routed through the landscape to the closest stream by applying a unit hydrograph to effectively distribute rainfall uniformly over a watershed and deliver water to the associated outflow reach. (3) Stream routing that collects all adjacent flows to each individual stream and routes the flow hydraulically through the stream network using a modified linear reservoir routing technique for solving the uniform channel flow equation (Manning's; Chow 1959). In WAM, one of three field-scale models is selected based on the LULC and soil characteristics of each cell: the Everglades Agricultural Area Model (EAAMOD), the Groundwater Loading Effects of Agricultural Management Systems model (GLEAMS), and a "Special Case" model (Bottcher et al. 2012; Soil and Water Engineering and Technology Inc. 2015). These models simulate daily runoff and nutrient loads at the source level. EAAMOD is the most widely used model in the Lake Okeechobee watershed and is designed to simulate processes influencing soluble and suspended phosphorus (P) levels, allowing for the calculation of P mass balance within each cell. The EAAMOD includes a simple P mass balance module that accounts for various P pools and transport processes. These include P inputs from rainfall, fertilization, and irrigation; P uptake by crops; vertical movement with water (downward through leaching and upward via evapotranspiration); mineralization of organic P; horizontal P transport with surface flow; and partitioning of P into soluble, adsorbed, and suspended forms. Water quality constituents are attenuated overland and in-stream using Equations (1) and (2), respectively. Outputs include streamflow and TP and TN loads at the reach level. Further details about WAM are found in previous technical publications that introduced the model (Bottcher et al. 2012; Khare et al. 2019).

$$C = \left(C_0 - C_b\right) * e^{\left(-a*\left(q^{-b}\right)*d\right)} + C_b \quad (1)$$

$$C = \left(C_0 - C_b\right) * e^{\left(-a * \frac{\tau}{R}\right)} + C_b \quad (2)$$

Where C indicates the concentration reaching the stream (ppm), C_0 represents the concentration exiting the source cell (ppm), C_b is the background concentration (ppm), a and b represent attenuation parameters, q is the flow rate leaving the source cell ($m^3 s^{-1} ha^{-1}$), d indicates the flow distance (m), τ indicates time interval, and R is hydraulic radius of stream.

WAM determines the characteristics of the source cells throughout the watershed based on LULC and soil characteristics to simulate the hydrology and chemical processes within each unique source cell. The LULC parameterization is extensive and includes processes that influence the water balance and nutrient load. LULC-based parameters can be divided into two sections: (1) a management calendar that includes parameter types that change temporally over the simulation period and (2) static parameters that will not change over the simulation period and are applied during LULC post-processing. Management parameters include irrigation, fertilizer application, animal population, plant uptake, harvest, etc. Post-processing parameters include nutrient fractioning, retention, remediation factors, etc. WAM has over 60 predefined LULC sub-categories that have been parameterized to represent over 360 different classes from the Florida Land Use, Land Cover Classification System (FLUCCS). WAM utilizes a dynamic classification scale where certain land use types are aggregated into a representative class in WAM that can parameterize all features within the aggregated group. To account for historical hydroclimatological variability, simulation periods included daily rainfall and temperature data from 1990 to 2018, inclusive of a 5-year warm-up period. Interannual variability was accounted for when reporting the spread in magnitudes of streamflow and nutrient loads, although analyzing temporal patterns during specific periods of time was not part of the scope of the study. The model simulations were calibrated/validated against monthly streamflow and nutrient observations at the outlets of each of the six watersheds. The calibration period ranged from 1995 to 2006, while the validation period ranged from 2006 to 2018. Performance evaluation metrics of the model included R^2, Nash Sutcliffe efficiency coefficient (NS), and Percent Bias (PBIAS). Two pairs of the watersheds are directly hydrologically connected (upper/lower Kissimmee and Indian Prairie/Lake Istokpoga), but to avoid compounding LULC effects, each watershed was simulated in isolation, with upstream boundary conditions from historical observations. Though simulations were computed at the daily scale, we summarize and describe results in this paper at the monthly scale.

2.3 | Data Sources

The modeling framework used in this study demands various spatially explicit data, such as topography, soil data, and LULC, along with time series data incorporating rainfall, water flow, and nutrients. Topographic data, essential for determining flow directions and distances to hydrologic features, were obtained from the South Florida Water Management District (SFWMD). This dataset consists of a continuous digital elevation map with 15 m × 15 m grid cells, which covers the entire study area. During the calculation of grid cell to stream distances, the topography data were resampled to one hectare, which is the typical grid cell size in WAM, to improve scenario run speeds given the large area of the watersheds. Soil characteristics data affecting hydrologic and water quality processes (e.g., soil texture, permeability, etc.) were obtained from the U.S. Department of Agriculture, Natural Resource Conservation Service published (SSURGO) data for 2013–2015. Baseline LULC information, crucial for defining source cell characteristics, was derived from a composite of the best-available data as of November 2016. This dataset includes 170 LULC classes for this region, categorized based on FLUCCS. Daily rainfall data came from 35 gauges spread across the entire watershed and were obtained using SFWMD's data portal (https://www.sfwmd.gov/science-data/dbhydro). We used Thiessen Polygons to create rain zones around these rainfall monitoring stations. Daily water flow data, used for boundary conditions and hydrologic calibration and validation purposes, were also gathered from the SFWMD's data portal. TP and TN were collected, processed, and curated by the SFWMD on a bi-weekly basis from various water quality sampling sites. Only data that passed SFWMD's QA/QC protocols were used. These data were also gathered from the SFWMD's data portal. These nutrient data were used for boundary conditions, as well as nutrient calibration and validation purposes.

The existing nutrient "Best Management Practices" (BMPs) data were obtained from the Florida Department of Agriculture and Consumer Services (FDACS), representing projects implemented in the study watersheds by the FDACS BMP program as of 2016. Urban BMPs currently implemented in Lake Okeechobee watershed include stormwater structural retention and detention strategies and spray fields among others. Meanwhile, agricultural BMPs include water retention, fertilizer management, animal density management, and drainage/water control structure BMPs among others. WAM simulates each BMP by parameterizing the associated LULC based on the BMP's characteristics; for instance, retention/detention ponds are simulated such that surface runoff is routed to and through the pond, maintaining a comprehensive water balance that accounts for an allowance for percolation to groundwater, rainfall, and evaporation. Besides, attenuation coefficients are adjusted properly to consider the flow to groundwater, which is influenced by the surface water flow passing through the retention/detention pond. However, for BMPs that cannot be simulated mechanistically such as fencing, and edge of the field chemical treatment, a user-defined nutrient reduction percentage is applied at the source cell. By utilizing these data sources, we aim to develop a comprehensive and accurate representation of the study area and the potential impacts of future LULC transitions on water quality and nutrient loads in the study watersheds. However, this study did not look at the effects of further nutrient BMP deployment, which is something that another study has recently analyzed (Tarabih et al. 2024).

2.4 | Land Use Land Cover (LULC) Geoprocessing

To evaluate the potential impacts of Florida's projected population growth, the Florida Department of Agriculture and Consumer Services (FDACS), the University of Florida's Geoplan Center, and the organization 1000 Friends of Florida developed the Florida 2070 (FL 2070) study, which anticipated LULC changes by 2070. That study outlined two scenarios:

Trend 2070, which assumes the projected population growth by 2070 follows current development patterns, leading to urban sprawl and reduced conservation efforts, and Alternative 2070, which considers the same population growth but adopts a more compact development strategy, emphasizing increased conservation and protection of natural lands. For our study, we focused on the Trend 2070 scenario to evaluate the potential worst-case outcomes of future urbanization if no additional protections or sustainable development practices are implemented. The first stage of the LULC geoprocessing involved extracting projections from the FL 2070 study, which illustrates the areas of land in Florida that are projected to be developed by the year 2070 (See Figure S6 in the Supporting Information for a graphical depiction of the geospatial and modeling steps of our analysis). These projections estimate an overall transition from 18% to 34% developed land in the state of Florida by 2070. The data were provided by the University of Florida Geoplan Center and confined to the boundaries of the six watersheds. The original dataset is divided into two categories only: land that is currently developed and land that is undeveloped and likely to be reclassified (See Figures S7 and S8 in Supporting Information). The FL 2070 land development map was projected to accommodate the forecasted 2070 population by county. To make this information on future development more useful in the context of specific LULC transitions and nutrient load predictions, we disaggregated this geospatial dataset into one with specific LULC classes using the standard FLUCCS (Figure S9 in Supporting Information). This was done by carrying out a series of geospatial processes, in which, basically, future undeveloped lands were assigned the LULC class from the present-day FLUCCS map, while for lands that are expected to be developed in the future, we identified the current predominant urban LULC class in each county and assumed that any projected 2070 development would likely be the current, most predominant urban LULC class for each county. This county-based approach was adopted to consider planning and jurisdiction spatial diversity, which in Florida is largely driven by each county's policies. The 11 counties located within the region of interest include Charlotte, DeSoto, Glades, Highlands, Lake, Martin, Okeechobee, Orange, Osceola, Polk, and St. Lucie. For most of these counties, the current dominant LULC class is medium density residential, which means that most of the new development in our projected 2070 LULC map resembles this residential class. The only exceptions were Fisheating Creek and Indian Prairie watersheds, covering two counties with different predominant urban LULC, and in which the resulting combined LULC classification of the new development was comprised of both medium and low-density residential land uses.

2.5 | Variability Analysis and Transition Attribution

To account for the variability generated by different possibilities of urbanization density in the projections, every watershed was modeled under three potential trajectories for the 2070 LULC scenario: low-, medium-, or high-density residential LULC classes. This was done by converting all future residential areas, identified based on Section 2.4, to low, medium, or high-density residential lands, generating three different future LULC scenarios. Lawn fertilizers represent the major source of nutrient loads from residential areas to water bodies, and our simulations assumed a fertilizer application rate of 257 kg/ha for low-density, 1121 kg/ha for medium density, and 392 kg/ha for high-density. These trajectories varied in the LULC class in the areas projected to be developed by 2070, depending on the results of the analysis described in Section 2.4. These different trajectories allow for the exploration of a range of possible outcomes depending on future urbanization patterns.

To determine the impact of changes in LULC on streamflow and nutrients, two analyses were conducted using the model results. The first analysis focused on determining the total streamflow and nutrient loads generated in the watersheds at the reach level, obtaining information for streamflow and concentration, which were then converted to monthly TP and TN loads. This information was then compared between the present and 2070 scenarios. The second analysis involved a spatial analysis of LULC change to investigate the relationship between specific LULC transitions and changes in nutrient loads. This analysis compares the streamflow and nutrient load generation patterns of the present and 2070 scenarios for each LULC class, with a focus on determining the extent to which nutrient load generation increases, decreases, or remains unchanged, as well as the magnitude of these changes. To do this, we estimated the difference in TP and TN loading between the baseline (present) and 2070 (future) scenarios. These results were then combined with the LULC transition data to attribute a change in LULC to a change in TP or TN loading.

3 | Results and Discussion

3.1 | Future LULC Estimation

The results of the LULC analysis show that Upper Kissimmee, which is the watershed with the largest proportion of developed LULC currently, will also be the one with the highest developed area by 2070. Overall, the fraction of developed land in the six watersheds increased from 14% in the present to 27% according to the FL 2070 projections (Table 1). For further modeling, we disaggregated this broad classification into specific LULC classes with relevant management implications and calibrated model parameters.

3.2 | Hydrological and Water Quality Model Calibration/Validation

A summary of all calibration and validation results is presented in Table 2, and time series of daily nutrient loads per watershed for the entire simulation period is available in the Appendix S2. The model demonstrated good performance in predicting streamflow in the Indian Prairie and Taylor Creek watersheds, with coefficients of determination (R^2) exceeding 0.74. Performance was satisfactory in the Lower Kissimmee, Fisheating Creek, and Lake Istokpoga watersheds (R^2 = 0.56–0.67). Notably, the model's performance was suboptimal in the Upper Kissimmee watershed (R^2 = 0.43) primarily due to the numerous water control structures within the watershed. Given the strong correlation between streamflow and nutrient loads, the model's nutrient prediction performance

TABLE 1 | Developed versus undeveloped land proportion for each watershed.

Watershed	Present		2070		Total area (km^2)
	Developed	Undeveloped	Developed	Undeveloped	
Upper Kissimmee	25%	75%	44%	56%	4162
Lower Kissimmee	3%	97%	6%	94%	1737
Taylor Creek	11%	89%	25%	75%	800
Indian Prairie	4%	96%	12%	88%	1119
Fisheating Creek	2%	98%	9%	91%	1285
Lake Istokpoga	19%	81%	30%	70%	1595
Total	14%	86%	27%	73%	10,700

TABLE 2 | Summary of calibration and validation results for each watershed.

Sub-watershed		Calibration (1995–2006)			Validation (2007–2018)		
		NS	R^2	PBIAS	NS	R^2	PBIAS
Upper Kissimmee	Streamflow	0.42	0.43	10.47	0.42	0.43	−4.08
	TP load	0.34	0.36	19.43	0.2	0.28	−13.85
	TN load	0.33	0.39	25.2	0.24	0.24	4.7
Lower Kissimmee	Streamflow	0.62	0.65	10.53	0.66	0.67	−1.45
	TP load	0.52	0.56	13.71	0.69	0.73	2.62
	TN load	0.61	0.64	13.38	0.72	0.72	−0.84
Taylor Creek	Streamflow	0.74	0.74	1.11	0.68	0.74	−13.95
	TP load	0.38	0.44	22.39	0.34	0.65	−49.89
	TN load	0.26	0.42	−2.93	0.59	0.66	−11.78
Indian Prairie	Streamflow	0.76	0.78	1.90	0.72	0.80	20.77
	TP load	0.45	0.66	−33.85	0.57	0.78	−42.78
	TN load	0.74	0.79	15.03	0.73	0.85	26.35
Lake Istokpoga	Streamflow	0.63	0.63	−1.62	0.55	0.6	25.99
	TP load	0.46	0.5	−24.42	0.23	0.35	−13.96
	TN load	0.71	0.71	5.24	0.32	0.36	20.63
Fisheating Creek	Streamflow	0.51	0.56	−0.87	0.49	0.59	−13.37
	TP load	0.62	0.63	−8.81	0.76	0.79	−15.72
	TN load	0.59	0.62	−6.37	0.6	0.67	−20.92

mirrored the trends observed in streamflow. Specifically, the model exhibited good performance in TP predictions in the Lower Kissimmee ($R^2=0.56$–0.73) and Indian Prairie ($R^2=0.66$–0.78). The model results demonstrated even higher performance in TN predictions, probably because TP simulation is often more sensitive due to its dependence on sediment dynamics and variability introduced by soil and erosion factors, particularly in the Lower Kissimmee ($R^2=0.64$–0.72) and Indian Prairie ($R^2=0.79$–0.85). In Fisheating Creek, the model's performance was good for both TP ($R^2=0.63$–0.79) and TN ($R^2=0.62$–0.67). However, in Lake Istokpoga and Taylor Creek, the model's performance was satisfactory for TP ($R^2=0.35$–0.65) and TN ($R^2=0.36$–0.71). Notably, the model performed poorly with TP and TN in the Upper Kissimmee ($R^2=0.28$–0.36 and 0.24–0.39, respectively), consistent with its suboptimal streamflow prediction performance. Overall, performance across the watersheds was satisfactory for the purpose of this study, with the worst performer being Upper Kissimmee, which can be attributed to the presence and operations of hydraulic structures, like dams, levees, and canals, which are prominent in this watershed. In contrast, watersheds with less complex water management, such as Taylor Creek and Indian Prairie, obtained much better model performance parameters.

3.3 | Spatial Variability and Magnitude of Future Changes in Streamflow and Nutrient Loads

Urbanization generally led to increases in streamflow across the six watersheds (Table 3 and Figure S12). An increase in urbanization is expected to result in increased impervious area and consequently more runoff. For instance, the Upper Kissimmee watershed has the highest proportion of existing urban LULC (25%) and is projected to have the largest proportion of future urban LULC (44%) by 2070. Simulations for Upper Kissimmee show that streamflow would be consistently higher for every month in the future scenario compared to the baseline scenario (Figure S12 in Supporting Information). The average monthly increase is expected to be 16%, with the largest increase expected in June (13%–33%) and the smallest in August (3%–13%). Summary statistics for flow simulations in all watersheds are presented in Table 3.

Spatial patterns of TP change (expressed as annual export coefficients in units of kg/ha) show a general tendency to increase, but with a different geographical distribution from TN (Figure 2a). A particular observation is that TP loads

TABLE 3 | Minimum, maximum, and average monthly streamflow in study watersheds for the present and 2070 in m^3/month. Values in parentheses are the percent increase from baseline.

	Baseline scenario			2070 Land cover		
Watershed	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**
Upper Kissimmee	7.5E+5	5.7E+8	8.5E+7	7.1E+6 (+3%)	6.0E+8 (+33%)	1.0E+8 (+16%)
Lower Kissimmee	5.6E+3	9.1E+8	1.2E+8	5.0E+5 (0%)	9.1E+8 (+2%)	1.2E+8 (+1%)
Taylor Creek	2.5E+5	2.0E+8	1.7E+7	1.2E+6 (+2%)	2.0E+8 (+123%)	1.9E+7 (+12%)
Indian Prairie	7.8E+5	3.0E+8	5.1E+7	2.0E+6 (+1%)	3.0E+8 (20%)	5.2E+7 (+5%)
Fisheating Creek	4.8E+5	2.5E+8	2.8E+7	9.1E+5 (+1%)	2.5E+8 (+59%)	2.9E+7 (+13%)
Lake Istokpoga	0.0E+0	1.6E+8	2.8E+7	0.0E+0 (0%)	1.7E+8 (+64%)	3.0E+7 (+14%)

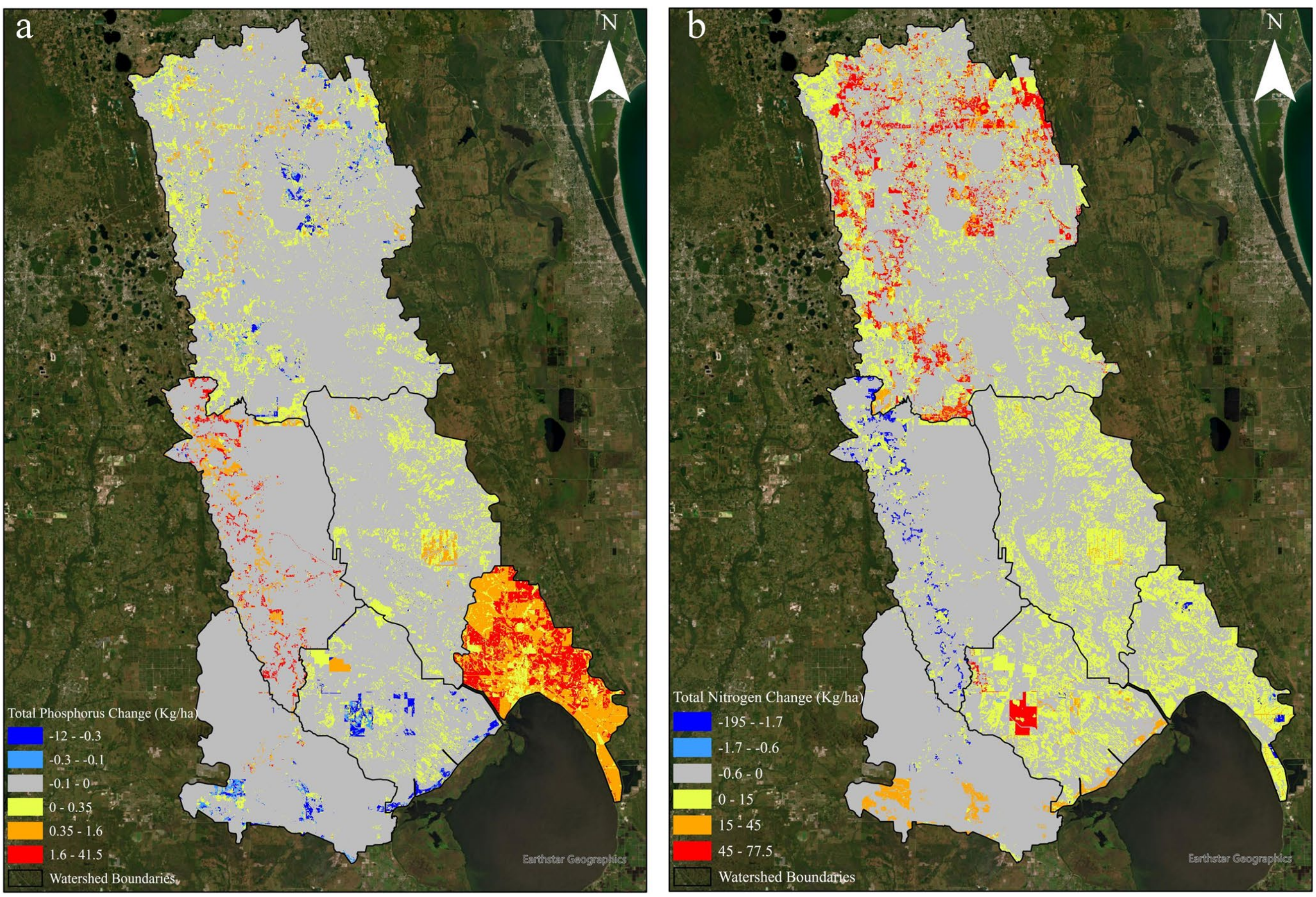

FIGURE 2 | Spatial distribution of expected future changes in annual export coefficients of (a) total phosphorus (TP; kg/ha) and (b) total nitrogen (TN; kg/ha). See Figure 1 for watershed names.

decreased for several months across all watersheds, with the exception of the Upper Kissimmee and Lake Istokpoga, where TP loads exhibited a consistent increase (See Table S2 and Figure S13 in the Supporting Information). Overall, this study found that TP load tends to increase with urbanization, possibly due to increased TP sources in developed areas including lawn fertilizers and pet waste, which is consistent with previous research in other regions (Fang et al. 2019; McGrane 2016; Zhao and Xia 2012).

Spatial patterns in future changes of TN (expressed as annual export coefficients in units of kg/ha) demonstrate a much larger variability among watersheds (Figure 2b). Most widespread increases in TN load were simulated for the Upper Kissimmee, where urbanization is expected to increase and lead to watershed-wide TN monthly increases of 63% (63.6 tons) on average. In contrast, some areas are expected to see mild decreases in TN loads, as is the case of Lake Istokpoga, where monthly loads are expected to decrease by as much as 8% (2.9 tons), most probably because of the transition of large areas of citrus plantations (18.8 kg ha/yr. of N runoff compared to 8.04 kg N/ha/yr. in medium density residential land; Figure S2). This reduction in TN loads aligns with findings by Wang and Kalin (2018), who observed that TN loads tend to decrease with urbanization due to the conversion of cropland to urban land. TP monthly loads are expected to increase in this watershed by as much as 74% (0.76 tons), probably for the same reason as with TN (citrus contributes just 0.41 kg P/ha/yr. compared to 5.46 kg P/ha/yr. for medium density residential

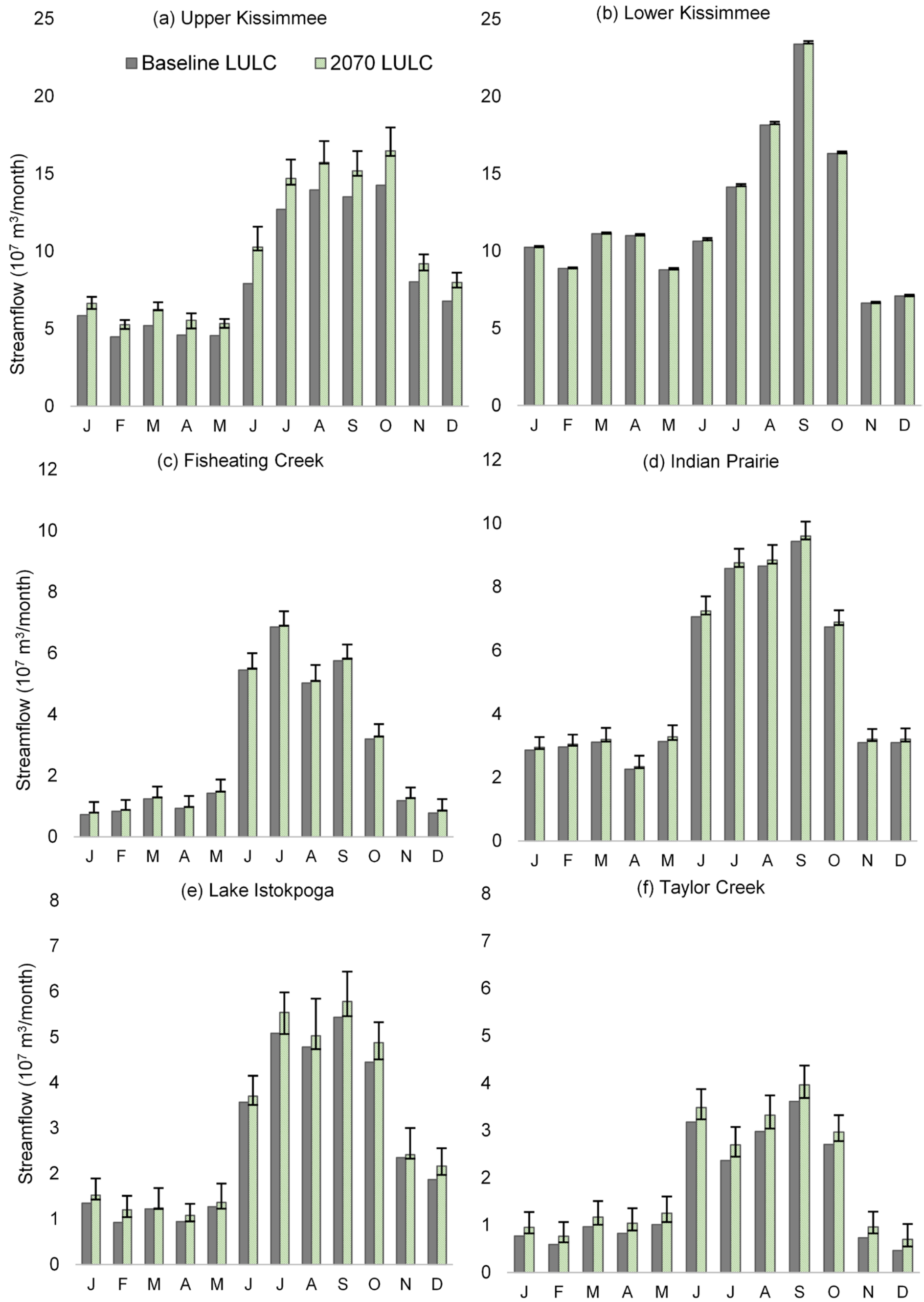

FIGURE 3 | Monthly streamflow comparison of baseline vs. 2070 Land Use/Land Cover (LULC). Error bars represent the variability associated with different scenario trajectories (low-, medium-, or high-residential development). Note that the vertical axes have different ranges.

land). Summary statistics for TN simulations in all watersheds are presented in Table S1 in the Supporting Information, and seasonal variability results are presented in Figure S14.

3.4 | Urbanization-Driven Streamflow Variability

There was a considerably large range of variability in the results from differences in urbanization density projections. In Upper Kissimmee, for instance, average monthly flows are expected to increase by 16% on average, but this increase can be as low as 7% if assuming future low-density residential development and as high as 20% if assuming medium density residential. Similarly, large variability was found for watersheds expected to have large portions of developed LULC (Taylor Creek (4%–36%), Lake Istokpoga (1%–25%), and Fisheating Creek (2%–17%)). In contrast, less variability was obtained for watersheds with lower expected developed LULC [Indian Prairie (1%–10%) and Lower Kissimmee (0%–1%)]. The minimal changes in streamflow (0% and 1%) in some watersheds were associated with low-density residential development during summer months. The most significant changes in streamflow were observed during the winter months—traditionally the low-flow season in most watersheds. These alterations are likely to disrupt the natural hydrologic regime, potentially leading to adverse impacts on the surrounding ecosystem. Results of the streamflow variability analysis for all watersheds are shown in Figure 3.

Overall, this study found that flow prediction variability was heavily dependent on the proportion of urban LULC in each watershed, with a consistent trend of increasing uncertainty as urbanization increased (Figure 4a). This highlights the importance of considering the specific LULC characteristics of each watershed when analyzing the impacts of urbanization on streamflow and underscores the need for robust modeling techniques to account for the hydraulic and nutrient transport alterations introduced by urbanization. The increase in streamflow variability

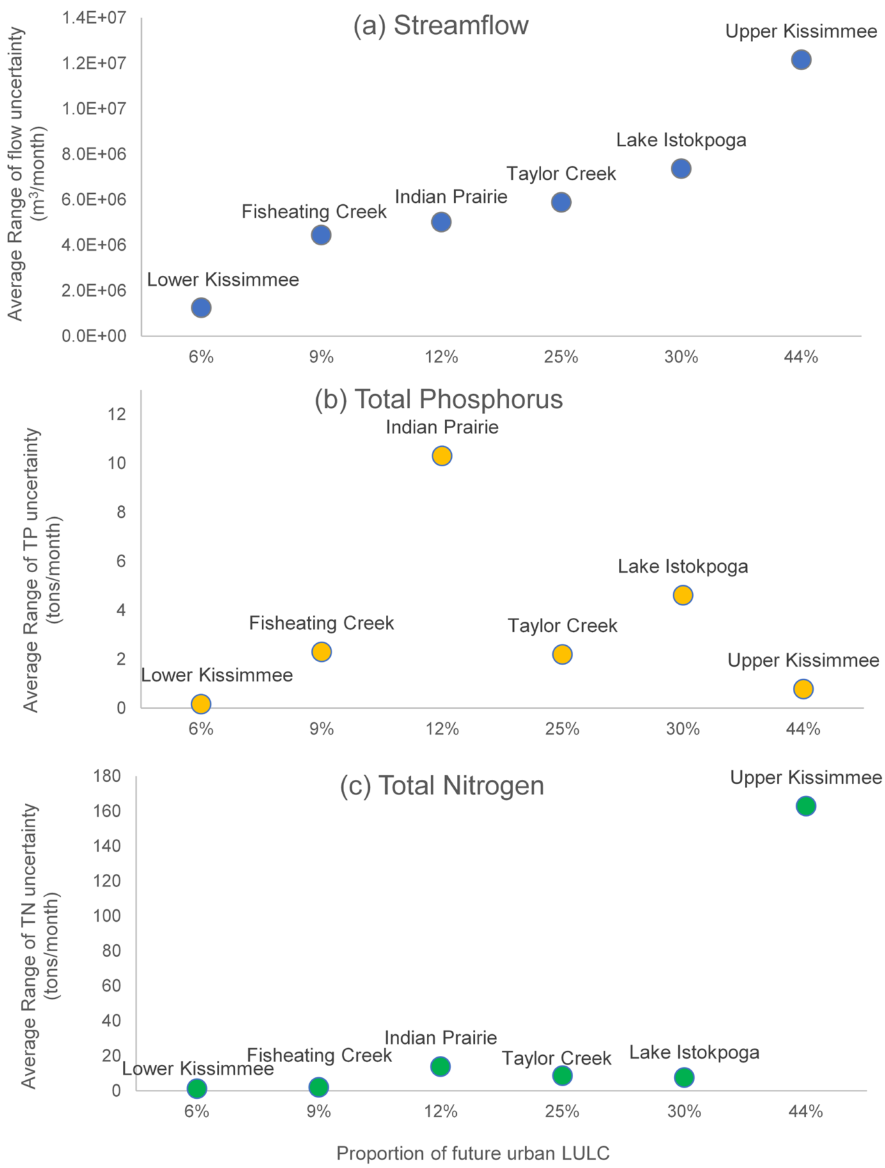

FIGURE 4 | Relationship between future urban Land Use/Land Cover (LULC) proportion and prediction variability for (a) streamflow, (b) total phosphorus, and (c) total nitrogen.

found in this study is consistent with previous research looking primarily at deforestation (Arias et al. 2018; Farinosi et al. 2019; Shrestha et al. 2017) and agricultural development (Fang et al. 2019; Li et al. 2018), with this study demonstrating that urbanization will contribute to those trends even more.

3.5 | Total Phosphorus Load Variability

Similar to streamflow, results for TP loads displayed a general tendency to increase in all watersheds in the future, although there is more distinct variability in the increased loads (Figure 5). The largest variability was obtained in Lake Istokpoga, with increases in mean monthly TP loads of 7%–141% (0.22–4.42 tons). While also displaying major future increases with high urban density, the variability in three of the study watersheds included a potential decrease in TP loads associated with future low/medium density urbanization in Indian Prairie (−3% to 82% equivalent to −0.3 to 9.1 tons), Taylor Creek (−8% to 15% equivalent to −0.71 to 1.32 tons), and Fisheating Creek (−1% to 33% equivalent to −0.1 to 2 tons). These reductions can be attributed to the reduction in fertilizer use from

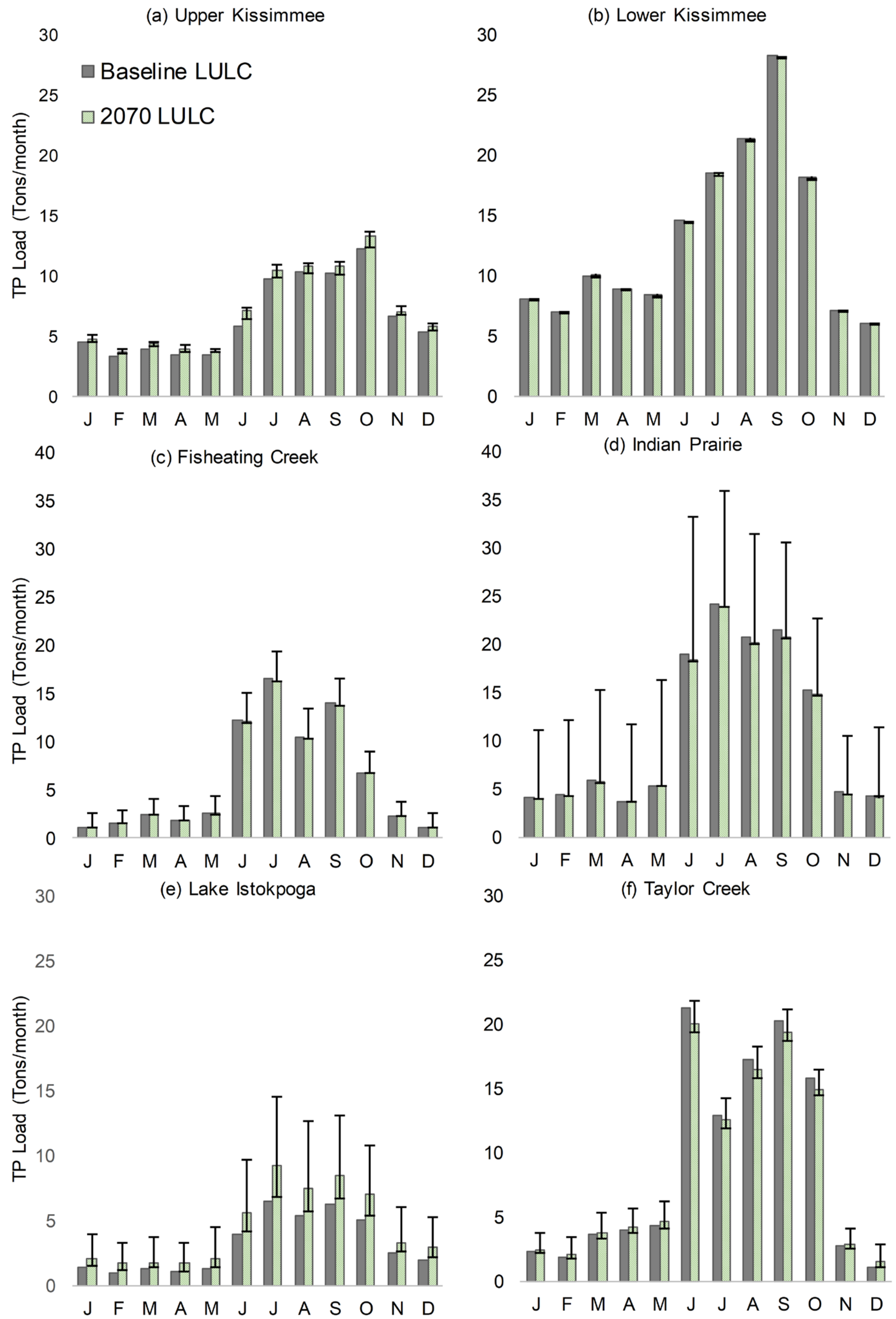

FIGURE 5 | Monthly total phosphorus load comparison of baseline vs. 2070 Land Use/Land Cover (LULC). Error bars represent the variability associated with different scenario trajectories (low-, medium-, or high-residential development). Note that vertical axes have different maximum values.

the conversion from agricultural land to low/medium density residential areas. The observed decreases in TP loads align well with findings by Wang and Kalin (2018) and Wade et al. (2022), who reported similar trends under future urbanization scenarios. It should also be noted that in our study, however, all simulations considering urbanization toward high-density residential LULC class resulted in monthly TP load increases.

TP variability did not follow a specific trend in relation to the future urban proportion in the watershed (Figure 4b). The largest variability was observed for the Indian Prairie watershed, with an expected urbanized coverage of 12%. For the three watersheds with a higher proportion of future urban LULCs (25%–44%), however, the uncertainty in TP loads actually decreased when compared to Indian Prairie. This discrepancy could be a result of the specific LULC changes (described in more detail in Section 3.7), as in Indian Prairie a significant proportion (58%) of the transition area is classified as *Improved Pastures*.

3.6 | Total Nitrogen Load Variability

The summary of projected monthly TN loads as a function of future LULC demonstrates a likely and more consistent increasing trend for most watersheds (Figure 6). The largest monthly load

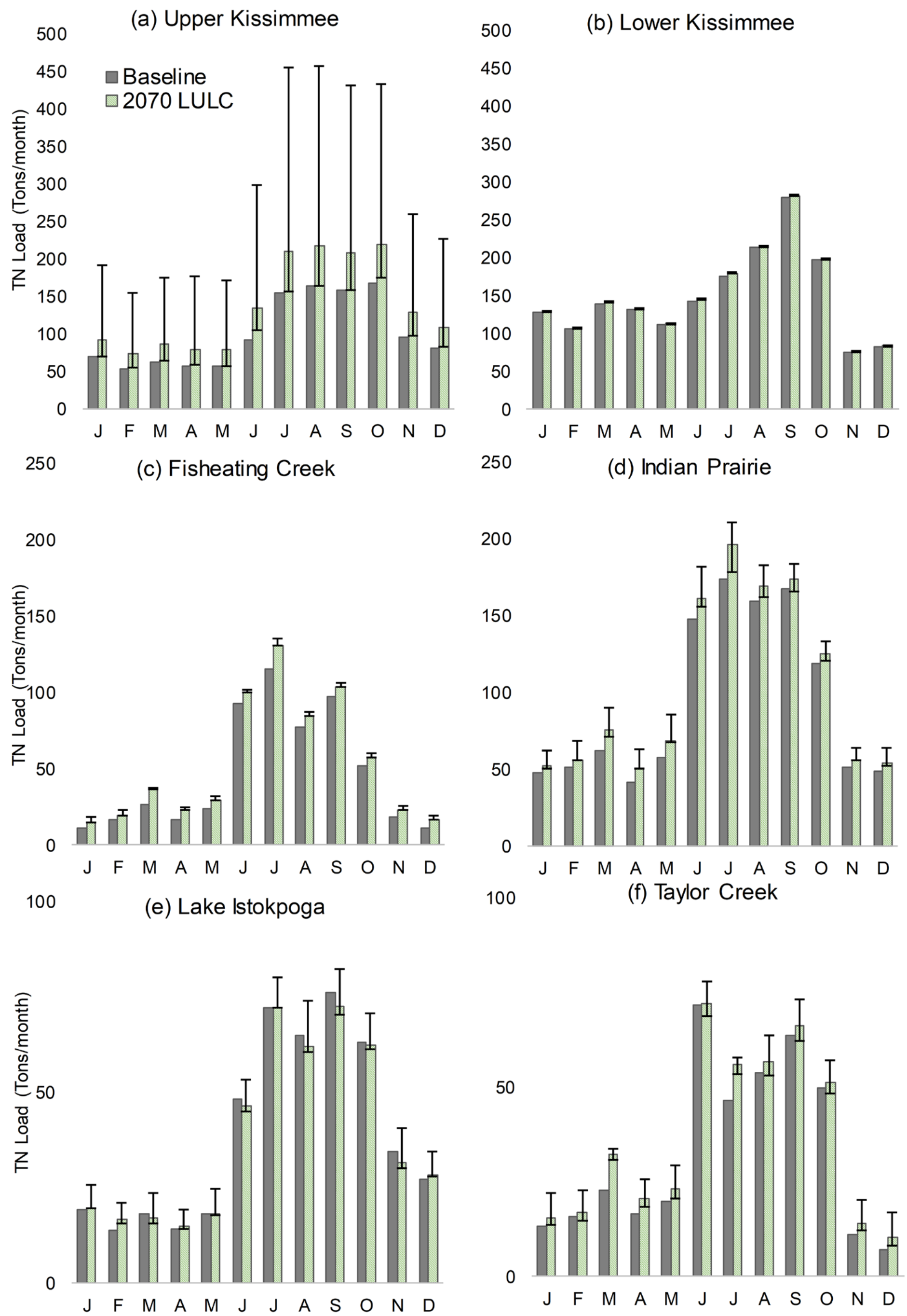

FIGURE 6 | Monthly total nitrogen load comparison of baseline vs. 2070 Land Use/Land Cover (LULC). Error bars represent the variability associated with different scenario trajectories (low-, medium-, or high-residential development). Note that vertical axes have different maximum values.

increases are expected in Upper Kissimmee, associated with the vast area of urban lands projected in the watershed (3%–151%, or 2.9–152.5 tons), Taylor Creek (3%–28%, or 1.1–9.1 tons) and Indian Prairie (6%–23%, or 5.4–21.8 tons), followed by Fisheating Creek (14%–18%, or 6.7–8.5 tons), Lake Istokpoga (−2% to 17%, or −0.6 to 6.6 tons) and Lower Kissimmee (1%–2%, or 1.3–2.3 tons). TN variability associated with urban density trajectories was smaller than for TP, with the high and mid-density trajectories typically leading to much more TN than the low-density trajectory. This more consistent increasing trend in TN is likely due to a widespread increase in ammonia fertilizer usage expected in residential LULC, ranging from 257 to 1121 kg fertilizers/ha. In most of the watersheds, notable increases in TN loads were observed during the winter season, coinciding with the changes in streamflow. However, the UK watershed exhibited TN consistently increasing throughout the year.

3.7 | LULC Transition Attribution to Nutrient Load Change

This study analyzed the potential effects of urbanization on nutrient loads, with the transition to urban LULCs resulting in both increased and decreased nutrient loads, depending on the precedent LULC. Therefore, we carried out an attribution analysis in which nutrient load changes associated with transitions from specific historical LULC classes (as per the FLUCCS system) to residential were estimated. These results are presented in Figures 7 and 8 for TP and TN in absolute terms, respectively. Similar results normalized by area are presented in Figures S10 and S11 in the Supporting Information. For the entire study area, the largest decrease in TP load was quantified for the transition from *cattle feeding operations*, probably associated with the reduction of manure, as cattle feeding operations produce 9.9 kg P/ha/yr. compared to 5.46 kg P/ha/yr. produced by medium density residential lands. The largest increase in TP load was quantified for transitions from agricultural land categories, in particular citrus groves that produce only 0.41 kg P/ha/yr. Transition from natural wetland categories ranked second in TP load increase, in particular *freshwater marshes, swamps, mixed wetlands*, and *prairies*. Urbanization of upland forests also showed that it increases TP, in particular conversion of *upland shrub and brushland*, *pine flatwoods*, and *hardwood-coniferous mixed*.

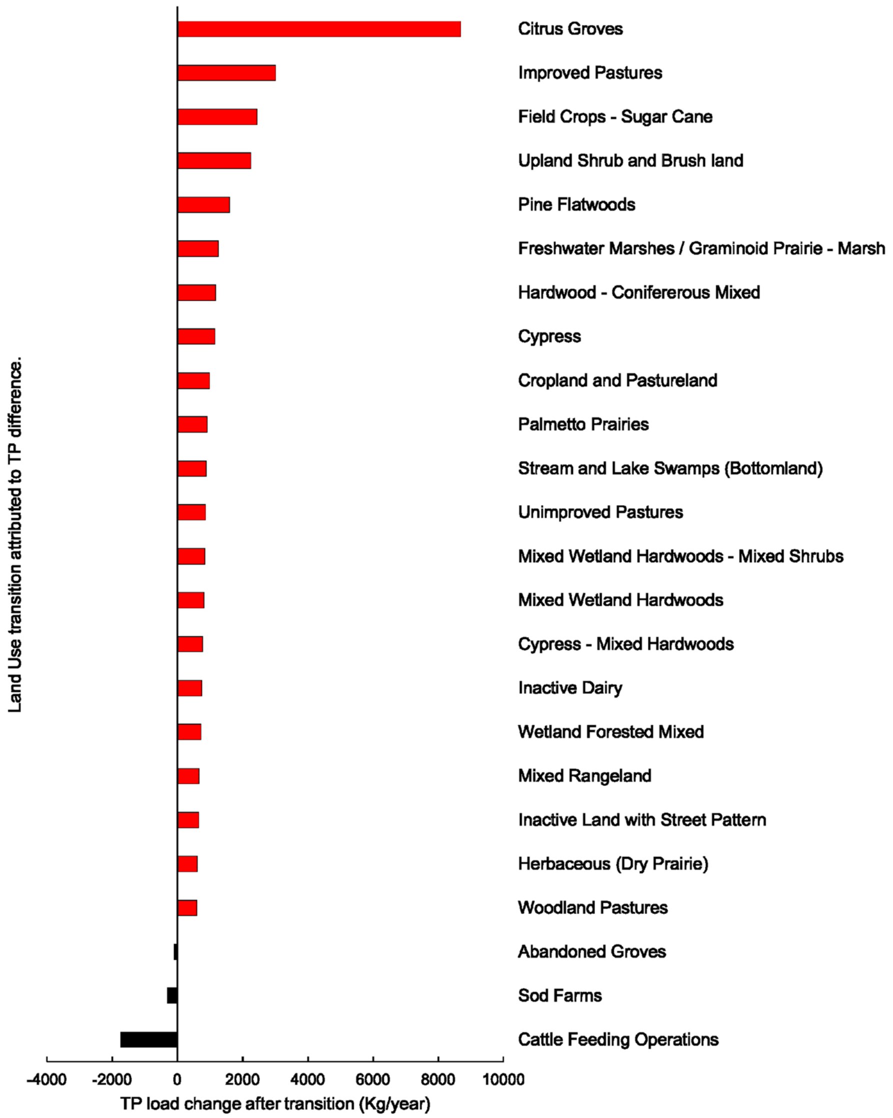

FIGURE 7 | Basin-wide absolute total phosphorus load change corresponding to land use transition to urban Land Use/Land Cover classes.

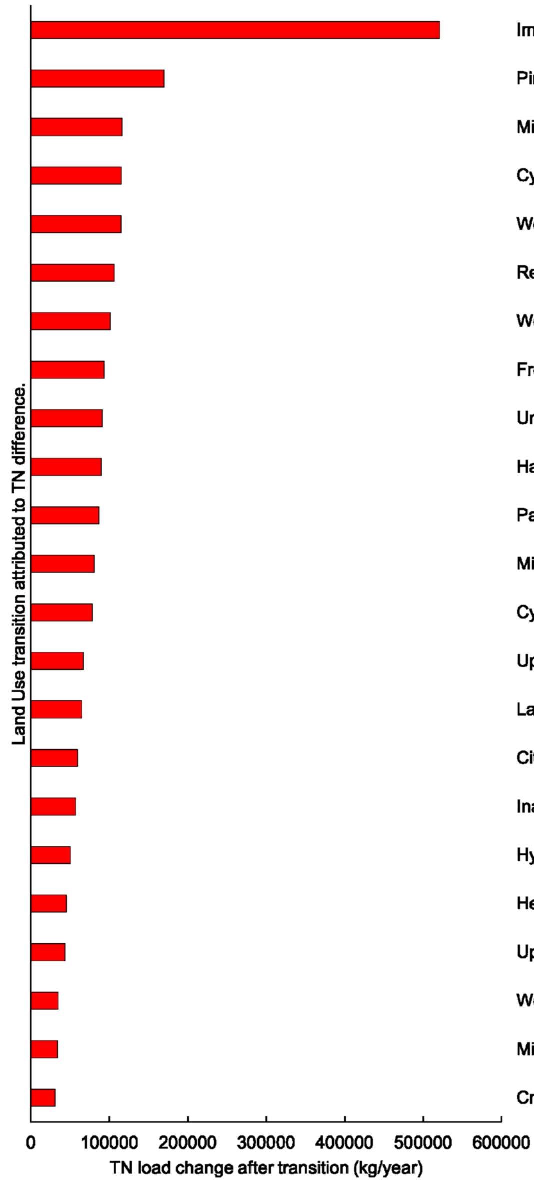

FIGURE 8 | Basin-wide absolute total nitrogen load change correspondent to land use transition to urban Land Use/Land Cover.

An overview of the transition attribution analysis for TN is presented in Figure 8. When analyzing TN loads, a slight decrease was estimated for transitions from dairies. The largest increase in TN load was associated with transitions from agricultural lands, in particular *improved pastures* that produce 3.62 kg N/ha/yr compared to 8.04 kg N/ha/yr produced by medium density residential, followed by urbanization of freshwater wetlands, both forested and marshes. Other important transitions leading to TN increase included those from upland secondary forests (*upland shrub/brushland* and *pine flatwoods*). Overall, these findings highlight the importance of considering the potential impact of land use changes on water quality in Florida's watersheds, and the particular role that conserving natural land could have on regulating nutrient loads in the landscape.

The urbanization of agricultural land, such as groves and cattle feeding operations, could result in a decrease in nutrient loads in some cases. It is important to note that the magnitude of nutrient load change differs for various transitions. For example, in Indian Prairie, a 5% transition of freshwater marshes to urban land uses (resulting in increased TP load) counteracted the effect of a 58% transition of improved pastures to urban land uses (resulting in decreased TP load). In the case of TN, the conversion of agricultural land uses to urban land uses may lead to a minimal decrease in TN loads, if any, compared to the increase attributed to the urbanization of marshes and wetland systems. These findings emphasize the importance of considering the type of land use transition when assessing nutrient loads and underscore the need for effective land management strategies to mitigate nutrient pollution in urban areas.

3.8 | Study Limitations and Future Research

This study faced a few limitations that ought to be considered in future research. The FL 2070 dataset projected future urbanization as developed lands, though it did not specify the type of developed land uses. Our study assigned each developed land the existing predominant urban LULC in each county in the study area. This assumption was reasonable for the deterministic nature of our land use variability analysis, though a probabilistic approach might be recommended for future studies to assess the effect of different future urban land uses on streamflow and nutrient loads in the watershed. The deterministic approach was used in this study because WAM simulations require significant computational resources and extended runtime to accurately represent future streamflow and nutrient loads in the watershed. In addition, this study did not account for the future implementation of BMPs, which could improve water quality in the watershed to address future urbanization, though Tarabih et al. (2024) conducted a comprehensive analysis of BMP scenarios in the Lake Okeechobee watershed that could provide valuable guidance for future BMP implementation in this area. Moreover, the study did not account for the potential effects of future climate change, which will certainly bring additional changes to both streamflow and nutrients. Such studies have been carried out recently for the watersheds in question (Shin et al. 2023; Song et al. 2023), suggesting an overall increasing trend in nutrient loads due to expected increases in rainfall intensity. Now that variability in projections associated with urbanization has been explored, future studies could compare the differences in water quantity and quality driven by urbanization and climate change.

4 | Conclusions

This study investigated the impact of future urbanization on the variability of water quality projections in regional watersheds. Using geoprocessing analysis along with hydrological and water quality modeling, the research demonstrated that transitioning from natural or agricultural to urban lands generally led to increased nutrient loads at the watershed scale. This increase was generally more pronounced and more consistent for TN than for TP. The analysis also highlighted that different LULC transitions influenced nutrient loads in the watersheds to varying degrees. For example, urbanization of prairies and brush land in the Lower Kissimmee watershed led to the highest increase in TP load, while urbanization of inactive land and freshwater marshes in the Indian Prairie watershed caused the most significant increase in TP load. It is noteworthy that urbanization could affect TP and TN loads differently depending on the initial LULC type; for instance, urbanization of improved pasture caused the highest increase in TN loads, though it was reflected in the highest decrease in TP loads in the Indian Prairie watershed. Variability in predictions associated with differences in residential density was evident in this study. The analysis showed that high-density residential housing tended to produce the highest TP loads, while low-density residential produced the lowest TP loads. As expected, medium density residential resulted in intermediate TP loads. This pattern was also observed for streamflow, but for TN, some watersheds produced the highest TN loads through the medium density trajectory, while others illustrated the highest TN loads associated with simulations with low-density and high-density trajectories.

This research has important implications for water resource management in Florida and other fast-urbanizing landscapes. By anticipating and mitigating the potential impacts of future LULC transitions in the region, water managers can proactively develop planning strategies. The study offers valuable watershed-level insights into the potential impacts of different urbanization patterns, indicating that not only urbanization in general, but also the density of urbanization, affects water quantity and quality. The research also highlights the importance of preserving natural lands such as freshwater marshes and swamps, which experience the most significant increases in TP and TN following urbanization.

In conclusion, this study highlights the intricate relationship between future LULC transitions and water quality, providing critical information not only for the scientific community but also for policymakers and environmental managers. Our results support the need to prioritize preserving natural lands, especially freshwater marshes and swamps, which experience the greatest increases in TP and TN once urbanized. It is also recommended that specific LULC transitions be considered in decision-making related to land development, as different urbanization patterns can have varying impacts on water quality.

Author Contributions

Andres Lora Santos: data curation, formal analysis, investigation, methodology, writing – original draft. **Osama M. Tarabih:** formal analysis, investigation, software, supervision, visualization, writing – review and editing. **Mauricio E. Arias:** conceptualization, funding acquisition, project administration, resources, supervision, visualization, writing – review and editing. **Mark C. Rains:** conceptualization, funding acquisition, supervision, writing – review and editing. **Qiong Zhang:** conceptualization, funding acquisition, project administration, resources, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The pre-calibrated hydrological-water quality model used in this study (WAM) has been made publicly available through the Florida Department of Environmental Protection: http://publicfiles.dep.state.fl.us/DEAR/BMAP/LakeOkeechobee/WAM/2019_Pre-drainage_Abatement%20Reports/PreDrainage/. Time series of simulated nutrient loads per watershed analyzed in this study is included as a Appendix S2.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.