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The land use legacy effect: looking back to see a path forward to improve management

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Abstract

Water quality has suffered as humans have increased nutrient inputs across the landscape. In many cases, management actions to reduce nutrient inputs have not been met with concomitant ecosystem responses. These missed expectations are partly due to the continued slow delivery of nutrient-enriched groundwater pre-dating input reductions resulting from management actions. Land use legacies as expressed through this time lag are important to quantify in order to adjust management expectations. We present a novel coupling of nitrogen source maps with groundwater transport times to create a high-resolution (120 m) fully distributed estimate of the timing and magnitude of groundwater nitrogen deliveries to surface water across Michigan's Lower Peninsula. This new view of the landscape has been designed around common management timelines for: elected officials looking to make a difference for re-election (<5 years), career managers hoping to see the fruits of their labor (5–30 years), and advocacy groups whose work can span generations (>30 years). One striking result is that after 100 years, in our study area, approximately 50% of the nitrogen that enters the groundwater system remains in transit. This means that actions taken now may not show the expected lower nitrogen loads to receiving ecosystems for decades to centuries. We show that differences in groundwater travel times create a heterogeneous patchwork over which managers can prioritize actions to best match their targeted response times. Across the highest nitrogen inputs in our study region, less than 10% had short enough groundwater legacies to match the management timeline of most government and agency work. Agricultural practices (manure and chemical fertilizer) are the main nitrogen contributors across the top three management classes; however, human contributions through septic tank effluent and lawn fertilizers contribute 5%–8% of nitrogen.

1. Introduction

Since the mid-20th century, humans have altered nitrogen (N) cycling both through growing human and livestock populations and extensive use of chemical fertilizers (Vitousek *et al* 1997, Galloway *et al* 2004). Increases in nutrient applications have led to water quality challenges that harm humans and ecosystems, including increasing invasive species populations in coastal wetlands (Elgersma *et al* 2017, Hannah *et al* 2020), massive algae blooms in lakes (Paerl *et al* 2013, Watson *et al* 2016, Wurtsbaugh *et al* 2019), eutrophication in coastal estuaries (Howarth *et al* 1998, Zhou *et al* 2013, Fennel and Testa 2019), and higher concentrations of nitrate in shallow drinking water wells (Nolan and Hitt 2006). Remediation efforts typically begin with improving nutrient removal in wastewater treatment plants, which represent the most common point source nutrient input to surface waters (Puckett 1994). However, managing nutrient contamination from nonpoint sources that are applied broadly across the landscape, like fertilizer, manure, and septic effluent, is particularly difficult due to their diffuse nature. Unlike point source pollutants, these nonpoint nutrient sources are challenging to locate, quantify, and manage; they contribute to aquatic ecosystems via both surface and groundwater pathways. This suite of complexities can often make it difficult to understand if management actions are effective at reducing environmental degradation.

Recent nonpoint nutrient management efforts have focused on reducing the use of chemical agricultural fertilizers and manure through best management practices (BMPs) to limit nutrient fluxes into streams and lakes (Johnston and Bruulsema 2014). Many BMPs focus on reducing surface applications and nutrient transport via surface runoff, including identifying efficient timing and amounts for crop fertilization, using no-till practices, planting cover crops, or installing riparian buffer strips (Cole *et al* 2020). However, despite the widespread implementation of such practices (e.g. Kalcic *et al* 2018, Seifert *et al* 2018, Azzari *et al* 2019), water quality has not significantly improved (Liu *et al* 2017, McCrackin *et al* 2017, Lintern *et al* 2020). Studies have found that groundwater underlying many agricultural areas contains elevated nutrient concentrations due to fertilizer leached from soils into the unsaturated (Wang *et al* 2013, Turkeltaub *et al* 2018) and eventually saturated groundwater system (van Meter *et al* 2016, Hansen *et al* 2019, Yang *et al* 2020). This nutrient-enriched groundwater can then be transported along subsurface flowpaths, eventually emerging in down-gradient ecosystems over a wide range of timescales (Robinson *et al* 2015, Paradis *et al* 2018, Turkeltaub *et al* 2018). This potentially unanticipated nutrient pathway plays an important role in obscuring the positive effects of many management actions. However, advances in BMP development and implementation, including bioremediation, can in some cases intercept or remove nitrogen before waters reach streams or public supply wells (Critchley *et al* 2014, Rudolph *et al* 2015). Such developments offer an approach to mitigate pollutants already in the system.

Land use legacies can be defined as: 'those effects that continue beyond some expected or perceived endpoint in time' (Martin *et al* 2011). This concept has been investigated through the effects of historical changes in land use/cover on stream and lake nutrient concentrations (McTammany *et al* 2007, Martin *et al* 2011), fish and macroinvertebrate biodiversity (Harding *et al* 1998), and changes in sediment flux (Bain *et al* 2012). While legacy effects result from multiple mechanisms, transport delays via groundwater pathways are an important issue (U.S. Geological Survey 2019) that has recently been explicitly investigated (Martin *et al* 2017). This lesser studied and managed component of nutrient contamination involves the flux of nutrients via groundwater, where travel times range from years to decades and even centuries. In a recent study, Johnson *et al* (2020) report on the increasing importance of groundwater contributions to stream nitrate loading across the continental United States. Other studies quantifying slow unsaturated zone travel for nitrate in the Chalk aquifer of England showed decades-long travel times before even reaching the water table (Jackson *et al* 2006, 2007). Another research team dubbed their model the 'Nitrate Time Bomb', highlighting potentially unrealistic expectations of management efficacy due to the long lag time of nitrate travelling through unsaturated zones (Wang *et al* 2013, 2016). As a result, management actions taken today may take decades to show observable results in streams and lakes that continue to receive nutrient-enriched groundwater through these slow pathways, also referred to as lag time (Phillips and Lindsey 1999, Jackson *et al* 2008, Meals *et al* 2010, Vero *et al* 2018).

Here we build on a foundation of nutrient legacy research using new high-resolution maps of nonpoint nutrient inputs along with estimates of groundwater-specific transport pathways to help managers develop improved strategies for resource management and pollution mitigation. Our objective is to offer an answer to the question: how long will current land use practices (nutrient applications) continue to affect future water quality via groundwater? We frame our results from the perspective of the multitude of stakeholders that engage in resource management, divided into three groups: those with short-term (perhaps political) timeframe (<5 years), others that may include career managers (between 5 and 30 years), and finally those with a long-term interest such as advocacy organizations or individuals (>30 years).

2. Methods

2.1. Study area

We demonstrate our approach for Michigan's Lower Peninsula (LP), located in the heart of the Laurentian Great Lakes, which represents the world's largest surface freshwater resource (Herdendorf 1982). The region is a model system to study groundwater-driven land use legacy issues due to the wide range of groundwater influence on total annual streamflows (Neff *et al* 2005), aquifer geologic materials and hydraulic conductivities (Farrand and Bell 1982), and shallow aquifer thickness (Soller and Garrity 2018). While water quality and ecosystem health are good across much of the Great Lakes Basin, substantial portions of this basin are under stress, with broad areas of eutrophication and rapid increases in algal bloom size and duration in Lakes Erie and Michigan (Michalak *et al* 2013, Klump *et al* 2018, Manning *et al* 2019). These detrimental impacts affect all uses, imperiling both ecosystem and human health (Nolan and Hitt 2006, Verhougstraete *et al* 2010, Jetoo *et al* 2015). Regional stakeholders have long recognized these issues and have worked for decades to reduce nutrient inputs to aquatic ecosystems (Botts and Muldoon 2005, Jetoo 2018). More recently, bi-national action plans across the US and Canada have called for reductions of nutrient loads to the lakes, including a 40% reduction of P to Lake Erie from 2008 levels—noting that N loads are expected to decrease concomitantly (USEPA 2018).

Michigan's LP has large swaths of agricultural, forested, and urban land uses, which translates into a diverse range of nitrogen sources and management practices (Homer *et al* 2015). Agriculture in this region ranges from intensive corn-soy rotations in the southern and central portions of the state, to potato cultivation in the central and northern areas, to the fruit belt along the coast of Lake Michigan (USDA NASS 2019). Soil types span the entire range of textures, from coarse sands to heavy clays (Soil Survey Staff 2020). These soils overlay a Quaternary geology of glaciofluvial deposits from glacial advances and retreats, leaving behind sediments that range from low hydraulic conductivity (K) lacustrine deposits and fine textured tills, to high K coarse outwash deposits (Farrand and Bell 1982). Thicknesses of this unconsolidated glaciofluvial aquifer system vary from essentially absent to more than 300 meters (Soller and Garrity 2018). Groundwater contributes the majority of water that eventually flows to surface water across the region (Wollock 2003) due to the humid continental climate (Koppen–Geiger classes Dfa and Dfb, Kottek *et al* 2006) and high hydraulic conductivity aquifer materials.

2.2. Conceptual framework

We leverage two high spatial resolution datasets to classify the study area into groundwater nitrogen management-focused classes. First, we enhance a nutrient transport model and incorporate saturated groundwater travel time, driven using a spatially explicit nutrient source map (both described below and in supplementary material). The resulting estimates of groundwater-borne nitrogen loadings to surface water are divided into 'high' loading (top 25%) and 'lower' loading (bottom 75%). We classify groundwater paths into 'short' (<5 years), 'medium', (5–30 years), and 'long' (>30 years) travel times. We then juxtapose these classifications of nutrient load and expected travel time to create management classes relevant to stakeholders.

2.3. Groundwater nitrogen loads

Nitrogen loads to streams through groundwater were quantified using the *Spatially Explicit Nutrient Source Estimate* framework input *maps* (SENSEmap) and *flux* model (SENSEflux) (Hamlin *et al* 2020a, 2020b, Luscz *et al* 2015, 2017). The SENSE framework estimates nitrogen and phosphorus inputs to the landscape circa 2010 (here we focus on N) and fluxes across the landscape from point sources and six nonpoint sources. The six nonpoint sources are chemical agricultural fertilizer, manure, nitrogen fixation from legumes, chemical non-agricultural fertilizer, septic tanks, and atmospheric deposition. Nutrient inputs (SENSEmap) are derived from remote sensing products (e.g. land cover, crop classifications), government records (e.g. USDA Agricultural Census, county-level fertilizer inputs, drinking water well databases), and scientific literature (e.g. atmospheric deposition studies, nitrogen fixation equations). Figure 1(B) shows total N input to the landscape from SENSEmap at 30 meter resolution.

SENSEflux is an updated version of the statistical nutrient transport model first described by Luscz *et al* (2017). These updates are described in the supplementary material, including a diagram detailing the model framework (figure S1 (available online at stacks.iop.org/ERL/16/035005/mmedia)). Briefly, SENSEflux uses a Geographical Information System (GIS) and statistical modeling framework to estimate the fate and transport of nutrient inputs through surface and groundwater pathways, based on calibration to nutrient loads delivered to the in-stream sampling locations (Robertson *et al* 2011, Read *et al* 2017). Surface pathways include both overland routing (both water and sediment) and flow through agricultural tile drains. Groundwater pathways include transport through bulk groundwater as well as via septic plumes. Each pathway has calibrated coefficients to quantify distance-dependent loss rates of total N and P from the sources within each point on the landscape to the receiving water body. The model also includes nutrient loss via crop harvest, in-place removal of nutrients within septic systems, and long-term storage in the soil and deeper unsaturated zone. For this study, we use the total N load delivered to nearest downgradient streams via groundwater pathways at 120 meter resolution, as SENSEflux incorporated aggregated SENSEmap inputs for modeling (figure 1(C)).

2.4. Groundwater travel times

Here, we apply a relatively simple method to estimate groundwater travel times. Water table (figure S4) and aquifer hydraulic properties (figure 2(A)) across Michigan's LP were calculated using data from a state-wide drinking water well database ($n > 270\,000$, Michigan Wellogic dataset, 2019). We use a GIS and data-driven method to estimate groundwater travel times at each 120 m pixel across Michigan's LP (figure 2(B)). This approach, similar to methods applied in Pijanowski *et al* (2007), Ray *et al* (2012) and Martin *et al* (2017), and described in detail in the supplementary material, involves the following steps: (a) interpolate water level measurements from wells to produce a map of the regional water table, (b) compute groundwater flow directions, and (c) calculate travel times along flowpaths from each cell to receiving waters in streams, lakes, or wetlands. These

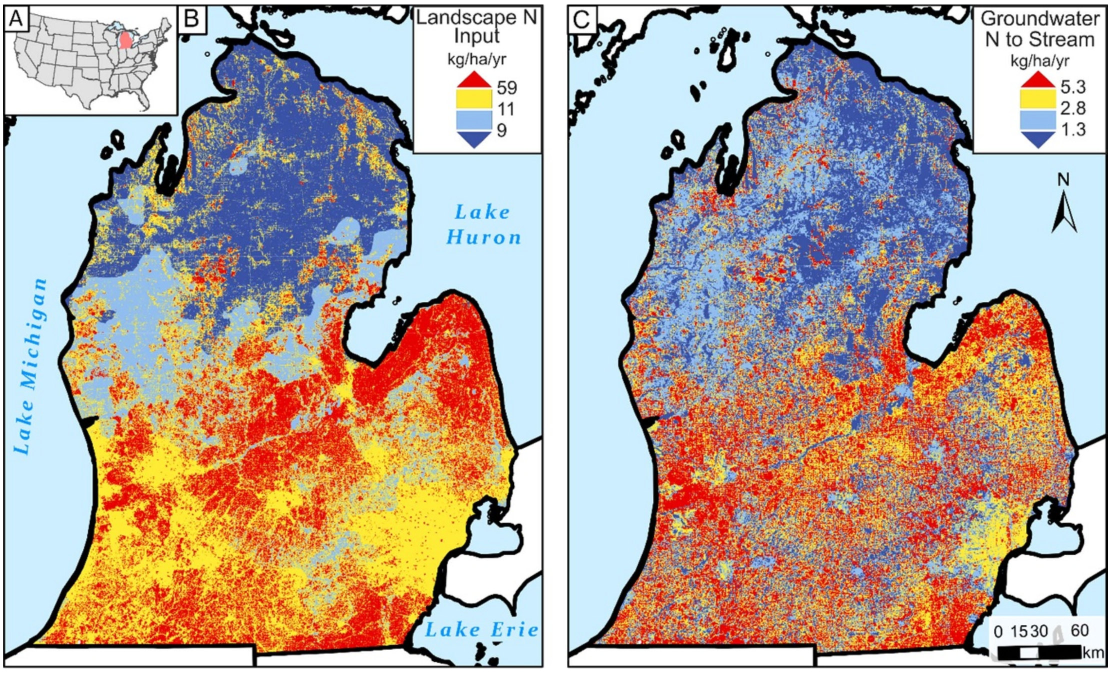

Figure 1. Study area map showing nitrogen data used in analysis. (A) Continental US locator map, (B) estimates of total nonpoint nitrogen inputs (kg ha yr^{-1}), and (C) total nonpoint nitrogen delivered to streams via groundwater (kg ha yr^{-1}). Maps are classified in quantiles, with each color representing 25% of the study area.

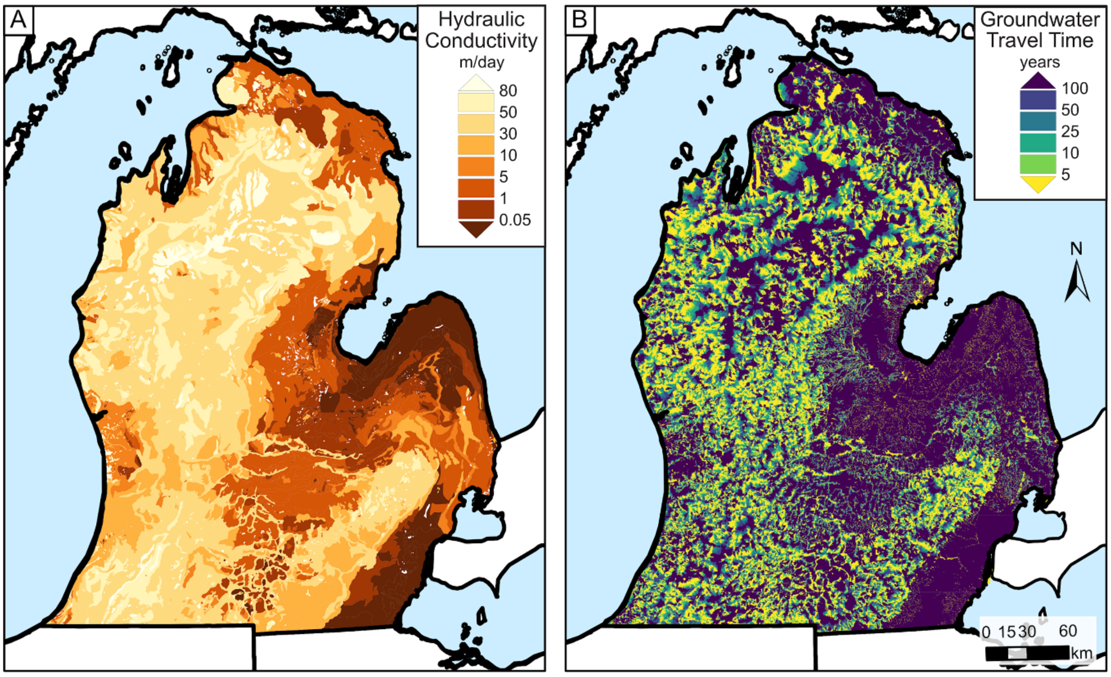

Figure 2. Estimates of (A) hydraulic conductivity (m d^{-1}) and (B) groundwater travel time (years to nearest stream).

groundwater travel times are then used as part of defining management classes, described in the next section.

We note that in areas with low K values, travel time estimates can become quite long (greater than 500 years in some cases). While this may be accurate, based on our research in this region, there can be order of magnitude uncertainties in low K values, thus we truncate the traveltime distribution where estimates exceed 100 years.

Our intent with this paper is to focus on how a spatially explicit understanding of likely nutrient loads and travel times can lead to more informed planning, considering the simulated future legacy of

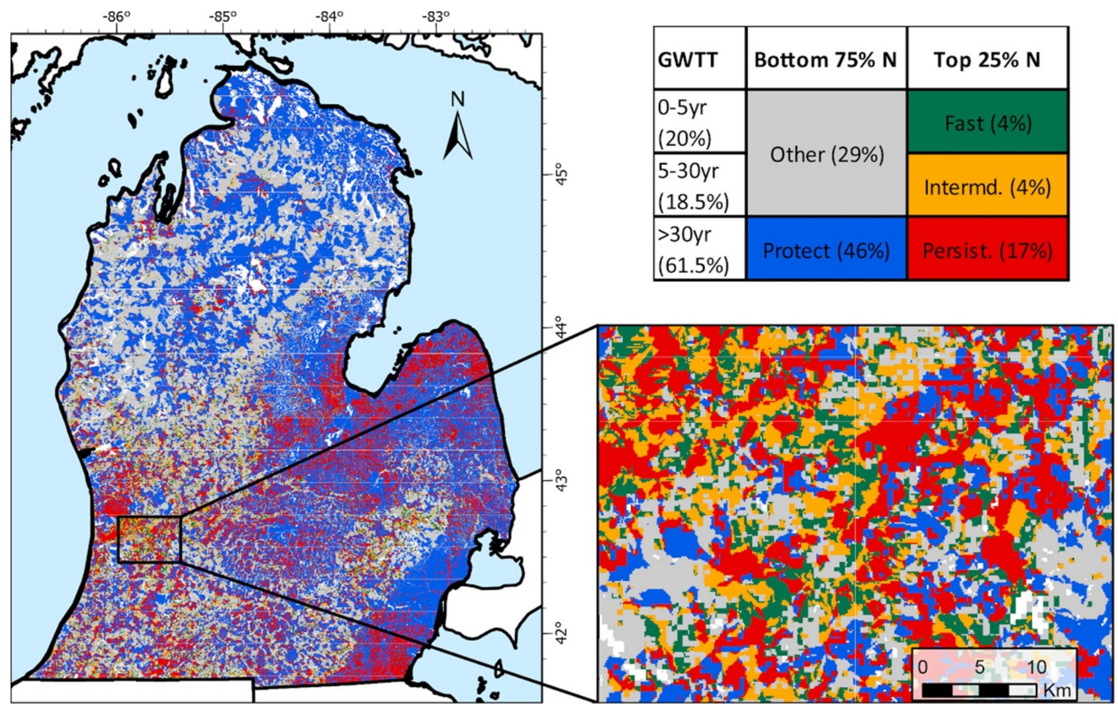

Figure 3. Management classifications across the study area with a zoom box to show the patchwork nature. Colors in table are indicative of management class assignment. The table highlights the structure of management classes as divisions of groundwater travel times (GWTT) and groundwater delivered nitrogen loads. Percentages are reported for each division.

current land use. We argue that a more complex groundwater travel time model would likely not significantly reduce uncertainty at this regional scale, though we do recommend that for more targeted planning efforts local-scale travel time characterization be undertaken. Further, because the LP of Michigan is nearly entirely covered by quaternary-age glacial drift sediments of varying thickness, we focus on travel times within the shallow surficial aquifers.

2.5. Defining management classes

We created 'management classes' that correspond with the interest timeframes of three main stakeholder groupings: elected officials, regulatory agencies, and advocacy groups. We characterized a potential timeline within which measurable results would likely be observed by dividing our estimated groundwater travel time data into three categories corresponding to these identified stakeholder groups: less than 5 years, 5–30 years, and greater than 30 years. Then, we assume that cells with groundwater nitrogen deliveries to streams in the top 25% (for the study area) are where management actions would be expected to have the most significant effect. The combination of high-delivery cells with the three groundwater travel time divisions create the 'Fast', 'Intermediate', and 'Persistent' categories (figure 3). We then subdivide the relatively lower nitrogen delivery areas (bottom 75%) into those with long groundwater travel times as the 'Protect' category, and those with short to medium travel times as 'Other', as they are less likely to specifically relate to management targets and timelines. These five different management classes frame our discussion.

Defining nutrient management thresholds using quartiles rather than defining manual thresholds in nitrogen deliveries limits the total area that can be in the 'Fast', 'Intermediate', and 'Persistent' categories and creates a structure that prioritizes target areas. Additionally, determining thresholds manually for nutrient deliveries would not be appropriate without knowing the full fate and transport through groundwater in a region.

3. Results and discussion

The groundwater component of land use legacies integrates surface inputs, fractional delivery of those inputs to the groundwater system, and groundwater travel times to receiving surface water bodies (excluding delays in the soil or unsaturated zones). Our approach uses novel high-resolution data products that estimate surface nitrogen inputs (SENSEmap), a fate and transport model that estimates groundwater-specific deliveries to water bodies (SENSEflux), and estimates of groundwater travel times. Synthesizing this information to locate areas where the combination of conditions results in 'hot spots' (e.g. high groundwater delivery of nutrients and faster groundwater travel times) provides a valuable resource to help stakeholders prioritize limited resources for management actions. It is also critical for planners to understand that slower groundwater travel times delay the benefits of management actions, and thus is important to temper expectations of positive benefits in short time periods.

Here, we provide high-resolution (120 m) fully distributed estimates of the timing and magnitude of groundwater nitrogen deliveries to lakes and rivers across Michigan's LP. Bulk groundwater travel times vary widely, as does the scale of variability (figure 2(B)). Some areas of the study region feature exclusively longer travel times—driven both by low hydraulic gradients (figure S4) but also by low hydraulic conductivity (figure 2(A)). Aggregating N deliveries (figure 1(B)) by groundwater travel time, we find that half of the N transported through this groundwater system only emerges in lakes and rivers after 100 years, ~35% arrives within 30 years, and ~17% arrives within 5 years (figure S7). By taking the perspective of a stakeholder involved in the management of these ecosystems, this means that actions taken now will likely not show the expected nitrogen load reduction in the receiving ecosystem for years to decades. However, the magnitude, local-variability, and overall significance of these lags is highly heterogeneous across the LP of Michigan.

3.1. Management patchwork

Management actions are envisioned and planned by multiple stakeholder groups that work within different timelines of projected success. Specifically, many elected officials work within a relatively short timeline (frequently <5 years) whereas career regulatory agency staff (e.g. within State Departments of Natural Resources or Environmental Management) have longer periods to execute management strategies (as long as 30 years). Outside of these governmental groups, many passionate citizens and advocacy groups work diligently towards their environmental interests for their entire lives. By acknowledging these differences, we can help a wide variety of stakeholder groups prioritize areas where they might best focus their investments in management actions, such that results are observable within their expected timelines.

Overlaying and classifying the maps of groundwater deliveries to streams (figure 1(A)) with groundwater travel time (figure 2(B)) creates a mosaic of management classes (figure 3). These classifications can be used to prioritize areas for management actions. The 'Fast' category (4% of the landscape, figure 3) has high nutrient deliveries and short travel times (<5 years). These areas are similar to the timeline of most elected officials and are thus likely to have the largest political return on financial investment. The 'Intermediate' class (4%) has high nutrient delivery and medium travel times (5–30 years). Actions taken within these areas can potentially make a difference within the career of a manager in state or local regulatory agencies. The 'Persistent' category (17%) includes areas of high nutrient delivery and long travel times (>30 years). These areas are likely to supply excess nutrients long into the future due to slow transport in the groundwater system. Management actions here might focus on mitigation strategies at groundwater discharge sites, such as riparian buffers or treatment wetlands, to minimize future risk with the understanding that the reward will be mostly delayed for future generations. The 'Protect' class (46% of the landscape) has relatively lower nutrient deliveries (bottom 75%) and long travel times (>30 years). These areas, widely distributed across the domain, can be prioritized for preservation strategies that could be employed to minimize the risk of becoming significant long-term sources of pollutants, where consequences would be high for generations to come.

The management classifications show a wide spatial distribution across the LP of Michigan (figure 3). Classes are spatially distinct. For instance, much of the eastern edge of the state is dominated by both Protect and Persistent classes, resulting from the generally long travel times (figure 2(B)) in this part of the state. The southern portion also has more area categorized as Fast and Intermediate than the northern portion. In contrast, the central and western portion of the LP is a mixture of management classes, resulting from the highly variable travel times and nutrient loads in this area. The inset map (figure 3) provides a close-up view of how the management classes are intermingled across the landscape, creating a complex patchwork due to the combination of highly variable groundwater travel times and groundwater delivered nitrogen loads.

This overall classification approach can be applied at varying scales, with nitrogen quartiles uniquely defined to the study area. Here, the Fast, Intermediate and Persistent classes are all defined as having high groundwater nitrogen deliveries (above 5.2 kg ha yr^{-1}) but have different groundwater travel times (<5 years, 5–30 years, and >30 years, respectively). However, these quartiles result from having a large region with both very low and very high nutrient loads through groundwater; much of the upper portion of the LP of Michigan experiences N loads to groundwater <1.3 kg ha yr^{-1}, while areas in the southeast corner have groundwater loading rates 4 or more times greater (figure 1(C)). Thus, for example, managers tasked with reducing nitrogen inputs to Lake Erie could define their area of interest to identify more locally relevant 'hot spots' within their jurisdiction where management actions might best be targeted.

3.2. Moving towards action at the surface

Once an area has been chosen as a management priority (the 'where'), looking for the source and quantity of the nitrogen inputs using SENSEmap can help identify management actions to focus their attention and efforts toward (the 'what'). By shifting the focus back to the surface, we can identify land management actions that stakeholders can quantify without a detailed fate and transport model like SENSEflux (e.g. fertilizer applications). Moreover, measuring landscape nutrient inputs is relatively direct in comparison to understanding leaching to the subsurface, effects of tile drainage, and what proportion of the applied nutrients end up in the groundwater system.

SENSEmap describes nutrient inputs to the landscape in intensity units familiar to stakeholders (i.e. rates of application) and can be used to calculate the total amount of nitrogen within each management class. Across the study area, the inputs within the Persistent class contribute the most nitrogen (37%), followed closely by the Protect class (33%) (figure 4(A)). These results are driven largely by groundwater travel times; this largest portion of the study area has the longest groundwater travel times (figures 2 and 3). Although similar total amounts of nitrogen are input within these two classes, the Persistent class covers roughly ⅓ the area of the Protect class, resulting in much higher nitrogen input intensities in the Persistent class (figure 4(B)). Areas within Fast and Intermediate classes contribute the smallest relative amounts of nitrogen (6% and 8%, respectively). Therefore, if the management focus is on reducing the most nitrogen input across the study area, efforts should focus on the Persistent and Protect classes. However, due to their long groundwater travel times, ecosystem responses to management actions taken on sources in these classes will take a similarly long time to observe. To reiterate this point, the areas in which management practices can have the largest total impact also take the longest time to respond.

To further understand the characteristics of nitrogen inputs in our management classes, we calculate mean nitrogen inputs from the six SENSEmap nonpoint sources: manure, chemical agricultural fertilizer, nitrogen fixation from legumes, atmospheric deposition, chemical non-agricultural fertilizer, and septic tanks (figure 4(B)). Each colored slice in the stacked bar chart represents the mean input intensity from a given source, where taller bars sum to higher total nitrogen input intensities within those classes. These mean input intensities are calculated across the full area of each management class and include all land use types within that area. For example, the mean intensity of chemical agricultural fertilizer shown for any management class includes areas that do not use fertilizer (e.g. urban land use), resulting in mean intensities lower than farmers' application rate. Viewing this through the lens of average inputs provides insight about the composition of sources contributing to the total nitrogen inputs within a management class. In addition, we calculate the distribution of each source's input intensity only within areas it is applied (e.g. fertilizer where fertilizer > 0) by management class (figure S8). This alternative view is directly comparable to the rates at which fertilizer is being applied, and can help explain the differences in nitrogen sources between management classes. Together, source-specific mean intensities (figure 4(B)) and intensity distributions (figure S8) allow us to understand the differences in where and how nitrogen enters the environment across management classes.

Although it is not surprising that the Fast, Intermediate, and Persistent classes have the highest nitrogen inputs (inherent in the class definitions), the magnitude of their dominance is striking. Agricultural contributions from manure and chemical agricultural fertilizer dominate these classes with perceptible differences in total intensity (figure 4(B)). The Persistent class has the highest average N input intensity at 90 kg ha yr^{-1}, compared to 78 and 69 kg ha yr^{-1} for Intermediate and Fast, respectively (figure 4(B)). Despite this intensity difference, nutrient source compositions (i.e. proportions of colored slices within a bar relative to each other) are similar. In these three classes, manure makes up the largest share with 38%–40% of total intensity, while chemical agricultural fertilizer contributes 28%–36% (figure 4(B) and table S2). Mean nitrogen input rates (i.e. calculated only where the specific source is present) are similar for agricultural sources across Fast, Intermediate, and Persistent, with manure ranging from 255 to 267 kg ha yr^{-1} and chemical agricultural fertilizer from 42 to 50 kg ha yr^{-1} (figure S8). Due to the similarity in both the proportion of total input and source input intensity, management strategies targeted at these areas on the landscape may be similar. At the scale of the study area, management actions aimed at minimizing groundwater nitrogen contributions from agricultural practices will likely have the largest impact on decreasing excess nitrogen in short, medium, and long terms.

Human contributions of nitrogen from lifestyle and infrastructure characteristics are another main area where active management could help reduce nutrient inputs. Chemical non-agricultural fertilizer (used mainly for maintaining grass in lawns and golf courses) and septic tanks contribute an estimated 5%–8% of nitrogen, across the top three management classes (figure 4(B)). Septic tanks are the main form of wastewater treatment in rural areas and some suburban areas. These systems discharge nutrients directly into groundwater across large regions and can be an important target for regulation and maintenance. Although septic effluent and lawn fertilizer contribute a much lower proportion of overall nitrogen than agricultural sources within the management classes, these two sources can be locally significant in

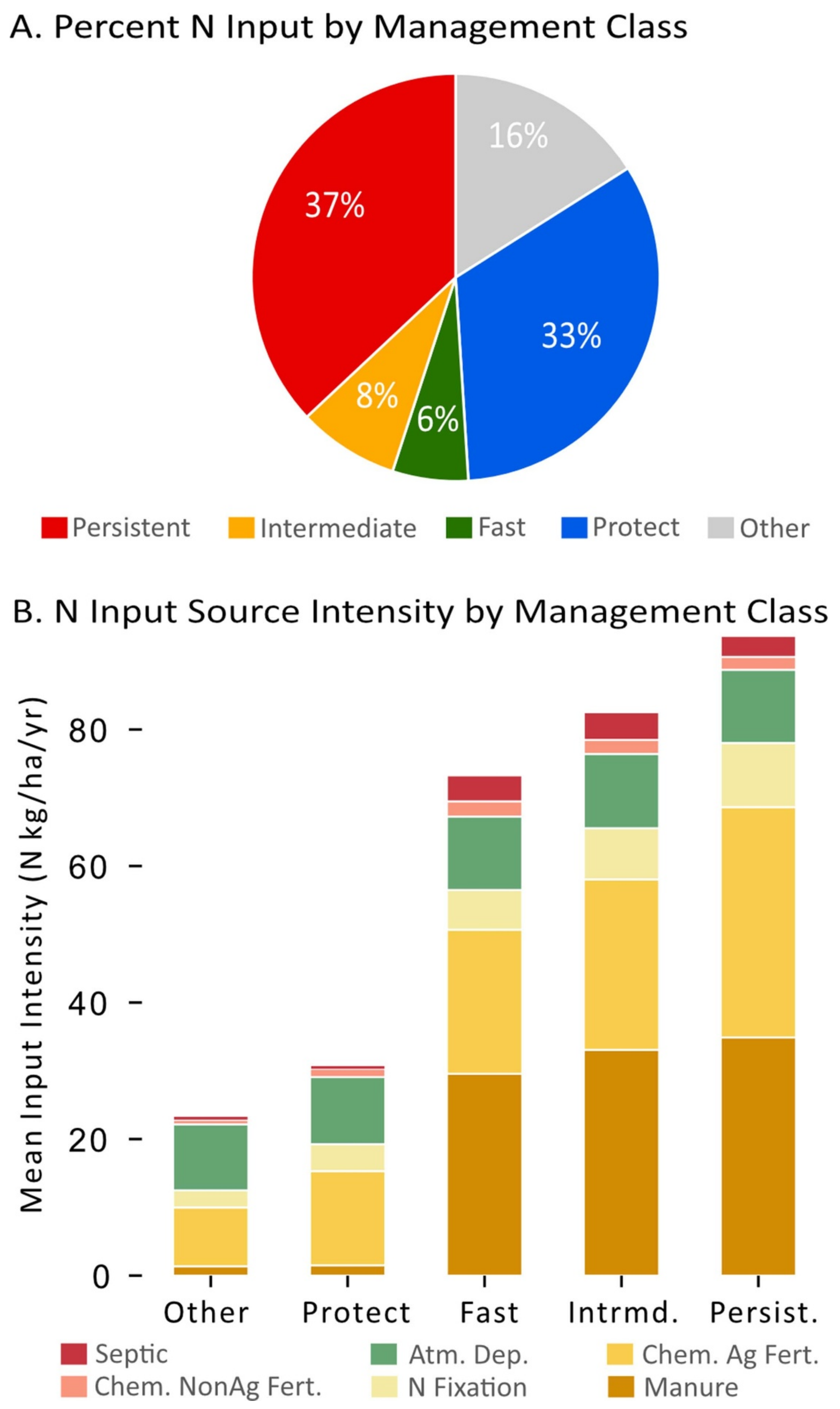

Figure 4. Summary of N by management classes. (A) Pie chart of total N inputs by management class and (B) stacked bar of N inputs by source, averaged within each management class. Total N in kg ha yr^{-1} for each class: Other 23, Protect 30, Fast 69, Intermediate 78, and Persistent 90. Note: the stacked bar chart averages N within each source over the entire management class, and therefore includes areas that do not receive N from that given source. These areas are calculated as zeroes, and thus result in lower average input intensities than would be expected for each source (e.g. chemical agricultural fertilizer is applied to fields at a higher rate than shown here).

non-agricultural watersheds and offer an avenue for a multitude of individual stakeholders to help achieve management goals (for example within and around major metropolitan centers such Detroit, located in the southeastern corner of the state just north of Lake Erie, figure 1(B)).

The Protect management class was defined to capture areas with long groundwater travel times

(>30 years) that have relatively lower groundwater delivered nitrogen (bottom 75%). Agricultural sources also dominate this class, with chemical agricultural fertilizer contributing approximately 45% of total nitrogen inputs (figure 4(B)). Nitrogen input intensity from atmospheric deposition is similar across all management classes (∼10 kg ha yr^{-1}; figure S8) but plays a larger proportional role in the Protect class, contributing about 32% of nitrogen inputs to the surface. It is important to recognize that managing nitrogen inputs from atmospheric deposition may be more difficult and involves many more stakeholders across multiple governmental jurisdictions, but this source still needs to be considered when setting expectations for management outcomes. Based on our analysis, managing agricultural fertilizer will have the largest impact in protecting these areas from becoming the next Persistent source of nitrogen.

4. Conclusions

Our analysis shows how combining surface applied nutrients with groundwater-specific transport pathways and travel times can produce a novel view of the management landscape. This novel approach helps identify priority management areas for stakeholders looking to reduce nutrient impacts over a multitude of time horizons, matched here to three main groups: elected officials looking to make a difference for re-election, career managers hoping to see the fruits of their labor, and advocacy groups whose work can span generations. Recognizing that groundwater pathways contribute nutrients to downgradient ecosystems over an extended period will help temper management expectations and potentially reduce conflicts. Even in the relatively permeable sediments of our study area, half of the estimated groundwater nitrogen remains in the system for decades to centuries after arriving at the water table. Moreover, changing patterns of precipitation may exacerbate or alleviate issues associated with nutrients routed through groundwater pathways and the subsequent delivery to downgradient ecosystems.

In addition to time, our spatially explicit approach produces predictions at spatial scales relevant to managers. We produced a regional map of estimates where management actions (e.g. BMP implementation) can be prioritized. For stakeholders looking to observe results of management actions in a short to medium time frame, only 8% of the study area falls within the Fast and Intermediate management classes. Due to long groundwater travel times (>30 years), 62% of the region is classified in Protect or Persistent, suggesting management of groundwater nitrogen today will affect ecosystems far into the future.

This approach is transferable to other locations given availability of input data. The particular combination of tools used here allowed us to create a high-resolution (120 m) estimate of groundwater-driven N legacies. One database, Michigan's WellLogic system, provided a rich source of data about the groundwater system. Many states in the US have similar databases (Perrone and Jasechko 2019), although they vary in terms of available information and well density.

Future work could include a more sophisticated and detailed groundwater travel time model. Relaxing some of the assumptions made here (supplemental materials), such as simulating three-dimensional flowpaths, or explicit simulation of both advective and dispersive transport, is relatively common for site-scale contaminant modeling; this is becoming more common at the regional-scale. Three-dimensional groundwater models would also better describe the nested local, intermediate, and regional groundwater flow systems that exist in glaciofluvial landscapes. This heterogeneity of flow systems would produce more pronounced variability in both groundwater travel times and management classes. Localized analyses would also allow for greater variability in management classes at smaller scales, allowing for targeted management priorities within watersheds or smaller domains.

This paper presents a novel, spatially explicit classification of the landscape based on estimates of groundwater travel times and nutrient deliveries to streams. The results are specific to the study area, but the approach is generalizable globally. Groundwater transport creates substantial lags between land use actions and eventual water quality impacts. Considering both the nature of the delays, and their linkage to the varied management timeframes of different stakeholders, could help focus efforts and build more realistic expectations.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.4211/hs.1a116e5460e24177999c7bd6f8292421.

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