HOW LONG WILL IT TAKE TO MEASURE AN IMPROVEMENT IN IOWA'S WATER QUALITY?

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Key Points

- Iowa waterways have high nitrate concentrations (mg NO_3^- L^{-1} water) and deliver large nitrate loads (kg NO_3^- per year) to the Gulf of Mexico for two key reasons:
    - Annual croplands dominate Iowa's land use, occupying ~67% of the state's land area.
    - Annual croplands, as currently managed, have long fallows with little-to-no plant nutrient demand; most nitrogen is lost during these times.

- Although annual cropping systems are the primary source of nitrate in Iowa's waterways, weather causes extreme year-to-year variability in the amount of nitrate transported from croplands to waterways (Figure 1).

- High year-to-year variability in nitrate levels creates a major challenge for the measurement of long-term trends in nitrate. Did nitrate levels increase or decrease due to weather patterns or changes in land use and management?

- We used a statistical approach, known as Monte Carlo analysis, to determine the probability of measuring a real 41% reduction in nitrate concentrations and loads over periods of 5, 10 and 15 years in the context of year-to-year weather variability. We used a 41% reduction because this is the targeted nonpoint nitrogen loss reduction in the Iowa Nutrient Reduction Strategy. Our analyses were conducted across 44 Iowa watersheds and used the 5-year rolling average annual flow-weighted nitrate concentration and load.

- Reductions in flow-weighted nitrate concentration (FWNC) can be measured more rapidly than reductions in nitrate load. Hence, measurements of FWNC can better inform progress on nitrate loss reduction.

- On average, across the 44 watersheds, **there is a 93% probability of measuring a 41% reduction in FWNC over a period of 15 years but only a 50% probability of measuring a 41% reduction in nitrate load over the same period of 15 years**. Probabilities of measuring reductions in FWNC and nitrate load across periods of 5 and 10 years are lower.

- Owing to a large range of year-to-year variability in FWNC and load across the 44 watersheds, **reductions in some watersheds can be measured much faster than in other watersheds**.

- Three factors explain the probability of measuring a reduction in FWNC and nitrate load. **Longer monitoring times** (e.g., 5 vs. 15 years), **greater reductions in nitrate levels** (e.g., 20 vs. 40%), and **lower year-to-year variability in nitrate levels** allow faster measurement of a real reduction.
- Across the watersheds, mean annual FWNC and nitrate load were weakly but positively correlated.

- This analysis generated several future research questions that can be answered to improve water quality monitoring (see page

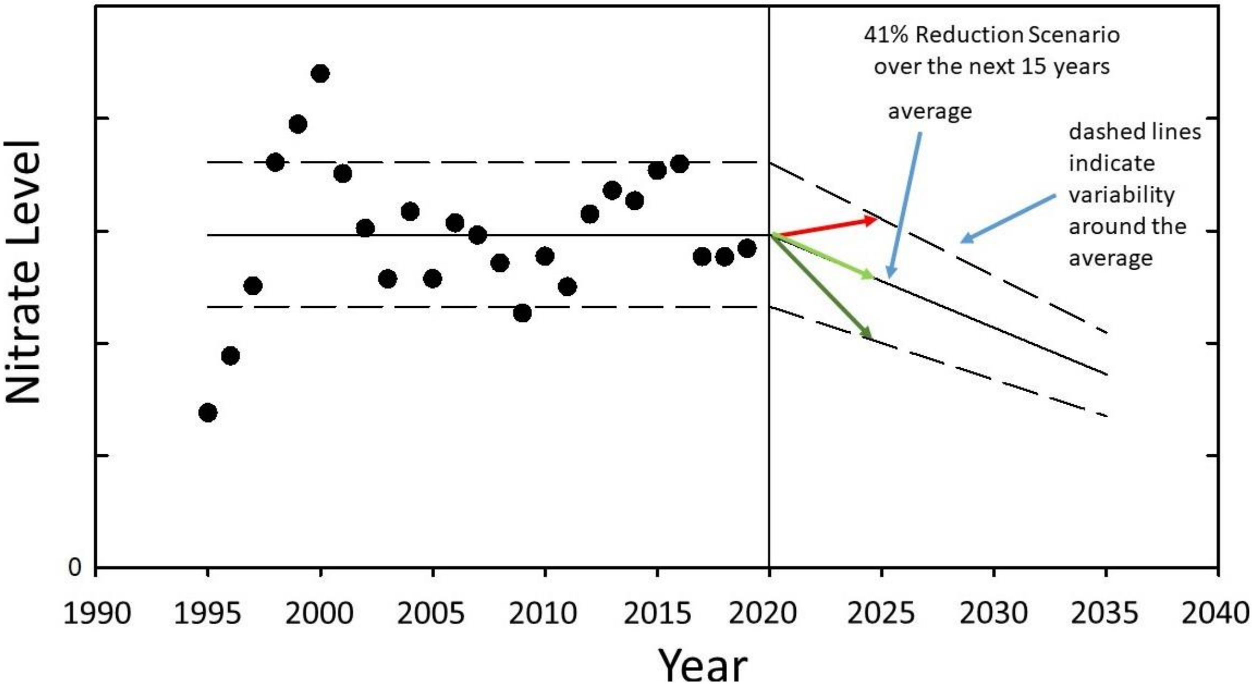

FIGURE 1. A conceptual visualization of the effect of weather on year-to-year variability in nitrate levels and the ability to measure a change in nitrate levels. Closed circles represent 5-year rolling average nitrate levels. The solid line represents the long-term average and the dashed lines represent the year-to-year variability owing to weather patterns (one standard deviation of the mean). There was no change in nitrate level from 1995 to 2020. However, if a 41% reduction occurred from 2020 to 2035 it is possible that the observed/measured data could underestimate (red arrow) or overestimate (dark green arrow) the reduction owing to the 'luck of the draw' on weather years. For example, there are relatively short timeframes (e.g., 2000 to 2010) where nitrate levels are increasing or decreasing despite no long-term change when the full data record is examined.

Background

Measuring and observing changes in water quality are challenging. Although land use and management are the primary factors causing high nitrate levels in Iowa waterways, annual weather patterns create enormous variability in nitrate levels. Measuring and observing a change in nitrate levels in the context of interannual weather variability is extremely challenging. With current land use, wet years generally increase nitrate loads while dry years generally decrease nitrate loads.

Three indices are commonly used to describe nitrate levels. The **nitrate concentration** in water is reported as milligrams of nitrogen in the form of nitrate per liter of water (mg NO_3^--N L^{-1} water). This is equivalent to parts per million or 'ppm'. The US Environmental Protection Agency National Drinking Water Regulations set a maximum level at 10 mg NO_3^--N L^{-1} water[1] (i.e., 10 ppm). However, the instantaneous concentration of nitrate provides only information about current conditions. To describe longer-term patterns, the nitrate concentration can be weighted by the flow of water in river or stream to describe the average concentration per unit of water that flows by a particular measurement location. This flow-weighted average is known as the **flow-weighted nitrate concentration** (FWNC) and is also reported as mg NO_3^--N L^{-1} water. Finally, nitrate load is the product of nitrate concentration and the flow of water at a measurement location (i.e., 'discharge'). **Nitrate load** describes the total amount of nitrate that flows by a particular location or from a particular watershed. It is generally reported as megagrams (Mg) of NO_3^--N per year (1 Mg = 1,000 kg = 1.1 tons). Water utilities are concerned with nitrate concentration whereas the Iowa Nutrient Reduction Strategy aims to reduce nitrate load. Nitrate load is affected more by the discharge of water than it is the nitrate concentration; hence, FWNC and load typically are not well correlated.

Although land use and management are the cause of elevated nitrate loads, discharge, which is controlled mostly by precipitation, explains most of the year-to-year variation in nitrate load. And the amount of precipitation from year-to-year can vary by 100%. For example, 10-year average precipitation in central Iowa is ~35 inches per year. However, 2010 had 46 inches and 2012 had 23 inches. Hence, it is extremely challenging to measure changes in nitrate loads over relatively short periods of time (e.g., 5-15 years).

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[1] https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#one

Objective

Our objective was to evaluate the probability of observing and measuring a 41% reduction in nitrate load (Mg NO_3^--N year^{-1}) and flow-weighted nitrate concentration (mg NO_3^--N L^{-1} water) across periods of 5, 10, and 15 years should the reductions occur. Although it is well known that will take a longer amount of time to measure a real reduction in watersheds with less year-to-year variability in nitrate FWNCs and loads, to our knowledge, the amount of time it will take to measure a reduction has not been quantified. Hence, we calculated the probabilities of measuring a 41% reduction in FWNC and load – should they occur – across periods of 5, 10 and 15 years.

Methods

We used a water quality monitoring data set provided by Iowa Department of Natural Resources that contained information for 55 Iowa watersheds that are monitored for discharge and nitrate concentration by IDNR and the US Geological Survey. The data contained watersheds that had been monitored for different numbers of years. However, to compare the probability of measuring reductions across watersheds, our analyses required that all watersheds be analyzed with a common set of years. Hence, we reduced the data set to 44 watersheds that were monitored from 2001-2018.

For each of the 44 watersheds, we used five variables in our analyses: mean annual FWNC, the standard deviation of mean annual FWNC, mean annual nitrate load, the standard deviation of mean annual nitrate load and watershed size. The FWNC, nitrate load and the SDs of these variables were calculated as a 5-year moving average. Hence, the 2001 FWNC was the average of 1997-2001 and the 2002 FWNC was the average of the 1998-2002, etc. The standard deviation of mean annual FWNC and load is a measure of the year-to-year variability. However, the standard deviation (SD) is proportional to the mean; hence, we converted the standard deviation to the coefficient of variation (CV) to standardize the variation across watersheds as a percent of mean FWNC and load. The CV is calculated as SD/mean and reported as %. The SD and CV were calculated from the 5-year moving average FWNC and load.

We determined if 5-year moving average FWNC and nitrate load were changing (increasing or decreasing) across the 2001-2018 for each watershed by fitting a linear model to the data. If the model fit was statistically significant (Type I error p

< 0.05), we eliminated the watershed for that variable (either FWNC, nitrate load or both) because our calculations of the probability of measuring a reduction should it occur assume that the FWNC and load are not currently increasing or decreasing. This process resulted in the elimination of 6 of 44 watersheds for FWNC and 16 of 44 watersheds for load.

Next, we simulated a 41% reduction in the 5-year moving average mean FWNC and load for each watershed. The simulated reductions were linear over scenarios of 5, 10, and 15 years. For example, in year 5 of the 10-year reduction scenario, the total reduction was 20.5%. We assumed that the CV is unaffected by reductions in FWNC and load. For example, a 41% reduction in FWNC from 10 mg NO_3^--N L^{-1} water with a SD of 3.0 was set equal to a FWNC of 5.9 mg NO_3^--N L^{-1} with a SD of 1.77. Both have a CV of 30% (3/10*100 = 30 and 1.77/5.9*100 = 30).

The data simulation method, known as Monte Carlo analysis, simulates the 41% reduction scenarios based on the mean and SD of FWNC and load. The simulation generates a value based on the potential data distribution calculated from input mean and SD in the IDNR data set such that the probability of generating a value at the mean is greatest; 68% of the generated data fall within one SD of the mean; 95% of the generated fall within two SDs of the mean, and so on. For each scenario (i.e., a 41% reduction over one period of time in one watershed) we simulated the reduction 5,000 times and then calculated the proportion of simulated reductions for each watershed and time-to-reduction scenario that resulted in a statistically significant linear model fit. The proportion was the probability of measuring reduction in the given watersheds over the 5, 10, and 15 year time periods. We conducted 990,000 simulated reductions (FWNC = 38 watersheds * 3 time scenarios * 5,000 simulations per scenario + Nitrate load = 28 watersheds * 3 time scenarios * 5,000 simulations per scenario)

Results

Reductions in flow-weighted nitrate concentration (FWNC) can be measured faster than reductions in nitrate load because FWNC has lower year-to-year variability. Within watersheds and across years, the coefficient of variation (CV) for the mean annual FWNC ranged from 4 to 23% whereas the CV for mean annual nitrate load ranged from 14 to 48% (Table 1). Across the monitoring period (2008-2019) for all watersheds, the mean CV for FWNC was 12% whereas the mean CV for nitrate load was 26%. The CV is closely related the amount of time it will take to measure a reduction (Figure 2), and the CV of FWNC was less than half of the CV for nitrate load.

Over a 15-year period, the probability of observing and measuring a statistically significant (see methods) 41% reduction in **FWNC** was 100% in 21 of the 38 watersheds that could be included in our analysis. In contrast, over a 15-year period, the probability of observing and measuring a statistically significant 41% reduction in **nitrate load** was 100% in zero of the 28 watersheds that could be included in our analysis. Across all 38 watersheds included in our analysis, the average probability of observing and measuring a statistically significant 41% reduction in FWNC across the 5, 10, and 15 year time periods was 60, 86, and 93% respectively. Across all 28 watersheds included in our analysis, the average probability of observing and measuring a statistically significant 41% reduction in load across the 5, 10, and 15 year time periods was only 18, 37, and 50% respectively (Figure 3).

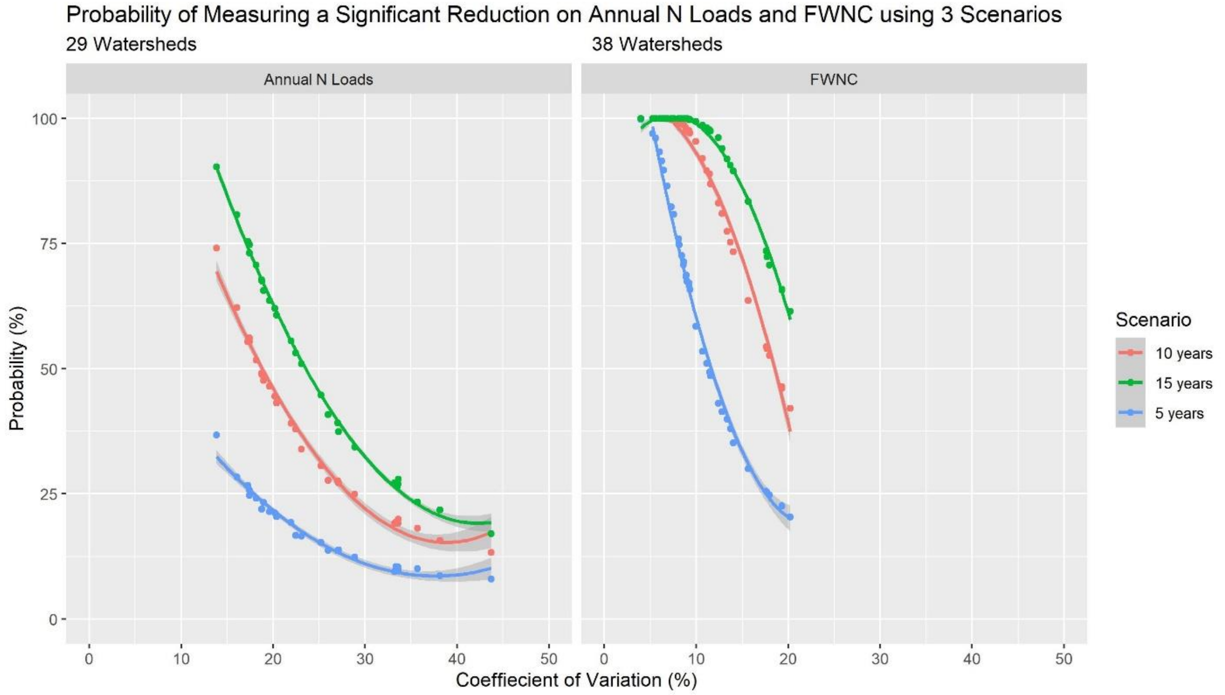


FIGURE 2. Relationship between the probability of detecting a real reduction in nitrate levels and the coefficient of variation (that is, year-to-year variability) of annual nitrate loads and flow-weighted nitrate concentration.

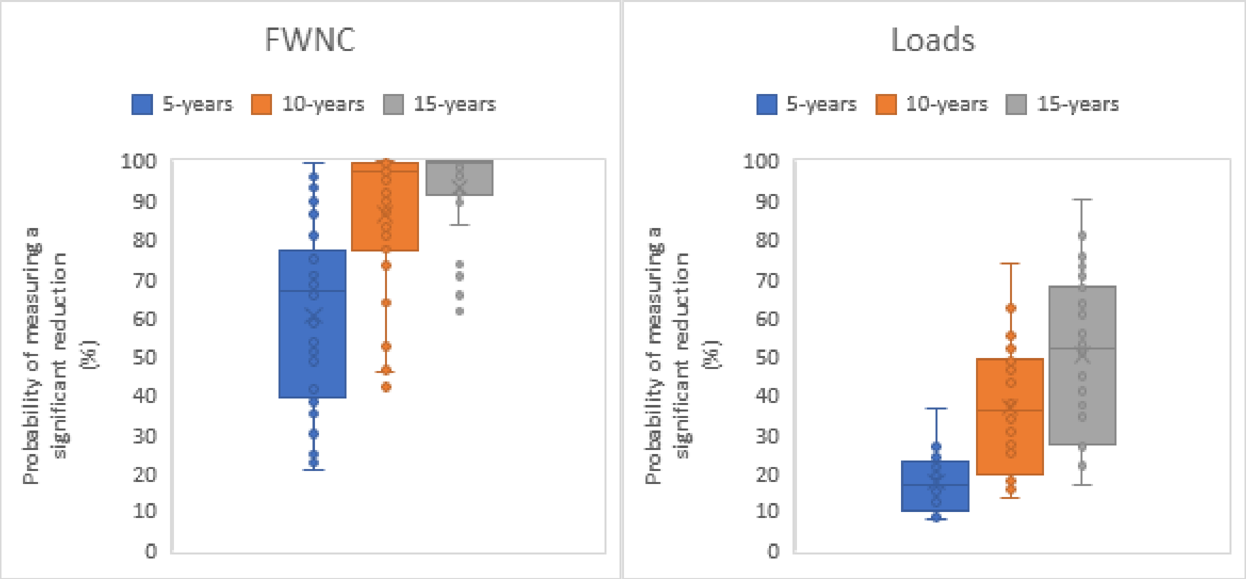


FIGURE 3. Distributions of probability of measuring a 41% reduction in FWNC (left) and nitrate load (right) across the watersheds included in the analysis (N = 38 for FWNC and N = 28 for nitrate load). Note, all analyses based on 5-year moving average FWNC and load.

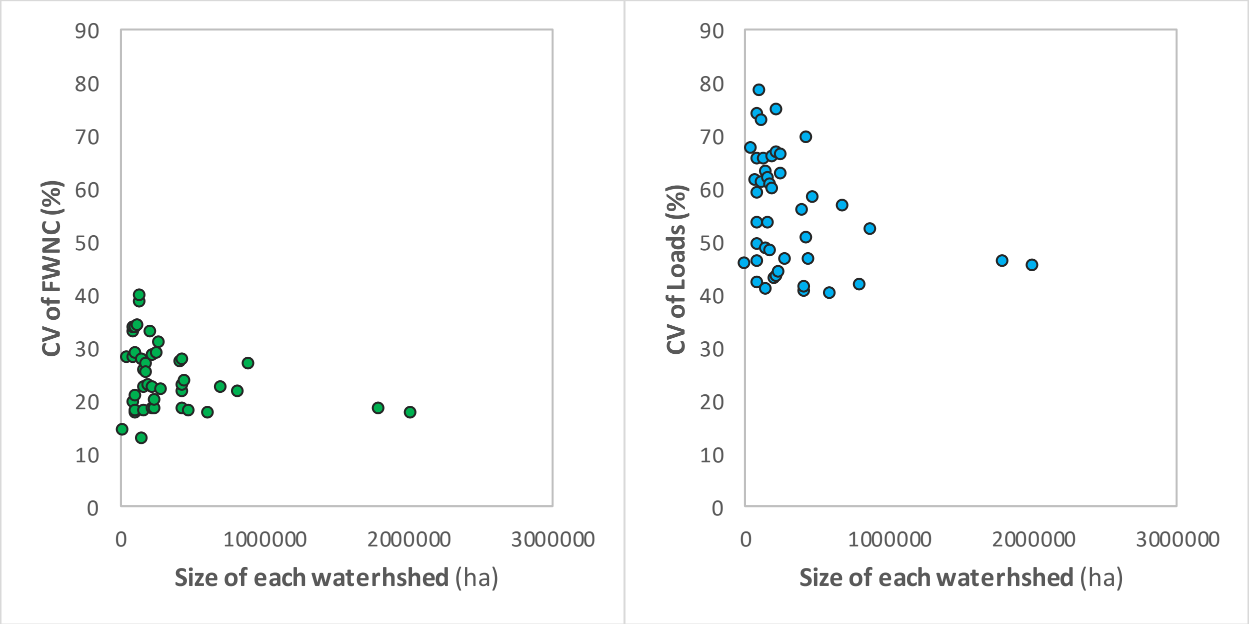


FIGURE 4. Relationship between the watershed size and the coefficient of variation in mean annual flow-weighted nitrate concentration (FWNC; left panel) and nitrate load (right panel). Note: CVs based on 5-year moving average FWNC and load.

The CVs and probabilities of measuring reductions in FWNC and load were not correlated with the size of the watershed (Figure 4). Although, the two largest watersheds in the study, which were more than 2x the size of the third largest watershed, did have relatively low CVs for mean annual FWNC and load, it is important to note that these watersheds are nested.

Future Work

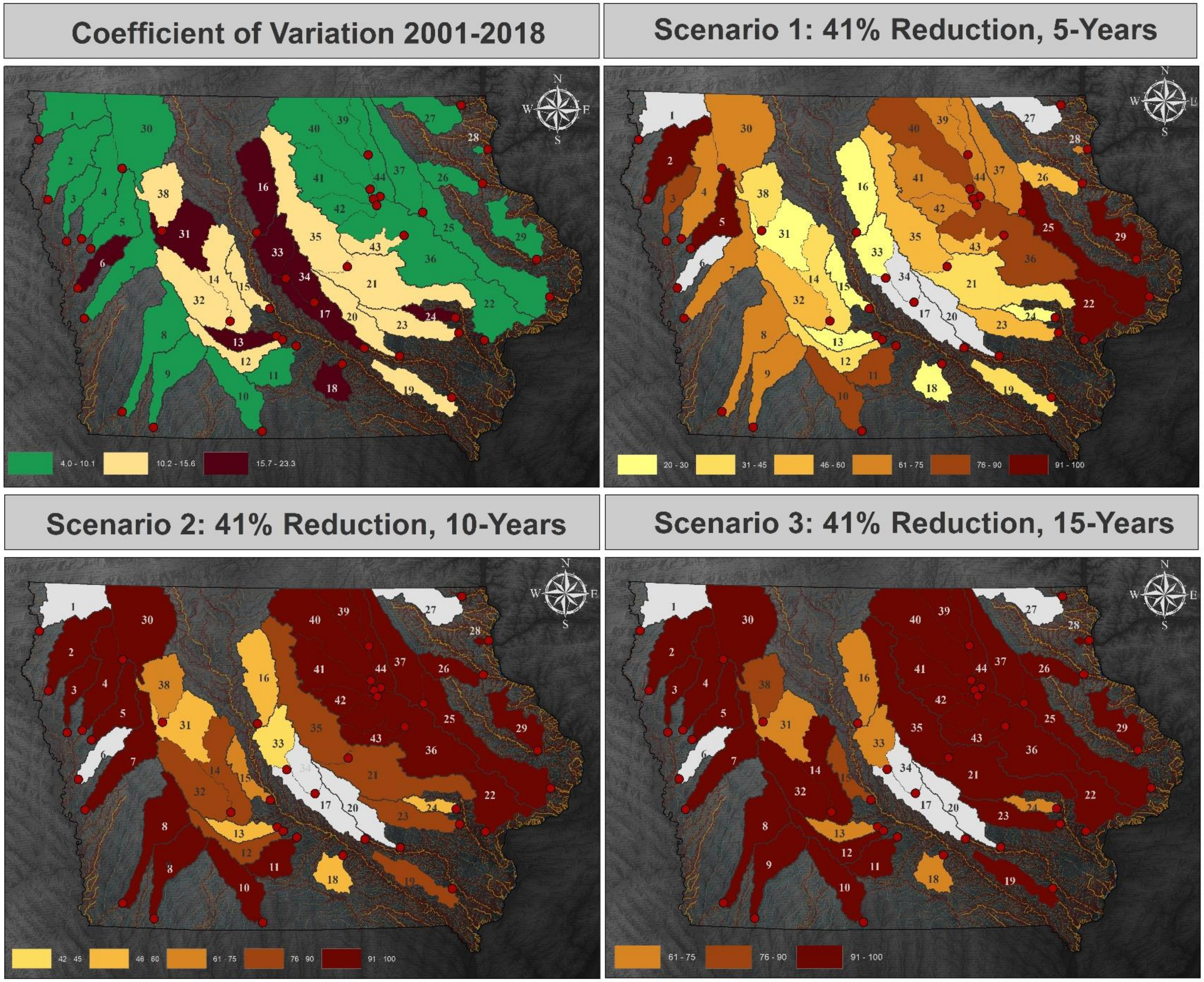
- What is the optimum sampling frequency to detect changes in nitrate load and FWNC? How much does daily vs. weekly vs. monthly sampling reduce the amount of time required to measure a 41% reduction?
- What are the characteristics of watersheds where reductions are measured relatively rapidly?
- With optimum sampling frequency and targeting, how long will it take to confidently measure smaller reductions?
- What is the likelihood of measuring a false reduction or increase in nitrate loss owing to weather rather than changes in land use and management?

Answers to these questions can improve the efficiency of monitoring operations. By determining watershed properties that are associated with low year-to-year variability and high probability of measuring reductions, watershed monitoring programs can be better targeted. In six watersheds, there was >90% probability of measuring a 41% reduction in FWNC when it occurs over 5 years. Yet, in eleven watersheds, there was <50% probability of measuring a 41% reduction in FWNC over the same 5-year period. Although it will take more time to measure reductions in nitrate load than FWNC, some watersheds exhibited relatively low year-to-year variability in load and high probability of measuring a reduction should it occur. For example, the probability of measuring a 41% reduction in nitrate load over 5 years was <38% in all watersheds (mean = 18% probability), but the probability of measuring a 41% load reduction over 10 years ranged from 13-74%. Factors such as soil type, slope, and cropland area may help to identify watersheds where reductions in FWNC and nitrate load can be measured with greater confidence. Future work could also use the Monte Carlo simulation to calculate probabilities of measuring spurious increases or decreases in nitrate levels that are the result of weather patterns rather than changes in land use and management. For example, if nitrate levels do not change over a period of 10 years, what is the probability of measuring a statistically significant, but spurious increase or decrease in nitrate levels during the time?

Table 1. The probability of measuring 41% reduction in flow-weighted nitrate concentration (FWNC) and nitrate load for 44 watersheds that were monitored from 2001 to 2018. Of these watersheds, some were eliminated from further analysis of FWNC, nitrate load or both because these variables exhibited a significant change over time (empty cells). The 'ID' corresponds to the watersheds number displayed in Figures 4 and 5. The coefficient of variation (CV) for FWNC and nitrate load is displayed. All data calculated using 5-year moving average of raw water quality monitoring data.

		Probability of measuring a 41% reduction in FWNC (%)				**Probability of measuring a 41% reduction in nitrate load (%)**			
ID	**NAME**	**5-years**	**10-years**	**15-years**	**CV**	**5-years**	**10-years**	**15-years**	**CV**
1	Rock River near Hawarden				9				20
2	Floyd River near Sioux City	93	100	100	6				27
3	West Fork Ditch at Hornick	90	100	100	6				33
4	Little Sioux River near Smithland	73	99	100	8	25	56	75	17
5	Maple River near Mapleton	91	100	100	6				25
6	Soldier River near Pisgah				23				48
7	Boyer River near Missouri Valley	75	99	100	8				34
8	East Nishnabotna River near Shenandoah	67	98	100	9				30
9	West Nodaway River near Shambaugh	68	98	100	9	10	20	27	34
10	Thompson Fork Grand River at Davis City	76	99	100	8	10	20	28	34
11	South River near Ackworth	82	100	100	7	8	13	17	44
12	Middle River near Indianola	43	83	96	12	14	28	39	27
13	North River near Norwalk	25	54	72	18	15	31	45	25
14	Raccoon River upstream of Des Moines	41	81	94	13	19	39	56	22
15	Beaver Creek near Grimes	30	64	83	16	20	43	61	20
16	Boone River near Stratford	25	53	71	18	27	55	75	17
17	South Skunk River near Oskaloosa				21	22	49	68	19
18	Cedar Creek near Bussey	23	46	66	19	9	19	27	33
19	Cedar Creek near Oakland Mills	38	75	91	14	10	19	27	33
20	North Skunk River				14	14	28	41	26
21	Iowa River upstream of Iowa City	40	77	92	13	21	45	62	20
22	Cedar River near Conesville	96	100	100	6				21
23	English River at Riverside	49	89	98	11	10	18	23	36
24	Old Mans Creek near Iowa City	26	54	74	18	9	16	22	38
25	Wapsipinicon River at De Witt	97	100	100	5	22	49	68	19
26	Volga River near Elkport	58	95	99	10				23

27	Upper Iowa River near Dorchester				10				29
28	Bloody Run Creek Site	71	99	100	9				26
29	North Fork Maquoketa River near Hurstville	100	100	100	4	14	27	37	27
30	Little Sioux River near Larrabee	69	98	100	9				18
31	North Raccoon River near Jefferson	23	46	66	19	17	38	53	22
32	South Raccoon River near Redfield	51	90	98	11	12	25	34	29
33	South Skunk River near Cambridge	20	42	61	20	26	55	73	17
34	Indian Creek near Colfax				23	37	74	90	14
35	Iowa River downstream of Marshalltown	49	87	97	12	23	48	66	19
36	Cedar River downstream of Cedar Rapids	86	100	100	7				22
37	Wapsipinicon River near Independence	71	99	100	9				19
38	North Raccoon River near Sac City	35	73	90	14	24	52	71	18
39	Cedar River near Charles City	67	97	100	9				21
40	Shell Rock River at Shell Rock	81	100	100	8	28	62	81	16
41	West Fork Cedar River at Finchford	75	99	100	8	21	46	64	20
42	Beaver Creek near Cedar Falls	67	98	100	9	17	34	51	23
43	Wolf Creek at La Porte City	53	92	99	11	10	19	27	34
44	Cedar River near Janesville	66	97	100	9				24
-	**Mean Across Watersheds**	**60**	**86**	**93**	**12**	**18**	**37**	**50**	**26**
-	**Maximum Across Watersheds**	**100**	**100**	**100**	**23**	**37**	**74**	**90**	**48**
-	**Minimum Across Watersheds**	**20**	**42**	**61**	**4**	**8**	**13**	**17**	**14**

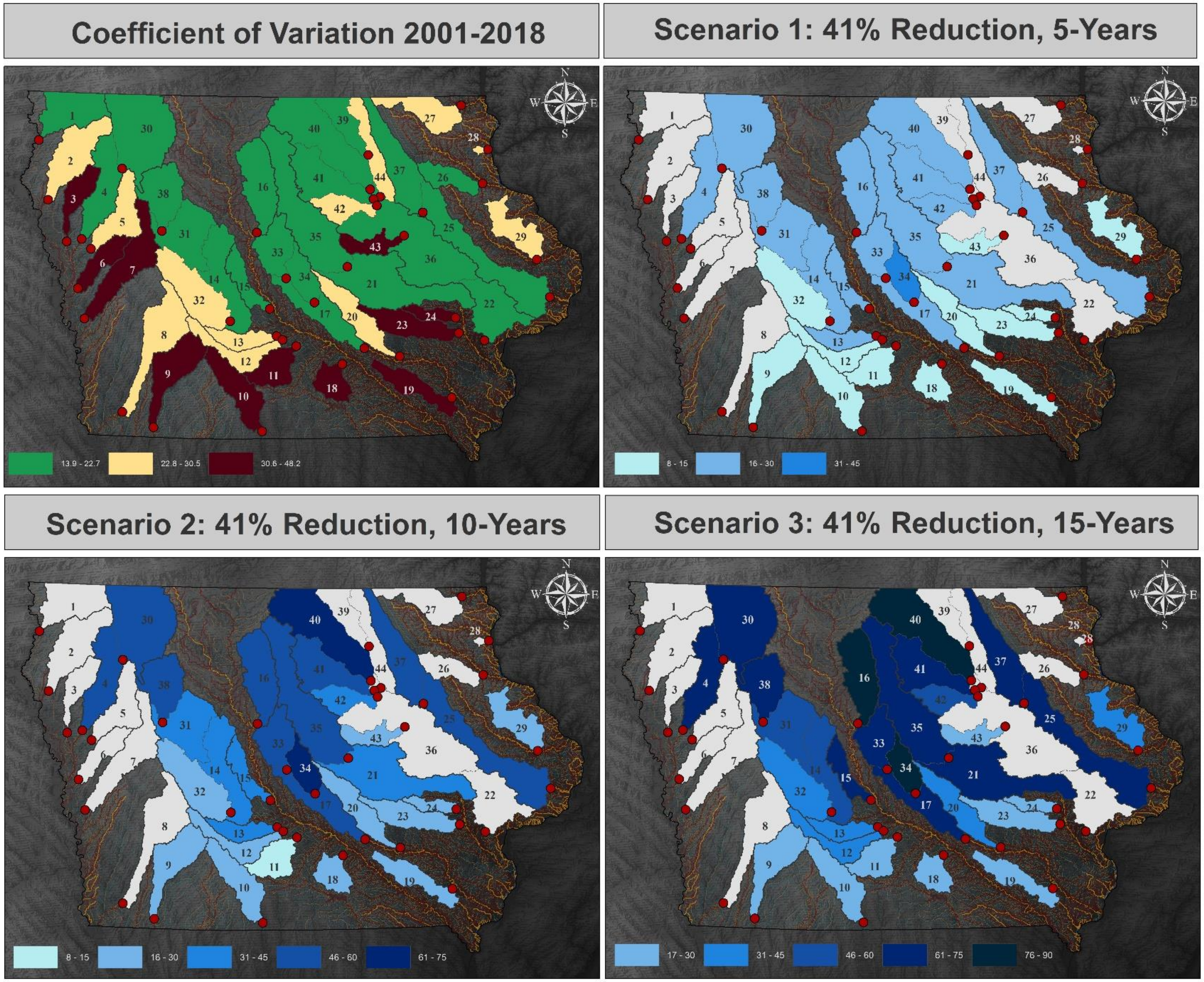

Coefficient of Variation 2001-2018

Scenario 1: 41% Reduction, 5-Years

Scenario 2: 41% Reduction, 10-Years

Scenario 3: 41% Reduction, 15-Years

Figure 4. The year-to-year variability in flow-weighted nitrate concentration (upper left) and the probability of measuring a 41% reduction in FWNC over periods of 5, 10 and 15 years – should the reduction occur. Darker colors indicate higher probability of measuring a reduction. Watersheds that could not be analyzed are colored gray. Numbers correspond to Table 1.


Coefficient of Variation 2001-2018

Scenario 1: 41% Reduction, 5-Years

Scenario 2: 41% Reduction, 10-Years

Scenario 3: 41% Reduction, 15-Years

Figure 5. The year-to-year variability in nitrate load (upper left) and the probability of measuring a 41% reduction in nitrate load over periods of 5, 10 and 15 years – should the reduction occur. Darker colors indicate higher probability of measuring a reduction. Watersheds that could not be analyzed are colored gray. Numbers correspond to Table 1.

Appendix 1. Mean flow-weighted nitrate concentration (FWNC) and nitrate load for the 44 watersheds that were monitored from 2001 to 2018. Unlike other data presented in this work, these data are not 5-year moving averages; hence, the coefficient of variation (CV) for these variables is higher than displayed in Table 1.

ID	NAME	FWNC (mg NO_3-N/L)	CV FWNC	Load (Mg NO_3-N/year)	CV Load	Size (ha)	Yield (kg NO_3-N/ha/y)
1	Rock River near Hawarden	9	23	7.3.E+06	70	4.37E+05	16.8
2	Floyd River near Sioux City	12	22	5.1.E+06	75	2.30E+05	22.3
3	West Fork Ditch at Hornick	10	18	2.0.E+06	74	1.04E+05	19.0
4	Little Sioux River near Smithland	7	22	1.1.E+07	57	6.94E+05	15.4
5	Maple River near Mapleton	10	18	3.8.E+06	62	1.67E+05	22.5
6	Soldier River near Pisgah	6	34	1.5.E+06	78	1.06E+05	14.3
7	Boyer River near Missouri Valley	8	18	4.4.E+06	67	2.36E+05	18.7
8	East Nishnabotna River near Shenandoah	6	31	4.5.E+06	63	2.65E+05	17.0
9	West Nodaway River near Shambaugh	5	33	2.6.E+06	66	2.05E+05	12.8
10	Thompson Fork Grand River at Davis City	2	27	7.8.E+05	61	1.80E+05	4.3
11	South River near Ackworth	1	34	3.3.E+05	73	1.23E+05	2.7
12	Middle River near Indianola	3	39	1.0.E+06	61	1.27E+05	8.2
13	North River near Norwalk	6	33	1.2.E+06	59	9.05E+04	13.2
14	Raccoon River upstream of Des Moines	10	27	2.1.E+07	52	8.87E+05	24.1
15	Beaver Creek near Grimes	11	28	2.6.E+06	53	9.57E+04	27.1
16	Boone River near Stratford	12	28	7.6.E+06	43	2.30E+05	32.9
17	South Skunk River near Oskaloosa	8	27	9.6.E+06	41	4.25E+05	22.6
18	Cedar Creek near Bussey	1	33	2.1.E+05	65	9.63E+04	2.2
19	Cedar Creek near Oakland Mills	5	39	2.0.E+06	65	1.38E+05	14.4
20	North Skunk River	6	22	3.1.E+06	53	1.65E+05	18.5
21	Iowa River upstream of Iowa City	7	21	1.6.E+07	42	8.15E+05	19.7
22	Cedar River near Conesville	7	18	4.7.E+07	45	2.02E+06	23.1
23	English River at Riverside	6	25	2.9.E+06	63	1.62E+05	17.9
24	Old Mans Creek near Iowa City	7	28	1.1.E+06	68	5.22E+04	20.4
25	Wapsipinicon River at De Witt	7	17	1.5.E+07	40	6.05E+05	24.1
26	Volga River near Elkport	6	21	2.0.E+06	46	1.04E+05	19.1
27	Upper Iowa River near Dorchester	6	23	4.4.E+06	60	1.99E+05	22.2
28	Bloody Run Creek Site	6	14	1.5.E+05	46	8.88E+03	16.5
29	North Fork Maquoketa River near Hurstville	7	13	3.7.E+06	49	1.53E+05	24.4
30	Little Sioux River near Larrabee	7	18	7.1.E+06	58	4.80E+05	14.9
31	North Raccoon River near Jefferson	12	27	1.2.E+07	56	4.11E+05	29.4
32	South Raccoon River near Redfield	8	29	5.4.E+06	66	2.54E+05	21.1
33	South Skunk River near Cambridge	11	28	4.5.E+06	41	1.51E+05	29.7
34	Indian Creek near Colfax	8	29	2.4.E+06	42	1.03E+05	23.0
35	Iowa River downstream of Marshalltown	10	18	1.3.E+07	40	4.23E+05	29.5

36	Cedar River downstream of Cedar Rapids	7	18	4.5.E+07	46	1.80E+06	25.0
37	Wapsipinicon River near Independence	8	20	6.6.E+06	44	2.38E+05	27.7
38	North Raccoon River near Sac City	12	25	5.4.E+06	48	1.84E+05	29.4
39	Cedar River near Charles City	9	22	8.1.E+06	47	2.84E+05	28.4
40	Shell Rock River at Shell Rock	7	24	9.5.E+06	46	4.48E+05	21.2
41	West Fork Cedar River at Finchford	9	18	6.7.E+06	43	2.20E+05	30.3
42	Beaver Creek near Cedar Falls	10	17	3.4.E+06	49	1.02E+05	33.1
43	Wolf Creek at La Porte City	10	19	2.5.E+06	62	8.44E+04	30.0
44	Cedar River near Janesville	8	22	1.2.E+07	50	4.33E+05	27.4