Source Water Protection Challenges and Co-benefits

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Ryan Noe*, Bonnie Keeler, Terin Mayer

*Corresponding author

RRNoe@umn.edu

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Executive Summary

Access to clean safe water is essential for promoting health, recreation, and economic development in Minnesota. However, many of our state's most pressing water quality problems remain unsolved. Over 40% of our lakes and rivers are rated as "impaired" and a growing number of households and communities face rising costs and health risks due to contaminated drinking water. If we hope to reverse current trends of water quality decline and preserve the valuable ecosystem services provided by clean water, we need to account for both the risks to water resources as well as the benefits of water quality protection.

Source water resources include both surface waters (lakes, rivers, and streams) and groundwater that supply households and communities with drinking water. Source waters are affected by land management, including agriculture, industry, and residential development. Pollution in the form of excess nutrients or other contaminants moves from land into surface waters and groundwater aquifers with consequences for households and communities. The majority of the land area that affects source water quality is under private ownership meaning it is not always possible for the state to protect water quality. Land use and management actions on these lands that increase nutrients and other contaminants can affect the health and welfare of millions of Minnesotans. There are successful examples of private and public partnerships that have worked together to protect source water and enhance valuable ecosystem services while supporting agricultural and rural economic development (e.g. Worthington Wells Wildlife Management Area). At the same time, other communities in Minnesota are facing known or unknown threats to their water supply with consequences for health and rising treatment costs.

Degraded source water can have important equity and distributional impacts. Rural households may face larger water bills when investments in expensive water treatment infrastructure are distributed among a small population of ratepayers. Due to decades of disinvestment in water infrastructure, some tribal communities and immigrant communities lack access to safe and affordable water supplies. Climate change may exacerbate these disparities as changes in precipitation and temperature affect the quality of surface water, the timing and intensity of floods, change demand for water resources, or place stress on existing water infrastructure.

Agency leaders, water resource managers, and communities have identified an urgent need to map and quantify the risks facing source water areas in Minnesota, better articulate the value of clean water, and develop practical approaches that enhance community capacity to protect source water and ensure safe and equitable access to clean water for all Minnesotans.

In this report, we focus on the 1.23 million acres designated by the Minnesota Department of Health (MDH) as the groundwater catchments for Public Water Supplies (PWSs). This land is divided among 821 Drinking Water Supply Management Areas (DWSMAs), which are themselves composed of individual private or publicly-owned parcels. Water from one or more DWSMAs is aggregated at a PWS before distribution to consumers. We summarize data on the costs and benefits of source water protection at the PWS, DWSMA, and parcel level (Appendices A, B, and C) as appropriate. Below we summarize key findings under our three research objectives:

1) Mapping land use change and land protection costs.

On average, land use in source water protection areas remained relatively stable from 2001 to 2019, with built area increasing by 12% while natural vegetation and agricultural land use areas declined by 5% and 8%, respectively. Although the area covered by agriculture declined, agriculture is still the dominant land cover, covering 49% of areas with high or very high vulnerability to contamination. Most DWSMAs had little change in land cover over the last two decades, but the overall trend was an increase in developed land covers. Some smaller DWSMAs, such as Willow River, Minnetrista Central, and Woodland MHP, had a more than 20 percentage point in built area in 18 years. DWSMAs experiencing increases of built and/or agricultural land covers face more potential threats to water quality within their water supply.

We used a novel dataset of land value to calculate the opportunity cost of protecting unbuilt land in source water areas. Our analysis demonstrates the high opportunity cost of acquiring land for protecting source water. The total area of unprotected and unbuilt land in source water protection areas is over 634,000 acres, with a value of $8.8 billion. Targeting a subset of the lowest value, highest vulnerability land reduces the cost substantially, but the opportunity cost remains high. Protecting 15% of this subset would cost over $100 million, and would produce inequitable protection that excludes high land value DWSMAs. Our addition of land value data at the DWSMA and parcel levels provides insights on the opportunity costs of protection that will help practitioners prioritize projects with a high return on investment.

2) Valuation of the multiple public benefits of land protection for clean water.

Protecting source waters via the adoption of best management practices or converting lands from row-crop agriculture to perennial cover can result in a stream of public benefits including reduced treatment costs for community water suppliers and reduced risk of diseases associated with exposure to contaminated drinking water. Source water protection can also lead to benefits beyond drinking water quality such as improved recreation or habitat for wildlife. We applied monetary and non-monetary valuation techniques to three areas of co-benefits associated with source water protection.

First, we assembled data on the public water suppliers in the state and used estimates from the literature on the costs that similarly sized suppliers have paid to install and operate treatment for elevated nitrate. We estimated that the capital, operation and maintenance costs of installing reverse osmosis filtration for the 8% of PWSs with elevated (> 3 mg/L) nitrate concentrations ranged from 9.8 million to 45.7 million annually. If distributed uniformly between households, these costs would increase annual water rates by $161 to $751. However, rate increases would likely fall disproportionately on systems serving small populations. Our analysis estimated average annual household costs for systems serving fewer than 500 people of $803, while systems serving greater than 500 people had an average annual household cost of $269.

Second, we compiled demographic data on the population served by public water supplies, drinking water nitrate concentrations, and the risk for disease associated with exposure to nitrates. We used these datasets to implement a method for estimating disease incidence and associated costs attributable to exposure to elevated drinking water nitrate. Of the five types of cancer in our analysis, we estimated that 71 cases, roughly 1% of cases of these cancer types annually, can plausibly be attributed to elevated drinking water nitrate. Using recently developed methods, we also estimated 50 cases of adverse birth outcomes. We applied three valuation techniques that capture medical costs and the cost of premature mortality. The differing approaches to valuation produced annual cost estimates ranging from $27.2 million to $256.6 million.

Finally, we estimated the co-benefits of protecting DWSMAs through an analysis of 19 environmental co-benefits. We found that benefits such as pheasant habitat, bird watching, and lake recreation are overrepresented in unprotected, unbuilt source water protection areas relative to unbuilt, unprotected areas in the rest of the state. We applied spatial models of land use change to estimate potential threats to DWSMAs. Due to the proximity of DWSMAs to population centers, DWSMAs face greater than average development risks.

3) Enabling assessment of equity in source water protection

Many DWSMAs supply small or low-income populations that would be disproportionately burdened by an increase in water treatment costs. We designed and implemented a workflow that allows for combining information on public water supplies with census demographic data for municipalities or counties. We found that most PWSs did not have elevated drinking water nitrate, but those that did tended to be in the lower quartile for median household income. These datasets enable practitioners to assess where elevated drinking water nitrate and associated costs might fall on a small and/or vulnerable population that would be disproportionately burdened by increased drinking water costs.

In summary, our work highlights potential risks and opportunities to protect water quality and provide multiple public benefits, helps to identify programs that protect the value of clean water, and builds capacity among citizens and decision-makers to take action in source water protection areas to improve water quality and realize additional public benefits from land protection.

1. Mapping land use change and land protection costs

1.1 Drinking Water Supply Management Areas (DWSMAs)

In Minnesota, source water protection areas for groundwater are referred to as Drinking Water Supply Management Areas, or DWSMAs. DWSMAs are delineated by the Minnesota Department of Health (MDH) as part of the source water protection planning process required of Public Water Suppliers (PWS). Although a PWS may use surface or groundwater, DWSMAs are only delineated for groundwater. MDH defines a DWSMA as "the area on the land covering the groundwater that could flow to the well within 10 years[1]." DWSMAs include all wells that serve a PWS that have an overlapping 10-year time of travel. If a PWS has multiple well fields that do not have an overlapping 10-year travel time, they are delineated as separate DWSMAs. The total area of all 821 currently delineated DWSMAs is 1.23 million acres, of which 634,000 acres are viable for protection activity because they are not already protected or in a built land cover (Table 1).

The geology within a DWSMA determines how quickly and easily water and contaminants from the surface makes its way to groundwater. MDH classifies land within DWSMAs as 'Very Low', 'Low', 'Moderate', 'High', or 'Very High' vulnerability. The classification is based on the connectivity of surface to groundwater, with higher connectivity more readily enabling contamination on the surface to reach groundwater, thus increasing the vulnerability of the water supply. Vulnerability is mapped within DWSMAs, it is common for a DWSMA to be composed of several regions with different vulnerability classifications (Figure 1). In this report we summarize results for all DWSMAs, and when appropriate also highlight results among the portions of DWSMAs categorized as 'High' or 'Very High' vulnerability. Appendices contain data aggregated at the individual PWS, DWSMA, or parcel level where appropriate.

Table 1. Drinking Water Supply Management Areas acreage summary statistics. The Minnesota Department of Health delineates DWSMAs and classifies the land within them into five vulnerability classes based on how vulnerable the water is to surface contamination based on geologic characteristics. We calculated the area of DWSMAs that is not yet a built land cover or already protected as this represents the subset of land that is viable for conservation activities.

Vulnerability class	Total acres	Unprotected and unbuilt acres
Very High	23,489	14,772
High	447,409	281,354
Moderate	334,024	125,233
Low	377,506	186,957
Very Low	48,648	26,037
Total Area	**1,231,077**	**634,353**

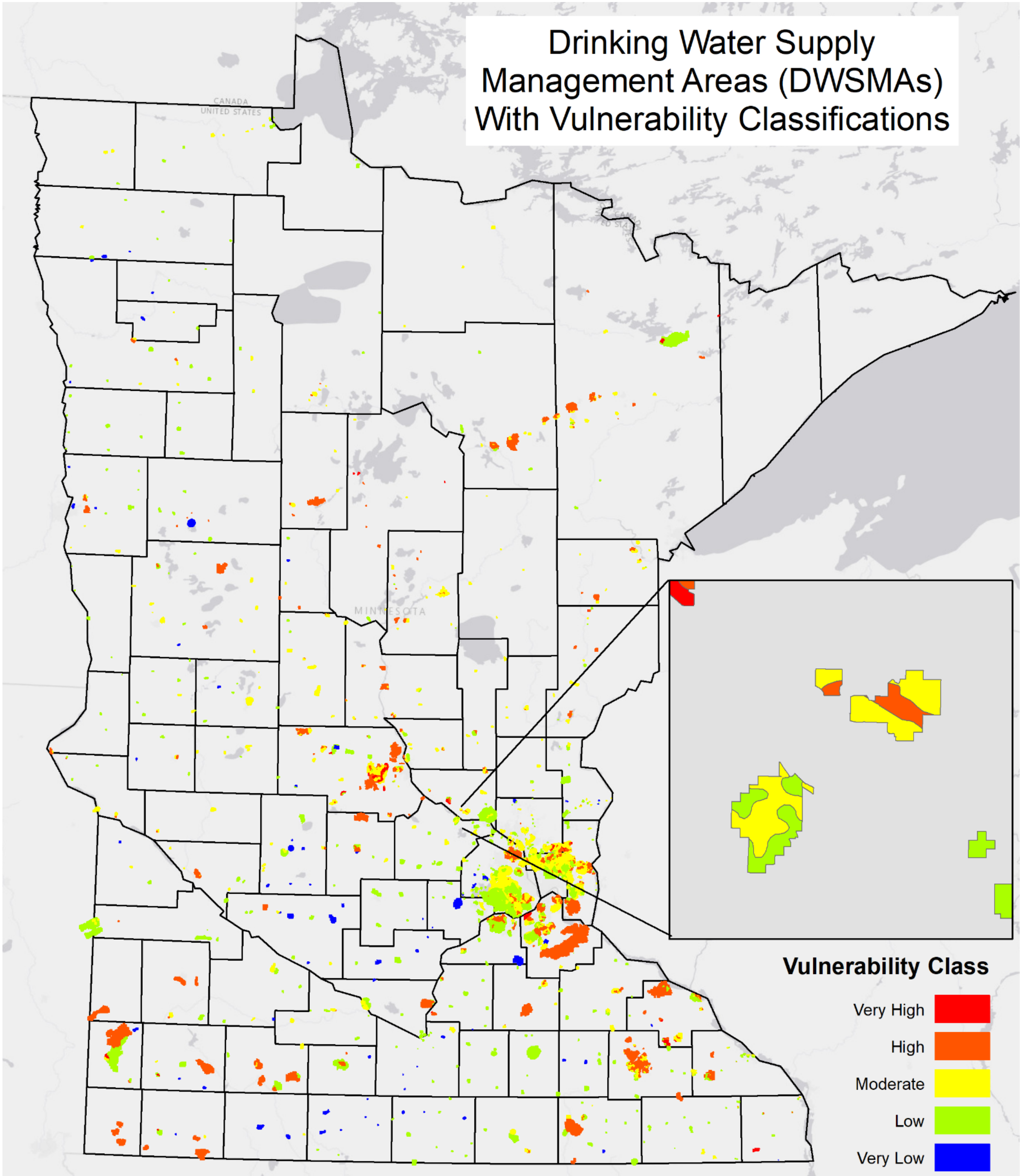

Figure 1. Overview map showing the location, size, and vulnerability classifications of all 821 Drinking Water Supply Management Areas (DWSMA) in Minnesota. Vulnerability classes are defined by the Minnesota Department of health and represent how susceptible groundwater is to surface contamination. The inset map shows a detailed view of how vulnerability classification can vary within a DWSMA depending on the geologic characteristics.

Source water faces risks from increasing urbanization and intensive agricultural practices, both of which can leach contaminants to groundwater. Nitrogen fertilizer used in agriculture and on lawns has led to elevated (>3 mg/L) drinking water nitrate concentrations in 8% of Minnesota's public water supplies[2]. Climate change has the potential to exacerbate sources of contamination like nitrate leaching with more frequent and more intense precipitation events in the spring[3] when fertilizer is typically applied.

Despite these threats, data on land use trends has been challenging to apply to source water protection. Inconsistent methods used to produce land cover maps confound actual changes, while the overlapping nature of DWSMAs is not compatible with the assumptions used in common spatial analysis tools. We address these challenges by applying newly available land cover data and custom spatial analysis tools to create a spreadsheet that allows users to measure and visualize trends in land use from 2001 to 2019 for any DWSMA. Additionally, we analyzed the value of land within DWSMAs to better understand the opportunity cost of mitigating risk through land protection. These datasets provide a comprehensive picture of the type and quantity of land use change and the cost of protection.

1.2 DWSMA land cover trends 2001-2019

To assess changes in land use and risks to sourcewater, we leveraged recent developments in longer term, methodologically consistent land cover datasets. We used the National Land Cover Dataset[4] (NLCD) analyzed using four aggregate land use classes; agriculture (NLCD classes 81, 82), built (21, 22, 23, 24, 31), natural vegetation (41, 42, 43, 52, 71, 90, 95), and water (11). Overlapping boundaries of some DWSMA's required us to develop a novel analysis technique for estimating land use trends. We used the Python packages geopandas and rasterstats to calculate land use trends for each DWSMA independently. From this analysis we created two outputs; statewide summary statistics and individual land use change statistics for each DWSMA.

Disaggregated results in Appendix A report land use change trends for each of the 821 DWSMAs. Using spreadsheet software, users can quantify changes in land cover and visualize trends from 2001 to 2019 for individual or groups of non-overlapping DWSMAs. Additionally, in the event a PWS is served by multiple DWSMAs, users can summarize land cover statistics for all of the land that contributes to it, giving a more accurate description of the aggregate influence of land use change.

Here we present aggregate trends in land use across all 1.23 million acres of land within the boundaries of Minnesota's DWSMAs. To prevent double counting, summary figures below merged overlapping DWSMAs, assigning the highest vulnerability class in the event overlapping DWMSAs had different vulnerability classes. In 2001, agriculture (including hay/pasture) was the most prevalent land cover in DWSMAs with 41% of the total area. However, over the next 18 years built land covers (e.g., roads, buildings, urban areas) increased by 53,118 acres, becoming greater in area than agriculture by 2019 (Figure 2). These gains were offset by a combination of losses of 40,529 acres of agricultural land and 11,516 acres of natural vegetation.

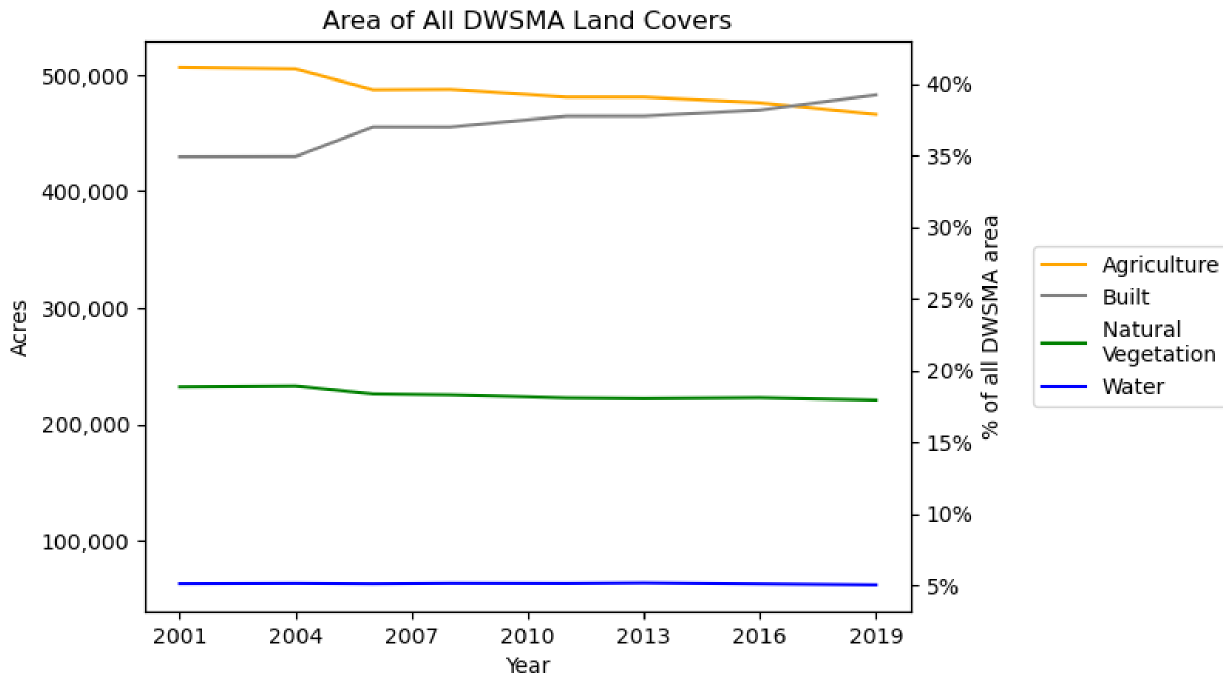

Figure 2. Land use change in all DWSMAs from 2001 to 2019. In 2001, agriculture was the most prevalent land cover in DWSMAs with 41% of the total area, however, over the next 18 years built land covers (e.g., roads, buildings, urban areas) gradually displaced agricultural land. By 2019 built land surpassed agriculture as the most prevalent land cover in DWSMAs. Natural vegetation experienced a decline of 1% of total DWSMA area.

We next analyzed land use trends in portions of DWSMAs ranked by the MN Department of Health as 'High' or 'Very High' vulnerability to surface contamination. We observed similar trends for this subset of vulnerable DSWMAs. Since 2001, built area in DWSMAs has expanded at the expense of agricultural and natural vegetation. High and Very High vulnerability DWSMAs have a higher proportion of agriculture, 49% in 2019 (Figure 3), compared to all DWSMAs which are 38% agriculture.

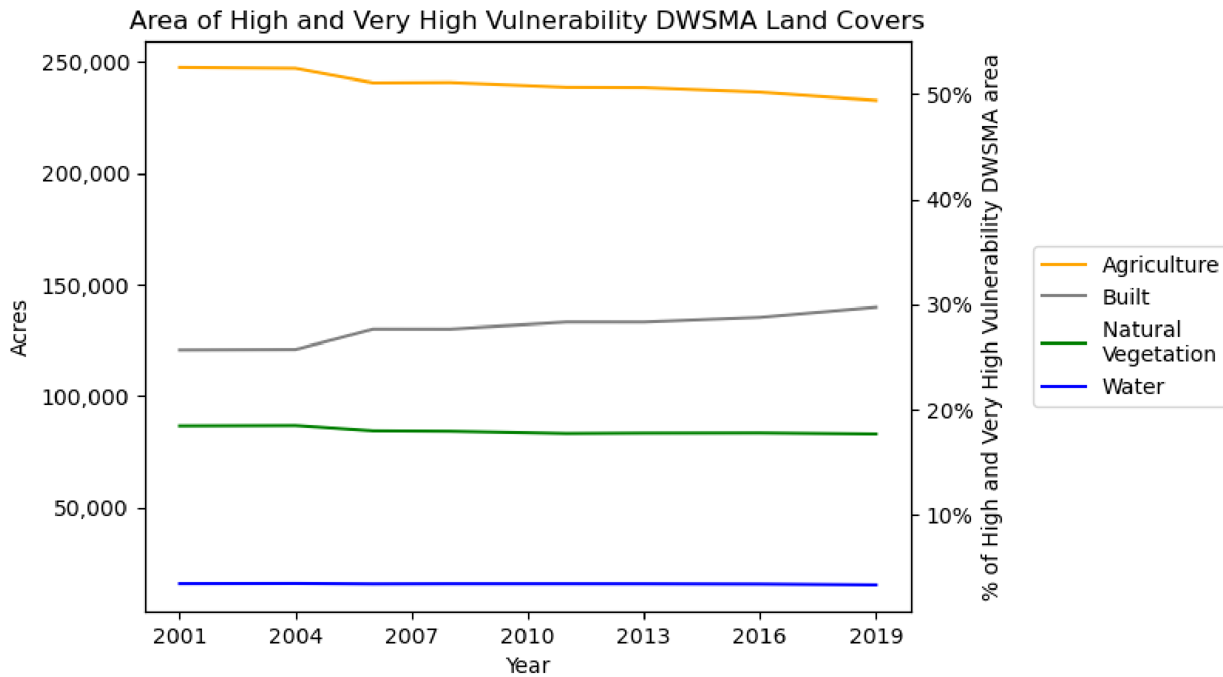

Figure 3. Land use change in the subset of High and Very High Vulnerability DWSMAs from 2001 to 2019. The trend of increased built area offset primarily by delines in agriculture and smaller declines in natural vegetation was also apparent in this subset of land. Despite similar declines in agricultural area, the higher initial proportion resulted in it remaining the dominant land cover in high vulnerability DWSMAs with 49% of the total area.

We were also interested in the spatial distribution of DWSMAs with elevated loss of natural land cover. Figure 4 highlights DWSMAs that experienced a greater than 10 percentage point decrease in natural vegetation (grassland, wetland, forest, and water) between 2001 and 2019. Change was concentrated in the metro area, however all regions of the state had at least one DWSMA with elevated loss in natural land cover.

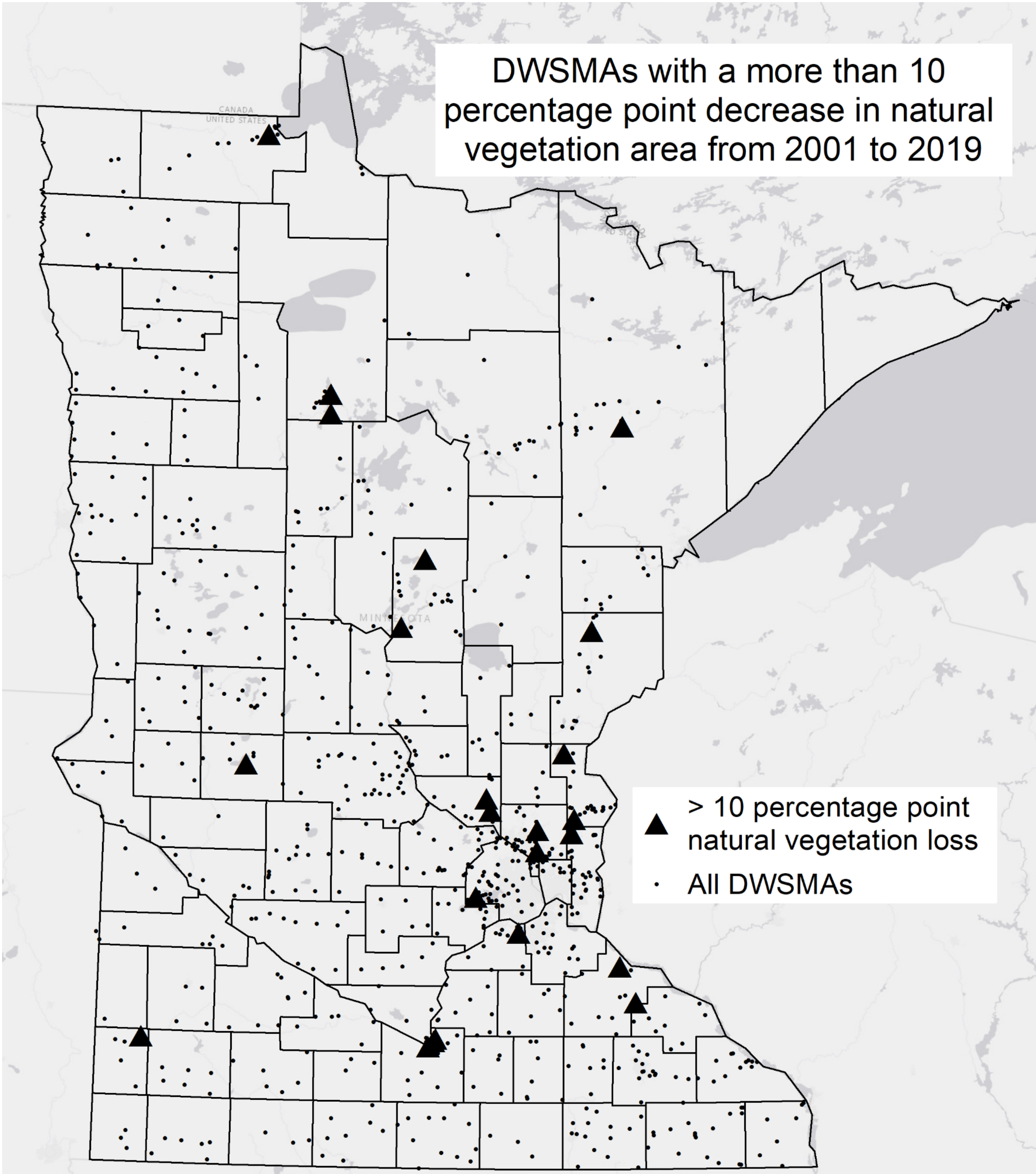

Figure 4. Map of Drinking Water Supply Management Areas in the state, highlighting those with a greater than 10 percentage point decrease in natural vegetation (grassland, wetland, forest, and water) area between 2001 and 2019.

Figure 5 presents a histogram of the change in developed (built, row crop agriculture, and hay/pasture) land covers between 2001 and 2019 in all DWSMAs. Most DWSMAs had little change, but the overall trend was an increase in developed land covers. Some smaller DWSMAs, such as Willow River, Minnetrista Central, and Woodland MHP, had a 20 percentage point or more increase in developed area in 18 years. DWSMAs experiencing increases of built and/or agricultural land covers face more potential threats to water quality within their water supply.

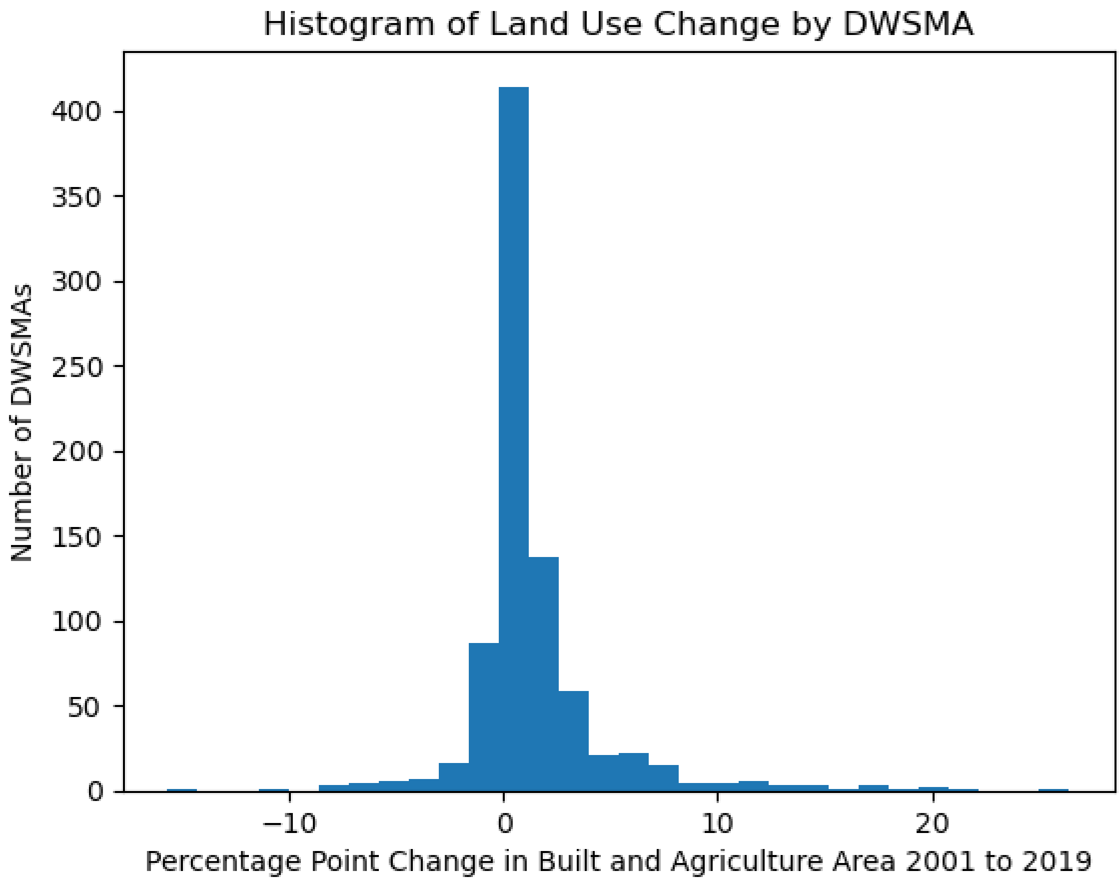

Figure 5. Histogram of change in build and agricultural area in each DWSMA between 2001 and 2019. Most DWSMAs had little to no change, but several had increases in developed land covers greater than 20% of their total area.

Despite record high corn and soy prices during the study period, agricultural area in DWSMAs declined by 3% of the total DWSMA area. Only built land covers showed a net increase in area between 2001 and 2019. Results aggregated to all DWSMAs can hide trends in the data. For example, although agricultural area also declined in High and Very High vulnerability DWSMAs, the proportion of agricultural area initially was higher than in all DWSMAs. Even after the growth in built area, agriculture remains the dominant land cover among the most vulnerable DWSMAs (Figure 3). Similarly, spatial disaggregation shows that although the loss of natural vegetation was 1% of the total DWSMA area, that loss occurred disproportionately in a subset of DWSMAs (Figure 4). Further disaggregation of these results at the DWSMA level is possible with the data provided in Appendix B.

1.3 Land value

Land protection or restoration to natural vegetation is one strategy to mitigate the development pressures and other risks to water quality within DWSMAs. However, preventing urban development and agriculture has an opportunity cost that must be considered when making water quality management prioritization decisions. To demonstrate the scale of the cost of drinking water protection using land acquisitions, we used newly available estimates of the fair market value of land statewide to quantify the amount of money required to purchase the unprotected, unbuilt land within DWSMAs.

Our analysis uses the Private-Land Conservation Evidence System (PLACES), a Boston University research effort led by Dr. Christopher Nolte to harmonize wide ranging spatial and tabular data on land ownership, development, and value (placeslab.org/places). While we explored using parcel and estimated market value of land directly from counties and the Minnesota Department of Revenue, we found that missing data and minor inconsistencies between counties limited the usefulness of the data in a statewide analysis. The PLACES data overcome these limitations by applying machine learning techniques to the same publicly available land value and parcel data, along with many other data sources, to consistently predict the cost of conservation acquisitions anywhere in the contiguous U.S., even when the underlying datasets are incomplete. In development of these data, Dr. Nolte compared his estimates to previously published estimates of the opportunity cost of conservation land, and found that his predictions were more accurate when compared to actual conservation land transactions, and that prior research tended to underestimate the value of land[5]. The sophisticated modeling techniques and validation with real-world transactions make this the ideal dataset to estimate opportunity costs of land acquisitions for source water protection.

Specifically, we used the PLACES Fair Market Value estimates trained on transactions of vacant land only. In this context, vacant means without buildings or structures, but includes agricultural land. Although land value estimates are modeled for the entire state, we only applied our analysis to land that could feasibly be protected or restored to protect water quality. To best match these assumptions, we used the NLCD to remove any estimates for water (i.e., lakes and rivers), roads, and urban development. We also removed estimates for land that was already protected by a state or federal conservation program. We adjusted the land values in the PLACES data for inflation (2017 to 2021 dollars), and aggregated the value of all of the land within DWSMAs.

While protecting all of this land is not feasible, the analysis and summary figures below serve two important purposes. First, they demonstrate the scale of the opportunity cost to protect all of the land in DWSMAs (Figure 6), or a subset of the land most vulnerable to contamination (Table 2, Figure 7). Second, in addition to statewide aggregations, we also provide the estimated value for every Public Land System quarter-quarter section parcel (approximately 40 acres) that intersects a DWSMA in Appendix C. The parcel level data provide decision support to practitioners seeking to balance the trade-offs between opportunity cost and source water protection.

To visualize the value of all unbuilt, unprotected land in DWSMAs we first sorted every hectare of land within a DWSMA from lowest to highest value. We then created a series of figures (Figures 6-7) that plots the total value on the Y-axis, and the proportion of all unprotected and unbuilt DWSMA land it represents on the X-axis. This shows the cumulative cost of the land that is viable for protection or restoration if you were to acquire land from least to most expensive.

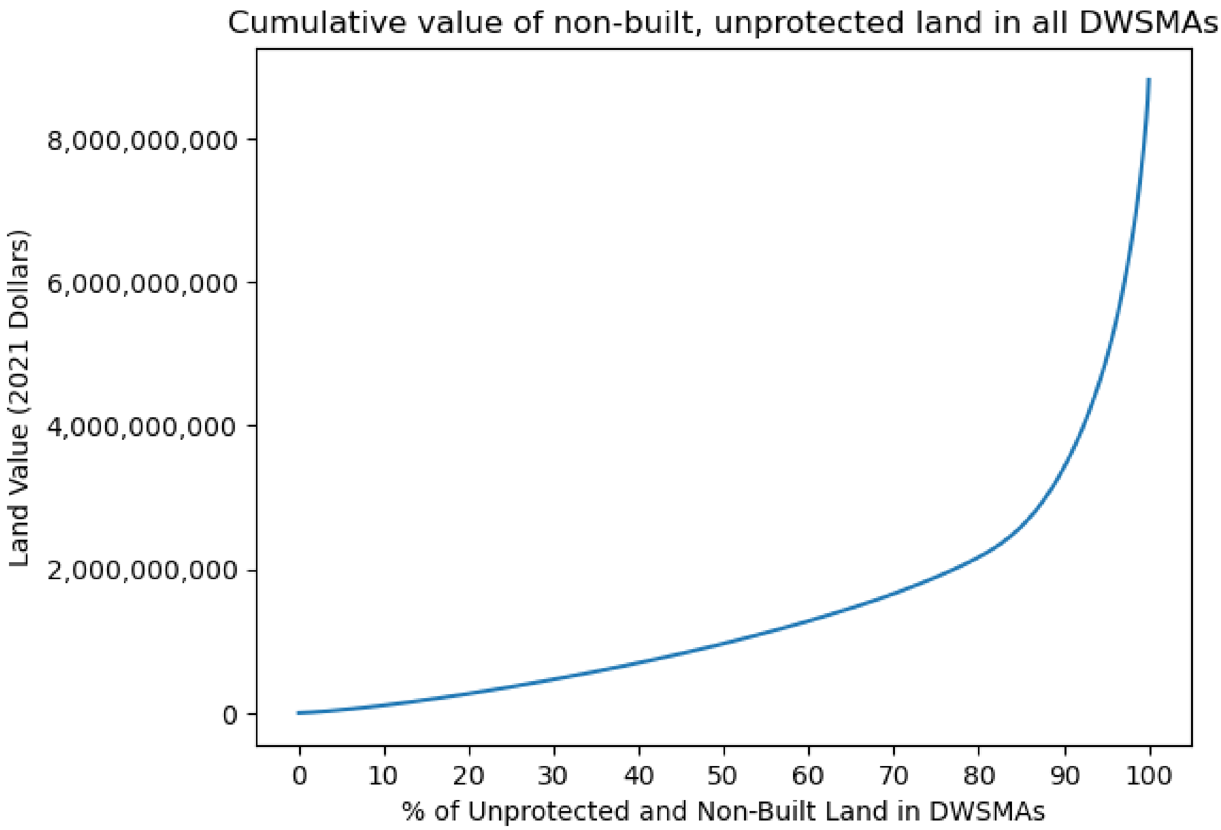

Figure 6. Cumulative value of unbuilt, unprotected land in all DWSMAs. Extremely high value land creates a skewed distribution where 15% of the land makes up over 75% of the total value. However, the value of the remainder of the land is still on the order of billions of dollars.

The total area of unprotected and unbuilt land covers is over 634,000 acres, an area larger than some counties, with a value of $8.8 billion. A point of rapid slope change at approximately the 85th percentile shows how just 15% of the land area makes up over 75% of the total value (Figure 6). Avoiding high value land is one strategy for maximizing the amount of protection for a given budget. However, it is impossible to avoid high cost land entirely without creating unequal protection of water quality between DWSMAs.

Table 2. Summary of value of unprotected and unbuilt land in DWSMAs by vulnerability class.

Vulnerability Class	Area (acres)	Total Value ($)	Average Value ($ / acre)	Median Value ($ / acre)
Very High	14,772	106,864,090	17,876	10,374

High	281,354	2,969,534,700	26,081	11,747
Moderate	125,233	2,982,303,700	58,846	12,627
Low	186,957	2,511,657,200	33,197	10,333
Very Low	26,037	244,283,940	23,183	11,315

Disaggregating land values by DWSMA vulnerability class shows that the highest average land value is Moderate vulnerability, likely due to large Moderate vulnerability DWSMAs in the metro area. The lowest average value was Very High vulnerability land. However, there are only 15,209 acres of Very High vulnerability land, compared to over 400,000 acres in the High and Moderate vulnerability classes (Table 2). Despite having the lowest average value and representing only 2.4% of the total area, the value of all High Vulnerability land still exceeds 100 million dollars.

Our analysis demonstrates the high opportunity cost of acquiring land for protecting source water. Even targeting the lowest cost and High or Very High vulnerability land, 100 million dollars would only be enough to acquire approximately 15% of that subset (Figure 7). Targeting strategies that produce more equal protection between DWSMAs are even more limited in the area they can protect as they must contend with high land values in urbanized DWSMAs. Despite these challenges, this analysis also reveals opportunities such as the lowest average land cost is found on the land with the highest vulnerability source water. This dataset informs the opportunity cost of potential activities and helps identify those with a high return on investment.

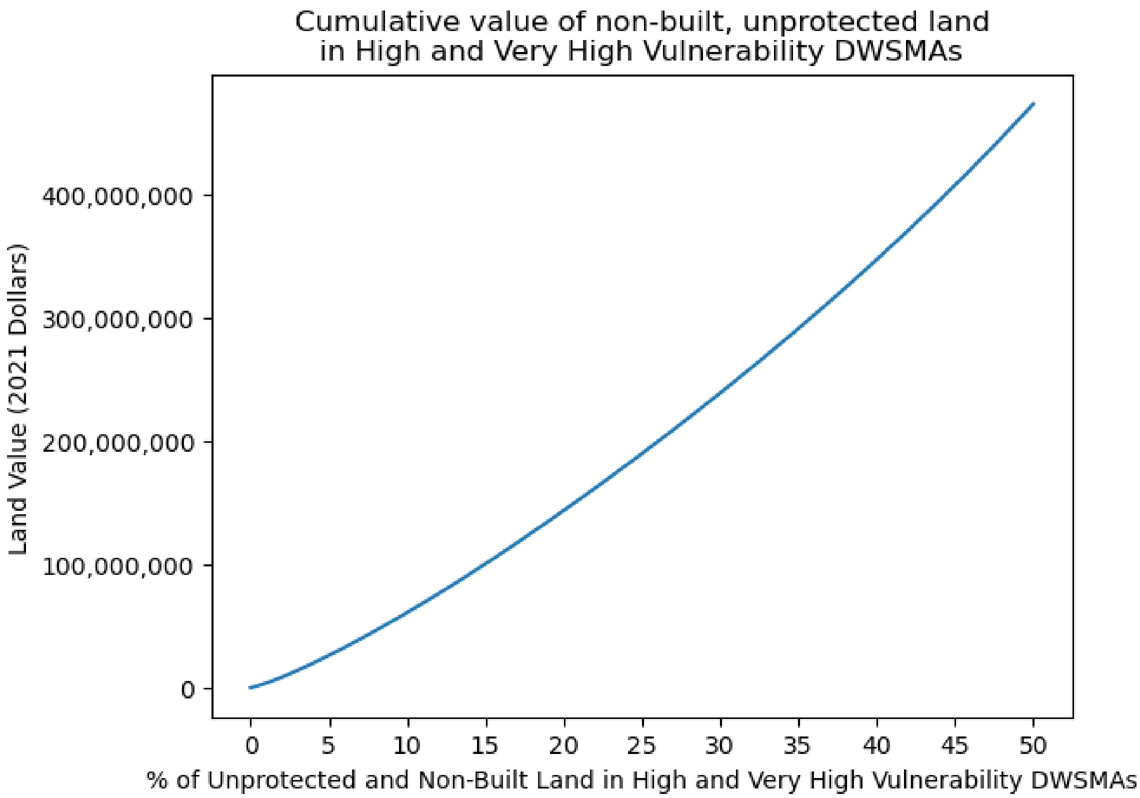

Figure 7. Cumulative value of unbuilt, unprotected land in DWSMAs with High or Very High vulnerability to surface contamination. This figure represents a subset of the land in all DWSMAs classified as High or Very High vulnerability and plots total value against the proportion of their total area. It only plots the lowest cost half of land to enable better visualization of the value of smaller subsets of land.

2. Valuation of the multiple public benefits of land protection for clean water

Source water protection can reduce water treatment costs, improve public health, and enhance recreation activities. These public goods or ecosystem services are important co-benefits of land protection or restoration but are often missing from planning and policy review because their values are difficult to quantify. We aimed to capture a comprehensive suite of potential benefits associated with source water protection in order to inform prioritization and planning decisions sensitive to the multiple values of public land protection for clean water. First, we assembled data on the public water suppliers in the state and used estimates from the literature on the costs that similarly sized suppliers have paid to install and operate treatment for elevated nitrate. Second, we compiled demographic data on the population served by public water supplies, drinking water nitrate concentrations, and the risk for disease associated with exposure to nitrates. We used these datasets to implement a method for estimating disease incidence and associated costs attributable to exposure to elevated drinking water nitrate. Finally, we include a non-monetary environmental benefit assessment technique to quantify how well 19 co-benefits are targeted when protecting DWSMAs as compared to other areas of the state. These activities will help to illuminate the true value of clean water and identify how this information can inform decisions ranging from payment programs or incentive schemes to evaluating the return on investment in land protection.

2.1 Avoided costs of drinking water treatment for elevated nitrate

One way to quantify the value of source water protection is to estimate the costs that public water supplies have to pay to install treatment to mitigate elevated drinking water nitrate. This approach is also applicable to other contaminants, but nitrate is well-studied and reflects a treatment need on the horizon of many PWSs in Minnesota. Common techniques for treating elevated nitrate include reverse osmosis, ion exchange, and blending with new or deeper wells. Of these methods, blending with new wells is often the cheapest, but it is contingent upon the availability of an uncontaminated water source. Because it cannot be used in all cases and its costs are dependent on local geology, blending is not included in this analysis. We limit our analysis to reverse osmosis because it is the most common approach used by PWSs that have had to install new water treatment in Minnesota. It is also effective against contaminants other than nitrate, such as chloride.

Previous research in California analyzed the total (capital, operation and maintenance) annual costs of reverse osmosis for PWSs of varying capacities. The researchers found total annualized costs of treatment systems ranging from $0.58 to $19.16 per 1,000 gallons. System size heavily influenced total costs, with average costs ranging from $6.64 per 1,000 gallons for very small systems to $2.38 for large systems[6]. We cross-referenced these estimates with more recent and local studies to ensure the estimates were relevant for Minnesota. A 2015 Minnesota Environmental Quality Board study described per household total costs ranging from $1,600 to $7,600 for new treatment plants for three communities with elevated drinking water nitrate[7]. Although the report does not specify what assumptions are used for amortization or household size, if we apply the assumptions described in Table 3, we find that the annual cost estimates range from $169 to $805 and are consistent with the estimates derived from Jensen et al.[6]

We applied the estimates found in table 24 of Jensen et al.[6] to Minnesota PWSs by using the MDH's population served value to estimate the annual amount of water treated. Using the typical average flow range reported by Jensen et al., we prorated the flow volume according to population. We then multiplied the estimated annual volume by the low, average, and high total combined cost estimates, and adjusted for inflation to 2021 dollars.

In Table 3 we report estimated treatment costs aggregated for all PWSs and just those with elevated nitrate. Appendix A provides the estimates specific to every PWS. If every PWS in Minnesota needed to install reverse osmosis treatment at the high end of the cost spectrum, the total would be over 1.3 billion dollars annually, exceeding the value of all of the unprotected and unbuilt land in DWSMAs within a decade (Tables 2, 7). A more plausible treatment cost scenario examining the 8% of PWSs with current elevated (>3 mg/L) drinking water nitrate shows the total cost for reverse osmosis ranges from 9.8 million to 45.7 million, or $161 to $751 per household annually if costs are uniformly distributed among all ratepayers. Summary treatment costs obscure the variability in costs associated with differing system sizes. Smaller systems with shallow wells are more at risk for nitrate contamination and are unable to take advantage of the economies of scale in treatment found in larger systems. Using our estimated average cost for PWSs with elevated nitrate, we found that annual costs for systems serving fewer than

500 people had a projected annual average household cost of $803, while systems serving greater than 500 people had an average annual household cost of $269.

Table 3. Estimated annual cost range for installing reverse osmosis filtration on all public water supplies, or a subset with a 2010-2020 average N concentration > 3 mg/L. Cost estimates include operation and maintenance and capital costs amortized over 20 years with an 7% interest rate. All estimates adjusted for inflation to 2021 dollars. Household costs use MDH population served estimate and assume 2.2 people per household. Household costs presented in this table assume costs are distributed uniformly across all households, in reality smaller systems have higher household costs because they lack economies of scale in treatment.

	Total Annual Cost			**Per Household Annual Cost**		
	Low	**Average**	**High**	**Low**	**Average**	**High**
All PWSs	298,712,303	884,487,145	1,375,188,492	150	444	691
PWSs with > 3 mg/L N	9,834,363	27,955,216	45,749,935	162	459	752

While new treatment system costs are influenced by many factors outside the scope of this analysis (e.g., construction costs, technology advances, existing infrastructure), the estimates shown here demonstrate that under some high cost scenarios, treatment costs can rival the costs of land acquisition. Even in low and average cost scenarios, additional treatment can increase costs to individual households by hundreds of dollars per year, with very small systems facing the highest costs.

2.2 Avoided health costs from exposure to elevated drinking water nitrate

Cost-benefit analyses of water pollution have typically assumed that drinking water treatment standards in the U.S. are sufficiently stringent to eliminate health risks [8], but a growing body of epidemiological evidence shows that nitrate exposure may be harmful even at levels below the threshold set by the Clean Water Act [9–11]. This emerging research links low-level nitrate exposure to a number of cancers and birth defects whose mortality and morbidity outcomes can be valued in dollar terms. While still tentative, as these links become substantiated by further epidemiological research they may dramatically increase the social cost of water pollution by incorporating yet uncounted health damages.

We replicated and expanded upon an approach from the environmental public health literature [11,12]. This method, first applied to drinking water nitrate in a European cost-benefit assessment [13], uses disease-specific estimates of relative risk due to nitrate exposure and observed cases of the disease to infer the portion of observed cases that can be attributed to nitrate. We combine disease incidences from the Minnesota Department of Health[14], the National Institutes of Health[15], and the March of Dimes Peristats database[16] with the demographics and population estimates of each public water supply to estimate counts of adverse health outcomes at each water provider. We then use measured nitrate levels in these supplies, as provided by MDH, and the relative risk values reported in table 1 of Mathewson et al.[11] to estimate counts of five different cancers and four adverse birth defects, including neural tube defects that are frequently fatal (Figure 8).

From case counts, we calculate a number of monetary figures that represent different approaches to valuing the social costs of these plausibly nitrate-caused diseases. Using estimates from the literature [12,17,18], we calculate direct medical costs for diagnosis and treatment. Following past research [12,19,20], we pursue two distinct approaches to valuing loss of life. The Value of a Statistical Life approach derives a value for mortality from observed trade-offs individuals make between job compensation and increased risk of fatality. The Quality Adjusted Life Years approach estimates a similar value for each year of lost life and for the diminution of quality of life during the course of the disease. The two approaches provide philosophically distinct, but complementary estimates to the health damages cleaner water could avoid.

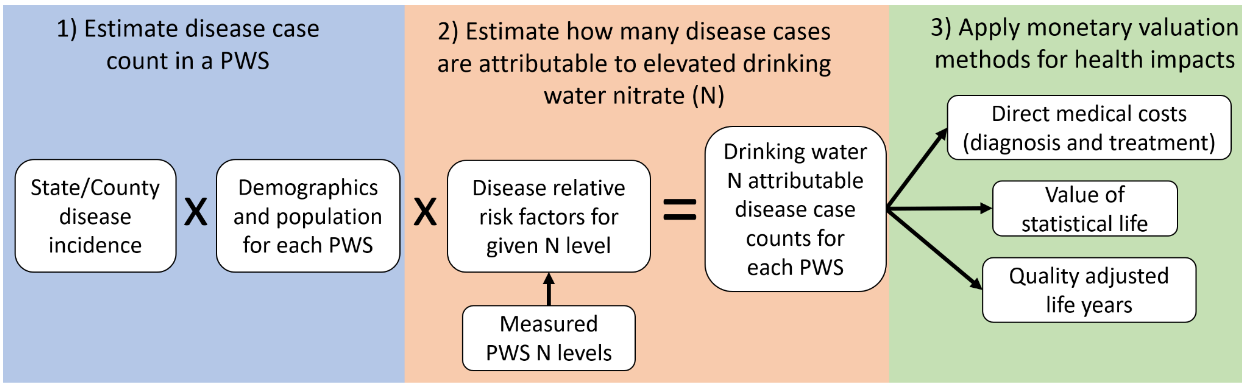

Figure 8. Conceptual diagram of avoided health costs calculations. Colored background boxes divide the process into three steps. First we estimate the number of disease cases that happen in each PWS based on local incidence rates and the population served by the PWS. Next we estimate how many of those are attributable to elevated drinking water nitrate using relative risk factors that correspond to the observed nitrate concentrations in the PWS. Finally, the disease cases attributable to elevated nitrate are monetarily valued using three techniques.

Our preliminary results show health impacts attributable to drinking water nitrate exposure include 51 adverse birth outcomes and 70 cases of cancer annually. Using the methods described in step 1 of this analysis (Figure 8), we estimated an annual average case count of all cancer types of 5,963. Despite being a small proportion of the total cancer cases, even the most conservative valuation methodology, direct medical costs, resulted in annual costs of $27.2 million. In contrast, the very commonly used value of a statistical life methodology produces estimates an order of magnitude higher, $256.6 million (Table 4). Of the diseases analyzed, colorectal cancer has the strongest link to elevated drinking water nitrate consumption in the epidemiological literature. Consequently, it is responsible for most cases, 39 annually, and highest annual costs, $137 million in our estimates (Table 4).

Table 4. Preliminary results of estimated annual disease and adverse birth case counts with three valuation techniques applied. Anencephaly is fatal at birth, resulting in no medical treatment costs. Thyroid cancer direct medical costs and data necessary for calculating adverse birth outcome quality adjusted life years were not available at the time of analysis. Further research is needed to better represent the underlying uncertainty and develop missing valuation techniques. All values adjusted for inflation to 2021 dollars. *Note the total excludes very preterm birth from total costs because these are highly correlated with low birth weight, however, both are included in the total case count.

Disease	Case count	Medical costs	Quality Adjusted Life Years	Value of a Statistical Life
Anencephaly	0.2			1,678,965
Spinabifida	0.5	322,606		601,741
Very low birth weight	30.1	8,663,286		21,169,152
Very preterm birth	20.7	7,457,095		13,119,672

Bladder cancer	0.2	27,464	66,173	579,012
Colorectal cancer	38.7	5,918,463	21,058,611	137,735,384
Kidney cancer	27.2	4,191,313	17,164,528	67,792,738
Ovarian cancer	2.7	628,387	2,510,934	13,824,115
Thyroid cancer	1.0		903,505	165,340
Total*	**121.2**	**27,208,614**	**41,703,752**	**256,666,119**

Our work also highlights the difficulty of attributing disease to exposure that can occur over decades. Rigorously estimating relative risk parameters, the key variable in the attribution method, is difficult to do in the face of numerous challenges: mobile populations whose lifetime nitrate exposure must be inferred, relatively rare maladies for which sufficiently large samples are not available, and mechanisms of nitrate metabolism that are sensitive to diet and other confounding factors. Our analysis used relative risk figures compiled in Mathewson et al.,[11] but our review of the epidemiological literature revealed that more research is needed to better characterize the uncertainty around the relative risks values that underpin this analysis. Future research will build on this work by incorporating simulations with a range of likely relative risk values informed by multiple studies weighted by their quality. Fully characterizing uncertainty would improve these results by representing them as a distribution of values weighted by likelihood, however, the health costs presented here are a useful starting estimate, and indicate that potential health damages may be significant if monetized.

2.3 Relative environmental benefit strengths of the DWSMA portfolio

Protecting source waters through adoption of best management practices, maintaining perennial cover, or protecting land from development has the potential to provide other environmental co-benefits, thus increasing the return on investment in protection activities. To assess the potential co-benefits of conservation or restoration activities within DWSMAs we mapped 19 unique spatial indicators representing a suite of environmental benefits. We applied the environmental benefit analysis at two scales; first analyzing all of the unbuilt land within DWSMAs as a single unit in comparison to unbuilt and unprotected land statewide, and second, by scoring all parcels within DWSMAs to facilitate comparisons between and within DWSMAs. We adapted methods developed over a decade of ecosystem services research in Minnesota and applied these methods for the first time to the context of source water protection.

Metrics were based on best-available ecological and social data and reflect the potential of land to deliver co-benefits. The metrics were designed to be applicable for either protection or restoration activities, so this analysis was applied to all unprotected and unbuilt land (i.e., it includes both natural vegetation and agriculture land covers). Environmental benefit scores range from 0 to 1. For binary metrics (trails, trout streams, and wild rice), 0 indicates a benefit is not provided by that land and 1 indicates it is. The remainder of the metrics are continuous, 0 indicates a benefit is not provided, low scores indicate lower potential to provide the benefit while scores near 1 indicate it is the best land in the state for that benefit. For example, land scoring higher on the co-benefit of lake recreation are those located within the catchment of lakes that also have public access and high visitation. Detailed explanations of co-benefits metrics are described in the 2021 report “Measuring what matters: Assessing the full suite of benefits of OHF investments”[21].

For the DWSMA level analysis, we reclassified the continuous metrics into binary maps where land received a score of 1 if it fell within the top quartile of land scores for that metric and a 0 if it was in a low-medium quality class, or outside of the area where the benefit is provided (e.g., lake recreation scores are 0 outside of the catchment of public lakes). Next, we calculated the proportion of highest quality class land for each metric within all DWSMAs and compared that to the proportion of high quality land found elsewhere in the state. If DWSMAs were no different than a random selection of land in the state then we assume that land protection or restoration in that DWSMA was no better than average (see Figures 9 and 10). However, if for example 22.5% of land within DWSMAs was in the highest quality class for pheasant habitat, but only 10% of the land statewide was in that class, the proportion for DWSMAs would be 125% that of the expected proportion in the state.

We found that unprotected and unbuilt land within DWSMAs scores higher than average on metrics of bird watching, pheasant habitat, and trail proximity relative to non-DWSMA land statewide. DWSMA lands scored lower for breeding habitat for forest, grassland, and wetland bird Species of Greatest Conservation Need (SGCN) (Figure 9). We also assessed metrics for risk of development, risk of conversion to agriculture, and nearby population. Methods for these metrics are documented in the aforementioned report[21]. The risk metrics are useful for targeting land with the greatest likelihood of conversion. The nearby population metric is important because it is an indicator of how accessible the environmental benefits land provides are to the public. DWSMAs are near more people, and the proportion of DWSMA area at high risk of development is nearly triple the proportion found statewide, likely due to their spatial correlation with population centers.

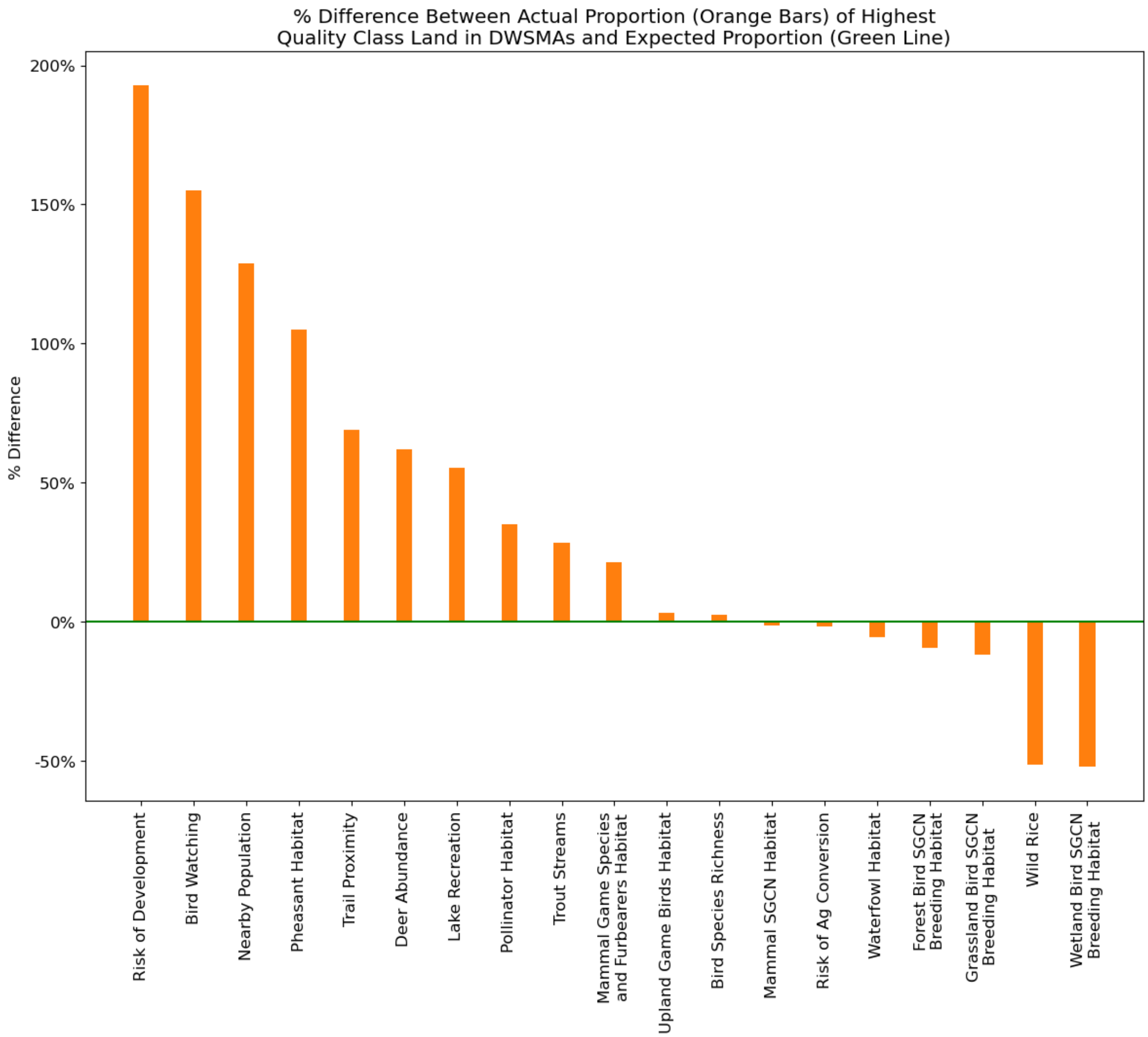

Figure 9. Comparison of the relative environmental benefit strengths of land in DWSMAs to the state. Analysis only applies to unprotected and unbuilt land. If the land in DWSMAs had the same proportions of highest quality class environmental benefits as are found in the rest of the state, the orange bars would be on the green 0% line. However, some benefits are more prevalent in DWSMAs (when the orange bars are positive) and some are less prevalent (when the orange bars are negative). The proportion of DWSMA area at high risk of development is nearly triple the proportion found statewide, and high quality pheasant habitat and bird watching are more prevalent than expected.

We applied the same analysis to the subset of High and Very High Vulnerability DWSMAs to identify co-benefits on the land most important for source water protection. Risk of development and nearby population were again the metrics that were disproportionately high in relative to the rest of the state (Figure 10). We found similar strengths of pheasant habitat and bird watching, and also found that metrics for lake recreation and trout streams were higher among High and Very High vulnerability DWSMAs than all DWSMAs and the state as a whole.

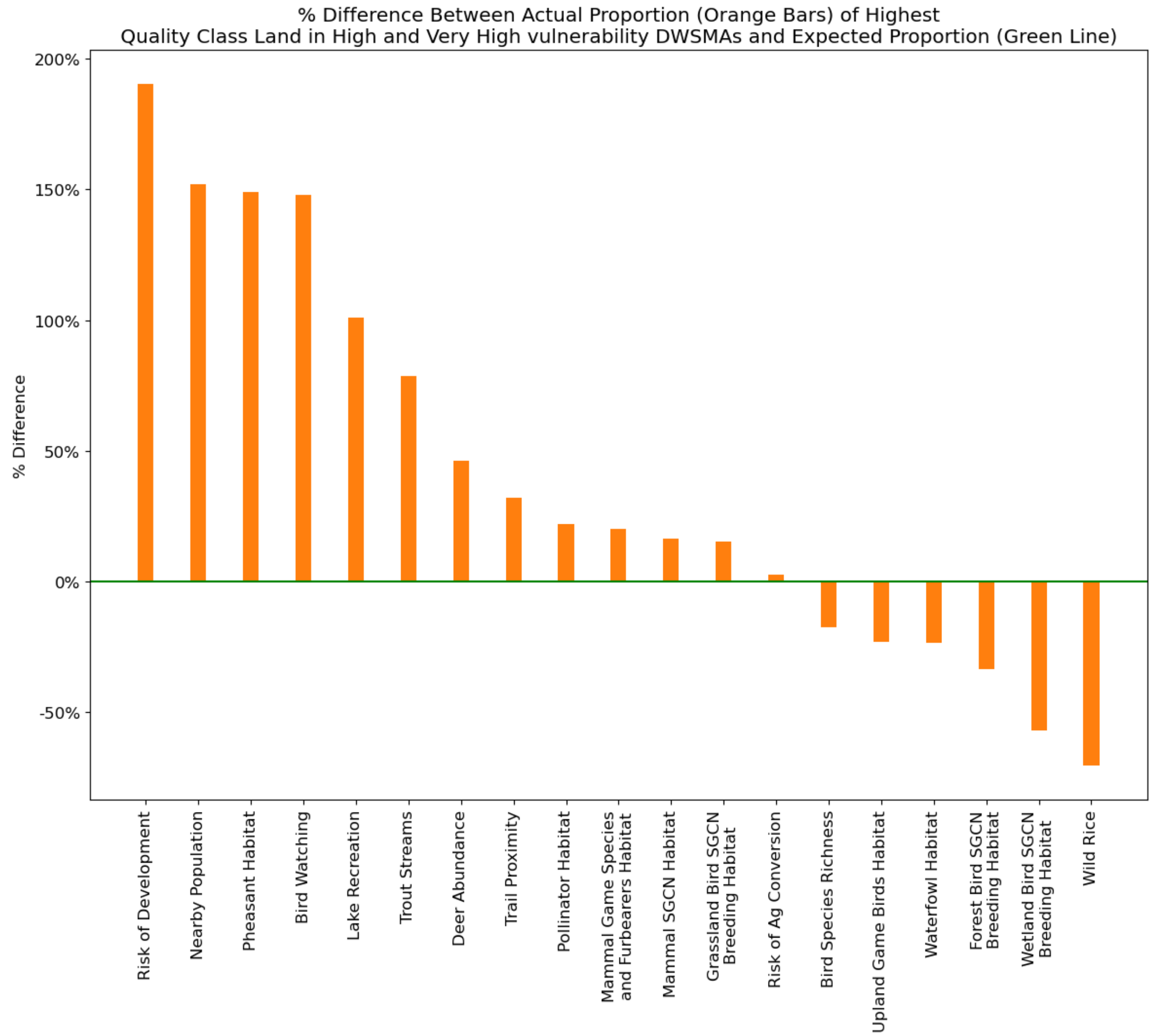

Figure 10. Comparison of the relative environmental benefit strengths of land in high and very high vulnerability DWSMAs to the state. See Figure 9 for detailed description of figure interpretation. The most disproportionately represented benefits are similar between DWSMAs and High and Very High vulnerability DWSMAs, however, note that the benefits are sorted in order from most represented to least represented, and the order is slightly different between the two figures.

Of the metrics in this analysis 12 of 19 were disproportionately found in DWSMAs compared to statewide. Four of those metrics (risk of development, nearby population, pheasant habitat, and bird watching) were more than twice as prevalent. High and Very High vulnerability DWSMAs performed similarly or slightly better than all DWSMAs with regards to number of benefits and magnitude of benefits represented. Metrics for wild rice, and breeding habitat for wetland bird species of greatest conservation need were under-represented in both of our DWSMA analyses. These benefits are still found within DWSMAs, just at a lower frequency than statewide. Given the high opportunity cost of protecting land, this analysis of co-benefit prevalence within DWSMAs is valuable for identifying partners to pursue multiple-benefit based source water protection strategies.

2.4 Parcel level attributes for screening and prioritization

The above figures and tables provide an overview of the costs and benefits associated with source water protection for all of the DWSMAs in the state. However, costs and benefits vary between and even within DWSMAs. Prioritizing areas with multiple benefits and a high return on investment requires higher resolution analysis. We scored over 30,000 Public Land Survey quarter-quarter section parcels (approximately 40 acres each) that overlap DWSMAs on the land cover, land value, and environmental co-benefits described above. The resulting table (Appendix C) can be sorted and filtered to identify parcels that score highly on any combination of our 19 environmental benefit metrics in addition to attributes such as land cover, land value, protection status, and DWSMA geologic vulnerability (Table 5). The table can also be joined to the included shapefile (Appendix D) for mapping and spatial analysis.

While all of the environmental benefit metrics are on a 0 to 1 scale, the scores are not comparable between metrics. Only comparisons between parcels for the same metric are appropriate. Because the underlying metrics are statewide maps, the highest scoring land may be located outside of the subset parcels that intersect with DWSMAs. This dataset is designed to facilitate comparison of relative environmental benefits of parcels within and between DWSMAs only.

Table 5. Definition of attributes and their source for parcel scores in Appendix C.

Column Name	Description	Source
forty_id	Unique identifier that corresponds to Appendix_D_parcel_shapefile.zip	Calculated
gis_acres	GIS calculated area of parcel in acres	Calculated
bird_sgcn_forest	Forest bird species of greatest conservation need habitat quality potential	Measuring what matters: Assessing the Full Suite of OHF investments (Appendix A)[21]
bird_sgcn_grassland	Grassland bird species of greatest conservation need habitat quality potential	
bird_sgcn_wetland	Wetland bird species of greatest conservation need habitat quality potential	
bird_species_richness	Bird species richness	
mammal_sgcn	Mammal species of greatest conservation need habitat quality potential	
pollination	Pollinator habitat quality	
bird_upland_game	Upland game bird species habitat quality potential	
pheasant	Pheasant habitat quality	
bird_waterfowl_game	Waterfowl species habitat quality potential	
mammal_fur+game	Mammal game and furbearer species habitat quality potential	

deer	Deer habitat quality potential	
bird_watching	Bird watching activity	
lake_rec	Lake recreation	
trails	Proportion of parcel within a 500m buffer of state trails	
wild_rice	Proportion of parcel within the catchment of a wild rice site	
population	Minnesotan population within 50 miles	
risk_of_dev	Risk of development (built land cover)	
risk_of_ag	Risk of conversion to agriculture	
trout_streams_bin	Proportion of parcel within catchment of a state designated trout stream	
dev-19	Proportion of parcel in developed (built and agriculture) land cover in 2019	National Land Cover Dataset[4]
undev-19	Proportion of parcel in undeveloped (natural vegetation and water) land cover in 2019	
ag-19	Proportion of parcel in agriculture (row crop and pasture/hay) in 2019	
built-19	Proportion of parcel in built (any intensity) land covers in 2019	
natveg-19	Proportion of parcel in natural vegetation (wetland, grassland, forest) in 2019	
water-19	Proportion of parcel with open water in 2019	
Very Low	Proportion of parcel with very low geologic vulnerability to contamination	Drinking Water Supply Management Areas[22]
Low	Proportion of parcel with low geologic vulnerability to contamination	
Moderate	Proportion of parcel with moderate geologic vulnerability to contamination	
High	Proportion of parcel with high geologic vulnerability to contamination	
Very High	Proportion of parcel with very high geologic vulnerability to contamination	
DWS_ID	The DWSMA ID of the highest vulnerability DWSMA the majority of the parcel falls within	
Avg Land Value per ha	Average value per hectare of parcel as modeled in Nolte 2020 (2021 USD)	Nolte (2020)[5]
Total Land Value	Total value of parcel as modeled in Nolte 2020 (2021 USD)	
Protected %	Proportion of parcel protected by a conservation program	Parcel Environmental Benefit Assessment Tool Expanded Documentation (Pages 5-7)[23]

In Table 6, a hypothetical example demonstrates how filters can be used to identify a small subset of parcels that meet the requirements of the user. This approach is useful if several interest groups are collaborating on a protection project that would be too large or expensive for any one of them individually. For example, in the Worthington Wells Wildlife Management Area, a partnership between Pheasants Forever, Worthington public utilities, and other local stakeholders resulted in the protection of high geologic vulnerability land within a DWSMA and high quality pheasant habitat[24]. By targeting parcels with multiple benefits, conservation practices can achieve a higher return of environmental benefits for their investment.

Table 6. Example of how filters can be used to screen for parcels that meet the users requirements. Each filter is applied to the output of the filter above it until the priorities of the user are satisfied and the number of parcels is reduced to a more manageable number for individual investigation. Parcels in all DWSMAs can be analyzed for statewide screening, or a subset from specific DWSMAs for targeted prioritization.

Filter	Number of parcels
Initial dataset	33,186
< 50% developed (built or ag)	6,051
Above average lake recreation score	1,488
Above average pheasant habitat score	233
Above average bird species richness score	118
Above average risk of development score	46
100% High or Very High geologic vulnerability	10
Average land value < $15,000 per hectare	5

3. Enabling assessment of equity in source water protection

Elevated costs for water treatment, higher incidence of disease, and reduced access to recreation amenities have the potential to disproportionately affect rural, low income, and traditionally underrepresented populations. We were interested in the distribution of source water contamination threats to different communities in Minnesota. Our work was also motivated by a need to include demographic and income data in prioritization exercises enabled by the co-benefits and land value analysis described above. If agencies and resource managers seek to target source water protection or restoration investments in DWSMAs that address water quality, environmental co-benefits, and environmental justice concerns, then new datasets would be needed to facilitate this analysis.

At the beginning of our work, there was no easy way to link census-based demographic data to DWSMAs or PWSs. Multiple DWSMAs may serve a single PWS, and census data at the block or tract-level cannot be joined to DWSMAs or PWSs using spatial intersection. Data for DWSMAs and PWSs were limited to estimates of population served and geologic vulnerability. Policy makers, practitioners, and the public are unable to assess if the benefits of protecting source water are equitably distributed if the data only represent the biophysical aspects of land and water protection.

We addressed this gap by manually correcting for mismatches between municipalities and PWSs and joining demographic attributes of populations served to PWSs. With indicators of social vulnerability available at the same management unit as water quality, we are enabling the inclusion of equity in source water protection decisions.

3.1 Demographic characteristics of Public Water Supplies

Despite a wealth of data on drinking water quality and management in the state, the complexity of the data often poses a challenge to analyzing multiple datasets simultaneously. For example, demographic data useful for identifying vulnerable populations is linked to municipalities, whereas DWSMAs correspond to the 10-year travel time for well fields. Connecting these management units allows practitioners to visualize where threats to drinking water quality and vulnerable populations co-occur.

To bridge this gap, we manually reviewed PWSs to identify those that serve a municipality and renamed them to match census records (e.g., ‘Blue Earth Light and Water’ to ‘Blue Earth’). We joined the resulting table to both the Minnesota Department of Health’s (MDH) records on drinking water nitrate[2], and a subset of U.S. census American Community Survey 2015-2019[25] demographic characteristics (Table 7).

Not all PWSs serve municipalities, many serve manufactured housing parks, colleges, prisons, and large businesses. For these, we include the demographic characteristics for the county of the PWS, along with the population served according to MDH records. For some non-municipal PWSs, the demographic characteristics of the county will be of limited use (e.g., age distribution for a county is likely not representative of the population served by a college). PWSs may also serve multiple municipalities, or only serve a subset of the population of a municipality. Demographic data should be interpreted carefully in this context and cross-referenced with population served estimates from MDH.

Demographic characteristics that we joined to PWSs are described in Table 7, and the full dataset is included as Appendix A. Appendix A can be joined to the MDH DWSMA shapefile on the ‘pwsId’ field for spatial analysis or analyzed in tabular format. Note that if a one-to-one join is desired, the DWSMA layer should be dissolved on the ‘pwsId’ first. Entries with a ‘join_type’ of ‘municipal’ indicate a PWS that joined to census municipality data, while entries labeled as ‘county’ indicate a PWS that is either not a municipality or did not have a name that matched a census municipality and is joined to census county data.

Table 7. Definition of values in each column and their source for appendix of public water supply demographic characteristics. Light grey rows indicate the attribute is only available if the PWS has one or more associated DWSMAs. DWSMAs are continuously being delineated, so not all PWSs have had theirs delineated yet. Dark grey rows indicate the variable is only available when a PWS is joined to census municipality data.

Column Name	**Column description**	**Source**
pwsId	MDH Public Water Supply ID	Minnesota Department of Health[2]
pwsNameRecent	Most Recent PWS Name	
county	County of PWS	
waterSource	Surface or Groundwater	
max_2010to2020	All time highest N concentration 2010 to 2020	
mean_2010to2020	Average of all N concentration readings 2010 to 2020	
MDH_pop	MDH estimate of population served	
AreaName	Municipality name (in census)	U.S. Census American Community Survey 2015-2019 5-year average[25]
geoid	census geographic ID	
census_pop	Total population from census data	
pctAge0_4	% Age 0 to 4	
pctAge5_9	% Age 5 to 9	
pctAge10_14	% Age 10 to 14	
pctAge15_19	% Age 15 to 19	
pctAge20_24	% Age 20 to 24	
pctAge25_34	% Age 25 to 34	
pctAge35_44	% Age 35 to 44	
pctAge45_54	% Age 45 to 54	
pctAge55_59	% Age 55 to 59	
pctAge60_64	% Age 60 to 64	
pctAge65_74	% Age 65 to 74	
pctAge75_84	% Age 75 to 84	
pctOver85	% Over 85	
MedianAge	Median age in years	
pctWomenGivingBirth	% Women 15 to 50 years old who had a birth in the past 12 months	
pctWhite1	% White alone	
pctBlack1	% Black or African American	
pctIndian1	% American Indian and Alaska Native	
pctAsian1	% Asian	

pctHawnPI1	% Native Hawaiian and Other Pacific Islander	
pctOther1	% Some other race	
pctHispanicPop	% Hispanic or Latino of any race	
pctMultiRace	% Two or more races	
MedianHHInc	Median household income	
pctPoor	% Persons below poverty	
pctCashRenterOver30Pct	% Gross rent 30% or more of HH income	
pctHUsMortOver30Pct	% Owner costs 30% or more of HH income	
pctNoVehicles	% No vehicles available	
RO_low_cost	Estimated low total cost for reverse osmosis filtration based on population served	Calculated based on Jensen et al. (2012)[6]
RO_average_cost	Estimated average total cost for reverse osmosis filtration based on population served	
RO_high_cost	Estimated high total cost for reverse osmosis filtration based on population served	
join_type	Indicates if the PWS is joined to 'municipal' or 'county' census data. Exercise caution when interpreting demographic characteristics from the county as the PWS may serve a non-representative sample (e.g, prisons, schools, manufactured housing parks, or companies).	Calculated
dev-19	Proportion of PWS DWSMA area in developed (built and agriculture) land cover in 2019	National Land Cover Dataset[4]
undev-19	Proportion of PWS DWSMA area in undeveloped (natural vegetation and water) land cover in 2019	
ag-19	Proportion of PWS DWSMA area in agriculture (row crop and pasture/hay) in 2019	
built-19	Proportion of PWS DWSMA area in built (any intensity) land covers in 2019	
natveg-19	Proportion of PWS DWSMA area in natural vegetation (wetland, grassland, forest) in 2019	
water-19	Proportion of parcel with open water in 2019	
Very Low	Proportion of PWS DWSMA area very low geologic vulnerability	Drinking Water Supply Management Areas[22]
Low	Proportion of PWS DWSMA area geologic vulnerability	
Moderate	Proportion of PWS DWSMA area geologic vulnerability	
High	Proportion of PWS DWSMA area high geologic vulnerability	
Very High	Proportion of PWS DWSMA area with very high geologic vulnerability	

Avg Land Value per ha	Average value of PWS DWSMA land as modeled in Nolte 2020 (2021 USD)	High-resolution land value maps reveal underestimation of conservation costs in the United States (2020)[5]
Protected %	Proportion of PWS DWSMA area protected by a conservation program	Parcel Environmental Benefit Assessment Tool Expanded Documentation[23]

3.2 Public water supply nitrate concentrations and demographic characteristics

In Figure 11, we demonstrate the only social vulnerability analysis that can be performed with data directly from the MDH Public Health Data Access: Drinking Water Query tool[2]. We plotted the population served against the average of all nitrate concentration readings for a PWS, to show where a PWS that serves a small population has elevated drinking water N. That combination has the potential to create a disproportionate burden on rate-payers because the large capital costs of installing additional water treatment is distributed among a small group of people relative to a larger PWS.

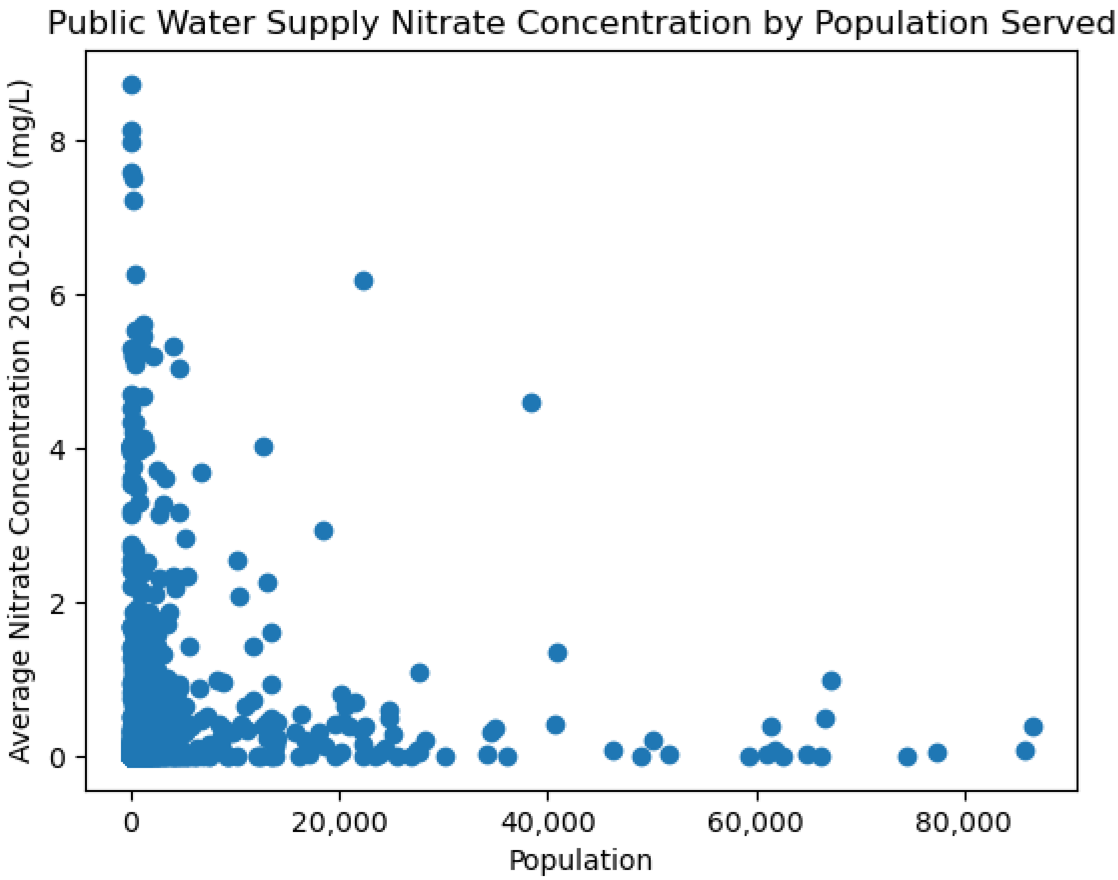

Figure 11. Plot of PWS average drinking water nitrate concentration and the size of the population it serves. The points in this figure represent all municipal and non-municipal public water supplies in the state, and use the MDH's estimate of population served. It shows that the public water supplies with the greatest nitrate contamination serve the fewest people, resulting in a higher individual cost for treatment upgrades.

With joins between water quality data from MDH and census demographic characteristics, it is possible to go beyond population size and analyze how the concentration of drinking water nitrate varied with other measures of social vulnerability. For example Figure 12 shows the relationship between drinking water nitrate concentration and median household income. Municipalities in the lower quartile for median household income had a higher proportion of elevated nitrate than higher income municipalities. Demographic characteristics or combinations of characteristics in Table 7 such as household income or percent of people whose rent is > 30% of their household income provide a more meaningful measure of the burden of increased drinking water treatment costs than population served alone. The attributes in Appendix A create the foundation to analyze and explore relationships between multiple indicators of social vulnerability in source water protection planning.

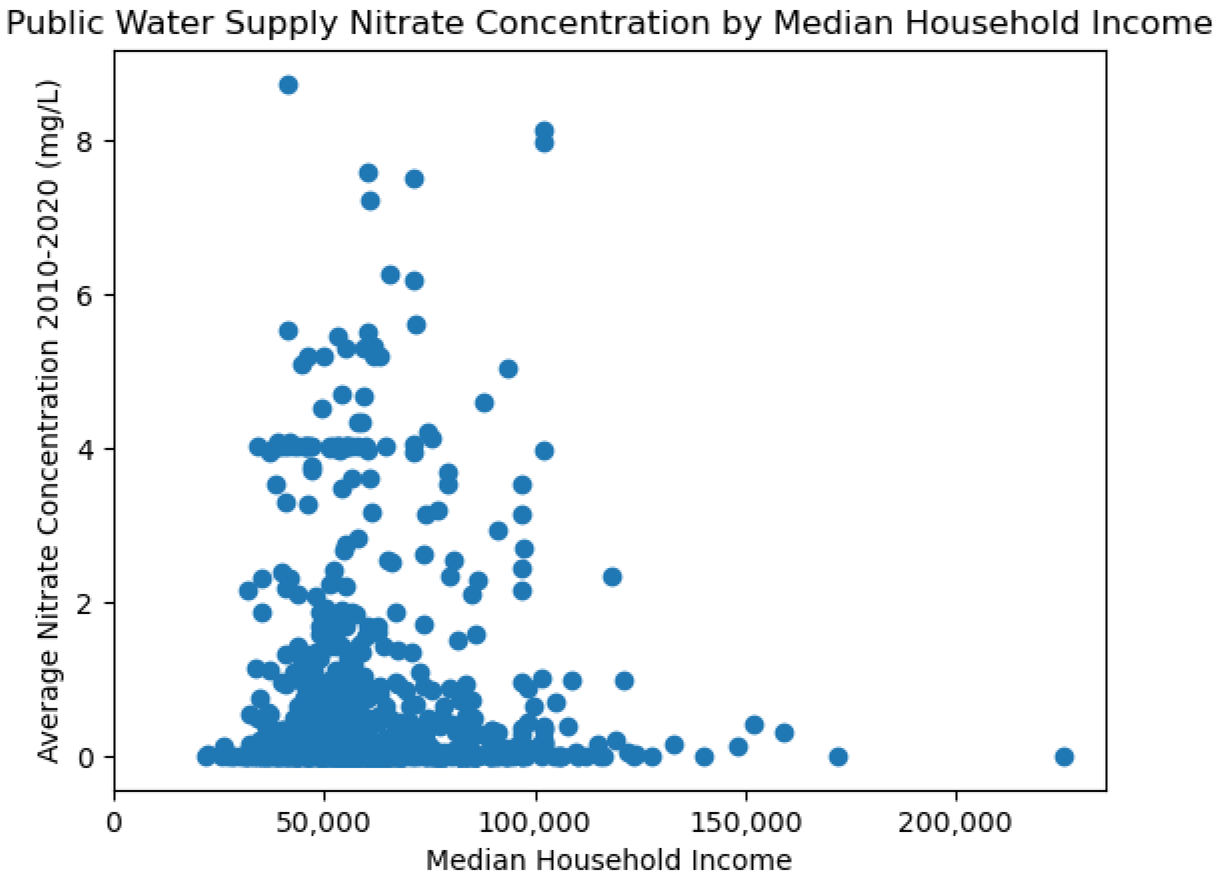

Figure 12. The points in this figure are limited to only municipal public water supplies that matched a municipality in census data, meaning that it excludes smaller public water supplies such as manufactured housing parks. While most PWS did not have elevated drinking water nitrate, those that did tended to be in the lower quartile for median household income.

4. Synthesis and future work

The analyses in this report describe the threats, costs, benefits, and distributional impacts that should be considered in source water protection activities. Our study is the first to combine data on these four topics for every DWSMA in Minnesota.

Threats

Our land use change analysis showed natural vegetation land covers that protect water quality are already less than 20% of total DWSMA area, and have declined slightly since 2001. Despite a period of record high crop prices, agricultural land area in DWMSAs declined over the last 20 years as built area expanded (Figure 2). However, agriculture remains the dominant land cover in High and Very High vulnerability DWSMAs (Figure 3). Mapping the distribution of DWSMAs with the elevated loss of natural vegetation shows this trend is occurring in all regions of the state, with a concentration in the metro area. In addition to observed land use change, we also modeled the risk of future development at the DWSMA level. We found that DWSMAs' proximity to population centers resulted in a proportion of land at high risk for development triple that of the statewide proportion.

Costs

The competition among land uses and proximity to population centers creates high opportunity costs for protection activities. We used a novel dataset to summarize the value of land at the parcel level in all DWSMAs. In total, the value of unprotected and unbuilt land is \$8.8 billion (Figure 6). An investment of \$100 million would be enough to acquire 15% of the least expensive, most vulnerable land (Figure 7). However, that strategy is unlikely to produce sufficient and equitable protection across all DWSMAs. The high cost of land requires consideration of the multiple benefits protection activities produce in order to prioritize investments with the highest return on investment.

Benefits

Preventing contamination of drinking water is associated with multiple benefits not in the form of avoided treatment costs or in avoided health damages associated with consumption of contaminated water. In this report, we applied previous research on monetary valuation techniques of topics to individual PWSs and the DWSMAs that supply them for the first time. Treatment costs for only PWSs with elevated nitrate ranged from \$9.8 to \$47.5 million annually (Table 3). Annual health costs from cancer and adverse birth outcomes ranged from \$26.2 to \$256.6 million depending on the valuation approach used (Table 4).

We also assessed potential co-benefits of source water protection in the form of habitat conservation, recreation, and other public goods using a non-monetary prioritization technique. This approach identifies the strength of DWSMAs for contributing to environmental benefits beyond drinking water quality, relative to the rest of the state. We found that DWSMAs have a disproportionate amount of high quality pheasant habitat, bird watching activity, proximity to trails, and deer abundance, among others (Figure 9). This analysis, which we also summarized at the parcel level, can be used to develop coalitions of interest groups to engage in source water protection targeting multiple benefits.

Distributional impacts

The benefits of source water protection have the potential to be inequitably distributed, resulting in high costs for vulnerable populations served by some PWSs. We addressed a limitation of PWS level data by creating a workflow to join census demographic data to PWSs. This analysis enabled us to visualize the relationship between drinking water nitrate concentrations and indicators of vulnerability such as median household income. We found that although most PWSs don't have elevated drinking water nitrate, those that do tend to be smaller and in the lower quartile for median household income. These variables can be used to both identify where PWSs serve vulnerable populations and ensure investments are equitably distributed between PWSs.

<u>Contributions to future work</u>

Our analysis integrated across several ongoing research efforts, and highlighted areas where future work was most needed to address remaining challenges. We anticipate building on the work presented here and pursuing new research in the following areas:

Characterizing uncertainty in drinking water nitrate health damages functions:
Our demographic join enabled us to create estimates of drinking water nitrate-related health damages at local scales. However, further work is required to represent the uncertainty in exposure and relative risk parameters.

Land use change prediction:
We improved on quantifying changes in land use change in DWSMAs using recent advances in the NLCD, and implemented a risk of development indicator at the parcel level. While these techniques are useful for quantifying threats from changing land use, we intend to improve on their respective strengths to better estimate both the quantity and location of land use change.

Integration of quantitative and qualitative methods for valuing water resources:
We are exploring the integration of the quantitative data on costs and benefits presented here with new research using deliberative and participatory methods of value elicitation, governance and institutional assessments related to groundwater, case studies in specific DWSMAs, and evaluation of alternative scenarios to protect water quality and multiple ecosystem services given budgetary constraints.

Coordination and data-sharing with state agencies:
While carrying out this research we observed numerous opportunities for collaboration with state agencies on the intersection between source water protection and topics such as climate change, watershed planning, nutrient modeling and the integration of source water protection benefits into policy. We will continue to engage with state agencies to ensure future research efforts complement and enhance their work.

Our work demonstrated that opportunity costs of protection of source water protection are high, but not insurmountable when compared to the value of its multiple benefit streams. Analysis at multiple scales, from statewide prioritization to parcel level comparisons are needed to identify where source water protection has a positive and equitable return on investment. The datasets included with this report on PWS level demographic characteristics and treatment costs, DWSMA level land use change trends, and parcel level environmental co-benefits and land value, provide foundational decision support data for weighing the threats to source water, costs and benefits of interventions, and the equity of outcomes.

5. Acknowledgements

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7. Appendices index

Appendix A: PWS land use and demographics

File name: Appendix_A_PWS_attributes.csv

Description: This .csv file contains data that can be analyzed independently or joined to a DWSMA shapefile (typically the user will want to dissolve the DWSMA shapefile on the 'pwsId' field prior to joining). This file contains attributes on the demographics of populations served by PWS, nitrate concentrations, estimated treatment costs of reverse osmosis, and aggregated geologic vulnerability, land value, land cover, and protected area of the DWSMAs that serve a PWS. See Table 7 for descriptions of all attributes.

Appendix B: DWSMA land use trends

File name: Appendix_B_land_use_trends.xlsx

Description: This .xlsx spreadsheet file contains data on land cover for every DWSMA disaggregated by vulnerability class for 2001 to 2019. The data are stored in a pivot table, so the user can select subsets of DWSMAs and automatically create a visualization and summary statistics of land use trends.

Appendix C: Parcel environmental benefits and land use table

File name: Appendix_C_parcel_scores.csv

Description: This .csv file contains data that can be analyzed independently or joined to Appendix D. This file contains attributes on the environmental benefits, geologic vulnerability, land value, land cover, and protected area of the parcels within DWSMAs. See Table 5 for descriptions of all attributes.

Appendix D: Parcel environmental benefits and land use shapefile

File name: Appendix_D_parcel_shapefile.zip

Description: This .shp shapefile contains a subset of Public Land Survey quarter-quarter section parcels (commonly referred to as forties because they are approximately 40 acres each) that intersect with DWSMAs. Users that want to map the data found in Appendix C should join it to this file on 'forty_id'.