Water Storage: A Planning and Decision Support Framework

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Contents

This paper was developed by an interagency workgroup under the auspices of the Climate Subcabinet, Natural and Working Lands Team and Resiliency and Adaptation Team.

Coordinators: Bob Patton (MDA) and Suzanne Rhees (BWSR). Workgroup members: Mark Dittrich, Jeppe Kjaersgaard (MDA), Matt Drewitz, Henry Van Offelen, Rita Weaver (BWSR), Tim Gieseke (DNR); David Wall (MPCA). Primary Authors: Rhees, Van Offelen, Wall.

Introduction

Climate change is affecting watershed hydrology across Minnesota, resulting in an increased need for and interest in water storage. More frequent and intense rainfall events are resulting in negative impacts to agriculture and infrastructure, significant erosion along watercourses, and degraded water quality. This paper presents a process and decision support framework that watershed partners can use to identify and prioritize water storage options/potential across the landscape to meet their goals. The step-by-step approach can be an effective way to help users evaluate a variety of storage strategies to meet local and regional needs. The storage strategies selected will differ depending on the issue or problem to be solved.

Purpose of this Document

This framework is intended to provide guidance for local water planners and other local government partnerships in setting goals for water storage and identifying and evaluating the type and amount of storage that will best achieve those goals, while taking watershed hydrology, land use and natural resources into consideration. Potential audiences and purposes include, but are not limited to:

- Watershed planning partnerships engaged in the One Watershed, One Plan process or in implementation of adopted comprehensive watershed management plans
- Soil and Water Conservation Districts (SWCDs) engaged in water management
- Watershed Districts, both metropolitan and non-metropolitan, engaged in management of stormwater, agricultural erosion, and stream ecology
- Drainage authorities with an interest in keeping drainage systems functional and managing downstream impacts
- City or county governments with an interest in reducing flood damage and protecting infrastructure
- Engineers, consultants, and non-governmental organizations engaged with water storage

One specific application of this paper relates to a new initiative: in 2021, the Minnesota Legislature directed BWSR to establish a water storage assistance program:

> The board must establish a program to provide financial assistance to local units of government to control water volume and rates to protect infrastructure, improve water quality and related public benefits, and mitigate climate change impacts.[1]

The legislation also defines the practices considered as “water quality and storage practices”:

> (d) "Water quality and storage practices" means those practices that sustain or improve water quality via surface water rate and volume and ecological management, including but not limited to:
>
> (1) retention structures and basins;

[1] Minn. Laws 2021, 1st Special Session, Chap. 6, art. 2, sec. 80 (Minn. Stats. §103F.05)

(2) acquisition of flowage rights;

(3) soil and substrate infiltration;

(4) wetland restoration, creation, or enhancement;

(5) channel restoration or enhancement; and

(6) floodplain restoration or enhancement.

This paper can be used to provide guidance to local governments considering water storage projects under this program.

"For the agriculture-dominated watersheds like the Minnesota River watershed, achieving state water quality standards for nutrients and sediment will require investment in water storage that increases infiltration, removes nitrate, and reduces runoff volume contributing to high river flows and bluff erosion." *State Water Plan: Water and Climate*, 2020.

Why Is Water Storage Needed?

Annual precipitation has increased in many Minnesota watersheds in recent decades due to climate change. Long-term observation sites have seen dramatic increases in 1-inch rains, 3-inch rains, and the size of the heaviest rainfall of the year. These changes in precipitation result in increased stream flow. Other factors amplifying these changes include a loss of available storage due to historical large-scale wetland drainage, loss of native vegetation, and changes in cropping patterns. Loss of storage can reduce evapotranspiration, increase peak flow volumes, increase annual runoff, create flashier stream flows, accelerate channel erosion, and increase risks of flood damage.

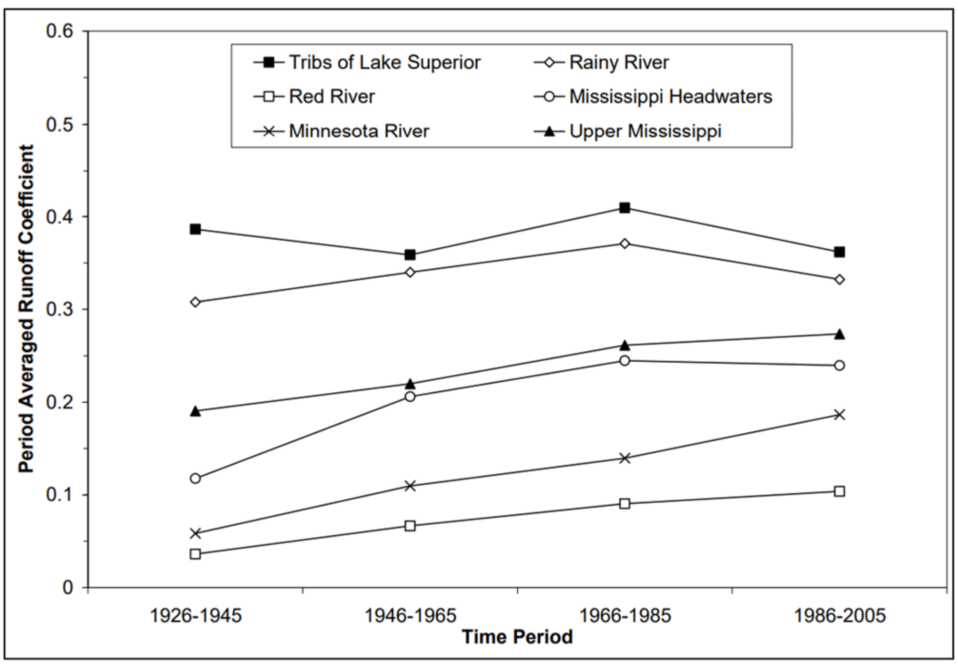

Fig. 1. Changes in runoff coefficients in all MN river basins. Runoff coefficients are ratios of the volume of runoff to the volume of precipitation in the same time period; an increase in the coefficient shows that more runoff is occurring relative to precipitation in the basin. The Red River, Minnesota River, Mississippi Headwaters, and Upper Mississippi river basins have observed substantial increases in runoff per unit precipitation during the 20th century. Source: Vandegraft & Stefan, 2010.

Figure 2 illustrates the increase in above-normal stream flows in the past 10-year period (2010-2019) compared to the previous one (2000-2009). The losses and changes to water storage have made the landscape less resilient to these increases.

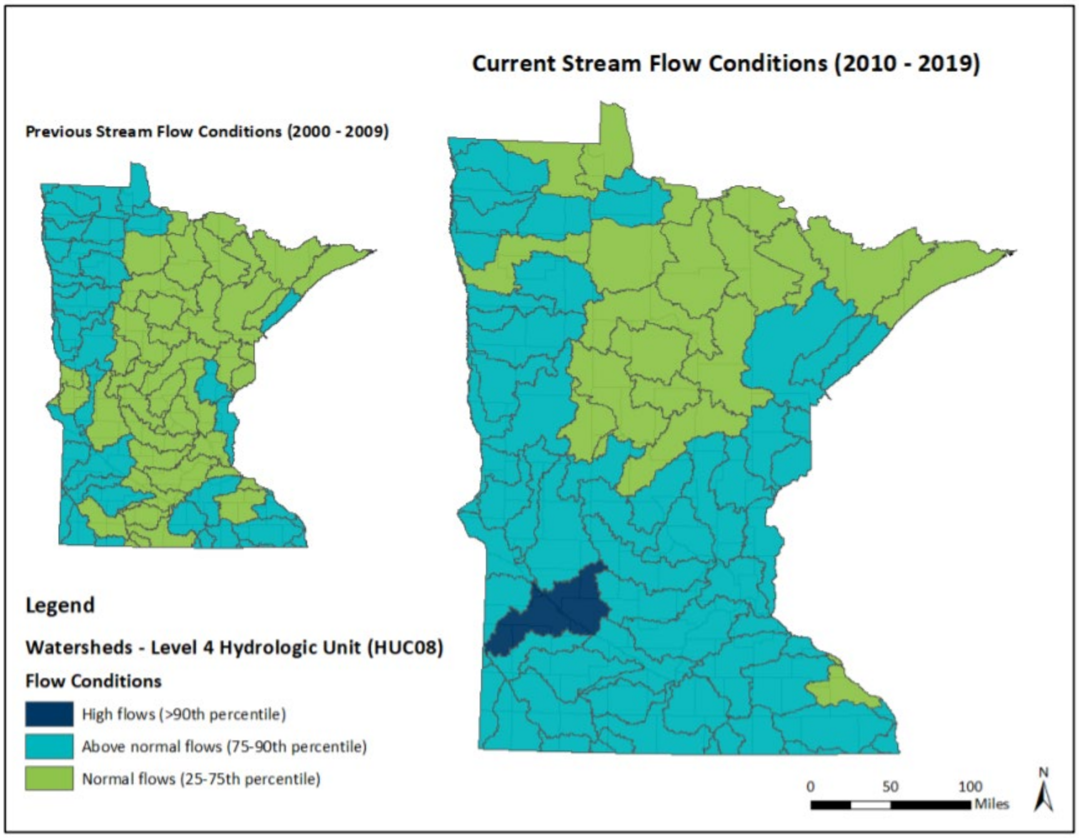

Fig. 2. Overall stream flow data for 2010-2019 compared to 2010-2019. Source: EQB [2020 Water Availability Report](#).

The need for water storage is one component of integrated water management at a watershed scale. This approach, recommended in the Minnesota Stormwater Manual, can also be applied to water runoff in general:

- Recognize natural features that are present, and how they can be preserved or enhanced to improve site hydrology while maintaining their ecological integrity
- Treat and store water as close to its source as possible. (See Minn. Stats. §103A.205)

Improved water management, both through adding water storage and improving the management of existing storage and drainage, will increase the resiliency of water resources and agricultural land to climate change. This approach also has the potential for multiple benefits: reducing erosion and damages to infrastructure; improving water quality, habitat, and the stability and ecological integrity of streams, wetlands and lakes, and increasing agricultural productivity. Improved water management is most likely to be achieved through thoughtful/deliberate consideration with public and private land and water managers during watershed planning processes.

Water Storage Defined

Water storage is often defined as holding water on the landscape through structural means such as impoundments, but water can also be stored in soils, in vegetation, or in shallow or deep groundwater. This paper uses the working definition created by the Minnesota Association of Soil and Water Conservation Districts:

> *The intentional retention or detention of water on or in the landscape for a desired period. Water storage can occur in specifically designed structures like created or restored wetlands or Water and Sediment Control Basins (WASCOBs) or within the soil through land management activities such as the use of cover crops, reduced tillage, drainage water management, or no-till farming systems. Water storage activities take place over many spatial and temporal scales. To achieve watershed-wide storage goals from a conservation district level of effort, many locally based projects will need to be installed which will have cumulatively significant storage impacts.*[2]

Definitions

"Retention" is long-term storage, including both volume control and rate control.

"Detention" is temporary storage, focusing on rate control only.

The primary focus of this paper is on surface and near-surface storage, but in some settings, such as karst, deeper groundwater also provides some level of storage. Water storage should always be considered in the context of watershed geology, topography, soils, land use and stream channel stability; all factors that affect the ability to manage water.

Steps in the Decision-Making Process

This paper identifies a series of steps that a local decision-making group, such as a watershed planning or implementation partnership, can follow to develop a water storage strategy:

1. Identify issue and problems to address through storage
2. Set measurable goals
3. Develop an understanding of water storage types and methods
    - Location and duration
    - Storage practices
4. Identify water storage options and set priorities to achieve your watershed goals
    - Examine your watershed for opportunities
    - Prioritize watershed areas where storage will be most effective
5. Estimate expected outcomes of adding intended storage
6. Assess factors affecting implementation of water storage
7. Selecting and implementing a water storage strategy

[2] MASWCD, 2020

There are likely to be multiple locations where water could be stored in any given watershed, but watershed planning groups need resources and information to make decisions about the most suitable locations. For each step, we identify what sort of information is needed and where gaps exist. Topics for further research are discussed under Next Steps and Research Needs.

1. Identify issues and problems to address through storage

Much of the discussion around water storage typically has focused on damage to infrastructure, especially to roads and bridges, but many other problems associated with high flow events and hydrologic changes demand attention. Water storage needs can be identified and quantified during a watershed planning process, with an overarching goal of adding water storage to improve hydrologic conditions. Improved hydrologic conditions relate directly to multiple issues typically found in watershed plans, including:

- Damage to public and private infrastructure
- Damage to agricultural land
- Increased runoff and other hydrologic changes,
- Degraded water quality
- Watercourse instability (including natural, artificial, and altered natural watercourses as defined in statute)
- Degraded aquatic habitat

During watershed planning processes, local watershed groups review and decide which issues are the highest priority and what combination of benefits is most greatly desired and needed.

2. Set measurable goals

Watershed plans often have hydrology goals related to three hydrology metrics: **peak flow, annual flow, and base flow**. These three types of goals are useful for framing water storage discussions related to resiliency.

Peak flow goals and considerations

Peak flow conditions are a commonly used indicator of hydrologic conditions. Size and duration of peak flows are often directly associated with flood damages and sediment loading (Figure 3). For example, 17 years of modeling with HSPF showed that only 6 peak months (3% of all months) delivered 28% of the sediment and 16% of the flow at the Minnesota River Jordan site. In HUC8 watersheds in the Minnesota River Basin, approximately 50% of all sediment was delivered during the highest 10% of flows. To reduce sediment loading, it will be important to reduce both the number of days in which the flow exceeds the 90^{th} percentile and the magnitude of the 90^{th} percentile flows.

When considering water storage goals in a watershed plan, it is important to determine the desired peak flow reduction expected for a given event level at priority locations within the watershed at specific times of year. For example, in many watersheds, spring runoff events are the largest in any given year and their peak flows are primarily associated with flood damages to infrastructure.

In other watersheds, summer runoff events are often associated with flood damage to agricultural land during the growing season. Watershed groups should consider peak flow related goals because extreme precipitation events are becoming more common in summer and fall.

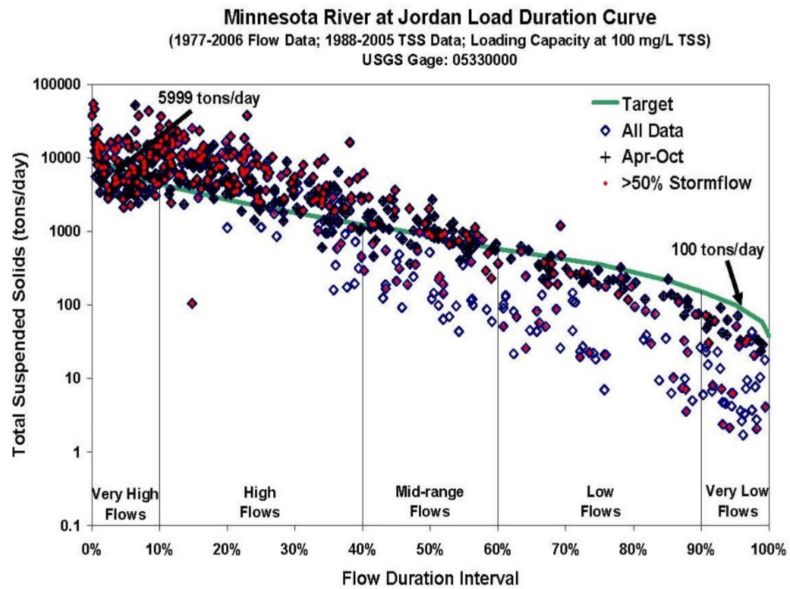

Figure 3. Load duration curve for the Minnesota River at Jordan. Highest levels of sediment are associated with highest flows. Source: MPCA, Sediment Reduction Strategy for the Minnesota River Basin and South Metro Mississippi River. Hollow diamonds represent samples taken from October through March.

Examples of peak flow related *protection* goal statements from watershed plans:

- No increase in 100-year, 10-day event peak flows.
- No increase in 10-year, 24-hour event peak flows.
- No increase in average annual runoff ratio considering trends in annual precipitation

Examples of peak flow *restoration* goal statements:

- Reduce 100-year, 10-day event peak flows by 10%.
- Reduce 10-year, 24-hour event peak flows by 20%.
- Reduce the number of days in which high flows (90th percentile flow) occur by 25%.

These types of goals should specify the specific peak flow event or events based on local knowledge and on other priority issues being considered in a watershed plan (e.g., flood damages). The time of year and location should also be specified in the narrative associated with the goal. For example, if agricultural flooding in summer is a priority issue, the 10-year, 24-hour event is often used in the goal statement because these types of flood events cause the most damage to agricultural production, particularly during the growing season.

Ideally, for flood damage reduction purposes, these goals would be related to specific damages associated with a particular event. In this case, the current peak flow could be associated with inundation of 1,000 acres of cropland and a reduction in the peak could be expected to reduce inundation by 500 acres at this 10-year frequency. This could be taken one step further with additional analysis to compare the costs and benefits of this 500-acre reduction in damages. If flood damage reduction for urban areas and infrastructure is a priority issue, then the 100-year, 10-day or 24-hour storm event is often used in the goal statement because these types of events usually cause the most infrastructure damage.

Peak flow related restoration goals should also specify the volume of water associated with the peak flow reduction percentage (inches of runoff or acre-feet) and the reduced risk of infrastructure damages. Watershed hydrology models can be used to estimate the volume of water associated with peak flow events. These volumes should directly relate to a measurable response on the landscape whenever possible. For example, in a 1,000 square mile watershed, hydrologic models may indicate that peak runoff volume would need to be reduced by 40,000 acre-feet to achieve a 20% peak flow reduction goal, or by 25,000 acre-feet to achieve a 10% reduction in peak flow. However, most watersheds lack specific data that directly connects these volume reductions to flood damages (acres, costs) or reduced sediment loading. In these cases, local land and water managers should evaluate available information and determine the appropriate storage goal for their watershed, just as they do for sediment or nutrient loading. (Some applicable models are discussed in Section 5.) Setting a reasonable storage goal for peak flow reduction based on available information ensures that hydrologic goals are considered in planning and implementation rather than delayed while waiting more extensive modeling data.

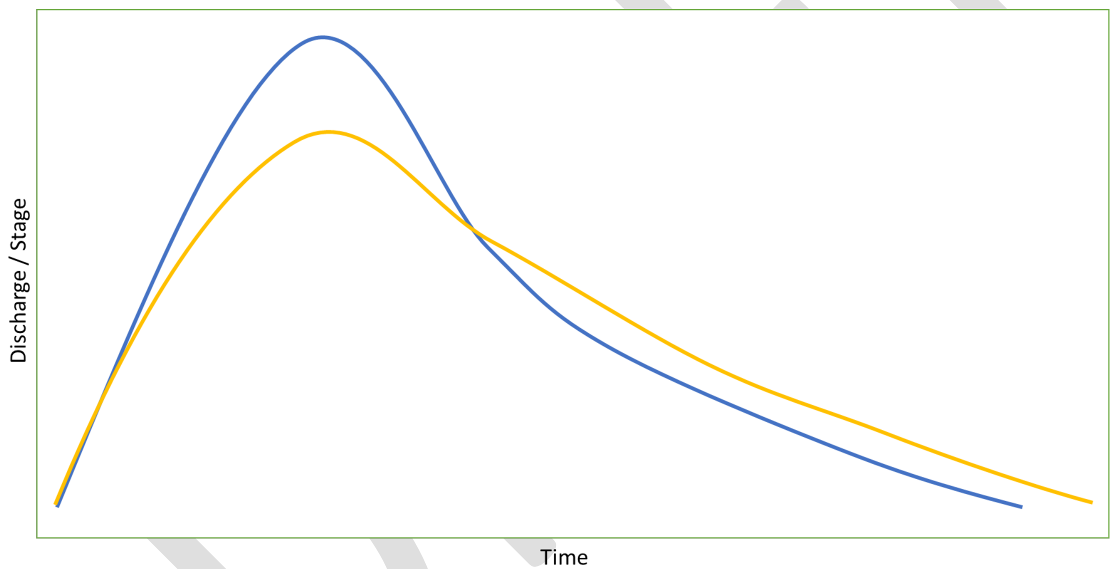

Figure 4. Conceptual comparison of hydrographs with and without peak flow reduction. The yellow line illustrates a change in the timing of runoff from the current condition (blue). Peak flow volumes are reduced, the tail of the hydrograph is extended but total event volume is similar.

Seasonal and annual flow goals and considerations

Flow-related goals within watersheds can also be proposed to reduce seasonal or annual flows at watershed or subwatershed scale. The annual water volume can be considered the annual water load, which is usually associated with sediment and nutrient loading throughout a watershed. As annual flows increase, so does the loading of sediment and nutrients. Managing annual flows can correspondingly reduce nutrient loads to downstream waters.

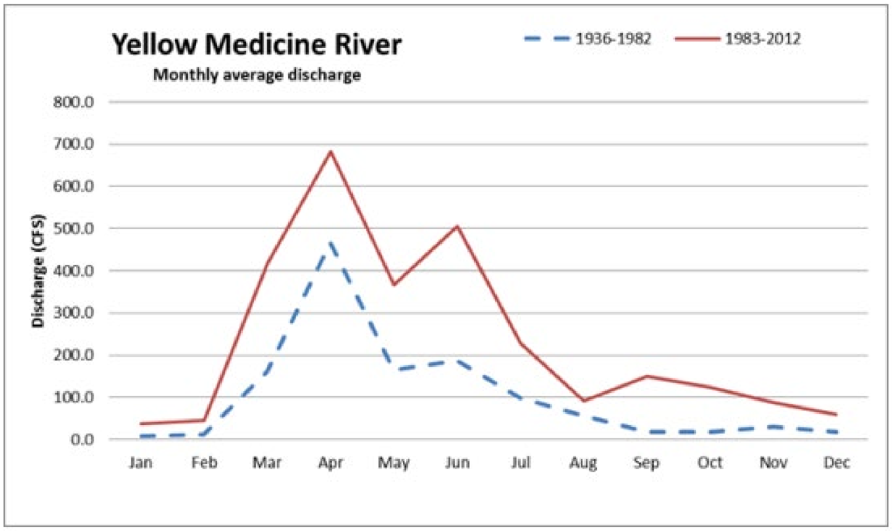

Fig. 5. Change in average annual flows. Source: Yellow Medicine River Hydrologic Analysis - Addendum to WRAPS, 2015

The dynamics of seasonal flows are also important for maintaining healthy aquatic communities. Aquatic communities (fish, invertebrates, riparian plants) have adapted to a "natural flow regime" with a spring peak flow, a relatively slow drawdown to low summer flows, periodic small peaks after rain events, and maintenance of flows throughout the rest of the year.[3] Changes to this flow regime can substantially disrupt the physical and chemical conditions of streams and their aquatic communities. For example, many fish spawn in early spring during periods of high flow and juvenile fish depend on relatively stable habitat conditions after they hatch in late spring. Unusually high peak flows during spawning may reduce reproductive success, while unstable flows later in the year can reduce survival rates of young fish.

Seasonal and annual flow indicators/metrics

Runoff volume is a common indicator to quantify annual flows. Gage data and hydrologic models are available in most watersheds to inform goal setting related to this metric. Runoff volume is often expressed as acre-feet of water or inches of runoff depth from the watershed. When setting a volume-based goal, a runoff depth or volume (e.g., acre-feet[4]) reduction should be specified for a watershed or subwatersheds (Table 1).

[3] Final EPA-USGS Technical Report: Protecting Aquatic Life from Effects of Hydrologic Alteration. https://www.epa.gov/sites/default/files/2016-12/documents/final-aquatic-life-hydrologic-alteration-report.pdf
[4] Volume of a one foot of water covering an acre (1 acre-foot = 43,560 cu feet).

Table 1. Water storage volumes associated with different runoff depths in 100 – 2000 square mile watersheds.

	Storage volume (ac-ft) by runoff depth		
Watershed Area (sq miles)	0.25 inch	0.5 inch	1 inch
100	1,333	2,667	5,334
500	6,667	13,333	26,667
1,000	13,333	26,667	53,333
2,000	26,667	53,333	106,667

Low flow thresholds are a common indicator to quantify seasonal flows. Low flows are defined as the "flow of water in a stream during prolonged dry weather" according to the World Meteorological Organization.[5] Low flows can harm aquatic life due to higher water temperature and reduced fish habitat and migration. Additionally, pollutants added from point sources during low flows can cause more harm than during higher flows.

Flow thresholds can be set in terms of maintaining a minimum flow of cubic feet per second. In Minnesota the Q90 value is often used to describe low flow conditions. The Q90 value indicates that 90% of the time, stream flow has been greater than that value – in other words, the stream flow has only been at or below that level 10% of the time. This value is also considered the protected low flow level and is used for adjusting or suspending water appropriation permits.

Examples of annual flow and seasonal flow goals:

Annual flow condition goals

Example of a *protection* goal statement:

- No net increase in annual runoff volume, considering increasing trends in annual precipitation and storm intensity.

Examples of *restoration* goal statements:

- Reduce or offset annual runoff volume by 0.5 inches.
- Reduce or offset spring runoff volume by 0.2 inches.

Seasonal flow conditions goals

Example of a *protection* goal statement:

- No decrease in mean daily flow (cfs) from September to December

Example of *restoration* goal statement:

- Maintain a mean daily flow of [x] (cfs) during June and July to support aquatic habitat

[5] Environmental Protection Agency, Definition and Characteristics of Low Flows. https://www.epa.gov/ceam/definition-and-characteristics-low-flows

When setting goals related to annual or seasonal runoff, watershed planners should consider climate/ precipitation trends. As discussed in the introduction to this paper, precipitation has increased over the past thirty-year period in many Minnesota watersheds (see Figure 2), resulting in more annual runoff and changes to seasonal runoff. In many watersheds, normal low flows are now higher except under drought conditions. Local planning groups should take these changes into account when setting goals related to annual and seasonal runoff reduction.

Watershed-scale volume reduction goals should directly relate to a measurable response on the landscape whenever possible, but this is often difficult. For example, in a 1,000 square mile watershed, historic annual flow volume may be 8 inches of runoff, or 426,667 ac-ft. The annual flow volume for the past 25 years may now have increased to 10 inches of runoff or 533,333 ac-ft. A local planning group could establish a long-term goal of reducing runoff by 2 inches (106,666 ac-ft) and a short-term goal of reducing runoff by 0.5 inches (26,667 ac-ft.). These volume reductions would reduce sediment and nutrient loading and contribute to improved stream stability, but it is challenging to quantify these expected improvements without more intensive modeling and monitoring.

Rather than waiting for more modeling and monitoring local land and water managers should evaluate available information and determine the appropriate storage goal for their watershed, just as they do for sediment or nutrient loading. (Some applicable models are discussed in Section 5). Setting reasonable runoff reduction goals for annual and seasonal flows based on available information ensures that hydrologic goals are considered in planning and implementation rather than waiting for more extensive modeling or monitoring data.

In contrast to peak flow reduction goals, the most effective practices to achieve annual and seasonal flow related goals are those that reduce the total volume of runoff throughout the year by increasing long term storage and evapotranspiration. This approach is similar to volume reduction practices associated with urban stormwater practices (e.g., green roofs). These volume reductions can reduce annual flows to a level closer to the historic flow regime.

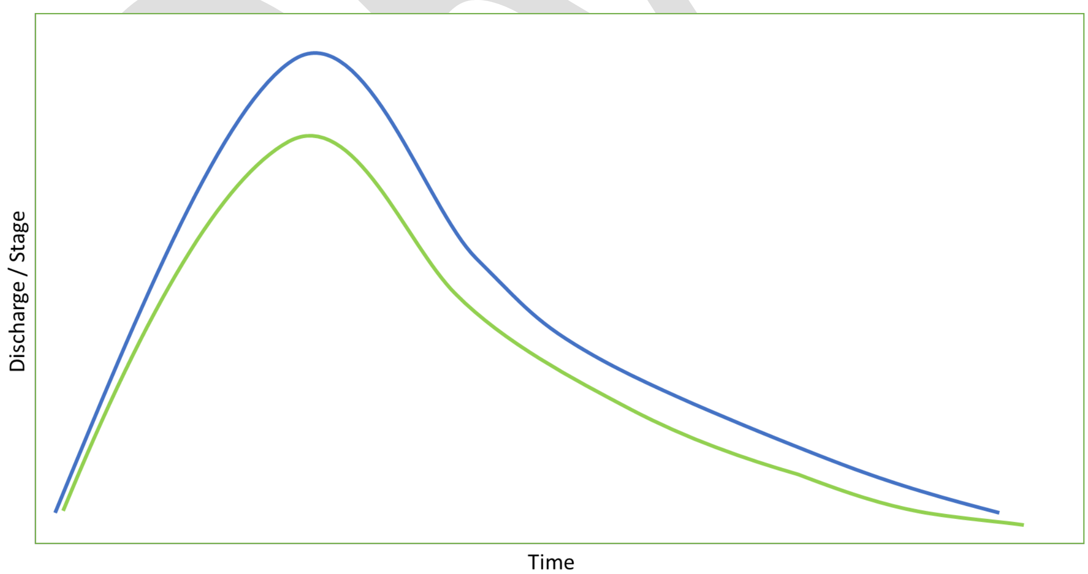

Figure 6. Conceptual comparison of hydrographs with and without peak flow reduction. The green line illustrates a change in the volume of runoff from the current condition (blue). Total flow volumes are reduced throughout the entire time period.

Base flow goals and considerations

Base flows are defined by the DNR as "the sustained flow in a channel because of sub-surface discharge to surface water." The purpose of protecting base flows is to maintain river flow at levels that are high enough to support the desired aquatic life, even during periods of lower precipitation.

Changes to base flows are common indicators of hydrologic change. Setting base flow goals can be particularly important for maintaining aquatic habitat and the health of aquatic communities in streams and wetlands. Most Minnesota streams are experiencing higher base flows due to long term increases in precipitation. However, in a drought, the reverse can be true – that is, base flows can be lower. Base flows can also change in tandem with changes in stream channel configuration. As higher flows erode streambanks and bluffs and the stream widens, more baseflow is needed to maintain the previous depth of water.

Base flow condition goals

Examples of *protection* goal statements:

- No change in 10th percentile (Q90) flows in January and July.
- No change in 3-day minimum flow magnitude compared to previous 10 years.

Examples of *restoration* goal statements:

- Increase the 10th percentile (Q90) flows in January and July by 20%.
- Increase the 3-day minimum flow values for the time period by 10 %.

3. Develop an understanding of water storage types and methods

Location and duration

As discussed above in "Water Storage Defined," water storage can be classified in several "buckets." This discussion defines water storage in terms of <u>where</u> the water is stored, how much, and <u>for how long</u>. Understanding these factors can help clarify the relationship of water storage types to the volume and timing of their effects.

Water storage types - Surface and sub-surface

Water can be stored on the surface and below the surface of the landscape (Table 1). Naturally occurring surface water storage features include lakes, wetlands, and floodplains. Artificially created surface water storage features include on-channel and off-channel impoundments where structures such as levees and dams are constructed to hold water.

Subsurface water storage features include the first 10-20 feet of soil. All soil, whether drained or undrained, stores water. Water stored in the soil is either available to plants, tightly bound to soil particles, or weakly bound to soil particles but available to be drained. Only the fraction of drainable water stored in the soil can actually be managed as "storage." Soil water holding capacity depends on many soil related factors including degree and depth of compaction, bulk density, percent clay and organic matter, soil type and land cover.

Whether stored on the surface or sub-surface, the amount of water stored can be measured as a volume, typically as cubic meters or acre-feet (1 foot of water over an acre), or as a depth, such as in millimeters or inches averaged across the entire area of interest.

Water storage duration - Short-term and long-term

Both the volume of water stored on the landscape and the duration of time that the water is stored are equally important. Surface and subsurface water can be stored for the short-term (hours or days) or the long-term (weeks or months).

Short-term storage of surface waters typically occurs over the course of hours or days, such as when a floodplain is filled during a flood event, when a wetland or lake stores water above its runout elevation, when the area of a field drained by a surface tile intake holds water, or when an impoundment temporarily fills. .

Long-term storage of surface waters occurs when water pools in an area (e.g. lake, wetland, impoundment) and is held so that it does not directly become runoff. Most of water held as long-term storage will evaporate or be transpired to the atmosphere (i.e., through vegetation during the growing season) and some will be stored in the soil to potentially be transpired or become groundwater (a portion of which may become base flow). Practices that provide long-term storage essentially hold precipitation until it can be removed from the surface water elements of the water cycle through evapotranspiration and groundwater recharge.

Similar to surface storage, water can be stored in the soil on a short-term or long-term basis. Water stored in soils without constructed drainage is generally stored long-term: the water is held in the soil until it is gradually removed by crops or other vegetation, through evapotranspiration, or through percolation to deeper groundwater. Some portion of this soil water may also move laterally through the soil and end up as runoff in surface waters after being stored for days, months, or years depending on soil and watershed conditions.

Generally, where subsurface (tile) drainage exists, water storage in the soil is converted from longer-term storage to short-term storage. However, when control structures are part of the drain tile system, the water storage in the soil can be managed for longer time periods.

Where surface drainage is in place, the time that the drainable soil water is held within the soil is reduced compared to an undrained landscape, but it still may be held longer compared to a sub-surface drained condition. In both situations, the volume of drainable water held in the soil does not change compared to an undrained condition. However, surface drainage can substantially lengthen the amount of time the drainable soil water is subject to plant uptake and evapotranspiration. See Table 2 below.

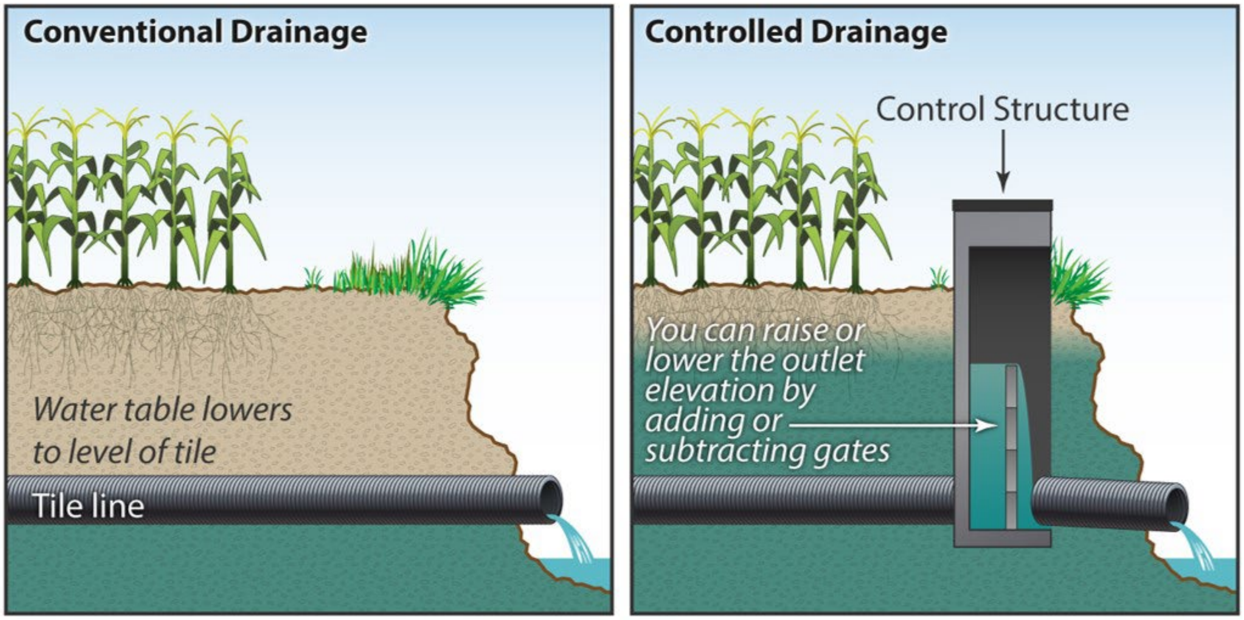

Figure 7. Conventional vs. controlled drainage. Christianson, L.E., J. Frankenberger, C. Hay, M.J. Helmers, and G. Sands, 2016. Ten Ways to Reduce Nitrogen Loads from Drained Cropland in the Midwest. Pub. C1400, University of Illinois Extension.

Table 2. Summary of water storage types

This table is intended to highlight existing storage conditions. It recognizes that existing landscape features as listed already provide long-term and/or short-term storage. The table does not attempt to summarize the potential positive or negative effects of the storage types on natural resources; these are discussed in the following sections.

Storage type and feature	Long-term storage	Short-term storage
Surface storage		
Wetlands and lakes	Wetlands and lakes (including restored wetlands) provide long term storage below their runout elevation. The amount of available storage volume depends on the shape of the basin and current water levels. The amount of runoff that a basin can hold depends on the size of its watershed and the size of the storm event.	Existing wetlands and lakes provide short-term storage above their runout elevation. The short-term storage volume depends on the morphology of the basin and the configuration of the outlet. The volume of runoff that a basin can temporarily hold depends on watershed size and conditions as well as the outlet hydraulics. The surface of the water acts like a parking lot, storing very little water above the runout elevation. Additional water above the runout elevation moves to a lower elevation, and to a downstream conveyance system.

Storage type and feature	Long-term storage	Short-term storage
Drained wetlands and lakes	Drained wetlands and lakes, often actively farmed, provide little long-term storage in their drained state.	Drained wetlands and lakes can provide short-term storage depending on the degree to which they're drained (via surface ditching and subsurface drainage). Many provide storage only for hours or days, but cumulatively across a watershed they can provide a substantial volume of short-term storage. These features can provide more short-term storage if cover crops, controlled drainage and subirrigation are integrated into the farming system.
Natural and altered natural watercourse floodplains	Floodplains provide little or no long-term storage. Wetlands found within floodplains can provide some long-term storage.	Floodplains can provide a substantial amount of short-term storage, depending on their width and cross-sectional area. Wider floodplains provide more storage than narrow floodplains
Artificial watercourses (ditches)	Ditches do not typically provide any long-term storage.	Ditches can provide some short-term storage, depending on their width and cross-sectional area. Wider ditches, including two-stage ditches, have the potential to provide more floodplain storage than narrow ditches.
Impoundments (on-channel, off-channel)	Impoundments with a permanent pool can provide long term storage below their runout elevation. The amount of available storage volume depends on the shape of the impoundment and current water levels. The volume of runoff that an impoundment can hold depends on watershed size and conditions as well as available water storage volume.	Impoundments with a permanent pool can provide short-term storage above their runout elevation. Impoundments without a permanent pool (dry impoundments) can provide considerable short-term storage. In either case, storage volume depends on the morphology of the basin and antecedent conditions. The volume of runoff that an impoundment can hold depends on watershed size and conditions as well as available water storage volume. The surface of the water acts like a parking lot, storing very little water above the runout elevation. Additional water above the runout elevation moves to a lower elevation, and to a downstream conveyance system.

Storage type and feature	Long-term storage	Short-term storage
Sub-surface storage		
Soil - undrained	Undrained soils provide long-term storage. The amount depends on soil type and condition and previous precipitation.	Undrained soils generally provide small amounts of short-term storage, but it depends on soil type and condition.
Soil - drained	Drained soils provide some long-term storage but less than undrained soils. The amount of water stored depends on the amount of soil organic matter, amount of tightly bound soil water, amount of moisture already held within the soil and soil conditions based on management and depth to the perched water table.	Drained soils provide similar amounts of short-term storage to undrained soils, but drainage results in lower water tables, which can increase the amount of time the storage is available.

Storage practices

Selection of storage practices will depend on each watershed's goals and other factors discussed in this paper.

Effective water storage practices for peak flows (listed by relative effectiveness)
The most effective practices to reduce peak flows are those that temporarily or permanently remove water from the peak flow portion of the hydrograph at an area of interest. (see examples in Section 4). All the water storage practices listed in Table 3 have the potential to reduce peak flows but two primary factors determine effectiveness:

1) the volume of water that can be captured and stored during an event, and
2) whether the water being stored by the practice would have been timed to coincide with the peak flow at your point of interest.

Practices that hold large volumes of water that are coincident with the peak at your point of interest will be most effective at peak flow reduction. Generally, the most effective practices to remove or delay the largest volume of water with the right timing at a downstream location are:

- Impoundments - off-channel and on-channel impoundments can be sited, designed, and operated to temporarily store large volumes of runoff coincident with peak flows.
- Wetland restoration - wetlands restorations can be sited, designed, and operated to temporarily store small to moderate volumes of runoff coincident with peak flows.
- Flood plain storage restoration - floodplains can be restored to increase the area adjacent to a river or stream that can hold water during an event.
- Drainage water management – installing drainage with the capacity to better manage flows in relation to the peak.
- Soil health improvements – land management practices that improve soil health (reduced tillage, cover crops, etc.) can increase evapotranspiration and increase the water holding capacity of the soil to reduce runoff volume.

- Land conversion to conservation (i.e., CRP) reduces runoff and increases infiltration through introduction of deep-rooted native vegetation.

Effective water storage practices for annual flows (listed by relative effectiveness)
The most effective practices for managing annual flows are those that hold water on the landscape or in the soil long enough to increase evapotranspiration or infiltration to deeper groundwater. Those practices that remove the largest volume of water over time will be most effective. The greatest opportunity to increase evapotranspiration throughout the year is in spring and fall months when crops are not actively growing. Agricultural practices that affect annual flows require widespread adoption. Practices include:

- Land use changes that increase evapotranspiration
- Soil health practices such as reduced tillage and cover crops
- Wetland restoration
- Flood plain storage
- Impoundments

Effective water storage practices for seasonal flows
The most effective practices for managing seasonal flows depend on watershed specific goal(s). If the seasonal goal relates to peak flow reduction, the peak flow reduction practices listed above apply. If the seasonal goal relates to promoting more "natural" hydrologic conditions in other times of the year, the annual flow related practices should apply.

Effective water storage practices for base flows
Effective practices for base flows are those that increase infiltration, hold water in the soil throughout the year and replenish groundwater. These include maximizing storage in groundwater recharge areas, stream corridor restoration, riparian buffers, filter strips and field borders, stream restoration (or using old oxbows for water storage), prairie strips, cover crops and conservation tillage

Summary of effects of storage practices

Table 3 identifies the general effects of water management practices that can be implemented to increase evapotranspiration (ET), soil water holding capacity, and short-term or long-term surface storage. Note that there will always be some overlap between categories since both ET and soil water holding capacity can also be considered long-term solutions.

Practices that increase ET and increase long-term storage are more likely to affect annual or seasonal runoff volume compared to the other categories. Practices that increase water holding capacity or short-term surface storage are more likely to affect peak flow volume and timing of runoff.

Table 3. Summary of water management practice effects

Practice Type (NRCS standard when available)	**Increase ET**	**Increase soil water holding capacity**	**Increase short-term surface storage (detention)**	**Increase long-term surface storage (retention)**
Crop and Soil Management				
Cover Crops (340)	x	x		

Practice Type (NRCS standard when available)	**Increase ET**	**Increase soil water holding capacity**	**Increase short-term surface storage (detention)**	**Increase long-term surface storage (retention)**
Conservation Cover (327)	x	x		
Conservation Crop Rotation (328)	x	x		
Conservation Tillage (329, 345 and 346)	x	x		
Contour Farming (330)	x	x	x	
Field Borders (386)	x	x		
Forage and Biomass Plantings (512)	x	x		
Manure Application		x		
Land use change to perennial cover (328, 512, etc.)	x	x	x	
In-field Drainage Water Management				
Controlled drainage (DWM 554)	x		x	
Alternative tile inlets			x	
Alternative drainage design, including drainage water capture and reuse, saturated buffers, etc.			x	x
Surface Flow Management				
Grassed Waterway (412)	x			
Filter Strips (393)	x			
Contour Buffer Strips (332)	x			
Structural Storage & Infiltration				
Saturated Buffers (604)	x	x		
Small Impoundments (356-dike)			x	x
Large Impoundments (356-dike)			x	x
Constructed Wetland (656)	x		x	x
Wetland Restoration (657)	x		x	x
Ponds (378)			x	x
Water and Sediment Control Basins (638)			x	
Terrace (600)			x	
In-Channel Water Retention				
Two-stage ditch (582)			x	
Protection/management of existing ditches with two-stage channel			x	
Design standards for surface drainage that reduce flood peaks			x	
Strategic culvert sizing			x	
Ditch plugging and/or abandonment			x	
Grade stabilization (410)			x	
Setting back existing levees			x	
Impoundments (356-dike)			x	x

Practice Type (NRCS standard when available)	**Increase ET**	**Increase soil water holding capacity**	**Increase short-term surface storage (detention)**	**Increase long-term surface storage (retention)**
Riparian Restoration and Protection				
Natural channel restoration			x	
Natural channel rehabilitation			x	
Riparian corridor rehabilitation/management	x		x	
Other				
Update operating plans of existing impoundments			x	
Manage outlets of existing lakes and wetlands			x	

4. Identify water storage options and set priorities to achieve your watershed goals

Once a water storage goal(s) has been established as well as a basic understanding of the types of water storage options available in the watershed, it is time to look for the best opportunities to site water storage in a given watershed. This decision will depend on many variables, including potential locations for storage, funding availability, and landowner interest. The following steps can help to systematically evaluate water storage options.

A. Examine your watershed for storage opportunities

Each watershed will include multiple opportunities to incorporate storage on the landscape. Selection of options will depend on several considerations, from cost of practices to availability of sites and permitting feasibility. Storage locations may include:

Existing lakes and wetlands

The location of existing lakes and wetlands are readily available (i.e. National Hydrologic Dataset; National Wetlands Inventory). However, no spatial resources are currently available to identify those lakes and wetlands that have the potential to hold more water through modification of their outlets. While some lakes and wetlands can potentially provide additional water storage, this approach also carries significant risks. Wetlands have plant communities that are adapted to their existing water regimes, and diverting more runoff will likely change the water regime and the plant community. Runoff also commonly carries nutrients and sediment. Wetlands and lakes do have some capacity to assimilate nutrients and sediments, but they can be easily overwhelmed. Local knowledge during a watershed planning process could help identify lakes and wetlands that may have the potential to provide additional water storage, with consideration of the risks and challenges this approach entails. (Note that any changes to Ordinary High Water Level as defined in statute require DNR approval; see discussion of environmental factors in Section 6.)

Drained wetlands and lakes

Partially or fully-drained wetlands and lakes can provide opportunities for both water storage and habitat improvement if restored. Many existing wetlands have been partially drained. A number of local efforts have identified the location of drained wetlands and lakes. A hydric soils map be also be a good resource. From a statewide or regional perspective, several resources are available for this category:

National Wetland Inventory example. Highlighted polygons indicate drained wetlands.

- National Wetlands Inventory (NWI). The NWI, originally created in the 1980's, was recently updated using more advanced techniques to identify and characterize Minnesota wetlands. The data for existing wetlands includes an attribute which indicates whether a basin has been drained or partially drained. These data can be queried to identify drained wetlands.

Restorable Wetland Inventory example.

- Restorable Wetland Inventory (RWI). The Minnesota RWI was completed in 2012. Drained wetlands were identified using traditional remote sensing and air photo interpretation. These data allow creation of a map of restorable wetlands where this analysis has been completed (the Prairie Pothole region). Data attributes include wetland size.

Restorable Wetland Index example.

- Restorable Wetland Index PCA/NRRI. The Minnesota Pollution Control Agency (MPCA) in partnership with The Natural Resources Research Institute (NRRI) created a restorable wetland inventory in 2019 using available Light Detecting and Ranging data (LiDAR). Data attributes include wetland size, soils and landscape position.

- Restorable Wetland Inventory LiDAR – Red River Basin. This inventory was established for the Red River Basin in 2017. This data is based on a hydrologically conditioned DEM, where ditches and other areas of channelized flow have been removed to identify areas where water naturally pools and places a digital dam at the outlet of all such locations. Final data attributes include size, depth, runout elevation, volume, and drainage area. The International Water Institute manages this inventory data.

Restorable Wetland Inventory LiDAR example.

Natural and altered natural watercourse floodplains.

The locations of natural and altered natural watercourses are readily available (i.e., National Hydrologic Dataset). No data are currently available to identify the floodplain areas of those streams that been narrowed or confined and thus have the potential to hold more water. However, several tools are available for mapping riparian zones or flood prone areas using LiDAR and readily available input data[6]. Local knowledge during a watershed planning process could help identify watercourses that may have the potential to provide additional water storage– for example, areas where floodplains have been narrowed by structures such as roads, bridges and trestles, and where natural watercourses have been straightened. These areas have the potential to provide additional water storage (Table 4). A more sinuous stream channel with a wide meander belt can store more water than a confined channel or ditch within a confined valley.

Table 4. Floodplain water storage available per mile of length based on floodplain width and water depth. For any given depth, expanding the floodplain provides substantially more storage.

	Water storage (ac-ft) per mile based on Floodplain Width (ft)				
Water Depth (ft)	**50**	**100**	**200**	**400**	**600**
1	6	12	24	48	73
2	12	24	48	97	145
3	18	36	73	145	218
4	24	48	97	194	291
5	30	61	121	242	364
6	36	73	145	291	436

Artificial watercourses

This term is defined in Minn. Stats. 103G.005 as "a watercourse artificially constructed by human beings where a natural watercourse was not previously located." Minnesota has over 19,000 miles of surface drainage ditches, including both altered natural watercourses and artificial ones. This large network of

[6] https://essa.com/explore-essa/tools/river-bathymetry-toolkit-rbt/
https://www.esri.com/arcgis-blog/products/analytics/analytics/usda-forest-service-uses-arcgis-to-protect-riparian-ecosystems/

existing infrastructure has the potential to be used to temporarily store water to achieve flow reduction goals. Systematic use of design standards for drainage systems and culverts has the potential to substantially reduce peak flows in some landscape settings (e.g., RRBC Technical Paper 15, – Figure 7) Local knowledge can be used to help identify artificial watercourses where this type of approach would be most effective for short-term water storage to dampen peak flows and the cumulative effects of intense rainstorms.

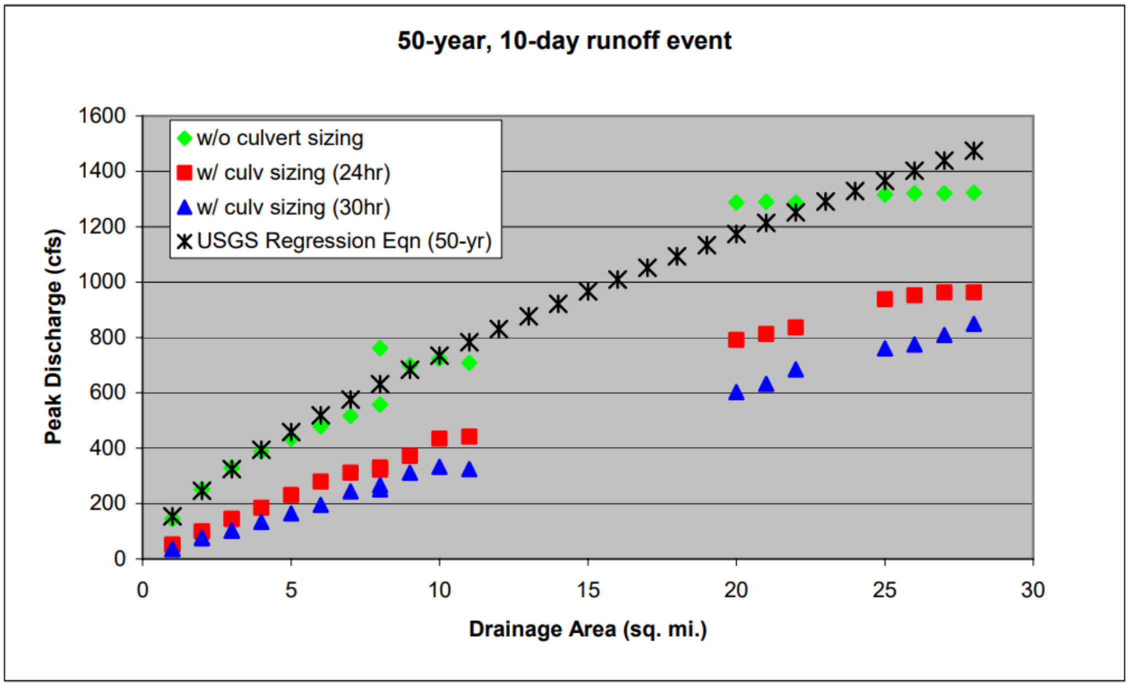

Fig. 8. Comparison of modeled peak discharge for drainage systems designed for peak flow reduction (blue and red markers) versus traditional culvert sizing (green markers) for a 50-year 10 day runoff event. Source: Figure 8c TP15

Impoundments

- **On-channel impoundments**. Minnesota has 1,150 dams on natural and altered natural watercourses, some of which provide short-term and long-term storage.[7] An inventory of dams and associated permits is available via the MN Geospatial Commons. Local knowledge of topography can be used to identify potential impoundment sites. From a water storage perspective, river valleys and ravines with large cross-section areas and moderate slopes are preferred locations. LiDAR data can provide watershed planners with valuable data to identify potential impoundment sites.

  Construction of large on-channel impoundments can have substantial environmental and funding related constraints (see Section 6). Impoundments, especially those on perennial streams, can exacerbate water quality problems and downstream erosion issues, and may create fish passage barriers which can contribute to biological impairments. Impoundments adjacent to streams (off-channel), on artificial watercourses, or in the upper reaches of a watershed tend to present fewer conflicts.

[7] https://www.dnr.state.mn.us/waters/surfacewater_section/damsafety/index.html

Figure 9. Brandt impoundment, Red Lake Watershed District located on a small altered natural watercourse. Designed to detain 3,912 ac-feet of runoff.

Off-channel impoundments. Off-channel impoundments include diversion of water from a watercourse to a water storage area with levees or embankments to hold water. Such impoundments can provide substantial short-term storage within a watershed. Local knowledge, as well as LiDAR data, are needed to identify locations where the topography is suitable to receive diverted water. Methods such as designing low levees in the floodplain that overtop during major flood events can provide short-term storage during a large flood.[8]

Figure 10. Off-channel Euclid East impoundment, Red Lake Watershed District. Provides detention of 2,443 ac-feet of runoff

[8] Anderson, C. and Kean, A. Red River Basin Flood Damage Reduction Framework, Technical Paper No. 11

Figure 11. North Ottawa impoundment in the Bois de Sioux watershed district: 1,920 acres (3.5 sections) which holds 18,000 acre-feet of runoff.

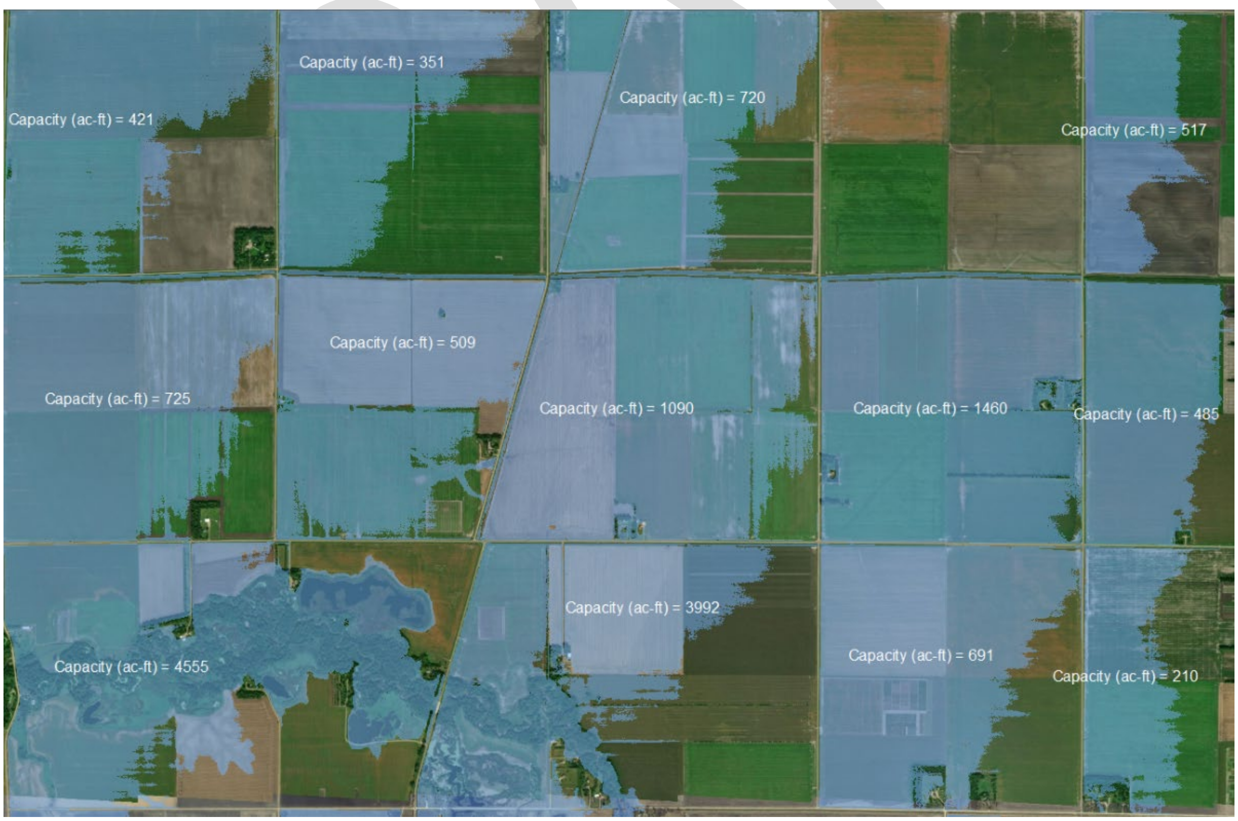

Figure 12. Example of an approach to identify areas of the landscape with suitable topography to store water. LiDAR and GIS techniques were used to identify potential water storage sites in the Red River basin assuming that

North-South roads were raised 3 meters. Shaded areas indicate where water could be stored if embankments were constructed to create either on-channel or off-channel storage impoundments. These planning level data were created using East-West oriented roads. The dataset includes a variety of attributes including estimates of water storage volume as indicated. Additional attributes include drainage area, area in acres, and watershed runoff volume retained. Source: IWI.

Other structural best management practices

- **Water and sediment control basins (WASCOBs).** GIS-based tools including ACPF and PTMApp can help identify the locations of this practice, which uses the natural topography of the landscape along with earthen embankments and constructed channels to intercept runoff.
- **Drainage water management.** Local knowledge of drainage systems can be used to identify opportunities for improved drainage water management, including controlled drainage, to help meet water storage goals.
- **Drainage water capture and reuse.** This practice involves capturing subsurface (tile) drainage water in an impoundment for later use for crop irrigation. The drainage water can be captured in a suitable natural depression or a constructed impoundment. See NRCS Practice Standard 447 for additional criteria. (USDA NRCS, 2020).
- **Saturated Buffers:** Diverting subsurface drainage water into a buffer along a waterway. The buffer should be at least 30 ft. wide and have stable stream banks. See NRCS Practice Standard 604 (USDA NRCS, 2021).

Soil water storage

As described in *Fields to Streams (Lewandowski et al. 2015)*, soil water is held in four basic ways:

- Surface water is stored in the depressions on the ground's surface.
- Tightly bound soil water is held by soil particles and cannot be accessed by plants
- Plant available water can be taken up by plants
- The remainder is drainable soil water.

Drainable soil water flows downward or laterally when all soil pores are filled. As stated in *Fields to Streams, "*The amount of water in agricultural soils drops sharply in the middle-to-late summer as crops grow vigorously and draw up large amounts of plant available water. Water levels are recharged in the fall, before soil is frozen, and continue to recharge in the spring with melting snow or precipitation."

The dynamics of soil and water interactions are extremely complex at both the field and watershed scale and are beyond the scope of this paper[9]. However, a few basic principles are known:

- Coarse-textured soils generally hold less water than fine-textured soils such as clays, but the water is not held as tightly to soil particles, so more water can be drained.
- Medium textured soils generally hold the greatest amount of plant available water, because the water is held tightly.
- Finer-textured soils have the greatest amount of pore space (unless compacted), but because the water is held tightly and drains slowly, less of it is available for drainage.
- Increased organic matter generally increases water-holding capacity

[9] Cates, A., 2020. The Connection between Soil Organic Matter and Soil Water.

- Before water can be stored in soil, it needs to infiltrate into the soil. Soil health and management affect the infiltration capacity of the soil.

B. Prioritize watershed areas where storage will be most effective

Different areas within watersheds provide different opportunities to meet the watershed hydrology goals described in Section 2. Priority areas for water storage will differ depending on your priority goals and your priority point or points of interest in a watershed. For example, if the top priority in your area is to reduce flood damage and peak flows at a specific point in your watershed, your priority water storage areas should be those parts of the watershed where each unit of water storage will have the greatest effect on peak flows at that point. These priority areas are those where the water coming from the area is timed to coincide with peak flow downstream at the point of interest.

The same approach can be used if the purpose of a peak flow reduction goal is to help moderate flow and improve stream stability. The point of interest would be the reach of stream most impacted by flow alteration. The approaches to prioritizing watershed areas described in this section were developed using a variety of hydrologic models (see discussion in Section 5 below). Watershed areas can be prioritized based on their potential to meet goals. The following are some examples of prioritization that can be developed using both models and geospatial information. Some of these data and models, such as HSPF, are readily available at a watershed scale.

Peak flow reduction priority areas

Areas of the watershed that contribute the largest volume of water to peak flows at your point of interest (i.e., where flood damages are most frequent) should be high priority areas for water storage practices. The intent is to control both the volume and the timing of peak flows as they affect your point of interest – for example, a city

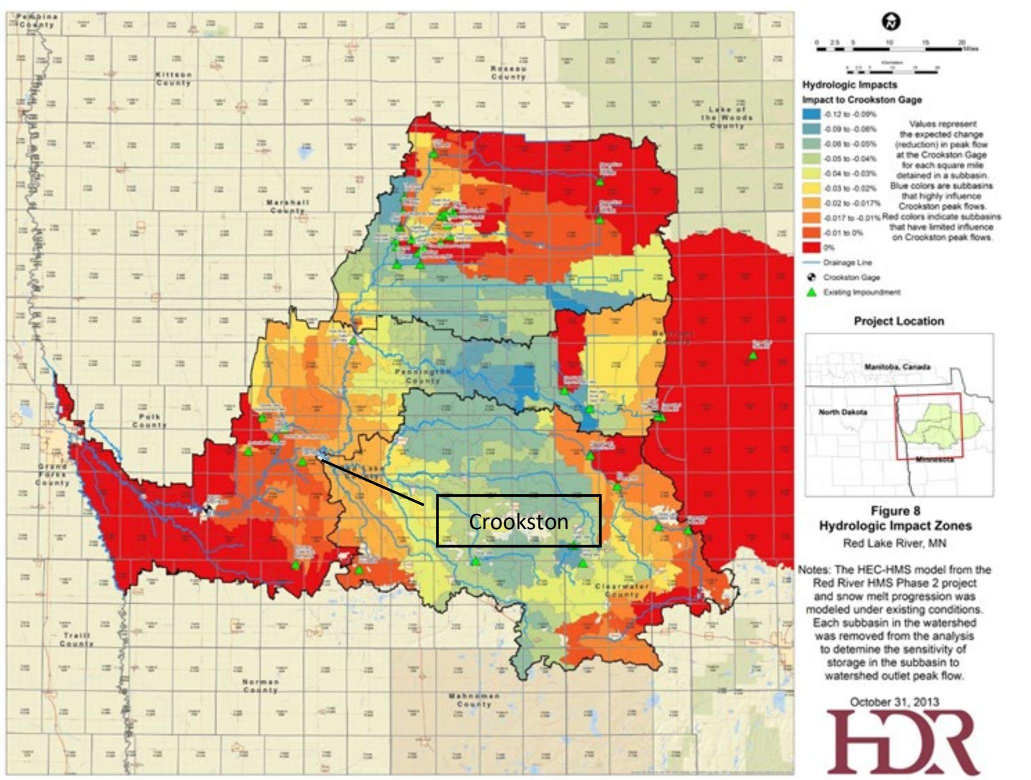

Fig. 13. In this example the HEC-HMS model was used to identify areas based on their peak flow reduction potential at Crookston. Areas in blue provide the most peak flow reduction per volume of water storage compared to areas in yellow, orange and red.

subject to flood damages. In Figure 13 the City of Crookston is the location of concern for flood protection.

A similar priority area map could also be made for East Grand Forks at the outlet of this watershed. The areas in blue would then shift to the west since the areas of the landscape that contribute to peak flows at East Grand Forks are likely located closer to this new pour point.

A similar approach can be used with the Hydrologic Simulation Fortran (HSPF) model. HSPF was used to identify subwatersheds that contributed the largest volume of water to the outlet of the Watonwan watershed during the top 10 highest flow events over a fifteen-year period (Figure 14). The outlet, or pour point, of the watershed could be the location of concern for flood damage reduction. The darkest areas have the greatest potential for water storage to reduce flood peaks at the outlet. However, if the flooding occurs further upstream in this watershed, additional analysis would be needed to identify the subwatersheds that contribute the most to the new point of interest. The optimal location to place water storage always depends on your point of interest

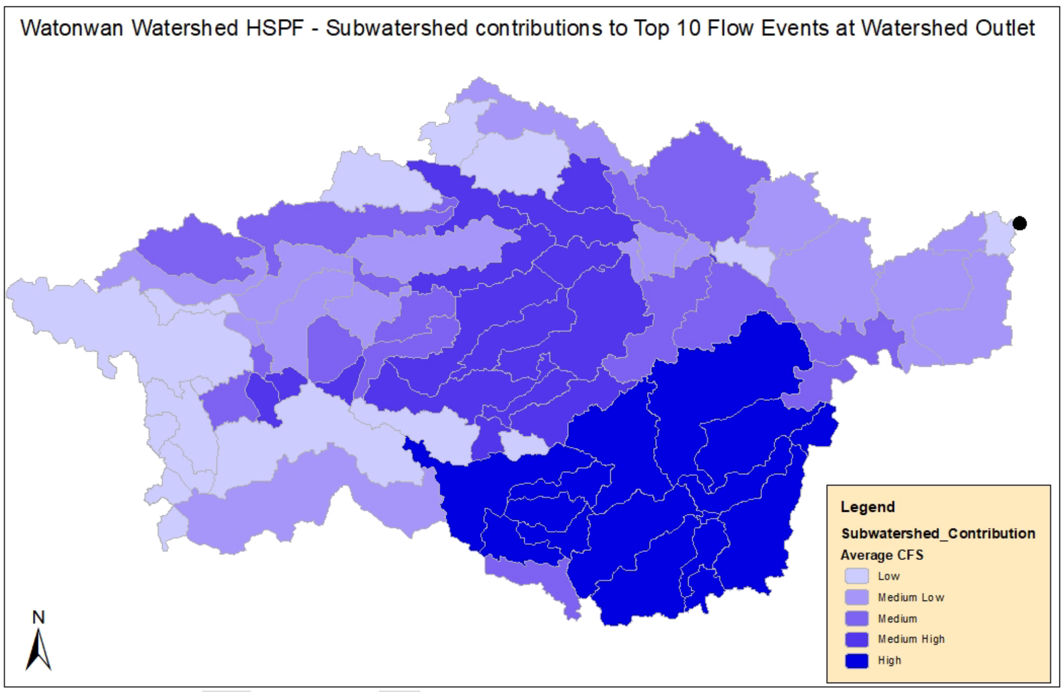

Fig. 14. Annual flow reduction priority areas in the Watonwan watershed. Areas in darker blue contribute the greatest volume of runoff to flood events at the outlet compared to areas in lighter blue. Source: MPCA and BWSR

Annual flow reduction priority areas

Unlike peak flow goals, all areas of the watershed that store water for the longer term and increase evapotranspiration will have an effect on annual flows. Those areas of the watershed that contribute the largest volumes of runoff throughout the year can be identified as potential priority locations for water storage (Figure 15). Based on a basic HSPF modeling exercise, it appears that long-term storage would be the best approach for managing annual flows in the red and orange-shaded areas of the watershed.

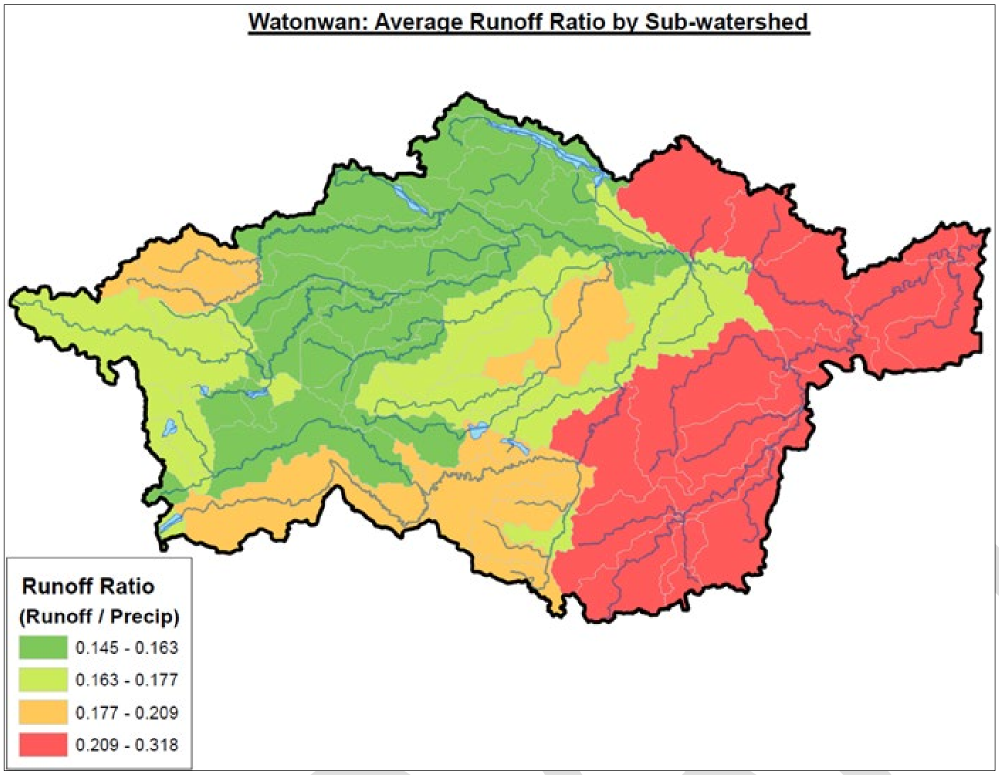

Figure 15. Subwatershed areas within the Watonwan watershed characterized by the amount of runoff per unit precipitation. The areas in red have the most runoff per unit precipitation and could be the highest priority areas for water storage. Source: MPCA and BWSR.

Further analysis may be needed, combined with local knowledge and modeling scenarios can also help identify the best options for water storage within a particular watershed.

Base flow protection or restoration areas

As discussed earlier in this paper, relatively little is known in most watersheds about priority locations to advance groundwater recharge. Local knowledge as well as Groundwater Restoration and Protection Strategies (GRAPS) reports and hydrogeologic atlases, where available, can be used to identify areas with important areas of groundwater recharge. Conservation practices along stream corridors may also be effective.

The HSPF model could be used to identify subwatersheds that contribute the most and least runoff during dry periods; however, no one has run the model for this purpose in Minnesota. Research and modeling are needed on the effects of riparian buffers on groundwater recharge, as well as on drinking water enhancement practices such as aquifer storage and recovery (ASR).[10]

[10] See Jennings et. al., Smith et. al., USGS 2014.

Non-contributing area protection and restoration areas

Modern GIS techniques have been combined with traditional approaches to surface runoff modeling to derive “non-contributing” areas in many Minnesota watersheds: areas where no surface runoff is expected to be contributed downstream in a given precipitation event (e.g. 10-yr, 24-hour). Mapping these areas provides a starting point for discussions about protection of existing conditions. These techniques can also be applied to identify watershed areas that contribute runoff in a 1-inch precipitation event but not a 0.5-inch precipitation event or those that contribute in a 2-inch but not a 3-inch event. Mapping these areas can identify opportunities to add storage to create additional areas of the landscape that will contribute less runoff.

C. Screen potential water storage sites

In item A above, potential water storage sites were identified. In item B the priority areas of the watershed were identified. In this step, these data can be combined with other available data to screen potential storage sites for their potential to meet hydrology, water quality, and habitat goals (Figure 16).

- Hydrological screening metrics include peak and annual flow reduction potential and storage volume needed to create non-contributing areas.
- Water quality screening metrics include sediment and nutrient reduction potential.
- Habitat screening metrics can be based on proximity to MN wildlife action network priorities or other local or regional priorities.

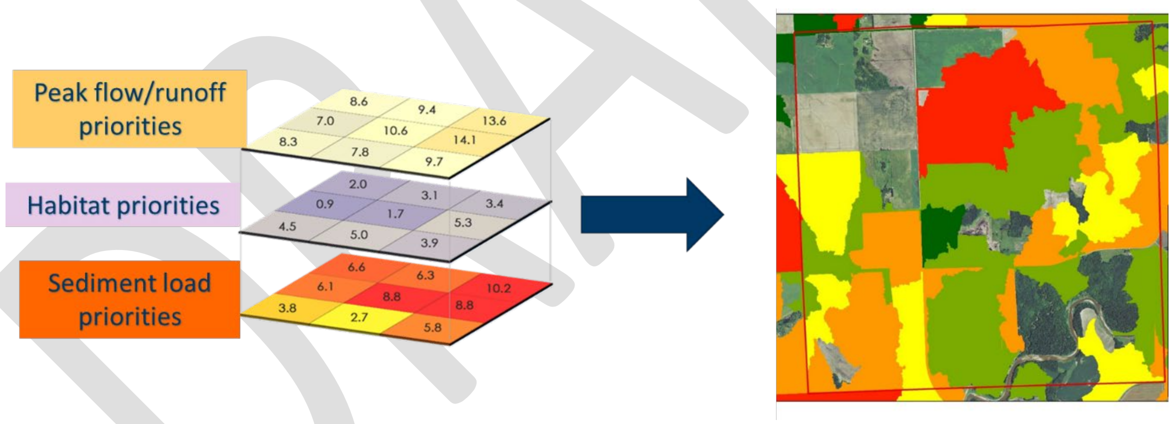

Figure 16. Representation of how hydrologic, habitat, and sediment load factors can be used to prioritize areas of a watershed for multipurpose benefits. Source: Henry Van Offelen.

Additional screening metrics (e.g life-cycle costs, permit likelihood) could also be derived for each potential storage location. These metrics will enable teams to objectively compare and prioritize water storage sites and create a water storage scenario to meet watershed goals.

5. Estimate expected outcomes of adding intended storage

A variety of models have been developed that can help identify estimated effects of best management practices on sediment/nutrient loading and peak flow rates and volumes. Given adequate data and resources a group could identify and screen water storage options in steps above, build water storage scenario(s) for a watershed and evaluate the effects of these practices on hydrology (Figure). However, given the time, cost, and computing power that modeling can require, watershed planners should consider using existing data to identify the most promising storage locations (as discussed above), then estimate the expected outcomes before investing in new models, using some basic rules of thumb. See Table 1 for a quick method for calculating a storage goal in acre-feet based on desired runoff reduction.

Some models in use in Minnesota for building and evaluating scenarios include the following. Each model has strengths and limitations, some of which are noted below.[11]

- The **HSPF** (Hydrologic Simulation Program – Fortran) and the **HSPF-SAM** (scenario application manager) allows users to build landscape and practice change scenarios to estimate the effects on water quality and flow. HSPF is a powerful hydrologic model but requires a high level of technical expertise. HSPF-SAM requires less technical expertise but has limits at present for modeling flow reductions through impoundments and floodplain types of storage. HSPF and HSPF-SAM have been completed for most Minnesota watersheds. HSPF was used to simulate the effects of common best management practices (BMP) on sediment, peak flow, and annual flow reductions in the Le Sueur and Cottonwood River watersheds (see Appendix A).

- The **SWAT** (Soil and Water Assessment Tool) model was used in the Cedar River Basin to identify and prioritize critical source areas throughout the watershed. SWAT was combined with the GSSHA (Gridded Subsurface Hydrologic Analysis) model (see below) to evaluate the effect of non-structural (soil health) and structural management practices in the Dobbins Creek Subwatershed. [12]
- **HEC-HMS** – This USACE's Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) model has been used within the Red River Basin to develop a long-term flood solution plan that set a 20% flow reduction goal for a 100-year flood event on the Red River. The plan sets water storage volume reduction goals for each tributary based on an evaluation of numerous potential water storage sites.
- **XP-SWMM** – This hydrologic and hydraulic modeling software was originally designed for urban storm sewer systems but is now often used to model watershed-wide ditch and river systems. The Cedar River Watershed District developed a watershed model using XP-SWMM to calculate how proposed structural storage practices would help the district achieve flow rate reduction goals in the City of Austin.
- **GSSHA** – the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model is an entirely two-dimensional flow model that the Cedar River Watershed District has used to evaluate the effects of conservation practices in Dobbins Creek, a smaller watershed within the district boundary. While GSSHA is a powerful tool that can calculate the effects of both structural and non-structural practices, it is very computationally heavy and is typically not used for watershed-wide modeling. (See Appendix B).

[11] See also MN Board of Water and Soil Resources, 2019, Water Quality Model, Tool, and Calculator Basics: Reference Guide. http://www.bwsr.state.mn.us/sites/default/files/2019-04/Water_Quality_Model_Tool_Calculator_Basics_Guide.pdf

[12] Appendix to Final Cedar River WRAPS, 2019,

https://www.pca.state.mn.us/sites/default/files/wq-ws4-59a.pdf

- The **Prioritize, Target and Measure Application** (PTMApp) currently identifies potential water storage areas (i.e. drained wetlands) and estimates the effects that building them will have on sediment and nutrient loading. BWSR intends to develop a complementary application based on existing PTMApp input data that will estimate the hydrologic changes expected from implementing conservation practices that effectively store water and/or slow runoff.

Limits of prediction in complex systems

Models are useful tools that can provide good estimates of the effects that water storage practices are likely to have on hydrology at a downstream point of interest. Given the complex interactions between the multiple landscape factors that contribute to a hydrologic response, there is inherent variability associated with the results. Models also have limitations regarding the types of events or outcomes that they can predict. For example, some models can be effective at predicting certain peak flow events but may not be as good at predicting annual and seasonal flows.

The collateral benefits and damages of water storage are also not always predictable. For example, a reduction in peak flow may also reduce sediment loading and improve stream stability, but in some situations it could result in channel aggradation and reduce stream stability. It is difficult to predict the specific quantifiable results. In these situations, a planning group should review available data and use their best judgment to set a reasonable and defensible goal that is achievable within their plan's time frame.

6. Assess factors affecting feasibility of implementing water storage

In the sections above we have identified issues, set goals, prioritized areas to implement practices and identified potential scenarios with specific sites for water storage implementation. While this information is essential to planning and prioritization, additional information is needed to make final decisions about implementation. These include:

Cost of land acquisition

Options for land acquisition needed to develop water storage sites include fee simple acquisition, easement acquisition, and the use of flowage easements that keep land in production except under specific flood conditions. In most watersheds where water storage is needed, at least 80-90% of the land is in private ownership. Furthermore, much of this land is likely to have a high value for agricultural production. Landowners are unlikely to support a strategy that removes high-value land from production, even temporarily. The most suitable candidate areas for storage may include lands with low Crop Productivity Index (CPI) values or lands enrolled in conservation programs such as the Conservation Reserve Program.

Payment rates for easement acquisitions

Easements may be used to compensate landowners for periodic inundation of land at a water storage site. However, current payment rates for some easement programs, based on fair market value, are generally set based on the land's value for habitat and are targeted towards more marginal land. These rates may not be adequate to fully compensate a landowner for the loss of more productive land used to store water.

Restrictions on use of existing private conservation lands

Some existing private lands enrolled in conservation programs (CREP, CRP, and RIM) have the potential to be used to store additional water. Legal restrictions are often in place that prevent these lands for use for additional water storage. For example, lands with conservation easements are typically managed under a conservation plan that identifies specific allowable practices for habitat or water quality improvement. Therefore, it's often unlikely that these plans could be amended to increase water storage capacity.

Wildlife management area enabling legislation

When federal funds such as the Pittman Robertson Act (Federal Aid in Wildlife Management Act, 16 U.S.C. 669-669), are used to establish a WMA, other uses of the land will likely be prohibited or restricted by the U.S. Fish and Wildlife Service, although there may be some situations in which water storage purposes align with habitat protection goals. For example, some wetlands have only been partially restored on Wildlife Management Areas because a full restoration would have extended onto private lands. There may be opportunities to store more water and provide more habitat in these types of wetlands with flowage easements or with acquisition of additional lands.

Environmental review

An Environmental Assessment Worksheet (EAW) can be required for some water storage projects. An EAW is mandatory for any project that will change or diminish the course, current or cross-section of one acre or more of any public water or public waters wetland; other mandatory categories apply to impoundments and certain wetland categories. (Minn. Rules part 4410.4300, subp. 27). Environmental review adds some cost and time to a project, can result in additional permitting conditions, and can result in the "responsible governmental unit" (RGU, which is usually the entity issuing a permit) ordering preparation of an environmental impact statement, which is a substantial and costly undertaking.

Environmental factors, permitting complexity and legal constraints

As discussed above under Section 4.A, storage projects can raise significant environmental concerns, including several laws and legally binding restrictions that may affect the ability to place a water storage practice in a given location. These include (but are not limited to):

- The Clean Water Act (CWA) establishes the basic structure for regulating discharges of pollutants into the waters of the United States, which include public water wetlands, and setting standards for quality of surface waters. Under the CWA a change to frequency, magnitude, and duration of water levels in a wetland may trigger a requirement for a permit from the U.S. Army Corps of Engineers (USACE) under Section 404 of the Clean Water Act.
- The Wetland Conservation Act (WCA) regulates wetlands in Minnesota that are not public waters, with the overarching goal of no net loss of wetlands. The Act is administered by local governments with oversight by BWSR, except for calcareous fens and wetlands affected by mining projects requiring a permit to mine, which are regulated by the DNR. Water storage activities that may change the frequency, magnitude, and duration of water levels in some types of wetlands may require review by the designated local government under the WCA.

- Public waters law (Minn. Stats. § 103G.245): Any change in the course, current, or cross section of a public water, including public water wetlands, requires a public waters work permit from the DNR (some exceptions apply to public drainage systems).
- Dam safety regulations (Minn. Rules parts 6115.0300 – 6115.0520) generally apply to dams that are greater than six feet high and could retain more than 15 acre-feet of water. The regulations apply to any alteration or modification of an existing dam subject to the regulations.

Other potential environmental and legal constraints include the presence of endangered, threatened or special concern species, rare native plant communities (the Natural Heritage Information System), and historic or culturally significant resources in the project vicinity.

Site conditions (i.e. soils, other geotechnical).

Site conditions often limit potential for water storage particularly for large impoundments where soil conditions may limit the height of embankments. These conditions can usually be overcome with engineering techniques, but may increase costs.

Funding

Water storage projects can be expensive. In Red River basin, impoundments typically cost $2,000 per acre-foot of water storage for land acquisition, design, engineering, and construction related costs. Even non-structural soil health practices such as cover crops often have public costs of around $40-50 per acre/per year which is equivalent to $2,000 per acre-foot per year. However, there are numerous funding sources that can defray the costs of storage projects, as shown in Table 5. It's typical for large projects often require multiple funding sources over several years.

Table 5. Typical Funding Sources for Water Storage Projects

Funding Source	Fund or Program	Purposes Typically Supported
Minnesota Management and Budget; MN Legislature	Bonding Funds	All Revenue Bond and State Appropriation Bond programs are approved by the Legislature to fund specific programs or purposes. Bonding funds may support land acquisition, engineering and construction.
Minnesota Department of Natural Resources	Minnesota Flood Hazard Mitigation Program – (aka Flood Damage Reduction Program)	Program uses bonding funds for land acquisition, engineering and construction. Geared toward providing technical and financial assistance to local government units for reducing the damaging effects of floods. Cost-share grants to local units of government can fund up to 50 percent of the total cost of a project.
Board of Water and Soil Resources	Clean Water Fund – Multipurpose Drainage Management grants target critical pollution source areas to reduce erosion and sedimentation, reduce peak flows and flooding, and improve water quality, while protecting drainage system efficiency	Practices include eligible on-field, on-farm, and on-drainage system practices within the benefited area or the watershed of a Priority Chapter 103E Drainage System. Will fund storage beyond what's needed to ensure an adequate outlet.

Funding Source	Fund or Program	Purposes Typically Supported
	and reducing drainage system maintenance for priority Chapter 103E drainage systems.	
Board of Water and Soil Resources	Clean Water Fund – Projects and Practices grants. This competitive CWF grant makes an investment in on-the-ground projects and practices that will protect or restore water quality in lakes, rivers or streams, or will protect groundwater or drinking water.	Practices include stormwater management, agricultural conservation, livestock waste management, lakeshore and stream bank stabilization, stream restoration, and SSTS upgrades.
Board of Water and Soil Resources	Clean Water Fund – Watershed-Based Implementation Funding (WBIF). WBIF is available to watersheds upon approval of a comprehensive watershed management plans developed under the 1W1P Program or the Metropolitan Surface Water Management Act.	Design, acquisition, engineering and construction for projects that protect, enhance and restore surface water quality and protection groundwater/drinking water. A 10% match is required.
Minnesota Pollution Control Agency	Clean Water Partnership, Section 319 Grants	EPA funds Section 319 projects in selected watersheds to address nonpoint sources of pollution. The CWP program provides financial assistance through State Revolving Fund loans to local units of government to lead pollution control projects.
Minnesota Department of Agriculture	Minnesota Agricultural Water Quality Certification Program AgBMP Loan Program	Programs support farms/landowners implementing BMPs to reduce runoff and improve water quality. Can reduce maintenance and repairs to flood damage reduction projects by reducing erosion and sedimentation on adjacent lands through best management practices.
Minnesota Department of Health	Clean Water Funds – Source Water Protection Grants	Small grants may include storage components. Habitat enhancement or land acquisition projects can result in reduced runoff.
Minnesota Department of Transportation	Bonding Funds	Funds to leverage flood damage reduction projects that protect public transportation infrastructure could be used for improved culvert designs.
Minnesota Department of Public Safety - Homeland Security and Emergency Management	Hazard Mitigation Grant Program (HGMP) Building Resilient Infrastructure and Communities (BRIC)	All three programs are offered through FEMA for pre-disaster planning, hazard mitigation projects, and long-term flood risk reduction.

Funding Source	Fund or Program	Purposes Typically Supported
	Flood Mitigation Assistance Program (FMA)	• HGMP is a competitive mitigation grant program for all types of hazards, including flood mitigation. • BRIC funding is used "pre-disaster" to reduce potential damages. BRIC funding can be used to construct storage projects, but a positive benefit-cost ratio must be provided. A 30% match is required (12% for disadvantaged rural communities). • FMA funds projects to reduce or eliminate the risk of repetitive flood damage to buildings and structures insured by National Flood Insurance Program. 25% match required.
Legislative-Citizen Commission on Minnesota Resources	Competitive grants on annual cycle	Land acquisition, project monitoring and research.
Lessard-Sams Outdoor Heritage Council	Habitat Funds	Habitat enhancement projects have included modifications of lake outlet structure, wetland restorations, dam replacement, and floodplain and natural channel restoration.
US Department of Agriculture – Natural Resources Conservation Service	Regional Conservation Partnership Program, PL-566 Program, and Related Funding Sources	Planning and construction assistance • RCPP is a competitive grant program for innovative projects with measurable improvements and outcomes. • Conservation Innovation Grants (CIG) focus on innovative conservation practices; priorities vary from year to year but have included soil health and water storage. • PL-566, Watershed Protection and Flood Prevention Program, helps units of federal, state, local and tribal of government (project sponsors) protect and restore small watersheds up to 250,000 acres. Use in MN has been limited by cost-benefit ratio requirements compared to land values.
US Department of Agriculture – Natural Resources Conservation Service	Environmental Quality Incentives Program (EQIP); Conservation Stewardship Program (CSP)	Assistance to ag producers with planning and implementation of conservation practices. Cover crops, conservation cover, no-till and reduced tillage are common practices in MN.
United States Fish and Wildlife Service	North America Wetlands Conservation Act	Provides matching grants to wetlands conservation projects that support

Funding Source	Fund or Program	Purposes Typically Supported
		migratory bird habitat; 1:1 match required. Wetland restoration may increase storage capacity.
Local government sources and private funding	Watershed districts SWCDs Private companies Foundations	Watershed districts have the authority to levy funds for projects. Some Minnesota companies and foundations have contributed funding for planning and implementation of storage projects.

Adapted from Red River Watershed Management Board

Lifecycle costs

Structural practices typically have one-time upfront costs and a limited but predictable life span, typically 10-25 years, during which time maintenance will be required. Non-structural practices such as cover crops and conservation tillage have lower installation cost, but these costs are usually incurred annually, or the water storage benefits will be lost. The lifecycle costs of different practices need to be determined to compare the costs among different types of practices.

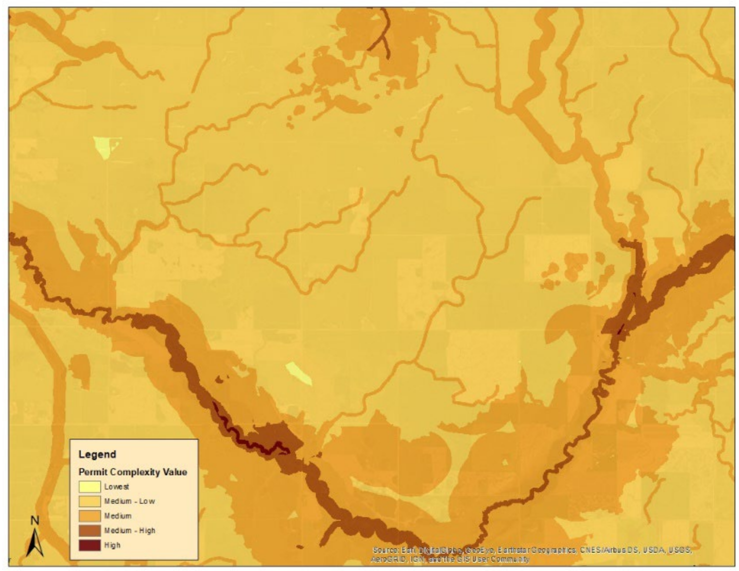

Figure 17. Permit complexity index for an area within the Sand Hill River watershed. Darker areas suggest environmental permitting will be more challenging than lighter areas (Source: Henry Van Offelen).

Screening for feasibility factors

Advanced mapping techniques can be used to help screen areas for some of the factors related to feasibility. For example, land acquisition costs are often related to the Crop Productivity Index. Overlaying potential water storage sites with crop productivity data could help identify those sites with the lowest land acquisition costs. Similarly, GIS data can be developed to identify areas where wetland and public waters related permitting issues are likely to occur (Figure 17). This GIS analysis uses proximity to public waters, wetlands, and rare natural features to develop a permit complexity index.

7. Selecting and Implementing a Water Storage Strategy

This paper has reviewed the multiple considerations and challenges involved in establishing measurable water storage goals, understanding storage practices, setting priorities, and assessing the many factors that come into play when developing a water storage project. Implementing water storage projects and practices is costly and challenging; however, there are numerous examples throughout the state where local governments and landowners have focused on opportunities rather than challenges, and have completed projects. Here are a few lessons learned from these successful implementors:

Early coordination: Given the length of time needed to bring major storage projects to fruition, it is critical to begin discussions with state and federal agencies, especially regulatory agencies, as early as possible. It is advisable to consult with BWSR Board Conservationists, DNR Area Hydrologists, local officials, drainage authorities, conservation staff and others with specialized knowledge or experience before initiating a project.

Plan at a watershed scale: Watershed-scale planning capabilities, which can often be achieved through and subsequent to the One Watershed One Plan process, can offer many advantages in establishing partnerships, setting goals, assessing feasibility of storage options, and identifying and managing funding. Watershed-scale planning also includes the principle that water should be managed as close to its source as possible, rather than sending it downstream.

Set quantifiable goals and state them in adopted plans and studies. Completion of a comprehensive watershed management plan through the One Watershed One Plan program provides access to funding sources (Watershed-Based Implementation Funding) and can also provide advantages when applying for other competitive grant programs.

Land acquisition is key to project success. In some locations, a particular property may be critical to success (e.g. the location of a restorable shallow lake), but in others, there can be considerable flexibility in project siting (e.g. within a subwatershed that is a priority area to reduce peak flows) . In the latter case, an opportunistic approach – in other words, working with any willing landowner – can help to achieve watershed goals. Soil health practices, for example, might be appropriate at any location in a subwatershed.

Funding, phasing and cost-effectiveness: Expect that funding will come from multiple sources over a period of years or even decades. Therefore, be prepared to phase any large project over several years, moving from planning to engineering, design, and permitting. When identifying a water storage strategy, it's important to assess the relative cost-effectiveness of various practices based on their up-front cost, expected life-span, and full life-cycle costs.

See Appendix A for an example of how the Cedar River Watershed District has worked methodically over many years to plan, design and implement water storage projects that reduce peak flow rates while improving soil health and reducing erosion.

Next Steps and Research Needs

As noted in the Introduction, in 2021, BWSR received new appropriations and authorities to partner with local government and landowners to implement a water storage assistance program. This working paper can be used as general guidance for local governments seeking assistance under this program.

While this working paper lays out a general process for identifying and prioritizing water storage opportunities, there is currently no comprehensive approach to prioritize, identify, and assess water storage projects' ability to achieve multiple benefits, such as: improve water quality, improve habitat, reduce flood damages, and increase landscape resiliency to climate change. The following research and training steps will begin building this comprehensive approach.

Support and expand the **cooperative stream monitoring network** operated by MPCA, DNR, USGS and other partners, and encourage establishment of a gage network on smaller watersheds to support improved modeling.

Evaluate how **water storage impoundments and long-term soil health improvements** can potentially help to reduce peak flows and near-channel erosion in selected watersheds.

- Review modeling/research studies on water storage and effects on flow, water quality and other benefits. Recognize regional differences and how the best suites of practices may change from one area to another.
- If impoundments effectively decrease peak flows and near-channel sediment, the next step will be to provide guidance to local watershed partners on siting, prioritizing and estimating the effects of various types of impoundments. The guidance would also show how to link water storage practices to expected outcomes in rivers.

Develop **feasible impoundment options** and conduct a GIS/LiDAR analysis to see where they could be placed and how much water they could store.

- Consider economics and social science aspects of water storage options when determining the most feasible options for GIS analysis.
- Include on-channel and off-channel water storage, including ditches with weirs, flood plain storage options, wetland construction designed for storage, dams, diversions, artificial watercourse opportunities for changes in culvert sizing, etc. Determine suitable lands and opportunities for the different impoundment methods.
- Relate the analysis to percent of runoff and inches of runoff in the area of study, especially during times of major runoff events.

Model the effects of different types of impoundments.

- Use HSPF to model effects on peak flow, near-channel and upland sediment loss reductions, and nutrient loss reductions. Link with other models or tools to estimate the effects on downstream flooding.
- Evaluate the potential for existing models/tools to be adapted for use during watershed plans to evaluate effectiveness of water storage strategies without the need for extensive modeling expertise.

In addition to the effects of different types of impoundments, **model effects of increased soil water storage** that could develop over decades by increasing ridge-till/no-till practices and long-term establishment of cover crops and perennials.

Document and estimate the **co-benefits of strategy practices to be used for water storage** – including benefits for agriculture, water quality and other ecosystem services. Develop an approach for prioritizing subwatersheds where multiple benefits can be achieved to the greatest extent.

Review and develop **coefficients for water storage** that can be incorporated into tools such as PTMApp, ACPF and HSPF SAM. Provide guidance on how to best use these tools for developing water storage strategies.

Assess any potential **unintended climate-related consequences** of storage practices and determine whether such consequences can be avoided or mitigated. For example, there is some concern that nitrous oxide emissions could increase due to denitrification or that methane emissions could increase due to changing water levels in impoundments. Some research has been conducted on emissions from stormwater basins[13], but for agricultural and other nonurban storage, this is an area where further research across a variety of landscapes and land use practices will be needed.

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Appendix A: Case Study – Effects of Storage Practices on Peak Runoff Rates in the Cedar River Watershed District

The Cedar River Watershed District (CRWD), in conjunction with its SWCDs, constructs flow retention structures (storage projects) and conservation practices throughout its watershed to improve water quality and reduce peak flows. The storage projects are intended to reduce peak flow rates in Austin, Minnesota and conservation practices such as cover crops or grassed waterways have been installed to improve soil health and reduce erosion. Individually, these types of projects help the CRWD meet its flood reduction or water quality goals; however, the cumulative effect of both types of practices were unknown until a study was completed in 2020 by the Minnesota Department of Natural Resources (DNR).

A detailed two-dimensional GSSHA (Gridded Surface Subsurface Hydrologic Analysis) model was developed by the DNR that calculated the combined benefits of the storage and conservation projects and was used to better understand their impacts during different sized storm events and rainfall intensities. The study area focused on the northeast portion of the Dobbins Creek watershed (Figure 1). The figure shows the locations of existing Water and Sediment Control Basins (WASCOBs), storage projects (CIPs), Grassed Waterways, and Conservation Reserve Program (CRP) areas in the watershed.

Figure 1 - GSSHA Study Area

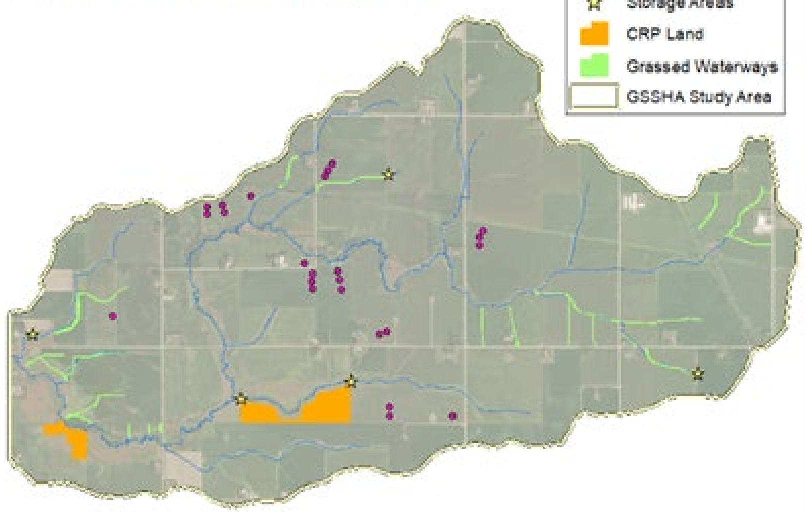
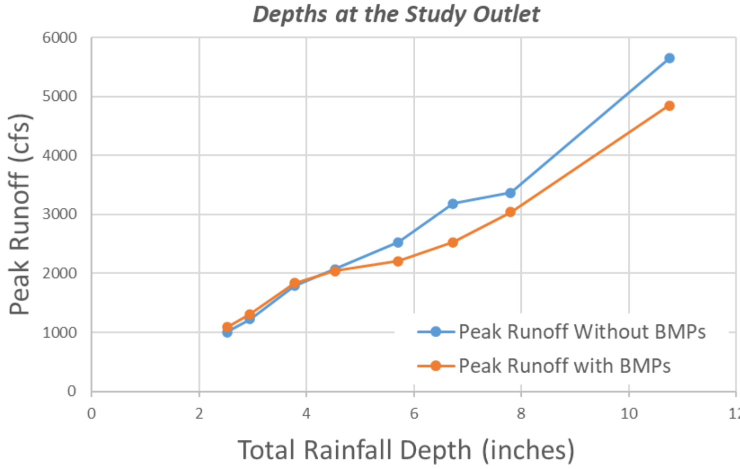


Figure 2 - Peak Runoff Rate for Different Precipitation Depths at the Study Outlet

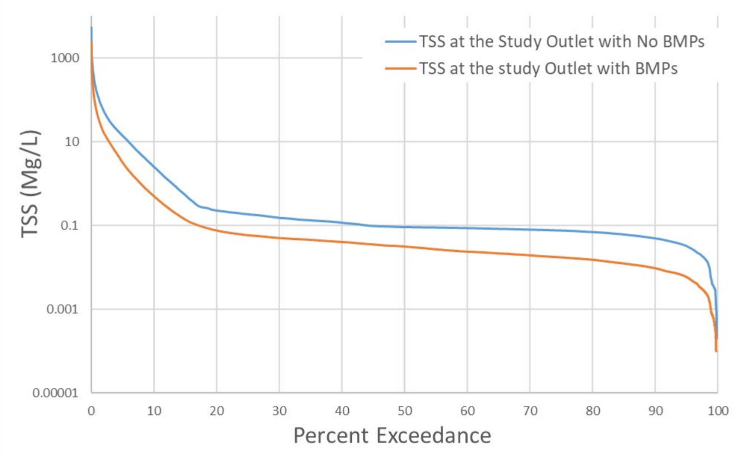


The GSSHA model simulates overland flow, streamflow, and groundwater. Grassed waterways and CRP were simulated in the model by changing infiltration and overland flow characteristics such as hydraulic conductivity, surface roughness, and evapotranspiration. WASCOBs and CIPs were simulated using discharge rating curves that were developed outside of the model. The model was run for storm events ranging from the 1-year, 24-hour event to the 500-year 24-hour event.

Locally, and to a lesser extent cumulatively, the BMPs performed as predicted with regards to peak flow reduction, with the storage projects showing significant flow rate reductions immediately downstream of the structures. The flow rate reductions were attenuated at the outlet of the study area, and due to the placement of the projects, there were even minor increases in flow rate in the channel for smaller storm events (Figure 2). This shows the importance of evaluating the placement of storage practices in a watershed and considering the effects of those practices on all storm events. The cumulative effect of the practices did decrease peak flow at the outlet of the study area for storm events larger than the 10-year event, including a 10-percent decrease in peak flow rate for the 100-year, 24-hour event.

By contrast, the BMPs performed better than expected for water quality treatment. Unlike peak flows, which attenuated as they went downstream, the erosion control practices resulted in direct impacts that persisted downstream. Total suspended solids were reduced throughout the study area and these reductions were also shown at the outlet of the study area. Furthermore, these benefits were observed at the full range of flow rates (Figure 3).

Figure 3 - Comparison of TSS by Flow Rate at the Study Outlet



The CRWD's resourceful approach to implementing various storage practices could be considered a model for the state. The district followed an approach much like what is outlined in the decision support framework for planning for water storage:

1) ***Identify the issue and problems to address through storage*** - Flooding in the City of Austin was the main issue that the CRWD wanted to address when they started their evaluation.
2) ***Set a quantifiable goal*** – The CRWD's goal was to reduce peak flows in Austin by 20%.
3) ***Identify water storage options and set priorities to achieve goals*** – Through a hydrologic and hydraulic modeling study of the watershed, the CRWD decided to focus on the Dobbins Creek subwatershed, a major contributor to peak flows in the city. Structural projects were planned as they would result in the most flood reduction benefits in the city, but other conservation projects have been included because of their water quality benefits.
4) ***Estimate expected outcomes of adding intended storage*** – The watershed wide model was used to estimate the potential impacts of the constructed projects.
5) ***Assess factors affecting feasibility of implementation*** – The watershed district and SWCD have evaluated sites by considering landowner interest, permitting complexity, and feasibility for construction at their sites.

The CRWD has taken an additional step by evaluating the progress towards their flow reduction goal by using their watershed wide model. Watershed-wide, fourteen structural projects have been constructed and peak flows have been reduced an estimated 10% at the Cedar-Dobbins confluence in Austin, MN.

Sources: Minnesota Department of Natural Resources. 2021. *Effects of Best Management Practices on Peak Flow Reduction for the Dobbins Creek Watershed (DRAFT).*

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Appendix B: Case Study – BMP effects on flow and sediment in the LeSueur and Cottonwood River Watersheds; HSPF Modeling Scenarios

As part of the technical assessment to support future revisions of the Minnesota River Basin Sediment Strategy, Tetra Tech (2019) simulated effects of best management practices (BMPs) with calibrated and linked HSPF models (Hydrologic Simulation Program – FORTRAN). Modeling scenarios assessed the potential sediment, "peak" flow (95th percentile) and annual flow reductions that could be achieved by implementing individual or combined BMPs (Figures 1-2 and more detail in Table 1). The modeling effort built on expected BMP performance from the literature and was refined through field-scale models. The study evaluated the effects of BMPs on both near channel sediment sources and upland erosion.

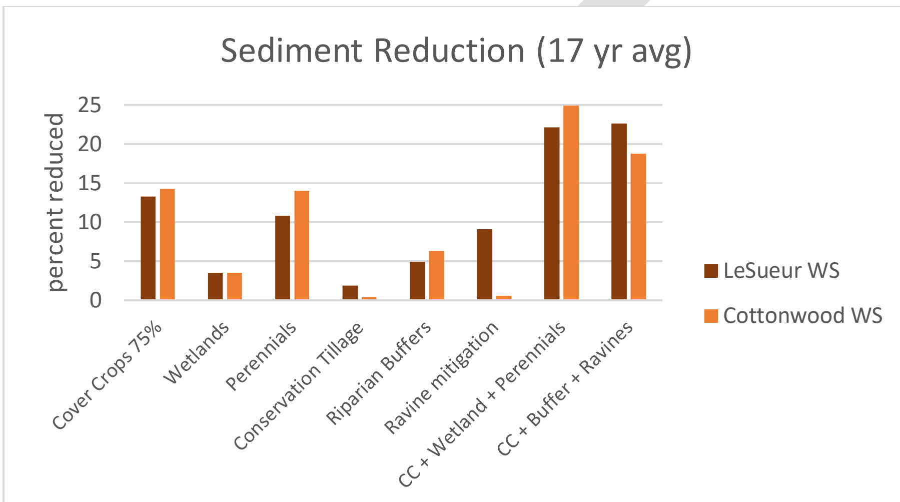

Figure 1. *Annual percent TSS reduction determined with HSPF models in the Le Sueur and Cottonwood River watersheds.*

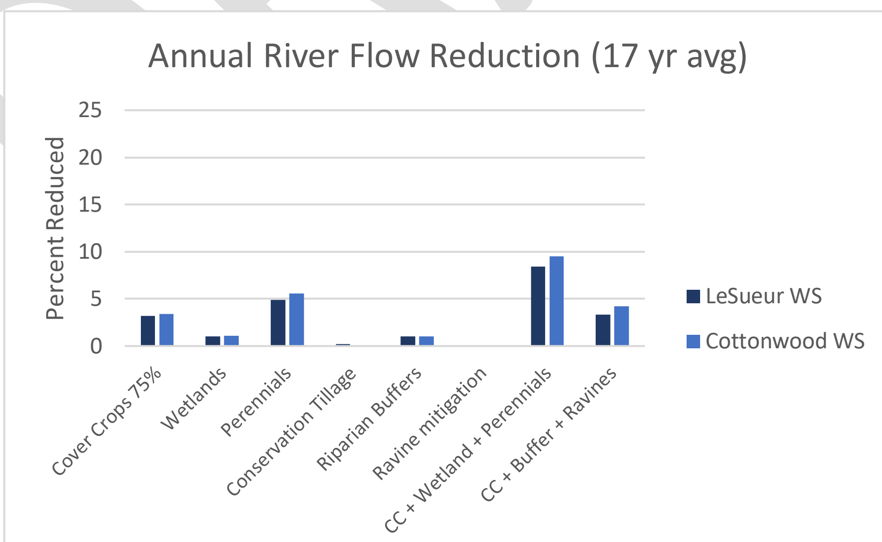

Figure 2. *Annual river flow reduction (%) determined with HSPF models in the Le Sueur and Cottonwood river watersheds.*

Table 1. Percent of TSS and River Flow reductions in LeSueur / Cottonwood Rivers estimated by modeling widespread addition of BMPs (highest reductions shaded yellow).

BMP	Adoption Level	TSS % reduced (17 yr avg)	TSS % reduced (wettest 3 years)	Annual flow % reduced (17 yr avg)	Peak flow % reduced (95th pctl)
Cover Crops	75% of row crops with interseeded rye	13.3 /14.3	12.7 /12.7	3.2 / 3.4	2.2 / 3.4
Wetlands	1% of the land with wetlands - treating 20% of watershed runoff	3.5 / 3.5	3.4 / 2.9	1.0 / 1.1	0.7 / 0.7
Perennials	In rotations 1/5 years or 20% of land during any given year	10.8 / 14	9.8 / 9.6	4.9 / 5.6	6.9 / 7.0
Conservation tillage (CT)	Increase from 60 to 68% of land with CT in Cottonwood; 33% to 70% in LeSueur	1.9 / 0.4	1.9 / 0.3	0.2 / 0.1	0.2 / 0.1
Buffers	Increase from pre-2015 to all public & nonpublic waters and ditches with buffers	4.9 / 6.3	4.8 / 5.5	1.0 / 1.0	1.5 / 1.0
Ravine mitigation	All mapped ravines mitigated with 80% sediment reduced	9.1 / 0.6	6.9 / 0.2	0 / 0	0 / 0
Combo 1	Cover Crops + wetlands + Perennials (adopted as noted above)	22.1 /24.9	20.8 /18.9	8.4 / 9.5	9.3 / 10
Combo 2	Cover Crops + Buffers + ravines (adopted as noted above)	22.6 /18.8	19.5 /16.5	3.3 / 4.2	2.3 / 4.3

Of the six BMPs chosen for high implementation in the two watersheds:

- The largest sediment reductions (10-14%) were from adding cover crops or perennials. Ravine mitigation also had high sediment reductions (7-9%) in the Le Sueur River Watershed.
- Annual flow and 95th percentile flow could be reduced by about 10% with combinations of BMPs adopted at very high levels.
- Modeled sediment reduction scenarios with combinations of practices range from 20 to 25%.
- Most sediment reductions from these BMPs were from upland source reductions rather than near channel sources. To achieve larger flow reductions and associated near-channel erosion reductions, a greater emphasis would be needed on volumetric water storage BMPs (i.e. water held in ponds, wetlands designed for storage, flood plains and channels).

Source:

Tetra Tech. 2019. Best Management Practice Modeling Scenarios for the Minnesota River Basin Sediment Strategy. May 29, 2019, final report prepared for Minnesota Pollution Control Agency by Michelle Schmidt, Jon Butcher, Jennifer Olson and Sam Sarker of Tetra Tech.