Environmental Science & Technology

Critical Review

Cite This: Environ. Sci. Technol. XXXX, XXX, XXX−XXX

pubs.acs.org/est

Non-floodplain Wetlands Affect Watershed Nutrient Dynamics: A Critical Review

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Supporting Information

ABSTRACT: Wetlands have the capacity to retain nitrogen and phosphorus and are thereby often considered a viable option for improving water quality at local scales. However, little is known about the cumulative influence of wetlands outside of floodplains, i.e., non-floodplain wetlands (NFWs), on surface water quality at watershed scales. Such evidence is important to meet global, national, regional, and local water quality goals effectively and comprehensively. In this critical review, we synthesize the state of the science about the watershed-scale effects of NFWs on nutrient-based (nitrogen, phosphorus) water quality. We further highlight where knowledge is limited in this research area and the challenges of garnering this information. On the basis of previous wetland literature, we develop emerging concepts that assist in advancing the science linking NFWs to watershed-scale nutrient conditions. Finally, we ask, "Where do we go from here?" We address this question using a 2-fold approach. First, we demonstrate, via example model simulations, how explicitly considering NFWs in watershed nutrient modeling changes predicted nutrient yields to receiving waters—and how this may potentially affect future water quality management decisions. Second, we outline research recommendations that will improve our scientific understanding of how NFWs affect downstream water quality.

INTRODUCTION

Human-accelerated alterations to nitrogen (N) and phosphorus (P) cycles have generated surplus nutrient inputs to surface waters across the globe. This excess N and P often imparts deleterious impacts on freshwater and marine systems, including eutrophication[1,2] and harmful algal blooms,[3] which have challenged water quality managers for decades. This has led to a focus on reducing both N and P inputs across freshwater and marine systems.[4]

Wetlands have long been heralded as efficient pollutant storage and processing systems that mediate surface water quality.[5] Knowledge regarding the storage and retention of nutrients by individual wetlands is grounded in a well-established understanding of their hydrological and biogeochemical processes[6] and the efficiency of their nutrient-uptake mechanisms.[7] Therefore, conservation, restoration, and creation of wetlands for point and nonpoint source management have increased through voluntary and mandated programs. Further, research quantifying wetland benefits has expanded to the explicit inclusion of these ecosystem services in some economic models.[8−12] Studies characterizing wetland benefits have largely focused on floodplain wetlands because they frequently interact via surface, shallow subsurface, and groundwater flows with fluvial systems, such as streams and rivers,[13] and because of their low site development rates (e.g., for agriculture) and their proximity to flowing water bodies.[14] However, to understand the cumulative benefits of wetlands for water quality fully, we need to focus on non-floodplain wetlands (NFWs), i.e., depressional wetlands outside of floodplains and riparian areas that are often surrounded by uplands, and to quantify NFW services using a watershed-scale approach.[15,16]

Received: December 24, 2018
Revised: May 23, 2019
Accepted: June 5, 2019
Published: June 5, 2019

DOI: 10.1021/acs.est.8b07270
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

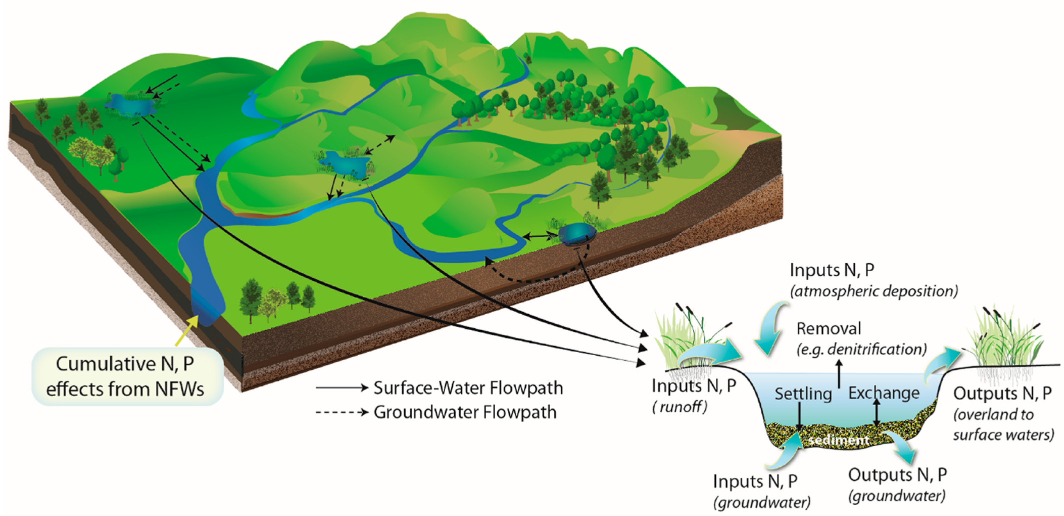

Figure 1. Example watershed with non-floodplain wetlands (NFWs) processing nitrogen and phosphorus. The bottom right NFW cartoon shows the various inputs and biogeochemical processes of NFWs. Nutrient loads, e.g., total nitrogen (TN) and total phosphorus (TP), assessed at the outlet of a watershed of any size may be mediated by the cumulative effects of the NFWs located within it. However, this signal may be challenging to detect because of other non-NFW processes (hydrological, biogeochemical, anthropogenic) not shown here that operate at local and watershed scales.

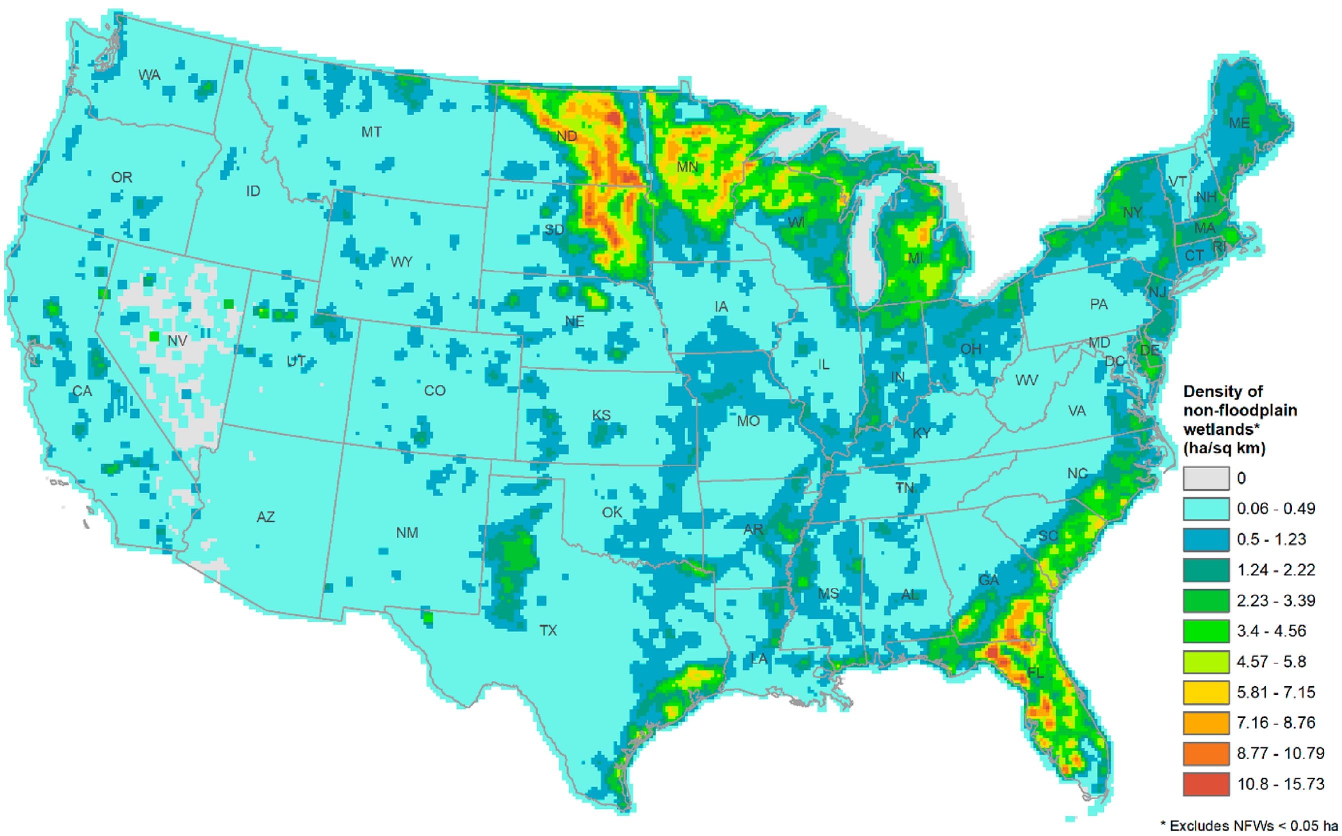

Figure 2. Potential extent of non-floodplain wetlands (NFWs) across the contiguous United States, as estimated by Lane and D'Amico[20] (reproduced with permission of Wiley).

A watershed approach, as described herein, considers wetlands that exist within a topographically defined drainage area of various sizes, e.g., 0.1 to 1000 km^2,[17] and the water quality effects of their processes at the watershed outlet (Figure 1). Scientists are just beginning to make strides toward directly understanding how NFWs process nutrients and mediate water quality at various watershed scales (e.g., refs 18, 19). NFWs stand in locational contrast to wetlands within floodplains and riparian areas adjacent to nearby streams and rivers, hereafter referred to floodplain wetlands. Advances in NFW research are specifically important because of the potential cumulative water quality consequences NFWs impart on surface waters, both from their continued ubiquity across some landscapes (ref 20

DOI: 10.1021/acs.est.8b07270
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

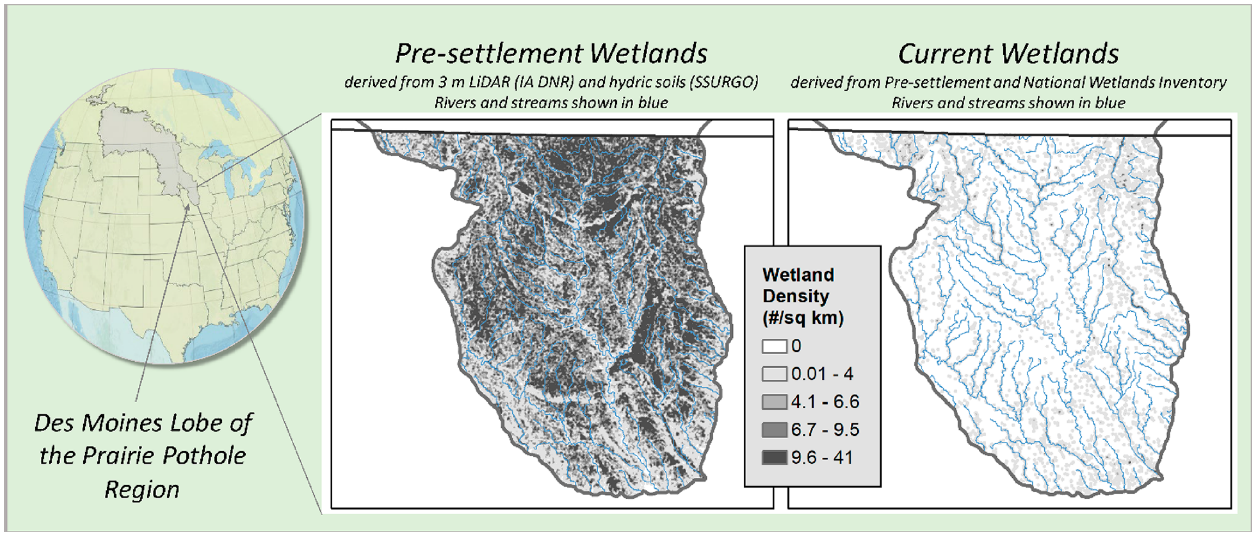

Figure 3. Example of historical wetland losses in agricultural landscapes, comparing those that existed prior to European settlement (based on the SSURGO Soil Survey Geographic Database[129] and Iowa Department of Natural Resources LiDAR data) to those that exist today (National Wetland Inventory[128]). Shown here is the Des Moines Lobe, located in the North American Prairie Pothole Region. Remaining wetlands exist, for the most part, in riparian or floodplain areas. (See Supporting Information on figure development; streams from the National Atlas of Rivers and Streams data set now distributed by ESRI, Inc., Redlands, California.)

Figure 2) and their widespread loss in others, particularly in agricultural watersheds (e.g., ref 21; Figure 3).

Despite the imperative nature of NFW research—particularly given the 87% loss of the world's original wetlands,[22] an incalculable number of which are NFWs[23]—quantifying the water quality effects of remaining and restored NFWs is challenging. This is true in large part because scientists have limited measured or modeled information on their locations in watersheds in relation to other surface waters.[23] Educated hypotheses are therefore commonly applied to link extant and restorable NFWs and watershed-scale water quality based on key concepts from the literature, namely: (1) NFWs individually[24] and cumulatively[25−27] provide potentially high levels of nutrient removal across landscapes and (2) NFWs influence watershed-scale hydrological, or water quantity-based, dynamics.[28−34] Conceptually, if NFWs, as receptors and sinks of nutrient loads, remove N and P across the landscape, nutrient transport from NFWs to other surface waters will be diminished and therefore protective of water quality.[35] However, limited direct evidence linking NFWs to water quality at watershed scales exists.

Factors contributing to critical research gaps that further limit direct knowledge of how NFWs affect watershed-scale water quality are that (1) it is difficult and resource intensive to measure direct links between nutrient removal rates of multiple wetlands and downstream water and quality and (2) most watershed modeling used to predict future N and P loads in response to changes in land management and other future hazards (e.g., temperature and precipitation extremes, fire) does not directly integrate NFWs into model simulations, e.g., refs 36−39. This can, at minimum, leave scientists and land managers with a void in knowing how NFWs influence water quality. At the most extreme, the exclusion of NFWs leads to inaccurate predictions of nutrient loadings across the landscape to future management and climate variations.

It is therefore clear that integrating NFWs into management and modeling approaches for projecting watershed nutrient loading to surface water is needed.[17,40] Narrowing the gap in our scientific understanding of how NFWs influence watershed-scale water quality is critical for future research and management focusing on (1) conservation, restoration, or creation of NFWs to minimize excess nutrients and pollutants from reaching other surface waters[23] and (2) modeled projections of watershed nutrient loads to surface waters in response to future land and climate conditions.

In this paper, we synthesize the state of the science about the watershed-scale effects of NFWs on nutrient-based (i.e., N, P) water quality, outline current research challenges, and make timely research recommendations. Specifically, we summarize research directly addressing NFWs and their watershed-scale effects on water quantity and water quality, discuss the primary missing information regarding how NFWs affect watershed-scale nutrient conditions, and describe key challenges that exist for garnering this knowledge. We next synthesize emergent concepts from the general wetlands nutrient literature that will advance the next phase of NFW nutrient-related watershed-scale research. Finally, we explore steps to advancing the science by (1) demonstrating via model simulations how directly considering NFWs in a watershed model changes the projected nutrient loads to receiving waters across a large watershed—and how this may affect water quality management decisions—and (2) outlining future research recommendations to improve our scientific understanding of how NFWs affect downstream water quality.

NFWS AND WATERSHED-SCALE NUTRIENTS: CURRENT KNOWLEDGE

Contextualizing NFWs. NFWs exist outside of floodplains and are typically surrounded by uplands. They therefore have their own drainage area, a "catchment", that contributes inputs of water to them. NFWs and floodplain wetlands both have anoxic soil conditions and plant/algal communities that allow biogeochemical processes such as denitrification, particulate settling, and plant/microbial uptake to occur. However, nutrient processing also depends on N and P inputs to the wetland and the wetland's hydrologic regime—and differences can exist

DOI: 10.1021/acs.est.8b07270
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Table 1. Wetland Terminology

Wetland Type	General Description
Non-floodplain wetlands (NFWs)	Depressional wetlands outside of floodplains and riparian areas that are often surrounded by uplands
Floodplain wetlands	Wetlands in floodplains and riparian areas adjacent to nearby streams and rivers. Floodplain wetlands can also be depressions; it is their location that defines them.
Natural wetlands	Extant wetlands with limited human disturbance
Restored wetlands	Wetlands created at sites where previous wetlands existed but were drained or filled. Restored wetlands can be either NFWs or floodplain wetlands.
Constructed wetlands	Wetlands developed specifically for receiving and treating polluted water, e.g., from stormwater or agricultural runoff. Constructed wetlands can be either NFWs or floodplain wetlands.

between NFWs and floodplain wetlands. For example, while N accumulation may be similar in NFW soils compared to those of floodplain wetlands, P accumulation may be higher in the latter due, in part, to particulate matter codeposition with P.[41] Moreover, the hydrological interactions of NFWs with other surface water exist along a continuum, from nonexistent to intermittent to persistent connections.[26] This contrasts with the likely more frequent interactions of floodplain wetlands with their adjacent stream or river system. We suggest, based on recent literature, that these hydrological variations drive the primary differences between NFW and floodplain wetland effects on downstream water quality.[19,26,42]

NFWs include existing, restored, and constructed wetlands (Table 1) and are considered in this review exclusively and independently from floodplain wetlands. This is important because NFWs are often the first to be lost to various anthropogenic activities, such as draining for agriculture and development.[23] Studies lumping NFWs with the effects of floodplain wetlands limits our capacity to quantify their role in regulating water quality and thereby potentially limits their perceived importance for management and protection.

State of the Science. Most of the insights gained on the watershed-scale effects of NFWs have focused on the cumulative hydrological effects of these systems combined with recent work demonstrating their potential to remove considerable amount of N and P from the landscape.[25] Few studies have directly linked these two concepts—the watershed-scale hydrological effects of NFWs and their capacity to remove N and/or P—to quantify the cumulative effects of NFWs on downstream nutrient conditions.

Early work revealed the potential for NFWs to serve as nutrient sinks, suggesting that they may potentially influence water quality downstream. Whigham et al. in 1988[43] and Johnston et al. in 1990[44] pioneered landscape-scale statistical approaches using spatial data derived from early geographical information system (GIS)-based processing to characterize wetland attributes and relate them to downstream water quality. Using these methods, Whigham and Jordon 2003[35] suggested that the transport of water and its associated solutes and materials from NFWs to downgradient surface waters does, in fact, occur, even if this movement of water is not readily visible during some parts of the year. The authors suggested that the cumulative impact of this transport on water quality and quantity in watersheds with a dense number of NFWs is potentially substantial. Yet for a period following this early work, progress on NFWs and their watershed-scale water quality effects was limited, and NFW impacts on watershed-scale nutrient conditions remained as "potentials".

A wave of studies on NFWs and their hydrological processes then emerged in the first years of the 21st century demonstrating that hydrological transport between NFWs and receiving waters occurs to varying degrees in different systems.[45−48] These works provided a first glimpse of evidence that NFWs influence the amount of water in, and the timing and frequency of water transport to, rivers, streams, lakes, and other wetlands downgradient from them. Therefore, in watersheds with a high density of NFWs, i.e., those with an extensive spatial coverage of NFWs relative to the size of the watershed, their cumulative hydrological influence at a watershed outlet could be substantial.[46,49] However, a recent paper suggests this impact could be somewhat smaller than that of lakes in large river systems, which have higher cumulative storage capacities and multiple nested watersheds.[50]

A second wave of papers has emerged in the past decade (beginning in 2009) demonstrating similar evidence of the cumulative hydrological effects of NFWs in watersheds using measurements,[51−54] network-based modeling approaches,[55] model simulations,[28,30−32,56−59] conceptual linkages of models and data,[60] and reviews of the previous literature.[19,61] Applications of novel measurement methods, such as stable isotopes with remotely sensed wetland inundation data[29] and conservative tracers[33] to track the influence of NFWs on the flow of water in downgradient surface waters have also provided key insights on how NFWs regulate streamflow. These studies demonstrated that NFWs exert a continuum of potential hydrological effects downstream (e.g., on flow rates, magnitudes, and timing), depending on factors such as precipitation and snowmelt, and the distance and location of NFWs in relation to other surface waters.

Fewer studies have directly targeted how groups of NFWs affect downstream water quality, specifically for nutrients. However, some initial findings show promise for NFWs and their watershed-scale effects on nutrient loads. For example, natural NFWs, i.e., those not exposed to irrigation, in the 7.5 km^2 Lerma catchment within the Ebro River Basin in Northeast Spain had the highest rates of nitrate and sediment retention compared to NFWs in irrigated catchments.[62] Because the natural NFWs were also in the lowest part of the catchment, they afforded considerable mitigation of sediment and nutrient loads to the stream.

Other recent research further emphasizes the potential for NFWs to affect downstream nutrient loads yet does not make the direct link. For example, natural NFWs may have greater nutrient removal efficiencies than constructed wetlands largely because of their dense and mature vegetation[63]—and possibly due to their more developed soils. Although the amount of nutrient removal may be higher in individual constructed wetlands because of their high nutrient inputs and large drainage areas compared to natural NFWs, the cumulative effects of multiple natural NFWs on watershed-scale nutrient load reductions may be greater than the individual effects of constructed wetlands. Using a first-order contaminant degrada-

DOI: 10.1021/acs.est.8b07270
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

tion model, Perkins et al.[64] found that reduction of P loads to groundwater discharge was the highest with a random placement of two to five NFWs in the model domain rather than one single wetland.

Additional insights on how NFWs affect watershed nutrient conditions may be gained from research focused on NFWs and the watershed export of nutrient-associated water quality constituents, such as dissolved organic matter (DOM). Hosen et al.[65] demonstrated this link whereby perennial streams with the highest NFWs also had the most elevated DOM concentrations. During the fall and winter when the stream network expanded and connected to NFWs, DOC (a component of DOM) levels peaked. These results are similar to those of Creed et al.,[66] where NFWs (termed "cryptic wetlands" in the paper), explained the majority of the variability in DOC export from a forested catchment.

Studies on disturbances, e.g., temperature and precipitation extremes or other anthropogenic changes such as wetland draining, may provide another window into how NFWs cycle and export nutrients from watersheds. For example, draining a single NFW for agriculture has been shown across studies to impart higher nutrient loads from the field edge.[67,68] Forested NFWs in peatlands revealed similar responses. Specifically, Badiou et al.[24] compared P uptake rates between single drained and undrained NFWs and found that intact individual NFWs may play an important role in mitigating nutrient export downstream.

Drained NFWs can also be sources of P. In several small forested catchments (0.2 to 0.8 km^2) in south-central Ontario, Canada, Pinder et al.[69] used long-term monitoring data to relate disturbance (tree mortality in individual wetlands due to flooding) to increased TP export from the study site. As TP uptake declined and decomposition increased from the tree mortality, export of this new pool of TP increased from the wetland areas. These findings point to potential implications of NFWs for downstream water quality but do not make that direct connection.

Given this piecemeal information regarding NFWs and their cumulative watershed-scale effects on nutrient loadings, we next explore three primary questions:

(1) What knowledge gaps and challenges limit our understanding of the cumulative NFW effects on watershed nutrient conditions?
(2) What emergent concepts from foundational wetland literature advance current understanding of how NFWs across the landscape mediate downstream water quality?
(3) What research will assist in advancing the science of the watershed-scale nutrient impacts of NFWs?

■ NFWS AND WATERSHED-SCALE NUTRIENTS: WHAT WE ARE MISSING AND WHY

Primary Knowledge Gaps. A major 2015 literature synthesis concluded that a NFW located downgradient of a pollution source and upgradient of a stream or river may mediate water quality to varying extents, depending the magnitude, frequency, and duration of its interactions with—or its distance from—those streams and rivers.[70] However, conclusive evidence directly linking groups of NFWs to nutrient conditions in downgradient surface waters is limited. Further, declarative statements regarding the differences in nutrient retention and water quality mediation properties between NFWs and floodplain wetlands also remain minimal.[19,26] While it is clear NFWs have the capacity to receive, retain, and remove nutrients via particulate settling, microbial and plant uptake, and removal to the atmosphere (e.g., denitrification[25,27]), evidence directly connecting groups of NFWs to cumulative watershed-scale nutrient conditions remains a relatively unexplored field of inquiry.

Challenges to Filling These Gaps. Our limited knowledge on understanding the effects of NFWs on downstream nutrient-based water quality directly stems from scientific challenges that can be binned into three primary categories: mapping, measuring, and modeling.

Mapping. One of the primary reasons for the knowledge gap linking NFWs to watershed nutrient concentration or loads is that we simply do not know where many small NFWs are located: they are largely unmapped. Unlike floodplain wetlands, many of which are included in national spatial databases such as the National Hydrography Data set, NFWs are challenging to study and manage when their presence and spatial locations are unknown.[23] Termed "cryptic" wetlands by Creed et al.,[66] NFWs are often not easily located or spatially mapped because they are small, dynamic, and inundated during only portions of the year or are difficult to detect in forested locations with heavy canopy.[71] This is true despite the use of novel radar-based and Light Detection and Ranging (LiDAR) remotely sensed detection methods. While wetland spatial data sets exist, such as the National Wetlands Inventory[72] in the US, these data are often not spatially resolved to capture all NFWs nor updated at regular intervals to account for land use changes. Because we lack information on where they exist, NFW locations vis-à-vis other surface waters are also largely unknown—except for groups of wetlands in large extensive open spaces like the Prairie Pothole Region of North America.

While new methods in detecting the presence of topographic surface depressions[73,74] and surface inundation patters across the landscape[75,76] are developing, determining whether these topographic depressions and areas of inundation are, in fact, NFWs, requires ground-truthing and development of algorithms linking watershed hydrology and the NFWs. This has yet to be done beyond small spatial extents, although this information is needed to consider how to determine protection, restoration, and construction locations properly for optimizing downstream water quality.

Measuring. We lack measured data linking the timing and magnitude of nutrient retention in NFWs to that of water quality conditions across watersheds. Whigham and Jordan[35] in 2003 pointed out the need for wetland monitoring data, e.g., water levels and water chemistry, across different physiographic settings where data are lacking. This remains a need over 15 years later. Ardon et al.[77] also noted that restoring multiple wetlands across watersheds requires measuring both organic and inorganic forms of N and P and the coupled transport of both key nutrients. This is particularly notable given recent evidence of the efficacy of jointly managing N and P rather than focusing on a single nutrient.[4]

Empirical data are increasing on how NFWs affect the hydrology across watersheds,[26,29] yet we continue to lack similar data connecting NFWs to water quality conditions. While it is resource intensive to measure direct links between nutrient removal rates of multiple wetlands and the magnitude and timing of variations in downstream nutrient-based water quality, data gains and improved understanding may outweigh the costs. However, even with resource investments, NFWs are often small and numerous, which makes them challenging to measure (and

DOI: 10.1021/acs.est.8b07270
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model) for their cumulative watershed-scale effects. Additionally, in specific regions, such as the Prairie Pothole Region in North America, wetland drainage areas are nested—meaning their effects on watershed-scale nutrients conditions are not independent of each other. Finally, in large river basins, it is challenging to discern the effects of NFWs compared to fluvial wetlands and lakes. Because these relationships are nonlinear, the signal of NFWs may be difficult to detect.

Modeling. Process-based watershed models are primary tools for understanding how NFWs cumulatively affect nutrient loads at watershed scales. Process-based watershed models represent and simulate watershed-scale hydrological (e.g., rainfall-to-runoff) and biogeochemical (e.g., nutrient cycling) processes, and output streamflow and water quality concentrations or loads to fluvial systems. These models theoretically allow a scientist or manager to ask "what if" scenarios regarding the placement of constructed wetlands and the optimal selection of restoration or conservation of existing wetlands for desired surface water nutrient levels.[40] For example, scenarios may be developed to project how different NFW spatial arrangements or physical characteristics, such as area and volume, and their buffering capacity to disturbance, e.g., climate change, influence downstream water quality.

Improved mapping and monitoring of NFWs refines input data for models.[78] These improvements also assist in advancing spatial optimization techniques, which are gaining popularity for locating wetland restoration or construction sites in watersheds based on an identified outcome, e.g., reducing watershed N and P loads. However, without improving the hydrological and biogeochemical processes in watershed models, better input data may result in limited gains.[79] We know a lot about individual wetland processes, and this knowledge has been integrated into individual wetland, or plot-scale, models. In fact, marked refinements have been made in recent years in simulating individual wetland nutrient biogeochemistry.[80,81] However, most watershed models have limited capacity to simulate both nutrient cycling in multiple NFWs across the landscape and the hydrological transport processes that link nutrient fluxes from NFWs to other surface waters[17,82]—in part because of the complexity and variability of these processes.

Additional challenges exist because coupling NFWs to hydrology and water quality simulation models is not straightforward. Complex GIS formats, large data volumes, and most importantly, data inconsistency with the models' spatial resolution and geodatabase architecture (e.g., grid-cells, subbasins or variable mesh) have made NFW integration in watershed models a "big data" problem. This is likely the reason why wetland-integrated flood, drought, and pollution forecasting models, especially at large, continental scales, do not exist—despite the potential influence of wetlands on water and ecosystem services. Further, it is challenging to calibrate a model for wetlands at watershed scales when limited wetland data, e.g., stage height or nutrient concentrations, are available.

NFWs therefore typically remain disregarded in watershed-scale modeling efforts, and they are only now beginning to be directly implemented into model simulations[17,83]—particularly for water quality.[80] Previously, in rare cases where wetlands were considered in a process-based model, NFWs were grouped with floodplain wetlands or spatially aggregated (lumped) by watershed, e.g., as with the soil and water assessment tool (SWAT) model. This limitation has been emphasized in recent work that makes advances toward direct, spatially explicit integration of NFWs into watershed models for water quantity simulations.[31,56]

An important implication of the lack of NFW integration into watershed water quality models relates to the simulation of future water quality conditions. Most watershed modeling used to predict future N and P loads in response to changes in land management and future climate variations (e.g., temperature and precipitation extremes) does not directly consider NFWs in model simulations. This can potentially result in misleading or inaccurate predictions and a scientific void in understanding the role of these systems on a watershed's water quality.

These challenges lead us to ask: what insights emerge from the foundational wetland literature to advance scientific understanding of the cumulative NFW effects on watershed-scale nutrient levels (e.g., concentrations, loads)?

■ EMERGENT CONCEPTS: ADVANCING NFW KNOWLEDGE

Previous wetland research provides insights on how NFWs potentially affect watershed-scale nutrient conditions. Based on the extensive body of research and historic use of wetlands as nutrient retention features, we would expect similar mechanisms of nutrient retention in NFWs compared to floodplain wetlands[70]—even if some variations exist.[41] Additionally, although the hydrological processes of NFWs range widely in their spatial and temporal interactions with downstream waters compared to floodplain wetlands,[19,26,42,49] concepts emerging from previous research may underpin and foster future research questions assessing the mechanisms by which NFWs mediate watershed-scale water quality. Here, we present 3 primary concepts that emerged from a synthesis of the general wetlands literature that are potentially transferrable to NFWs.

Concept 1. Knowledge Regarding Individual Wetland Nutrient and Retention Mechanisms May Be Applied to NFWs. This is the most basic of the emergent concepts: wetlands are often constructed or restored to capture and retain nutrients specifically, and knowledge about individual wetland N[84] and P[85] processing can likely be extended into NFW research. In fact, recent research formalized the potential efficacy of NFWs as nutrient processing powerhouses[26,27,31]—and some restored and constructed wetlands are NFWs. Therefore, how NFWs process nutrients may, in similar settings, be comparable to those restored or constructed for receiving agricultural[77,86−92] and stormwater[93−95] runoff.

Concept 2. Wetlands Cumulatively Affect Watershed Nutrient Conditions. Research within the past decade provides glimpses into the cumulative role of all wetlands, i.e., the combined effect of NFWs and floodplain wetlands, on watershed-scale nutrient conditions—in both mixed land use and agricultural watersheds[18,96−105] and for watershed-scale stormwater management systems.[106−110] These studies support hypothesis-driven research on the cumulative effects of NFWs exclusively. The drivers of these cumulative effects are, in part, related to evidence supported by the literature, including:

- ***The areal wetland extant of wetlands in a watershed influences their impact lon nutrient-based water quality conditions,***[13,107,111,112] although results are highly variable and watershed-dependent. However, estimates calculating the percent of wetland restoration needed to reduce N and P loads may inform expectations of similar (yet currently lacking) research on NFWs.

DOI: 10.1021/acs.est.8b07270
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

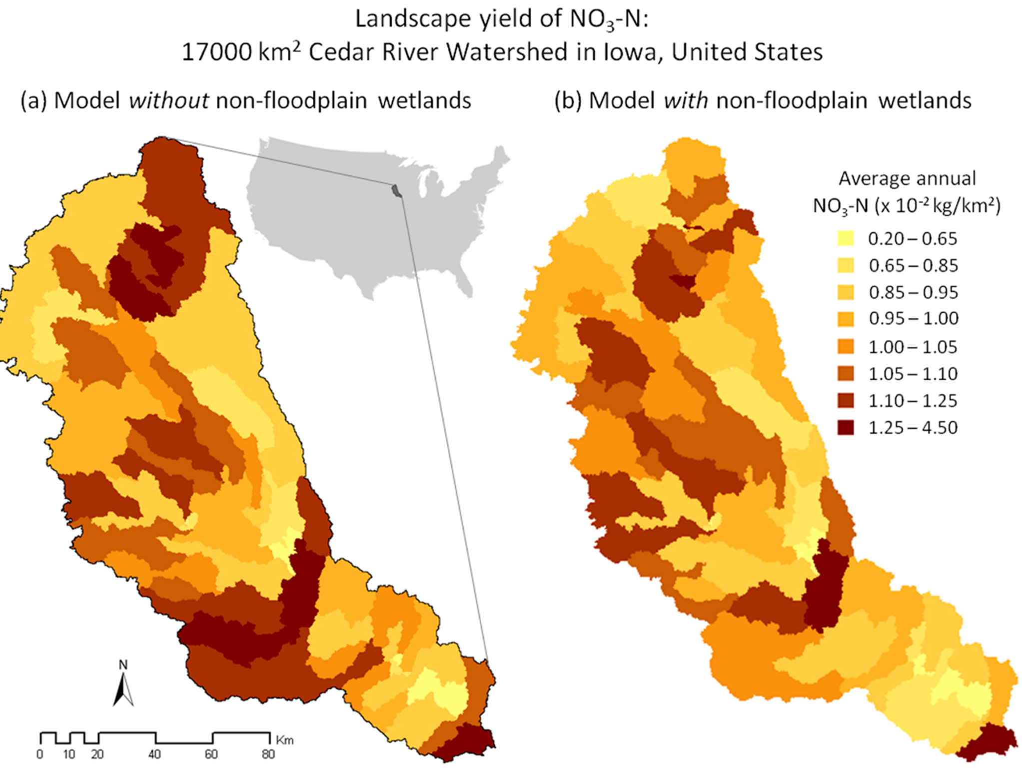

Figure 4. Comparison of simulated nitrate-N (NO_3-N) when the model was constructed (a) without and (b) with non-floodplain wetlands (NFWs). Values represent 9-year (2009−2017) average annual subbasin yields of NO_3-N ($\times 10^{-2}$ kg/km^2). We found ∼7% reduction in average annual NO_3-N yields across the subbasins when NFWs were integrated into the model.

- ***The watershed size to wetland areal extent ratio matters vis-à-vis wetland capacity to influence downstream nutrient conditions.***[96,113,114] This is a transferrable concept for NFW protection, restoration, and construction. Similarly, the variability in the contribution of wetland restoration to watershed-scale nutrient load reductions can be, in part, associated with the magnitude of N and P loadings to the wetlands and the land cover draining to the wetlands.[102] This emphasizes the need to consider N and P loads to the NFWs and watershed sizes when identifying the location of NFW conservation, restoration, and construction.
- ***Wetland characteristics, including their location and spatial arrangement in a watershed, influence the extent to which they mediate water quality.*** The location of wetlands in a watershed matters for mediation of streamflow and reducing nonpoint source pollution, a generalized concept applicable to NFWs.[115] For example, wetlands closer to water bodies may be more effective mediators of water quality than those further away from other surface waters.[44,109,116] Moreover, the spatial arrangement of wetlands, or the location of wetlands vis-à-vis other wetlands and the fluvial system, has a regulating effect on nutrient concentrations downgradient from the wetlands[18]—a transferrable concept to NFWs.

Concept 3. Targeted Wetland Construction May Increase the Efficacy of Watershed-Scale Wetland Nutrient Retention. Using a targeted approach for placing wetlands in watersheds, e.g., based on site conditions and position in the watershed compared to N and P loads and receiving waters, may lead to more substantial watershed nutrient load reductions compared to simply increasing wetland watershed coverage.[117,118] This concept could be readily applied to construction and restoration of NFWs. For example, spatial optimization approaches to select the most appropriate NFW sites based on targeted nutrient load goals and watershed and wetland characteristics are currently gaining traction.[119,120]

WHERE DO WE GO FROM HERE? INTEGRATING NFWS INTO WATERSHED MODELS

Process-based watershed modeling used to project the changes in N and P yields (or loads, fluxes, or concentrations) to different anthropogenic drivers of change, e.g., climate extremes and land management, traditionally do not integrate NFWs into their model simulations. Therefore, assimilating NFWs into process-based modeling affords a critical first step to advancing the science of the cumulative effects of NFWs on watershed-scale nutrient conditions. In this section, we explore how watershed nutrient yields differ across a landscape when NFWs are directly assimilated into a process-based watershed model, compared to the traditional method of excluding NFWs. Directly assimilating, or integrating, NFWs into these models means that the water balance and biogeochemical cycling of NFWs, and transport of water and chemicals out of the NFWs, are explicitly included and simulated in the model. Here, we provide an exemplar of the degree to which integrating NFWs into a watershed model changes projections of nutrient yields across the Cedar River Watershed, a 16 860 km^2 basin in Iowa, US. This watershed was selected because of its abundance of NFWs and publicly available streamflow and nutrient data for model calibration.

Model. For this exercise, we used the SWAT model and discretized the landscape into 95 subbasins. We calibrated two versions of the model in the Cedar River Watershed: (1) a model that uses the traditional model setup without directly integrating

DOI: 10.1021/acs.est.8b07270
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NFWs, i.e., NFWs are classified as a land cover to estimate a rainfall-runoff coefficient, and (2) the same model but with the deliberate inclusion of NFWs and their associated nutrient and hydrological processes. Each model is separately calibrated at a daily time step from 2009 to 2012 (verification 2013−2017) to streamflow at 5 sites throughout the watershed and daily N (here, NO_3-N) loads at the watershed outlet (US Geological Survey Gage 05464500 Cedar River at Cedar Rapids, Iowa; Figure S2). Detailed model descriptions, set up, and calibration information can be found in the Supporting Information.

Results. The NO_3-N yields per watershed subbasin in the two calibrated models are considerably different (Figure 4) even though the time series at the watershed outlet appears similar (Figure S3). Directly integrating NFWs into the model, without changing anything except the inclusion of NFWs, results in lower average annual NO_3-N yields across the watershed. We found ~7% reduction in average annual NO_3-N yield (over a span of 9 years from 2009 to 2017) across the watershed's subbasins when NFWs were incorporated in the model. This suggests that, with few exceptions, the presence of NFWs in the model affords NO_3-N attenuation and surface water storage that mediates, and decreases, average annual subbasin yields of both.

Previous studies have shown how NFWs directly influence the length of water storage timing across the landscape, i.e., residence times, and water yields at the watershed outlet.[28,31] However, the simulations presented here for the Cedar River Watershed provide a first window into the variability and differences of NO_3-N fluxes when NFWs are directly integrated into watershed models. The explicit inclusion of NFWs in watershed models may therefore have implications for projected watershed nutrient load responses to future scenarios of anthropogenic changes, such climate change and land management activities. It also provides insights into how NFWs may influence nutrient yields across a watershed.

■ WHERE DO WE GO FROM HERE? FUTURE RESEARCH RECOMMENDATIONS

Wetlands have been lost at prodigious rates over the past century,[22] and this is particularly true for NFWs.[23] Accompanying this loss is a decrease in the functions NFWs provide, including those related to nutrient removal processes. Therefore, a decline in NFW abundance in the landscape may play a considerable role in contributing to the intensity of eutrophication and harmful algal blooms in freshwater,[2] lake,[121] and coastal[1,3] systems. In this paper, we synthesize where the science stands regarding the watershed-scale effects of non-floodplain wetlands on nutrient-based (N, P) water quality, describe current research challenges, and identify emergent concepts from foundational studies on wetlands that may advance future NFW research. We further develop simulations comparing nitrate-N yields in a watershed model with and without NFWs. Results suggest that by disregarding NFWs in watershed models, projections of nutrient loads may be uncertain and therefore may have critical implications for model simulations of nutrient responses to future climate conditions and land management.

On the basis of the literature synthesis and modeling exemplar we present herein, it is evident more research is needed on how NFWs mediate watershed-scale nutrient loads. This elicits the question: where should NFW watershed-scale research go from here? We provide several recommendations as a start—noting that additional socioeconomic-related recommendations for the future of NFW (and other wetland) research and management are addressed elsewhere (e.g., ref 5). Our recommendations reflect the needs and challenges described in "NFWs and Watershed-scale Nutrients: What We are Missing and Why".

Mapping. *1. Improve Mapping of NFW Locations and Their Spatial Arrangement in Watersheds.* With the recent widespread availability of high-resolution topography data and satellite imagery (i.e., "big data") along with improved geospatial analyses techniques, detection of surface depressions, which may be NFWs, at large spatial scales is now increasingly possible.[73,74] However, we need to apply these methods while simultaneously developing algorithms to close the gap between identifying surface topographic depressions and linking those to mapped NFWs.

Measuring. *2. Advance Long-Term Water Quality Monitoring of NFWs at Watershed Scales.* Long-term data afford interpretation of water quality responses to loss or restoration of wetlands, in combination other drivers of change, e.g., future precipitation and temperature variations,[99] and provides improved data to calibrate and verify models used to project these changes. Additionally, garnering long-term monitoring data sets linking wetland nutrient concentrations to watershed nutrient loads to downstream waters in different physiographical provinces and ecoregions would provide insights to the processes governing wetland-to-stream nutrient conditions.

Measuring and Modeling. *3. Advance Interoperable Tools and Platforms To Make NFW "Big Data" Discovery, Processing and Model Assimilation Efficient for Research Scientists and Managers.* Having an efficient means to integrate new LiDAR-based NFW information into models, such as those estimating wetland storage capacities across landscapes[122] and models simulating water quality and quantity effects of NFWs,[30,56] is important to improve model calibration and therefore the accuracy of model projections.[123]

Modeling. *4. Apply Novel Computational Approaches for Targeting NFW Restoration Locations Using a Watershed-Scale Framework.* Spatial optimization approaches for identifying optimal locations for NFW conservation, restoration, and construction are necessary for moving the research forward. Combined with this, using multiple lines of evidence from measured data, spatial data analysis, model simulations, and site cost−benefit analysis for NFW (and other wetland) restoration, e.g., for improving watershed nitrate removal and loads,[124] may also maximize the success of watershed-scale restoration.

5. Integrate NFWs, as Important Surface Water Storage Features and Landscape Biogeochemical Processors, into Models Projecting Future Watershed-Scale Nutrient Responses. We demonstrate in this paper that disregarding NFWs in modeling watershed-scale nutrient loads (here, nitrate-N) produces potentially biased model projections and different responses. This is important for research projecting future watershed-scale nutrient concentration, load, or flux responses to drivers such as land management, climate variations, other potential disturbances, e.g., fires, particularly in systems with dense NFW populations in relation to a watershed's area.

6. Couple Recent Improvements in Modeling Wetland Nutrient Biogeochemistry with Watershed-Scale Models. Progress is needed in coupling refined wetland biogeochemistry models with multiple wetlands and hydrological transport models, while at the same time considering the trade-offs between model complexity and resources (e.g., computational time, funding resources, research scientists) to make this

DOI: 10.1021/acs.est.8b07270
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happen. A careful focus on model fidelity (i.e., the extent to which physical processes are represented) within individual wetlands is needed when scaling these processes to large river basins. Further, by necessity this upscaling requires simplifying process representation for watershed-scale scientific questions and management.[125]

7. Jointly Consider Nutrient Loads to NFWs with the Spatial Arrangement of NFWs in Research To Identify Watershed Locations That May Most Efficiently Respond to Conservation or Restoration. This recommendation is based on calls in the literature over the past several decades that targeted conservation, restoration, and construction of wetlands for water quality management practices need to be combined with efforts to reduce loads to them (e.g., refs 111, 126). Specifically considering the spatial arrangement of NFWs with regard to where the highest loads are occurring may be an important approach for future research and management[124]—as well as considering the stoichiometry of nutrients with constituents that affect N and P wetland processes at potential wetland restoration sites.[127] These approaches could be combined with #4.

8. Codevelop Refined NFW-Integrated Watershed Models with Practitioners. While this recommendation does not directly emanate from the stated challenges, it is important to recognize that as science and management are simultaneously evolving with regard to the current knowledge of how NFWs function and cumulatively "scale up" to affect downstream water quality, improved models for NFWs and water quality should be codeveloped with practitioners, such as land managers, who use the models.[128] Translational research and science methods have recently gained momentum in the ecological sciences.[129] Research scientists, watershed modelers, and land managers can bring together knowledge and resources to apply these approaches to advance scientific knowledge effectively for nonpoint source management in watersheds using wetland-based approaches.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b07270.

> Description of how wetland loss was calculated for Figure 3, and documentation (description, tables, figures) of the SWAT model set up, including parameter values, calibration procedures, and model evaluation (PDF)

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The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We appreciate helpful suggestions from Brent Johnson and Tim Canfield, in addition to the anonymous journal reviewers. We also thank Ellen D'Amico and Katherine Loizos for graphical assistance. This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Statements in this publication reflect the authors' professional views and opinions and should not be construed to represent any determination or policy of the U.S. Environmental Protection Agency.

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DOI: 10.1021/acs.est.8b07270
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