Minnesota Wetland Inventory:
Wetland Functional Assessment Final Report & Guidance Handbook

DEPARTMENT OF NATURAL RESOURCES

Science Museum of Minnesota

St. Croix Watershed Research Station

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CONTENTS

1 PURPOSE OF THIS DOCUMENT

The Minnesota Department of Natural Resources (MN-DNR) with funding from the Environment and Natural Resources Trust Fund commissioned an update of the National Wetland Inventory (NWI) resulting in the Minnesota Wetland Inventory. Project oversight, coordination, and quality control of the NWI update were provided by the DNR. Ducks Unlimited provided mapping services for east-central, northeast, and central Minnesota. St. Mary's University of Minnesota provided wetland mapping services for southern and northwestern Minnesota. More detailed information on the Minnesota Wetland Inventory, its development, and key enhancements is provided in Kloiber et al. (2019; https://files.dnr.state.mn.us/eco/wetlands/nwi-user-guide.pdf and https://www.dnr.state.mn.us/eco/wetlands/nwi_proj.html).

The updated NWI for Minnesota has mapped and identified the diversity of wetland types with much improved accuracy. These improvements make the updated NWI extremely valuable to resource managers. During the planning phase of the NWI update, surveys of potential data users identified landscape level wetland functional assessment as an important application. As a result, the NWI update project included enhanced wetland classification attributes that describe hydrogeomorphic characteristics that are often related to wetland function. Nonetheless, these functional assessments are often limited to qualitative evaluations based on best professional judgment.

This project was designed to demonstrate how to use the updated and enhanced NWI as the foundation for conducting watershed-based preliminary functional assessments of Minnesota wetlands. Furthermore, this project seeks to extend previous landscape level wetland functional assessments by incorporating terrain analysis of LiDAR data and other supporting data. This semi-quantitative level of assessment is meant to highlight higher functioning wetlands at watershed scales of management interest, and serve as a precursor to more rigorous in-field evaluations of individual wetland function.

This document proposes several different functional assessment approaches that construct semi-quantitative metrics of wetland function. A metric as defined in this project is a numerical index proportional to the degree of wetland functioning. Example metric datasets are presented for a selection of watersheds totaling over 2 million acres in southern Minnesota. We describe the GIS workflows and scripting methodologies used to build these datasets, which are available on the web (provide URL when available). This report also discusses several approaches for defining metrics based on the desired endpoint of the user as well as several possible alternative GIS/analytical methods for generating any one metric. Throughout the document, we reference existing GIS-based toolsets and functional assessment methodologies that were either used directly or adapted for use in the project, or that provide complementary alternatives for reproducing the data and results presented here.

2 INTRODUCTION

2.1 BACKGROUND

Wetlands provide multiple ecosystem services through their physical, chemical, and biotic functioning. Physically, they can attenuate peak flows, reduce total flows by promoting evapotranspiration, and generate groundwater recharge in some settings. Wetlands improve water quality by trapping suspended sediment, assimilating or adsorbing phosphorus, and removing nitrate by denitrification. In fact, our ability to address nonpoint-source pollution -- arguably the single largest cause of water-quality impairments in Minnesota today -- has been limited by our lack of understanding of how overland flow paths are intercepted by wetlands and how they treat the incoming runoff. Biologically, wetlands provide habitat for fish, wildlife and native plants, including rare species. In particular, wetlands promote biodiversity in agricultural regions dominated by monocultures of row crops where most wetlands have been already lost by drainage.

Because of differences in geometry, topographic setting, hydrology, and vegetation, wetlands are highly diverse and have different capacities for performing these ecosystem services. We believe that there is an overarching landscape-scale knowledge gap in our understanding of wetland physico-chemical hydrologic functioning: How is the functioning of a given wetland affected by any upstream wetlands connected to it by ephemeral overland flowpaths? How do these networks of connected wetlands that fill with runoff and, if they exceed their storage volume, spill over into the next downstream wetland behave in sum at different watershed scales? Understanding the importance and dynamics of connected wetlands using a "fill-and-spill" concept has been the subject of much research (e.g., Shaw et al. 2012; Spence 2007; Shook et al. 2013; Spence et al. 2010; Pomeroy et al. 2014; Cohen et al. 2016) but with little consensus about the aggregate impact of network connectivity on wetland function. The primary aim of this project is to demonstrate the value of the newly updated NWI through an example project that implements terrain analysis and a hydrological fill-and-spill based approach to quantify aggregate landscape-scale wetland function in light of network connectivity.

2.2 SIMPLIFIED HYDROGEOMORPHIC CLASSIFICATION

A key enhancement of the updated NWI was development of the *simplified hydrogeomorphic* classification attributes (SHGM). The SHGM for Minnesota's NWI is a modification of that developed by R. Tiner (2014) for the northeastern United States over the last 15+ years. Tiner's SHGM methodology is based on the more detailed hydrogeomorphic (HGM) assessment process developed by M. Brinson (1993) for the US Army Corps of Engineers in the 1990s. As discussed by Kloiber at al. (2019), the SHGM approach classifies Minnesota wetlands by their landscape position, landform/waterbody type, and water flow path (referred to as the "bare bones LLWW"). Within each of these broad categories, sub-classifications in Minnesota are shown in the table below. A crosswalk table that relates each SHGM LLWW class to Brinson's HGM classes is available in Kloiber at al. (2019).

Table 1. Simplified Hydrogeomorphic (SHGM) classes of Minnesota. *From Kloiber et al. (2019).*

Landscape Position	Landform/Waterbody	Water Flow Path
Lentic (LE) Lotic (LO) Terrene (TE)	Basin (BA) Flat (FL) Floodplain (FP) Fringe (FR) Island (IL) Peatlands (PT) Slope (SL)	Inflow (IN) Outflow (OU) Throughflow (TH) Bi-directional non-tidal (BI) Vertical (VR)
	Lake (LK) Pond (PD) River (RV)	

Using SHGM data, watershed based preliminary assessments of function have been conducted in many areas of the United States. The Association of State Wetland Managers maintains a compiled list of these assessment reports (mainly authored by Tiner) on their website (https://www.aswm.org/wetland-science/wetlands-one-stop-mapping/5044-nwi-reports). A list of functions commonly assessed in these past studies is presented below.

- Surface water detention
- Streamflow maintenance
- Nutrient transformation
- Carbon sequestration
- Sediment and other particulate retention
- Bank and shoreline stabilization
- Provision of fish and aquatic invertebrate habitat
- Provision of waterfowl and waterbird habitat
- Provision of other wildlife habitat
- Provision of habitat for unique, uncommon or highly diverse wetland plant communities.

For more detailed information and rationale for these wetland functions the reader is referred Mitsch and Gosselink (2007) and Tiner (2005).

3 Project Purpose and Overview

The purpose of this project was to develop watershed-level functional assessment methodologies for wetlands by combining terrain analysis and hydrological concepts with the updated NWI dataset. The proposed semi-quantitative, hydrology-based approach presented in this document -- while more complex to implement -- seeks to improve upon more generalized, qualitative approaches to functional assessment such as those based solely on the SHGM. More intensive assessment approaches have incorporated in-field functional evaluation of reference wetlands and correlation to HGM attributes (e.g., Whigham et al. 2007; Cole, Brooks, and Wardrop 1997); however, their applicability on a broad scale is limited by time and financial constraints.

The work of Tiner in many regions of the US has demonstrated use of the SHGM in the "Watershed-based Preliminary Assessment of Wetland Functions" (W-PAWF) approach. These SHGM-based functional assessments assign a "Moderate" or "High" rating based predominantly on correlations between SHGM classifications/sub-classifications and different wetland functions at a defined watershed scale (See Tiner 2003, 2011). Preliminary assessments like W-PAWF are "Level 1" types of assessment, meant for broader scale assessment and planning, and as a precursor to more rigorous in-field evaluations of individual wetland function (Levels 2 and 3; e.g., MnRAM; Minnesota Board of Soil and Water Resources 2010).

However, the generalized scope of SHGM based assessments limits the evaluation of two important functional variables: (1) the upstream watershed conditions that determine surface water and pollutant inputs to a given wetland, and (2) a wetland's ability to affect these inputs as pertains to its designated functions. Building on Tiner's work, Miller et al. (2017) proposed a more rigorous approach that considered these functional variables implicitly and integrated SHGM correlations with GIS derived metrics for a functional assessment of Wisconsin's wetlands. Our project can be seen as building upon the work of Miller et al. conceptually, and so we chose to adopt this terminology as well.

3.1 Overall Approach

For this project, a set of four hydrology-dependent functions were chosen based on the knowledge gap discussed above and Minnesota's focus on reducing runoff, increasing groundwater recharge, improving water quality, and restoring habitat in degraded urban and agricultural watersheds. The selected functions and their primary assessment criteria are listed in the table below.

Table 2. Selected Wetland Functions and Assessment Criteria

Project Function	Example Functions	Assessment Criteria
Surface water	Flood abatement	Storage and/or attenuation of upland surface runoff
Water quality	Sediment/particulate P retention, denitrification	Non-point source pollutant reduction based on surface runoff storage
Groundwater	Watershed drinking water supply, streamflow maintenance	Extent of recharge vs. discharge based on surface runoff storage

Project Function	Example Functions	Assessment Criteria
Habitat	Waterfowl, fish and aquatic habitat	Wetland water level bounce and inter-wetland connectivity based on surface runoff storage and fill-and-spill flowpath results

The overall project approach seeks to extend the enhancements of the updated NWI by using LiDAR geospatial analysis and hydrologic modeling concepts to better infer wetland surface-water, water-quality, groundwater, and habitat functions. The primary conceptual steps of this approach are these:

1. Quantify Wetland Storage by identifying topographic depressions and calculating depressional geometry in each wetland.
2. Predict Wetland Inputs by delineating direct drainage areas of wetlands and simulating runoff and pollutant delivery to each wetland.
3. Map Wetland Connectivity by analyzing the upstream and downstream linkages between wetlands, and between wetlands and the watershed outlet.
4. Quantify Interactions between Steps 1-3 by simulating the flow of runoff and pollutants through each connected wetland's storage to the watershed outlet using a fill-and-spill approach.
5. Analyze Results and Derive Functional Metrics from Step 4 by calculating a suite of proposed "raw" and ranked metrics relevant to each assessed function at multiple watershed scales.

The workflow of Steps 1-4 characterize the "fill-and-spill" behavior of individual wetlands and those connected in a network. Fill-and-spill is a process-based wetland hydrologic concept that describes the integrated effects of storage, runoff and network connectivity on wetland and watershed scale hydrology. Each wetland receives runoff from its direct drainage area, "filling" its available storage volume. If the runoff volume exceeds the wetland's storage volume the wetland "spills". Further, because of connectivity with other wetlands the filling and spilling of any given wetland is also dependent on the outputs ("spills") from any upstream connected wetlands. The fill-and-spill concept is most applicable to ephemerally connected wetlands (i.e., only connected during runoff events), commonly Terrene and Lentic wetlands. Consequently, Terrene and Lentic wetlands are the focus of this project with Lotic function analyzed less rigorously by using an ancillary approach discussed later in the document. Further, this approach is more directly applicable to surface-water and water-quality functions than groundwater and habitat functions. As a result, surface-water and water-quality functional metrics developed in this project are more diverse and detailed in their scope when compared to groundwater and habitat metrics.

3.2 Concept and Use of Wetland Complexes

In many cases, a given NWI polygon will share a boundary with one or more adjacent wetlands that are slight variants differing only in vegetation stature, water depth, or frequency of saturation. Common examples include associations of Terrene Fringe, Flat and Basin wetlands, Lotic Floodplain and River, and Lentic Lake, Fringe and Basin wetlands. In many cases, numerous wetlands of all three SHGM Landscape Position types may all be adjacent forming a large and complex association composed of many different functions and levels of function. In addition, the presence of depressions under portions of these complexes can further aggregate function. For example, the surface-water storage capacity of a basin wetland is based on depressional topography and is an aggregate function of the entire basin, not of the component wetland types, and nor is the associated function (once determined) easily partitioned back among the component types.

The aggregate effect of these associations on specific wetland functions across selected watershed scales necessitated defining wetland "complexes". As used here, complexes may be composed of multiple adjacent SHGM Landscape Position types (Terrene, Lentic, Lotic) and can comprise a considerable areal extent. Further, complexes are aggregated with any LiDAR derived depressions that lie outside their areal boundary owing to cases where mapped NWI polygons were not able to take into account depressional indicators. Thus, complexes were the spatial unit for developing and assigning function metrics for all parts of the project. The complex constituents' individual functional contribution could be roughly estimated (by disaggregating results by individual NWI polygon area or depressional storage), but this was not included in the scope of this project.

In Practice

Complexes need not be aggregated *across* Terrene, Lentic, Lotic SHGM landscape types as done in this project. Perhaps a better approach would be to aggregate *per* SHGM landscape type (Terrene or Lotic or Lentic but not combined) resulting in more functionally distinct NWI complexes that are easier to disaggregate for individual wetland functional assessment. However, adjacent complexes of different landscape types would have to be spatially altered (i.e., separated from each other) via additional GIS development in order for NWI complex subwatershed and connectivity delineation to be conducted.

3.3 Selection of Study Area

A study area was selected for development and analysis of functional metrics (see Figure 1). The extent was increased over the course of the project to comprise 21 watersheds of varying sizes totalling over 2 million acres. The large areal extent of the study area was an advantage for (1) enabling examination of proposed wetland function methodologies in a diverse range of soil, climate and landscape conditions representative of southern Minnesota's watersheds, and for (2) generating example results relevant and usable to the broadest audience possible. A primary requirement was availability of hydro-modified LiDAR data with appropriate level of accuracy (discussed below) at the time of the project start.

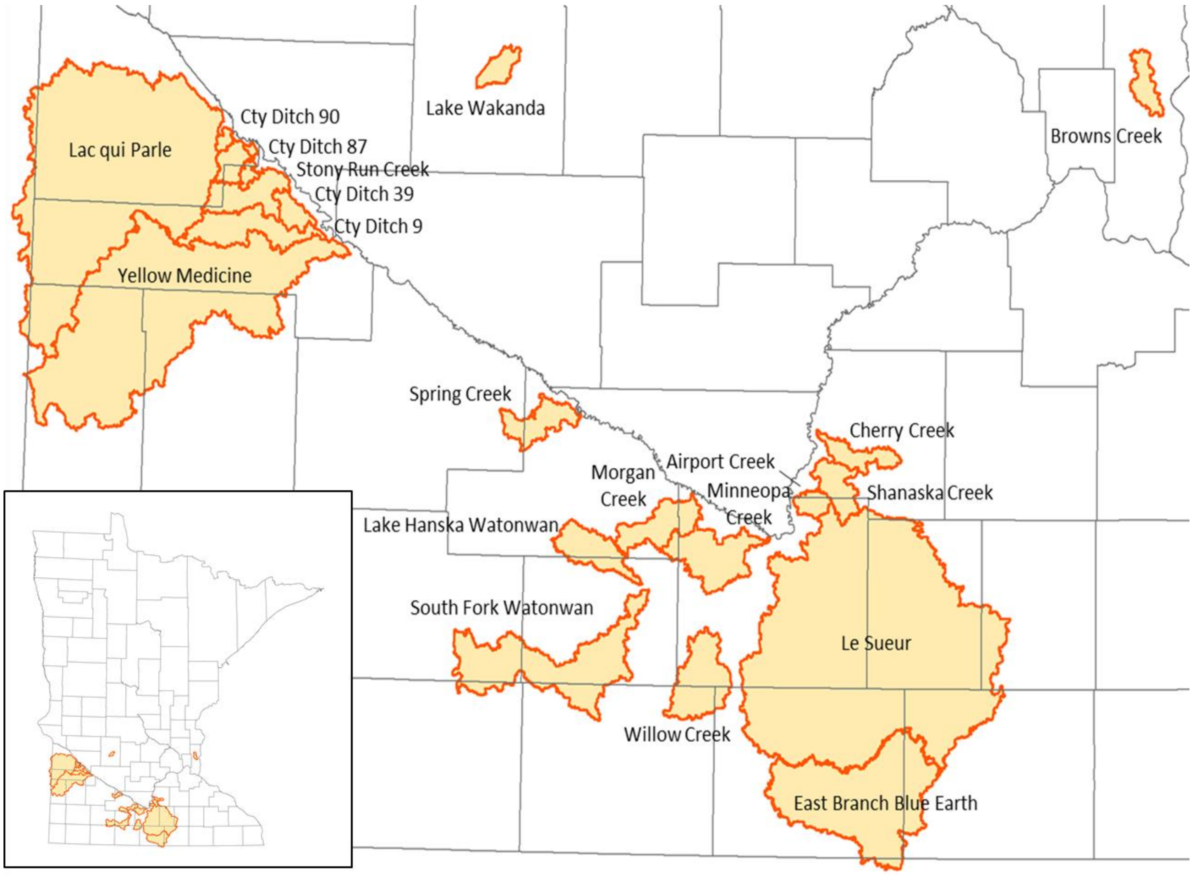

Figure 1: Watersheds of the Project Study Area

4 METHODS

The overall project approach was implemented in the following steps:A summary of each step is presented in the sections below. More detailed information is available in the Appendices where noted.

1. Hydro Conditioning/Modification of LiDAR DEMs
2. Existing Tools and Methodologies Selection
3. Depressional Analysis
4. Wetland and Subwatershed Connectivity Analysis
5. Fill-and-Spill Analysis
6. Extension of Fill-and-Spill Analysis for Water Quality
7. Analysis of Results and Development of Functional Metrics

A summary of each step is presented in the sections below. More detailed information is available in the Appendices where noted.

4.1 HYDRO CONDITIONING/MODIFICATION OF LIDAR DEMS

LiDAR hydro-modification was a necessary step in the project, being critical for ensuring the most accurate watershed-scale flow direction, wetland flow path connectivity, and identification of wetland depressions and storage volumes. LiDAR is hydro-modified to re-route flowpaths by "burning" manually digitized vector lines into the DEM thereby breaching artificial dams (primarily road/driveway embankments that actually have culverts or bridges) that create erroneous impoundments. The hydro-modified LiDAR DEMs used in the project were generated using these vector lines with the Manual Cutter tool available in the ACPF DEM Preparation toolset (version 3). For this project, we used three-meter resolution DEMs, which produced similar results as 1-m DEMs but required much less processing time.

Rick Moore and Sean Vaughn of the MN-DNR provided consultation regarding availability and quality of existing breachline datasets. Jessica Nelson of the Water Resource Center at Minnesota State University provided the Yellow Medicine and Lac-qui Parle/Yellow Bank Watershed District datasets. Karen Kill, administrator of Brown's Creek Watershed District (through Emmons and Olivier Resources Inc.) provided the Brown's Creek dataset; Rick Moore provided the remainder of the datasets.

In Practice

Hydro-modification can be a costly and time consuming effort. For this project, the most rigorous level of modification available ("Level 3") was used. Less rigorous modifications were not evaluated but could suffice depending on the number of wetlands and potential flow obstructions that impact depressional storage volume and flow path connectivity. Related information is discussed in the Depressional Analysis section below.

4.2 Existing Tools and Methodologies Selection

We used existing tools and methodologies where possible. In some cases, methodologies implemented in existing tools were adapted for use in the project without using the tools directly. ArcGIS 10.6 was the primary application used for project development. Within ArcGIS, Spatial Analyst and ArcHydro extensions were implemented in manual operations and used to construct ModelBuilder workflows. In a few cases, ArcHydro python codes were modified for key operations. Amongst several existing ArcGIS toolsets used in the project, the ACPF (Tomer et al. 2015) and PTMapp (BWSR 2016) toolsets were particularly useful. ACPF tools were used for LiDAR hydro-modification and depressional analysis, while several PTMapp approaches to GIS-based hydrology and water-quality modeling were adapted for use in the project. Where ArcGIS could not easily produce needed outputs, codes were written in R open source statistical software (R Core Team 2014). Use of specific tools and methodologies are noted in the sections below.

4.3 Depressional Analysis

Identification of depressions and quantification of depressional geometry – principally, volume – was a critical component of generating the fill-and-spill methodology (discussed above and outlined in detail in subsequent sections).

Depressions are generally identified by subtracting a LiDAR DEM from a filled version of the same DEM using raster GIS tools. However, spurious sinks and depressions are present on most LiDAR DEMs (despite hydro-modification) requiring a process to separate "real" depressional features from artifacts. An advantage of the updated NWI is that one can constrain where depressions can exist thereby reducing errors and saving considerable processing time. Our analysis assumed that depressions (1) must intersect NWI polygons or complexes and (2) not extend beyond a 100-meter buffer around the NWI polygons/complexes. These assumptions facilitated efficient computer processing time by excluding non-wetland areas in the DEM while allowing for depression extents that did not exactly conform to the boundaries of the NWI complexes. Depression locations were further constrained by a minimum surface area of 0.02 acres and a maximum depth of at least 15 cm, corresponding to the smallest NWI polygon surface area in the southern and east-central NWI regions and the reported elevation RMSE of LiDAR datasets in the project study area, respectively. ACPF Depression Identification and Drainage Area tools were used for this step.

Characterization of depressional volume as permanent (i.e., retention) and temporary (i.e., detention) storage was necessary to best predict hydrologic and water-quality impact of wetlands at local and watershed scales. Optimally, wetlands provide permanent storage, which reduces downstream runoff volumes and maximally traps pollutants, while temporary storage can reduce runoff rates resulting in smaller flood peaks and trap a lesser proportion of pollutants per unit volume. However, temporary storage can be mischaracterized as permanent storage if the depression's natural outlet is not large or prominent enough to be captured by LiDAR. Engineered outlets (covered and uncovered) on lakes are another common example of this LiDAR mischaracterization (unless breached by hydro-modification). Similarly, altered agricultural wetlands may be drained via ditches or more problematically by subsurface drain tiles. Efforts were taken to constrain what was characterized as permanent vs. temporary storage by using the updated NWI attributes such as the Cowardin 'd' ("partly drained/ditched") and 'f' ("farmed") flags (i.e., assumed drained by surface or sub-surface drainage =

temporary) as well as the SHGM Water Flow Path (e.g., depressional volume in *Isolated/Vertical* and *Inflow* wetlands = permanent; *Outflow*, *Throughflow, Bi-Directional* = temporary). In cases where permanent storage was designated (by existence of a depression and the Cowardin and SHGM criteria), temporary storage was assumed also be present. Temporary storage was estimated using the median elevation of linear boundary of the NWI complex polygon, which was assumed to be representative of the temporary storage inundation area/elevation. Using this elevation, a raster Fill operation calculated the resulting storage geometry. However, not knowing the true topography of the temporary "basin" and more importantly the outlet geometry, the temporary storage depth was capped at 25 cm for Terrene and Lentic non-lake features and 75 cm for Lentic Lakes features. More detailed information on determining depressional storage volumes is presented in Appendix B: Procedures and Algorithms.

In Practice

This project took a conservative approach to estimating permanent storage, especially in agricultural watersheds where a substantial number of wetlands are known to have been altered to convert permanent storage to temporary. Consequently, considerable effort was put into identifying depressional volumes that are most likely "true" permanent storage for purposes of estimating flood storage and water-quality functioning as accurately as possible. However, this identification and the SHGM/Cowardin attribute approach used in the procedure are not necessarily required for this step if a different endpoint or level of rigor is desired, or if other constraints or professional judgement can be applied.

4.4 Wetland and Subwatershed Connectivity Analysis

This step began with creation of wetland complexes introduced in 3.2. Complexes of adjacent NWI polygons were first aggregated in GIS using an iterative Dissolve operation, and then aggregated with intersecting depressions using a Union operation. This operation produced 20,188 complexes over the study area.

Next, subwatersheds for each complex were delineated using the ACPF Depressional Drainage Area tool producing a patchwork of 20,188 subwatersheds each terminating at the downstream outlet (pour point; point of maximum flow accumulation) of the complex. Connectivity between subwatersheds and down to each watershed's ultimate outlet was mapped using a Cost Path approach whereby downstream flowpaths from each complex were identified using Flow Direction data. ArcHydro was then used (1) to delineate subwatersheds for the remaining areas of each study watershed that did not contain an NWI complex, and (2) to assign next-downstream subwatershed connectivity. These operations resulted in a mosaic of 48,272 subwatersheds with connectivity and depressional geometry attributes where needed for the fill-and-spill analysis (i.e. for the 20,188 NWI complex subwatersheds).

In Practice

The resulting NWI complex subwatershed layer is distinctly different from a typical subwatershed delineation that is dictated by a derived stream network, using an arbitrary drainage area threshold. The project subwatershed layer is designed specifically to delineate each NWI complex direct drainage area and the flowpath connectivity between complexes, leading ultimately to the study watershed outlet. As such, this step relies on a somewhat different set of tools and procedures than a typical subwatershed delineation. See Appendices.

4.5 Fill-and-Spill Analysis

The Fill-and-Spill analysis was used to simulate the flow of runoff through all wetland complexes in the project study area. The procedure utilized the previously derived wetland complexes, storage volumes, and mapped up/downstream connectivity. An R code (R Core Team 2014) loops through all wetland complex watersheds starting with those in the headwaters (i.e., no upstream wetland, first order). Runoff from a set of design storms (1, 2, 5, 10, 25, 50 and 100 year/24 hour) to each wetland complex from its direct drainage subwatershed was predicted via the NRCS curve number method (AMC II) and whatever runoff spilled from the wetland complex permanent storage was routed to the next downstream complex; this upstream to downstream looping continued until a study watershed pour point outlet was reached. Runoff contributing to permanent vs. temporary storage was accounted for and stored as output. Detailed information on this procedure is presented in Appendix B: Procedures and Algorithms.

This approach assumes all runoff is generated simultaneously in all subwatersheds and propagates through the fill-and-spill network instantaneously. As such, a disadvantage is that it does not account for *rates* of runoff generation, runoff routing and wetland filling/spilling. Depending of the variability of wetland sizes and distances between them within a network, our approach will underestimate wetland storage because it assumes all the processes and rates mentioned above occur and propagate downstream to the pour point instantaneously, ignoring potential losses to infiltration and evaporation. Not considering rates also ignores backwater effects whereby a wetland depression could conceivably fill and merge with one or more upstream depressions (decreasing their utilizable storage) or flow into adjacent depressional networks not normally linked topologically (Chu et al. 2013).

In short, the approach does not take into account the complex hydraulic behavior that depends on parameters not generally known for each NWI complex (e.g., outlet geometry, water surface, rates of runoff flowing into the wetland). Nonetheless, the project approach remains a significant improvement for more explicitly estimating and comparing hydrologic function within and between wetlands/complexes.

In Practice

The use of an average "antecedent moisture condition" - AMC II - for the curve number modeling was potentially impactful because it assumed drier conditions than might be expected on average in the spring. Under spring conditions more runoff would generally be expected, potentially limiting the amount of runoff stored in wetlands as a proportion of total runoff. Application of the fill-and-spill approach would likely benefit from use of the wetter "AMC III" for runoff calculation depending on the context of the analysis. Equations exists to convert AMC II curve numbers available for the state via PTMapp (BWSR 2016) to AMC III (or the drier AMC I).

4.6 Extension of Fill-and-Spill Analysis for Water Quality

The water-quality function of a wetland complex is its ability to trap or reduce incoming pollutants, commonly nonpoint-source sediment and nutrients. Part of this function depends on factors external to the wetland complex, namely, the load of sediment and nutrients delivered to the wetland. All other factors remaining equal, a larger pollutant load implies at least the potential for larger removal, i.e., a greater water-quality function. Water-quality function also depends on factors internal to the wetland complex, especially the hydraulic residence time, which in turn depends on both flow rates and storage volumes. A larger residence time would generally imply a greater water-quality function.

To most explicitly predict sediment erosion and transport as it pertains to wetland trapping processes, event based simulations that incorporate flow rates are most appropriate. However, the widely used RUSLE model (e.g., as implemented within PTMapp) is an annualized prediction model and therefore cannot take into account event-based runoff rates and volumes for erosion prediction. A more appropriate method is the event-based MUSLE model (Williams 1975, and used in the model SWAT; Arnold et al. 1998) which uses the same multiplicative factors for as the RUSLE model (R, C, K, LS, P) except that it replaces the annual rainfall erosivity factor R with a runoff factor that is composed of peak runoff rate and total runoff volume. This approach avoids the necessity of estimating a sediment delivery ratio.

In this project, flow rates were estimated to the extent that peak flows could be derived. Peak flows are important for developing a relatively simple but explicit approach for simulating sediment and phosphorus erosion masses for each subwatershed for a representative design storm event. These pollutant masses served to identify subwatershed source hotspots (relative to a larger watershed scale) and provide estimates of pollutant inputs to NWI complexes for estimation of relative water-quality function. Summaries of the steps in the methodology are presented below. More detailed information is presented in the Appendices.

4.6.1 Estimation of subwatershed peak flows

Subwatershed peak flows required for MUSLE modeling were calculated using an approach that estimated subwatershed flow velocities across each 3 meter pixel in the LiDAR DEMs and analyzed the resulting statistical distribution of these flow velocities in terms of each pixel's travel time to the subwatershed outlet. From this information, estimated flow hydrographs were constructed for a 2yr/24hr design storm. General steps in this process are listed below and presented in more detail in the Appendices.

1. Calculate per-pixel travel times based on MnDNR Travel Time Tool.
2. Calculate accumulated travel times to each subwatershed outlet and output resulting travel time distributions using custom ModelBuilder workflow.
3. Convert subwatershed travel time distributions to runoff hydrographs using R code.

In Practice

The project approach for calculating peak flows is relatively complex and requires advanced GIS skills and development of codes in a python or R environment. Peak flow rates are a required input of the MUSLE model but may be estimated using less complex methods based on available variables such as runoff volume and subwatershed drainage area (USDA 1986; Chow 2010).

4.6.2 Prediction of water quality pollutant export and fill-and-spill integration

An existing GIS toolset (Blaszczynski 2003) designed to implement MUSLE using subwatershed peak runoff rates and total runoff volumes while also accounting for subwatershed Flow Accumulation patterns was adapted to predict sediment erosion mass from each design storm delivered to the subwatershed outlet. Primary inputs for this modeling approach were the total runoff volume (from curve number runoff calculation in fill-and-spill approach) and peak runoff discharge rate (calculated in previous step). Phosphorus mass was predicted by applying concentration factors to sediment mass whereby a unit mass of phosphorus was generated per unit mass sediment and the results incorporated in the fill-and-spill methodology. General steps in this process are listed below and presented in more detail in the Appendices.

1. Predict design storm sediment/phosphorus loads using GIS enabled MUSLE model.
2. Extend design storm sediment loads to include associated phosphorus.
3. Incorporate flow rates and sediment/phosphorus transport into fill-and-spill methodology.

4.7 Analysis of Results and Development of Functional Metrics

These sections present the approaches for analyzing results and generating a suite of proposed metrics meaningful for assessing wetland functions. However, these approaches and proposed metrics are not intended to limit or exclude other potential interpretations or adaptations. Rather they are intended as a starting point to promote further development as needed that can take into account scales and functions of individual interest, and factor in professional judgement as appropriate.

4.7.1 Surface Water and Water Quality function

The foundation for developing metrics of wetland function was the hydrologic and water quality fill-and-spill analysis. The analysis produced a considerable number of outputs, each with potential application for inferring wetland function. Examples of numerical outputs generated for each NWI complex are listed below.

Predicted hydrology functional metrics for each design storm (1, 2, 5, 10, 25, 50, 100yr/24hr):

1. Runoff from subwatershed (direct drainage area)
2. Runoff received from upstream subwatersheds (from upstream wetland “spills”)
3. Volume and ratio of runoff stored permanently
4. Volume and ratio of runoff stored temporarily
5. Total volume of runoff spilled downstream
6. A Yes/No flag indicating whether NWI complex subwatershed contributed flow to outlet

Predicted water quality (WQ: sediment, particulate phosphorus, nitrate) functional metrics for 2yr/24hr design storms:

1. WQ inputs direct drainage area
2. WQ inputs received from upstream (from upstream “spills”)
3. WQ inputs mass and trapping efficiency ratio stored permanently
4. WQ inputs mass and trapping efficiency ratio stored temporarily

Visualized using GIS, these results provide a first cut at assigning individual NWI complexes a relatively high or low function; however, potentially more useful metrics were also derived by percentile ranking each NWI complex result within different watershed scales (HUC-8, -10, -12) of common management focus. Further, results were *normalized* by watershed scale sums to add additional context for interpreting watershed function. Examples include:

1. Percent of total watershed runoff and WQ mass received by each NWI complex
2. Percent of total watershed runoff and WQ mass trapped or reduced by each NWI complex

A possible further step in metric analysis would be converting numeric outputs or percentile ranks at watershed scales into a metric based scoring system for a simpler conveying of metric results (e.g., 1=Low=0-33%, 2=Medium=33-66%, 3=High=66-100%). However, inferring function from the metric results requires some oversight from the user. Distributions of results within watershed scales may not vary enough to justify grouping metric numeric outputs or percentile rankings uniformly (i.e., Low,Medium,High) or at all (i.e., one score for the entire set of outputs). Creating scoring "rubrics" based on the shape of metric distributions (e.g., normal, log-normal, uniform) will create more realistic and useful interpretation and valuation of NWI wetlands/complexes. A helpful tool for visualizing metric data is ArcGIS which by default creates symbology using the Jenks natural breaks classification method, a form of cluster analysis that seeks to create groups (clusters) such that the variance between data *within* groups is minimized while the variance *between* groups is maximized.

4.7.2 Groundwater function

Groundwater interaction with wetlands is critically important but difficult to demonstrate, at least in detail. Groundwater can play a key role in wetland hydrologic function and thus influence the ability of wetlands to improve water quantity, quality or to provide good habitat.

The project approach for deriving metrics of groundwater function focused specifically on determining the extent to which a given NWI complex provides groundwater recharge versus discharge capability. The assumption is that both recharging and discharging wetlands can provide valuable functions (e.g., groundwater supply, drought resilience, baseflow maintenance, etc.). In some cases, recharging and discharging functions are coupled whereby recharging function provides the wherewithal for discharging function.

The approach aimed to leverage the results from the surface water function fill-and-spill results whereby the degree to which a wetland permanently stores runoff volume (i.e., a function of permanent/retention storage and total incoming upstream runoff volume) is the principal indicator of groundwater (recharge) function. The relative amount of recharge occurring in a given NWI complex in relation to recharge occurring in other watershed scale wetlands (via permanent storage of runoff) plus uplands (via infiltration) was a primary functional metric-- i.e. if a watershed infiltrates a relatively large volume of water prior to runoff generation, recharge from runoff stored in downstream NWI complexes is less important than in a watershed with less infiltration capacity.

Following this approach, groundwater function was assessed in the following steps:

1. Create subset of NWI complexes that contain Terrene features with available permanent storage and determine amount of runoff stored from a representative design storm (from fill-and-spill results; assume 1yr/24hr).
2. Rank NWI complexes based on estimated volume recharged based on runoff volume stored as a fraction of total watershed (HUC-12/10/8) design storm precipitation.

4.7.3 Habitat function

As with the other approaches in this project, deriving metrics of habitat function specifically leveraged the results from the surface water function fill-and-spill procedure. We therefore propose approaches at assessment based on the extent of runoff permanently stored in NWI complexes (i.e., determined by the available permanent storage volume and the amount of runoff that flows into it).

For example, the measure of water level stability (or “bounce“) is important for predicting where temporary hydrologic conditions dependent on overland flow inputs provide safe habitat for shallow-water, ground-nesting birds and aquatic-obligate organisms (e.g., dabbling ducks, their food sources and nesting locations). In these temporary wetlands (in which temporary is defined in longer – e.g., seasonal – time scales and is associated with *permanent* storage as defined in this project), water level should be high enough to promote food gathering and nesting but not too high.

Additional predictive factors for suitable shallow water habitat were explored in Specht et al. (2018) using the updated NWI in east-central Minnesota. Of those factors, edge complexity (the ratio of wetland perimeter to the perimeter of a perfect circle with equal area) was determined to be a significant positive predictor of dabbling duck feeding and nesting success. Edge complexity aims to quantify shoreland nesting availability whereby increasing complexity indicates a larger area of nesting habitat in proportion to wetland surface area (as discussed in Specht et al. 2018 citing Mauser et al. 1994).

Using these concepts, this project used the following approach to estimate the degree of temporary, shallow water habitat suitability in each NWI complex:

1. Create subset of NWI complexes that contain Terrene wetlands with a Cowardin moisture regime of A, B, or C (“Temporarily Flooded”, “Saturated” or “Seasonally Flooded”, respectively).
2. Determine available permanent storage and amount of runoff stored from a representative design storm (assume 1yr/24hr).
3. Rank NWI complexes based on their deviation (higher or lower) from an assumed optimal (mean) depth of 10 inches (i.e., targeting dabbling ducks and associated species).
4. Rank NWI complexes based on degree of edge complexity (of the depressional feature(s) comprising the permanent storage volume).

A second approach more generally assessed fish and aquatic habitat function associated with the degree of connectivity between temporary terrene, lentic and lotic features and perennial, open water Lentic/Lotic NWI features. The general approach is used in the context of individual wetlands in the work of Miller et al. (2017), but applied in this project, assumes function in NWI complexes increases with the (1) diversity (e.g., lotic, lentic, terrene) and (2) potential for seasonal flooding/inundation (expressed in this project as permanent storage) of adjacent features in NWI complexes.

As such, the second approach assessed habitat function in the following ways:

1. Identify NWI complexes with (1) Lentic or Lotic open water NWI features <u>and</u> (2) permanent storage associated with Terrene or non-open water Lentic features.
2. Rank NWI complexes based on indexes composed of ratios of Terrene or non-open water Lentic area to overall NWI complex area and permanent storage to overall NWI complex area.

5 Study Area Results and Applications

Results were derived for the 21-watershed study area using the methods described above. These data are downloadable for review and use by interested readers. This section presents examples of these results data for a single HUC-12 watershed, and demonstrates hypothetical/proposed applications of the data. In addition, applications of the methods and results data for areas *outside* the study area are discussed. TablesTable 4 -Table 6 contain fill-and-spill results for each of the 21 study area watersheds.

5.1 Study Area results and demonstration

Example project results from the study area are presented for a watershed within the Le Sueur HUC-8 watershed. The Le Sueur is an agriculturally dominated watershed that has been heavily altered hydrologically, and is the subject of much research on its runoff and pollutant export to the Minnesota and Mississippi Rivers. Within the Le Sueur, the “Little Le Sueur” headwaters HUC-12 watershed (15,485 acres) was selected to demonstrate example results at an interpretable scale (See Figure 2 and Figure 3) for a single design storm (2yr/24yr; 2.7 inches). The Little Le Sueur is predominantly agricultural with some significant inclusions of grassland in the west and east central areas of the watershed. Soils are generally loams, silt loams, clay loams and silty clay loams with a hydrologic soil group of ‘B’.

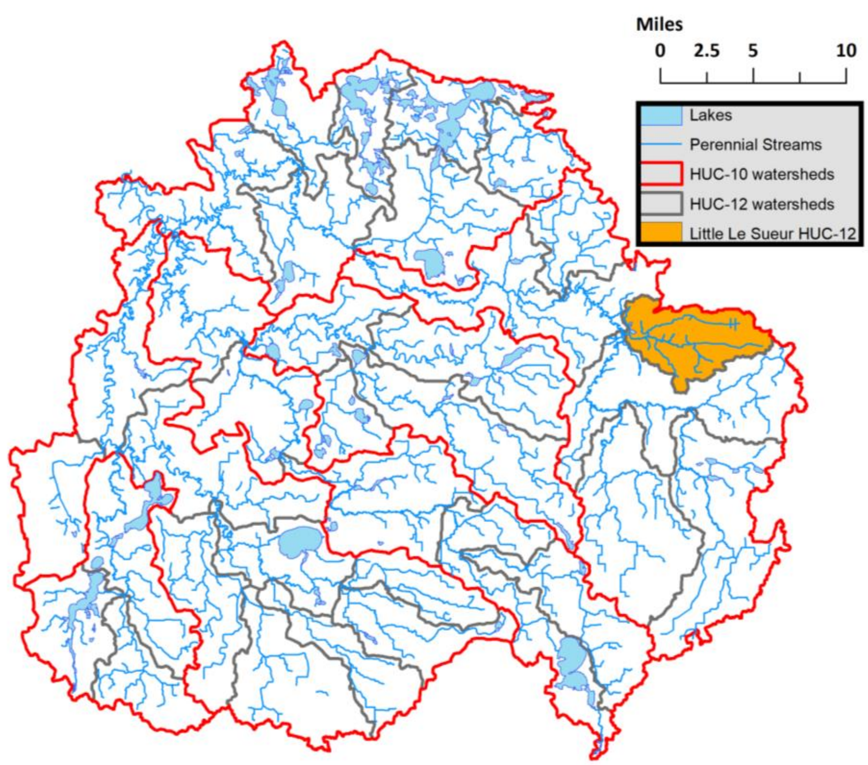

Figure 2: Le Sueur HUC-8 watershed with example HUC-12 watershed (Little Le Sueur) highlighted in orange.

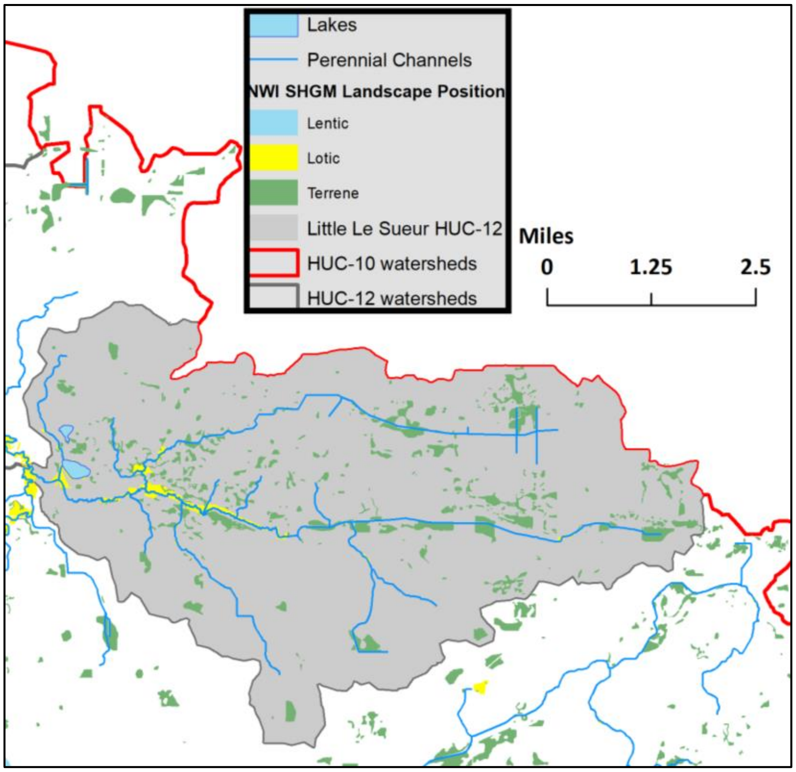

Figure 3: Little Le Sueur Watershed showing NWI SHGM Landscape Position distribution. Note: watershed outlet (pour point) is on the western side of the watershed.

5.1.1 Surface Water and Water Quality Function

For the fill-and-spill analysis, NWI complexes, connecting flowpaths and resulting subwatersheds were derived as discussed in the Methods section. FiguresFigure 4 andFigure 5 depict the 325 NWI complexes and connecting flowpaths, and 707 subwatersheds (325 containing NWI complexes) that were delineated for the watershed. Depressional analysis quantified storage volume in the watershed; however, as most NWI complexes in the watershed were composed of ditched/partly drained or farmed (Terrene) wetlands ('d' and 'f' Cowardin modifiers, respectively), a significant proportion of depressional volume was designated as 'temporary' rather than 'permanent' for purposes of the fill-and-spill modeling. Constraining the depressional storage in this manner resulted in significant shifts in level of wetland function at the NWI complex scale and watershed scale (i.e., the assumption that permanent storage is weighted higher than temporary). Figures Figure 6 andFigure 7 show the distribution of estimated permanent and temporary storage in the watershed.

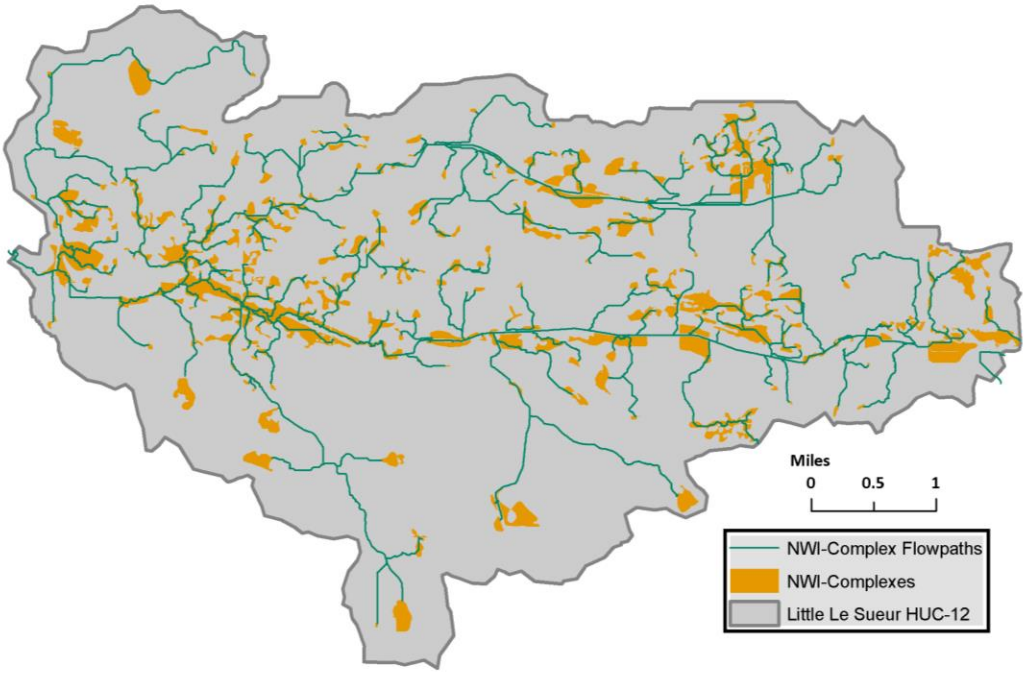

Figure 4. NWI complexes and connecting flowpaths for Little Le Sueur HUC-12 watershed

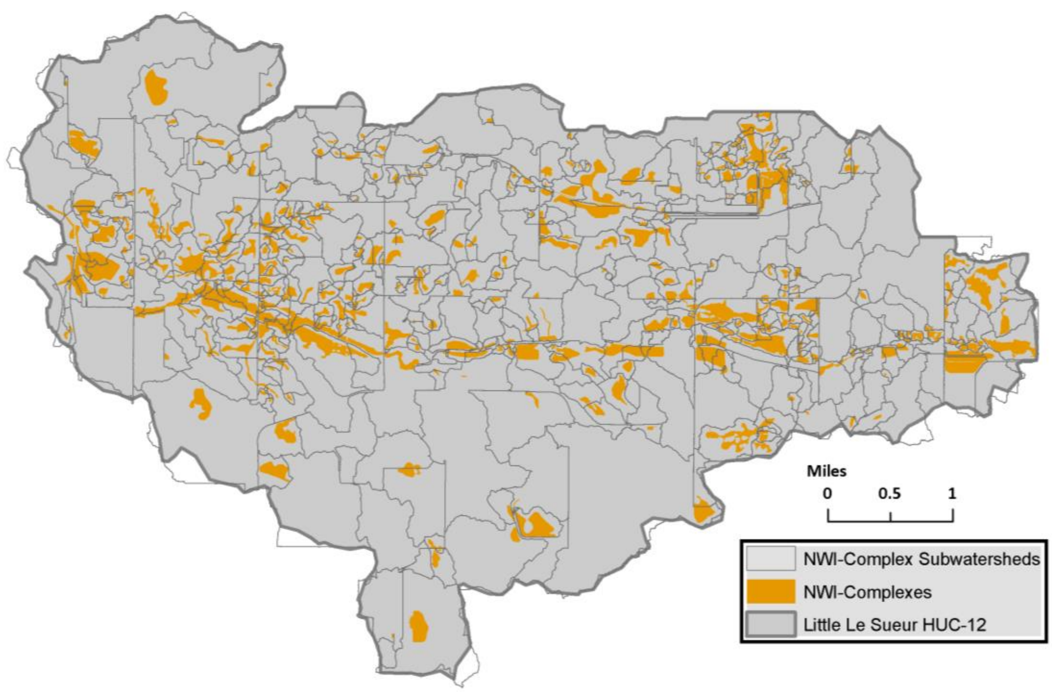

Figure 5: NWI complexes and direct drainage subwatersheds for Little Le Sueur HUC-12 watershed

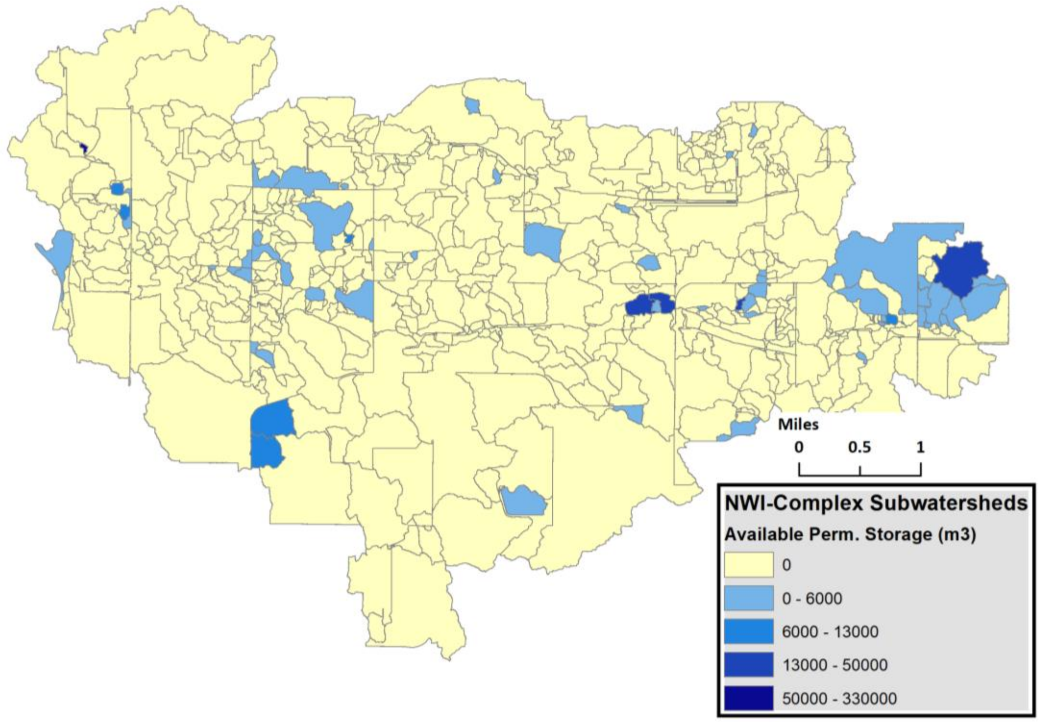

Figure 6: Available permanent storage volume for NWI complexes (but displayed for clarity at subwatershed scale) for Little Le Sueur HUC-12 watershed

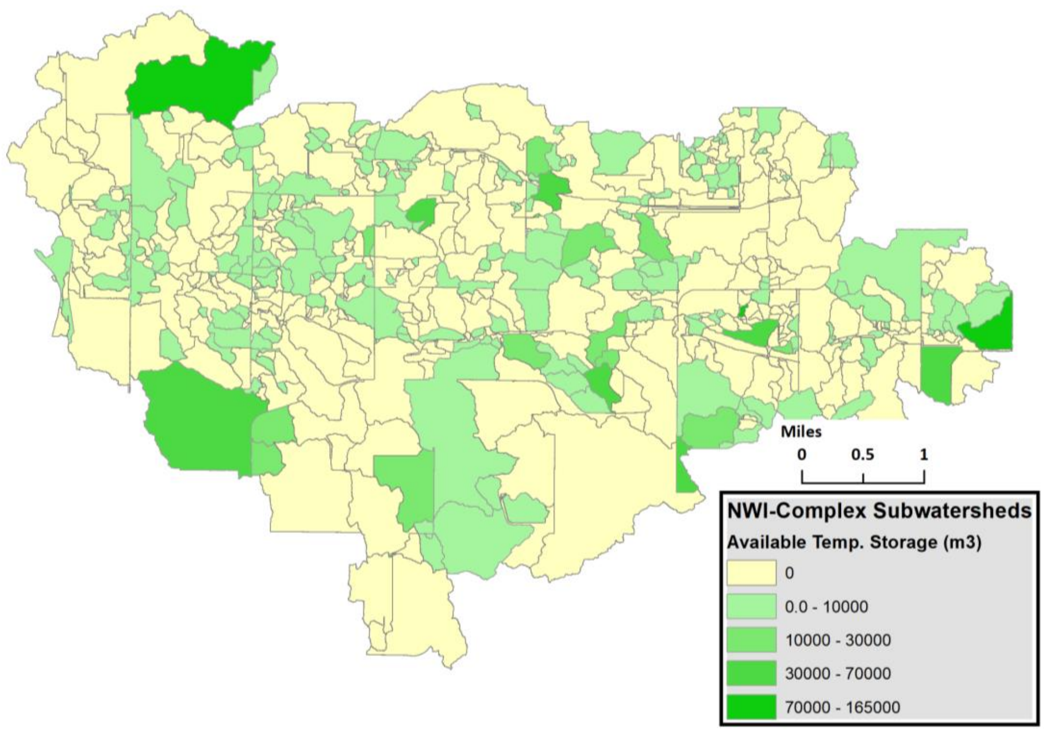

Figure 7: Available temporary storage volume for NWI complexes (but displayed for clarity at subwatershed scale) for Little Le Sueur HUC-12 watershed

Results of the runoff and sediment fill-and-spill analysis for a 2yr/24hr design storm are shown in Figures Figure 8Figure 12. The 2yr design storm (i.e., 50% chance of occurring in a given year) was selected as a demonstration because it is generally assumed to produce a significant flow event, and in smaller watersheds, a low magnitude river/stream flood event (i.e., over-bank). Predicted runoff for each NWI complex subwatershed (i.e., runoff originating in the subwatershed before "filling" and "spilling") is mainly a function of subwatershed size as the variability of curve numbers was low over most of the watershed. Predicted eroded sediment mass is a function of predicted subwatershed peak flow rate and total runoff volume, slope and soil type (USLE K factor). Wetland results intended for use as functional metrics include predicted runoff and sediment storage – in terms of volumes/masses as well as percentages normalized by HUC-12 aggregated sums. Note: erosion and storage of particulate phosphorus and nitrate were analyzed as well (See Methods), and are included as part of the study area results, but are not presented here.

Example figures presented here illustrate the types of NWI complex scale assessment possible with the approach and results data (but do not include all generated outputs). Possible applications of these results data include:

- Areas in the watershed with most and least wetland storage relative to their runoff and sediment inputs
- Areas to target wetland restoration
- Wetlands that need special focus because of high function (e.g., wetlands that store their direct drainage runoff as well as significant upstream inputs from "spills")
- Areas contributing and not-contributing during specific design storms
- Areas where wetland function is high and redundancy is present

At the watershed scale, aggregated function can assessed for an overall picture and/or for comparison with other watersheds of the same scale. The table below presents select outputs aggregated for the Little Le Sueur HUC-12 watershed.

Table 3: Example Metric Results for Little Le Sueur HUC-12 Watershed

Metric	**Value**
Area of watershed (ac)	15,485
NWI wetland area (ac)	978
NWI wetland/complex area as percent of total watershed area	6
Runoff:	
Precipitation depth from 2yr/24hr storm design storm (in.)	2.7
Predicted runoff from 2yr/24hr storm (m^3)	960,092
Available NWI perm. storage vol. (m^3)	646,550
Available NWI perm. storage vol. as % of predicted runoff	67
Available NWI perm. storage vol. utilized for predicted runoff (m^3)	75,736
% Predicted runoff stored in available NWI perm. storage	8
% Available NWI perm. storage vol. utilized for predicted runoff	12
Sediment:	
Predicted sediment erosion mass from design storm (ton)	18,152
Predicted sediment erosion mass trapped by NWI perm. and temp. storage (ton)	7,890
% Predicted sediment erosion mass trapped by NWI perm. and temp. storage	43

Results in Table 3 show that while wetlands comprise 6% of the watershed by area, their permanent storage volume is perhaps a surprising 67% of the predicted runoff from a 2yr/24hr storm event. However, the fill-and-spill modeling results estimate that only 8% of this predicted runoff is actually stored (i.e., intersects dominant runoff flowpaths) and 88% of the total available storage volume is not utilized (i.e., 100%-12%). These results reinforce that wetland storage and inter-wetland connectivity is not often distributed uniformly in a watershed with respect to its runoff distribution. However, 43% of predicted eroded sediment from the design storm is estimated to be trapped in wetland permanent and temporary storage (as predicted by the relationship between available storage volume and incoming runoff volume – See Methods). This relatively high sediment storage proportion would seem to indicate that wetland storage is located in areas downstream/-gradient of dominant sediment erosion sources (i.e., row-crop agriculture with relatively high slopes and erodible soils). Note: fill-and-spill sediment erosion modeling was only conducted for the 2yr/24hr design storm; however, runoff modeling was conducted for all design storms (See Methods).

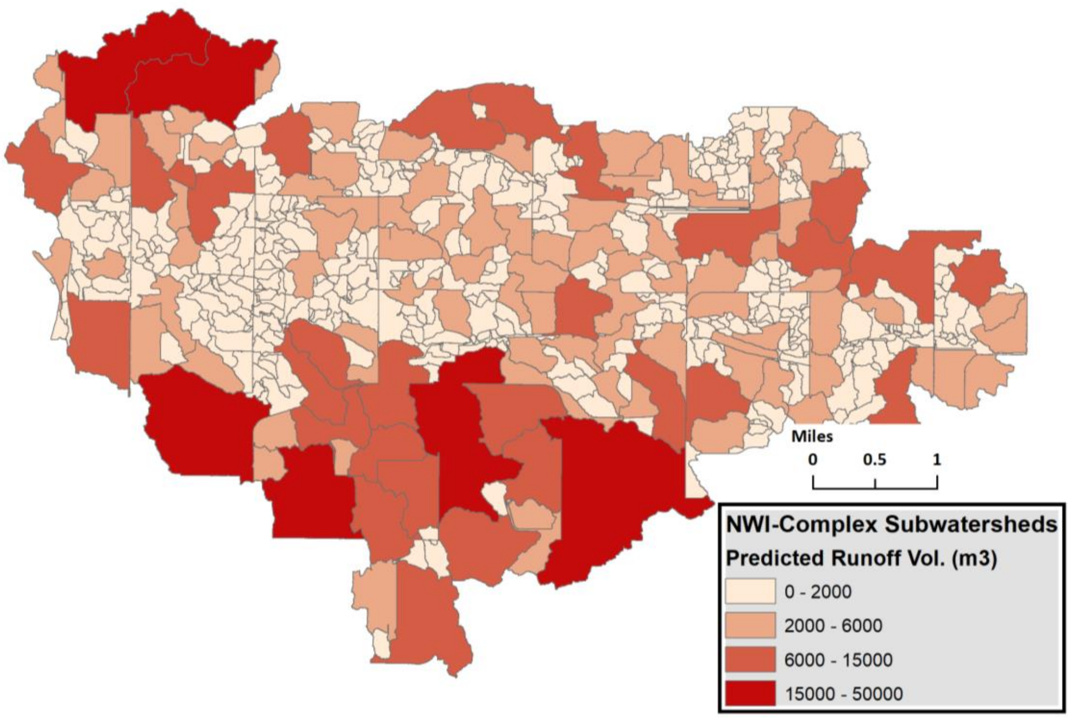

Figure 8: Predicted runoff volume for each NWI complex subwatershed for Little Le Sueur HUC-12 watershed. Because relative uniformity of soil and landuse conditions, runoff volume variability is mainly a result of subwatershed size.

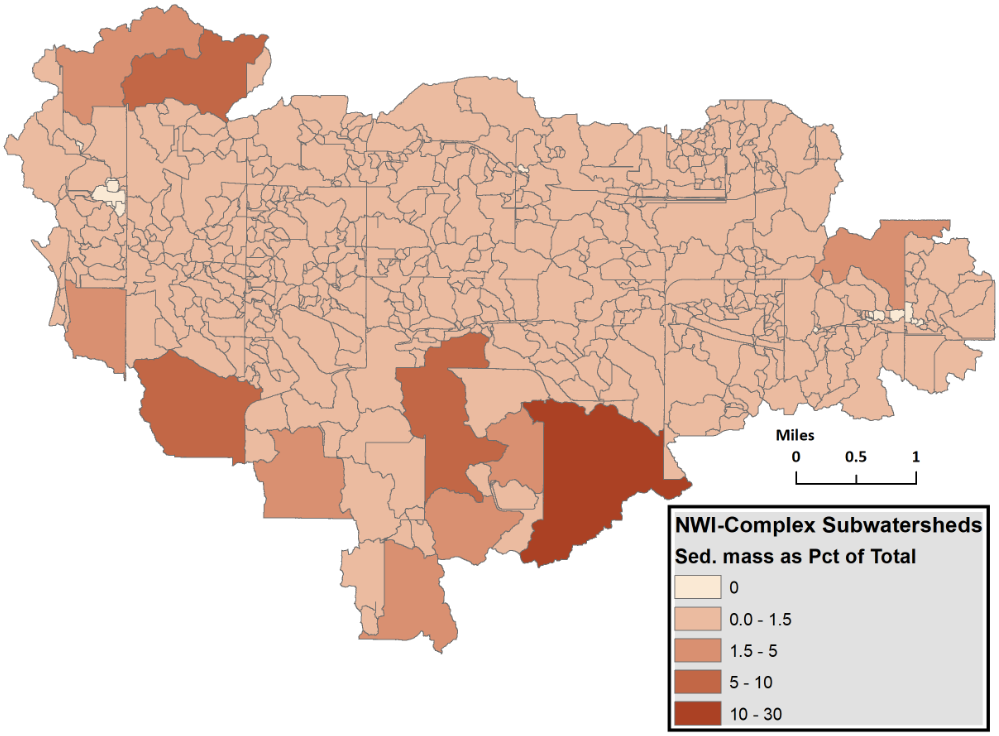

Figure 9: Predicted sediment erosion mass in NWI complex subwatersheds for Little Le Sueur HUC-12 watershed. Expressed as percent of total predicted sediment mass across entire HUC-12.

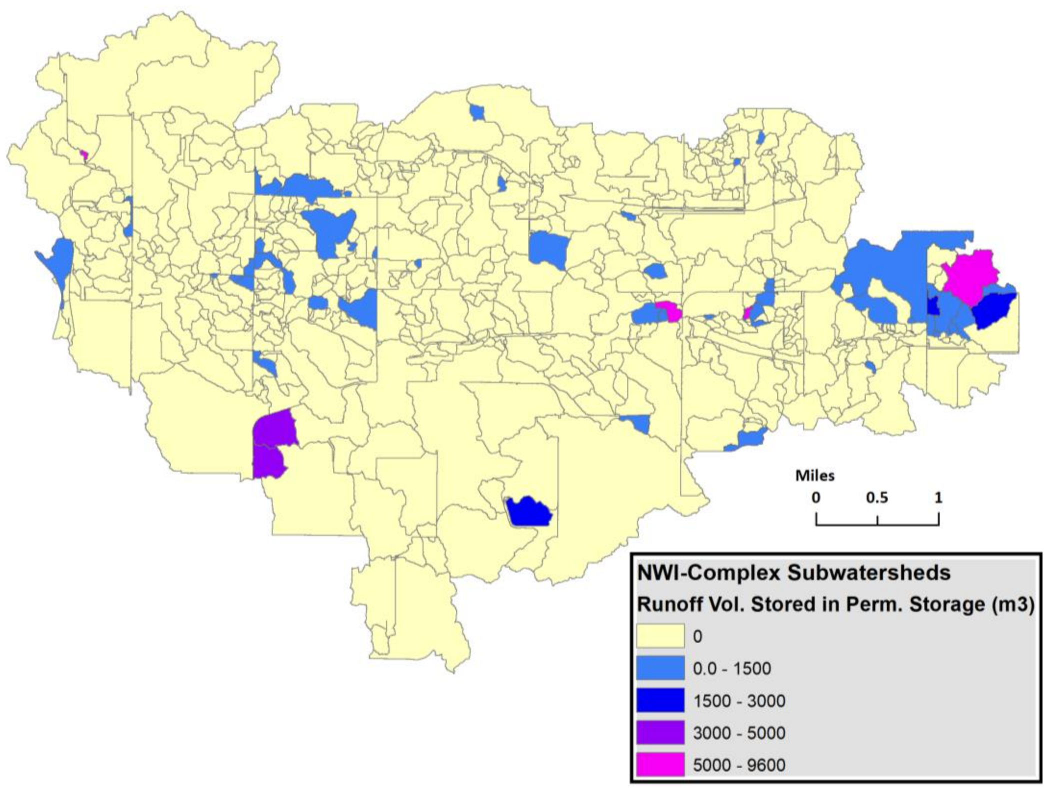

Figure 10: Predicted runoff volume stored in NWI complex permanent storage per subwatershed.

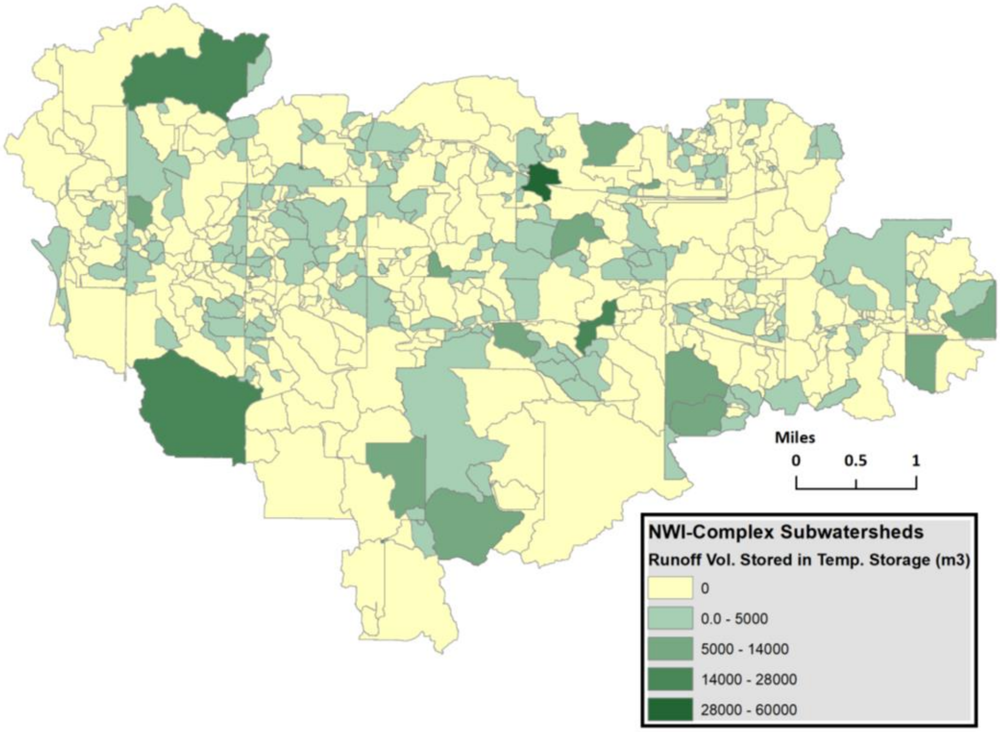

Figure 11: Predicted runoff volume stored in NWI complex temporary storage per subwatershed.

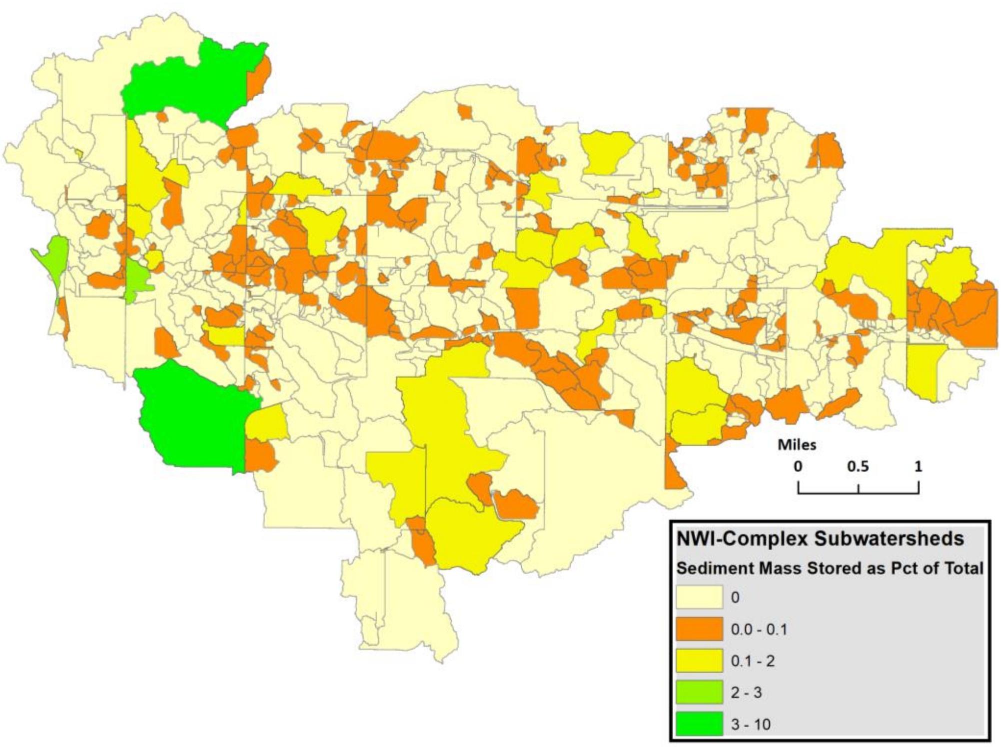

Figure 12: Predicted sediment mass trapped in NWI complex permanent and temporary storage per subwatershed as a percent of total watershed sediment trapped.

5.1.2 Groundwater Function

As discussed in the Methods, relative degree of recharge potential is the primary function targeted by the project approach. Figure 13 presents a proposed metric of potential recharge in 57 NWI complexes with permanent storage in the Little Le Sueur HUC-12 watershed. The potential is expressed as the fraction of total HUC-12 precipitation from a 1yr/24hr design storm stored as runoff in permanent storage based on the fill-and-spill results. Potential recharge fraction of design precipitation in NWI complexes ranged from near zero to 0.2% of total precipitation volume. Estimates of proportionalities of where recharge may be occurring (and where it may not be occurring) can be particularly important in altered landscapes like the Le Sueur, where a disproportionate amount of precipitation leaves the watershed as surface runoff, thereby bypassing groundwater recharge opportunities.

Other possible indicators of recharge potential could be explored with the existing approach and are included in the study area dataset. Examples include estimations of which NWI complexes with recharge potential as defined above have the highest saturated conductivity (soil K_{sat}) and total depressional perimeter – indicators of potential recharge rate and active recharge area, respectively.

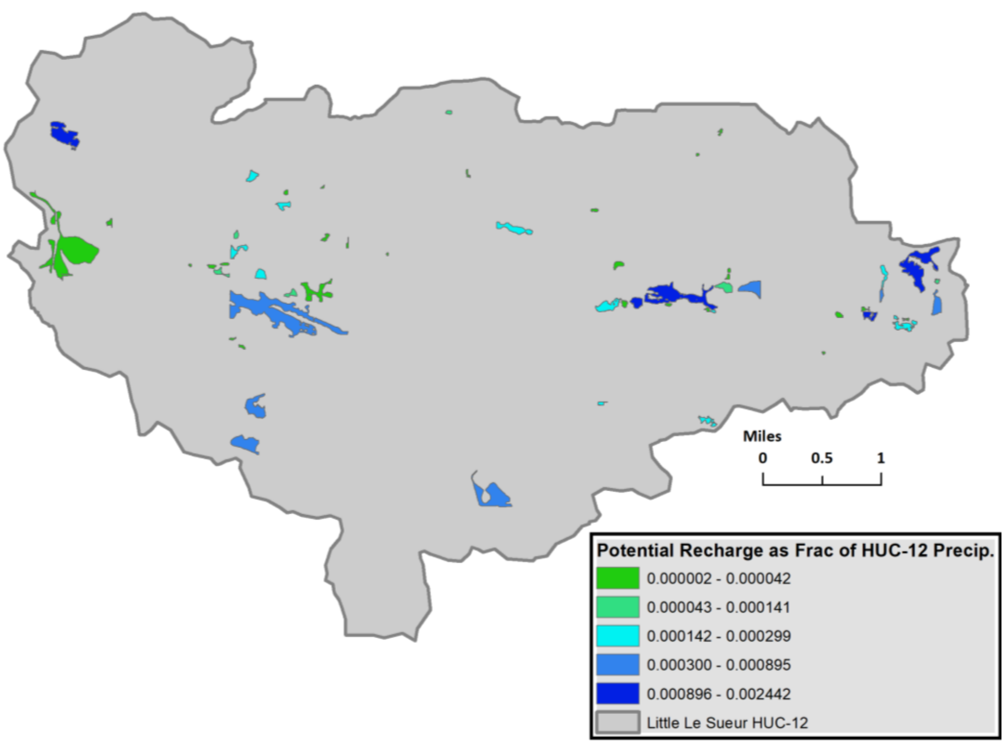

Figure 13. NWI complexes estimated to have greatest recharge potential based on permanent runoff volume stored for 1yr/24hr design storm as a fraction of total design storm precipitation for Little Le Sueur HUC-12.

5.1.3 Habitat Function

Habitat function was assessed using the fill-and-spill results to estimate runoff storage depth in temporary wetlands and the resulting inundation area at depths of 5 to 25 cm as an indicator of dabbling duck habitat suitability. Figure 14 presents these results for the Little Le Sueur HUC-12 watershed. Of the 325 NWI complexes in the Little Le Sueur, 38 were estimated to have optimal storage depth areas greater or equal to 0.25 acres (mean = 1.16 acres).

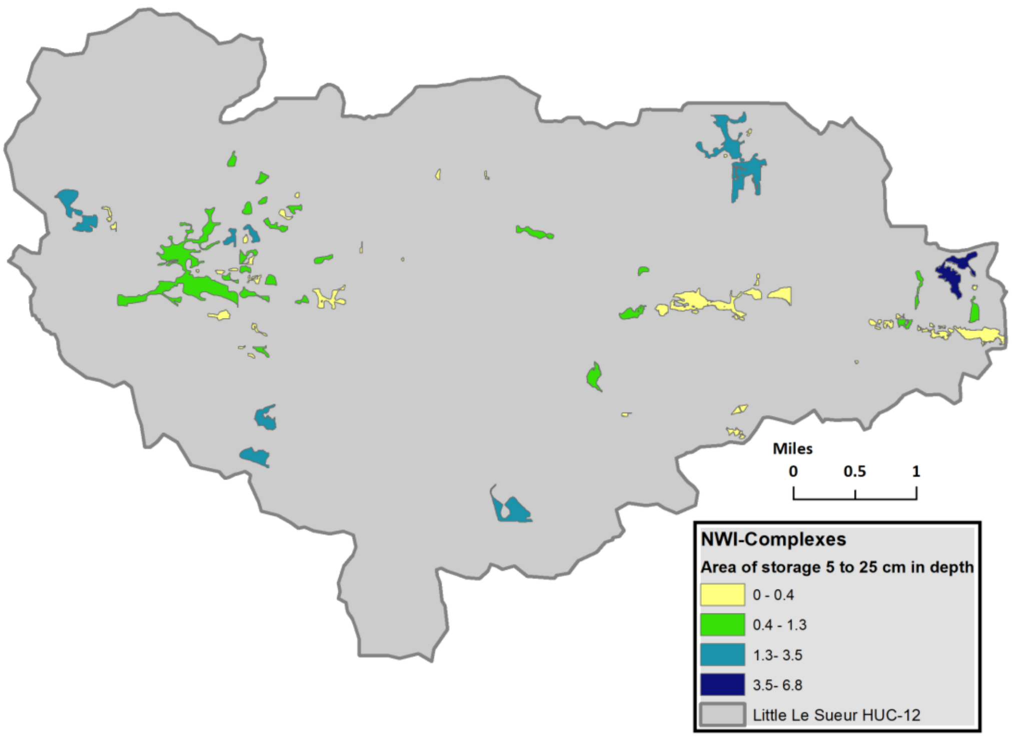

Figure 14: Estimates of dabbling duck habitat expressed as the area (acres) of NWI complexes at a depth range of 5 to 25 cm as a result of permanent storage of runoff from a 1yr/24hr design storm.

5.2 Application in Areas Outside Study Area

Implementing the approaches outlined in this document outside the project's study area will require additional effort and development, as the project did not result in a set of GIS tools. This is particularly important in the case of the fill-and-spill modeling that is central to the project's functional assessment approach. However, here we suggest options to assess wetland function in areas outside the study area, while still leveraging the updated NWI:

1. **Use the project approaches as outlined in this document.** Implementation can use approaches directly *or in a simplified way*. Both these options are covered in the Methods and Appendices sections but require additional intermediate to advanced GIS skill/development.

2. **Use an established approach based mainly or exclusively on the SHGM attributes.** As discussed in the introductory sections, preliminary functional assessment methodologies have been developed that provide simplified, qualitative results using the SHGM attributes exclusively. Readers are directed to the work of Miller et al. (2017) and Tiner (2011). In addition, Miller et al. document a series of GIS based procedures to add further spatial context to SHGM based functional assessments.

3. **Extend results from the project study area.** This option entails using study area fill-and-spill results to help inform functional assessments outside the study area by means of statistical relationships. The following section discusses extending results to other watersheds to estimate aggregate hydrologic and water quality function, e.g., flood storage, sediment retention.

5.2.1 Extending project results from the study area

One approach for inferring watershed-scale wetland function is to correlate GIS variables that can be derived relatively easy with the study area fill-and-spill results—particularly, those estimating aggregated watershed permanent storage (applicable to estimates of flood storage, etc.). Example results presented above discussed the significantly greater *total* watershed permanent storage (from depressions) when compared to the storage predicted to be *utilized* during runoff events (resulting from uneven distribution of storage, inter-wetland connectivity, and runoff sources). Thus, given total storage, it would be of potential value to watershed planners, engineers, hydrologic modelers, etc. to be able to estimate the more applicable *utilized* wetland storage ("effective") available for runoff under a range of design storms.

To use the approach it is required that depressional analysis be conducted at known NWI polygon locations using a hydro-modified LiDAR. Depressional analysis will yield total "raw" permanent storage volume. As discussed in the Methods, this project used "corrected" permanent storage volume for fill-in-spill modeling. Corrected permanent storage was considerably less than raw due to certain depressional volumes being designated as temporary storage based on SHGM and Cowardin criteria.

Reviewing Table 5 reveals 17% of raw permanent storage being designated as corrected (representative) permanent storage across the 21 study watersheds (median percent of per-watershed percents). In other words, this project approach (through application of SHGM and Cowardin attributes) estimated over 80% of GIS derived depressional storage was actually not permanent but contained a surface or subsurface outlet not discernible using 3 meter LiDAR. If realistic, this is an important distinction when estimating potential watershed storage from depressional analysis, or more commonly, using total wetland/lake surface area as a proxy for watershed storage.

However, the extension of results lies in the percent of permanent storage volume (corrected) utilized to store runoff during design storms shown in Table 6. A median percent of 19% of watershed permanent storage is utilized as runoff storage for a 1yr/24 event and 53% for a 100yr/24hr event. Using these percentages as adjustment factors, analyses of raw or corrected depressional analyses can be extended to account for fill-and-spill behavior. An interpretation is that distribution of depressional storage is not uniform with respect to distribution of runoff, resulting in overestimates of flood storage at even small watershed scales if wetland fill-and-spill behavior/wetland network connectivity are not accounted for.

Further statistical analysis of the project study area results could yield additional insights. One example, similar to the approach above but without requiring LiDAR analysis, would relate study area results of total watershed flood storage from watershed different scales with the areal extent of NWI SHGM types constrained in the project to contain permanent storage (See Methods). Thus, a relationship between runoff stored in permanent storage and NWI polygons could be established to estimate watershed scale flood storage without the need for more detailed GIS analysis. Additionally, statistical relationships could be investigated such as the relationship between watershed area, shape, drainage density, landuse, slope and number and type of NWI features.

Table 4: Fill-and-Spill modeling inputs for 21-watershed study area: watershed area in acres; available raw and corrected permanent storage volumes as watershed depth, percent of raw perm. vol. as corrected perm. vol.; available temporary storage volumes expressed as watershed depths; precip depths of design storms per return period

Name	Acres	Perm. Vol. (in)			Temp. Vol (in)	Design storm depth (in) per return period (yr)						
		Raw	Corr	Pct		1	2	5	10	25	50	100
Airport Creek	10,544	1.35	0.33	24%	1.95	2.5	2.7	3.5	4.2	5.3	6.2	7.1
Browns Creek	16,473	16.1	12.71	79%	0.88	2.4	2.6	3.4	4.1	5.2	6.1	7.2
Cherry Creek	19,805	0.64	0.07	11%	2.72	2.5	2.7	3.5	4.2	5.3	6.2	7.2
East Branch Blue Earth	183,066	0.67	0.09	13%	0.74	2.6	2.8	3.8	4.6	5.9	6.9	8.1
Lac qui Parle	504,186	1.01	0.21	21%	0.86	2.2	2.4	3.1	3.7	4.6	5.3	6.1
Lake Hanska Watonwan	32,694	0.44	0.32	73%	1.84	2.4	2.6	3.4	4.1	5.1	6	6.9
Lake Wakanda	13,621	0.29	0	0%	0.71	2.5	2.6	3.3	4	5	5.8	6.7
Le Sueur	704,078	0.97	0.17	18%	1.25	2.5	2.7	3.6	4.4	5.6	6.5	7.6
Minneopa Creek	51,940	0.71	0.11	15%	1.31	2.5	2.7	3.5	4.2	5.3	6.2	7.2
Morgan Creek	35,503	0.43	0.09	21%	0.39	2.4	2.6	3.4	4.1	5.2	6	7
Shanaska Creek	23,644	3.31	0.4	12%	4.04	2.5	2.7	3.5	4.2	5.3	6.2	7.2
SF Watonwan	123,194	0.59	0.22	37%	0.6	2.5	2.6	3.5	4.2	5.3	6.2	7.2
Spring Creek	27,728	0.29	0.14	48%	0.16	2.4	2.5	3.3	3.9	4.9	5.7	6.5
Willow Creek	51,638	0.24	0.08	33%	0.2	2.6	2.7	3.6	4.4	5.5	6.5	7.6
YM1 - CD90	4,058	0.09	0.01	11%	0.1	2.2	2.4	3.1	3.7	4.6	5.4	6.2
YM2 - CD87	14,405	0.09	0	0%	0.1	2.3	2.4	3.1	3.7	4.7	5.5	6.3
YM4 – Unn. Creek	6,556	0.34	0.03	9%	0.27	2.3	2.4	3.1	3.8	4.7	5.6	6.5
YM4 - Stony Run Creek	35,088	0.15	0.02	13%	0.15	2.3	2.4	3.2	3.8	4.8	5.6	6.5
YM5 - CD39	13,147	0.08	0.05	63%	0.11	2.3	2.5	3.2	3.9	4.9	5.8	6.8
YM6 - CD09	47,445	0.7	0.11	16%	0.6	2.3	2.4	3.2	3.8	4.8	5.7	6.6
YM7- Yellow Medicine	427,121	0.64	0.16	25%	0.71	2.3	2.5	3.3	3.9	4.9	5.7	6.6
AVERAGES	**111,711**	**1.39**	**0.73**	**26%**	**0.94**	**2.40**	**2.57**	**3.36**	**4.04**	**5.09**	**5.96**	**6.91**
MEDIANS	**32,694**	**0.59**	**0.11**	**18%**	**0.71**	**2.4**	**2.6**	**3.4**	**4.1**	**5.1**	**6**	**6.9**

Table 5: Fill-and-Spill modeling results for 21-watershed study area. Predicted runoff depth and Runoff stored as permanent storage as watershed depth

Name	Predicted Runoff Depth (in) per design storm (yr)							Runoff Depth (in) stored in Perm. Vol. per design storm (yr)						
	1	2	5	10	25	50	100	1	2	5	10	25	50	100
Airport Creek	0.63	0.74	1.25	1.75	2.61	3.34	4.16	0.11	0.12	0.21	0.26	0.27	0.27	0.28
Browns Creek	0.44	0.54	0.97	1.41	2.17	2.87	3.7	0.42	0.51	0.91	1.3	1.93	2.42	2.98
Cherry Creek	0.69	0.81	1.34	1.86	2.74	3.49	4.32	0.02	0.02	0.03	0.03	0.03	0.03	0.03
East Branch Blue Earth	0.62	0.75	1.36	1.94	2.93	3.79	4.81	0.02	0.02	0.03	0.03	0.04	0.05	0.05
Lac qui Parle	0.5	0.59	1.02	1.43	2.09	2.68	3.35	0.03	0.04	0.05	0.06	0.07	0.08	0.09
Lake Hanska Watonwan	0.51	0.61	1.08	1.53	2.29	2.98	3.76	0.02	0.02	0.03	0.04	0.06	0.07	0.09
Lake Wakanda	0.68	0.74	1.2	1.7	2.45	3.16	3.94	0	0	0	0	0	0	0
Le Sueur	0.69	0.82	1.42	2.01	2.94	3.78	4.72	0.04	0.04	0.05	0.06	0.07	0.08	0.09
Minneopa Creek	0.55	0.66	1.15	1.65	2.45	3.18	4	0.03	0.03	0.04	0.05	0.06	0.07	0.08
Morgan Creek	0.47	0.56	1.03	1.49	2.27	2.96	3.74	0.01	0.01	0.02	0.03	0.04	0.04	0.05
Shanaska Creek	0.82	0.95	1.51	2.05	2.96	3.73	4.58	0.1	0.11	0.15	0.19	0.25	0.3	0.32
South Fork Watonwan	0.51	0.6	1.09	1.59	2.4	3.14	4	0.04	0.05	0.07	0.09	0.11	0.13	0.14
Spring Creek	0.52	0.57	1.04	1.47	2.18	2.82	3.55	0.01	0.01	0.02	0.02	0.03	0.04	0.04
Willow Creek	0.69	0.8	1.38	1.96	2.88	3.71	4.65	0.03	0.03	0.04	0.05	0.05	0.05	0.05
YM1 - CD90	0.41	0.51	0.91	1.3	1.95	2.56	3.25	0	0	0	0	0	0	0
YM2 - CD87	0.46	0.52	0.92	1.32	2.03	2.66	3.39	0	0	0	0	0	0	0
YM3 - Unnamed Creek	0.48	0.53	0.95	1.41	2.11	2.76	3.52	0.02	0.02	0.02	0.02	0.02	0.02	0.03
YM4 - Stony Run Creek	0.44	0.5	0.93	1.35	2.06	2.71	3.48	0.01	0.01	0.01	0.01	0.02	0.02	0.02
YM5 - CD39	0.43	0.53	0.93	1.39	2.13	2.82	3.63	0	0	0	0	0	0	0.01
YM6 - CD09	0.43	0.51	0.93	1.36	2.09	2.76	3.53	0.02	0.02	0.03	0.03	0.04	0.05	0.05
YM7- Yellow Medicine	0.51	0.62	1.09	1.55	2.31	2.98	3.74	0.03	0.03	0.04	0.05	0.06	0.06	0.07
AVERAGES	**0.55**	**0.64**	**1.12**	**1.60**	**2.38**	**3.09**	**3.90**	**0.05**	**0.05**	**0.08**	**0.11**	**0.15**	**0.18**	**0.21**
MEDIANS	**0.51**	**0.6**	**1.08**	**1.53**	**2.29**	**2.98**	**3.74**	**0.02**	**0.02**	**0.03**	**0.03**	**0.04**	**0.05**	**0.05**

Table 6: Fill-and-Spill Modeling results for 21-watershed study area. Percent of corrected and raw permanent storages storing predicted runoff per design storm

Name	Percent of Corrected Perm. Vol Storing Runoff per design storm (yr)							Percent of Raw Perm. Vol Storing Runoff per design storm (yr)						
	1	2	5	10	25	50	100	1	2	5	10	25	50	100
Airport Creek	33%	36%	64%	79%	82%	82%	85%	8%	9%	16%	19%	20%	20%	21%
Browns Creek	3%	4%	7%	10%	15%	19%	23%	3%	3%	6%	8%	12%	15%	19%
Cherry Creek	29%	29%	43%	43%	43%	43%	43%	3%	3%	5%	5%	5%	5%	5%
East Branch Blue Earth	22%	22%	33%	33%	44%	56%	56%	3%	3%	4%	4%	6%	7%	7%
Lac qui Parle	14%	19%	24%	29%	33%	38%	43%	3%	4%	5%	6%	7%	8%	9%
Lake Hanska Watonwan	6%	6%	9%	12%	19%	22%	28%	5%	5%	7%	9%	14%	16%	20%
Lake Wakanda	--	--	--	--	--	--	--	0%	0%	0%	0%	0%	0%	0%
Le Sueur	24%	24%	29%	35%	41%	47%	53%	4%	4%	5%	6%	7%	8%	9%
Minneopa Creek	27%	27%	36%	45%	55%	64%	73%	4%	4%	6%	7%	8%	10%	11%
Morgan Creek	11%	11%	22%	33%	44%	44%	56%	2%	2%	5%	7%	9%	9%	12%
Shanaska Creek	25%	27%	37%	48%	62%	75%	80%	3%	3%	5%	6%	8%	9%	10%
South Fork Watonwan	18%	23%	32%	41%	50%	59%	64%	7%	8%	12%	15%	19%	22%	24%
Spring Creek	7%	7%	14%	14%	21%	29%	29%	3%	3%	7%	7%	10%	14%	14%
Willow Creek	38%	38%	50%	62%	62%	62%	62%	12%	12%	17%	21%	21%	21%	21%
YM1 - CD90	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
YM2 - CD87	--	--	--	--	--	--	--	0%	0%	0%	0%	0%	0%	0%
YM3 - Unnamed Creek	67%	67%	67%	67%	67%	67%	100%	6%	6%	6%	6%	6%	6%	9%
YM4 - Stony Run Creek	50%	50%	50%	50%	100%	100%	100%	7%	7%	7%	7%	13%	13%	13%
YM5 - CD39	0%	0%	0%	0%	0%	0%	20%	0%	0%	0%	0%	0%	0%	12%
YM6 - CD09	18%	18%	27%	27%	36%	45%	45%	3%	3%	4%	4%	6%	7%	7%
YM7- Yellow Medicine	19%	19%	25%	31%	38%	38%	44%	5%	5%	6%	8%	9%	9%	11%
AVERAGES	**22%**	**22%**	**30%**	**35%**	**43%**	**47%**	**53%**	**4%**	**4%**	**6%**	**7%**	**9%**	**9%**	**12%**
MEDIANS	**19%**	**22%**	**29%**	**33%**	**43%**	**45%**	**53%**	**3%**	**3%**	**5%**	**6%**	**8%**	**9%**	**11%**

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Appendix A: Project Study Area Information

Watershed name	Watershed area (ac)	NWI-complex total area (ac)[1]	Lentic (ac)	Lotic (ac)	Terrene (ac)
Airport Creek	10,595	1,509	449	45	921
Browns Creek	16,592	3,566	739	402	1,592
Cherry Creek	20,262	3,525	1,295	559	1,602
East Branch Blue Earth	183,508	11,914	1,774	3,878	4,986
Lac qui Parle	504,542	50,960	4,968	14,600	27,687
Lake Hanska Watonwan	32,815	2,936	2,093	127	575
Lake Wakanda	13,652	1,557	0	35	1,523
Le Sueur	704,481	60,437	18,590	15,357	22,370
Minneopa Creek	52,095	4,343	2,111	350	1,548
Morgan Creek	35,530	915	271	119	406
Shanaska Creek	24,065	6,317	4,111	346	1,728
South Fork Watonwan	123,586	6,725	1,879	2,498	1,880
Spring Creek	27,884	300	78	8	153
Willow Creek	51,732	1,294	26	508	635
YM1 - CD90	4,056	43	0	0	35
YM2 - CD87	14,402	165	0	14	115
YM3 - Unnamed Creek	6,555	281	0	108	161
YM4 - Stony Run Creek	35,081	1,019	0	325	614
YM5 - CD39	13,145	220	0	21	178
YM6 - CD09	47,432	1,759	36	106	1,215
YM7- Yellow Medicine	426,887	38,889	4,962	9,310	22,551

[1] NWI complexes are composed of dissolved NWI polygons combined with intersecting depressional areas; as a result, total complex area can exceed sum of Lentic, Lotic and Terrene areas.

7 Appendix B: Procedures and Algorithms

7.1 Overall Fill-and-Spill Procedure

#	Action	Tool	Description
1	Selectively Fill DEM	ArcGIS ArcHydro	• Create DEM with only NWI-complex + 100 m buffer – null-out raster in other locations. • Fill DEM
2	Identify Depressions and combine with intersecting NWI-complexes	ArcGIS ACPF	• Identification based on/constrained by intersection with NWI-complex polygons above using ACPF toolset • UNION depressions with intersection NWI-complexes
3	Calculate NWI Complex permanent depth and volume	ArcGIS Spatial Analyst	• Raster Calc: Sink Filled (ACPF) DEM - NWI filled DEM (ArcHydro) = depth • Convert Raster to Polygon: ACPF depressions • Create Zonal Stats raster: mean depth of each ACPF depression
4	Calculate NWI Complex temporary depth and volume	ArcGIS Spatial Analyst	• Convert NWI-complex outer boundary to polylines; convert to raster • Run Zonal Stats to get median elevation • Subtract median elevation from Filled-DEM to get temporary depth
5	*Create Drainage Points*	ArcGIS ArcHydro	Creates pourpoints intersecting max flow accumulation and NWI complex watershed boundary
6	*Cost Path*	ArcGIS Spatial Analyst	Creates least cost path raster between Drainage Points using (unfilled) DEM and Flow Direction as input and backlink rasters respectively
	Create Point Connectivity (Customized)	ArcGIS ArcHydro	• Convert Cost Paths to DrainageLines with up and downstream relationship attributes • Delineate Catchments for pour points and stream junctions • Results in NWI-complex network connectivity model

#	Action	Tool	Description
7	*Spatial Join* Catchments to NWI-complexes	ArcGIS	Uses zonal statistics: create linkage between ArcHydro Catchment and ACPF depression DA IDs
8	Join other important attributes	ArcGIS	Join Curve Number and dep geometry params (area, depth, volume, DA)
9	Export to CSV	ArcGIS	Make available to R
10	Process topology and calc fill and spill	R	R does the heavy lifting and exports a csv back to ArcGIS to be joined to depressional layers
11	Import CSV with results back into ArcGIS from R; Join to NWI Complex layer	ArcGIS	Make results viewable in ArcGIS

7.2 Fill-and-Spill Coding Approach

This appendix section lays out the procedural coding approach used for routing runoff through each NWI complex in the fill-and-spill analysis. As discussed in the Methods, a code was developed in R that used inputs from ArcGIS and resulted in outputs to be imported back into ArcGIS for visualization and analysis. However, the implemented code is at best a rough prototype and not in a form usable or discernible by potential users. Yet, using the pseudo-code below a code could be written to simulate the fill-and-spill methodology as implemented in the project using R, Python (in ArcGIS or QGIS) or Excel VBA. As with many programming problems, there are many ways to solve it coding wise; the methods presented here are but one way. The reader is encouraged to develop codes accordingly to their own logical understanding of the problem and the available data.

The approach requires an input file (the code relied on attribute table data exported as .csv files) of all NWI complex subwatersheds (1-row per subwatershed) with the following pieces of data:

Variable Description	Pseudo-Code Abbreviation
NWI Complex Subwatershed ID	SubID
Next Downstream NWI Complex Subwatershed ID	NextDownSubID
Available Permanent Storage Volume (m^3)	PermVol
Available Temporary Storage Volume (m^3)	TempVol
Curve Number	CN
Rain Event precipitation (in.)	Pcp

Calculate Runoff for each Subwatershed

We will need to compute the estimated runoff for each subwatershed resulting from a desired rain event using the NRCS curve number method. This could be done in ArcGIS prior to exporting the subwatershed attribute data (attribute table Field Calculation), in the exported .csv (using Excel and re-saving the file as .csv) or in the code/script. The formula, using Pcp in inches, is:

Runoff depth (in.) =

$RO = \frac{(Pcp - I_a)^2}{Pcp - I_a + S}$ for $Pcp > Ia$

$RO = 0$ for $Pcp \leq Ia$

Where $S = \dfrac{1000}{CN - 10}$ and $I_a = 0.2S$

This can be generally written programmatically as:

S = max moisture storage after runoff begins = 1000/CN – 10

Ia = initial abstraction = 0.2*S

RO = ifelse (Pcp > Ia, (Pcp - Ia)^2 / (Pcp - Ia + S), 0)

About Accessing and Modifying Variables Stored in Data Structures

An important provision of R data structures as well as SQL databases is the ability to find/access and modify many pieces of data simultaneously based on a set of query criteria; this is in contrast to a "conventional" procedural programming where if a given set of data needed to be modified, the individual rows/array elements would be found and selected, and then a routine would have to loop through each element, changing the data one element at a time. The approach used here assumes the ability to modify data (and add new data) in any number of elements simultaneously. This entails using query-like operations that can easily find specific subsets of data to be modified. The pseudo-codes below assume this ability and do not discuss it in detail. This type of data access/modification can be done easily in R using data.frames or in ArcGIS/QGIS python using collections or by modifying filegeodatabase tables directly using sql commands constructed and executed in python. An analogue for Excel may be possible but cannot be confirmed here.

Assign Subwatershed Order

First, a coding loop to assign an "order" for the main program to progress through each subwatershed (sub) starting from upstream to downstream. Each headwater sub (i.e., has no upstream subs) is assigned a 0, the next downstream subs are assigned a 1, the next downstream subs a 2, and so on until a watershed outlet is reached (i.e., no downstream sub available) which is assigned a -1. This ordering is necessary so that the code does not progress past any one sub until all of that sub's upstream subs (and their upstream subs and so on) have been processed and their resulting runoff outputs routed into that sub in sum.

Pseudo-code

1. Set all sub order variables to 0 to start (whether headwater or not).
2. Loop 1: Loop through each subwatershed (SubID) that is assigned the current loop order number (starts with 0)

2.1. Find the immediate downstream sub associated with each subwatershed in the loop (there will only one sub immediately downstream) using the NextDownSubID and assign the downstream sub the current order number + 1.
2.2. Proceed with next pass through loop with new order equal to the current order + 1
2.3. Continue looping until watershed outlet is reached

Fill-and-Spill Processing

The fill-and-spill modeling starts with the headwater subs (assigned an order of 0) and loops through each order from 0 to the max order determined above. In each loop pass, the direct drainage runoff (calculated above or at this point in the code using the curve number method discussed above) is routed through any NWI complex permanent storage associated with the sub – not every sub has an NWI complex, and not every NWI complex has permanent or temporary storage volume. Any runoff exceeding the sub's permanent storage volume is assigned as part of the accumulated runoff inputs to the next downstream sub (i.e., is "spilled" into the next downstream sub). After the headwater subs have been processed (loop pass 1; order = 0), the runoff to be potentially stored in next downstream sub is the sum of its own direct drainage runoff plus the sum of all spills from any upstream subs connected to it (the sum of all spills is accumulated incrementally as each upstream sub is processed in turn). This process is continued until the last sub in the watershed has been reached. Runoff stored temporarily is passed to the next downstream sub (unlike permanently stored runoff) but this storage amount is recorded for post-processing analysis.

Pseudo-code

1. Set variable maxord = to the maximum order in all subs.
2. Loop 1: Loop through every order from 0 to maxord
   2.1. Loop 2: Loop through every sub (SubID) assigned to the current order
      2.1.1. Determine next downstream sub using NextDownSubID
      2.1.2. Calc total runoff to sub = direct drainage runoff + any upstream accumulated spill runoff
      2.1.3. If permanent storage volume (PermVol) exists, substract this volume from total runoff volume
         2.1.3.1. If this difference <= 0, then no runoff passes downstream and this sub and all its upstream connected subs are non-contributing to the watershed outlet for the rain event.
         2.1.3.2. If this difference is > 0, this is amount of runoff spilled and is added to the *accumulated* inputs for the next downstream sub (next downstream sub inputs = next downstream sub inputs + runoff spills from current sun)
         2.1.3.3. If this difference is > 0, subtract any temp storage volume (TempVol) from this amount and assign the difference to the current sub

7.3 Extension of Fill-and-Spill Modeling Approach for Water Quality

7.3.1 Estimation of subwatershed peak flows

1. **Calculate per-pixel travel times based on MnDNR Travel Time Tool.**

This python-based ArcGIS tool (Loesch 2017) uses manning's equation to estimate velocity-based travel times across every LiDAR pixel (in this case, 3 meter resolution). The tool uses 15-meter landuse (resampled to 3-meter) as a determinant of manning's *n* roughness on a per pixel basis, LiDAR derived slope, and accounts for different tiers of hydraulic radius based on Flow Accumulation thresholds (as a proxy for decreasing flow retardance due to flow convergence) as well as known, mapped channels. The output of this workflow was a travel time raster (time to travel across each pixel) for each of the study area's 48,000+ subwatersheds. The approach is based on that implemented in PTMapp (BWSR 2016).

2. **Calculate accumulated travel times to each subwatershed outlet and output resulting travel time distributions using custom ModelBuilder workflow.**

A ModelBuilder tool was constructed to iterate through and clip each subwatershed's required LiDAR derived rasters, determine the accumulated travel time from every LiDAR pixel to its closest downstream subwatershed outlet, and export the output as binned histogram data. The Flow Length tool (Spatial Analyst) was used to calculate accumulated downstream travel times; the process uses Flow Direction as the main input and the previously generated travel time raster as the optional weight raster. The Flow Length approach is based on that implemented in PTMapp.

The resulting raster for each subwatershed was processed using the Zonal Statistics to Histogram tool which split each travel time distribution into 256 bins (each bin representing a time increment equal to 1/256 the maximum accumulated travel time for each subwatershed). Lastly, the model exported the histogram data as a .dbf database table file unique to each subwatershed.

3. **Convert subwatershed travel time distributions to runoff hydrographs in R.**

An R code was developed to generate runoff hydrographs for each subwatershed outlet. The code incorporates (1) the design storm total rainfall depths with (2) gridded Atlas 14 rainfall distribution curves for 24-hour storms (all design storms used in this project were 24 hours in duration) and, (3) travel time distributions derived in the process above.

The Atlas 14 (NOAA 2013) curves disaggregate the 24-hour design storm total precipitation depths into a 15-min interval time series -- i.e., a hyetograph. It was decided that a representative timestep for the resulting runoff hydrographs would be 1-minute as it was observed that the lowest range of maximum travel times (i.e., the maximum time from any pixel to the outlet)) for all project subwatersheds was commonly 10 minutes and less. Thus, the rainfall hyetograph was further disaggregated (using linear interpolation) into 1-minute timesteps, and resulting runoff volume per-timestep simulated using the curve number method. Since travel time distribution intervals varied widely (i.e., each interval being 1/256 of the maximum travel time for each subwatershed), these intervals were either aggregated or disaggregated (using linear interpolation) to produce a 1-minute travel time distribution for each subwatershed. (Aggregation vs. disaggregation applied depending on whether maximum travel time was greater than or less than 256 minutes, respectively.)

Last, the runoff hydrographs for each subwatershed were generated by "overlaying" the runoff volume vs. hyetograph time series with the travel time distributions whereby the each timestep's runoff volume was "lagged" by the travel times in the travel time distribution. The resulting hydrographs aided in quantifying the fill-and-spill timing of NWI complexes with permanent and temporary storage. In addition, peak flows from the hydrographs were a necessary input to the MUSLE erosion model. A similar approach for deriving travel time distributions is found in Usul and Yilmaz (2002). Project applications of the runoff hydrographs are described in more detail below.

7.3.2 Prediction of water quality pollutant export and fill-and-spill integration

1. Prediction of design storm sediment loads using GIS enabled MUSLE model

An important consideration of wetland water quality function is how much sediment a wetland receives. For example, a wetland of otherwise equivalent geometry and trapping efficiency compared to another wetland will have a higher level of function if it receives a higher mass of sediment. To most explicitly predict sediment erosion and transport as it pertains to wetland trapping processes, event based simulations that incorporate flow rates are most appropriate. However, the widely used RUSLE model (used in PTMapp) is an annualized prediction model and therefore cannot take into account event based runoff rates and runoff volumes for erosion prediction. A less frequently implemented but more appropriate approach is to use the event based MUSLE model (used in the model SWAT; Arnold et al. 1998) which uses the same multiplicative factors for as the RUSLE model (R, C, K, LS, P) except that it replaces the annual rainfall erosivity factor R with a runoff factor that is composed of peak runoff rate and total runoff volume. This approach avoids the necessity of estimating a sediment delivery ratio. An existing ArcGIS approach (Blaszczynski 2003) designed to implement MUSLE using subwatershed peak runoff rates and total runoff volumes while also accounting for subwatershed Flow Accumulation patterns was adapted to predict sediment erosion mass from each design storm delivered to the subwatershed outlet.

2. Extending design storm sediment loads to include associated phosphorus.

Many approaches for estimating phosphorus loading assume a landuse-specific event mean concentration or annual per unit area mass yield. However, as phosphorus mass is tied to sediment mass to a considerable degree, and that sediment mass was already estimated in previous steps, an approach directly relating phosphorus to sediment was used. An example of this approach is the HSPF model which uses a sediment-phosphorus potency factor that relates sediment mass to phosphorus mass (per landuse) by use of a ratio – i.e., phosphorus mass per unit mass of sediment. As such, MPCA's Minnesota River watershed HSPF model documentation was consulted for potency parameter values, and a lookup table created relating the project study area's landuse raster values to potency factor. Mean subwatershed potency factors were then computed using Zonal Statistics and multiplied by the predicted subwatershed sediment mass to calculate phosphorus eroded and delivered to the subwatershed outlet.

3. Incorporate flow rates and sediment/phosphorus transport into fill-and-spill methodology.

Once subwatershed runoff rates and associated sediment and phosphorus were estimated for design storms, the methodology was integrated into the existing fill-and-spill R code to enable routing of sediment and phosphorus through any NWI complexes present in the subwatersheds and to any downstream subwatersheds. The code first checks to see if any NWI complex permanent and/or temporary storage exists in the subwatershed. If so, the sediment/phosphorus is routed through the storage uniformly distributed with the runoff hydrograph (i.e., concentrations of sediment and phosphorus are constant over all timesteps of the hydrograph). It was assumed for this analysis that filling and spilling occurred instantaneously rather than in a lagged manner -- i.e., when spilling occurred during a timestep, volume spilled equaled volume filled. Therefore, the driver of residence time was the time it took for the NWI complex storage to fill to the point of spilling, rather than also including the likely reduction in spill rate relative to fill rate because of the flow (hydraulic) characteristics of the natural wetland outlet.

Sediment and phosphorus settling behavior of NWI complexes required some simplifications both because of the simplification of filling and spilling rates discussed above but also because of the inherent complexities and unknowns involved in predicting settling in water bodies irrespective of flow rates, e.g., incoming sediment particle size distributions, turbulence, resuspension, effects of vegetation, “short-circuiting” of storage volume preventing “stirred reactor” assumptions, etc. A relatively easy approach was adapted from PTMapp that was reasonably representative of important variables but not parametrically or computationally intensive. In PTMapp, trapping efficiency of a water body is a function of the ratio between incoming flow volume and permanent storage expressed as a user-defined analytical curve that varies trapping efficiency between zero and a maximal value based on literature – in this project, it was assumed maximal trapping efficiency to be a relatively conservative 75% based on literature values presented in the MDA Ag BMP Handbook (Lenhart and Peterson 2017).

An additional consideration was also included in the rate-based fill-and-spill code that acknowledges that sediment/phosphorus deposition occurs irrespective of intersections with depressional wetland storage as a function of the distance traveled from the point of erosion to the nearest downstream watershed outlet. Here, subwatershed travel time distributions were used again to implement another PTMapp approach to reduce sediment and phosphorus masses based on analytical curves formulated using concepts of exponential decay. Adopting this additional approach prevented wetlands from being the sole source of deposition and therefore their water quality function overvalued in watershed scale analyses.