

CONTRIBUTION OF CROPLAND WIND EROSION TO DAM SEDIMENT ACCUMULATION IN
AGRICULTURALLY DOMINATED WATERSHEDS OF THE NORTHERN GREAT PLAINS

by

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DEDICATION

I dedicate this paper to those who inspired and made it possible for me to go back to graduate school, even at the relatively old age of fifty. To my mom and dad, both of whom went back for their M.S. degrees later in life, Leslie Arth who made sure I was an engineer with writing skills, Phyllis Phillips who made me believe I could accomplish anything, and Mary Podoll who gave me the opportunity to work with the North Dakota NRCS dams used in this paper and has supported me throughout my graduate education. To my sister Kim who always models perseverance through the storm and reminds me that, in the end, you sell more boxes of Girl Scout cookies in the heaviest rain. Most especially my wife, Toni Neslen, who has kept me sane through doubts and stress, fed me through the late nights of balancing college with a demanding full-time job, proofed all of my papers, and has been the greatest cheerleader of my life.

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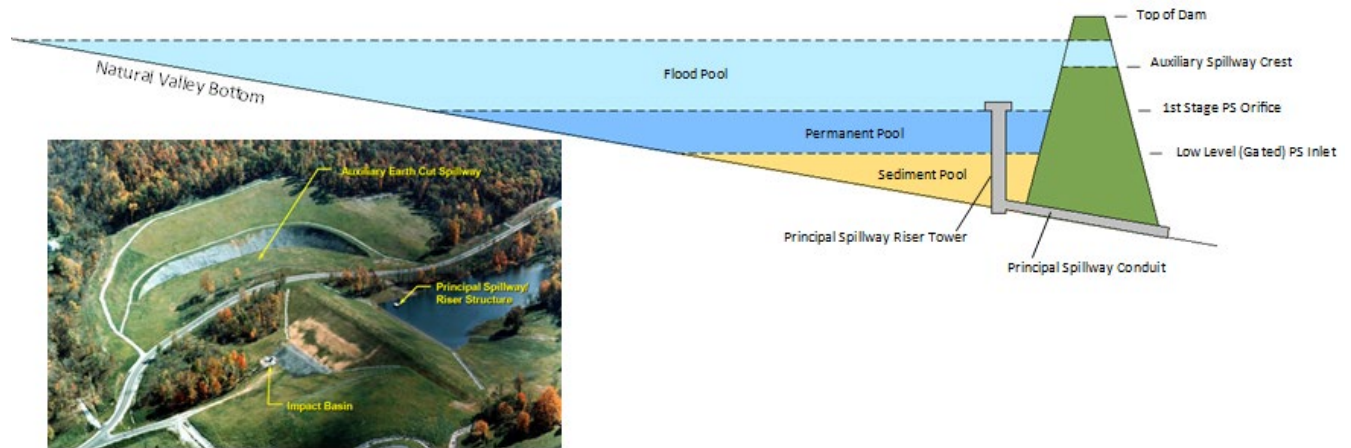
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GLOSSARY

Dam specific terminology used within the study is defined below.

Term	Definition
Aerated Sediment	Sediment that is not subject to consolidation due to long term submergence at the bottom of a reservoir. These sediments may be carried as bedload or suspended sediment by the incoming river or deposited along the reservoir above the elevation of the permanent pool.
Auxiliary Spillway	A secondary spillway designed to be operated infrequently, during major floods (typically in excess of the 100-yr recurrence interval event).
Flood Pool	The dam storage volume designated to provide downstream flood control benefits.
Permanent Pool	The dam storage volume designated for beneficial use, such as recreation or water supply. The upper elevation is set by the first stage principal spillway orifice elevation and the lower elevation is set by the top of the anticipated sediment pool.
Principal Spillway	The primary spillway designed to convey flows through the dam, consisting of a riser tower with multiple gated and ungated inlets and conduit. The upper inlets are ungated, with the first stage opening controlling the elevation of the permanent pool and the second stage designed to convey flood flows up to the 100-year recurrence interval event.
Sediment Pool	The volume of the dam pool planned for sediment accumulation over the lifespan of the structure. Also termed “dead storage”. The lowest gated principal spillway inlet is typically set at the predicted elevation of the top of sediment pool.
Sediment Delivery Ratio	The overall sediment yield from an area divided by the gross erosion from that same area, representing the efficiency of the watershed in moving soil particles from areas of erosion to the downstream point where sediment yield is measured. For a dam, this would be the last free flowing segment of river upstream of the backwater pool from the reservoir.
Submerged Sediment	Sediment that deposited below the water surface elevation of the permanent pool behind the dam. Over time, this sediment consolidates to a higher density than initial deposits.
Trap Efficiency	The ratio of sediment deposited within the reservoir to the sediment inflow from the upstream river.

Dam Terminology Schematic

Unit Conversions

The paper is written in U.S. customary units because engineers and hydrologists that work on dam rehabilitation and design projects in the northern Great Plains, for whom the data presented in this paper would be of value, use this system of measurement. In addition, the cropland erosion modeling tools used for the study use U.S. units for input and output. Conversions are provided below to the International System of Units:

1 U.S. ton = 0.91 metric ton

1 acre (ac) = 0.4047 hectare

1 square mile (sqmi) = 259.00 hectare

1 inch (in) = 2.54 centimeter

1 foot (ft) = 0.3048 meter

1 acre-foot (ac-ft) = 1233.5 cubic meters

1 acre-foot per square mi (ac-ft/sqmi) = 4.76 cubic meter per hectare

1 U.S. ton per square mile (tons/sqmi) = 3.503 kilogram per hectare

1 pound (lb) = 0.454 kilogram

1 pound per cubic foot (lb/cft) = 16.019 kilogram per cubic meter

ABSTRACT

Sediment accumulation in reservoirs is a worldwide issue of concern, and particularly acute in agricultural watersheds of the midwestern United States. Historical design methods used to estimate sediment storage needed over the lifespan of dams in agricultural watersheds focused on cropland sheet and rill erosion caused by the forces of water. However, research over the last two decades has considered the additional sediment contributions of cropland gully erosion, streambank erosion, urbanization, upstream impoundments, and road construction to dam sediment accumulation. Previous studies have not evaluated the contribution of cropland wind erosion to reservoir sedimentation rates. Therefore, I investigated the extent to which wind erosion generated sediment loads contribute to reservoir sedimentation in the wind erosion prone landscape of the northern Great Plains. I used measured sediment accumulation data at six northeastern North Dakota dams, in conjunction with models for sheet and rill erosion, wind erosion, and local data for streambank erosion rates, to construct a sediment budget for each dam and estimate a sediment delivery ratio for wind erosion. My results indicated that 31% to 73% of accumulated sediment volume in the reservoirs originated from wind erosion, with a median value of 46%, excluding one dam where the sheet and rill erosion model did not perform well. For the five dams a reasonable sediment budget could be computed, the sediment delivery ratio for the creep and saltation component of modeled wind erosion ranged from 0.05 to 0.31, with a median value of 0.16.

I also conducted a separate evaluation of the relationship between accumulated sediment and the extent of wind protection provided by trees adjacent to cropland over the lifespan of the dams. I manually digitized extents of cropland adjacent windbreaks, shelterbelts, and forests using aerial photos from 1962, 2003, and 2020. Results of this analysis indicated an inverse relationship between cropland wind protection and sediment accumulation, providing further support for wind erosion as a sediment source to the reservoirs.

BACKGROUND

Human reliance on water supply and flood control dams will continue to increase, particularly under the extreme and variable climate conditions predicted for the future. The trend towards increased precipitation in the northeastern portion of the Northern Great Plains of the U.S. and Canada, for example, has been evident over the last two decades (McCullough, 2012) and is predicted to increase by an additional 30% by the end of the century (USGCRP, 2018). As crop yields decline over time in southern portions of the U.S. due to drought, ensuring cropland productivity in northern regions through maintenance of flood control dams will be critical to providing reliable food supply. Dams cause river flow velocities to decrease drastically, resulting in deposition of bedload, suspended sediment load, and wash load into their reservoirs. The average rate of loss in storage capacity of the world's reservoirs was 0.5-1% by volume annually, leading to a 50% loss in storage volume by 2050 (WCD, 2000). The U.S. has more than 91,000 dams, the average age of which is 57 years old (ASCE, 2021), and a survey of dam owners indicated that as many as 51% of reservoirs in the central U.S. have significant issues with excess sediment accumulation (Krogman, 2016). Sediment accumulation decreases function for water supply and flood control and can necessitate expensive dredging operations or replacement of riser towers and spillway gates that become buried in sediment.

The ability to model future sediment transport to a reservoir is critical to decision making on whether and how to rehabilitate or decommission an aging dam with excess sediment accumulation, as well as for design of new dams. Standard methods for predicting sediment loads over the lifespan of a dam in agriculturally dominated watersheds have relied on various versions of the Revised Universal Soil Loss Equation (RUSLE) over time to predict cropland

sheet and rill erosion (USDA, 1998). Past studies have noted that although sheet and rill-based estimates have proven accurate for some dams, for others they have over or underestimated sediment loads. For example, URS (2013) used sediment surveys at 28 dams in Texas in combination with streambank erodibility measurements and detailed watershed erosion modeling, found that dams with excess sediment above RUSLE estimates were most likely to have urbanization and/or channel incision and streambank erosion in their drainage areas. Dams in the Texas study that had lower sediment accumulation rates than predicted by RUSLE typically had a high density of small stock ponds or urban stormwater ponds in their watersheds (URS, 2013). Juracek (2014) showed a positive correlation between sediment yield and precipitation rates over the lifespan of a dam in Kansas. McIntyre (2007) found the rate of sedimentation in an Oklahoma reservoir declined by a factor of six from 1934 to 1987 due to reductions in total cultivated cropland plus reduced roadway erosion; streambank erosion and precipitation were found to be insignificant factors. However, another Oklahoma reservoir's sediment accumulation correlated highly with precipitation rate and had a 50-60% overall contribution from streambank erosion (Garbrecht, 2007). Cropland gully erosion and streambank erosion combined were identified as significant additional sediment sources, comprising 25-42% over and above the sheet and rill erosion total, for dams in Texas (Greiner, 1982).

Despite improvements in conservation tillage, cover crops and other soil health practices, cropland erosion due to both wind and water continues to be widespread. The average cropland erosion rate in the U.S. was estimated to be 4.63 tons/acre/year, of which 58% was water generated sheet and rill erosion and 42% was wind erosion, in the 2017 National Resources Inventory (USDA, 2020). By comparison, the USDA (2020) estimate for average cropland

erosion rate in 1982 was 7.13 tons/acre/year, with 55% attributed to water caused erosion and 45% to wind erosion. Despite the substantial sediment volume generated by wind erosion, both historic and current technical guidance to dam designers neglect this as a potential source (Dutta, 2016; USBR, 2006; NRCS, 1982). Likewise, my literature review did not locate any studies where the relationship between wind erosion and reservoir sedimentation was investigated. The Northern Great Plains is a cropland dominated region with high wind erosion rates. After crops are harvested in fall, before snow and ice cover establishment for the winter is when much of that wind erosion occurs, particularly in dry years. In spring, with soil particles loosened due to thawing and before crop growth, high wind erosion occurs as well. Windblown sediments deposit along tree rows, shelterbelts, in road and drainage ditches, and in stream channels where they intermix with layers of snow and ice as fall proceeds into winter. During spring snow melt, which represents the dominant peak flow condition in these landscapes, the fine, windblown soil particles that have collected within channels are transported into downstream streams, rivers, and reservoirs.

STUDY OBJECTIVES

The purpose of the study was to investigate the extent to which wind erosion generated sediment contributes to reservoir sedimentation rates in agriculturally dominated watersheds of the Northern Great Plains. Cropland, defined for this study as land annually tilled to produce crops, is the major sediment source in these landscapes. No-till cropping systems do disturb soil, albeit at a lower intensity (for example seeding, side dressing anhydrous ammonia), therefore they are included in the category of cropland. No-till systems make up less than 10% of overall cropland in the counties in which dams are present (USDA, 2017). I used measured sediment

accumulation data at six northeastern North Dakota dams, in conjunction with a model for sheet and rill erosion, a model for wind erosion, local data for streambank erosion, and literature values for sediment density, consolidation, and reservoir trap efficiency to construct a sediment budget for each dam. To further evaluate the relationship of wind erosion to reservoir sediment delivery, I examined the historical extents of wind protection provided via field adjacent trees in windbreaks, shelterbelts, and natural forest in each dam watershed in comparison to reservoir sedimentation rates.

STUDY DAMS AND WATERSHEDS

The six dams used for the study are in the Tongue River and Forest River watersheds in northeastern North Dakota, located as shown in Figures 1 and 2. All six are in cropland dominated watersheds, with no incorporated communities or industrial facilities that would act as significant sediment sources. Climate is humid continental with characteristic fluctuating temperatures and cold winters. The lack of topographic barriers to the north and south of North Dakota allows air masses to easily travel across the state where the cold, dry air from the north and warm, humid air from the tropics result in almost continuous winds as



Figure 1- Location Map

well as extreme daily temperature fluctuations (Entz, 2003). The Edmore, North Dakota weather

station represents the drainage areas with an average of 35 inches of snowfall, total precipitation of 20 inches per year, growing season of 110 days, and an average January low of -7°F and average July high of 79°F (US Climate Data, 2022). Additional climate details that relate

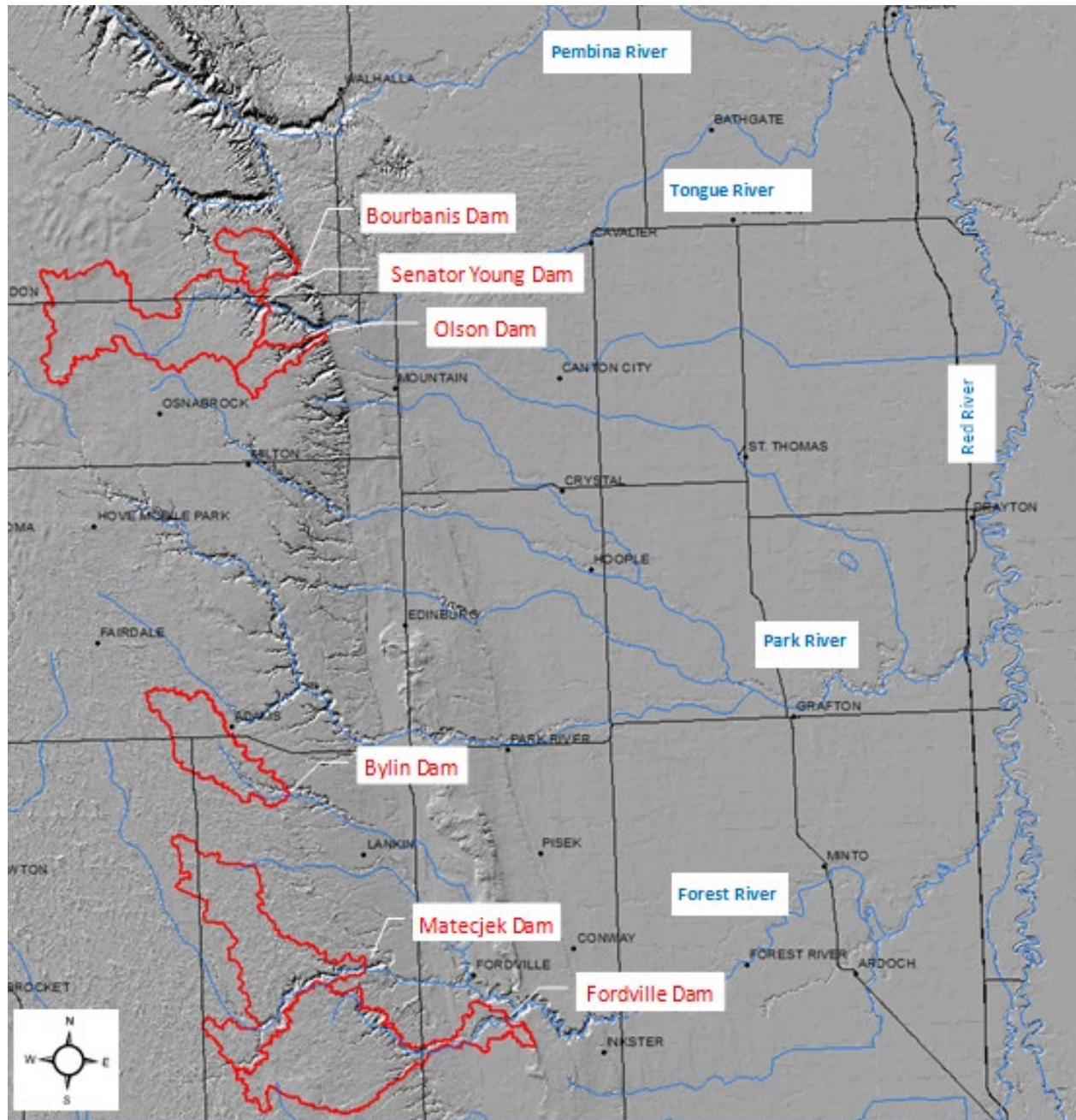


Figure 2- Project Dams and Watersheds Map

specifically to wind erosion are summarized in Section 4.3. Hydrology is dominated by spring snowmelt, with the majority of annual runoff occurring in April due to snowmelt and/or rainfall on snow or partially frozen soils (Nustad, 2020). From May through September streamflow recedes, as snowmelt runoff diminishes, and net evaporation increases. From September to November base flow from groundwater dominates, except for summer thunderstorms and from December to March flow is minimal due to frozen channel conditions (Nustad, 2020). The range of drainage area, maximum dam height, permanent pool storage, and storage volume to the auxiliary spillway crest vary for the six dams (Table 1). Dams were constructed with design and construction funding from the USDA-Soil Conservation Service (now called the Natural Resource Conservation Service) primarily to reduce downstream flood damage to cropland, infrastructure, and communities. Fordville, Bylin, and Matecjek Dams were also designed to support recreation and are stocked as warm-water fisheries, have boat ramps, and day use areas. Fordville Dam has a 45-site campground. Senator Young Dam was designed to provide backup water supply to a nearby Air Force Missile Station. The dams were designed to store a predicted volume of sediment, based on sheet and rill erosion, over their 50-year planned lifespan.

Table 1- Study Dam Watershed, Dam Height, Storage Volume, and Sediment

Dam	Watershed	Maximum Dam Height (ft)	Remaining Permanent Pool Storage (ac-ft)	Remaining Storage to AS Crest (ac-ft)	Maximum Sediment Depth (ft)	% Designed Sediment Storage Filled
Senator Young	Tongue R.	81	3,969	4,747	15.0	145
Olson	Tongue R.	65	< 1	701	19.5	395
Bourbanis	Tongue R.	61	<1	1,012	22.0	100
Bylin	Forest R.	57	2,790	4,223	6.8	127
Matecjek	Forest R.	76	5,608	7,274	5.1	92
Fordville	Forest R.	54	4,609	7,089	9.2	343

As of 2019, the dams were 42 to 63 years old, and the originally designed sediment storage volume is now 90-395% full. In other words, sediment accumulation has already reached or exceeded the sediment pool design volume in most of the reservoirs and is now encroaching on the storage intended for recreation, water supply, and/or flood control. Resulting shallower and warmer water in the reservoirs has detrimental impacts to water quality, fisheries, and recreation usage. The six dams are considered high hazard in terms of threat to human life downstream and are currently in the planning process for improvements to address both sediment accumulation and dam safety deficiencies. Prediction of future sediment accumulation is an integral component of current dam rehabilitation planning efforts, as well as a key input to the design of new dams; several of which are in the planning stage in northeastern North Dakota.

The study dams are located within the Level III ecoregion of the Northern Glaciated Plains, specifically the Level IV sub-region of the Drift Plains. The pre-settlement condition here consisted of transitional grasslands within a continental climate zone formed on recent glaciation (Bryce, 1998). The dams are built near the base of the Pembina Escarpment, which separates the glaciated plains to the west from the lacustrine valley formed by Glacial Lake Aggasiz to the east (Waldkirch, 1999). Retreating glaciers left gently rolling topography in thick glacial till, forming the high density of wetlands characteristic of the Prairie Pothole Region above the escarpment. The dam drainage areas are dominated by loam textured soils, which reflects the underlying deep glacial till. These soils are moderately erodible for both wind and water on cropland, with higher clay content soils (clay loams and silty clay loams) having a slightly lower erosion potential (Bluemle, 2016). Most of the depressional wetlands are farmed except in years with very wet

springs that preclude planting, and many have been drained with in-field grading and drainage ditches.

Relatively low slopes and drainage network density may be a key influence on sediment transport in these watersheds. Note that the mean basin slope includes the 300 to 400 foot high escarpment, which is largely in hardwood forests (Table 2). Slopes are gentler in the lower relief cropland that makes up the highest percentage of the drainage areas, as illustrated by the cropland slope classes (Table 2) and the land use distribution (Exhibits 1-6). The ratio of drainage area maximum length to maximum width influences sediment delivery in some watersheds (NRCS, 1998) and varies between the watersheds as well (Table 2).

Table 2- Study Dam Watershed Characteristics

Dam	Direct Drainage Area (ac)	Mean Basin Slope (%)	Stream Network Density (mi/sqmi)	DA Length to Width Ratio	% Cropland in 0-2% Slope Class²	% Cropland in 2-4% Slope Class²	% Cropland in >4% Slope Class²
Senator Young	30,797	2	1.0	3.9	92	7	1
Olson	4,030	6	1.9	3.1	86	10	4
Bourbanis	5,511	5	2.3	1.4	88	10	2
Bylin	13,346	2	0.8	3.1	71	24	5
Matecjek¹	27,439	2	0.8	0.7	60	33	7
Fordville	31,693	3	1.5	2.1	68	27	5

¹ The full drainage area to Matecjek Dam is 77,560 acres; however, drainage areas to Whitman and Sarnia Dams upstream were removed from the direct drainage area used within this analysis.

² Determined by resampling available LiDAR topographic data to 30-meter by 30-meter grid cells, clipped to 2019 NASS annual crop extents.

Within the Matecjek Dam watershed, the upstream Sarnia and Whitman Dams were excluded from the direct drainage area used for the study. While some amount of suspended sediment is transported through those dams, their reservoirs trap the majority of incoming fluvial sediment load, even for the fine-grained soils within these watersheds. Land use was determined

from the USDA National Agricultural Statistics Service (NASS) 2020 Cultivated Layer, which is a 30-meter raster dataset generated from multiple satellite data sources with remote sensing methods (Table 3). Prairie pothole wetlands are mainly located within annual crop fields and therefore largely included in that classification. Lands within the “other” category typically include unfarmed wetlands, roads, farmsteads, missile sites, and small communities; all typically with gravel surfacing. Hay fields, pastures, lands enrolled in the Conservation Reserve Program (CRP), and natural areas are grouped together as lands in perennial herbaceous vegetation. Hardwood forests consisting of elm, box elder, basswood, burr oak, cottonwood, and aspen are located on the steeper slopes of the Pembina Escarpment

Table 3- Study Dam Watershed Land Cover

Dam	% Annual Crops	% Perennial Herbaceous	% Non-farmed Wetlands	% Forest	% Other
Senator Young	90	2	1	3	3
Olson	73	4	1	20	3
Bourbanis	78	4	1	16	2
Bylin	68	15	12	1	5
Matecjek	62	16	14	2	6
Fordville	71	15	7	2	5

Use of the 2019 NASS data for the purpose of this analysis is a concern, to an extent, because the acreage of cropland taken out of production and enrolled in the Conservation Reserve Program (CRP) changes over time. Soils with perennial vegetation are not the major source of sediment that soils farmed for annual crops are. NASS data are not available before 2008, and the study analysis begins in 1957-1978 when the dams were constructed. CRP came into existence in 1985, offering payments to plant marginal cropland to permanent grass cover for wildlife habitat and soil erosion reduction. USDA statistics for acreage enrolled by county, by year, are available

and plotted in Figure 3 for the four counties that the study dam watersheds overlap.

Unfortunately, CRP data is not available in geospatial form, where it can be derived for the dam watersheds directly. I selected the 2019 NASS dataset given it was one of the lower CRP enrollment years available, therefore better representing the pre-1985 extents of perennial herbaceous vegetation in the dam watersheds

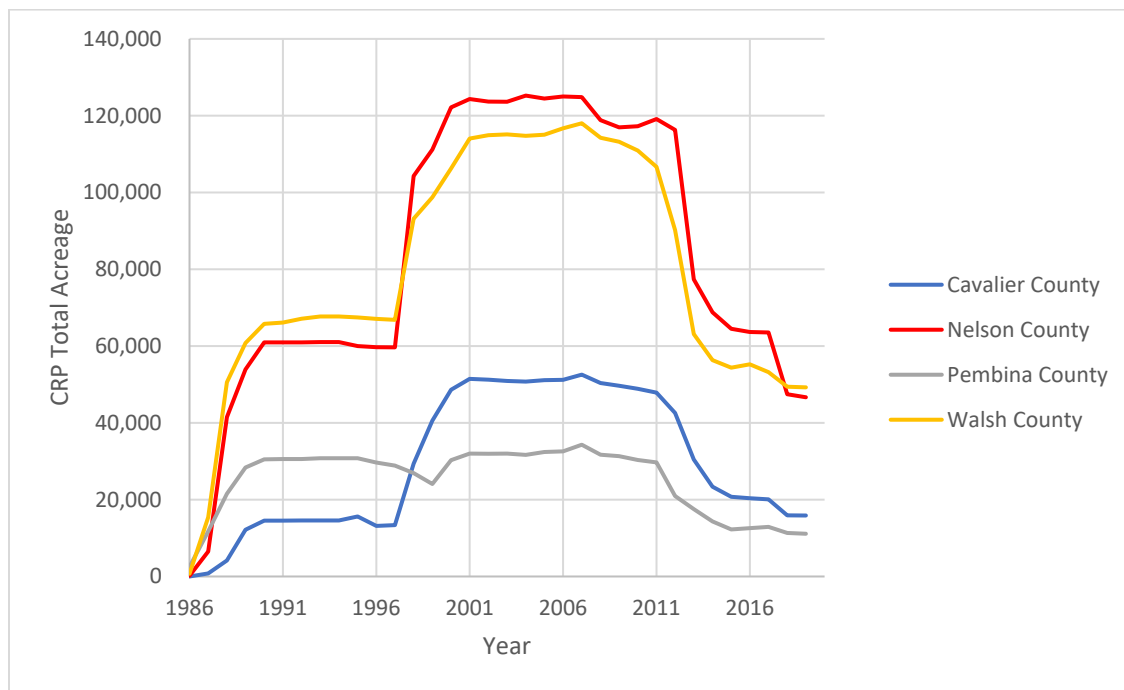


Figure 3- Acreage Enrolled in CRP, 1986-2019 by County

Acreage in annual crops is a key input into both sheet and rill erosion estimates, as well as wind erosion modeling. Wind erosion model results are also sensitive to crop types within typical rotations. Cropland in the watersheds is dominated by spring wheat and canola, based on the 2019 NASS (Table 4). Crops within the “other” category include rye, flaxseed, potatoes, and sugar beets. Although potatoes and sugar beet fields generate high water and wind erosion, those are a relatively low proportion of the watersheds. The dry bean, corn, and soybean acreages planted over the last decade have been possible due to development of more cold tolerant plant

varieties and the warming climate, which has extended the growing season in northeastern ND. Those crops would not have been typical during the 1957 to 2000 period making up most of the dam lifespan. Spring wheat – canola rotations make up the bulk of planted acreage in 2019, except for Matecjek Dam. In the earlier decades of the dams, canola would not have been a widespread crop. Instead, the predominant crop grown in rotation with spring wheat would have been flax.

Table 4- Study Dam Watershed Crops

Dam	% Spring Wheat & Canola	% Corn & Soybean	% Peas	% Sunflower	% Dry Beans	% Barley	% Fallow	% Other
Senator Young	74	14	7	0	3	0	1	1
Olson	66	22	10	1	0	0	1	0
Bourbanis	62	10	0	17	10	1	0	0
Bylin	53	14	0	4	10	6	12	1
Matecjek	40	25	0	4	17	1	10	3
Fordville	52	6	0	6	19	1	9	7

SEDIMENT BUDGETS

The first method I used to establish a relationship between wind erosion and sediment accumulation at each dam entailed development of a sediment budget for each of the six watersheds. Sediment budgets are a widely used accounting framework to understand the processes of sediment erosion, transport, and storage within a watershed (EPA, 2018). The most basic form of a watershed sediment budget equation is $I - \Delta S = O$, where I equals the sediment input, ΔS equals the amount in sediment storage, and O equals the sediment output (EPA, 2018). Current technical guidance for agricultural watershed dam design recommends estimation of

total watershed erosion rates based on (a) sediment production by cropland sheet and rill erosion, cropland gully erosion, and streambank erosion, (b) sediment delivery ratios (SDR) representing the proportion of total erosion from each source that is transported through the hydraulic network to a dam, and (c) reservoir trap efficiency representing the fraction of incoming sediment retained by the dam (NRCS, 1982). Gully erosion is rarely present on the low topographic relief cropland within the six watersheds in this study, based on observations from NRCS soil conservationists who have worked in these watersheds for decades, and is therefore omitted from this study. Similar to the other regional dam studies in Texas, Kansas, and Oklahoma cited in Section 1, data on instream sediment loads immediately downstream of the dams is not available to estimate outputs. Therefore, I used the following form of the sediment budget equation:

$$\Delta S = [(I_{S\&R} * SDR_{S\&R}) + (I_{SE} * SDR_{SE}) + (I_{WE} * SDR_{WE})] * TE$$

where:

- ΔS = sediment collected in each dam reservoir, converted to unconsolidated, aerated form (tons/yr/sqmi)
- $I_{S\&R}$ = total sheet and rill erosion (tons/yr/sqmi)
- $SDR_{S\&R}$ = proportion of sheet and rill erosion that becomes fluvial sediment load entering the reservoir
- I_{SE} = total streambank erosion (tons/yr/sqmi)
- SDR_{SE} = proportion of streambank erosion that becomes fluvial sediment load entering the reservoir
- I_{WE} = total wind creep and saltation erosion from cropland (tons/yr/sqmi)

- SDR_{WE} = proportion of wind creep and saltation erosion that becomes fluvial sediment load entering the reservoir
- TE = reservoir trap efficiency, or the proportion of fluvial sediment load permanently captured

In the equation, ΔS is a measured variable and SDR_{WE} is the variable being investigated. ΔS is converted to an aerated density, rather than the in-place submerged density formed after years of sitting on the reservoir bottom, to be comparable with the input densities. Units of either weight (tons) or volume (ac-ft) could be used in the sediment budget equation, and those could be expressed as totals, or as ratios of time and/or drainage area. Weight (tons) was selected as the unit of measurement for this study given that is the unit used in the two models relied on for the study. To have comparable results among the six dams, sediment weight was divided by years of accumulation and square miles of contributing drainage area. The following subsections provide further definition of each physical erosion process, outline the methods used, and summarize the results for each component of the sediment budget. A summary illustration of the process and sources for development of the sediment budget components is provided (Figure 4).

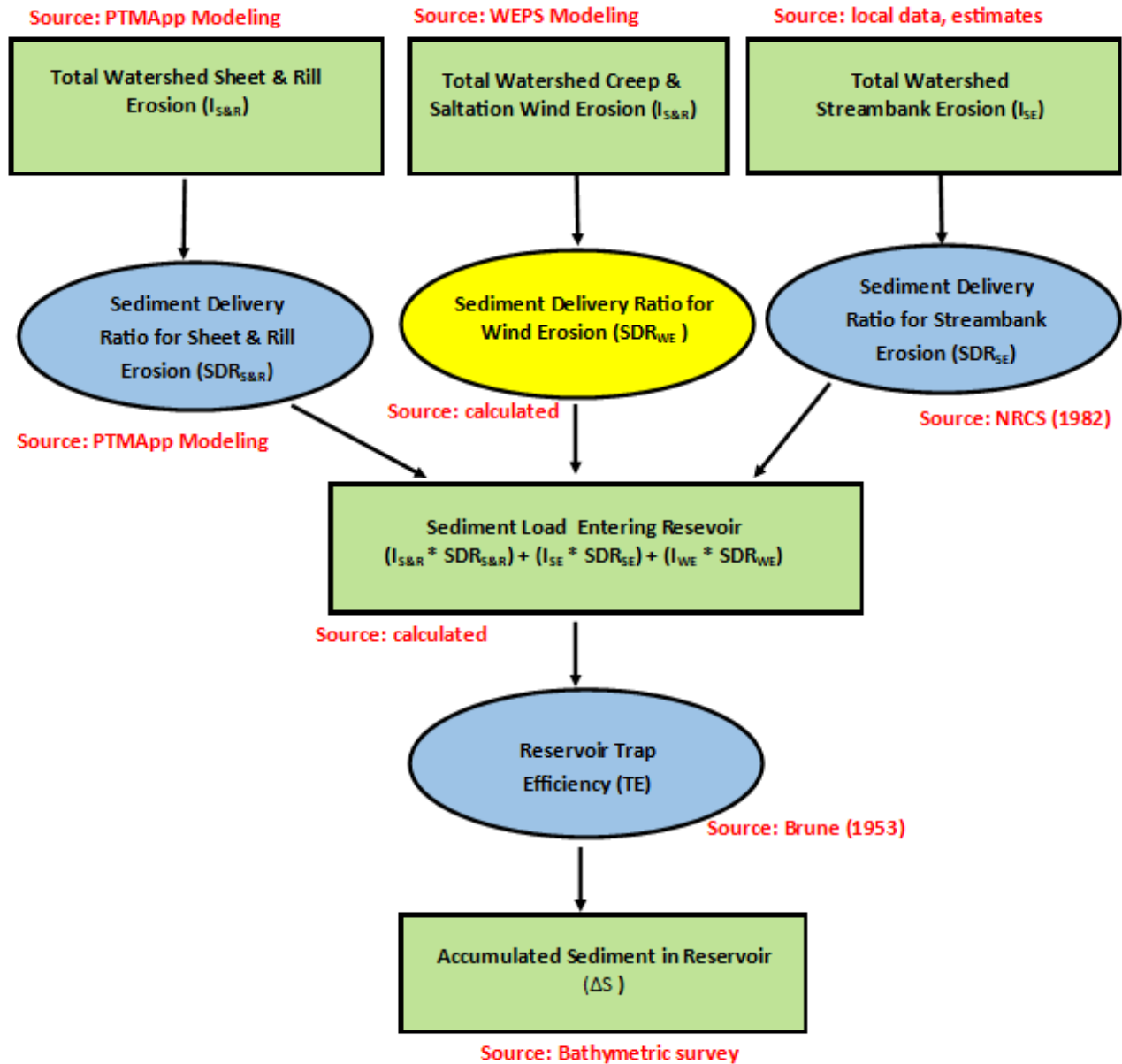


Figure 4- Sediment Budget Components and Data Sources

Accumulated Sediment

In 2019 and 2020 bathymetric surveys were completed on the reservoirs utilizing a GPS linked, multi-frequency sonar (Specialty Device Inc.'s BSS+ Sediment Profiling System) which combines wide-spectrum sub-bottom reservoir profiling with sonar depth sounding to generate elevations of the pre-dam ground elevation versus accumulated sediments. At each dam, cores were taken to confirm readings, as well as for sampling. Historical as-built surveys of the dam projects were also used to verify sediment profiles. Testing of core samples did not include density; instead a median value of 56.63 lbs/cft from literature review was used to convert sediment volume to weight at each dam (Christensen, 1999; Dendy, 1978; Minear, 2009). Maximum accumulated sediments depths range from 5 to 22 feet and 92 to 395 percent of originally planned sediment storage for the dams is now filled (Table 1). Total annual sediment accumulation rates at the dams range from 0.12 to 0.38 acre-feet per square mile and 152 to 466 tons per square mile (Table 5). Sediment distribution in the pools of Bourbanis, Olson, and Bylin Dans is predominantly near the dam, at Fordville and Matejek Dams is well distributed throughout the reservoirs, and at Senator Young Dam is predominantly within the delta area (Exhibits 1 to 6). Sediment accumulation rates are reported as quantity of sediment accumulated in each reservoir divided by the contributing watershed area, which excludes the Sarnia and Whitman Dam drainage areas upstream of Matecjek Dam.

Table 5- Dam Sediment Accumulation Rates

Dam	Year Constructed	Year of Sediment Survey	Accumulated Sediment Volume¹ (ac-ft)	Sediment Accumulation Rate by Volume^{1,2} (ac-ft/sqmi/yr)	ΔS Sediment Accumulation Rate by Weight^{2,3} (tons/sqmi/yr)
Senator Young	1961	2020	350	0.12	152
Olson	1957	2020	150	0.38	466
Bourbanis	1957	2020	145	0.36	330
Bylin	1964	2020	179	0.16	189
Matecjek	1966	2019	305	0.13	166
Fordville	1978	2020	446	0.22	264

¹Volume listed on the basis of existing (submerged, consolidated) density.

²Rates listed on the basis of total direct contributing drainage area as listed in Table 2.

³Rates listed on the basis of originally delivered (aerated, unconsolidated) density.

Cropland Sheet and Rill Erosion

Water generated erosion mechanisms on cropland include sheet, rill, and gully erosion.

Sheet erosion occurs when a thin layer of soil is removed from the entire field, via overland sheet flow, that has been loosened by raindrop splash, tillage, or freeze/thaw mechanisms. Soil erodibility can be particularly high in recently thawed soils, since high water content decreases the cohesive strength of soil aggregates (Van Klavern and McCool, 1998). Sheet erosion generally lasts for a short period before minute channels, termed rills, begin to form. Rill erosion carries soil particles from the field in shallow, concentrated channels that are responsible for most water generated cropland erosion. Erosion on the soils located between rills is termed interrill erosion and is essentially sheet erosion that is transported more efficiently due to its proximity to a rill. During typical farming operations, rills are effectively removed as a field is worked, and then reform in new locations in the next runoff event. During runoff events on higher slope fields, rills may form into gullies, defined as channels which are too deep to farm

through. Lacking vegetation during the growing season, gullies will continue to erode, and head-cut up into the field. Given the low slopes of crop fields in the six study dam watersheds, gully erosion is rarely observed according to NRCS conservation planners that have decades of experience working with farmers in the dam watersheds.

The Revised Universal Soil Loss Equation (RUSLE) is a well-established, widely used method to estimate average annual rill and interrill erosion using soil properties, topographic indices, land cover, and management factors (ARS, 2013). The equation estimates average annual soil loss on the basis of a rainfall and runoff factor, which accounts for the impact of meteorological characteristics of the watershed on erosion rates; soil erodibility factor, which accounts for soil characteristics that relate to sheet and rill erosion susceptibility; length-slope factor, which provides the relationship for rill slope length and steepness relationship; annual precipitation; and cover and management factor, which accounts for the effects of land use, canopy cover, surface cover, surface roughness, and soil moisture (ARS, 2013). A regional model for Minnesota and North Dakota, called PTMApp, has been developed for multiple watersheds (8-digit HUC level) using RUSLE in combination with hydrologically conditioned Lidar topographic data. Within PTMApp, developers applied cover factors based on the 2013 NASS geospatial crop data and assumptions for typical farming practices for those crops in the region (HEI, 2016). After the RUSLE sediment yield is generated on an individual soil map unit within a cropfield, PTMApp estimates the sediment reaching the selected catchment outlet using a sediment delivery ratio computed for each digital elevation model grid cell as a function of catchment area, adjusted by the distance from the cell to the nearest location of channelized flow (HEI, 2016). In-channel sediment transport is then reduced by an exponential decay function

using travel time and median sediment diameter (HEI, 2016). The hydrologic routing performed by PTMApp is particularly critical in these glaciated landscapes with extensive topographically closed depressional areas. During runoff events, these areas follow a “fill and spill” hydrologic sequence, with resultant varying levels of sediment deposition and transport. PTMApp modeling for the six dam drainage areas was completed by Houston Engineering for dam rehabilitation planning efforts in 2019-2020 (unpublished NRCS datasets). Delivered annual sediment loads to the dams range from 75 to 306 tons per square mile (Table 6).

Table 6- Sheet and Rill Erosion Estimates

Dam	Direct Drainage Area (sqmi)	PTMApp Total Estimated Sheet and Rill Erosion ISR (tons/sqmi/yr)	PTMApp Sediment Delivery Ratio SDR_{SR}	PTMApp Sheet and Rill Delivered to Dam ISR x SDR_{SR} (tons/sqmi/yr)
Senator Young	48.1	205	0.64	131
Olson	6.3	376	0.66	248
Bourbanis	8.6	372	0.65	242
Bylin	20.9	317	0.59	186
Matecjek	42.9	506	0.61	306
Fordville	49.5	114	0.66	75

As noted previously, Matecjek Dam has two large dams within its drainage area which have likely collected substantial sediment from their drainage areas. Unfortunately, bathymetric surveys of those reservoirs have not been completed. The annual sediment accumulation rate at Matecjek Dam was 0.61 tons per square mile, based on bathymetric survey, which is higher than Bylin but lower than the other dams (Table 5). However, the PTMApp modeled annual sheet and rill erosion delivered to Matecjek Dam is 506 tons per square mile, which is 26 percent higher than Olson Dam, which had the next highest modeled rate and the highest measured sediment

accumulation rate (Table 5; Table 6). The fact that the modeled delivery rate to Matecjek is so high, while the measured rate is so low, suggests that PTMApp underestimates trap efficiency for large reservoirs, such as Sarnia and Whitman Dams.

Streambank Erosion

Streambanks can be a significant sediment source as soil particles loosened through fluvial erosion, mass wasting, or freeze-thaw action are then entrained within flowing water and moved through hydraulic forces. The Tongue River below Senator Young and Olson Dams, for example, is currently experiencing high levels of streambank erosion due to incision caused by lateral confinement, accompanying channel widening, and landslides from the undercut adjacent terrace. Given that these six dams are located near the base of the Pembina Escarpment, however, most upstream channels consist of small, shallow, grass choked intermittent stream channels and road/drainage ditches with slopes typically less than 0.5%. Bank erosion on these channels is largely negligible, based on personal observations. A moderate level of erosion does occur on the larger perennial channels and ditches, particularly those sections that traverse the steep, forested slopes of the Pembina Escarpment and newly constructed drainage ditches in their initial years of establishment.

The only data source available for bank erosion in the area is a study conducted by NRCS on the Tongue River below Senator Young Dam, consisting of 5-years of monitoring cross-section surveys, bank pins, bed chains, and Bank Erosion Hazard Index/Near Bank Shear ratings validated by sediment surveys at the downstream dam (NRCS, 2021). The median value from that study was 0.022 tons/yr/ft for riverbanks located on the outside of meander bends. While likely high for the smaller perennial channels upstream of the dams, I applied the 0.022 tons/yr/ft

value to 50% of the length of perennial channel banks above each dam. The ratio of outer meander bend length to total channel length is likely lower than 50%. Lacking any data source for bank erosion in intermittent channels, I made chose to apply 10% of the 0.022 tons/yr/ft rate to their total length. Methodology intentionally overestimated bank erosion upstream of the dams, to ensure wind erosion contributions would not be overestimated in the sediment budgets. Given the fine-grained soils in these watersheds, all sediment mobilized by streambank erosion is transported as suspended sediment. Although streambank erosion logically has a higher sediment delivery ratio than sheet and rill erosion, given transport losses from the source to the channel are not involved, portions of that sediment do settle out on floodplains, behind beaver dams, and on depositional features such as point bars in the channel. Technical guidance provided by NRCS (1982; 1998) indicated a SDR_{SE} range of 60 to 100%, with the higher end of the range representing the most incised channels. The dam watersheds have a range of channel types, with rates of incision high through the escarpment and lower on the west side of the watersheds. A mid-range value of 0.8 was selected for the SDR_{SE} , which is 15-20% higher than the PTMApp-generated routing results for sheet and rill erosion.

Table 7- Streambank Erosion Estimates

Dam	Total Length of Upstream Channels (ft)	Length of Perennial Channels (ft)	Bank Erosion Estimate (tons/yr)	Total Bank Erosion I_{SE} (tons/sqmi/yr)	Delivered Bank Erosion $I_{SE} \times SDR_{SE}$ (tons/sqmi/yr)
Senator Young	262,505	13,125	837	17	15
Olson	63,703	0	140	22	19
Bourbanis	104,660	0	230	27	23
Bylin	91,828	0	202	10	8
Matecjek	184,321	47,923	1,354	32	27
Fordville	382,271	53,518	1,901	38	33

Cropland Wind Erosion

Wind erosion occurs when the force of wind against individual soil grains exceeds the gravitational force acting on the grains. Wind exerts positive velocity pressure on the windward side of a soil particle, which varies directly as the square of the velocity, and is counteracted by the frictional drag due to viscous shear between soil grains and water (or ice) at the surface (Chepil, 1963). Lift occurs when static pressure at the top of the soil particle decreases below that at the base. Wind generated erosional processes are differentiated as suspension, saltation, and surface creep. In a wind erosion event, larger soil particles (or aggregates of individual particles) in the range of 0.5 to 2.0 mm are rolled across the ground surface causing them to collide with and dislodge other soil particles. This process, termed surface creep, can create a downwind avalanching effect as it moves across a long crop field (Chepil, 1963). Particles in the range of 0.05 to 0.5 mm are light enough to lift off the ground surface, but too heavy to become fully suspended in the air. As a result, these particles move through a series of low bounces termed saltation, causing abrasion on the soil surface and breaking aggregates into smaller size particles. Sediments moved through creep and saltation form dunelike deposits in leeward zones of road and drainage ditches, stream channels, and near trees, buildings, or other obstructions (Cihacek, 1993). Very fine particles, less than 0.1 mm, are blown into the air and are carried in suspension for extensive distances.

The Wind Erosion Prediction System (WEPS) model is a process-based, daily time-step model that simulates the effects of soils, hydrology, crop growth, climate, farming operations, residue decomposition, structure, and soil processes to predict wind erosion rates (ARS, 2020). Extensive validation testing has been done on WEPS by various researchers, both in crop fields

and wind tunnels, with resulting R^2 values ranging from 0.71 to 0.99 (ARS, 2020). The model uses 32 input parameters, the majority of which are derived from the USDA-NRCS Soil Survey Geographic Database and climate station data to generate estimates for cropland wind erosion separated into components of a) creep and saltation, b) suspension of particles with a diameter greater than 10 micrometers, and c) suspension of particles less than or equal to 10 micrometers. The model is intended for use at the scale of an individual crop field and does require the user to enter site specific data regarding field dimensions, crop rotation, crop yields, and field operations. To use WEPS at a watershed scale, it was necessary to make standardized assumptions for these manually entered variables. A 40-acre field size with dimensions of 1320 ft by 1320 ft was selected as typical, at a latitude of 48.421°N and -98.079°W and elevation of 1550 ft for all WEPS runs. This location, near Adams, was an approximate median of all the dam watersheds. From that location, the model interpolates wind data between the Devils Lake and Grand Forks Airports and uses climate data from the Edmore weather station. Selecting other locations within the study would slightly change input parameters, but not appreciably; the 30-year average of monthly annual rainfall varies less than 0.3 inches within the study area (NDDWR, 2022). A spring wheat-canola rotation was selected to represent typical rotation at the date of the dam sediment survey, and a spring wheat-flax rotation was selected to represent the typical rotation in 1960, as supported by the data provided in Section 3. Ted Alme, USDA-NRCS ND State Agronomist, provided guidance as to crop yields and farming operations that would have been typical in 1960 versus the 2019/2020 date of the dam sediment surveys.

Documentation of standardized inputs for current and 1960 conditions are provided in Exhibits 7 and 8 for Barnes-Buse Loam Soil. This soil map unit was selected for illustration

given it is the most widespread soil map units across all six of the dam watersheds, making up 22% of all cropland soils. Wind erosion is strongly related to soil moisture, with dry soils blowing at higher rates. Exhibit 7-5 depicts the climate data used for all WEPS runs; note that most precipitation falls May 15 to August 19. No irrigation was included in the runs, given that the Fordville Dam watershed is the only with any irrigation and that covers less than 2% of cropland. Wind energy data used in the analysis is shown in Exhibit 7-6. The peak period for wind energy is October 15 to May 31, of which only the last two weeks of May overlap high soil moisture conditions due to precipitation. While plant canopy, residue cover, and total biomass over time differ slightly by individual crop, as shown in Exhibits 7-3 and 7-4, the time periods of at least 25% cover are generally in the May to August period. So, the soil is most protected by vegetative cover and moisture conditions when wind energy is the lowest. This unfortunate timing is one of the factors driving high wind erosion rates in the area. The geographic area is also simply a high wind energy zone; the 133-tower 200-megawatt Langdon Wind Energy Center is located just southwest of the Senator Young and Olson Dam watersheds.

Typical farming operations in 1960 for wheat would have involved two passes of a cultivator in the spring, with a type of disk called a “sweep” that does not entirely invert the soil but tills the soil 6-12 inches deep. Following those tillage operations, a pass with a harrow would be needed to smooth the soil and pulverize remaining large clods, before seeding with a double disk seeder. Following harvest, the field would have been heavily tilled with a moldboard plow, which fully inverts the soil to a depth of 6-12 inches, followed a month later by a chisel plow operation to further mix up the soil and break clods. The only differences with flax operations would have been that a single pass of a cultivator with 6-12” sweeps would be used in the spring.

A full description of all field operations, circa 1960, is provided in Exhibit 8-2. By comparison, the typical farming sequence for both wheat and canola assumed in 2019/20 involves a disc harrow operation in spring, which is a lighter tillage operation that disturbs only the top 1 to 4 inches of soil, after which an air seeder or drill with hoe chisel points on it will plant and place fertilizer into the furrow simultaneously. Fall tillage with an offset disk, followed by a harrow, remains the standard practice in this region, despite efforts by the USDA and other conservation partners to promote no-till, largely out of a desire for “black dirt” to absorb warmth and to dry out more quickly in the spring thereby allowing for an earlier planting date. Resulting erosion predictions for the example Barnes-Buse Loam Soil, as shown in Exhibits 7-7 and 8-5, indicate most wind erosion taking place in fall and spring, as would be expected. The additional residue and less intensive fall tillage operations result in estimated total wind erosion dropping from 8.0 tons/ac in 1960 to 3.0 tons/ac with current farming practices. The creep and saltation portion of wind erosion, which is the component that collects in areas of low velocity, such as along tree rows or in depressional areas such as channels (Chepil, 1963), makes up 56% of the 1960 estimate and 46% of the current day estimate.

Each of the soil map units making up the top 70% of cropland soil map units within in each watershed was individually modeled in WEPS, to derive wind erosion rates for both current day and 1960 farming practices. The average of the top 70% soils, by area, was determined and that rate applied to remaining cropland soils in the watershed. Wind erosion rates for each watershed were then computed, based on the acreage of each soil and construction date of the dam, assuming a linear relationship over time of farmers adopting the lower tillage/higher residue farming practices. Appendix Exhibit 9 provides a listing of modeled tons per acre of

cropland by soil map unit. The annual composite rates for the full watersheds, which accounts for the date of dam construction as well as the percentage of cropland in the overall drainage areas, ranged from 2,287 to 3,355 tons. Given that only the creep and saltation component of wind erosion collects in ditches, stream, and river channels, that composite volume was the key output of the WEPS analysis used in the sediment budget computation. Modeled composite watershed creep and saltation annual wind erosion ranged from 1,294 to 1,907 tons per square mile.

Table 8- Wind Erosion Estimates

Dam	1960 Total Wind Erosion (tons/yr)	2019 Total Wind Erosion (tons/yr)	Composite Total Wind Erosion (tons/sqmi/yr)	Composite Creep and Saltation Wind Erosion I_{WE} (tons/sqmi/yr)
Senator Young	234,812	46,571	3,355	1,907
Olson	22,126	4,360	2,411	1,366
Bourbanis	31,876	6,257	2,536	1,429
Bylin	71,473	14,496	2,421	1,365
Matecjek	136,760	28,078	2,287	1,294
Fordville	194,121	34,518	2,645	1,505

Reservoir Trap Efficiency

Trap efficiency describes the proportion of incoming fluvial sediment load that remains permanently trapped in the reservoir. Sediment particles settle when their weight exceeds both the buoyant and drag forces of water; Stokes Law outlines a relationship for settling velocity for a particular spherical size sediment particle based on diameter, particle density, and the dynamic viscosity of water (Streeter, 1985). Diameter is the variable that carries the most weight in Stokes Law, with the settling velocity for a particle increasing linearly with diameter, which explains the

fact that gravels will typically accumulate on the farthest upstream end of the reservoir, then sands, and then silt/clay particles within the main reservoir. Brune (1953) developed relationships between particle size, annual reservoir inflow to reservoir capacity ratio, and trap efficiency from measurements at 44 dams, which remains the common design reference for trap efficiency today (Dutta, 2016; NRCS, 1982). The constructed dam capacity, or active storage between the principal and auxiliary spillways on the dams, was obtained from the original as-built drawings on file with NRCS. Annual inflow was determined for each dam utilizing the 50% exceedance probability data provided by Williams-Tether (2020). Given the fine-grained soils in these watersheds (perennial stream channels have silt or fine sand beds upstream of the dams), the fine-grained curve from Brune (1953) was used to determine the trap efficiencies. Resulting trap efficiencies ranged for the six dams utilized in my study were 94%, with the exception of Senator Young Dam that was 92% (Table 9). Note that trap efficiencies of Sarnia and Whitman Dams are provided for reference only, to document that most incoming sediment to those dams is trapped rather than being transported downstream to Matecjek Dam.

Table 9- Reservoir Trap Efficiencies

Dam	Capacity (ac-ft)	Annual Inflow (ac-ft)	Capacity/Inflow	Trap Efficiency TE (%)
Senator Young	4,747	409.0	1.9	92
Olson	701	53.5	13.1	94
Bourbanis	1,012	73.2	13.8	94
Bylin	4,223	166.8	8.6	94
Fordville	7,089	346.6	7.2	94
Matecjek	7,274	321.6	5.2	94
Whitman	8,059	425.3	19.0	94
Sarnia	310	149.3	2.1	92

Dam Sediment Budgets

As noted in Section 4, the field surveyed sediment volume must be adjusted from the existing consolidated density to the original inflow density for the sediment budget equation to be valid. The measured sediment volume was multiplied by a factor of 1.4 based on the NRCS (1982) listed average ratio of 1.4 between aerated and submerged silt and clay sediments. With all individual components of the sediment budget estimated, other than the sediment delivery ratio for wind erosion (SDR_{WE}), that factor was determined by rearranging the terms of the sediment budget equation to complete the following calculations:

- $(I_{WE} \times SDR_{WE}) = \Delta S - [(I_{S\&R} \times SDR_{S\&R}) - (I_{SE} \times SDR_{SE})]/TE$
- $SDR_{WE} = (I_{WE} \times SDR_{WE}) / I_{WE}$

Table 10- Sediment Budgets

Dam	Delivered, Sheet and Rill Erosion² $I_{S\&R} \times SDR_{S\&R}$ (tons/sqmi/yr)	Delivered, Streambank Erosion $I_{SE} \times SDR_{SE}$ (tons/sqmi/yr)	Total Delivered Wind Erosion $I_{WE} \times SDR_{WE}$ (tons/sqmi/yr)	Creep & Saltation Wind Erosion I_{WE} (tons/sqmi/yr)	Wind Erosion Delivery Ratio SDR_{WE}
Senator Young	131	15	85	1907	0.05
Olson	248	19	427	1366	0.31
Bourbanis	242	23	227	1429	0.16
Bylin	186	8	87	1365	0.06
Matecjek	306	27	-87	1294	-0.06
Fordville	75	33	286	1505	0.19

As noted previously, the model for sheet and rill erosion appears to generate erroneously high results for Matecjek Dam, yielding the physically impossible negative value for SDR_{WE} at that dam. The computed SDR_{WE} values for the other five dams indicate that 5 to 31% of total

watershed creep and saltation wind eroded sediment volume is delivered to downstream reservoirs via the hydraulic network. The median SDR_{WE} value, excluding Matecjek, was 0.16. The sediment budget results indicate that wind erosion is the dominant sediment source at Olson and Fordville Dams and a significant source at Senator Young, Bourbanis, and Bylin Dams (Figure 5). As expected, streambank erosion inputs are relatively insignificant, even with the conservatively high assumptions used to generate those estimates. Interestingly, despite apparent issues with the Matecjek Dam sheet and rill erosion modeling, that watershed did also have the lowest modeled wind erosion rate, which would be a logical reason as to why it has one of the lowest overall sediment accumulation rates.

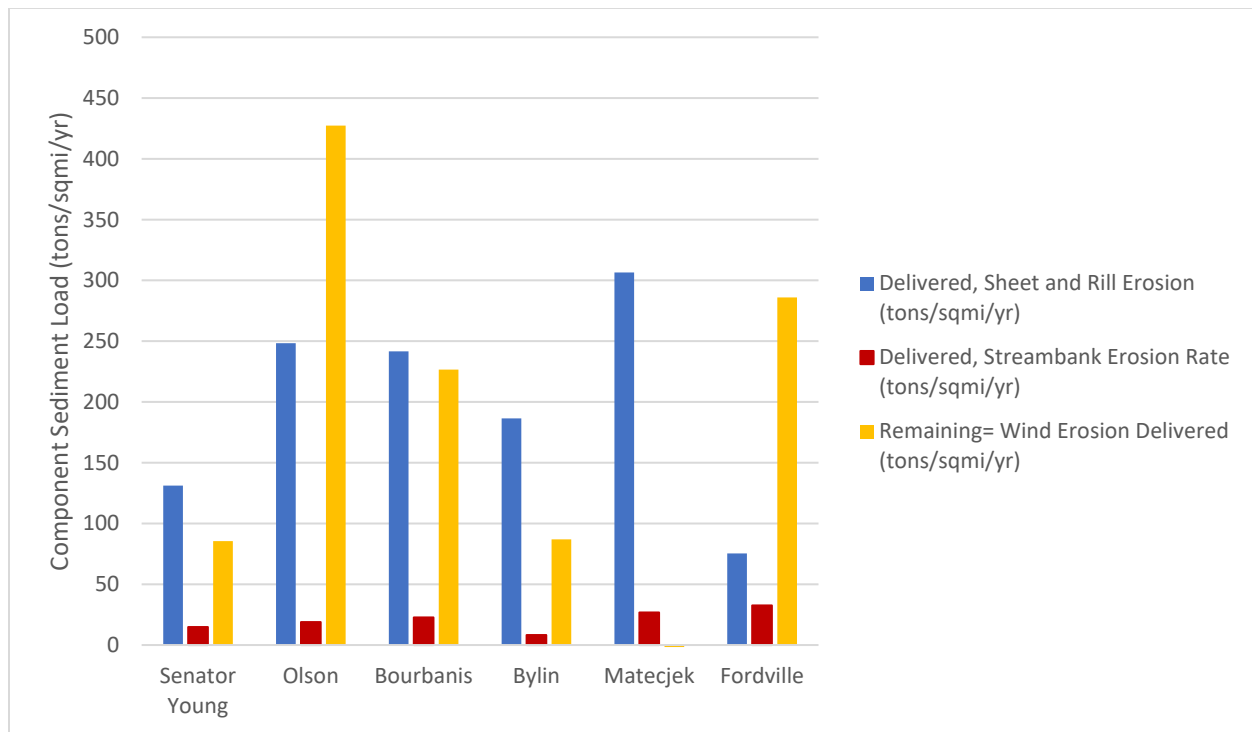


Figure 5- Sediment Budget Results

EROSION REDUCTION DUE TO CROPLAND ADJACENT TREES

I completed a second, independent evaluation of the extent to which cropland wind erosion impacts reservoir sedimentation, by investigating the relationship between wind protected area and measured sediment loads. Since the Dust Bowl of the 1930s, planting long rows of trees oriented perpendicular to the prevailing wind direction (termed field windbreaks) has been encouraged by USDA and other agencies to reduce wind erosion on cropland. As wind blows against the porous barrier of trees, air pressure on the windward side builds and causes large quantities of air to move up and over the windbreak while a low-pressure zone develops on the leeward side. In addition to the direct effects of creating these low velocity zones, windbreaks reduce saltation induced avalanching by effectively shortening the length of field. Height (H) of the trees in the windbreak is the most important factor in determining the horizontal extent of wind protection; Brandle (1991) reported lower wind speeds for a distance of 2H to 5H on the windward side of the trees and 5-30H on the leeward side, with the most extensive effects occurring at wind speeds of 20 miles per hour (mph) or more and the lower end of the range at 10 mph. Chepil (1963) indicated that leeward velocities may be reduced for distances as long as 40-50H, dependent upon wind velocity. For planning purposes, a general assumption of 10H has been adopted as the distance of effective leeward wind protection (Brandle, 1991)

Field windbreaks, termed “windbreaks” in this study, in the watersheds of the six dams typically consist of a single row of Siberian elm, most typically, at an average height of 30 feet. Windbreaks are planted both North-South and East-West in the watersheds reflecting the fact that winds blow strongly from both the north and west. Trees planted around farmsteads, termed “shelterbelts”, often border cropland on the opposite side thereby providing protection to it as

well as the home, shop, barns, and corrals. Shelterbelts in the area contain a mix of conifer and hardwood tree species in multiple rows, often with larger shrubs incorporated, with an average maximum height of 30 feet as well. Natural forests also border cropland, providing similar wind erosion protection benefits; a 30 ft average height was assumed for these as well. I reviewed all of the available imagery from the ND State Water Commission Aerial Photography Dissemination Map Service and the USGS Earth Resources and Observation and Science Center for the dam watersheds, both in orthorectified and single image form. Unfortunately, although there was extensive data available throughout the dam lifespans, the only imagery with adequate resolution to be able to identify windbreaks before 2003 was from a U.S. Air Force sponsored flight completed in 1962. As illustrated in the examples (Exhibit 10), I manually digitized windbreaks, shelterbelts, and forests where adjacent to cropland on aerial photos from 1962, 2003, and 2020. I did not digitize trees rows that had been planted but were not grown to the point crowns on the trees had developed, on the assumption that such young trees would not provide substantial wind protection (Exhibit 10). Where portions of tree rows had been, due to aerial spray or wind, I stopped and started the digitizing accordingly. A 300 ft buffer (10H) was applied to digitized forest and shelterbelt lengths and a 600 ft buffer (10H on two sides) was applied to windbreaks. Total watershed tree rows varied widely, with 2003 being the year with the highest total in all six dam watersheds (Exhibit 10). Resulting lengths and wind protected cropland acreage, by year, varied from 1 to 14% (Exhibit 10). A linear relationship over time was assumed and based upon the year of dam construction, a time weighted average of protected cropland acreage calculated and from that, the percentage of wind protected to total cropland in

each dam watershed was computed (Exhibit 10; Figure 6). The time weighted average of percent wind protection was oddly similar between the dam watersheds, with a range of only 3-9%.

STUDY RESULTS

Except for Matecjek Dam, where PTMApp seems to overestimate sheet and rill erosion as noted previously, sediment budgets for all dams indicate a significant source of sediment beyond sheet and rill erosion. This quantity, not accounted for by sheet and rill erosion, is termed “excess sediment” in the remainder of this paper. The positive relationship between percentage of watershed in annual crops and excess sediment suggests that the source of that excess sediment is cropland rather than an unaccounted-for source such as road construction (Figure 7). Senator Young Dam is a distinct outlier in this relationship, given it has a relatively low excess

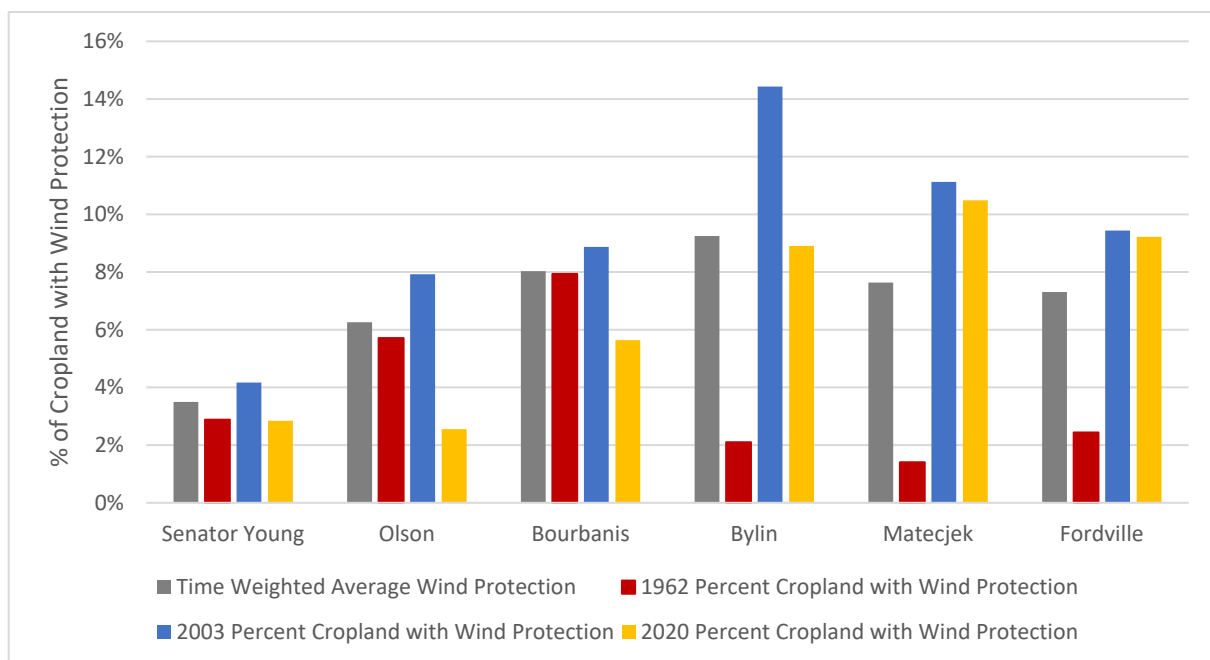


Figure 6- Percentage of Wind Protected Cropland by Year

sediment rate despite having the highest percentage of cropland in its drainage area. The road network in these watersheds is of similar density and surfacing (gravel), with the typical Midwest 1 mile by 1 mile pattern and has very low levels of traffic use. These results are in line with a reservoir study in Oklahoma which used radioisotope dating of sediment cores to establish that the only variable with a significant influence on the rate of sediment accumulation was the ratio of cropland to pastureland in the watershed (McIntyre, 1993). Except for CRP enrolled lands moving from cropland to grassland and back, since 1990, the land use in these watersheds has remained relatively stable since construction of the dams, based on historic aerial photos.

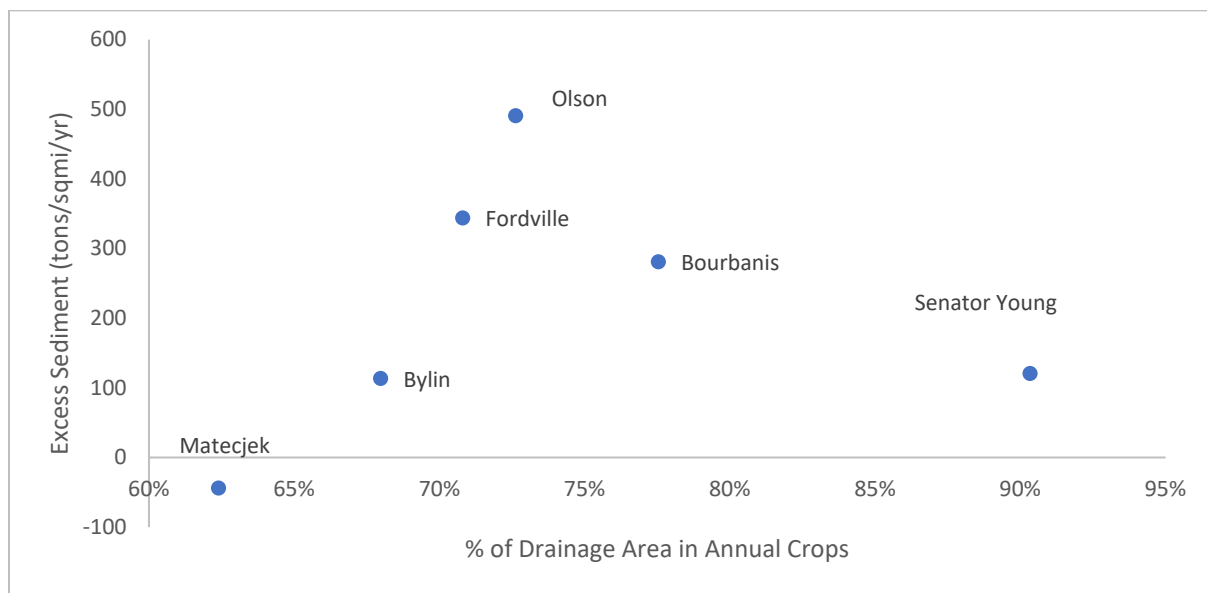


Figure 7- Percentage Cropland vs Excess Sediment

Given the lack of historic gully erosion in these watersheds, as discussed in Section 4, the only unaccounted for cropland erosion source is wind erosion. Sediment budget development was, therefore, based on this assumption. Wind erosion contribution to overall reservoir sediment ranged from 0% at Matecjek Dam to 73% at Fordville Dam (Figure 8). As discussed in Section 4, the PTMAApp results for Matecjek appear to underestimate sediment retention in the two large

upstream dams, thereby yielding an unreasonably high estimate for delivered sheet and rill erosion. As a result, the calculation for excess sediment is a negative value, leading to an estimate of no delivered wind erosion. Results from the other five dams indicate an average of 50% and median of 46% of accumulated sediment in the reservoirs is derived from wind erosion.

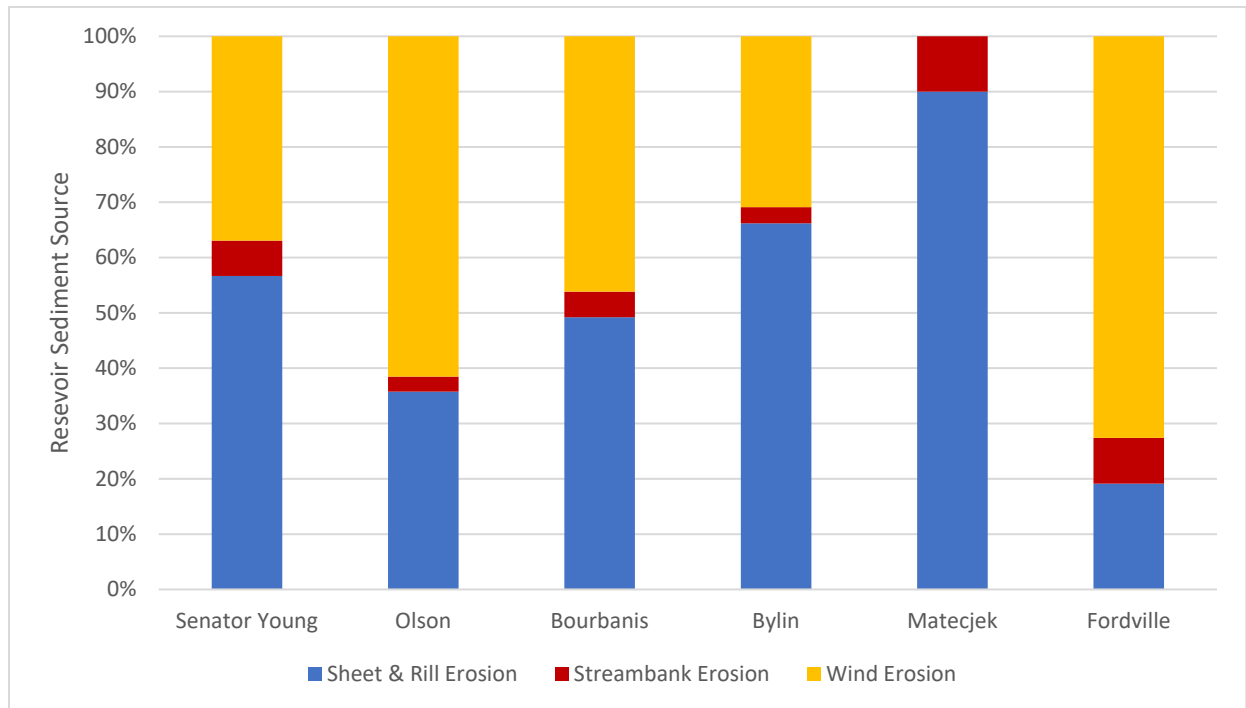


Figure 8- Reservoir Sediment Source

Modeled cropland wind erosion rates used in the sediment budgets ranged from 7.08 to 8.68 tons/acre in 1960 and 2.43 to 2.87 tons/acre in 2019. The NRCS Natural Resources Inventory (NRI) similarly uses the RUSLE and WEPS models, run based on regional assumptions. By comparison, NRI average cropland wind erosion rates in North Dakota are reported as 6.6 tons/acre in 1982 and 5.5 tons/acre in 2017 (USDA, 2020). Modeled sheet and rill erosion rates used in the sediment budgets ranged from 0.2 to 0.8 tons/acre, which are lower than the NRI estimated cropland sheet and rill erosion rates across North Dakota, estimated as 1.5

tons/acre in 1982 and 0.92 tons/acre in 2017 (USDA, 2020). The lower figures for these watersheds, compared to the statewide average, may be logical given that northeastern North Dakota has a combination of lower average temperatures (NDSU, 2022) and higher snowfall totals (Williams-Sether, 2019) than the rest of the state. Higher periods of snow cover and frozen soils reduce erosion rates from both wind and water, which are factors incorporated into the models. In addition, the typical farming practices used for this study were likely more accurate to this specific geographic region than general assumptions made for the NRI analysis.

Use of wind protected area was the second method attempted for establishing a relationship between wind erosion and sedimentation rate, as summarized in Section 5. The relationship between the measured sediment accumulation rate and wind protected cropland indicates the inverse relationship that would be expected (Figure 9); i.e more wind protection over time in the watershed yielded less sediment accumulation at the dams. Findings support the premise that wind erosion is a significant source. The trend line between percentage of wind protection and sediment accumulation, with Senator Young removed given that it appears to be an outlier (as with Figure 7), has a coefficient of determination of . The fact that the range of values is so narrow, for the time weighted average percent of cropland with wind protection, is unfortunate. A wider range of the independent variable would have yielded a more convincing data set. It was also unfortunate that no aerial photography with adequate resolution was available between 1970 and 1985, as local conservation staff indicate that would have been the peak of field windbreak extents. In fact, many newly planted shelterbelts and wind breaks that were evident in the 1962 imagery were no longer present in the 2001 imagery. Having an additional imagery year might have created a wider spread among the values, thereby increased

confidence in results. The Olson Dam watershed, which had the highest estimated wind erosion rate, did have one of the lowest percentages of wind protection and the Bylin Dam watershed, which had the lowest estimated wind erosion rate, had the highest percentage of wind protection.

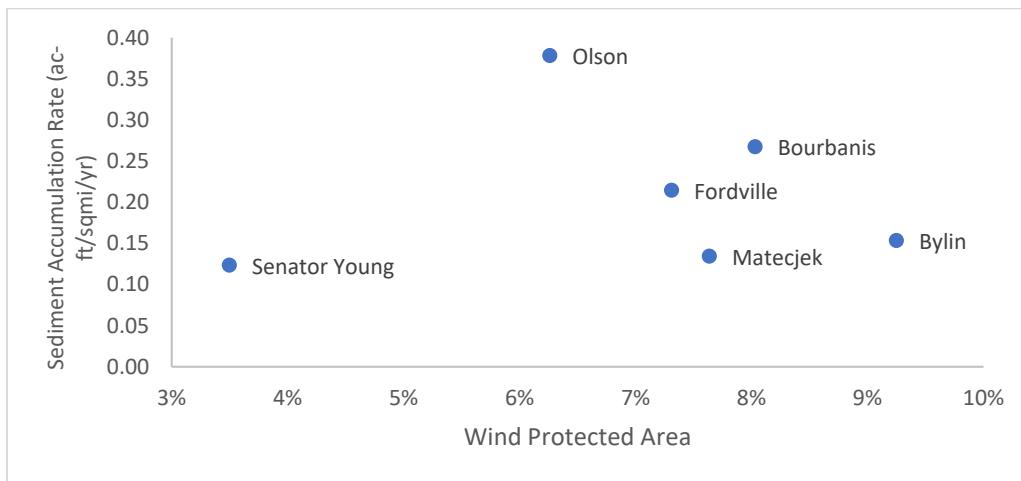


Figure 9- Percent Wind Protection on Cropland vs Sediment Accumulation Rate

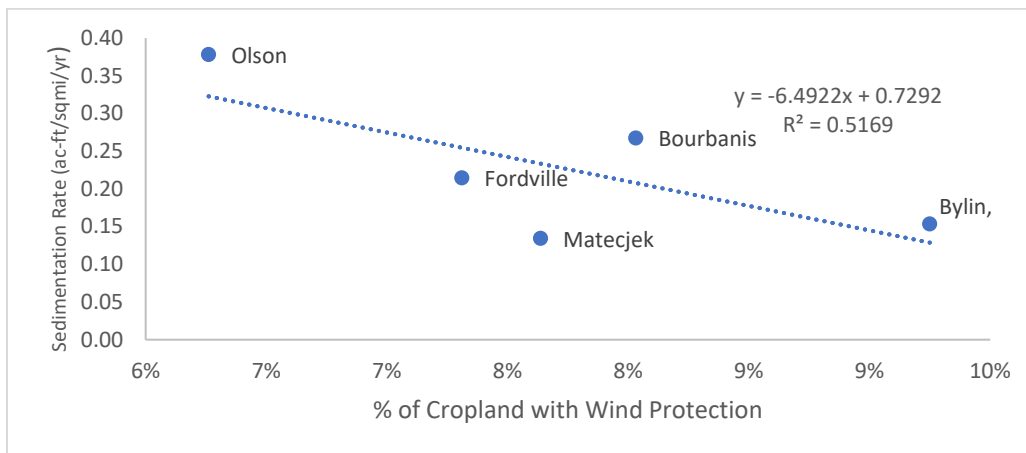


Figure 10- Percent Wind Protection on Cropland vs Sediment Accumulation Rate (Senator Young removed)

Although statistics on such a small dataset are of limited utility, I computed Pearson's correlation coefficient with a range of variables for the full dataset, as well as without Senator Young. First, evaluating the relationships for all 6 dams indicates that channel network density

and mean drainage area slope correlate most strongly with excess sediment volume. Neither necessarily support nor contradict the fact that wind erosion is the source of excess sediment. Instead, they likely indicate a higher overall transport efficiency from the landscape to the hydrologic network. Iowa NRCS (1998) guidance indicates that watersheds with a channel density in the range of 6-12 mi/sqmi may have an SDR twice those with channel densities in the 0-6 mi/sqmi range. The range of channel densities for the six North Dakota dam watersheds ranges from only 0.8 to 2.3 mi/sqmi, so at the very low end of what is found in Iowa watersheds, therefore transport likely is a factor (although the PTMApp model accounts for that). Conversely, an argument could be made that the strong correlation to channel network density and mean drainage area slope could indicate that streambank erosion was underestimated.

Table 11- Pearson's Correlation Coefficient, Response Variable = Excess Sediment

Explanatory Variable	Correlation Coefficient, Dataset = All Dams	Correlation Coefficient, Dataset = All Dams Except for Senator Young
Mean Drainage Area Slope	0.841	0.832
Channel Network Density	0.775	0.758
Percent of DA in Annual Crops	0.196	0.754
Percent of 800 ft Channel Buffer in Annual Crops	-0.717	-0.746
% Cropland in 0-2% Slope Class	0.456	0.734
% Cropland in 2.1-4% Slope Class	-0.484	-0.741
% Cropland in >4% Slope Class	-0.408	-0.743
Drainage Area Max Length / Max Width (L/W)	0.274	0.563

As with channel density, the shape of a watershed can affect sediment transport efficiency from the landscape to the fluvial network. In a long, narrow watershed sediment generated from crop fields has less distance to traverse to reach a stream or ditch. NRCS (1998) guidance indicates that watersheds with a Length to Width ratio of 2 can have an SDR of twice

those with L/W of 1, and four times that of a L/W of 0.5. The L/W ratios of the 6 dam watersheds do have a wide range, from 0.7 to 3.9 (Table 2). Somewhat of a correlation does appear to be the case with the L/W ratio, particularly in the dataset with Senator Young removed. This again supports the likelihood that more widely distributed wind erosion is the source of excess sediment rather than near channel sources like gully or streambank erosion.

Gully erosion is the variable intentionally omitted from the sediment budgets, based on local knowledge of cropland erosion. Gully erosion on cropland would be highly related to field slope. An indicator of gully erosion would be a negative correlation between the percentage of cropland in a 0-2% slope class and excess sediment; instead, results were positive. Likewise, a positive correlation would exist between the percentage of higher slope class cropland and excess sediment; instead, results were negative. Gully erosion is more prevalent adjacent to channels and, in fact, is often driven by downstream channel incision initiating a head cut into adjacent cropland. A buffer width of 800 ft from channels was arbitrarily chosen and correlation between percent of cropland within this buffer zone and excess sediment examined. Results are negative indicating that more cropland adjacent to channels generates less sediment, which is both counterintuitive and discounts the likelihood gully erosion is the source. On the other hand, the explanation for low correlation to cropland in the buffer could simply be that very erodible land next to channels is less likely to be farmed.

The reason for Senator Young appearing as an outlier in some of the relationships may be related to sediment distribution within the reservoir (Exhibit 5). While the other five dams have accumulated sediment spread throughout their reservoirs, the sediment in Senator Young has deposited almost entirely on the upstream end of the reservoir. If the Senator Young watershed

had a high proportion of gravelly soils, that would be logical given that sands and gravels typically deposit in the delta area of a reservoir while lighter weight silt and clay particles distribute evenly across the reservoir bottom, however that is not the case. USBR (2006) guidance indicates that sediment distribution within a reservoir can be related to the ratio of flood pool to permanent pool depth, multiplied by the percentage of time reservoir stage exceeds the permanent pool. The ratio of flood pool to permanent pool depths, at construction, of the two highest dams in the study (Senator Young and Matecjek) are identical at 1.2 and hydraulic modeling completed on the dams indicate similar drawdown time for a 100-year precipitation event, therefore this does not appear to be a differentiating factor. Glacial deposits downstream of Senator Young dam have resulted in a relatively high density of large round boulders in the channel. It may be that those similar features were present on in the delta area of the reservoir, causing variation in currents and interspersed lower velocity zones that encouraged sediment deposition. Alternatively, cross currents from the other arm of the reservoir on Senator Young could be influencing deposition patterns. Both cross currents and undercurrents can have a large impact on even fine sediment deposition in reservoirs (USBR, 2006). Additional field sampling, in the form of sediment cores, suspended sediment sampling, and velocity measurements during flood events on the upstream extents of the reservoir would be needed to establish the reason for the odd distribution pattern. It is possible that the plug of sediment has backwatered the upstream river to the point that sediment is depositing outside of the reservoir extents, and therefore the bathymetric survey should have extended upstream. Increasing the ΔS on Senator Young would have brought the sediment budget for that dam in line with the others

RECOMMENDATIONS

Although six dams are not a large sample size, my study results support the premise that cropland wind erosion can be a significant source of reservoir sediment. Results for the six North Dakota dams could be improved with additional work to better quantify total sediment accumulation on Senator Young Dam, correcting PTMApp modeling for Matecjek, and locating higher resolution aerial photography for the watersheds at some point between 1970 and 1985. The reason such high-resolution images are available in 1962 is that the U.S. Air Force funded data collection due to missile sites located across the dam watersheds. Although no additional imagery was available through either the North Dakota State Water Commission Aerial Photography Dissemination Map Service or the USGS Earth Resources and Observation and Science Center, it seems that it likely exists in Air Force archives. Contacting the Grand Forks Air Base, however, did not yield a helpful response. In addition, the streambank erosion component of the sediment budgets would be better supported by long-term monitoring in the dam watersheds or an approach like that taken by URS (2013), using field soil mechanics testing.

One of the most immediately useful outputs of the study are the sediment budgets determined for the six dams, all of which are currently undergoing rehabilitation plans. The sediment budgets for Fordville, Olson, Bourbanis, and Bylin are suitable to use directly to forecast sediment accumulation for the next 50-100 years, applying the 2019 WEPS rates. The sediment accumulation data for Senator Young and PTMApp model for Matecjek should be addressed, and those sediment budgets corrected, before finalizing forecasts. Until additional research becomes available, the 0.16 median sediment delivery ratio for creep and saltation wind erosion could be used in conjunction with WEPS modeling to develop sediment budgets for new

dams being planned. While there have been no other studies that evaluated wind erosion sediment delivery ratios to the fluvial network, Cihcek (1993) set up a study in the North Dakota portion of the Red River Basin to collect wind-blown sediment from ditches downwind of crop fields, to characterize cropland nutrient export associated with wind erosion. That project did not attempt to measure quantity of windblown sediments, but a similar one that did would provide solid data to support sediment delivery ratio for wind erosion.

Additional research, with an expanded dataset both in terms of number of dams and geographic extents, is needed to generate definitive guidance for dam designers working in watersheds prone to cropland wind erosion. Datasets for sediment accumulation at dams are rare, but the existing datasets from Texas, Oklahoma, and Kansas noted in Section 1 could be used to reanalyze results in consideration of wind erosion inputs. Use of WEPS at a watershed scale is tedious and time consuming, so it would be ideal if a batch run option was developed that would allow multiple soils to be run with a single management file. Those previous studies used simplistic forms of RUSLE to generate sheet and rill erosion rates, which would ideally be updated with the use of a more sophisticated routing model such as PTMApp. Lack of high quality, hydro-conditioned, LiDAR topographic data would potentially be an impediment to accomplishing that. The USGS Advisory Committee on Water Information, Subcommittee on Sedimentation, is currently in the process of consolidating datasets and analyses for reservoir sedimentation. A partnership between USGS and USDA-ARS to investigate wind erosion contributions to dam sediment accumulation in agricultural watersheds, using those datasets, would be an ideal approach for additional research.

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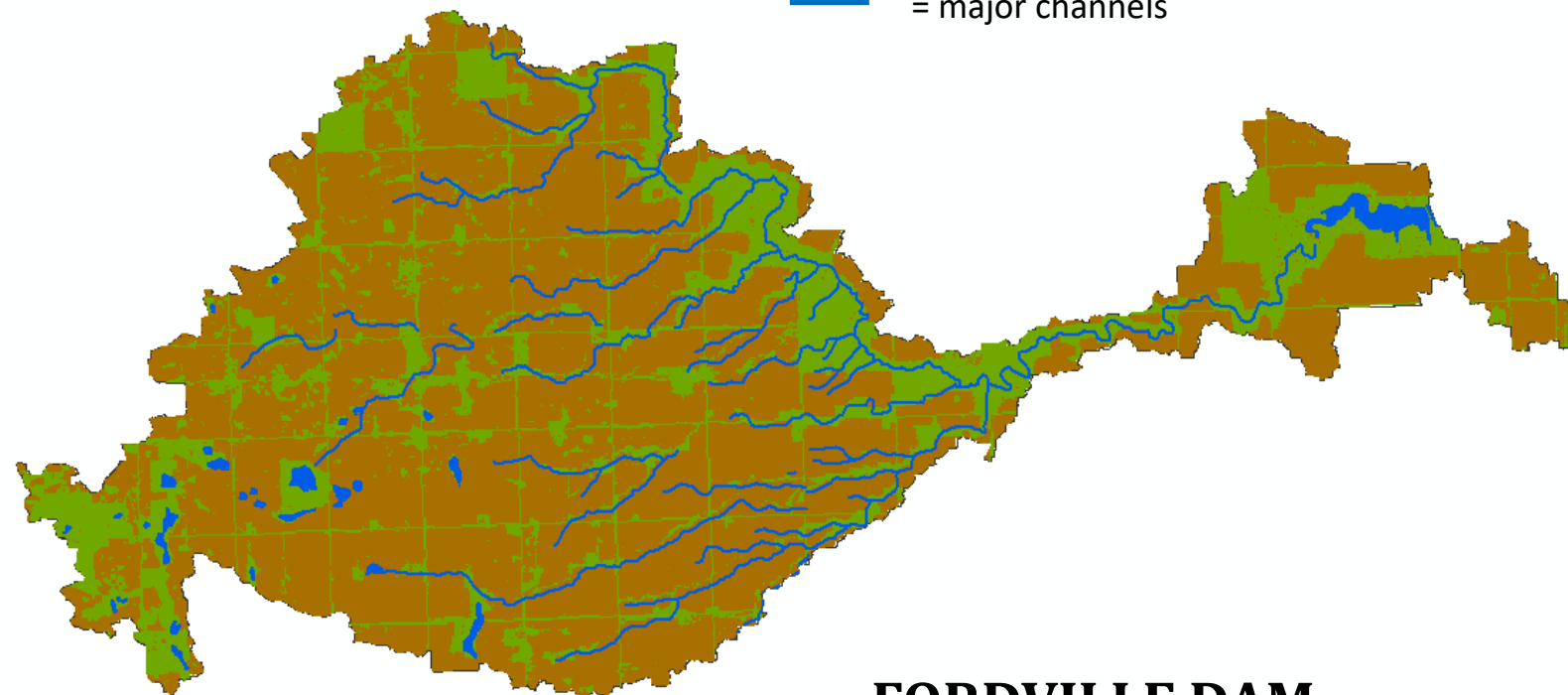
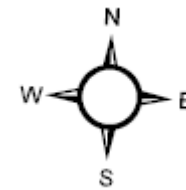
APPENDIX

Photo From Centerline of Dam

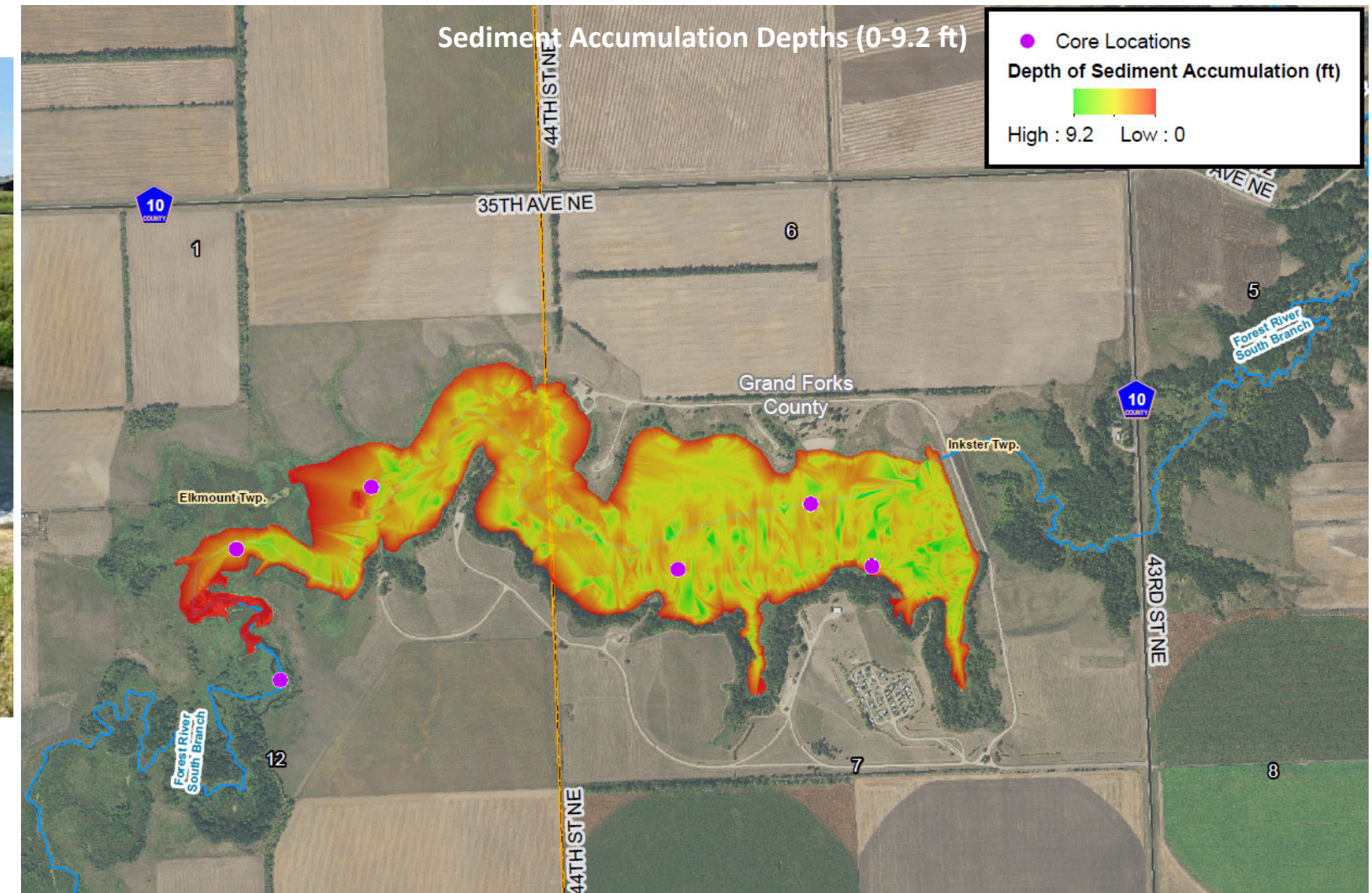


Drainage Area– Land Use

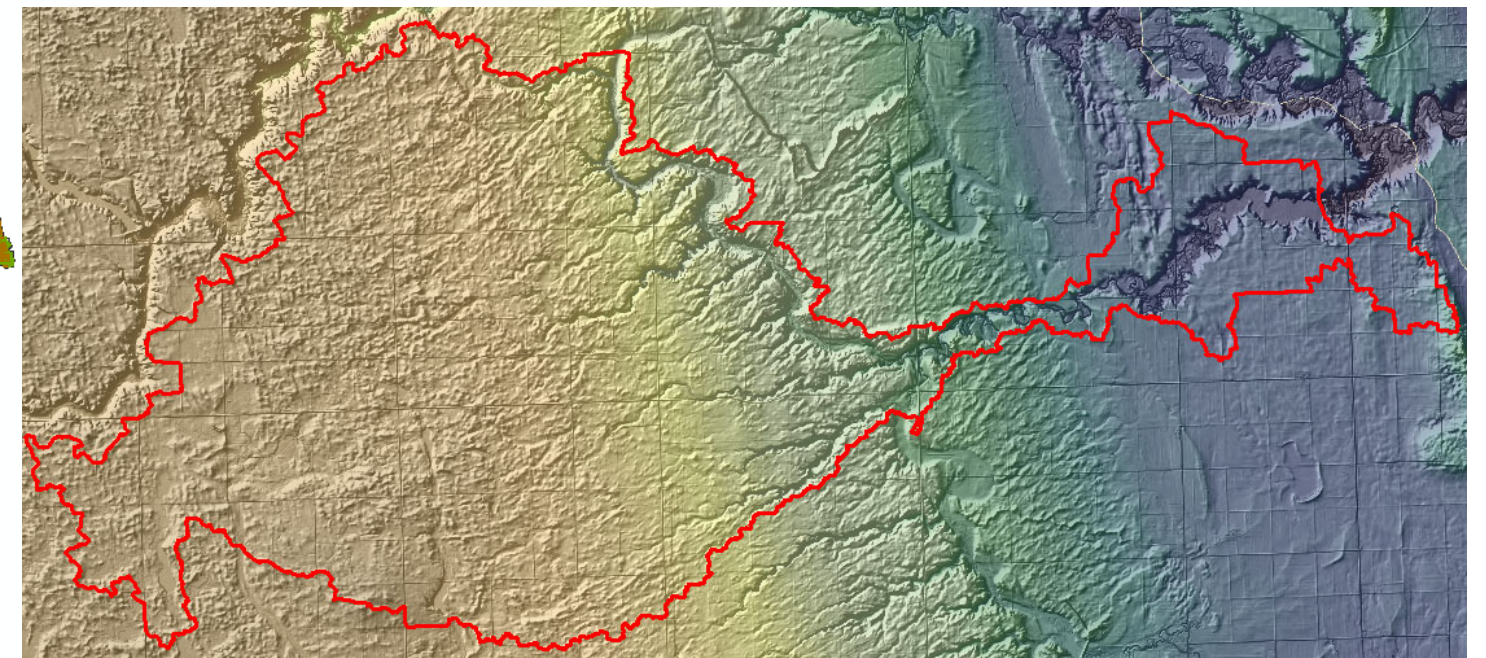
- = land in row crops
- = perennial vegetation
- = major channels

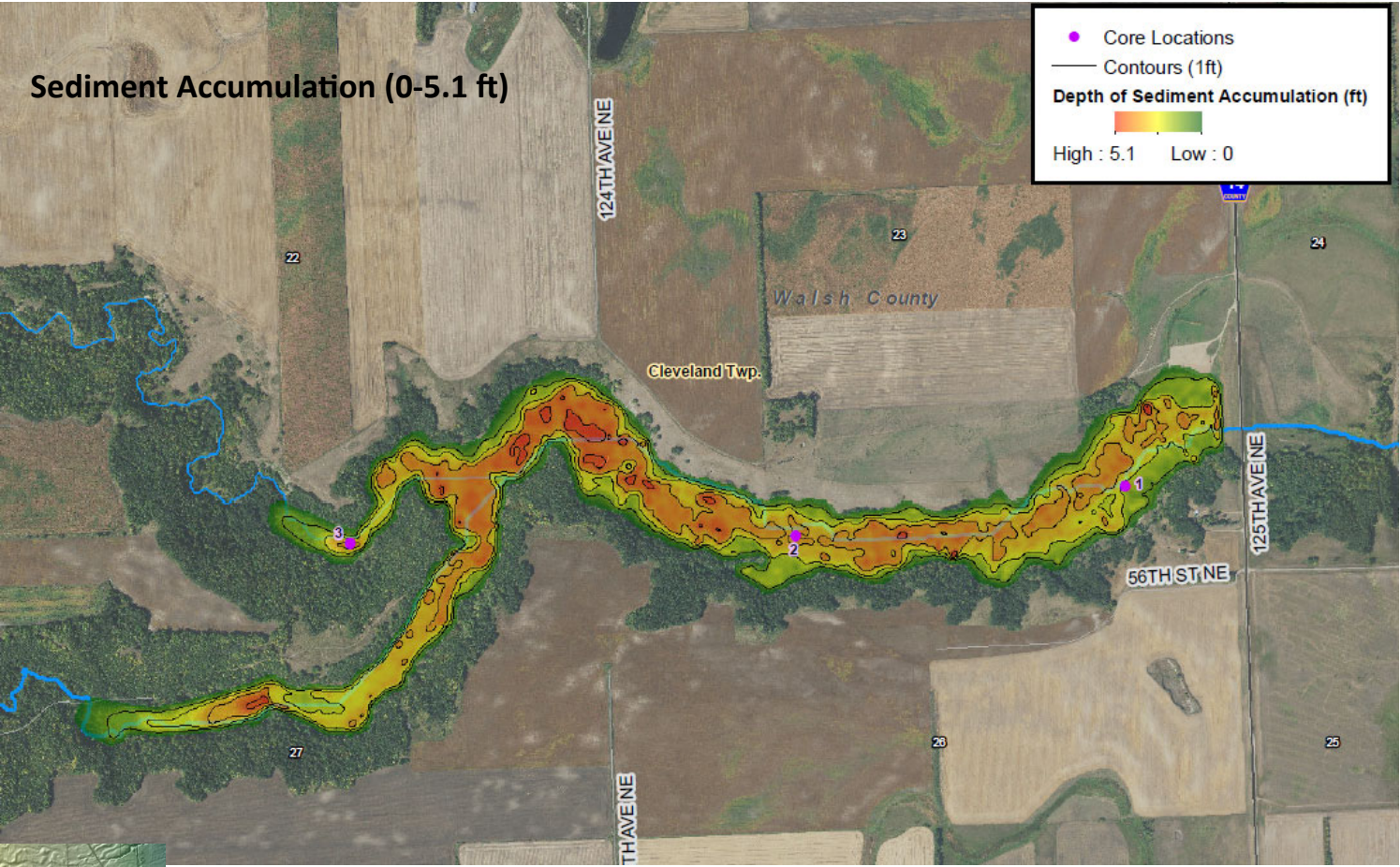
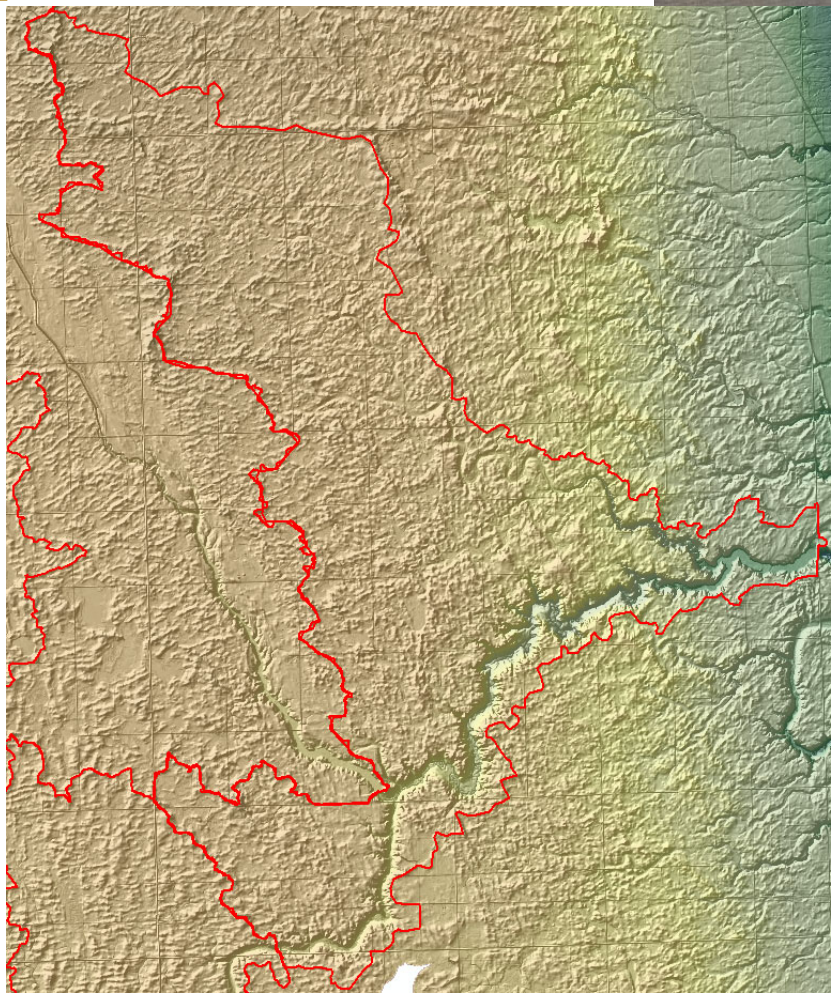
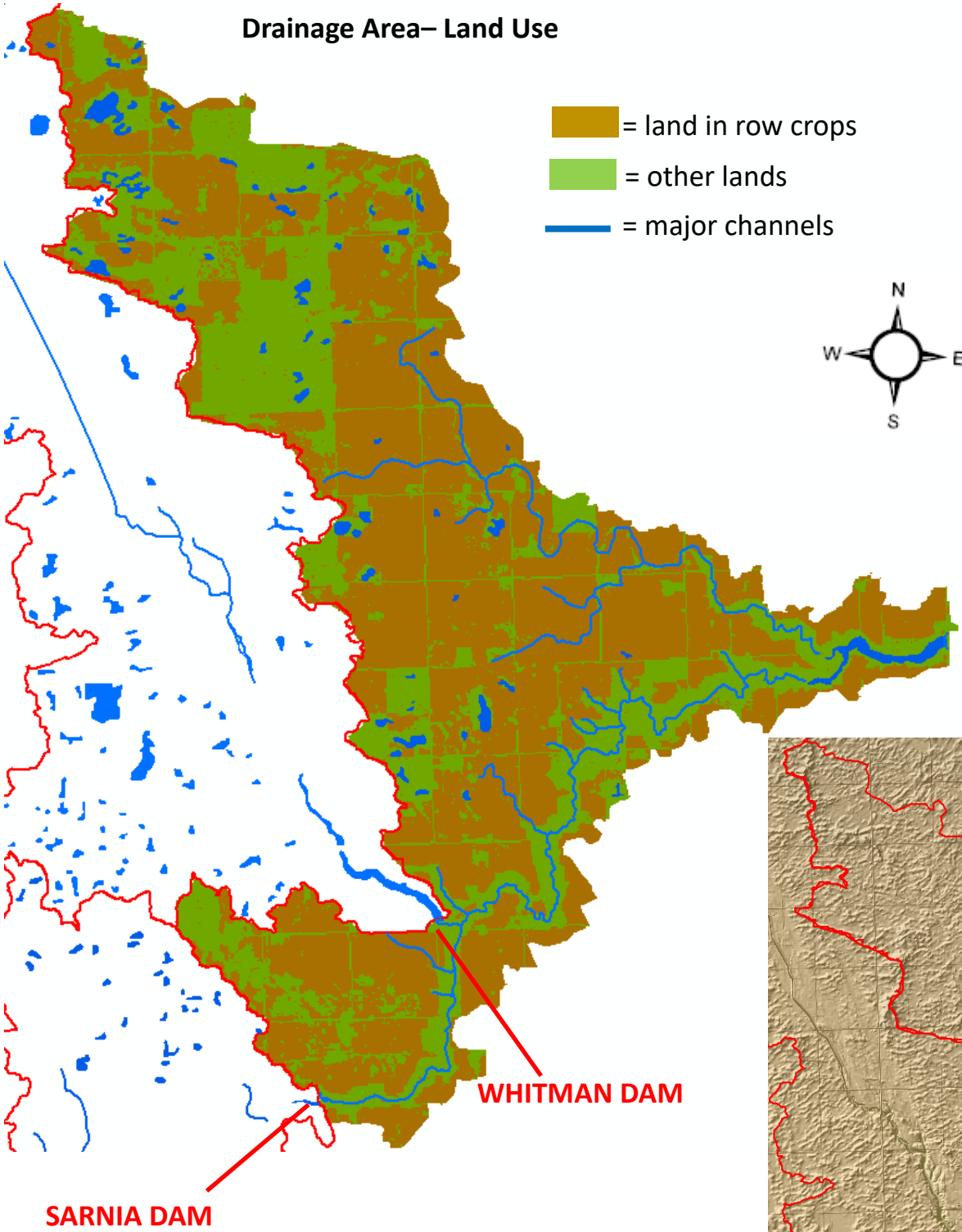


FORDVILLE DAM



Drainage Area– Topography





Photo, North Side of Embankment



MATECJEK DAM

BYLIN DAM

Drainage Area– Land Use

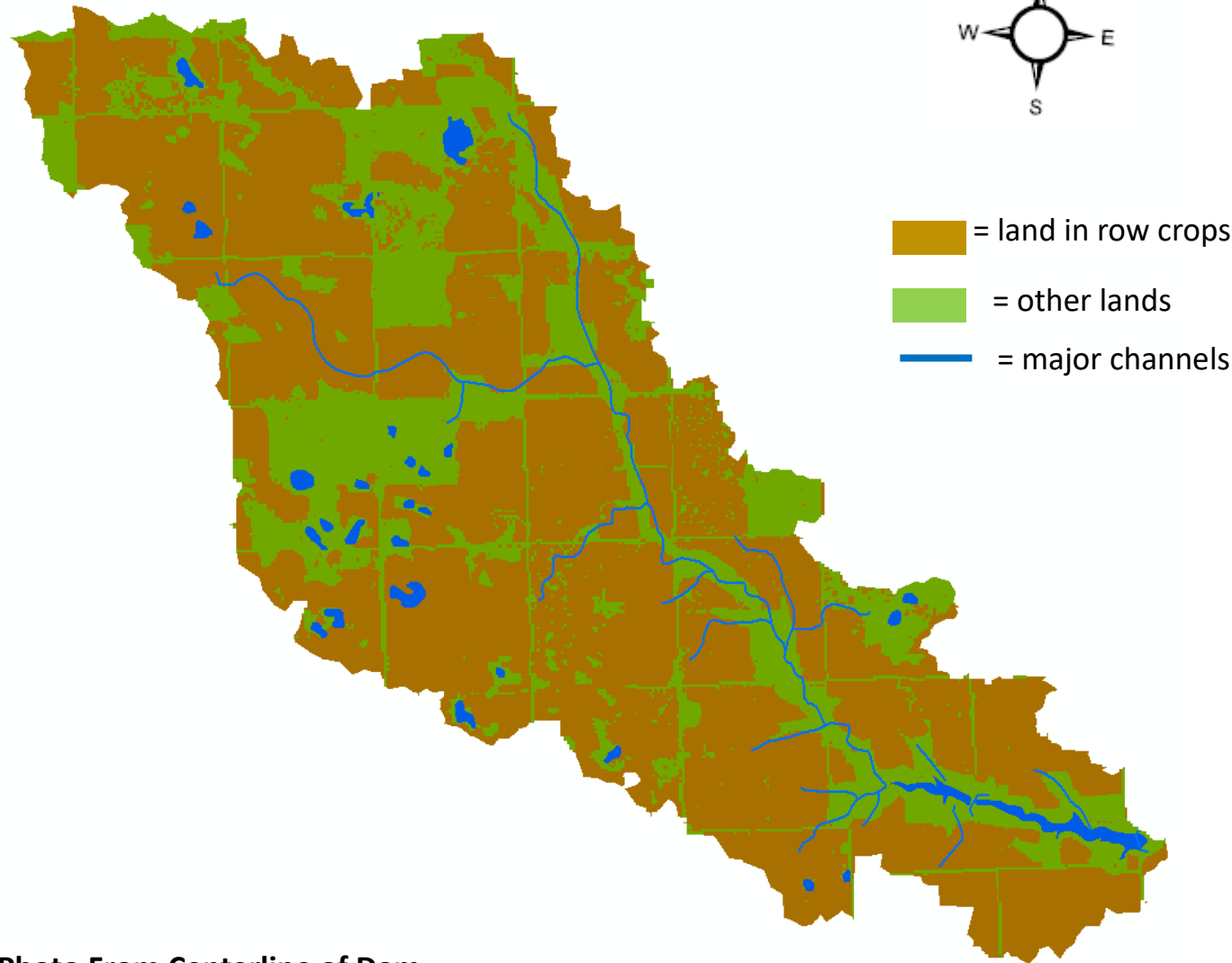
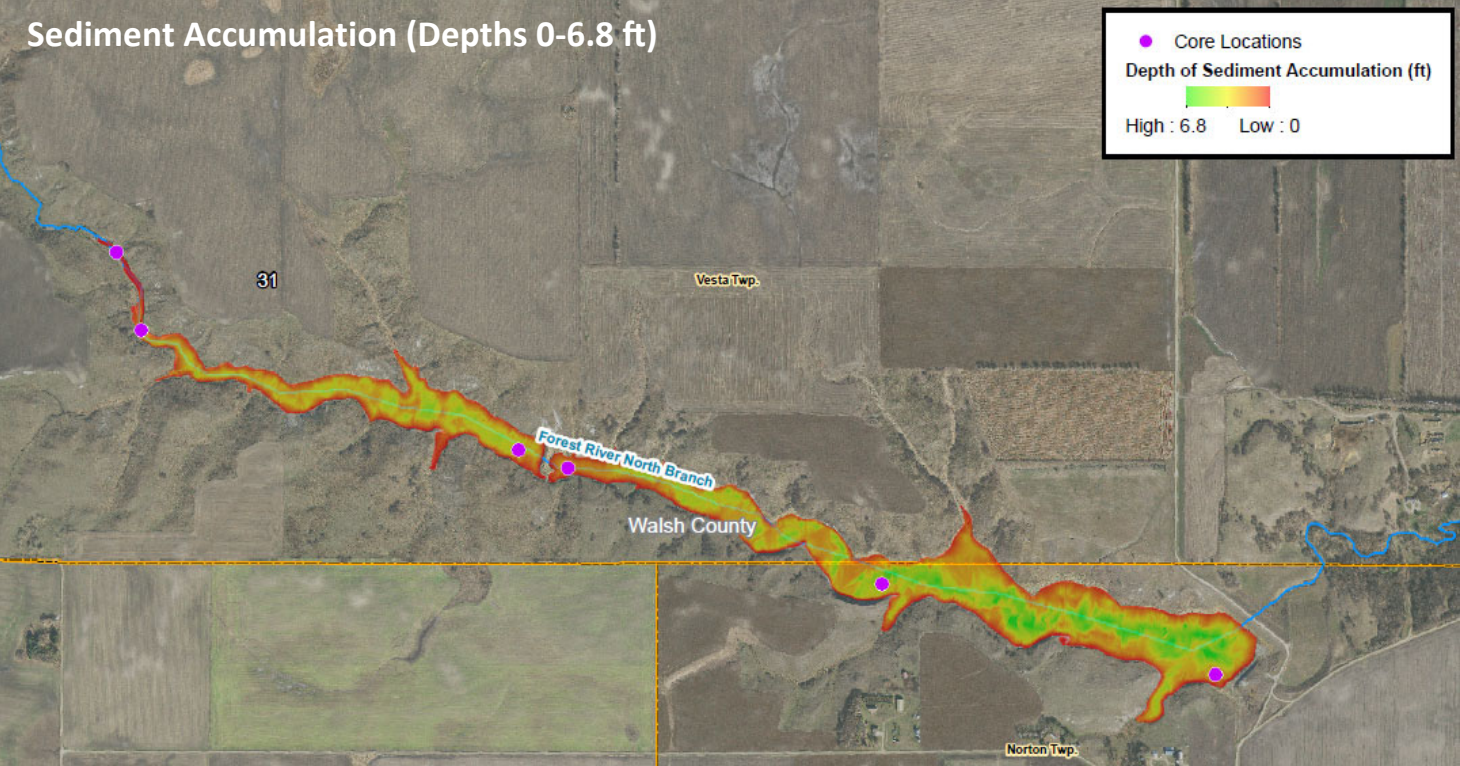


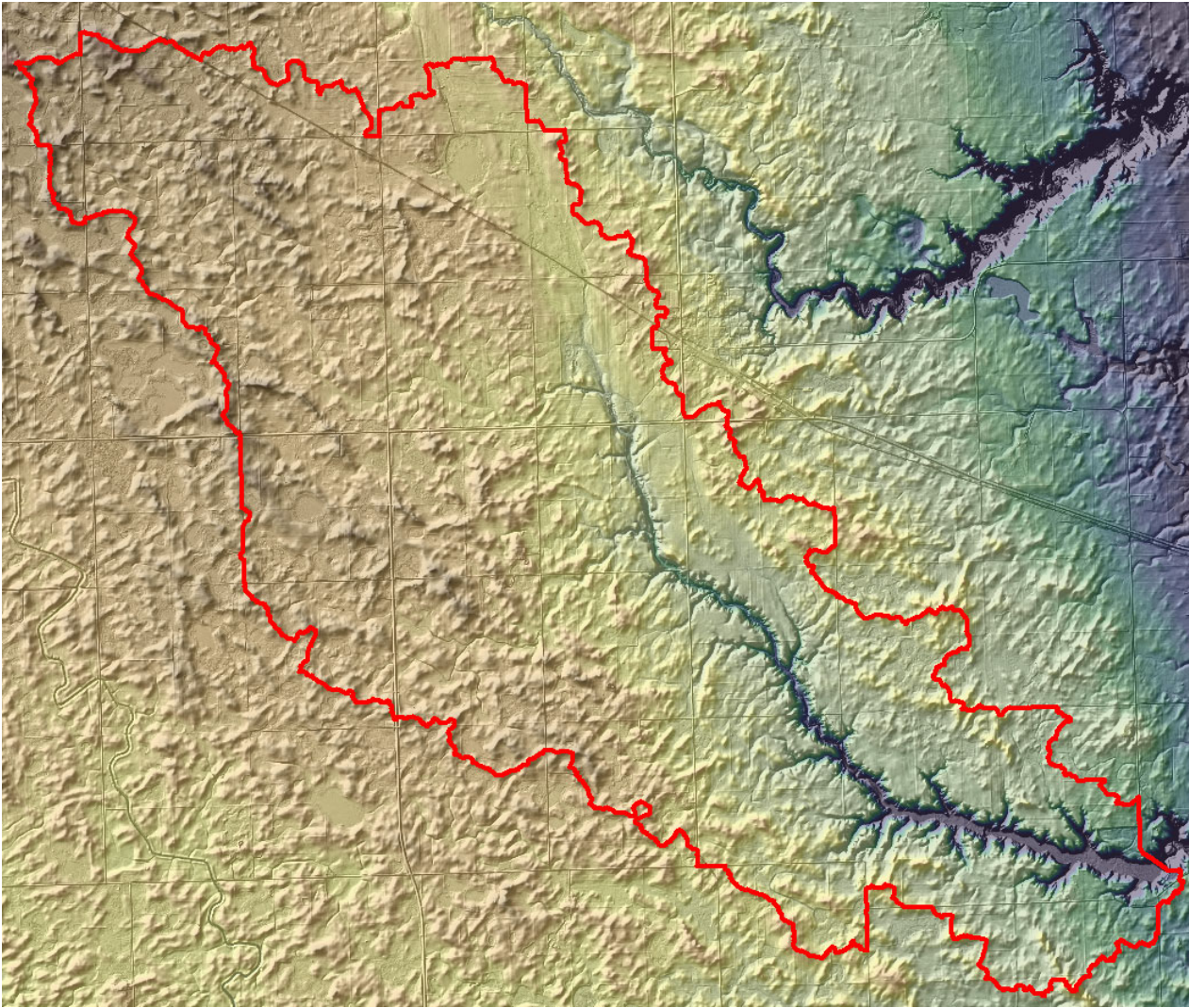
Photo From Centerline of Dam



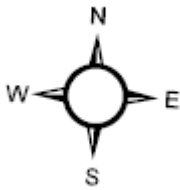
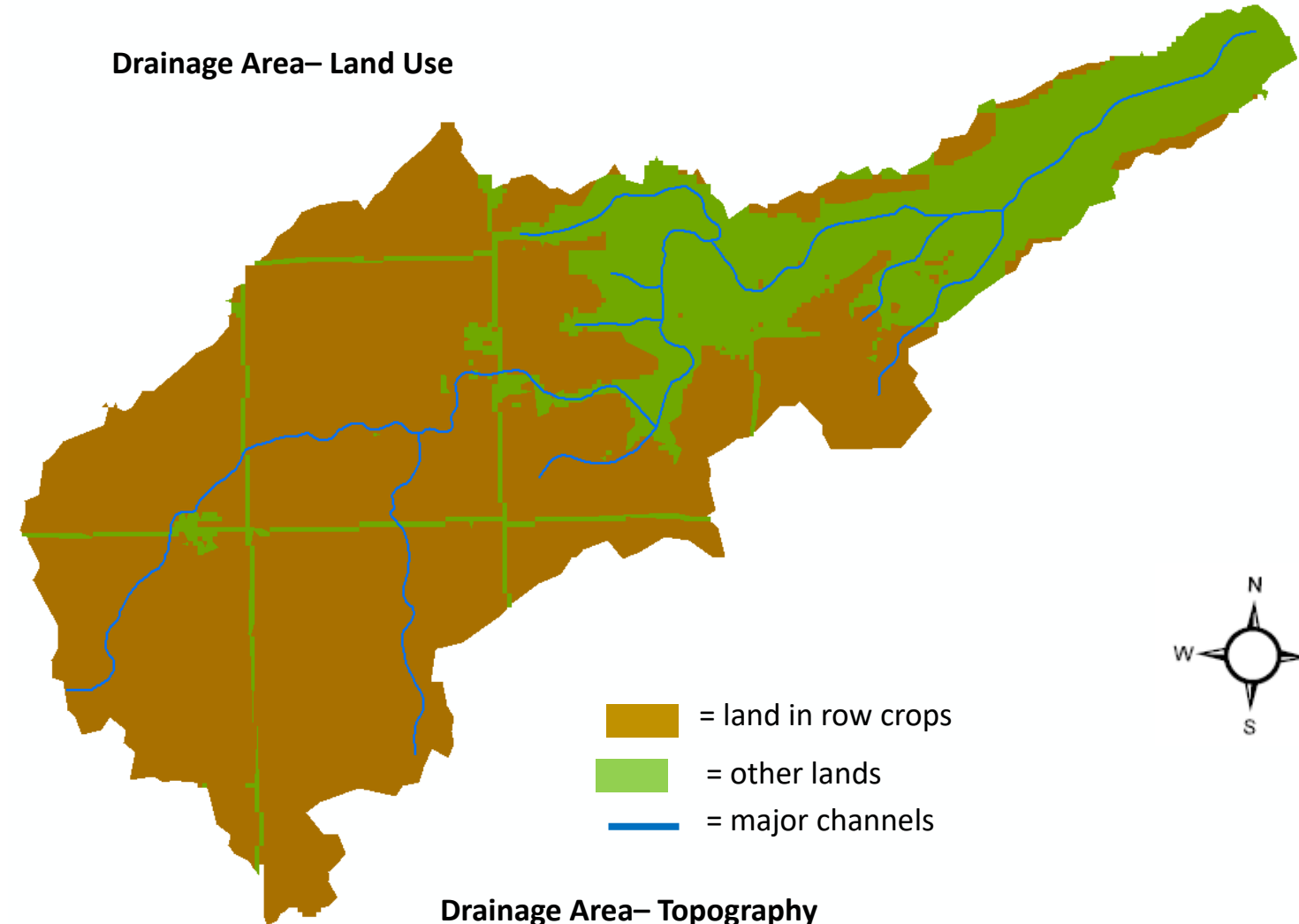
Sediment Accumulation (Depths 0-6.8 ft)



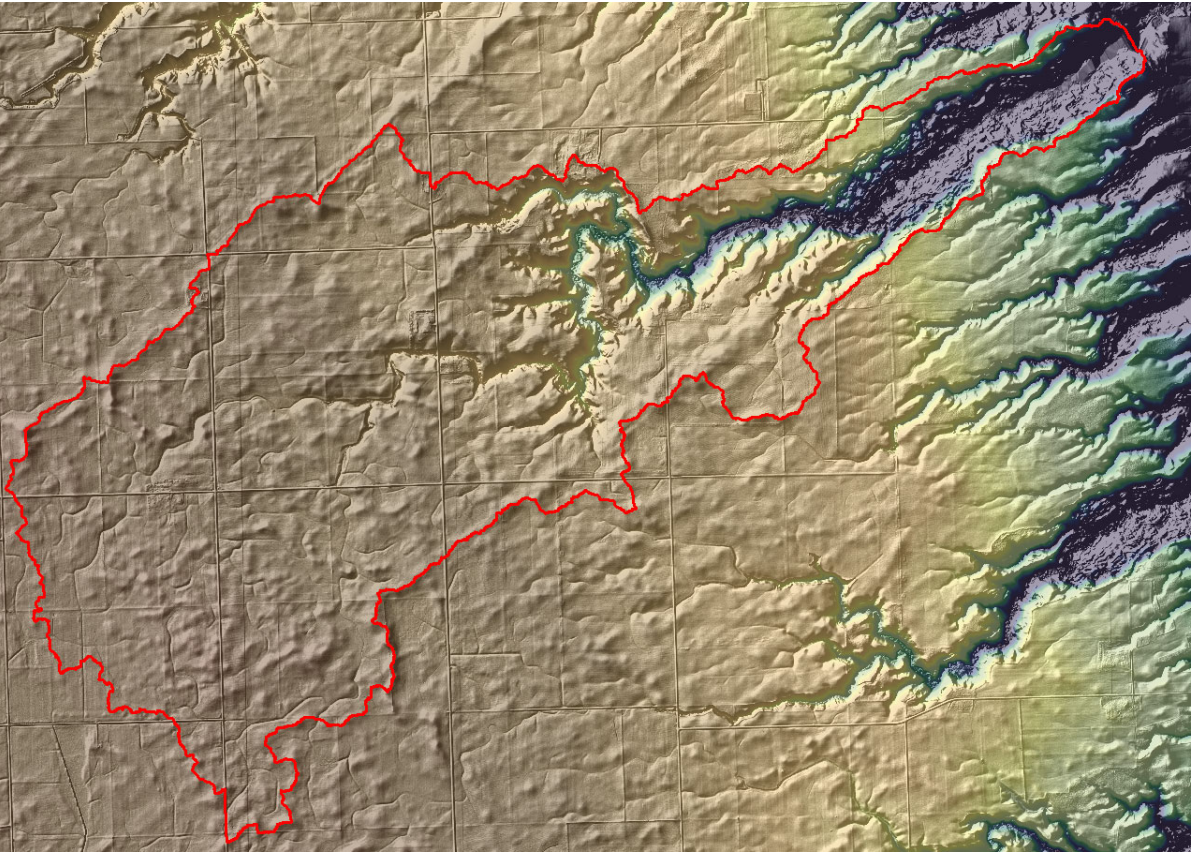
Drainage Area– Topography



Drainage Area– Land Use



Drainage Area– Topography



OLSON DAM

Sediment Accumulation (0-20 ft)

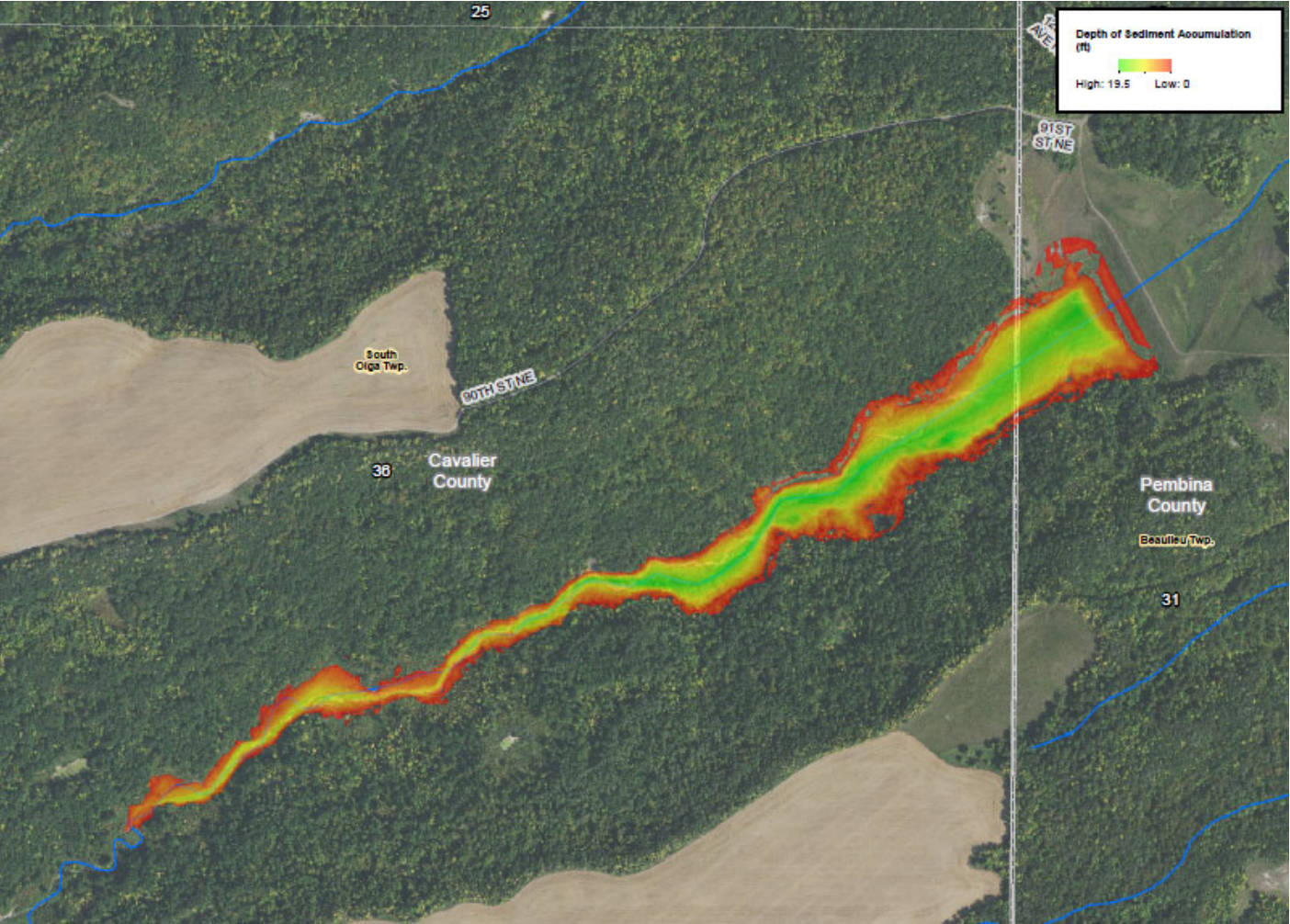


Photo From North Side of Embankment



SENATOR YOUNG DAM

50

Drainage Area— Land Use

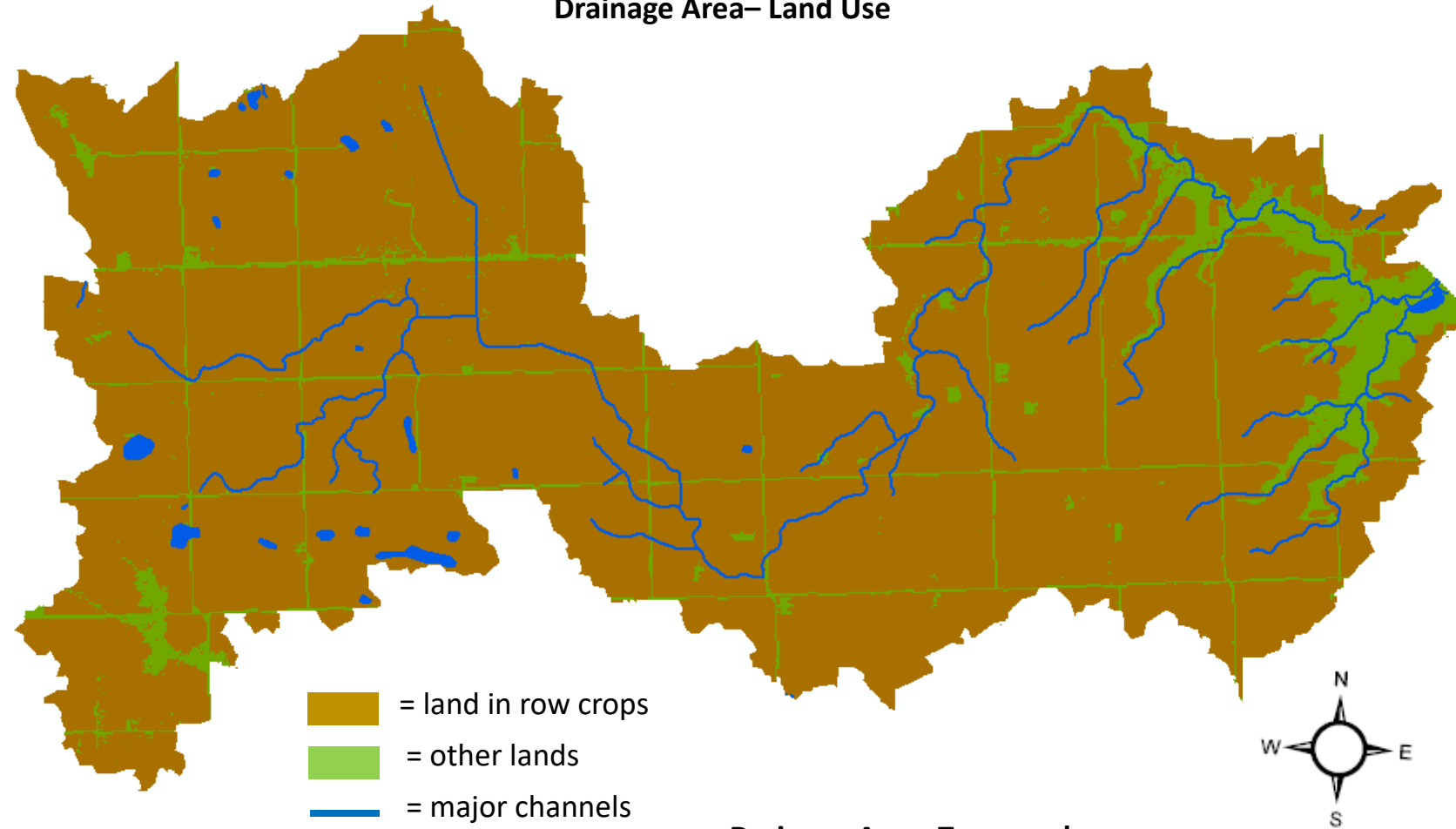
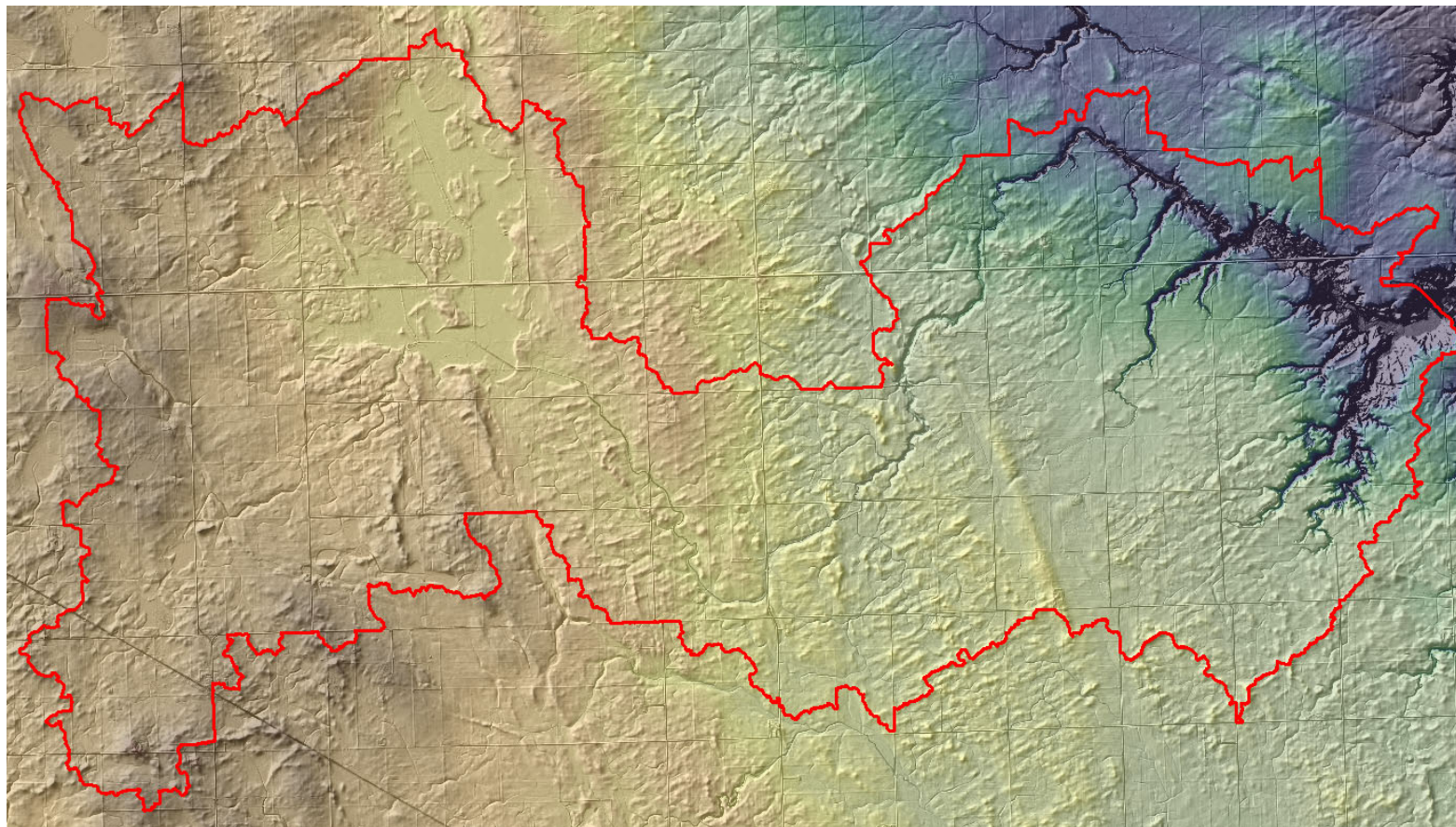


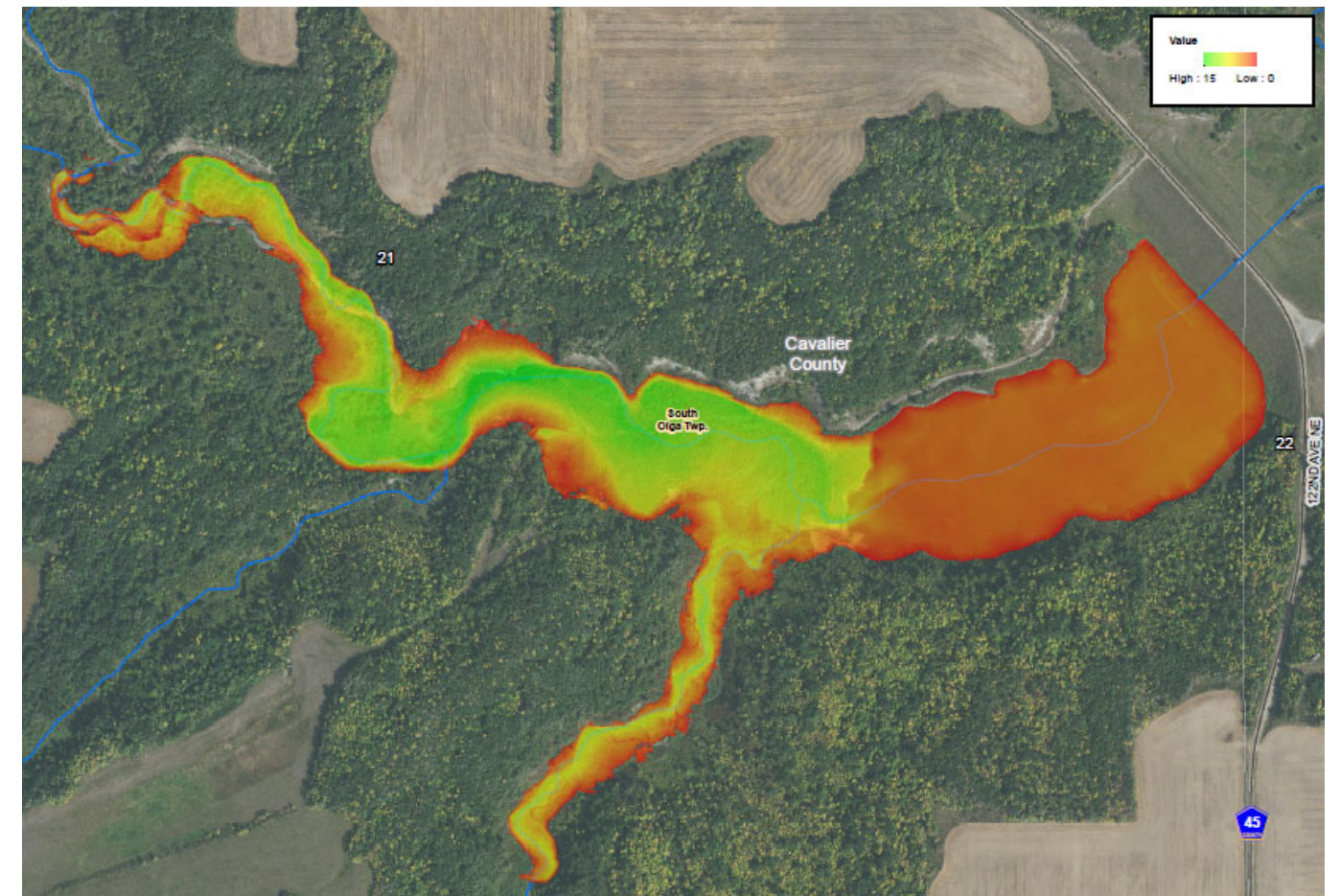
Photo From SE Corner Dam Embankment



Drainage Area- Topography

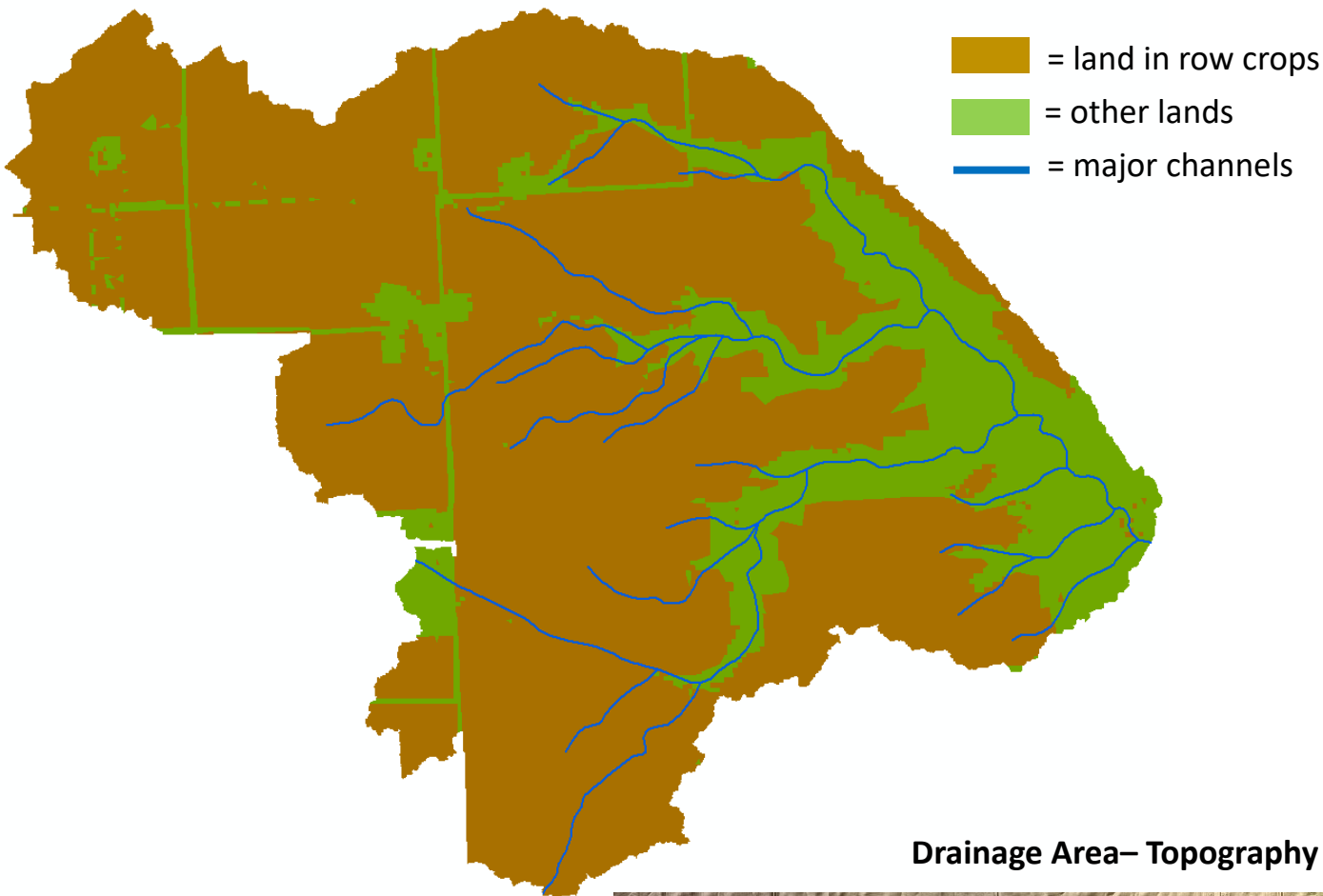


Sediment Accumulation Depths (0-15 ft)



BOURBANIS DAM

Drainage Area– Land Use



Drainage Area– Topography

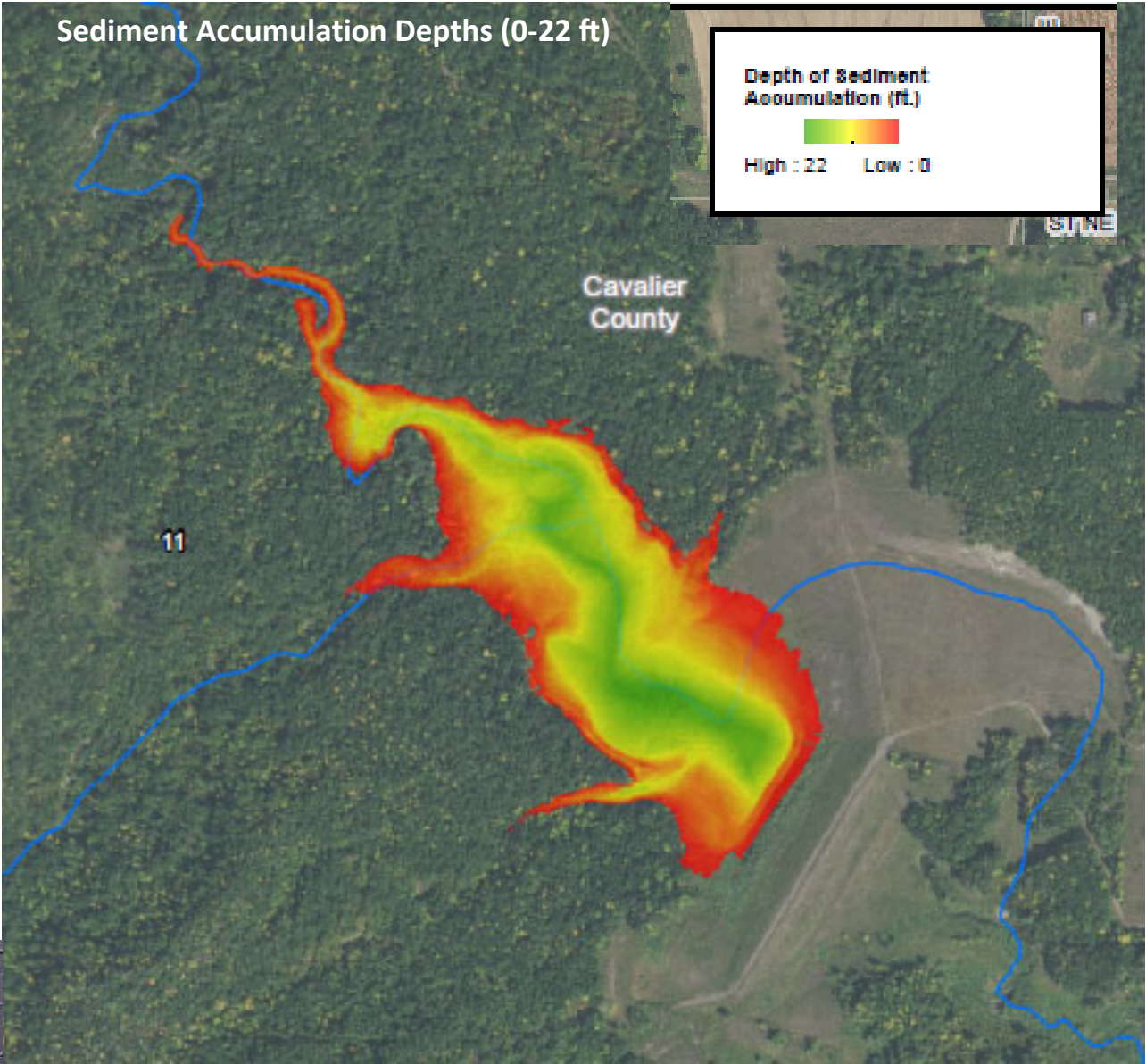
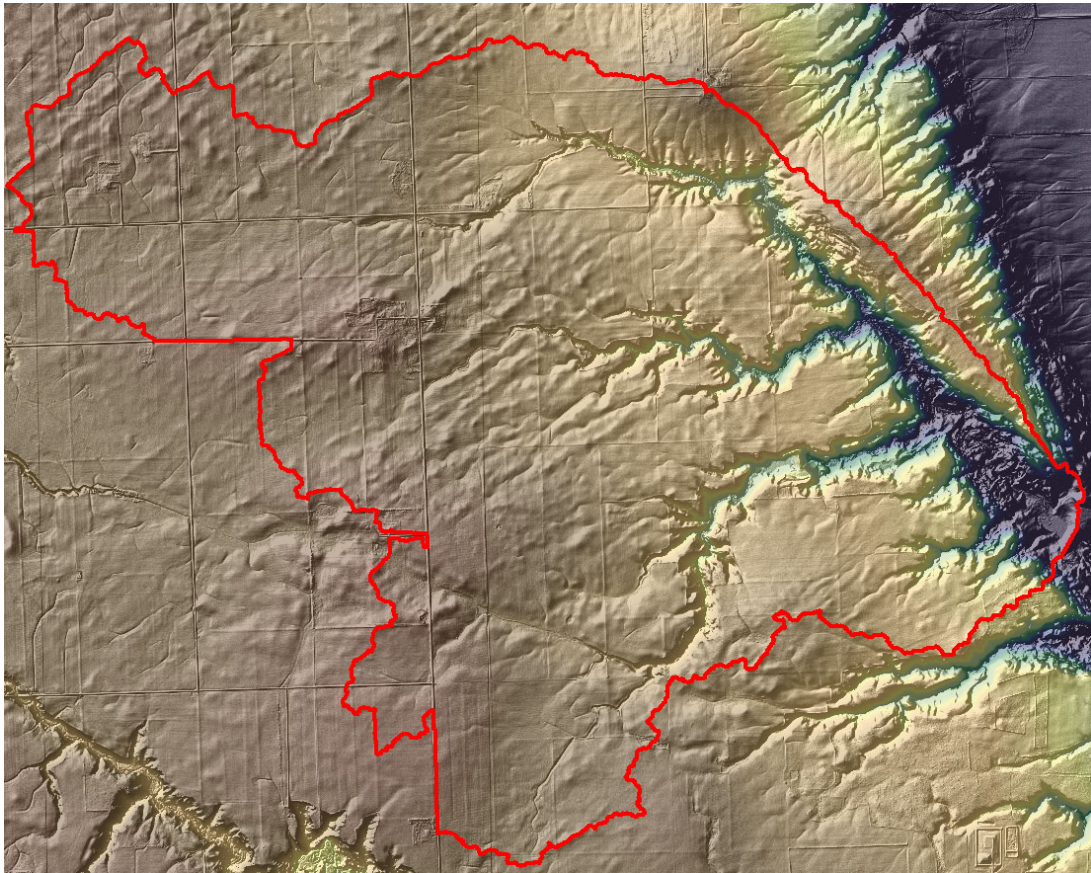


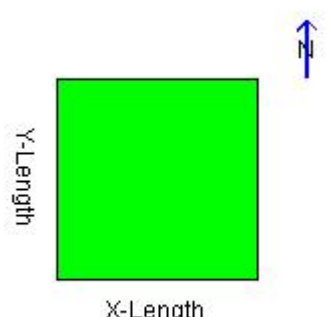
Photo From Upstream SW End of Embankment



Run Summary

F144B_2019

Run Date:	Sunday, February 20, 2022, 02:18 PM		
Client Name:	F144B_2019		
Farm No:	---	Tract No:	---
		Field No:	---
Run Location:	Project		
Management:	wheat.spr-canolaMT.man		
Soil:	Buse_F144B_27_L.ifc		

Location Site Information		
	X-Length:	1320.0 ft
	Y-Length:	1320.0 ft
	Area:	40.0 ac
	Elevation:	1550.0 ft
	Orientation:	0.00 °
	Mode:	NRCS
	Soil Loss Tolerance (T):	5.0 t/ac/yr
	Site:	UNITED STATES NORTH DAKOTA WALSH
	Location:	48.421° N, 98.079° W
	Cligen:	EDMORE 1 W
	Windgen:	Interpolated (48.36940° N, 97.72153° W)

Erosion						
Period	Crop/Residue	Gross Loss t/ac	Net Soil Loss From Field (t/ac)			
			Total Creep+Salt	Suspen.	PM10	
Rot. year: 1	Wheat, spring, grain	1.97	1.97	1.202	0.771	0.0187
Rot. year: 2	Canola, spring, grain	4.05	4.05	2.269	1.784	0.0419
Ave. Annual		3.01	3.01	1.735	1.278	0.0303

Crop Interval Erosion							
Date Range	Days	Crop	Gross Loss t/ac	Net Soil Loss From Field (t/ac)			
				Total Creep+Salt	Suspen.	PM10	
Sep 01, 02 - Aug 09, 01	342	Wheat, spring, grain	0.98	0.98	0.583	0.400	0.0094
Aug 09, 01 - Sep 01, 02	388	Canola, spring, grain	5.04	5.04	2.888	2.155	0.0522

Harvests				
Date	Crop	Residue lb/ac	Harvest Yield	Yield % Moisture
Aug 09, 01	Wheat, spring, grain	2,459	31.7 bu/ac	13.5
Sep 01, 02	Canola, spring, grain	2,887	1461.5 lbs/ac	10.0

Run Summary

53

F144B_2019

SCI Summary

Soil Conditioning Index:	-0.174	SCI Subfactors
Energy Calculator:	5.185 gal diesel/ac	OM: -0.1208
Average Annual STIR:	123.300	FO: -0.2208
Wind Erosion Soil Loss:	3.013 t/ac	ER: -0.1861
Water Erosion Soil	0.000 t/ac	

Rotation Cover/Standing Silhouette/STIR

Date	Operation	Crop (planted)	RR std dev in	Surface Cover fraction	Eff. Standing Silhouette ft ² /ft ²	STIR
Apr 19, 01	Harrow, heavy		0.40	0.248	0.000	15.60
Apr 24, 01	Drill or air seeder, hoe-chisel, 6-12 in spac., fert opnr	Wheat, spring, grain	0.44	0.171	0.000	26.65
May 24, 01	Sprayer, post emergence		0.35	0.151	0.107	0.15
Jun 24, 01	Sprayer, post emerge, fungicide		0.27	0.124	0.594	0.15
Aug 09, 01	Harvest, killing crop 50pct standing stubble		0.22	0.542	0.355	0.15
Sep 13, 01	Disk, offset, heavy		0.69	0.177	0.008	39.00
Sep 13, 01	Harrow, heavy		0.69	0.177	0.008	15.60
Apr 19, 02	Chisel, sweep shovel		0.65	0.121	0.000	45.50
Apr 19, 02	Harrow, heavy		0.65	0.121	0.000	15.60
Apr 30, 02	Drill or air seeder, hoe-chisel, 6-12 in spac., fert opnr	Canola, spring, grain	0.47	0.103	0.000	26.65
Jun 04, 02	Sprayer, post emergence		0.37	0.091	0.014	0.15
Jul 02, 02	Sprayer, post emerge, fungicide		0.30	0.077	0.085	0.15
Sep 01, 02	Harvest, killing crop 30pct standing stubble		0.24	0.766	0.054	0.15
Sep 19, 02	Chisel, sweep shovel		0.82	0.490	0.025	45.50
Sep 24, 02	Harrow, heavy		0.58	0.384	0.004	15.60
2 yr rotation (total/ac)						246.60
avg yearly (total/ac/yr)						123.30

Crop Interval STIR Energy

Date Range	Days	Crop	STIR	Energy diesel (gal)/ac	Cost USD/ac
Sep 01, 02 - Aug 09, 01	342	Wheat, spring, grain	103.800	4.778	19.12
Aug 09, 01 - Sep 01, 02	388	Canola, spring, grain	142.800	5.591	22.37

Notes

Total Above Ground Crop and Residue Biomass

F144B_2019

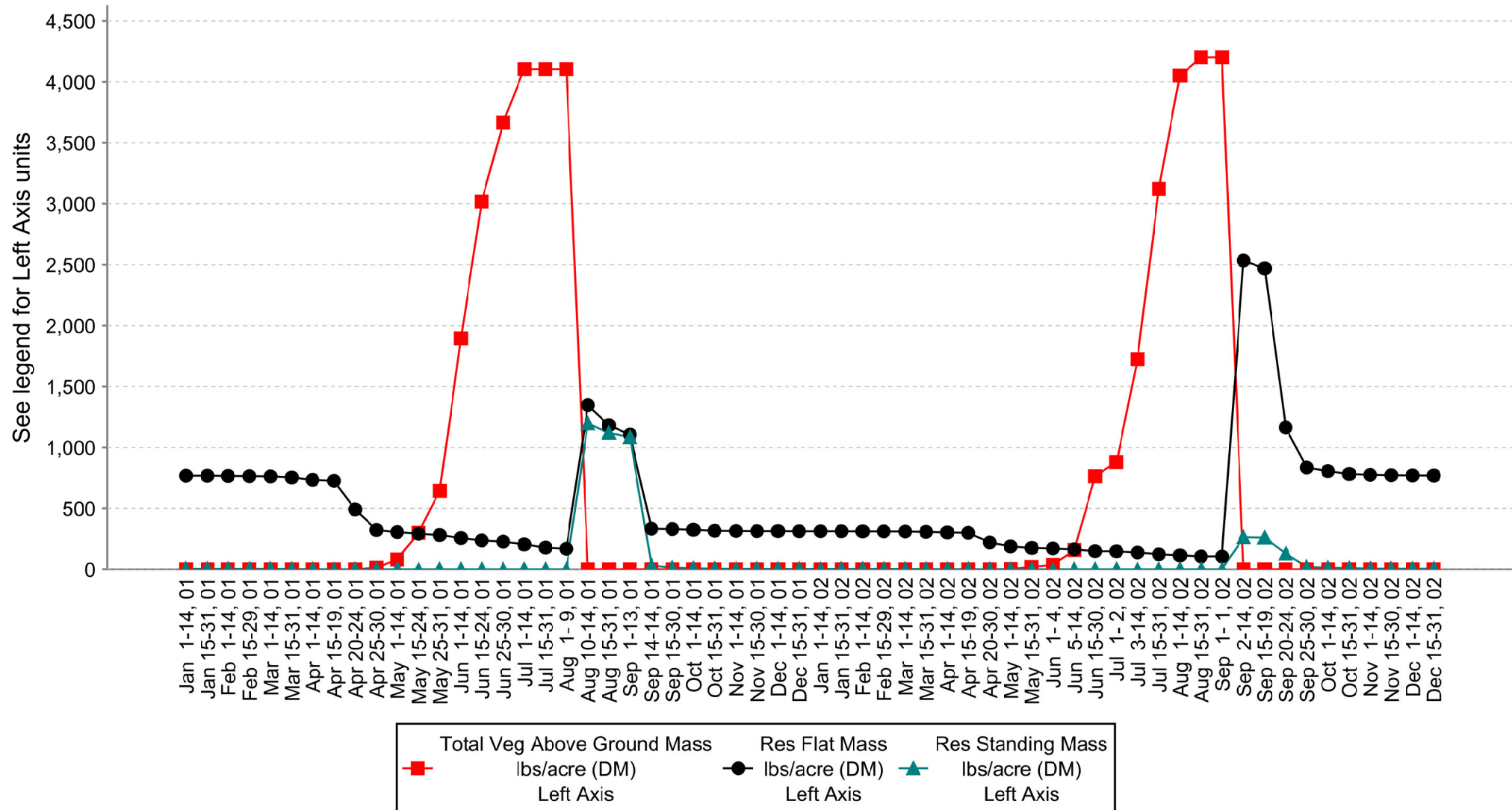


Exhibit 8-3

F144B_2019

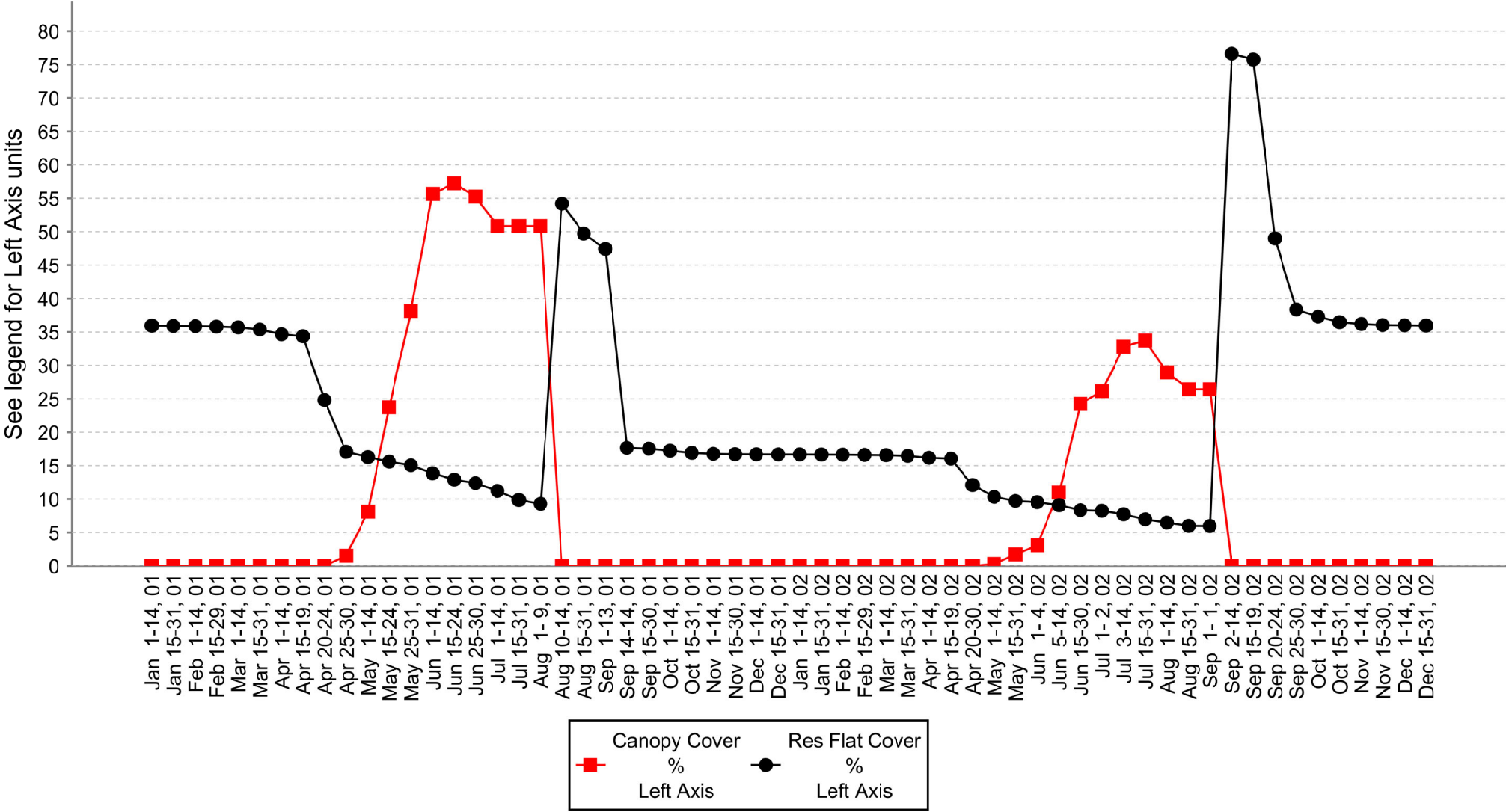
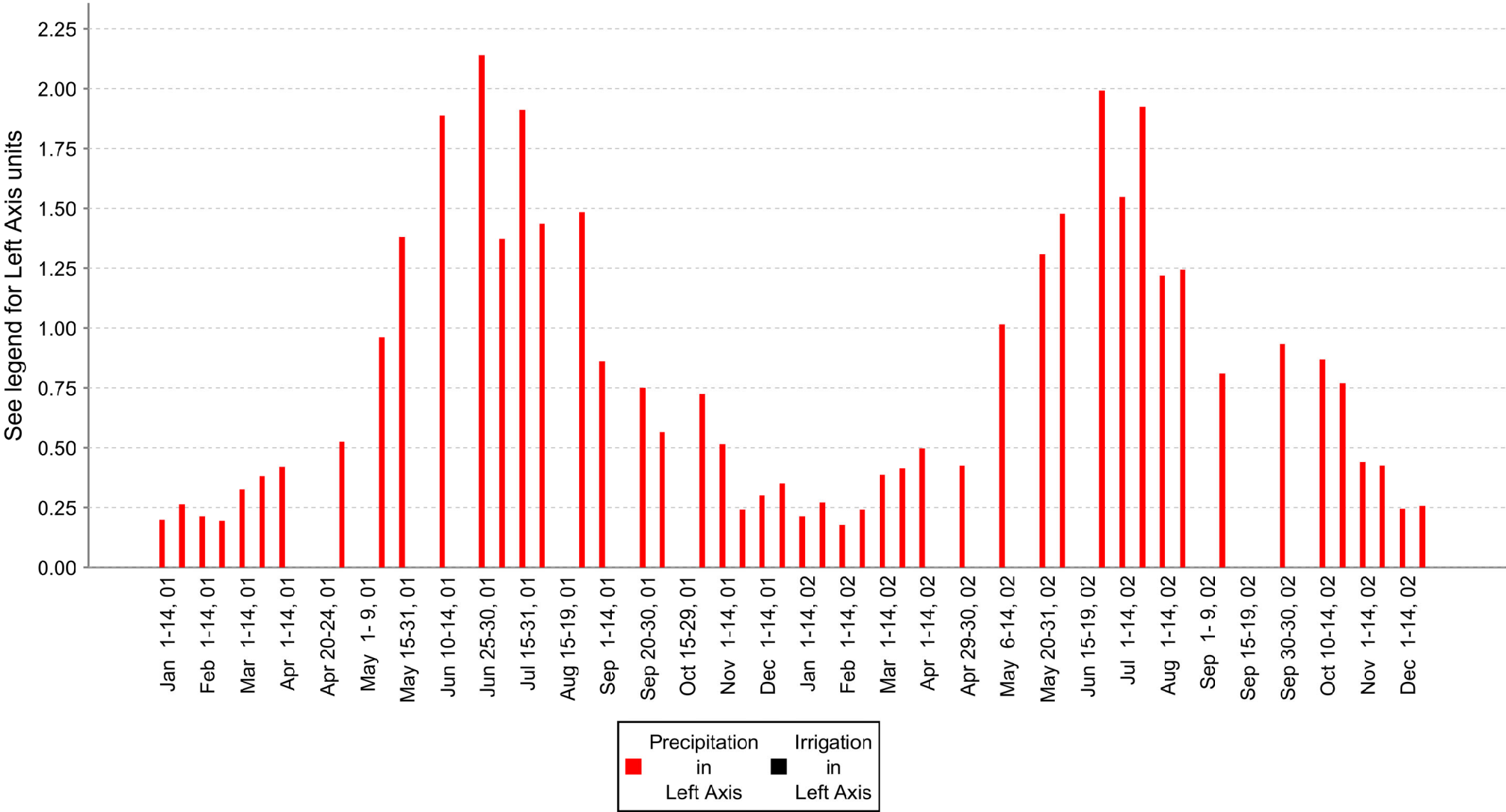


Exhibit 8-4

F144B_1960



F144B_2019

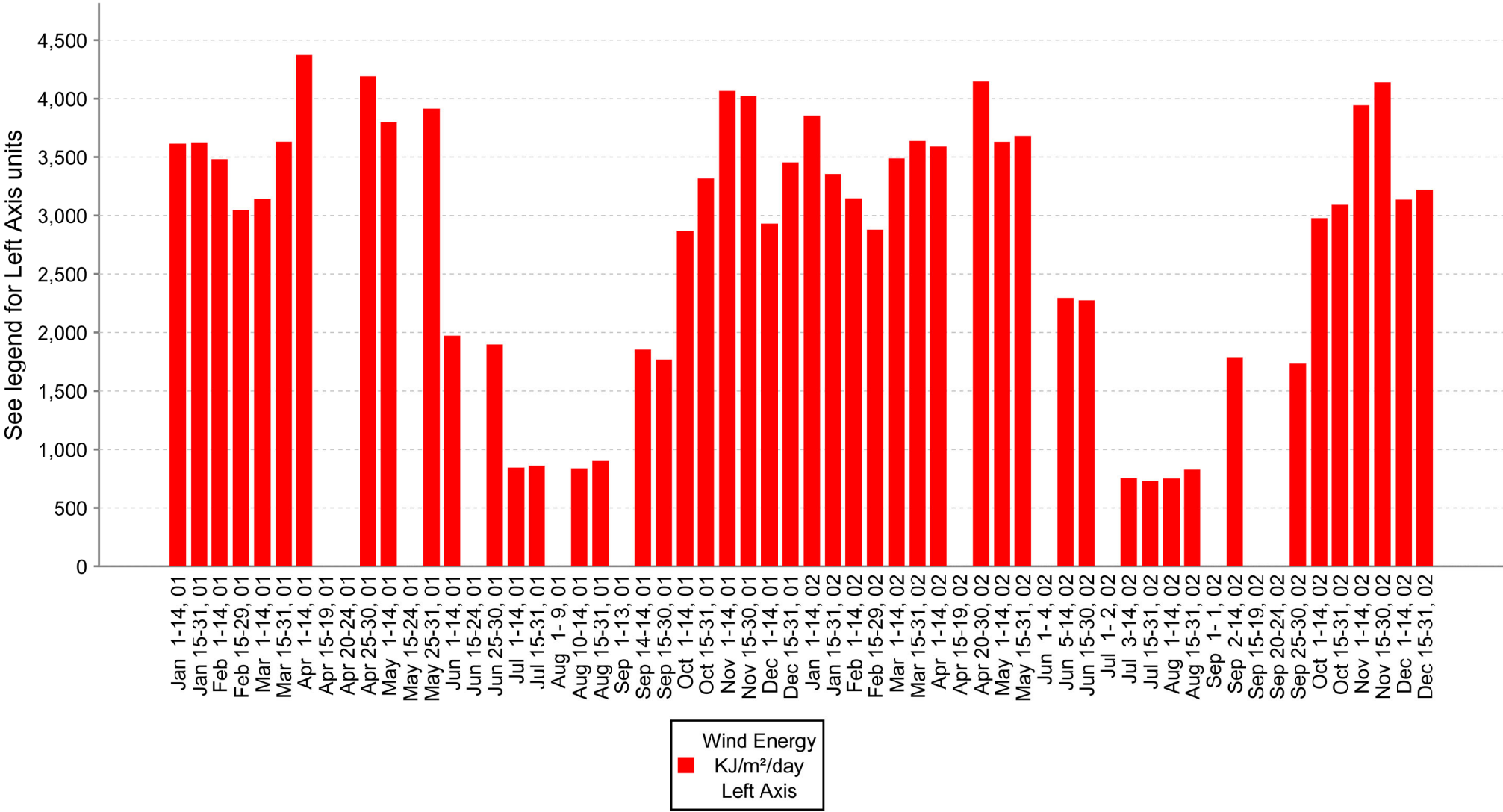


Exhibit 8-5

Total Wind Erosion Soil Loss (Gross, Net)

F144B_2019

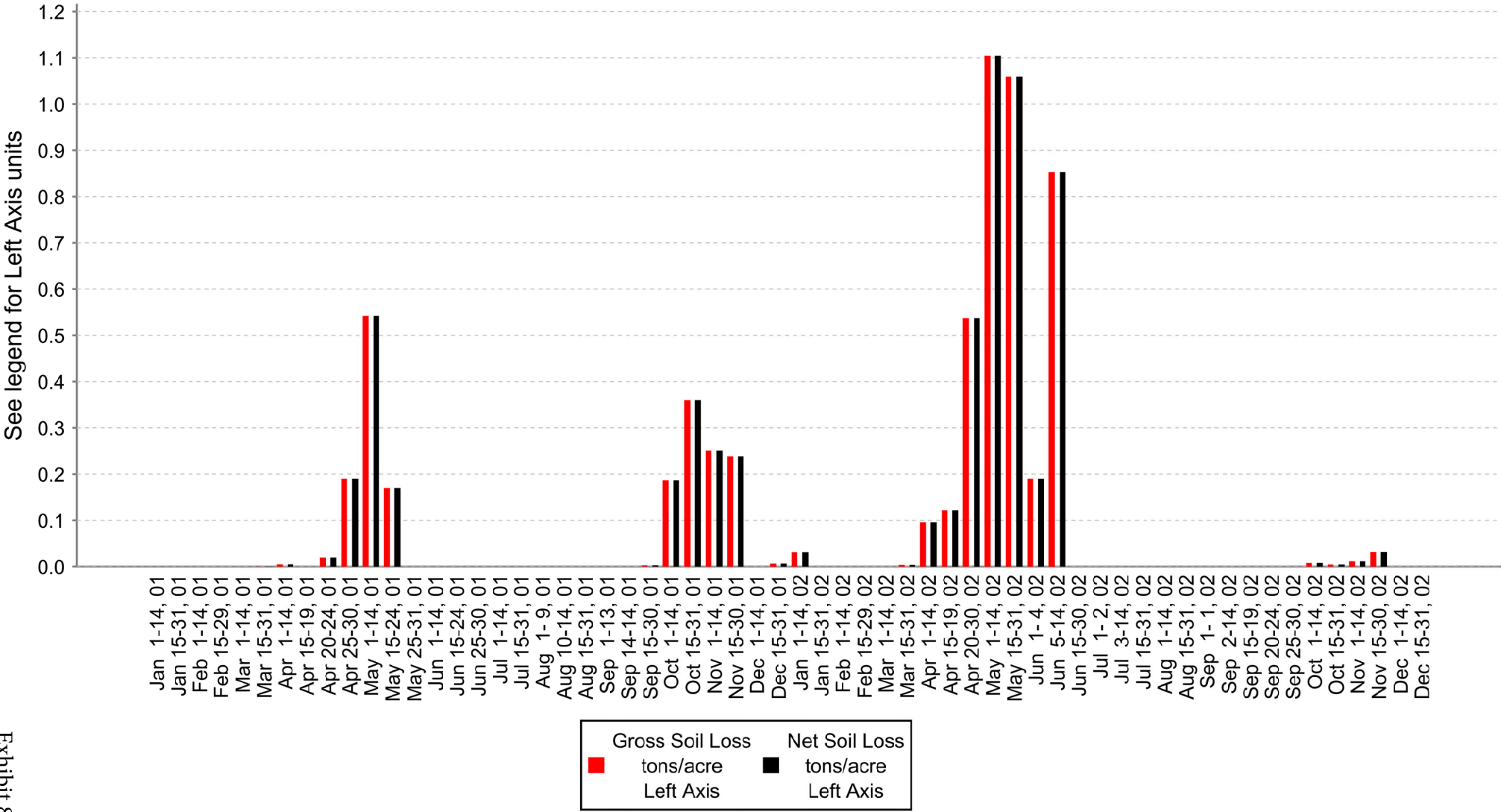
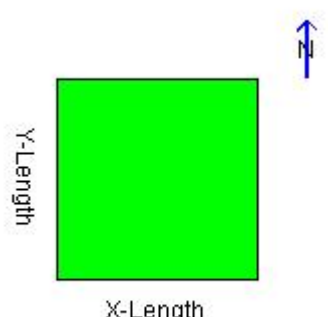


Exhibit 8-6

Run Summary

F144B_1960

Run Date:	Sunday, February 20, 2022, 02:44 PM		
Client Name:	F144B_1960		
Farm No:	---	Tract No:	---
		Field No:	---
Run Location:	Project		
Management:	Wheat, spring;flax, fall plow 1960, Z2.man		
Soil:	Buse_F144B_27_L.ifc		

Location Site Information		
	X-Length:	1320.0 ft
	Y-Length:	1320.0 ft
	Area:	40.0 ac
	Elevation:	1550.0 ft
	Orientation:	0.00 °
	Mode:	NRCS
	Soil Loss Tolerance (T):	5.0 t/ac/yr
	Site:	UNITED STATES NORTH DAKOTA WALSH
	Location:	48.421° N, 98.079° W
	Cligen:	EDMORE 1 W
	Windgen:	Interpolated (48.36940° N, 97.72153° W)

Erosion						
Period	Crop/Residue	Gross Loss t/ac	Net Soil Loss From Field (t/ac)			
			Total	Creep+Salt	Suspen.	PM10
Rot. year: 1	Wheat, spring, grain	8.94	8.94	5.065	3.873	0.0919
Rot. year: 2	Flax, grain	7.03	7.03	3.931	3.100	0.0745
Ave. Annual		7.99	7.99	4.498	3.487	0.083

Crop Interval Erosion						
Date Range	Days	Crop	Gross Loss t/ac	Net Soil Loss From Field (t/ac)		
				Total	Creep+Salt	Suspen. PM10
Sep 09, 02 - Aug 19, 01	344	Wheat, spring, grain	8.24	8.24	4.620	3.619 0.0856
Aug 19, 01 - Sep 09, 02	386	Flax, grain	7.73	7.73	4.375	3.355 0.0803

Harvests				
Date	Crop	Residue lb/ac	Harvest Yield	Yield % Moisture
Aug 19, 01	Wheat, spring, grain	3,132	41.3 bu/ac	13.5
Sep 09, 02	Flax, grain	1,441	18.4 bu/ac	9.0

Run Summary

60

F144B_1960

SCI Summary

Soil Conditioning Index:	-0.853	SCI Subfactors
Energy Calculator:	6.592 gal diesel/ac	OM: -0.307
Average Annual STIR:	177.196	FO: -0.7544
Wind Erosion Soil Loss:	7.985 t/ac	ER: -2.1437
Water Erosion Soil	0.000 t/ac	

Rotation Cover/Standing Silhouette/STIR

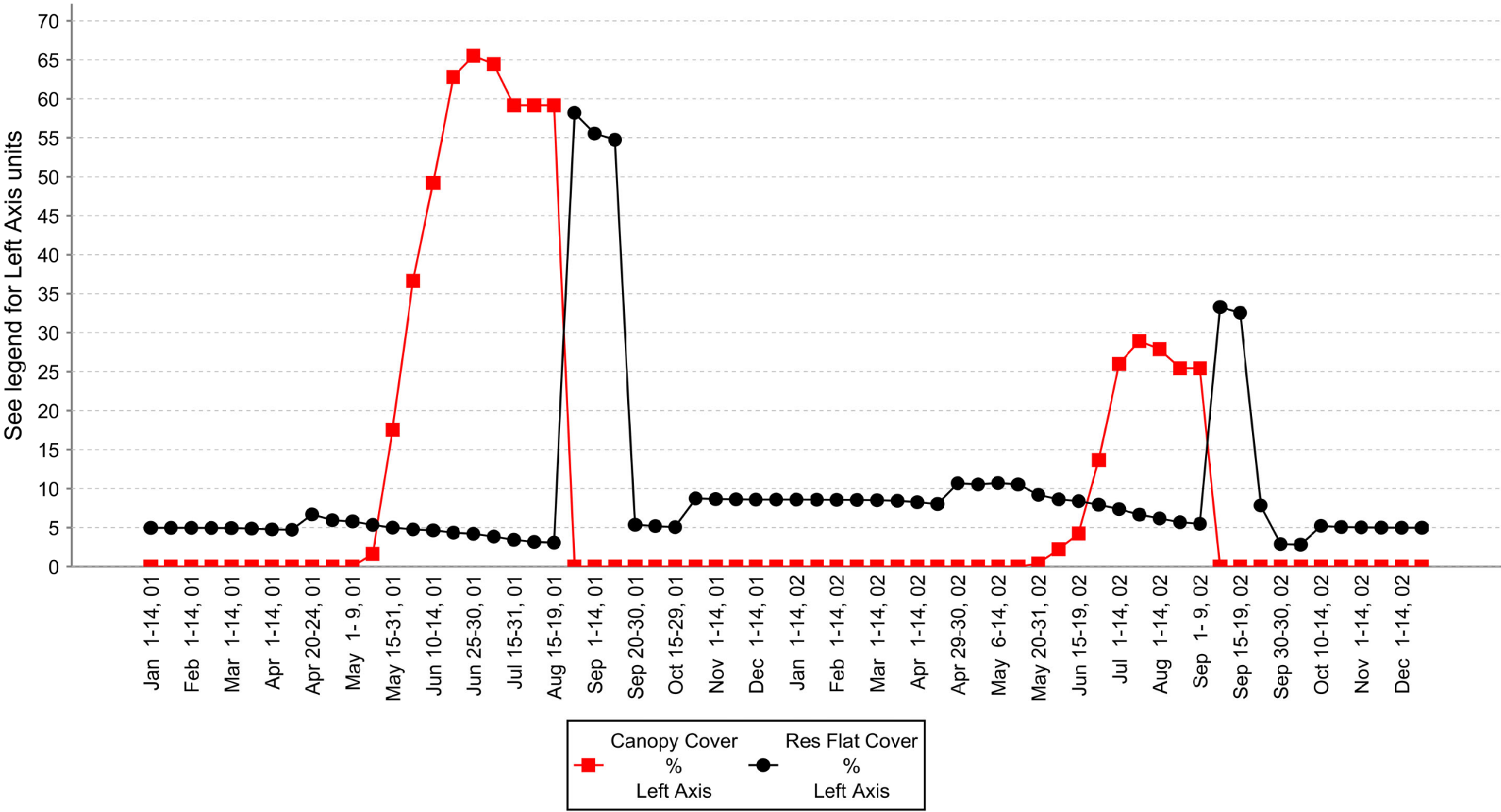
Date	Operation	Crop (planted)	RR std dev in	Surface Cover fraction	Eff. Standing Silhouette ft ² /ft ²	STIR
Apr 19, 01	Cultivator, field 6-12 in sweeps		0.50	0.067	0.000	26.00
Apr 24, 01	Cultivator, field 6-12 in sweeps		0.42	0.059	0.000	26.00
Apr 24, 01	Harrow, coiled tine		0.42	0.059	0.000	15.60
May 09, 01	Drill or air seeder, double disk	Wheat, spring, grain	0.34	0.053	0.000	6.34
Jun 09, 01	Sprayer, post emergence		0.26	0.046	0.174	0.15
Jun 24, 01	Sprayer, post emerge, fungicide		0.22	0.042	0.500	0.15
Aug 19, 01	Harvest, killing crop 50pct standing stubble		0.16	0.582	0.457	0.15
Sep 19, 01	Plow, moldboard, 6 to 12 inch deep		1.07	0.054	0.000	65.00
Oct 29, 01	Chisel, sweep shovel		0.93	0.087	0.000	45.50
Apr 28, 02	Cultivator, field 6-12 in sweeps		0.58	0.107	0.000	26.00
May 05, 02	Fert applic. surface broadcast		0.47	0.107	0.000	0.06
May 05, 02	Sprayer, pre-emergence		0.47	0.107	0.000	0.15
May 05, 02	Cultivator, field 6-12 in sweeps		0.36	0.092	0.000	26.00
May 19, 02	Drill or air seeder, double disk	Flax, grain	0.27	0.079	0.028	6.34
Jun 19, 02	Sprayer, post emergence		0.19	0.333	0.264	0.15
Sep 09, 02	Harvest, killing crop 50pct standing stubble		0.18	0.078	0.230	0.15
Sep 19, 02	Remove residue, bale 75 percent		1.18	0.029	0.000	0.15
Sep 29, 02	Plow, moldboard, 6 to 12 inch deep		0.80	0.052	0.000	65.00
Oct 09, 02	Chisel, sweep shovel					45.50
2 yr rotation (total/ac)						354.39
avg yearly (total/ac/yr)						177.20

Crop Interval STIR Energy

Date Range	Days	Crop	STIR	Energy diesel (gal)/ac	Cost USD/ac
Sep 09, 02 - Aug 19, 01	344	Wheat, spring, grain	185.040	6.905	27.63
Aug 19, 01 - Sep 09, 02	386	Flax, grain	169.350	6.280	25.13

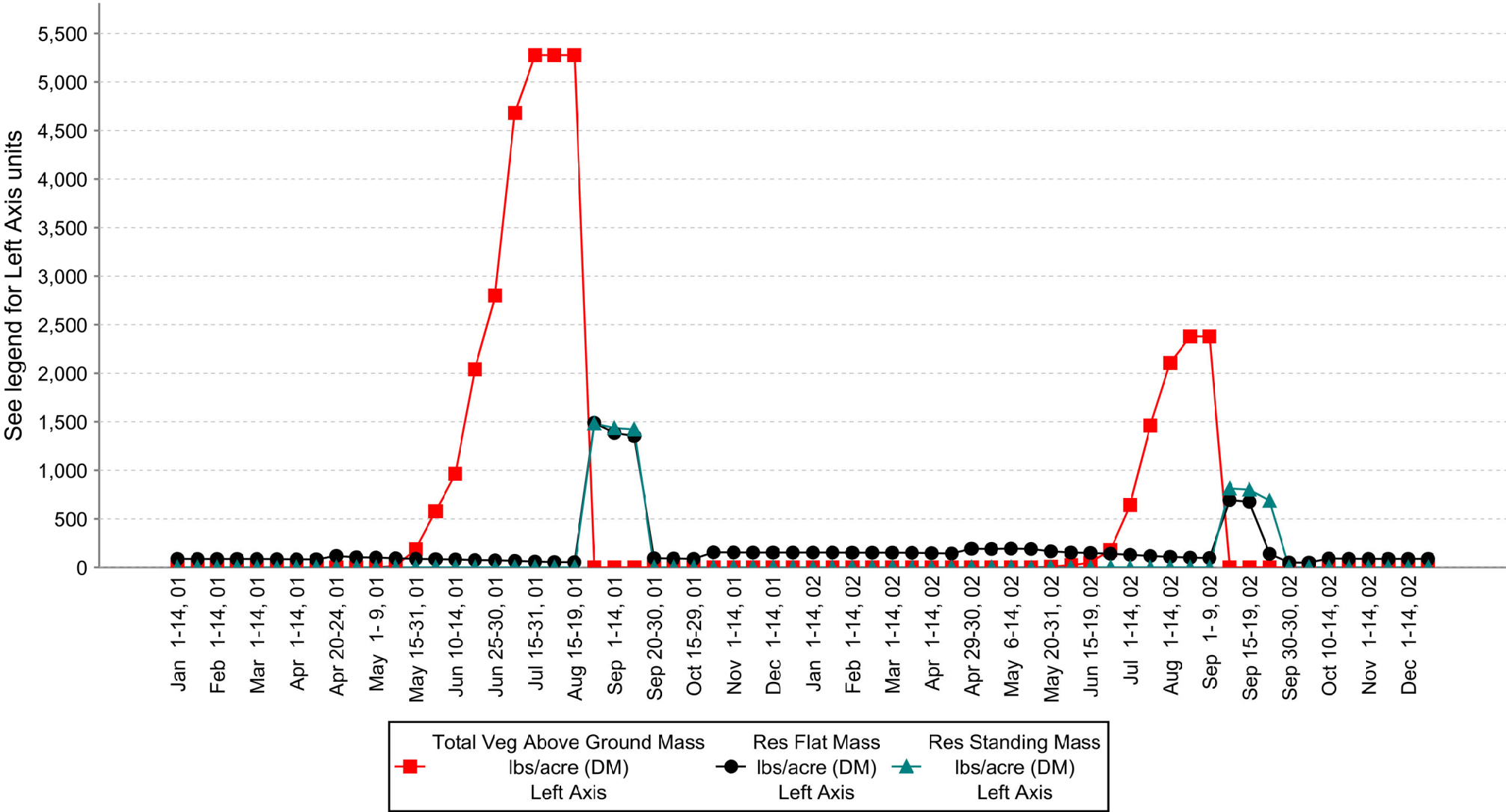
Canopy and Residue Cover

F144B_1960



Total Above Ground Crop and Residue Biomass

F144B_1960



Wind Erosion Soil Loss (Creep+Salt, Susp)

F144B_1960

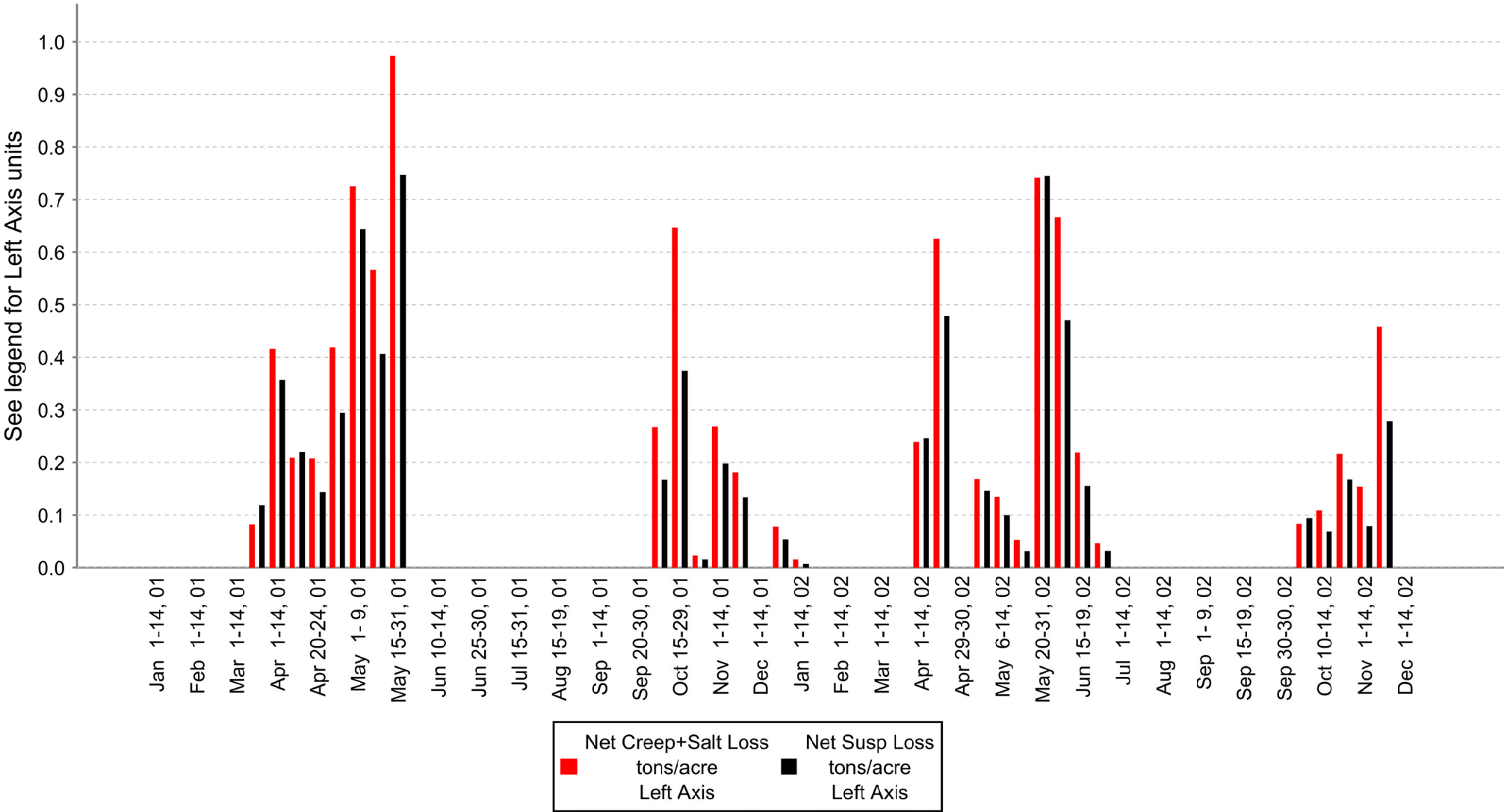
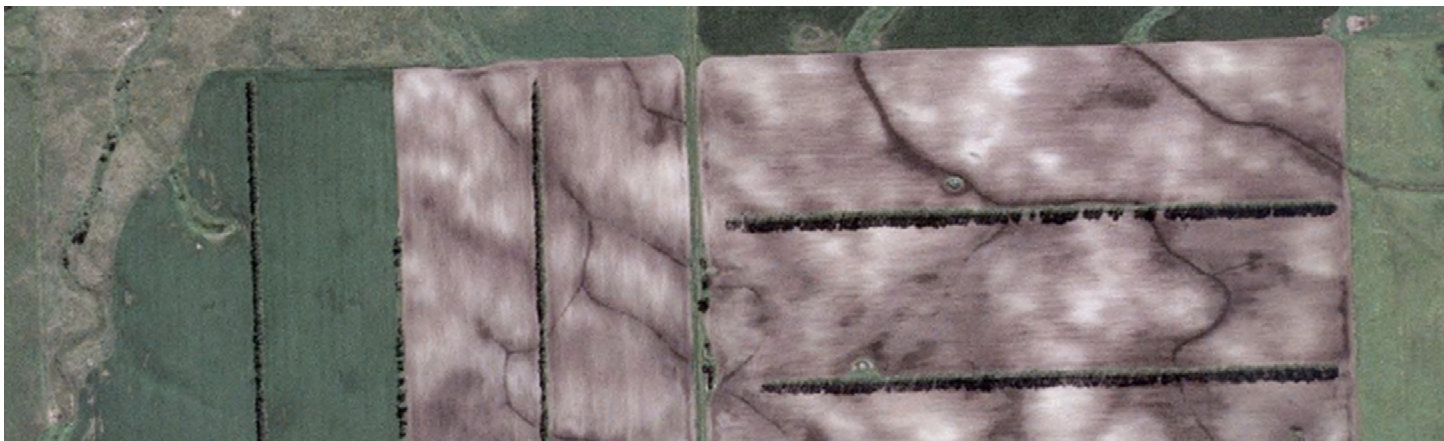


Exhibit 9 -Wind Erosion Prediction System Results, By Soil Map Unit, By Dam Drainage Area

Dam	Soil MU	Acreage	%	2019 Total Wind (tons/ac/yr)	2019 Creep&Salt (tons/yr)	1960 Total Wind (tons/ac/yr)	1960 Creep&Salt (tons/yr)
Senator Young	F100A	5,275	19%	3.07	1.75	8.25	4.72
	F143A	4,285	15%	2.67	1.55	8.00	4.44
	F125A	3,589	13%	3.08	1.80	9.18	5.13
	F122A	3,387	12%	2.59	1.52	8.04	4.52
	F119A	2,598	9%	3.05	1.81	9.44	5.42
	F143B	2,095	8%	2.75	1.59	7.88	4.39
	Avg	21,230	76%	2.87	1.67	8.47	4.77
Olson	F122A	487	17%	2.59	1.52	8.04	4.52
	F143A	468	16%	2.67	1.55	8.00	4.44
	F100A	466	16%	3.07	1.75	8.25	4.72
	F143B	457	16%	2.75	1.59	7.88	4.39
	F154B	253	9%	0.89	0.51	3.16	1.83
	F125A	171	6%	3.08	1.80	9.18	5.13
	Avg	2,302	79%	2.51	1.46	7.42	4.17
Bourbanis	F125A	805	19%	3.08	1.80	9.18	5.13
	F143A	745	17%	2.67	1.55	8.00	4.44
	F122A	645	15%	2.59	1.52	8.04	4.52
	F143B	385	9%	2.75	1.59	7.88	4.39
	F203A	363	8%	0.82	0.46	2.64	1.51
	F203B	219	5%	2.68	1.50	6.75	3.67
	Avg	3,163	74%	2.43	1.40	7.08	3.94
Bylin	F144B	1,826	20%	2.75	1.59	7.88	4.39
	F143A	1,664	18%	2.67	1.55	8.00	4.44
	F143B	1,625	18%	2.75	1.59	7.88	4.39
	F101A	1,517	17%	3.07	1.75	8.25	4.72
	Avg	6,632	73%	2.73	1.57	7.64	4.26
Matecjek	F144B	4,610	27%	2.75	1.59	7.88	4.39
	F167B	3,554	21%	2.95	1.68	8.10	4.61
	F101A	1,993	12%	3.07	1.75	8.25	4.72
	F143B	1,521	9%	2.75	1.59	7.88	4.39
	F143C	1,051	6%	2.71	1.57	7.78	4.33
	Avg	12,729	74%	2.85	1.64	7.98	4.49
Fordville	F144B	5,804	26%	2.75	1.59	7.88	4.39
	G144B	1,974	9%	2.69	1.60	10.17	5.78
	F122B	1,638	7%	2.63	1.56	9.52	5.43
	F143C	1,223	5%	2.71	1.57	7.78	4.33
	F122A	1,071	5%	2.59	1.52	8.04	4.52
	F100A	1,028	5%	3.07	1.75	8.25	4.72
	I163A	992	4%	2.91	1.75	11.30	6.56
	G122A	938	4%	2.67	1.58	11.20	6.37
	F12A	647	3%	0.86	0.46	3.12	1.51
	G122B	634	3%	2.63	1.56	9.52	5.43
	Avg	15,949	70%	2.55	1.49	8.68	4.90

Field windbreaks, wind protection 300 ft for cropland both sides



Natural forest bordering cropland, effective protection for 300 ft one side. <300 ft wide only a single line



Farmstead shelterbelts, only lengths bordering cropland were digitized. Protection for 300 ft, 1 side.



Newly planted field windbreak, crowns not yet developed therefore not digitized

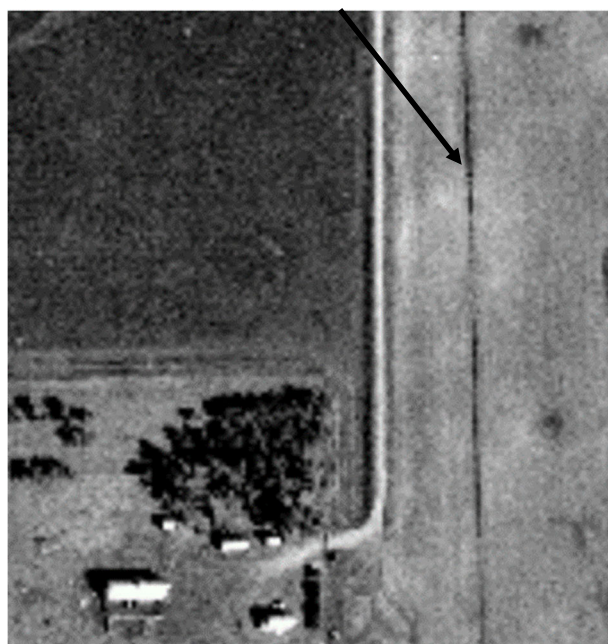


Exhibit 11 -Wind Protection Digitizing Results

Year	Field Windbreaks (ft)	Field Adjacent Shelterbelts (ft)	Field Adjacent Forest (ft)	Total Wind Protected Area (ac)	Wind Protected Area-Time Weighted Avg (ac)
Bourbanis Dam					
1962	7,774	13,601	40,161	339	343
2003	9,599	15,721	40,290	379	
2019	780	13,294	40,290	241	
Senator Young Dam					
1962	21,495	50,059	46,539	801	973
2003	48,183	50,997	42,223	1,160	
2019	27,802	35,210	48,150	791	
Olson Dam					
1962	8,110	5,050	5,996	167	183
2003	12,062	6,554	5,996	232	
2019	1,186	5,736	5,509	75	
Bylin Dam					
1962	1,802	24,073	0	191	839
2003	77,855	34,390	0	1,309	
2019	44,136	29,046	0	808	
Matecjek Dam					
1962	2,481	12,844	34,424	241	1,307
2003	110,685	40,925	28,512	1,905	
2019	102,036	41,139	30,940	1,795	
Fordville Dam					
1962	13,517	28,777	47,421	548	1,641
2003	111,344	63,515	42,779	2,118	
2019	105,315	65,179	49,527	2,070	

Wind Protected Area As Percent of Cropland

Dam	Time Weighted Average Wind Protection	1962 Percent Cropland with Wind Protection	2003 Percent Cropland with Wind Protection	2020 Percent Cropland with Wind Protection	Wind Erosion Delivered (tons/sqmi/yr)
Senator Young	3%	3%	4%	3%	106
Olson	6%	6%	8%	3%	472
Bourbanis	8%	8%	9%	6%	258
Bylin	9%	2%	14%	9%	105
Matecjek	8%	1%	11%	10%	0
Fordville	7%	2%	9%	9%	311