2025

Final Report SPR-FY24(033)

Drainage Area Limitations of Single Watershed, Peak Flow Estimates from NRCS Methods

Timothy A. Maughan, M.S.
Graduate Research Assistant
Department of Civil and Construction Engineering
Brigham Young University

Rollin H. Hotchkiss, Ph.D.
Research Professor
Department of Civil and Construction Engineering
Brigham Young University

Riley Hales, Ph.D.
Technical Director
Department of Civil and Construction Engineering
Brigham Young University

Nebraska Department of Transportation Research
Headquarters Address
1400 Nebraska Parkway
Lincoln, NE 68509
ndot.research@nebraska.gov
(402) 479-4697
https://dot.nebraska.gov/business-center/research/

Nebraska Transportation Center
262 Prem S. Paul Research Center at Whittier School
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-1932
http://ntc.unl.edu

This report was funded in part through grant from the U.S. Department of Transportation Federal Highway Administration. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. Department of Transportation.

Drainage Area Limitations of Single Watershed, Peak Flow Estimates from NRCS Methods

Timothy A. Maughan, M.S.
Graduate Research Assistant
Department of Civil and Construction Engineering
Brigham Young University

Rollin H. Hotchkiss, Ph.D.
Research Professor
Department of Civil and Construction Engineering
Brigham Young University

Riley Hales, Ph.D.
Technical Director
Department of Civil and Construction Engineering
Brigham Young University

A Report on Research Sponsored by

Nebraska Department of Transportation

and

Nebraska Transportation Center

University of Nebraska-Lincoln

May 2025

Technical Report Documentation Page

1. Report No. FY24(033)	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Drainage Area Limitations of Single Watershed, Peak Flow Estimates from NRCS Methods		**5. Report Date** May 2025 **6. Performing Organization Code**
7. Author(s) Timothy A. Maughan, Rollin H. Hotchkiss		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Brigham Young University Department of Civil and Construction Engineering 430 Engineering Building Provo, UT 84602		**10. Work Unit No.** **11. Contract** FY24(033)
12. Sponsoring Agency Name and Address Nebraska Department of Transportation Research Section 1400 Hwy 2 Lincoln, NE 68502		**13. Type of Report and Period Covered** Final Report May 2023 – May 2025 **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

Most state Department of Transportation roadway design sections predict peak flow for culvert design using, amongst other approaches, Natural Resources Conservation Service (NRCS) TR-20 technology. Even though this technology is more than 50 years old, there are no clear guidelines for how large a single watershed drainage area may be while remaining appropriate for predicting peak discharge with this method. Our objective was to identify the drainage area where TR-20 peak flow predictions significantly deviate from flow frequency predictions.

We developed flow frequency estimates for 130 small-area stream gage sites in rural Nebraska and compared the calculated return period discharges with those from TR-20 using both the segmental and lag equation approaches for estimating the time of concentration. Additionally, we compared available regression predictions to both flow frequency and TR-20 estimates.

We found that there are no significant differences between peak discharges calculated using the TR-20 lag method and segmental method for estimating the time of concentration. If TR-20 continues to be used in the future, we recommend using the segmental approach to be more consistent with commonly accepted practice. Results did show, however, that predictions are consistently higher than those from stream gage estimates and become worse for drainage areas larger than fifteen square miles. The regression equations developed for small drainage areas (perhaps uniquely available for Nebraska) perform better than the TR-20 estimates. As a first step to further investigate the performance of the TR-20 equations, we made peak flow estimates assuming drier soil conditions that effectively reduce the runoff curve number for each watershed. Results again showed poor agreement, but instead of being consistently high, were consistently low. We therefore discourage using an uncalibrated TR-20 model to calculate peak flow for culvert design for any size drainage area in Nebraska. If peak discharge estimates are required for changing land use conditions, we recommend a TR-20 model be calibrated to the regression model results for present conditions, thus allowing the simulation of changed land use conditions easily done with TR-20.

Next generation hydrologic approaches such as the National Water Model and GEOGloWS currently lack the resolution required to simulate peak flows from smaller watersheds. Tests showed universally low estimates compared to gage estimates of return period discharges.

	18. Distribution Statement		
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 82	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Figures

List of Tables

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Transportation or the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. Trade names or manufacturers' names that may appear in this report are cited only because they are considered essential to the objectives of the report.

The United States government and the State of Nebraska do not endorse products or manufacturers. This material is based upon work supported by the Federal Highway Administration under SPR-P1(20) M116. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration.

This report has been reviewed by the Nebraska Transportation Center for grammar and context, formatting, and compliance with Section 508 of the Rehabilitation Act of 1973.

Abstract

Most state Department of Transportation roadway design sections predict peak flow for culvert design using, amongst other approaches, Natural Resources Conservation Service (NRCS) Technical Release 20 (TR-20) technology. Even though this technology is more than 50 years old, there are no clear guidelines for how large a single watershed drainage area may be while remaining appropriate for predicting peak discharge with this method. Our objective was to identify the drainage area where TR-20 peak flow predictions significantly deviate from flow frequency predictions.

We developed flow frequency estimates for 130 small-area stream gage sites in rural Nebraska and compared the calculated return period discharges with those from TR-20 using both the segmental and lag equation approaches for estimating the time of concentration. Additionally, we compared available regression predictions to both flow frequency and TR-20 estimates.

We found that there were no significant differences between peak discharges calculated using the TR-20 lag method and segmental method for estimating the time of concentration. If TR-20 continues to be used in the future, we recommend using the segmental approach to be more consistent with commonly accepted practice. Results did show, however, that predictions were consistently higher than those from stream gage estimates and become worse for drainage areas larger than fifteen square miles. The regression equations developed for small drainage areas (perhaps uniquely available for Nebraska) performed better than the TR-20 estimates. As a first step to further investigate the performance of the TR-20 equations, we made peak flow estimates assuming dry soil conditions that effectively reduce the runoff curve number for each watershed. Results again showed poor agreement, but instead of being consistently high, were

consistently low. We therefore discourage using an uncalibrated TR-20 model to calculate peak flow for culvert design for any size drainage area in Nebraska. If peak discharge estimates are required for changing land use conditions, we recommend a TR-20 model be calibrated to the regression model results for present conditions, thus allowing the simulation of changed land use conditions to be easily completed with TR-20.

Next generation hydrologic approaches such as the National Water Model and GEOGloWS currently lack the resolution required to simulate peak flows from smaller watersheds. Tests showed universally low estimates compared to gage estimates of return period discharges.

Chapter 1 Introduction

The design of culverts and bridges necessitates an estimation of peak flow using one of many available methods, often selected according to the general watershed size. The rational method is commonly used for small watersheds of less than 200 acres, though Nebraska permits its use in watersheds up to 640 acres (NDOR, 2006). Conversely, for larger drainage areas, the preference shifts towards regional regression equations. Regression equations are created using gage data from watersheds of varying sizes, making the equations valid only within the constraints of the data from which they are derived. For medium-sized watersheds, Natural Resources Conservation Service (NRCS) curve number methods (CN methods) are generally applied, despite a lack of clear understanding regarding their drainage area limitations. Regardless of the uncertainty, CN methods are used in 45 out of 50 state DOTs (unpublished review of Department of Transportation drainage manuals).

This study tests for a drainage area limitation of NRCS Technical Release 20 (TR-20) methods in Nebraska. TR-20 predictions using the lag and segmental methods for estimating the time of concentration are compared to regression equation and flow-frequency estimates to test accuracy.

Chapter 2 Previous Work

2.1 Origins of the Curve Number Method

Published by the Natural Resource Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), the NRCS curve number method was created by Victor Mockus to predict runoff volume based on precipitation and a curve number accounting for losses (NRCS, 2024; Ponce & Hawkins, 1996). This development was driven by the NRCS's need for a reliable way to estimate runoff at an ungaged site (Hawkins et al., 2008). Much to the scrutiny of others, the curve number method and procedures outlined in NEH-630 were conceived as an NRCS agency procedure, exempting it from a journal review (Fennessey et al., 2001; NRCS, 2024). The method has since expanded beyond an agency procedure to become a common runoff model in engineering practice, with NEH-630 being the newest and only official source documentation (Fennessey et al., 2001; NRCS, 2024; Ponce & Hawkins, 1996).

2.2 TR-20

Technical Release 20 (TR-20) and its derivative, Technical Release 55 (TR-55) (NRCS, 1986), both offer ways of estimating peak discharge using curve number theory. Individuals should ensure their software uses TR-20, the parent methodology, to predict peak flow rather than TR-55.

TR-20 runs the procedures outlined both in NEH-4 and NEH-630 to ultimately produce a runoff hydrograph (NRCS, 2024). It requires a weighted curve number (CN) and a time of concentration estimate. The time of concentration and synthetic unit hydrograph relationships are used to compute the unit hydrograph peak discharge and the time to peak discharge. To create a unit hydrograph for a watershed, the method applies the time to peak and the peak discharge to dimensionless SCS unit hydrograph ratios (NRCS, 2024). The user is also prompted to create a storm distribution by applying a return-period-of-interest precipitation depth to an SCS design storm assuming the lack of real storm data or an alternative distribution. The NRCS runoff volume equation calculates runoff volume for each time step of the design storm, and runoff volumes are multiplied by unit hydrograph increments to convert them to incremental discharge values. Discharge values are graphed on their time increments and, if necessary, a cumulative runoff hydrograph is computed by convolution and NEH-630 routing techniques (NRCS, 2024).

This method is commonly programmed due to the complexity of convolution, which involves multiplying each ordinate of the rainfall hyetograph by each ordinate of the unit hydrograph to create a series of smaller hydrographs (Autodesk, 2010; NRCS, 1986). These smaller hydrographs are then summed to form the final runoff hydrograph, resulting in high accuracy but practical challenges without supporting software (Autodesk, 2010).

2.2.1 Time of Concentration

A key part of TR-20 is the time of concentration (T_c) estimate. The two most common methods for estimating the time of concentration for TR-20 models are the lag method (NRCS, 2024) and the velocity method (formally called the segmental method) (NRCS, 1986). The lag method was developed by Victor Mockus concurrently with the SCS unit hydrograph (Folmar et al., 2007). It is an empirical equation that requires a weighted curve number, a watershed slope, and watershed length, and returns lag time as shown in equation (2.1) (NRCS, 2024). Lag time is then converted to time of concentration using equation (2.2) (NRCS, 2024). The lag equation was developed from observations made on agricultural watersheds (Folmar et al., 2007).

$$Lag = \frac{L^{0.8}\left[\left(\frac{1000}{CN} - 10\right) + 1\right]^{0.7}}{1900\sqrt{Y}} \tag{2.1}$$

where:
Lag=Lag Time (hrs.)
L=Watershed Length (ft)
CN=SCS Weighted Curve Number
Y=Watershed Slope (%)
(NRCS, 2024)

$$Lag = 0.6T_c \tag{2.2}$$

where:
Lag=Lag Time (hrs.)
T_c=Time of Concentration (hrs.)
(NRCS, 2024)

The segmental method was introduced with the publication of TR-55. It uses variations of Manning's equation to calculate the travel time of three different classifications of flow: sheet flow, shallow concentrated flow, and open channel flow. These flow times are summed to estimate T_c as shown in equation (2.3). The method allows engineers to customize T_c estimates for urban settings by introducing the three flow types and user-defined flow paths (NRCS, 1986). The lag equation does not apply well to urban settings due to its inability to account for infrastructure (Folmar et al., 2007). TR-55 requires the use of the segmental method for estimating the time of concentration (NRCS, 1986). However, the NRCS does not specify which method is most appropriate for TR-20 (Cerrelli, 2024).

$$T_c = T_{sheet} + T_{Shallow} + T_{channel} \tag{2.3}$$

where:
T_c=Time of Concentration (hrs.)
T_{sheet}=Sheet Flow Time (hrs.)
$T_{shallow}$=Shallow Concentrated Flow Time (hrs.)
T_{open}=Open Channel Flow Time (hrs.)
(NRCS, 1986)

2.3 Drainage Area Limitations

Recent curve number studies (Chin, 2022, 2023; Mecham, 2008; Mishra & Singh, 2013; Moglen et al., 2022; Ormsbee et al., 2020) have not addressed drainage area limitations. NEH-630 states that single basin drainage areas should not exceed 20 square miles (NRCS, 2024).

This limitation is commonly referenced in the literature (Hawkins et al., 2008; McCuen, 1982; NRCS, 2024; Sorrell, 2010; Thompson, 2004). However, NEH-630 does not justify this 20-square-mile restriction, leaving the reasoning behind it unclear (NRCS, 2024).

Watersheds less than 50 square miles were selected for this study due to the several drainage area limitations present in the literature (Haan et al., 1982; Hawkins et al., 2008; NRCS, 2024; Ponce, 2021; Ponce & Hawkins, 1996). Table 2.1 and Table 2.2 list suggested drainage area limitations on the curve number method due to the data from which NEH-630 elements were derived.

Table 2.1 Possible Drainage Area Limitations

Citation	Referencing	D.A. Limitation (mi^2)	Commentary
(Fennessey et al., 2001)	-	-	NRCS models should not be used to model small, wooded watersheds less than 20 acres
(Haan et al., 1982)	-	0.1-10	-
(Hawkins et al., 2008)	-	5-100	-
(Hawkins et al., 2008)	Ponce and SCS	38.6-1930.5	-
(Hawkins et al., 2008)	Pilgrim and Cordery	-	Small to medium drainage basins
(Hawkins et al., 2008)	Singh	-	large watersheds with multiple land uses
(Hawkins et al., 2008)	Boughton	0.001- 386.1	-
(McCuen, 1982)	-	0.002- 3.125	Specifically limiting the chart method
(Mishra & Singh, 2003)	Ponce	< 100	-
(Ponce)	Mockus	< 400	https://ponce.sdsu.edu/my_conversation_with_vic_mockus.html
(Ponce, 2021)	Mockus	< 10	https://www.youtube.com/watch?v=4DGrO-HV-tY
(Ponce, 2021)	Mockus	-	Perhaps no limit if uniformity assumptions were met. https://www.youtube.com/watch?v=4DGrO-HV-tY
(Ponce, 2021)	National Weather Service	< 400	The national weather service boundary between medium and large basins
(Thompson, 2004)	-	-	Drainage area not useful for selecting a method for estimating discharge
(Hawkins et al., 2008; McCuen, 1982; NRCS, 2024; Sorrell, 2010; Thompson, 2004)	-	< 20	"To assure that all contributing subareas are adequately represented, it is suggested that no subarea exceed 20 square miles in area…"
(Panel, 2020)	-	< 300	“For watersheds greater than about 300 square miles in size, WinTR-20 models are not recommended.”

Table 2.2 Limitations from Data and Inputs

Citation	Referencing	D.A. Limitation (mi^2)	Commentary
(Mishra & Singh, 2003)	Ponce	3 - 6	Bounds on the original time of concentration equation from NEH-4
(Mishra & Singh, 2003)	Ponce	> 3	The velocity method is appropriate for drainages greater than 3 mi^2
(Simanton, 1996)	-	-	The curve number tends to decrease as drainage area increases.
(NRCS, 2024)	-	< 19	Watershed area used in NEH-630 lag equations is limited to 19 mi^2
(Chin, 2022)	-	0.009-1004	NRCS equation 4 for lag time
(Hawkins et al., 2008)	-	0.0004-72	Range of drainage areas of the 199 watersheds from which the first CN tables were constructed
(Hawkins et al., 2008)	-	0.0016-3.125	D.A. limitation in Texas due to time of concentration constraints
(McCuen, 1982)	-	< 400	A possible drainage area limitation exists in the fact that the SCS dimensionless unit hydrographs were created using rainfall frequency data for areas less than 400 square miles.
(Ponce, 2021)	Mockus	< 10	Victor Mockus didn't use any watersheds over 10 square miles when developing his equations.
(Ponce, 2021)	Mockus	-	Victor Mockus generally worked with small agricultural basins.
(NRCS, 2024)	Mockus	-	"The standard unit hydrograph ratios were developed by Victor Mockus from analysis of small watersheds where the rainfall and streamflow were gaged."
(Sorrell, 2010)	NEH-630	< 20	One of the reasons for this limit is that UH theory assumes uniform rainfall and runoff from the entire drainage basin. This assumption is less reliable if the drainage area becomes too large.
(Ponce & Hawkins, 1996)	SCS	< 0.016	"[$I_a = \lambda S$] was justified on the basis of measurements in watersheds less than 10 acres in size."
(Ponce & Hawkins, 1996)	-	-	"...the runoff curve number is assumed to apply to small and midsize catchments, comparable in size to those that would normally fall within SCS scope."
(Fennessey et al., 2001)	Mockus	> 20	"...the NRCS developed the original [lag] equation using watersheds predominately over 20 square miles in size (average size approximately 400 sq. mi.), and only ten of the watershed data sets used were from watersheds less than 50 acres (0.078 sq. mi.) in size."

Chapter 3 Methodology

Our analysis involves comparing peak flows for 2-, 5-, 10-, 25-, 50-, and 100-year return periods by drainage area for all 130 watersheds. We compare peak flows from Bulletin 17C flow frequency analyses, TR-20 models, and regional regression equations. The Bulletin 17C flow frequency analyses are considered to be the observed peak flows. Meaning all other peak flow predictions are assessed against the flow frequency predictions. Flow frequency is chosen as the benchmark because it predicts peak flow based off recorded gage data (England Jr et al., 2019). Our sample includes 130 gaged USGS watersheds in Nebraska with drainage areas less than 50 square miles and a minimum of 10 years of annual peak flow data. Figure 3.2 and Figure 3.3 summarize the drainage area sizes and continuous record lengths. All selected USGS gage sites are listed in Appendix E.

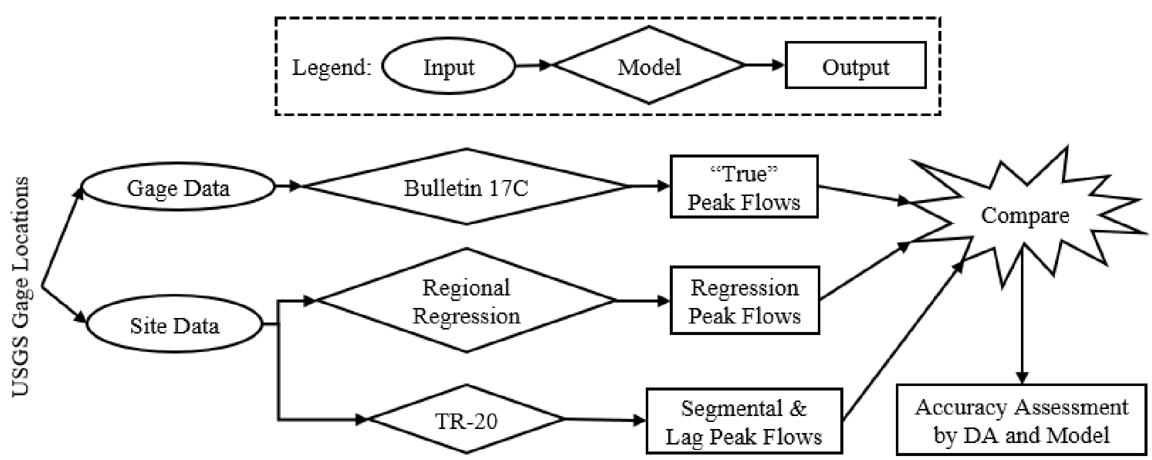

Figure 3.1 Basic Study Methodology

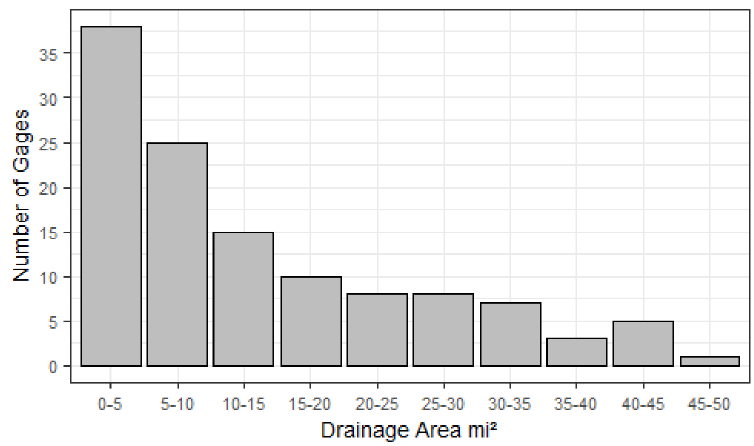

Figure 3.2 Number of Gage Sites by Drainage Area

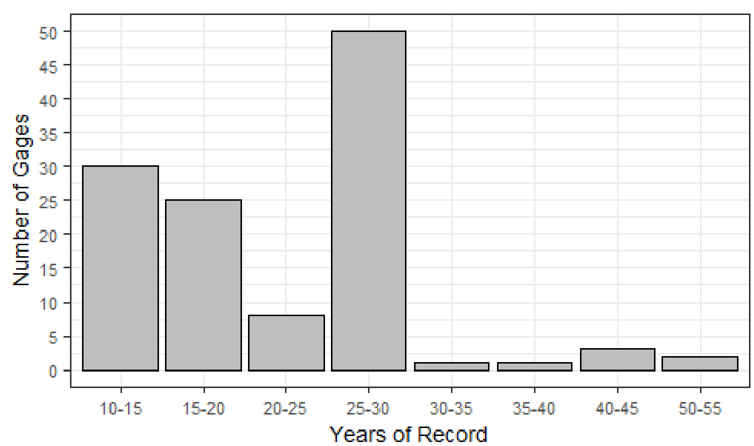

Figure 3.3 Number of Years of Record at Gage Sites

Table 3.1 Average Years of Record and Count by D.A. Category

Watershed Drainage Area Category mi^2	Average Years of Record for D.A. Category	Count of Watersheds by D.A. Category
0-5	20.2	38
5-10	19.6	25
10-15	23.4	15
15-20	22.0	10
20-30	22.8	16
30-50	27.7	16

3.1 Bulletin 17C

The flow frequency peaks in our study are log-Pearson Type III quantile estimates with an expected moment adjustment. This method is federally endorsed and presented in Bulletin 17C (England Jr et al., 2019). A minimum amount of 10 recorded peaks at a gage location are needed for a Bulletin 17C analysis. The peaks used in the analyses include only gaged peaks and historical peaks reported by the USGS (England Jr et al., 2019).

3.1.1 Limitations

Bulletin 17C peak flow predictions and confidence limits are limited by the number of years of record reported at a gage. Increasing the number of gaged instantaneous peaks makes the predictions more accurate and confidence intervals tighter. All selected USGS gage sites have unequal amounts of gaged peaks with a minimum of 10. Unequal amounts of annual peak flow data at each gage site could affect results if biased by drainage area. Table 3.1 shows a maximum average difference of 3.8 years of record between the four smallest drainage area categories. The fifth and largest drainage area category, 30-50 mi^2, has at least four and at most eight more years of record on average compared to the other categories. This gives the 30-50 mi^2 watersheds a small advantage over the other sizes.

3.2 TR-20 Inputs

TR-20 models require inputs summarized in Table 3.2. Although sources of TR-20 inputs are readily available, it is usually unknown which combination of inputs creates the best model and therefore the best peak flow predictions. Without collecting field data or calibrating to recorded data, selecting TR-20 inputs becomes a subjective process, leaving the user to assign inputs based on intuition, literature, or accepted practice (Panel, 2020). We followed NDOT practices for selecting TR-20 input sources while improving their procedures where reasonable.

All input options, source options, problems, and used sources are summarized in Table 3.2. More detailed descriptions of the chosen inputs are available in Appendix A.

Table 3.2 TR-20 Input Sources

Input	Source Options	Problems	Final Source
Land Use Shapefile Data	1. 2005 UNL land use (UNL, 2024) 2. USGS land use through WMS web services (Aquaveo, 2023b) Other UNL land use (UNL, 2024)	• Land use descriptions and CN descriptions are rarely exact matches. (Panel, 2020)	We matched CNs to closest LU description
Soil Type Data	1. SSURGO data through WMS web services (Aquaveo, 2023b) 3. NDOT statewide SSURGO shapefile	• Small differences due to yearly updates to SSURGO data (NRCS, 2019)	Download SSURGO data using WMS web services (Aquaveo, 2023b)
Agricultural Curve Numbers	1. TR-55 (NRCS, 1986) 2. NEH-630 (NRCS, 2024) 2. Averaged agricultural curve number set used in NDOT projects	• Land use shapefiles don't account for contoured, terraced, or row crops (Panel, 2020) • Curve numbers for individual crop species such as soybeans or sunflowers, are not specified (NRCS, 1986, 2024).	Classified all agricultural land uses as the same averaged agricultural curve numbers from NDOT projects.
Time of Concentration	1. Lag Method (NRCS, 2024) 3. Segmental Method (NRCS, 1986)	• TR-55 requires the segmental method (NRCS, 1986). Is the lag method required for TR-20 (Folmar et al., 2007)?	Estimated peak flow using both methods
Open Channel Flow Length for Natural Channels	1. Satellite Imagery (Aquaveo, 2023b) 2. Topo Maps (Aquaveo, 2023b)	• Length based on user judgment.	Started open channel flow at end of USGS blue line and checked against satellite imagery .
Open Channel Flow Manning's n	1. Literature (Barnes, 1967; Chow) 2. example NDOT projects 3. Back-calculate from gage data 2. NDOT drainage manual average value, 0.035	• Subjective selection by user (Panel, 2020)	Choose 0.03, 0.04, or 0.05 by inspection. Supported by NDOT projects examples and literature.
Cross-Sectional Area for Hydraulic Radius	1. Extract from digital elevation data (USGS) 4. Assume trapezoidal channel, estimate dimensions	• Most digital elevation data does not show bathymetry • Where should we cut the cross-section so that it is representative of the reach?	We used the 1-meter elevation data even though it does not penetrate the water surface.

Input	Source Options	Problems	Final Source
			We cut cross sections near the middle of the open channel flow arc
Elevation Data for Cutting Cross-Sections	1. USGS 3DEP data (USGS) 2. NDOT 1-meter data	• Small differences between the two datasets. • NDOT 1-meter files are large and difficult to transfer	USGS 3DEP data for convenience
Shallow Concentrated Flow Equations	1. Generic Unpaved equation (NRCS, 2024) 2. Cerrelli and Humpal equations (Anciaux Humpal & A Cerrelli, 2009; NRCS, 2024)	• Only unpaved/paved equations available as options in WMS	Used generic unpaved equation in all circumstances which represents shallow concentrated flow for grassy channels.
Sheet Flow Length	1. TR-55 (NRCS, 1986) 2. NEH-630 (NRCS, 2024)	• Use 100 ft. or 300 ft.	More publications supporting the use of 100 ft (NRCS, 1986, 2009, 2024; Panel, 2020)
Elevation Data for Delineating Watersheds	1. WMS Worldwide Elevation data (Aquaveo, 2023b) 2. Other	• Only offers resolution >= 10-meters (Dees, 2017)	Delineate all watersheds using this data at a 10-meter resolution. Try to match delineated watershed area to USGS watershed area.
Watershed Slope	1. Extract from WMS 10-meter DEM 2. NHD dataset	• Unsure which is best for estimating T_c using lag equation	WMS 10-meter DEM approximation was used.
Statistical Rainfall Depth	1. NDOT drainage manual depths averaged by county (NDOT, 2018) 2. NOAA atlas 14 interactive map	• Unsure when NDOT values were last updated • NDOT values are averaged by county • No confidence limits given for NDOT values	Used NDOT values due to convenience and uncertainty associated with all statistical rainfall depth sources.
Initial Abstraction	1. 0.2S 2. 0.05S (Hawkins et al., 2008; Moglen et al., 2022)	• Studies have shown 0.05S may be more appropriate than 0.2S but standard curve numbers were derived using the latter (Hawkins et al., 2008)	Used 0.2S for initial abstraction
Antecedent Moisture Condition	1. AMC I 2. AMC II 2. AMC III	• Unsure if change is warranted	Used AMC II
Peaking Factor	1. 484 3. Other	• Unsure if change is warranted	Used 484

3.2.1 Appropriate T_c Estimation Method

Due to the of the lack of guidance on which T_c estimation method to pair with TR-20, we and others have questioned whether it is theoretically acceptable to use the segmental method in place of the lag method (Folmar et al., 2007). The SCS unit hydrograph and the lag equation were parts of the original theory developed by Mockus, possibly making these two elements inappropriate to use separate from each other (Folmar et al., 2007). TR-55 methods were derived from TR-20 results and do not directly incorporate the SCS unit hydrograph (NRCS, 1986). This, in addition to TR-55 explicitly stating that the segmental method is to be used for TR-55 predictions, makes the decision between T_c estimation methods a TR-20 problem (NRCS, 1986). Through personal email communications with the NRCS, we verified that there is no official guidance on which T_c method to pair with TR-20 procedures (Cerrelli, 2024). The few guidelines available for selecting a T_c estimation method include using the lag method in rural settings (Folmar & Miller, 2008) and using the segmental method for conservative peak flow predictions (Cerrelli, 2024; Panel, 2020). Our results and the results of others indicate that the segmental method tends to return shorter times of concentration which result in higher peak flow predictions (Cerrelli, 2024; Panel, 2020). We predicted TR-20 peak flows using both the lag method and the velocity method for comparison.

3.3 Regression Equations

We have elected to estimate return period discharge using all regional regression equations currently used at NDOT (Beckman, 1976; Cordes, 1993; Soenksen, 1999; Strahm & Admiraal, 2005). The performance of equations developed by Admiraal for small Nebraskan watersheds (1-10 mi^2) are compared to TR-20 performance in Section 5.3. The solutions for the Admiraal equations have been pre-calculated by the Nebraska Department of Natural Resources (NeDNR) for every stream reach in Nebraska with the results recorded in an agency GIS tool called N-FACT (Nebraska Flood Assessment Calculation Tool). This tool was created by the NeDNR in collaboration with ESRI (Esri, 2014).

3.3.1 Limitations

All regression functions are fit to real data. Because of this, each regression equation has limitations imposed on it by the range and quantity of the data from which it was created. Regularly, regression equation sets were disqualified at gage sites due to their input parameters not being within the range of data from which the equations were created. The quantity of data must also be considered. Later regression sets incorporate more gage data than earlier sets, implying that the latest regression set will usually outperform earlier sets. Also, regression equations cannot account for land use changes which means they are limited to the land uses they are derived from, usually rural. Limitations specific to the Admiraal small watershed equations are discussed in Section 5.2.1.

Chapter 4 Results

4.1 Rasterized Root Mean Square Error

A common error metric used to compare predicted and observed results is the root mean square error (Hodge & Tasker, 1995; Hodgkins et al., 2007; Jackson et al., 2019). The root mean square error (RMSE) of log transformed results is often calculated identically to the standard error of estimate (SEE) (Hodgkins et al., 2007; Strahm & Admiraal, 2005). SEE is an error metric commonly reported in regression studies (Beckman, 1976; Moglen et al., 2006; Panel, 2020; Soenksen, 1999; Strahm & Admiraal, 2005) and is often used interchangeably with RMSE (Jackson et al., 2019; Law & Tasker, 2003). In our study, we compared all model predictions to flow frequency results from PeakFQ. RMSE expresses errors in the same units as the measurements used for its calculation (Jackson et al., 2019) but can be expressed as upper and lower 68% confidence departures in percent as seen in Figure 4.1 to Figure 4.3 (Tasker, 1978).

Figure 4.1 to Figure 4.3 below show RMSE organized by drainage area category and return period for the TR-20 (segmental), TR-20 (lag), and Admiraal results, respectively, with darker shades indicating smaller RMSE in log units and more accurate model performance. The two percentages in each cell correspond to the lower and upper 68% departures derived from RMSE in log units. A 68% level of confidence is claimed due to two thirds of flow frequency peaks falling within one standard error of the model peak, assuming log-normal differences. Additionally, the number of sites used to estimate the root mean square errors are shown in each cell. The error values can be interpreted by using the negative and positive departures reported by cell. For example, there is approximately a 68% probability (Hardison, 1969; Panel, 2020; Tasker, 1978) that a 100-year flow frequency prediction at a 6 mi^2 site will be no more than 56% smaller or 126% larger than the 100-year TR-20 (segmental) prediction at that same site according to Figure 4.1.

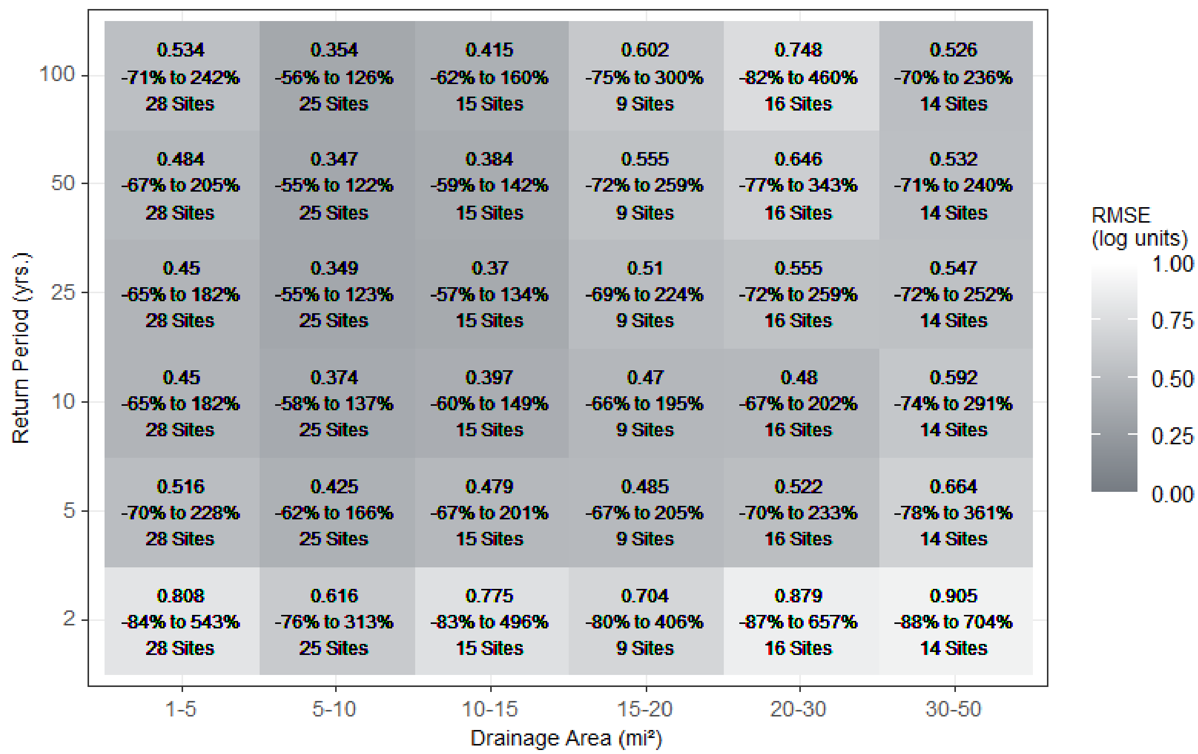

Figure 4.1 TR-20 (Segmental) RMSE in Log_{10} Units by Return Period and Drainage Area Category

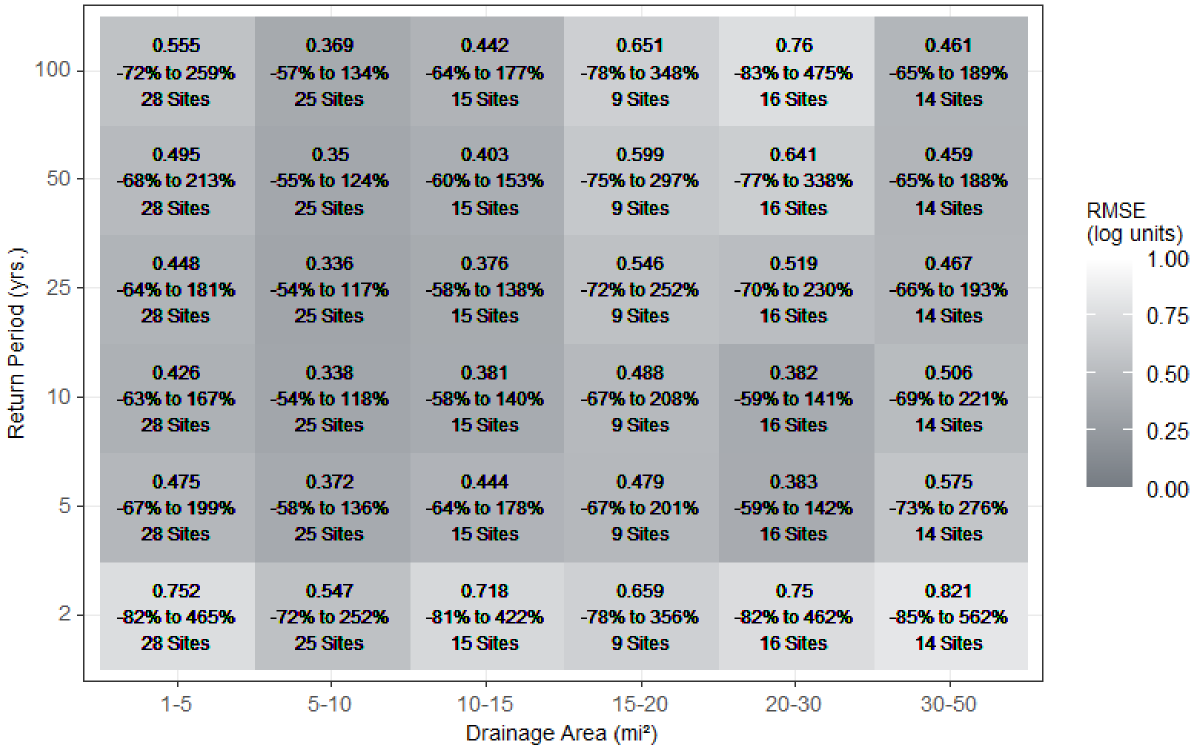

Figure 4.2 TR-20 (Lag) RMSE in Log_{10} Units by Return Period and Drainage Area Category

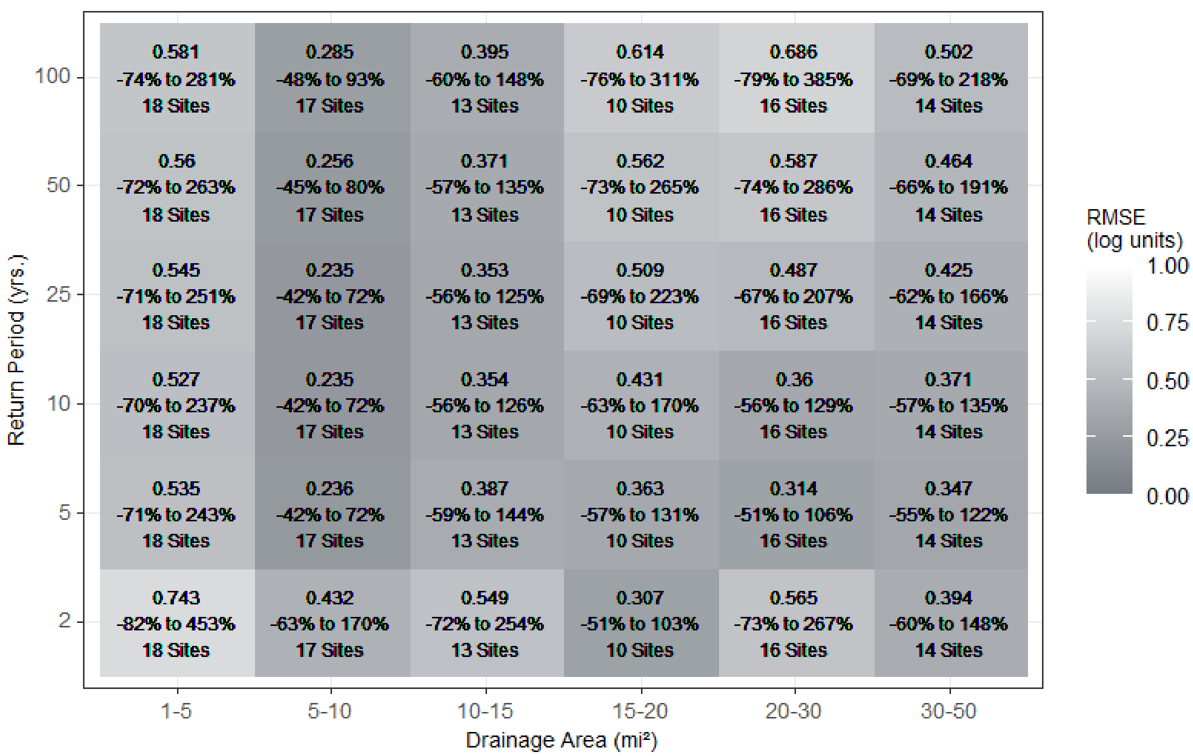

Figure 4.3 Admiraal RMSE in Log_{10} Units by Return Period and Drainage Area Category

4.2 Model Prediction Location Relative to Flow Frequency Buffer

We created Figure 4.4 through Figure 4.6 by buffering each flow frequency prediction by ±30% of its untransformed value and recording whether the associated model result fell above, inside, or below the flow frequency buffer. These plots indicate model accuracy but also whether a model tends to overpredict or underpredict. We assigned a ±30% buffer to the flow frequency results with an assumption that a culvert barrel diameter designed to pass the flow frequency peak would likely need to be sized up or down if the model prediction exceeded ±30% of the flow frequency prediction. The ±30% buffer does not correspond to a specific level of confidence. Figure 4.4 to Figure 4.6 show a count of how many TR-20 (segmental), TR-20 (lag), and Admiraal predictions fell above, inside, or below the ±30% flow frequency buffer, respectively. The rasters are organized by drainage area category on the x-axis and by separate plots for each return period, with darker cells indicating a higher percentage of model predictions and their locations indicated by the y-axis.

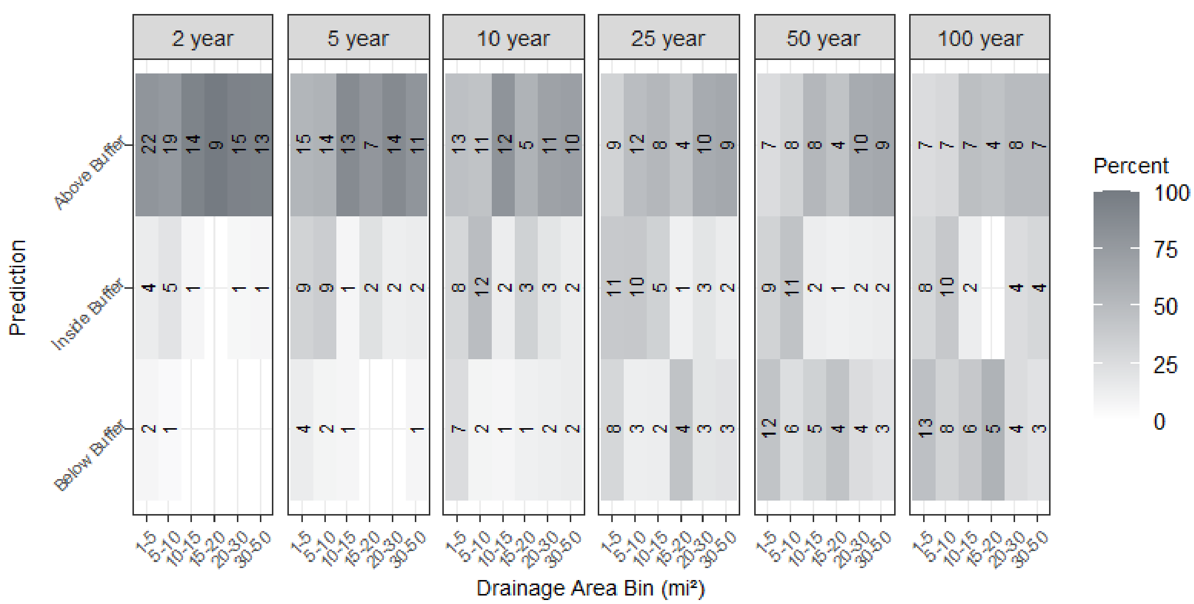

Figure 4.4 Percent TR-20 (Segmental) Predictions Above, Inside, or Below ±30% Buffer

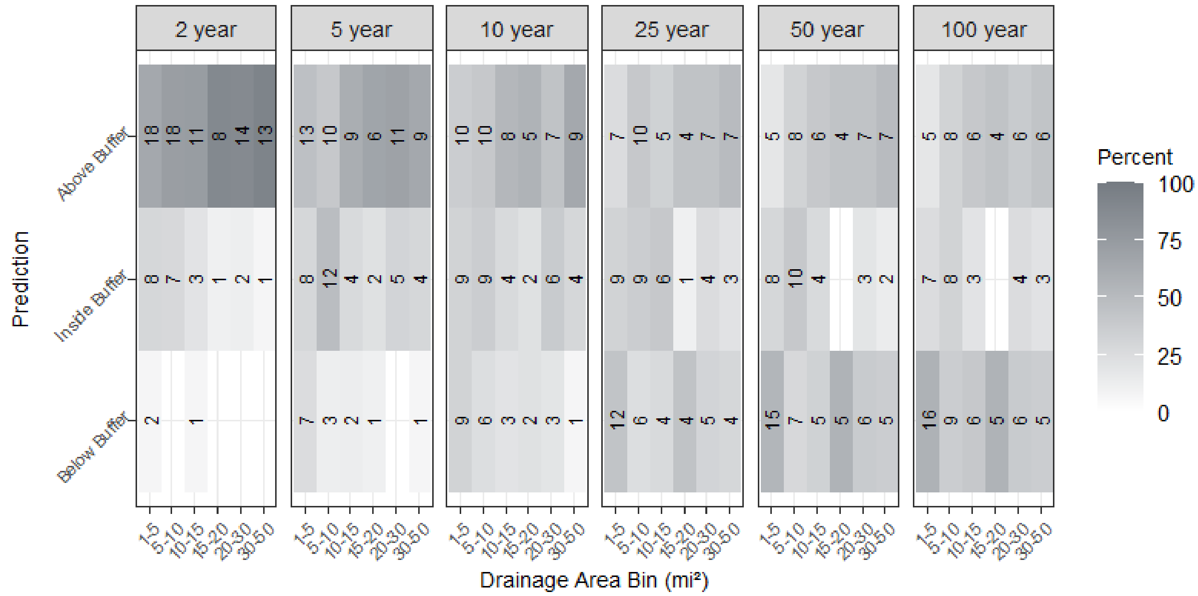

Figure 4.5 Percent TR-20 (Lag) Predictions Above, Inside, or Below ±30% Buffer

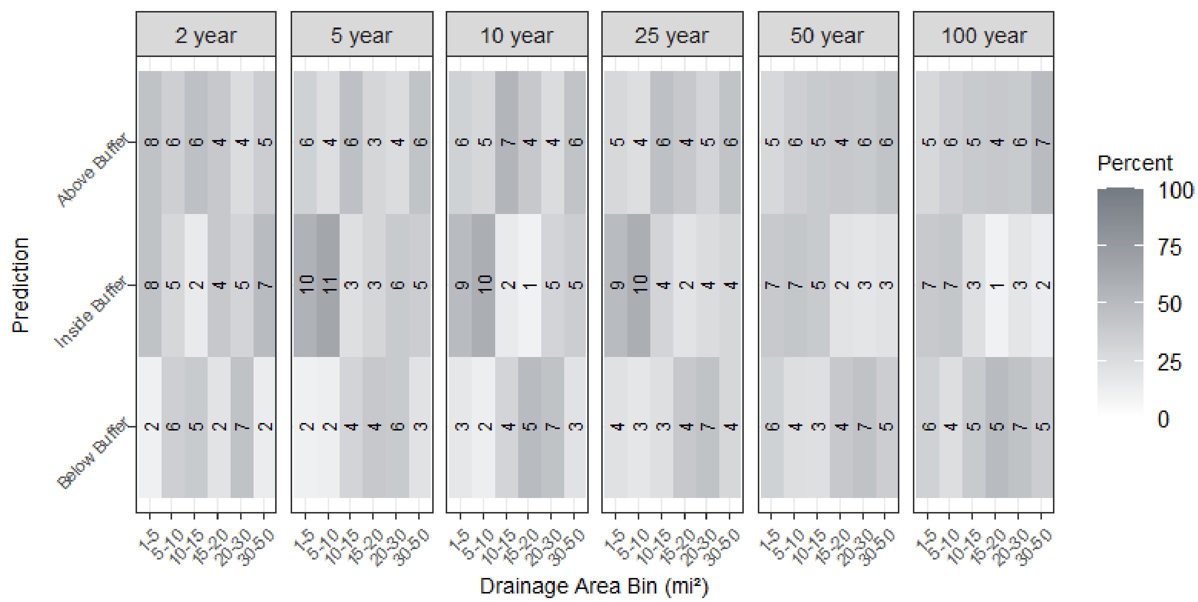

Figure 4.6 Percent Admiraal Predictions Above, Inside, or Below ±30% Buffer

4.3 Average Model Prediction Compared to Average Flow Frequency Prediction

Figure 4.7 below does not include drainage area but instead examines model performance by return period for all sites. We created scaling factors in Figure 4.7 by dividing the average model peak by the average flow frequency peak for each combination of model and return period. Figure 4.7 shows how much each model tends to overpredict, with darker shaded cells indicating a smaller difference between the flow frequency average peak and the TR-20 average peak.

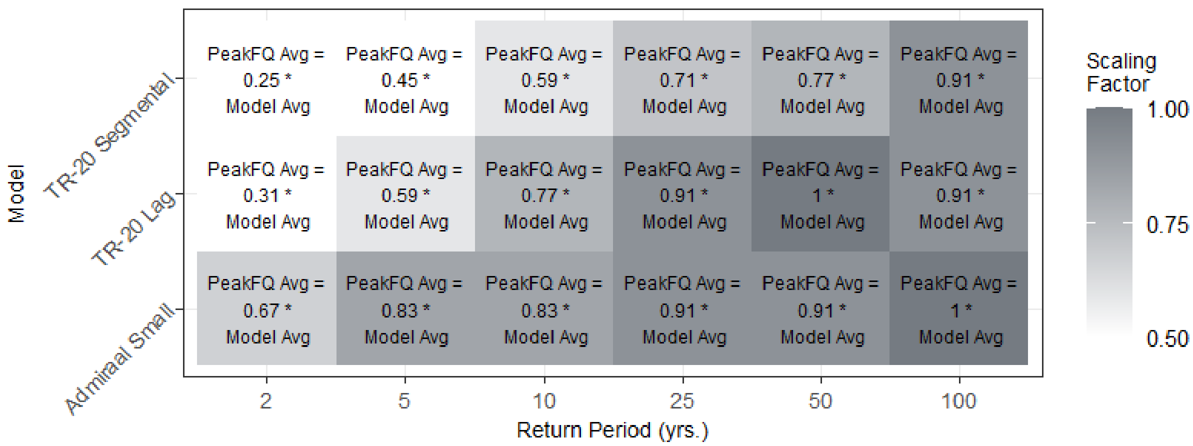

Figure 4.7 Average Model Peak Compared to Average PeakFQ Peak, 1-50 mi^2

Chapter 5 Interpretation and Discussion

5.1 TR-20 Performance

Figure 4.1 and Figure 4.2 show the RMSE for TR-20 (lag) and TR-20 (segmental) increasing across all return periods (except the 2-year) for drainages greater than 15 mi^2. From Figure 4.4 and Figure 4.5, TR-20 (segmental) overestimates peak flows more frequently for lower return period flows (2-, 5-, 10-, 25-year). TR-20 (lag) matches TR-20 (segmental) but does not overpredict as frequently for the 25-year return period. TR-20 overprediction is also apparent in Figure 4.7. Additionally, Figure 4.4 and Figure 4.5 show TR-20 overpredicting more frequently for drainages greater than 10 or 15 square miles.

5.1.1 Lag vs Segmental Method for Estimating Time of Concentration

Figure 4.1 and Figure 4.2 show that the lag and segmental methods for estimating the time of concentration have negligible RMSE differences across all tested return periods and drainage area categories. From Figure 4.4 and Figure 4.5, the lag method appears to overpredict less frequently than the segmental method. Despite this, there are negligible differences between the number of segmental and lag estimations that fall between the ±30% buffer. A table showing all lag vs segmental time of concentration estimates is included in Appendix F.

5.2 Admiraal Regression Equation Performance

Figure 4.3 shows the RMSE results for the Admiraal regression equations. In Figure 4.3, Admiraal's small watershed equations were used for drainage areas less than 10 mi^2 and Admiraal's large watershed equations were used for drainage areas greater than 10 mi^2. The Admiraal equations show inconsistent errors by drainage area below 15 mi^2, with the 1-5 mi^2 bin returning 68% confidence ranges at most 23% larger than TR-20 (segmental), the 5-10 mi^2 bin being at least 24% smaller, and the 10-15 mi^2 range being at least 5% smaller than TR-20 (segmental). Figure 4.6 shows the Admiraal equations predicting more peaks within the ±30%

buffer for drainage areas less than 10 mi^2, indicating a higher level of performance from Admiraal's small watershed equations than from his large watershed equations.

5.2.1 Admiraal Small Watershed Equation Limitations

Out of 130 USGS gage sites selected for our study, 69 sites are less than 10 mi^2. Admiraal used 56 of these 69 sites to create his small watershed equations. The considerable overlap between datasets causes the Admiraal small watershed equations to perform better than if the equations were run at sites not included in Admiraal's study. To illustrate, we calculated RMSEs shown in Figure 5.1 for two subsets of our 130-site sample. The first subset (left) shows RMSEs calculated using only gage sites from both our studies which shall be referred to as mutual sites. The second subset (right) shows RMSEs calculated using only gages in our study that were not included in Admiraal's study. Although there is a large difference in sites used to calculate the RMSEs, these plots show the mutual sites performing better overall than the non-mutual sites, as expected. The 1-5 mi^2 range saw a large increase in errors after disqualifying mutual sites. The errors calculated after disqualifying mutual sites are not representative of accuracy statewide given the small sample size used in their calculation. However, they show an expected drop in accuracy when the Admiraal small watershed equations are used to estimate peak flow at locations not included in the original regression study.

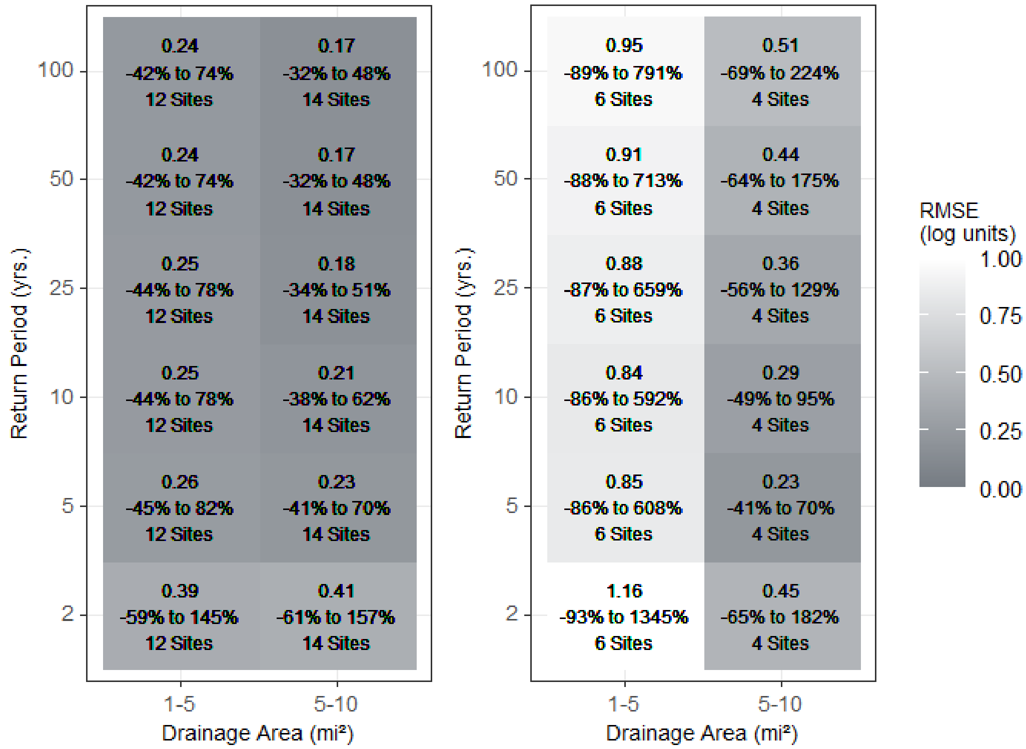

Figure 5.1 Admiraal (Small) RMSE in Log_{10} Units for Mutual Sites (left) and Non-Mutual Sites (right)

Additionally, the small number of gage sites used to create each regional set of small watershed equations decreases the reliability of their predictions. Table 5.1 below shows the number of gage sites used to create Admiraal's small watershed equations vs Admiraal's large watershed equations. There are fewer sites included in Admiraal's small watershed study because it was limited to sites less than 10 mi^2. Through personal communications with the USGS, we have learned that 10 gages per region plus 10 gages per covariate is a typical minimum number of gages used to create a regression equation (McCarthy, 2024). Additionally, a small sample size of gage sites contributes to larger errors as shown by equation (5.1). As a result, the SEE's reported in Admiraal's study and the RMSEs reported in our study were negatively affected.

$$SEE = \sqrt{\frac{\sum\left(Log(Q_{LP3}) - Log(Q_{Model})\right)^2}{N}} \tag{5.4}$$

where:

SEE = standard error of estimate in log units

Q_{LP3} *= flow frequency discharge*

Q_{Model} *= model discharge*

N = number of gaging stations

Table 5.1 Number of Gages Used in Admiraal Study by Region

Region	Admiraal Small # Gages Used	Admiraal Large # Gages Used
Big Blue River Region	8	41
Eastern Region	21	51
Northeastern Region	13	49
Central and South-Central Region	11	46
Upper Republican Region	7	36
Northern and Western Region	12	36
High-Permeability Region	NA	51

5.2.2 Admiraal Small Watershed Equation Extrapolation

The Admiraal small watershed equations are applicable up to only 10 mi^2. If the Admiraal small watershed equations maintain low RMSEs for drainage areas beyond 10 mi^2, they would continue to be a useful model for calibrating TR-20. This section discusses the performance of the Admiraal small watershed equations when used to predict peak discharges for watersheds up to 15 mi^2. RMSE results for the Admiraal small watershed equations extrapolated up to 50 mi^2 are shown in Appendix B. Using the small watershed equations beyond 10 mi^2 is considered extrapolation because the equations were created using drainage areas roughly between 1 mi^2 and 10 mi^2 (Strahm & Admiraal, 2005). Figure 5.2 shows the Admiraal large watershed equation RMSEs compared to the Admiraal small watershed equation RMSEs for the 10-15 mi^2 range. The results show smaller errors by the Admiraal small watershed equations extrapolated up to 15 mi^2 when compared to the Admiraal large watershed equations, suggesting extrapolation up to 15 mi^2 is beneficial.

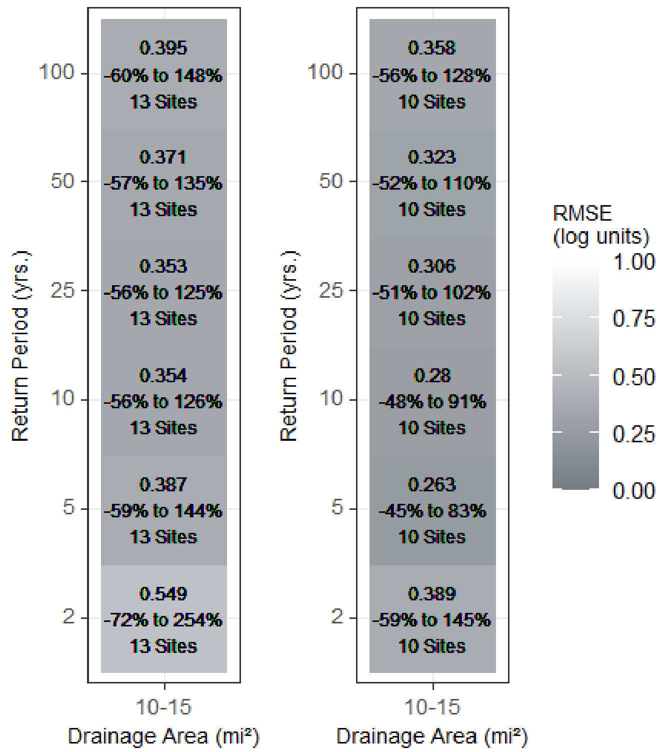

Figure 5.2 Admiraal (Large) (Left) and Extrapolated Admiraal (Small) (Right) Log_{10} RMSE for 10-15 mi^2

5.3 TR-20 Segmental vs. Admiraal Small Watershed Equations

Figure 5.3 below shows a side-by-side comparison of the TR-20 (segmental) errors and the Admiraal small watershed errors with results extrapolated up to 15 mi^2. Although possessing larger errors for drainages from 1-5 mi^2, the Admiraal small watershed errors are smaller than the TR-20 (segmental) errors for the 5-15 mi^2 range. Additionally, ±30% buffer plots showing the 1-15 mi^2 range for TR-20 (segmental) and the Admiraal small watershed equations are given in Figure 5.4 and Figure 5.5 for comparison.

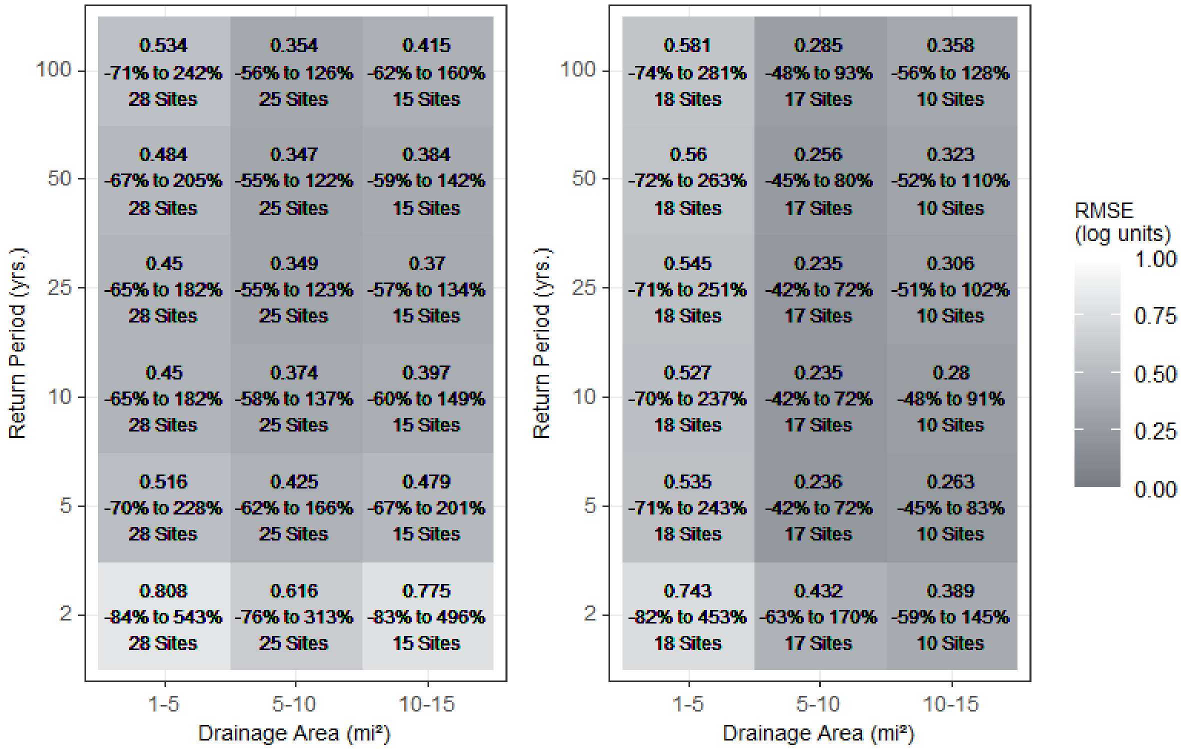

Figure 5.3 TR-20 (Segmental) RMSE (left) vs. Admiraal (Small) RMSE Extrapolated up to 15 mi^2 (right)

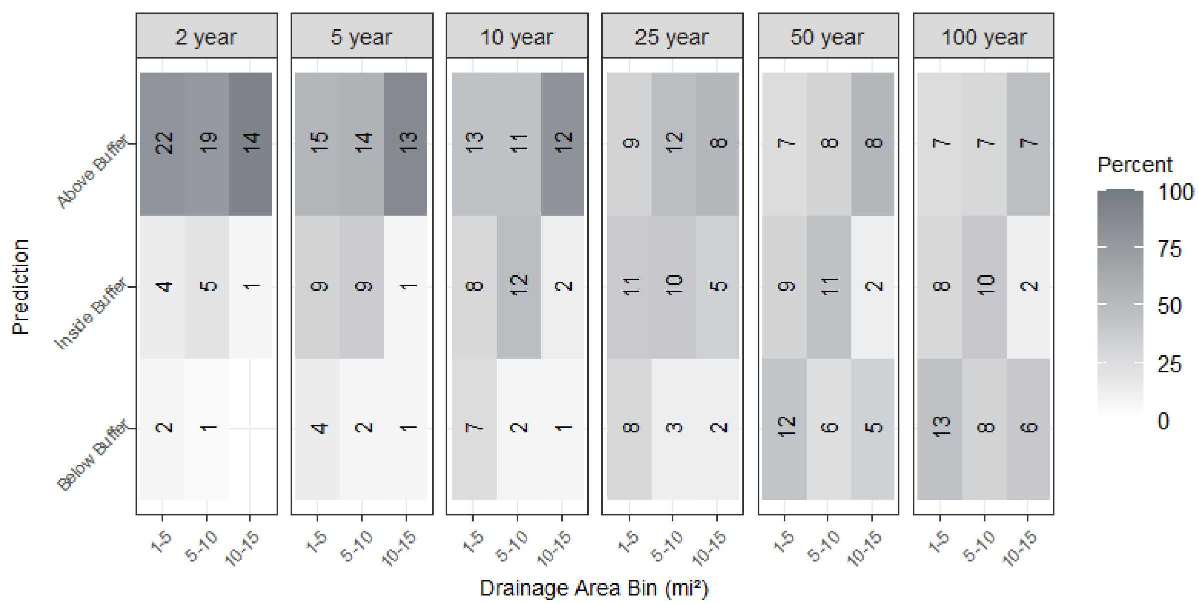

Figure 5.4 Percent TR-20 (Segmental) Predictions Above, Inside, or Below ±30% Buffer, 1-15 mi^2

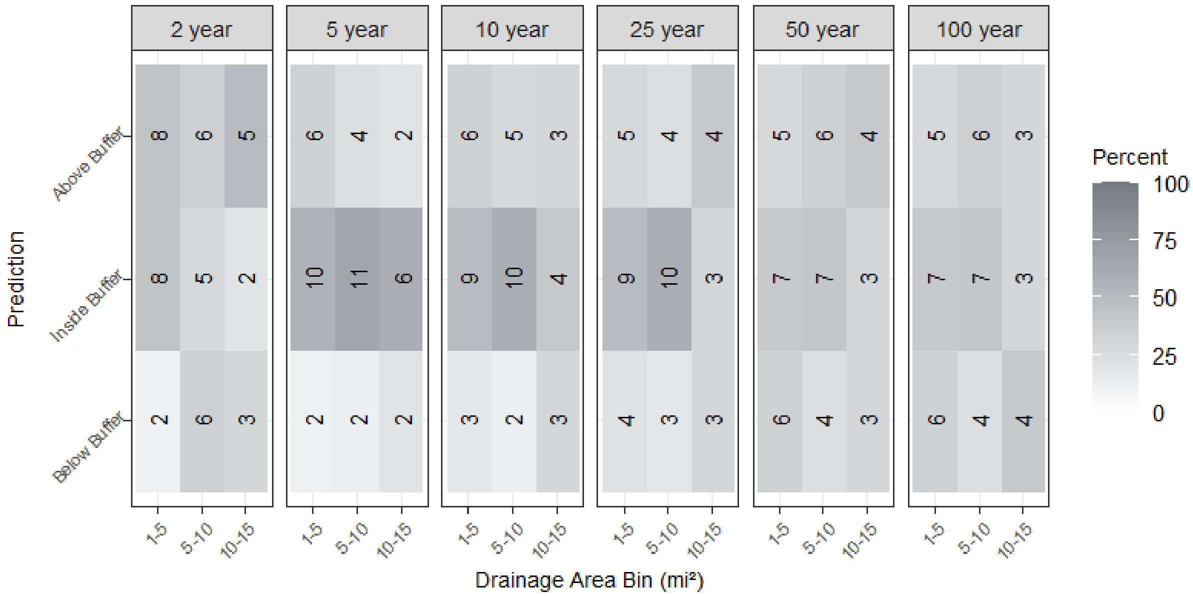

Figure 5.5 Percent Admiraal (Small, Extrapolated) Predictions Above, Inside, or Below ±30% Buffer, 1-15 mi^2

5.3.1 TR-20 Suggested Application

From section 5.2, the Admiraal small watershed equations show the potential to improve the accuracy of our TR-20 models through calibration. Regional regression equation predictions, being generally easier to use and more reproducible, are an attractive option for estimating peak flow when compared to TR-20 (Newton & Herrin, 1982). TR-20 models, however, find useful application in scenarios where land cover is changing. In projects where an estimate of peak discharge is needed pre-construction and post-construction, a TR-20 model can be calibrated to the Admiraal small watershed equations to decrease the likelihood of a TR-20 model overpredicting peaks for the pre-construction state. Then changes can be made to the TR-20 model land cover to simulate discharge for the post-construction state (Hodgkins et al., 2007; Panel, 2020). The change in peak discharge due to a change in land cover cannot be modeled by regional regression equations, which are generally developed for rural conditions.

5.4 TR-20 Calibration

When predicting peak discharge with a TR-20 model, calibration to the best statistical estimate is recommended primarily to check for overprediction. Using the segmental method for estimating the time of concentration is recommended due to the several segmental method inputs that may be calibrated. The calibrated TR-20 model can be adjusted as watershed land cover changes occur.

The statistical methods for predicting peak discharge discussed in this study are flow frequency analyses and fixed region regression equations. These statistical methods, unlike TR-20 models, have error estimates which help quantify the uncertainty inherent in their peak flow predictions. Since most culvert design projects will occur at ungaged sites, it is recommended that TR-20 be calibrated to the Admiraal small watershed equations due to their relative accuracy and recency. The Admiraal small watershed equations overpredict less on average for the 2-, 5-, 10-, and 25-year return periods at the 1-15 mi^2 range when compared to TR-20 (segmental) as illustrated in Figure 5.6. TR-20 model calibration is especially encouraged when estimating peak flow for these return periods.

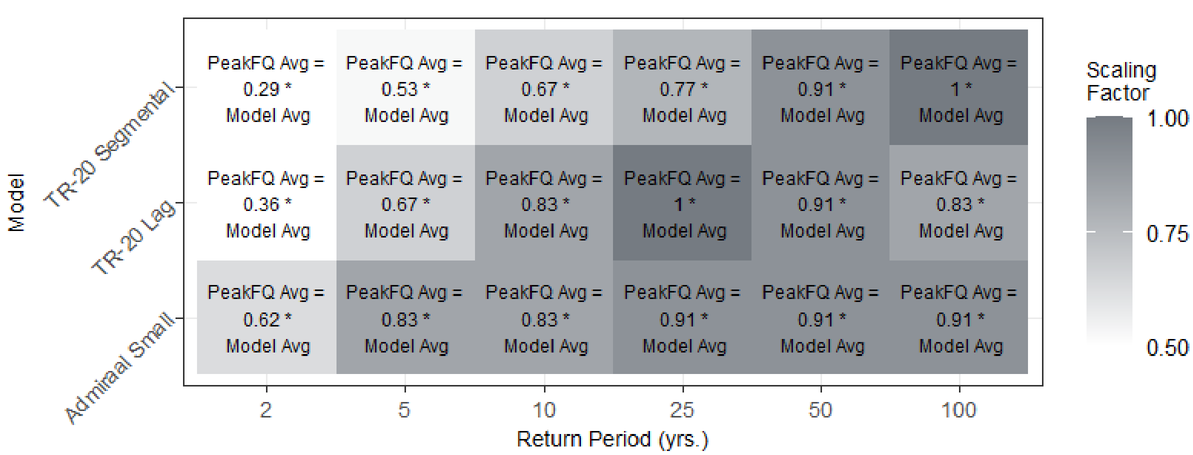

Figure 5.6 Average Model Peak Compared to Average PeakFQ Peak by Model and Return Period, 1-15 mi^2

If high frequency predicted flows from a TR-20 model are larger than the Admiraal small watershed predicted flows at a site, the TR-20 model is likely overpredicting and would benefit from calibration. Figure 5.7 shows how many TR-20 models predict higher peak discharges compared to the Admiraal small watershed equations by return period and drainage area for the 1-15 mi^2 range, indicating the number of TR-20 models in our study that would benefit from calibration.

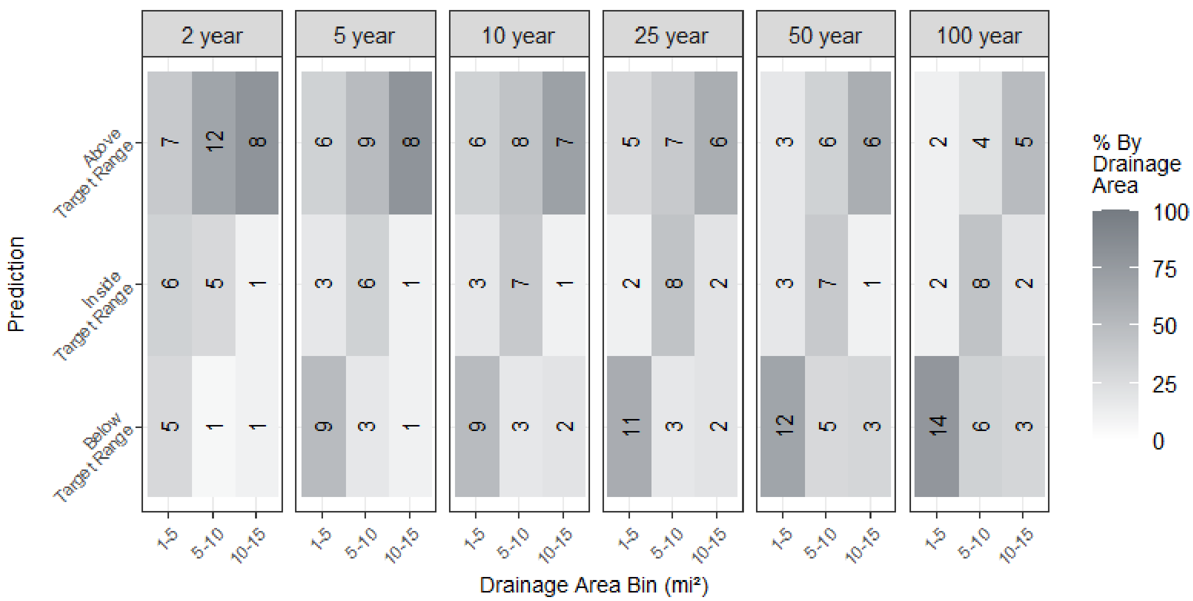

Figure 5.7 Percent TR-20 (Segmental) Predictions Above, Inside, or Below ±1 Admiraal Small Watershed Standard Error

5.4.1 Building Regression Confidence Limits

For watersheds undergoing land cover changes, it is recommended that Nebraskan TR-20 models be calibrated to within one standard error of the Admiraal small watershed equations. New regression studies in Nebraska may surpass the accuracy of the Admiraal small watershed equations. A one-standard-error buffer corresponds to roughly a 68% level of confidence around the regression result (Hardison, 1969; Panel, 2020; Tasker, 1978). The plus or minus departures in percent that form the 68% confidence limits can be calculated using equation (5.2) which account for the asymmetry of the log-normal distribution (Hardison, 1969; Riggs, 1968; Tasker, 1978). The standard errors of estimate in log units needed for calculating upper departures are typically included in published regional regression reports. The upper departures for the Admiraal small watershed equations have been pre-calculated and are shown in Table 5.2. The upper confidence limit can be estimated by simply multiplying the regression prediction by one plus the upper departure expressed as a decimal as shown in equation (5.3).

$$SEE\% = \frac{100(|10^{1\pm SEE} - 10|)}{10} \tag{5.5}$$

where:

SEE% = ± departure in percent

SEE = standard error of estimate in log$_{10}$ units
(Riggs, 1968)

$$Q_u = Q(1 \pm \frac{SEE\%}{100}) \tag{5.6}$$

where:

Q_u = calibration upper limit for regression
peak flow prediction

Q = regression peak flow prediction at a site

SEE% = ± departure in percent

Table 5.2 Upper Departures (%) for Admiraal Small Watershed Equations by Return Period and Region

Region	2-year	5-year	10-year	25-year	50-year	100-year
BBR	79%	44%	33%	24%	20%	18%
ER	26%	24%	26%	29%	31%	33%
NER	78%	44%	33%	26%	26%	29%
CSCR	131%	73%	49%	38%	41%	49%
URR	94%	46%	31%	24%	27%	34%
NWR	279%	121%	95%	61%	40%	37%

Confidence limits were built using the SEE rather than the standard error of prediction (SEP) because information needed to calculate the statistic was not published. It is more accurate to construct confidence limits using the SEP rather than the SEE (Hardison, 1971; Hodge & Tasker, 1995; Panel, 2020).

5.4.2 Calibration Procedure

Before beginning the calibration procedure, care should be taken to ensure that all Admiraal (small) watershed equation inputs are within the data limits of each equation, with the 10-15 mi^2 extrapolated drainage areas being an exception. The primary goal of this calibration procedure is to decrease the likelihood of overprediction from a TR-20 model (Panel, 2020). To accomplish this, TR-20 design flows that are greater than the Admiraal (small) estimate upper limit should be calibrated to fall between the Admiraal (small) estimate and its upper limit. The area between the Admiraal (small) estimate and its upper limit will be referred to as the target range (Panel, 2020). An example of the target range is labeled in Figure 5.8. The upper limit is defined in Section 5.4.1 assuming that calculating SEP at a site is not feasible. The Admiraal (small) estimate lower limit is not needed for this calibration procedure.

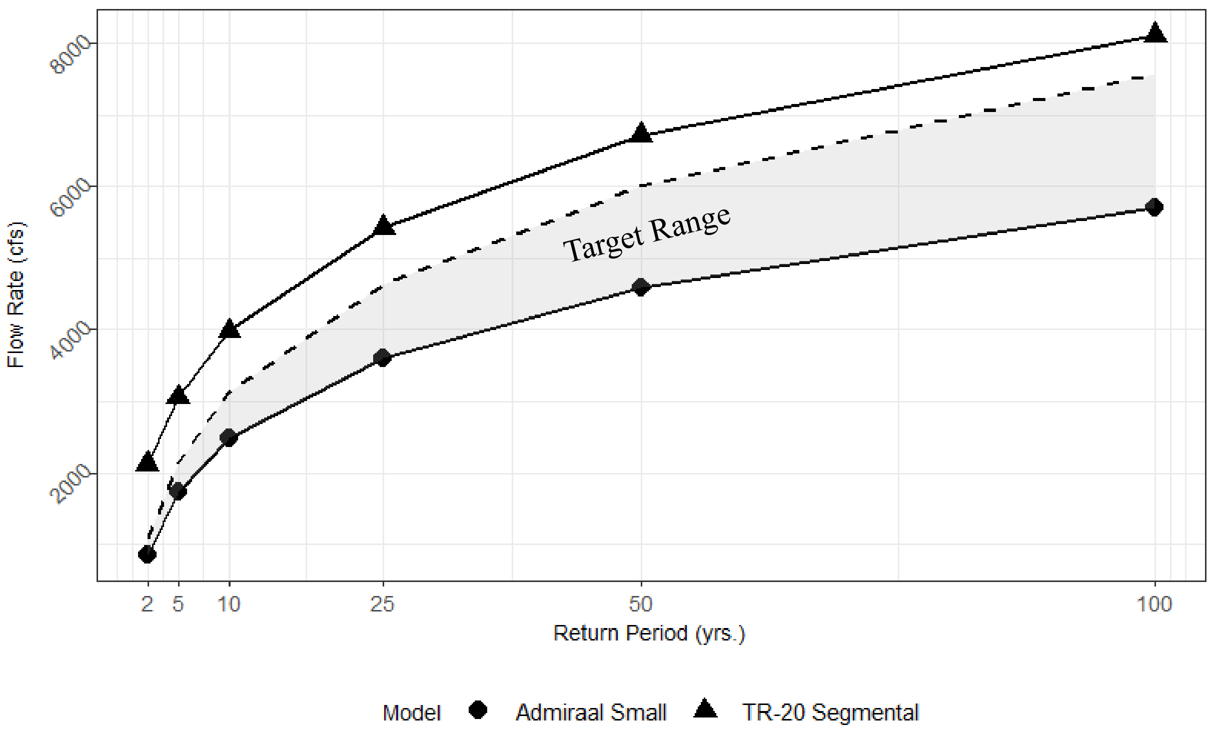

Figure 5.8 TR-20 (Segmental) Predictions Compared to Admiraal Small Watershed Equation Predictions Plus One Standard Error, 6610700

The time of concentration is the primary calibration variable in this procedure (Panel, 2020). A simplified version of the Maryland Panel of Hydrology calibration order and limits is given in Table 5.3. Table 5.3 is ordered by calibration priority. Meaning, the variables near the top should be calibrated first. Table 5.3 is meant to be a guide for adjusting TR-20 variables during calibration and is not intended to be a list of fixed limits. There may be different adjustment ranges or other logical calibration progressions that are more appropriate depending on circumstance. All final input values must be consistent with standard hydrologic practice, documented, and supported with field investigations when permitted (Panel, 2020). A TR-20 model will be considered calibrated when the design flows fall within the target range (Panel, 2020).

Table 5.3 Calibration Variables and Limits Recommended by Maryland Panel of Hydrology (Panel, 2020)

Variable Listed by Priority	Common Error Trend	Adjustment Limits
Open Channel Flow Manning's n	Low	±50%
Open Channel Flow Representative Cross-Sectional Area	Low	±25%
Open Channel Flow Length	Low	See 1.
Sheet Flow Manning's n	Low	±25%
Runoff Curve Number Conditions	High or Low	See 2.
Statistical Rainfall Depth	NA	See 3.

1. During the initial model setup, begin the open-channel-flow arc at the end of the USGS blue line. If the USGS blue line shows a longer open channel flow arc than is observed in satellite imagery, the open channel flow arc may be adjusted to begin where the channel becomes recognizable via satellite.
2. The WMS mapping table curve number conditions may be adjusted from poor, to fair, to good, with each increment resulting in a decrease in peak flow
3. The upper or lower 90% confidence limit from the NOAA Atlas 14 interactive map may be used rather than the best rainfall depth estimate.

5.4.3 Calibration Example

Consider Big Papillion Creek near Orum, Nebraska which has a drainage area of 8.52 mi^2. Since this gage site is located in the eastern region, the calculated upper departures for the eastern region from Table 5.2 are used to find the target range upper limit as shown in Table 5.4. Suppose we select the 25-year, 50-year, and 100-year discharges as design flows. The TR-20 (segmental) predicted design flows fall above the target range as shown in Figure 5.9. To decrease the TR-20 (segmental) predicted design flows to be within the target range, we will first adjust the open channel flow Manning's n value as instructed in Table 5.3. Increasing the open channel flow Manning's n value from 0.03 to 0.045 reflects a +50% change, the maximum allowable change given in Table 5.3. This new Manning's n value corresponds to a minor stream with a fairly regular section and dense weeds according to the NDOT drainage manual, making this adjustment consistent with Nebraskan hydrologic practice (NDOR, 2006). This single adjustment decreased the TR-20 (segmental) design flows to be within the target range as shown in Figure 5.9. No further calibration is needed.

Table 5.4 Calibration Design Flows and Target Range Upper Limits

1. Return Period (Years)	2. TR-20 (Segmental) Predicted Discharge (cfs)	3. Admiraal (Small) Predicted Discharge (cfs)	4. Eastern Region Upper Departures (%)	5. Q_u Equation (5.3) (cfs)
25	5430	3610	29	4657
50	6720	4596	31	6021
100	8112	5711	33	7596

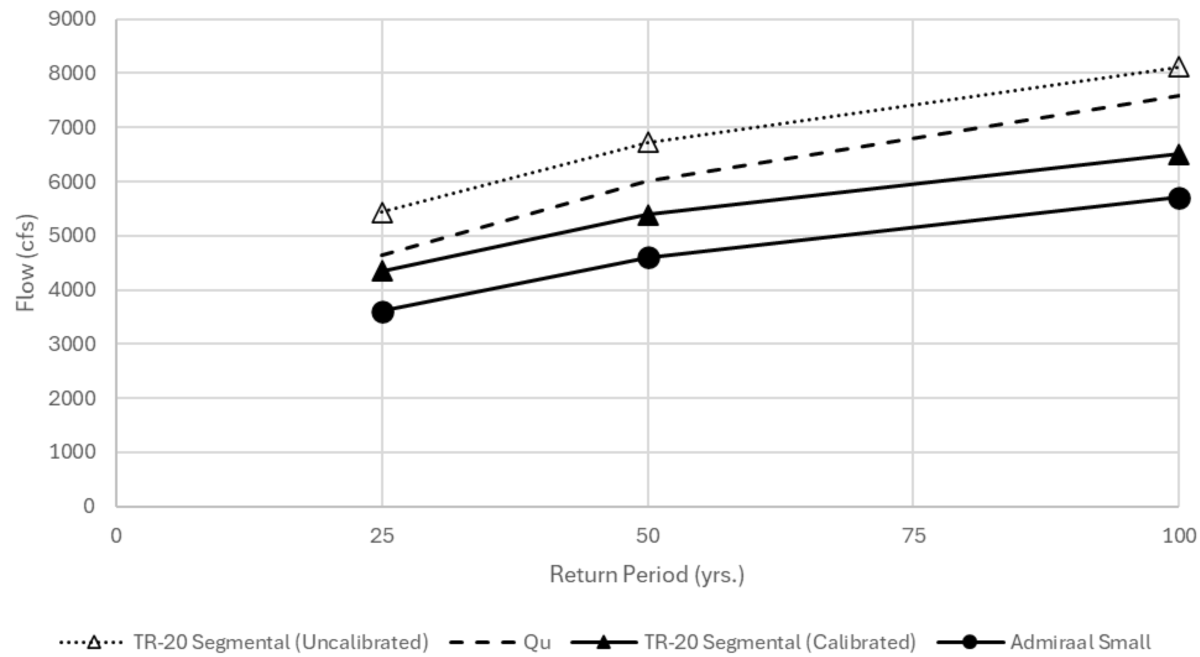

Figure 5.9 Uncalibrated vs Calibrated TR-20 (Segmental) Design Flows Compared to Admiraal Small Watershed Equation Target Range, 6610700

5.4.4 Calibration Complications

Listed below are two complications that could arise during the calibration procedure.

1. What if my high frequency design flows fall above the target range and my low frequency design flows fall below the target range?

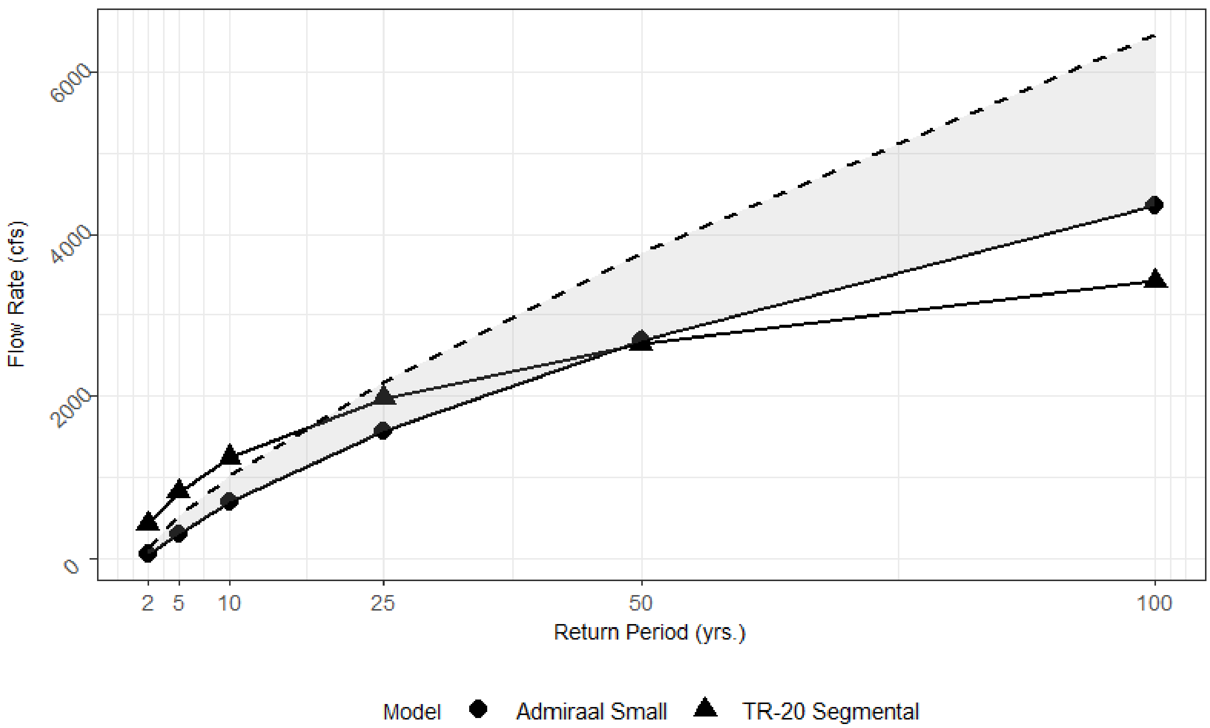

Figure 5.10 Example of High Frequency Peaks Falling Above Target Range and Low Frequency Peaks Falling Below Target Range, 6769200

Figure 5.10 shows an example of high frequency peaks falling above the target range and low frequency peaks falling below the target range. First, remember that only design flows, not all return period peaks, must be calibrated to fall within the target range. Second, most calibrations shift all peaks up or down. This means, if the TR-20 (segmental) peaks follow a different slope than the regression peaks for a site, it could be difficult to fit all design flows within the target range.

Assuming the TR-20 (segmental) model was built using methods similar to those presented in Section 3.2, consider calibrating the high frequency design flows (2- to 25-year) to fall within the target range and using the upper 90% confidence limit of the statistical rainfall depth to increase the 50-year or 100-year peaks if necessary. Although high frequency design flows tend to overpredict peak discharge, low frequency flows are less predictable, especially for drainage areas between 1-15 mi^2 as shown in Figure 4.4.

2. What if all my design flows are below the target range?

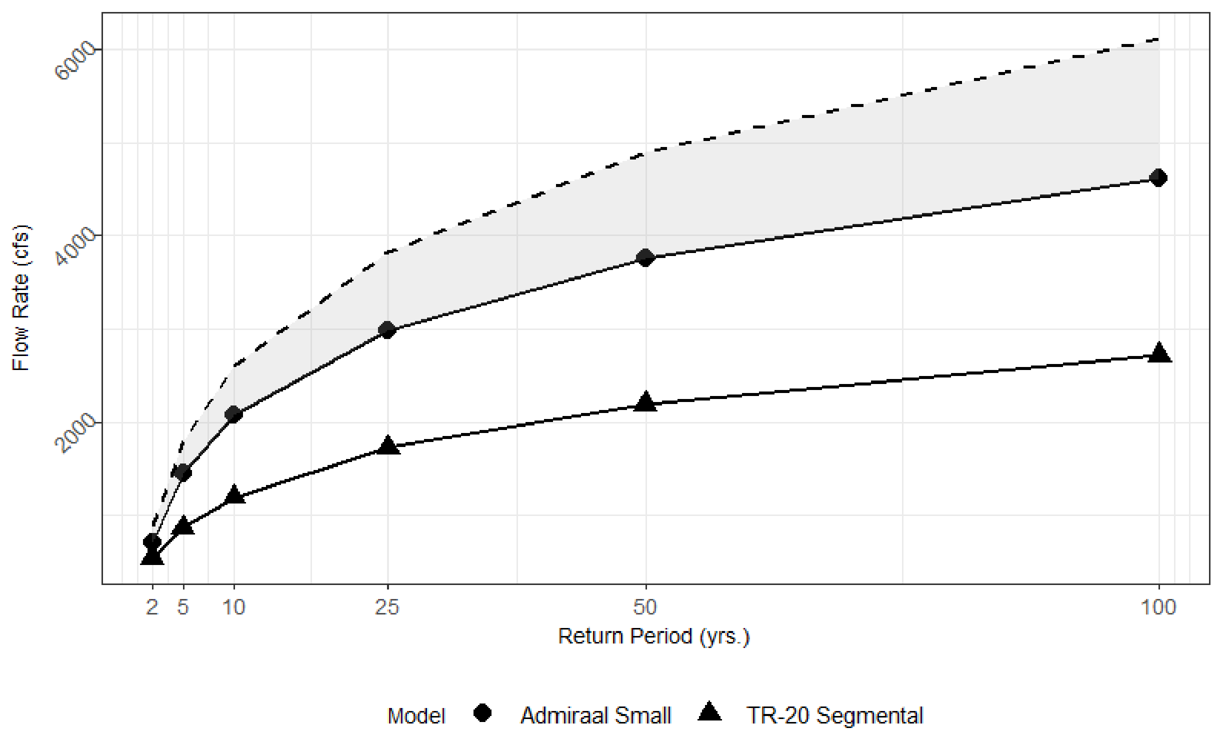

Figure 5.11 Example of All Peaks Falling Below Target Range, 6607800

Figure 5.11 shows an example of all peaks falling below the target range. Assuming the TR-20 (segmental) model was set up using methods similar to those presented in Section 3.2, no calibration is necessary. Calibrating TR-20 (segmental) peaks using the Admiraal small watershed equations is primarily meant to reduce the likelihood of overprediction. If the predicted TR-20 (segmental) peaks fall below the target range for all design flows, the TR-20 (segmental) peaks are less likely to be overpredictions. Considering that many high frequency flows (2- to 25-year) recorded in this study were overpredictions (see Figure 4.4), it would be illogical to increase those peaks to be within the target range. The Admiraal small watershed equations, despite not showing strong trends of overprediction like TR-20 (segmental), are not immune to overpredicting peak discharge. For the case when high frequency design flows are below the target range and low frequency design flows are above the target range, no calibration is needed for the same reasons.

5.5 Simulations with Antecedent Runoff Condition I

Given that TR-20 estimates of peak flow were generally higher than the stream gage estimates, we performed additional simulations using Antecedent Runoff Condition (ARC) I, which corresponds to a drier soil moisture condition than that used in this study, ARC II. A drier soil profile reduces the runoff CN as shown in Table 5.5. For example, the overall average CN for ARC II in this study is 73.4, while the ARC I corresponding average CN is 55.7

A summary of these additional simulations is shown in Table 5.6. Shown are the percentages of predictions using the TR-20 lag equation approach and segmental approach that fall either above, below, or within ±30% of the stream gage estimates by return period. Estimates using ARC I most frequently underestimate peak runoff compared to stream gage and ARC II estimates, often because there was insufficient rainfall to produce runoff.

Table 5.5 Runoff Curve Numbers for Antecedent Runoff Conditions I, II, and III (NRCS, 2024)

1	2	3
CN for ARC II	- - CN for ARC - - I	III
100	100	100
99	97	100
98	94	99
97	91	99
96	89	99
95	87	98
94	85	98
93	83	98
92	81	97
91	80	97
90	78	96
89	76	96
88	75	95
87	73	95
86	72	94
85	70	94
84	68	93
83	67	93
82	66	92
81	64	92
80	63	91
79	62	91
78	60	90
77	59	89
76	58	89
75	57	88
74	55	88
73	54	87
72	53	86
71	52	86
70	51	85
69	50	84
68	48	84
67	47	83
66	46	82
65	45	82
64	44	81
63	43	80
62	42	79
61	41	78

* For CN in column 1.

Table 5.6 ARC I vs ARC II Peak Discharge Estimates Compared to Stream Gage Estimates

Model	Percent of Estimates Above, Within, and Below +/- 30% of Gage Estimates for Indicated Return Period					
	2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
TR-20 lag						
ARC I						
% over	24.2	11.7	11.7	8.3	9.2	30.8
% Within	17.5	12.5	16.7	16.7	15.8	22.2
% Under	58.3	75.8	71.7	75	75	47
ARC II						
% over	73.5	51.3	43.6	35.0	32.5	30.8
% Within	23.1	32.5	30.8	29.1	24.8	22.2
% Under	3.4	16.2	25.6	35.9	42.7	47.1
TR-20 Segmental						
ARC I						
% over	16.7	12.5	10.0	10.8	12.5	-
% Within	14.17	13.3	17.5	19.2	21.7	0.8
% Under	69.2	74.2	72.5	70.0	65.8	99.2
ARC II						
% over	82.9	65.8	55.6	46.2	41.0	35.9
% Within	12.8	23.1	27.4	29.1	24.8	24.8
% Under	4.3	11.1	17.1	24.8	34.2	39.2

Chapter 6 Recommendations and Conclusions

We recommend the following.

1. Do not use uncalibrated TR-20 models to predict peak discharge.
2. Use calibrated TR-20 models to predict peak discharge after land cover changes.
3. For ungaged basins less than 15 mi^2, calibrate TR-20 models to the Admiraal small watershed equations.

The root mean square errors calculated by return period and drainage area for TR-20 predictions become larger after 15 mi^2, indicating a limit of uncalibrated models in Nebraska. Despite having its lowest errors for watersheds between 1 mi^2 and 15 mi^2, using an uncalibrated TR-20 model is discouraged due to its likelihood to overpredict peak flows. Calibrated TR-20 models can be useful for predicting peak discharges after land cover changes. A drainage area limitation for calibrated TR-20 models is unknown. However, calibrated TR-20 models will understandably begin to mimic the trends of the statistical model they are calibrated to, reinforcing the need for low error, robust regression equations for greater accuracy at ungaged sites.

Despite the lag methods connection to curve number theory, there is no official NRCS stance on whether the lag or segmental method should be paired with TR-20 (Cerrelli, 2024). The lag method typically estimates larger times of concentration than the segmental method. Despite this, TR-20 (lag) and TR-20 (segmental) show negligible differences in root mean square errors by return period and drainage area. Both TR-20 (lag) and TR-20 (segmental) tend to overpredict the 2-, 5-, and 10-year return period flows. TR-20 (segmental) typically overpredicts the 25-year return period flows while TR-20 (lag) does not. For the 50-year and 100-year return periods, no strong trends are evident in either model.

The Admiraal small watershed equations can be used to check for TR-20 overpredictions. They can also be usefully extrapolated up to 15 mi^2. The Admiraal small watershed equations overpredict peak flow less frequently and possess low RMSE's relative to TR-20 in most cases, making them useful for detecting instances where TR-20 has overpredicted peak flow. Future regression studies may surpass the accuracy of the Admiraal small watershed equations and become the best statistical model for ungaged sites. It is recommended that TR-20 models be calibrated to the best statistical estimates available.

References

Abdelkader, M., Temimi, M., & Ouarda, T. B. (2023). Assessing the national water model's streamflow estimates using a multi-decade retrospective dataset across the contiguous United States. *Water*, *15*(13), 2319.

Agnihotri, J., Behrangi, A., Tavakoly, A., Geheran, M., Farmani, M. A., & Niu, G. Y. (2023). Higher frozen soil permeability represented in a hydrological model improves spring streamflow prediction from river basin to continental scales. *Water Resources Research*, *59*(4), e2022WR033075.

Anciaux Humpal, A., & A Cerrelli, G. (2009). *A Closer Look at Unpaved Shallow Concentrated Flow* 2009 Reno, Nevada, June 21 - June 24, 2009, St. Joseph, MI. https://elibrary.asabe.org/abstract.asp?aid=26978&t=5

Anderson, J. R. (1976). *A land use and land cover classification system for use with remote sensor data* (Vol. 964). US Government Printing Office.

Aquaveo. (2023a, 4/15/2024). *Compute GIS Attributes*. Aquaveo. Retrieved 9/13/2024 from https://www.xmswiki.com/wiki/WMS:Compute_GIS_Attributes

Aquaveo. (2023b, 5/11/2023). *Import from Web*. Aquaveo. Retrieved 6/3/2024 from https://www.xmswiki.com/wiki/Import_from_Web

Autodesk. (2010). AutoCAD Civil 3D Hydraflow Hydrographs Extension User's Guide. In (pp. 106). 111 Mclnnis Parkway San Rafael, CA 94903, USA: Autodesk, Inc.

Barnes, H. H. (1967). *Roughness characteristics of natural channels*. US Government Printing Office.

Beckman, E. W. (1976). *Magnitude and frequency of floods in Nebraska* [Report](76-109). (Water-Resources Investigations Report, Issue. U. S. G. Survey. https://pubs.usgs.gov/publication/wri76109

Cerrelli, G. (2024). Peak Flow From Mockus Unit Hydograph. In R. Hotchkiss (Ed.).

Chin, D. A. (2022). Essential Considerations in Applying the Curve-Number Method. *Journal of Irrigation and Drainage Engineering*, *148*(2). https://doi.org/10.1061/(asce)ir.1943-4774.0001649

Chin, D. A. (2023). Discussion of "NRCS Curve Number Method: Comparison of Methods for Estimating the Curve Number from Rainfall-Runoff Data". *Journal of Hydrologic Engineering*, *28*(8), 07023003. https://doi.org/doi:10.1061/JHYEFF.HEENG-5904

Chow, V. *1959, Open channel hydraulics, McGraw-Hill, New York*.

Cordes, K. E. (1993). *Design discharge of culverts*. University of Nebraska--Lincoln.

Cosgrove, B., Gochis, D., Flowers, T., Dugger, A., Ogden, F., Graziano, T., Clark, E., Cabell, R., Casiday, N., & Cui, Z. (2024). NOAA's National Water Model: Advancing operational hydrology through continental-scale modeling. *JAWRA Journal of the American Water Resources Association*, *60*(2), 247-272.

David R. Maidment, E. P. C. (2016, 11 July 2016). NHDPlus and the National Water Model. AWRA GIS in Water Resources Specialty Conference, Sacramento CA.

Dees, I. (2017, 11/13/2017). *Data Sources*. Retrieved 6/11/2024 from https://github.com/tilezen/joerd/blob/master/docs/data-sources.md

Duan, Y. (2019). *Potential Predictability of Streamflow and Soil Moisture in a Humid Alabama-Coosa-Tallapoosa River Basin using the National Water Model* Auburn University].

England Jr, J., Cohn, T., Faber, B., Stedinger, J., Thomas Jr, W., Veilleux, A., Kiang, J., & Mason, R. (2019). Guidelines for Determining Flood Flow Frequency–Bulletin 17C, Techniques and Methods 4-B5. *US Geological Survey, https://doi. org/10.3133/tm4B5*.
Esri. (2014). *NDNR Arc Hydro N-FACT Hydrology Component*. E. P. Services.
Fennessey, L. A. J., Miller, A. C., & Hamlett, J. M. (2001). ACCURACY AND PRECISION OF NRCS MODELS FOR SMALL WATERSHEDS1. *JAWRA Journal of the American Water Resources Association*, *37*(4), 899-912. https://doi.org/10.1111/j.1752-1688.2001.tb05521.x
Folmar, N. D., & Miller, A. C. (2008). Development of an empirical lag time equation. *Journal of Irrigation and Drainage Engineering*, *134*(4), 501-506.
Folmar, N. D., Miller, A. C., & Woodward, D. E. (2007). History and development of the NRCS lag time equation 1. *JAWRA Journal of the American Water Resources Association*, *43*(3), 829-838.
GEOGloWS. (2024). *About Us*. Retrieved 08/19 from https://www.geoglows.org/
Haan, C. T., Johnson, H. P., & Brakensiek, D. L. (1982). Hydrologic modeling of small watersheds.
Hales, R. *GEOGloWS Hydrological Model Version 2*. Retrieved 08/19 from https://registry.opendata.aws/geoglows-v2/
Hardison, C. H. (1969). Accuracy of streamflow characteristics.
Hardison, C. H. (1971). Prediction error of regression estimates of streamflow characteristics at ungaged sites. C228-C236.
Hawkins, R. H., Ward, T. J., Woodward, D. E., & Van Mullem, J. A. (2008). Curve Number Hydrology: State of the Practice. https://doi.org/10.1061/9780784410042
Hodge, S. A., & Tasker, G. D. (1995). *Magnitude and frequency of floods in Arkansas*. US Department of the Interior, US Geological Survey.
Hodgkins, G. A., Hebson, C., Lombard, P. J., & Mann, A. (2007). *Comparison of peak-flow estimation methods for small drainage basins in Maine* (2328-0328).
Jackson, E. K., Roberts, W., Nelsen, B., Williams, G. P., Nelson, E. J., & Ames, D. P. (2019). Introductory overview: Error metrics for hydrologic modelling–A review of common practices and an open source library to facilitate use and adoption. *Environmental Modelling & Software*, *119*, 32-48.
Kim, D. H., Naliaka, A., Zhu, Z., Ogden, F. L., & McMillan, H. K. (2022). Experimental coupling of TOPMODEL with the national water model: effects of coupling interface complexity on model performance. *JAWRA Journal of the American Water Resources Association*, *58*(1), 50-74.
Law, G. S., & Tasker, G. D. (2003). *Flood-frequency prediction methods for unregulated streams of Tennessee, 2000* (Vol. 3). US Department of the Interior, US Geological Survey.
Lozano, J. S., Lesmes, D. R., Bustamante, E. R., Hales, R., Nelson, E., Williams, G., Ames, D., Jones, N., Gutierrez, A., & Almeida, C. C. (2025). Historical simulation performance evaluation and monthly flow duration curve quantile-mapping (MFDC-QM) of the GEOGLOWS ECMWF streamflow hydrologic model. *Environmental Modelling & Software*, *183*, 106235.
McCarthy, P. M. (2024). Questions Regarding Uncertainty and Regression Equations. In R. H. Hotchkiss (Ed.).
McCuen, R. H. (1982). *A guide to hydrologic analysis using SCS methods*. Prentice-Hall, Inc.

Mecham, C. M. (2008). *NRCS Curve Number Calibration Using USGS Regression Equations* Brigham Young University - Provo]. BYU ScholarsArchive. https://scholarsarchive.byu.edu/etd/1388

Mishra, S. K., & Singh, V. (2003). *Soil conservation service curve number (SCS-CN) methodology* (Vol. 42). Springer Science & Business Media.

Mishra, S. K., & Singh, V. P. (2013). *Soil Conservation Service Curve Number (SCS-CN) Methodology*. Springer Netherlands. https://books.google.com/books?id=DbXnCAAAQBAJ

Moglen, G., Sadeq, H., Hughes, L., Meadows, M., Miller, J., Ramirez-Avila, J., & Tollner, E. (2022). NRCS curve number method: comparison of methods for estimating the curve number from Rainfall-Runoff Data. *Journal of Hydrologic Engineering*, *27*(10), 04022023.

Moglen, G. E., Thomas, W., & Cuneo, C. G. (2006). Evaluation of alternative statistical methods for estimating frequency of peak flows in Maryland. *Final Rep*.

NDOR. (2006). *Nebraska Department of Roads Drainage and Erosion Control Manual*.

NDOT. (2018). Drainage and Erosion Control Manual (Draft). In (pp. (1-24)-(21-37)): Nebraska Department of Transportation.

Newton, D. W., & Herrin, J. C. (1982). Assessment of commonly used methods of estimating flood frequency. *Transportation research record*, *896*, 10-30.

NGA. (2023). *TanDEM-X Hydro Technical Documentation*. https://earth-info.nga.mil/

NOAA. *NOAA National Water Model CONUS Retrospective Dataset*. Amazon Web Services. Retrieved April 3rd from https://registry.opendata.aws/nwm-archive/

NOAA. (2023, March 2023). *FAQ: United States Interagency Elevation Inventory*. NOAA Office for Coastal Management. Retrieved 6/11/2024 from https://coast.noaa.gov/inventory/

NRCS. (1986). Urban Hydrology for Small Watersheds. In N. R. C. Service (Ed.), *Technical Release 55*: United States Department of Agriculture.

NRCS. (2009). Small Watershed Hydrology. In U. S. D. o. Agriculture (Ed.), *WinTR-55 User Guide*. WinTR-55: Natural Resources Conservation Service.

NRCS. (2019, 7/31/2019). *Web Soil Survey*. Natural Resource Conservation Service. Retrieved 6/11/2024 from https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

NRCS. (2024). National Engineering Handbook, Part 630, Hydrology. In N. R. C. Service (Ed.): US Department of Agriculture Washington, DC.

Ormsbee, L., Hoagland, S., & Peterson, K. (2020). Limitations of TR-55 curve numbers for urban development applications: Critical review and potential strategies for moving forward. *Journal of Hydrologic Engineering*, *25*(4), 02520001.

Panel, M. H. (2020). Application of hydrologic methods in Maryland. In (5th ed.): Report.

Ponce, V. *Notes of my Conversation with Vic Mockus*. Victor Ponce. Retrieved June 22nd from https://ponce.sdsu.edu/mockus_conversation.html

Ponce, V. M. (2021). *CN Oral History Victor Miguel Ponce* [Interview]. Glenn Moglen. https://www.youtube.com/watch?v=4DGrO-HV-tY&t=106s

Ponce, V. M., & Hawkins, R. H. (1996). Runoff curve number: Has it reached maturity? *Journal of Hydrologic Engineering*, *1*(1), 11-19.

Riggs, H. (1968). *Techniques of water-resources investigations of the united states geological survey chapter a1 some statistical tools in hydrology book 4 hydrologic analysis and interpretation*. US Department Of The Interior Geological Survey.

Sanchez Lozano, J. L. (2023). Enhancing Local Hydrological Services with the GEOGloWS ECMWF Global Hydrologic Model.

Simanton, J. R., R.H. Hawkins, M. Mohseni-Saravi, and K.G. Renard. (1996). Runoff Curve Number Variation with Drainage Area, Walnut Gulch, Arizona. *Transactions of teh ASAE*, *39*(4), 1391-1394.

Soenksen, P. J. (1999). *Peak-flow frequency relations and evaluation of the peak-flow gaging network in Nebraska* (Vol. 99). US Department of the Interior, US Geological Survey.

Sorrell, R. C. (2010). *Computing flood discharges for small ungaged watersheds*.

Strahm, B. J., & Admiraal, D. M. (2005). NDOR Regression Equations.

Tasker, G. (1978). Relation between standard errors in log units and standard errors in percent. *WRD Bulletin, Jan-Mar–Apr-June*, 86-87.

Thompson, D. (2004). *Literature review for TxDOT project 0–4405: Scale issues in hydrology* (FHWA/TX - 06/0-4405-1). T. D. o. Transportation.

UNL. (2024). *Land Use / Land Cover Related GIS Data*. University of Nebraska-Lincoln School of Natural Resources. Retrieved 9/13/2024 from https://snr.unl.edu/data/geographygis/land.aspx

USGS. *3D Elevation Program*. United States Geological Survey. Retrieved 07/01/24 from https://www.usgs.gov/3d-elevation-program

Appendix A TR-20 Input Descriptions

A.1 Velocity Method Shallow Concentrated Flow Equations

The velocity method includes empirical equations for estimating shallow concentrated flow time in paved or unpaved channels (NRCS, 2024). The generic unpaved equation was created assuming a grassed waterway (NRCS, 2024). (Anciaux Humpal & A Cerrelli, 2009) created shallow concentrated flow equations for other land uses including “row crops-no till” and “row crops-conventional till”. Although these equations would be more appropriate for a shallow concentrated flow segment falling in agricultural land, the equations were not programmed into WMS, making them inconvenient to incorporate. Additionally, many of our TR-20 models fit the grassed waterway description within reason.

A.2 10-Meter Elevation Data

We used 10-meter DEM’s to delineate watershed boundaries within WMS. We downloaded 10-meter elevation data from the worldwide elevation dataset available through WMS webservices. This dataset offers no greater than 10-meter resolution across Nebraska despite WMS giving users the option of interpolating to finer resolutions (Dees, 2017).

A.3 1-Meter Elevation Data

Although 10-meter resolution digital elevation data is sufficient for delineating watershed boundaries, it is not sufficient for cutting cross-sections along small streams. A cross-section estimate is needed to calculate the hydraulic radius, and subsequently, the segmental time of concentration (NRCS, 2024). We downloaded one-meter resolution elevation data from the USGS 3DEP dataset for finding cross-sectional areas. One-meter elevation data is available through this dataset for all of Nebraska. However, the flow accumulation software associated with WMS, TOPAZ, runs slowly with resolutions greater than 10 meters. Despite this, the 3DEP dataset sets a high standard for elevation product quality and should be used when reasonable and relevant (NOAA, 2023).

A.4 Open Channel Flow Manning's N

Manning's n values for open channel flow can be obtained from various sources, with commonly referenced texts being "Open Channel Hydraulics" by Chow (1959) and "Roughness Characteristics of Natural Channels" by Barnes (1967). An alternative method for obtaining a Manning's n value involves back-calculating Manning's n from the Manning's equation using stream characteristic information from selected USGS gage sites. The Maryland Hydrology Panel suggests beginning at a Manning's n value of 0.05 and calibrating as needed (Panel, 2020). We, however, chose to assign one of three n values to our models: 0.03, 0.04, or 0.05. Our choice of Manning's n for each model was supported by an NDOT project that used the same Manning's n value for similar conditions.

A.5 Sheet Flow Manning's N

Relatively little is known about sheet flow as it occurs in nature due to it being difficult to observe. A small table of typical sheet flow Manning's n values is included in NEH-630 (NRCS, 2024). We used this table along with past NDOT example projects as references when selecting a sheet flow Manning's n value.

A.6 Land Use

USGS vector land use data, accessible through WMS web services, serves as a resource for hydrologic modeling but classifies the majority of Nebraska's land as either cropland and pasture or other agricultural land (Anderson, 1976). NDOT is accustomed to using a statewide land use shapefile available through the University of Nebraska-Lincoln's GIS webpage. This shapefile provides several different classifications of agricultural and rural land. We used this shapefile to help calculate weighted curve numbers for our TR-20 models.

A.7 Soil Data

SSURGO soil data available through the NRCS web soil survey page has typically been the standard for high resolution digitized soil data. This dataset was used in each of our TR-20 models. The dataset is updated with corrections and improvements yearly (NRCS, 2019).

A.8 Weighted Curve Number

Weighted curve number results from a combination of other inputs, namely land use data, soil data, and curve numbers mapped to specific land uses and soil types. Tables of curve numbers with land cover descriptions are presented in NEH-630 and TR-55 (NRCS, 1986, 2024). WMS automatically calculates a weighted curve number using the TR-20 watershed boundary, soil data, land use data, and a user provided table responsible for mapping all combinations of land use and soil type to a curve number. This table will be referred to as the WMS mapping table. Examples of WMS mapping tables can be found on the WMS wiki site (Aquaveo, 2023a). The mapping table used in our TR-20 models is shown in Table A.1.

A problem with using GIS land use data to calculate a weighted curve number is that the GIS land use descriptions rarely match the curve number land use descriptions. For example, a GIS land use description may read "irrigated corn". For this case, the user must select one set of curve numbers that matches the "irrigated corn" description. However, there is not a set of curve numbers specific to irrigated corn. It is left to the user to choose an alternative curve number set such as "straight row crops", "contoured row crops", or "contoured and terraced row crops". There is not a one-size-fits-all set of row crop curve numbers. This is an example where the curve number land use descriptions are more specific than the GIS land use descriptions. Conversely, there are instances where the GIS land use descriptions are more specific than the curve number land use descriptions. For example, a GIS land use description could read "irrigated soybeans" in which case the user will find that there is not a set of curve numbers for irrigated soybeans. An alternative set assigned to this GIS land use description could be “straight row close-seeded legumes”. This problem stems from the fact that GIS land use data are usually created for a wide variety of uses and not specifically for hydrologic modeling using NRCS methods.

NDOT addressed this problem by assigning an average set of curve numbers to all GIS agricultural land uses. The non-agricultural GIS land use descriptions were mapped to similar curve number land cover descriptions. This NDOT procedure is one of few alternatives to matching curve number land covers to GIS land uses on a one-to-one basis, with a similar procedure existing in Maryland (Panel, 2020). Our WMS mapping table is shown in Table A.1 shows how the UNL land use shapefile descriptions compare to the curve number land cover descriptions. Additionally, the University of Nebraska-Lincoln land use shapefile is downloadable through the school of natural resources GIS data webpage (UNL, 2024). Note that our WMS mapping table has not been calibrated and future work can be done to alter this table for improved results.

Table A.1 WMS Mapping Table

Land Use ID	Land Use Description	Curve Number for Soil Group A	Curve Number for Soil Group B	Curve Number for Soil Group C	Curve Number for Soil Group D
0	Unidentified	67	77	83	87
1	Irrigated Corn	67	77	83	87
2	Irrigated Sugar Beets	67	77	83	87
3	Irrigated Soybeans	67	77	83	87
4	Irrigated Sorghum	67	77	83	87
5	Irrigated Dry Edible Beans	67	77	83	87
6	Irrigated Potatoes	67	77	83	87
7	Irrigated Alfalfa	67	77	83	87
8	Irrigated Small Grains	67	77	83	87
9	Range, Pasture, grass	39	61	74	80
10	Urban Land	57	72	81	86
11	Open Water	100	100	100	100
12	Riparian Forest and Woodlands	43	65	76	82
13	Wetlands	100	100	100	100
14	Other Agricultural Land	67	77	83	87
15	Irrigated Sunflower	67	77	83	87
16	Summer Fallow	76	85	89	91
17	Roads	98	98	98	98
18	Dryland Corn	67	77	83	87
19	Dryland Soybeans	67	77	83	87
20	Dryland Sorghum	67	77	83	87
21	Dryland Dry Edible Beans	67	77	83	87
22	Dryland Alfalfa	67	77	83	87
23	Dryland Small Grains	67	77	83	87
24	Dryland Sunflower	67	77	83	87
25	Barren	76	85	89	91

Table A.2 Land Use Descriptions Compared to Curve Number Descriptions

Land Use ID	Land Use Description	Curve Number Description
0	Unidentified	Agricultural
1	Irrigated Corn	Agricultural
2	Irrigated Sugar Beets	Agricultural
3	Irrigated Soybeans	Agricultural
4	Irrigated Sorghum	Agricultural
5	Irrigated Dry Edible Beans	Agricultural
6	Irrigated Potatoes	Agricultural
7	Irrigated Alfalfa	Agricultural
8	Irrigated Small Grains	Agricultural
9	Range, Pasture, grass	Open Land-Good, Pasture, grassland, or range-continuous forage for grazing
10	Urban Land	Residential 1/3 acre lots
11	Open Water	Water
12	Riparian Forest and Woodlands	Thin Woods, Woods-grass combination (orchard or tree farm)
13	Wetlands	Water
14	Other Agricultural Land	Agricultural
15	Irrigated Sunflower	Agricultural
16	Summer Fallow	Agricultural
17	Roads	Impervious, Paved parking lots, roofs, driveways, etc.(excluding right-of-way)
18	Dryland Corn	Agricultural
19	Dryland Soybeans	Agricultural
20	Dryland Sorghum	Agricultural
21	Dryland Dry Edible Beans	Agricultural
22	Dryland Alfalfa	Agricultural
23	Dryland Small Grains	Agricultural
24	Dryland Sunflower	Agricultural
25	Barren	Fallow Crop residue cover poor

A.9 Sheet Flow Length

There is no equation for estimating sheet flow length due to the difficulty of observing sheet flow naturally. NEH-630 and TR-55 seem to settle on 100 feet as a reasonable sheet flow length in most cases and 300 feet as a maximum sheet flow length (NRCS, 1986, 2024; Panel, 2020). We opted to use 100 feet for sheet flow length in all our TR-20 models seeing that it is supported in literature and accepted in common practice.

A.10 Open Channel Flow Length

Deciding at what point shallow concentrated flow changes to open channel flow in the time of concentration arc can be subjective. To make our approach consistent, open channel flow begins at the end the USGS topographic blue line in all our models and is verified using aerial imagery. The USGS topographic maps are available through the WMS's get online maps tool. We checked against aerial imagery to judge the reasonableness of the location. This workflow is acceptable in practice (Cerrelli, 2024; Panel, 2020).

A.11 Hydraulic Radius Alternatives and Complications

Estimating the open-channel flow travel time using the velocity method requires determining a representative hydraulic radius for the stream. The hydraulic radius is defined as the cross-sectional area divided by the wetted perimeter (NRCS, 2024). To find these variables we need a representative stream cross-section which, as we previously mentioned, can be extracted from a one-meter DEM. An alternative to extracting a cross-section from a DEM is assuming a trapezoidal channel. However, estimating the dimensions of the trapezoidal channel also proves difficult without a site visit. Finally, users could assume a typical open channel flow velocity of three or four feet per second and bypass estimating a hydraulic radius entirely. Given that 3DEP one-meter DEMs provide consistent, high-quality data, we selected WMS's cross-section tool for estimating hydraulic radius.

There is no guidance on where the cross section should be taken for it to be truly "representative" of the open channel portion of the stream. The only guidance given by NEH-630 and TR-55 is that that the hydraulic radius should be calculated using a bankfull stream depth (NRCS, 1986, 2024). For our TR-20 models, we aimed for the middle of the open channel flow reach when extracting a representative cross-section for estimating the hydraulic radius. Bankfull depth was also difficult to define at times due to some channels not having identifiable banks.

A.12 Watershed Slope and Length

Watershed slope and length are two variables needed to estimate lag time. WMS automatically estimates these variables from the same 10-meter DEM used to delineate the watershed boundary. Although finer DEM resolution would result in a better estimation, 10-meter resolution was used for convenience.

A.13 Statistical Rainfall Depth

NOAA Atlas 14 is a common source of statistical rainfall depth. NDOT has a table in their draft drainage manual of NOAA Atlas 14 statistical rainfall depths averaged by county (NDOT, 2018). Given the uncertainty already present in statistical rainfall depths, we opted to use NDOT's county averaged values for convenience. TR-20 estimates peak flow for a specific return period from a rainfall depth of the same recurrence. This is an approximation due to losses.

A.14 Other Input Considerations

Other inputs that could be altered include initial abstraction, antecedent moisture condition, peaking factor, and storm distribution (NRCS, 2024). The defaults were accepted for these inputs. For initial abstraction, 0.2S was used rather than 0.05S out of convenience. Recent studies suggest that 0.05S may better estimate initial abstraction but all curve number tables were built using 0.2S, making 0.2S the more convenient choice (Moglen et al., 2022). Antecedent moisture condition II was used for all our models because it represents average conditions, and we could not justify changing it. The same reasoning applies to leaving the peaking factor unchanged at 484. A lower peaking factor may be justified for flat or swampy areas (Panel, 2020). However, a separate study would likely be needed to justify an alteration. We used a type-

II 24-hour storm distribution for all our TR-20 models. We chose to use the NRCS standard 24-hour rainfall distribution since we are testing NRCS methods specifically.

Appendix B All Nebraskan Regional Regression Results

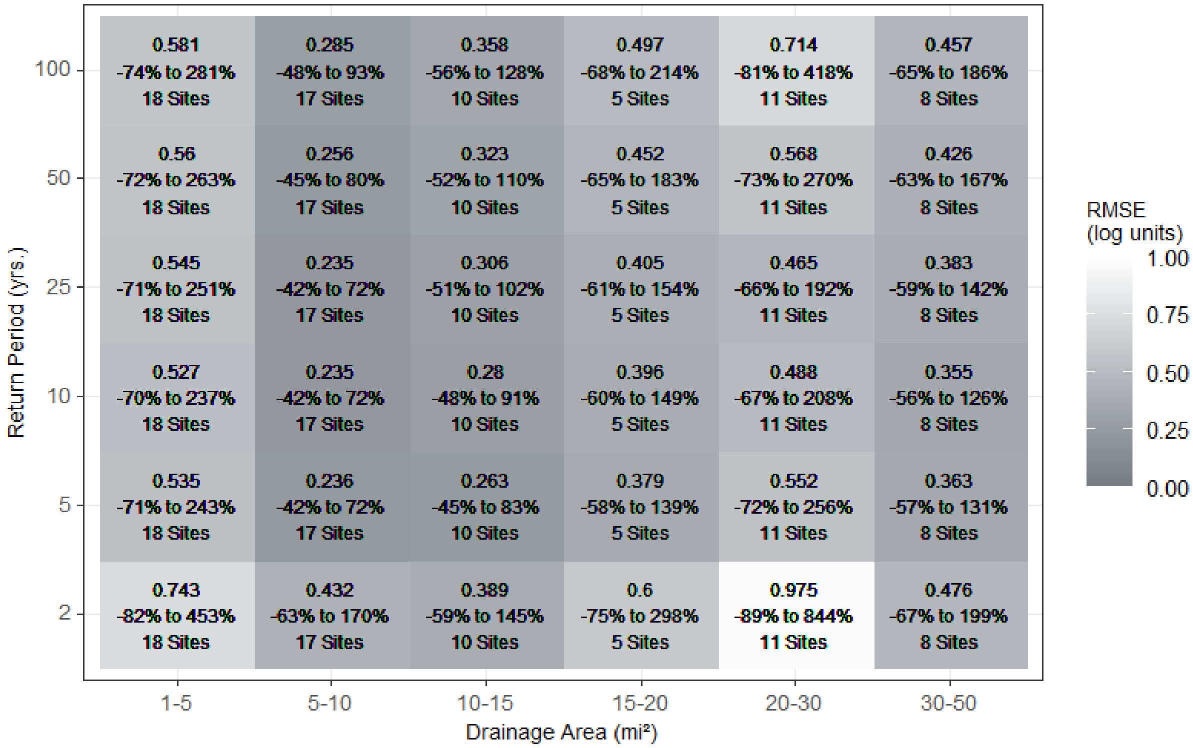

Figure B.1 Admiraal (Small, Extrapolated) RMSE in Log_{10} Units by Return Period and Drainage Area Category

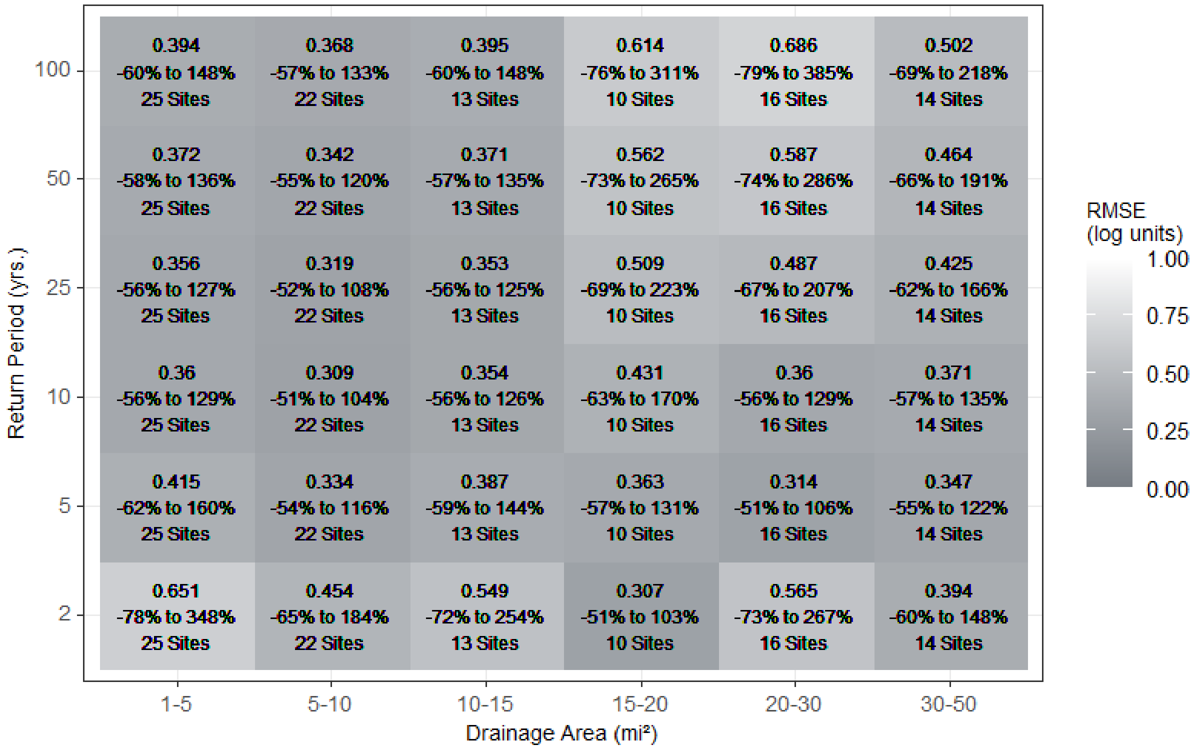

Figure B.2 Admiraal (Large) Watershed RMSE in Log_{10} Units by Return Period and Drainage Area Category

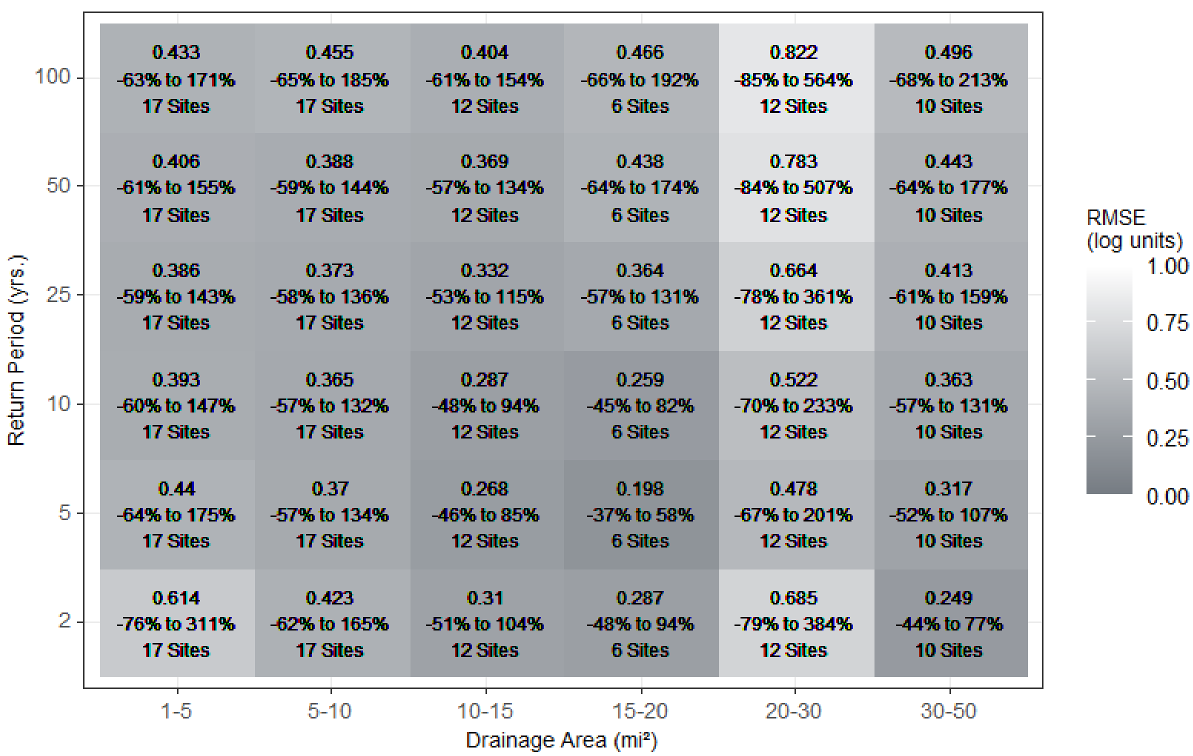

Figure B.3 Soenksen RMSE in Log_{10} Units by Return Period and Drainage Area Category

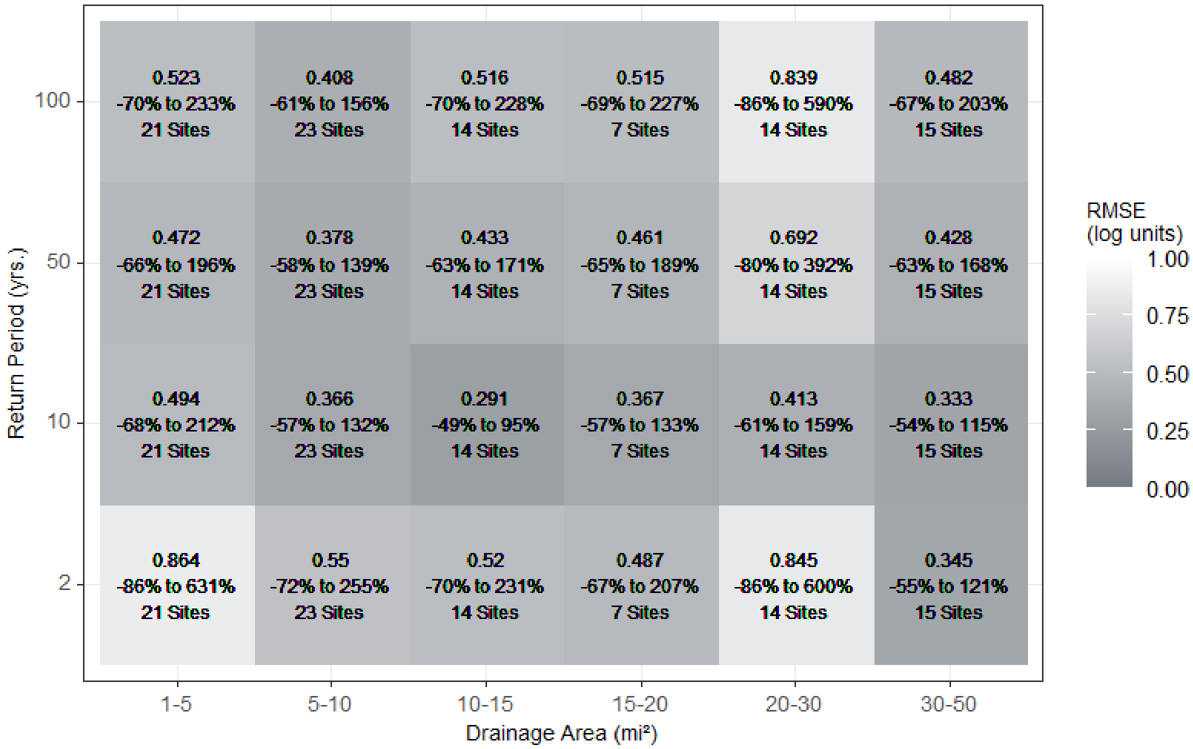

Figure B.4 Hotchkiss RMSE in Log_{10} Units by Return Period and Drainage Area Category

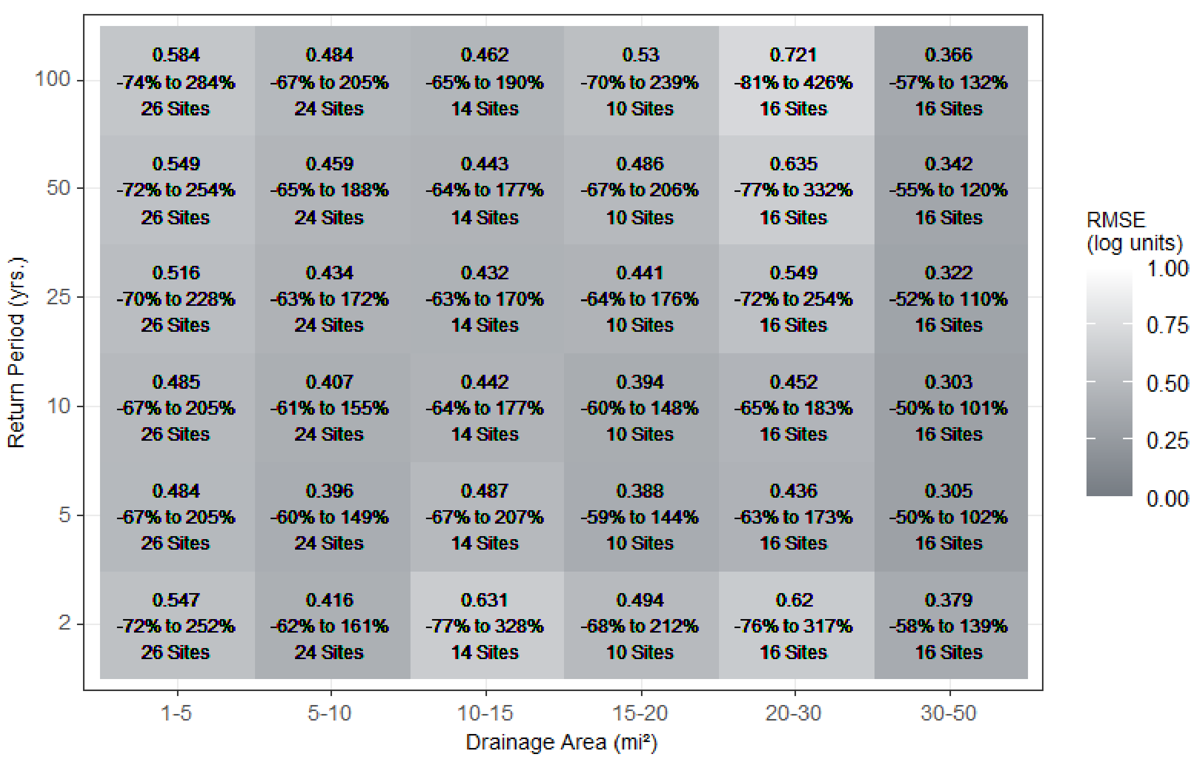

Figure B.5 Beckman RMSE in Log_{10} Units by Return Period and Drainage Area Category

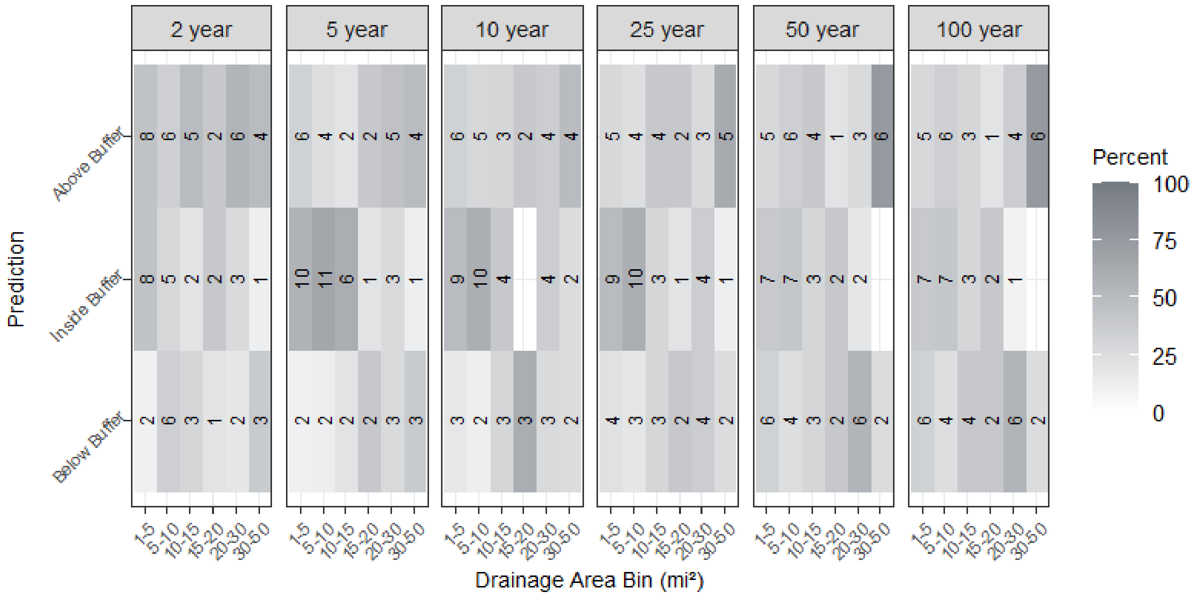

Figure B.6 Percent Admiraal (Small, Extrapolated) Predictions Above, Inside, or Below ±30% Buffer

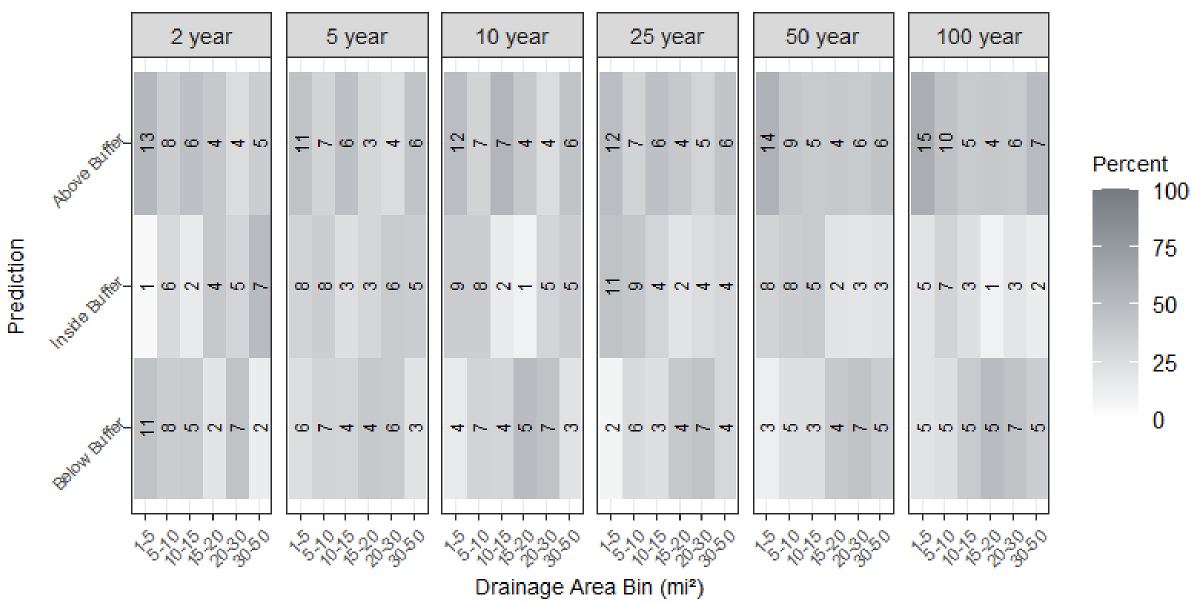

Figure B.7 Percent Admiraal (Large) Predictions Above, Inside, or Below ±30% Buffer

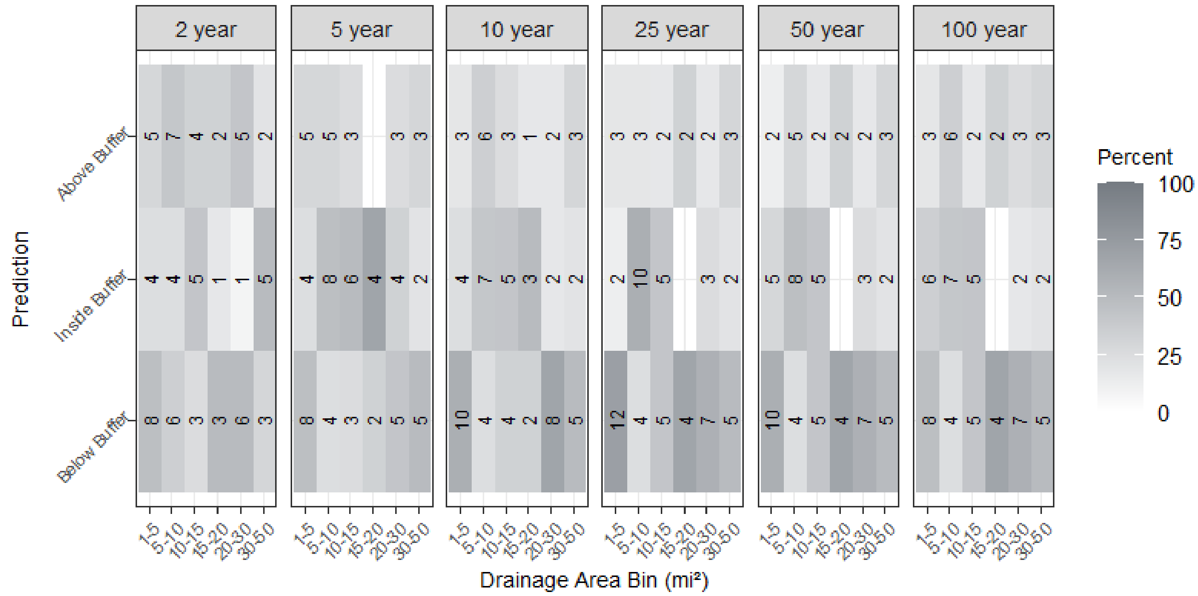

Figure B.8 Percent Soenksen Predictions Above, Inside, or Below ±30% Buffer

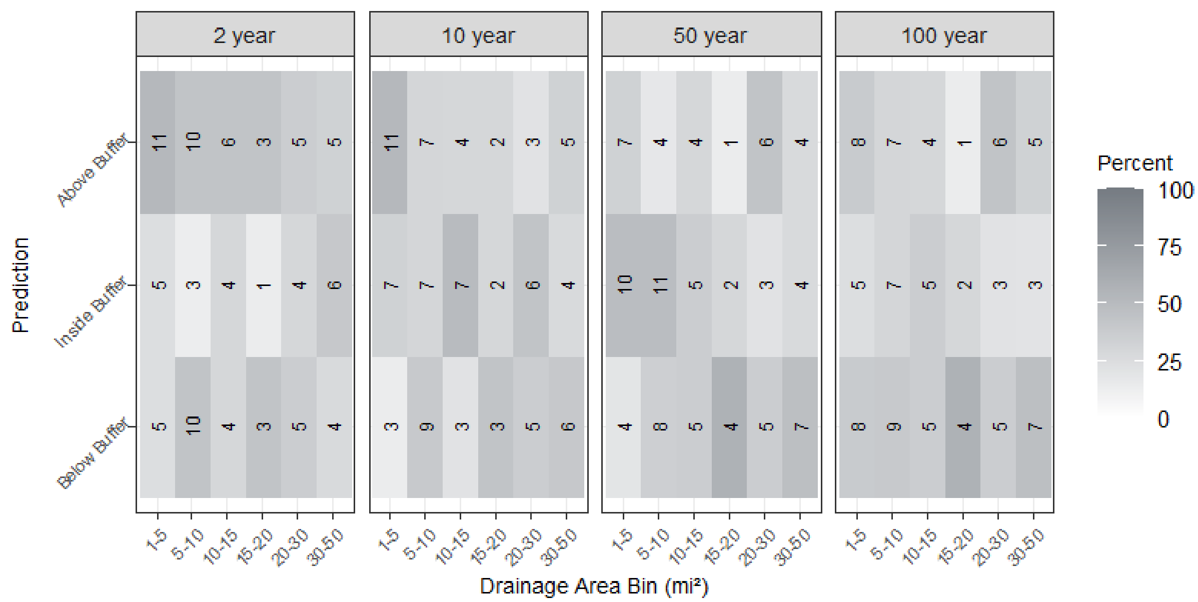

Figure B.9 Percent Hotchkiss Predictions Above, Inside, or Below ±30% Buffer

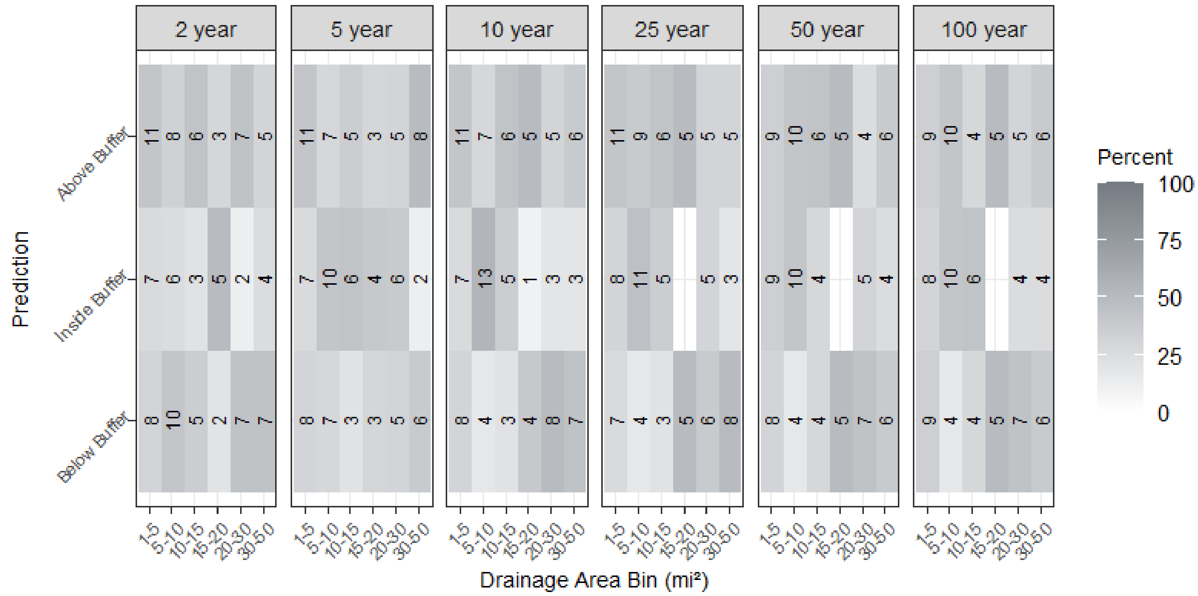

Figure B.10 Percent Beckman Predictions Above, Inside, or Below ±30% Buffer

Appendix C Next Generation Hydrologic Models

C.1 The National Water Model

Created by NOAA in collaboration with others, the National Water Model (NWM) is a vector-based runoff and routing model which takes grid-based meteorological data as input to simulate past (retrospective) and future (forecasted) streamflow for the United States. It has produced hourly simulated retrospective streamflow rates for 2.7 million US stream reaches (Cosgrove et al., 2024).

C.1.1 Product

All retrospective data may be accessed through the NOAA National Water Model CONUS retrospective datasets available through amazon web services in Zarr and NetCDF format (NOAA). Data in this format is best sorted using a script. We extracted simulated retrospective peak flow data for each gage location using version 3.0 of the NWM, which provides over 40 years of data between the years 1979 and 2023 (NOAA). Because the NWM starts at dry conditions, the first annual peak from each record was dropped. The data has an hourly time step and has not been corrected using stream gage data (NOAA). The NWM annual peak flow data in csv format by gage was loaded into HEC-SSP for Bulletin 17C flow frequency analyses.

C.1.2 Limitations

Like the N-FACT tool used in Nebraska, the National Water Model is limited by the amount of stream reaches in its stream reach layer. At 2.7 million stream reaches, users can obtain simulated retrospective data for nearly every stream reach in the U.S. (Cosgrove et al., 2024). The National Water Model stream reach layer was derived from the NHDPlus Version 2 dataset, which has an average basin size of 3km^2 (1.16 mi^2) (David R. Maidment, 2016). However, the NWM had a stream reach for all 130 sites, including the smallest (0.07 mi^2).

The NWM returned 0 cfs as the annual peak for several water years. Additionally, several annual peaks were flagged as low outliers by the Bulletin 17C multiple Grubbs/Beck low outlier test (England Jr et al., 2019). These combined data insufficiencies meant 33 sites did not qualify for a Bulletin 17C flow frequency analysis.

C.2 GEOGloWS

GEOGloWS simulates stream flow worldwide rather than only in the United States. Group on Earth Observations (GEO) created this model to address Global Water Sustainability (GloWS) with the support of NASA, NOAA, ECMWF, ESRI, the World Bank, and others (GEOGloWS, 2024). Like the National Water Model, GEOGloWS is a vector-based runoff and routing model which takes grid-based meteorological data as input to simulate past (retrospective) and future (forecasted) streamflow. It has produced daily simulated retrospective streamflow rates for seven million stream reaches worldwide (Hales). By special request, retrospective data for Nebraska was acquired at an hourly timestep to support a fair comparison between GEOGloWS and the National Water Model.

C.2.1 Product

All retrospective data may be accessed through the GEOGloWS hydrologic model version 2 retrospective datasets available from Simple Standard Storage (S3) cloud storage buckets in Zarr and netCDF format (Hales). We extracted simulated retrospective peak flow data for each gage location using GEOGloWS version 2.0 which provides over 80 years of data between the years 1940 and 2023 (Hales). Because GEOGloWS starts at dry conditions, the first annual peak from each record was dropped (Lozano et al., 2025; Sanchez Lozano, 2023). The data has an hourly time step and has not been corrected using real data from stream gages (Hales). The GEOGloWS annual peak flow data in csv format by site was loaded into HEC-SSP for Bulletin 17C flow frequency analyses.

C.2.2 Limitations

GEOGloWS is also limited by the amount of stream reaches in its stream reach layer. GEOGloWS provides worldwide coverage with seven million stream reaches, making a GEOGloWS stream reach available for 92 of our 130 selected locations. The GEOGloWS stream reach layer was derived from the TDX-Hydro dataset produced by the United States National Geospatial Intelligence Agency (Hales). The TDX-Hydro technical documentation states that an accumulation area of 5 km^2 (1.93 mi^2) was used to create their stream network (NGA, 2023). However, the GEOGloWS model does not report flows on all the upstream reaches, causing some variability in the minimum area before modeled flows are available. While most watersheds less than 1.93 mi^2 did not have a corresponding GEOGloWS stream reach, some watersheds did, such as South Fork Big Sandy Creek Near Edgar, Nebraska despite having a drainage area of 0.07 mi^2. Oppositely, there were some locations, such as North Branch Indian Creek Near Max, Nebraska, that did not have a corresponding GEOGloWS stream reach despite having a drainage area of 4.76 mi^2.

Although GEOGloWS had several values flagged as low outliers by the multiple Grubbs/Beck low outlier test, no sites were disqualified due to the lack of data. This is because GEOGloWS provides twice as many annual peaks as the National Water Model. Additionally, there are few 0 cfs peaks reported compared to the National Water Model.

C.3 National Water Model and GEOGloWS Results

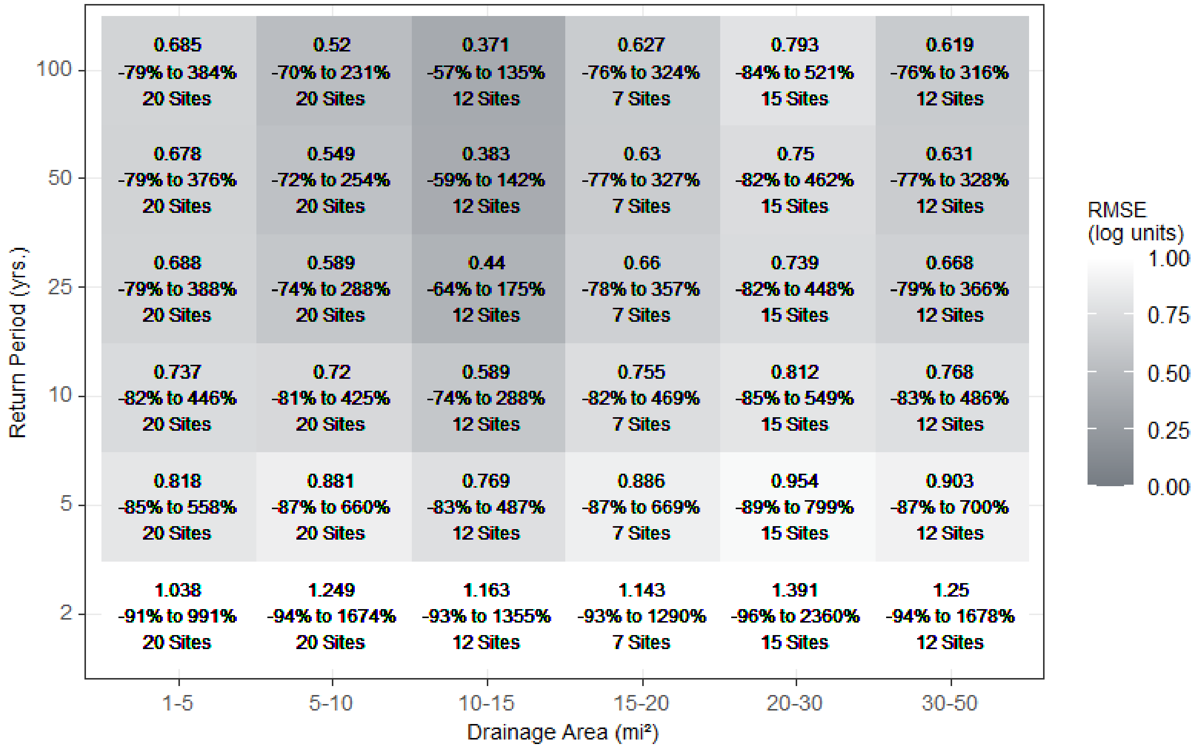

Figure C.1 National Water Model RMSE in Log_{10} Units by Return Period and Drainage Area Category

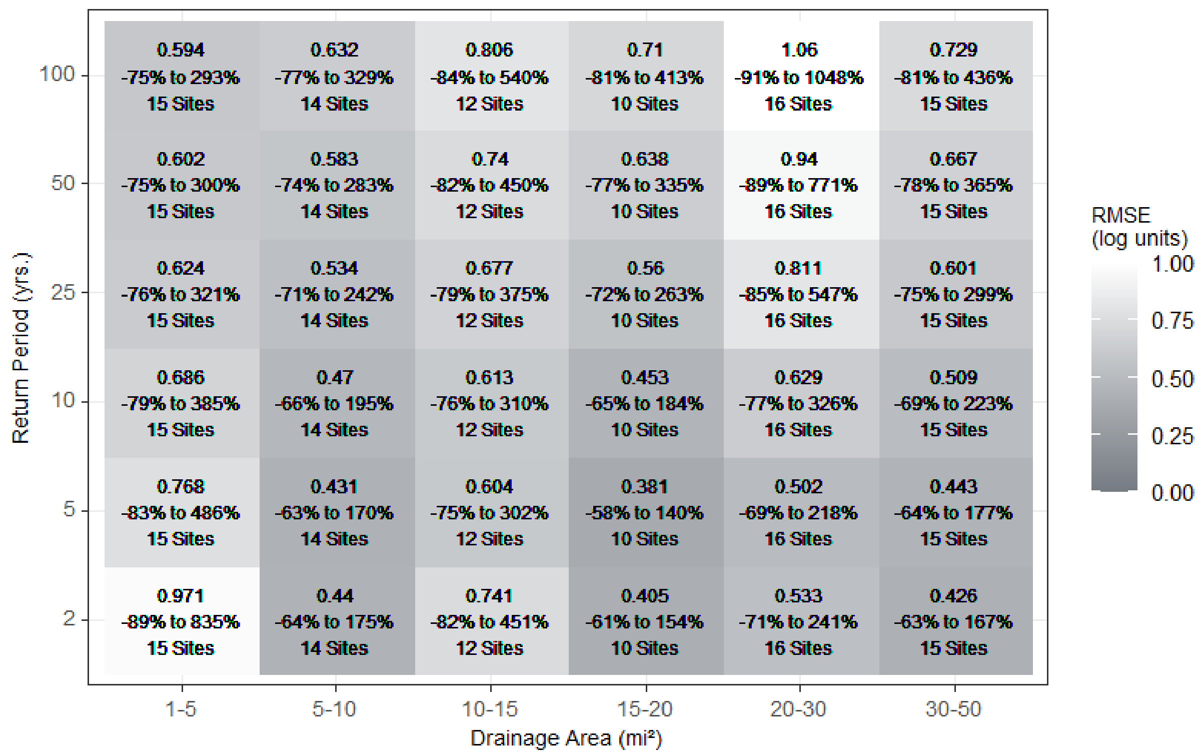

Figure C.2 GEOGloWS RMSE in Log_{10} Units by Return Period and Drainage Area Category

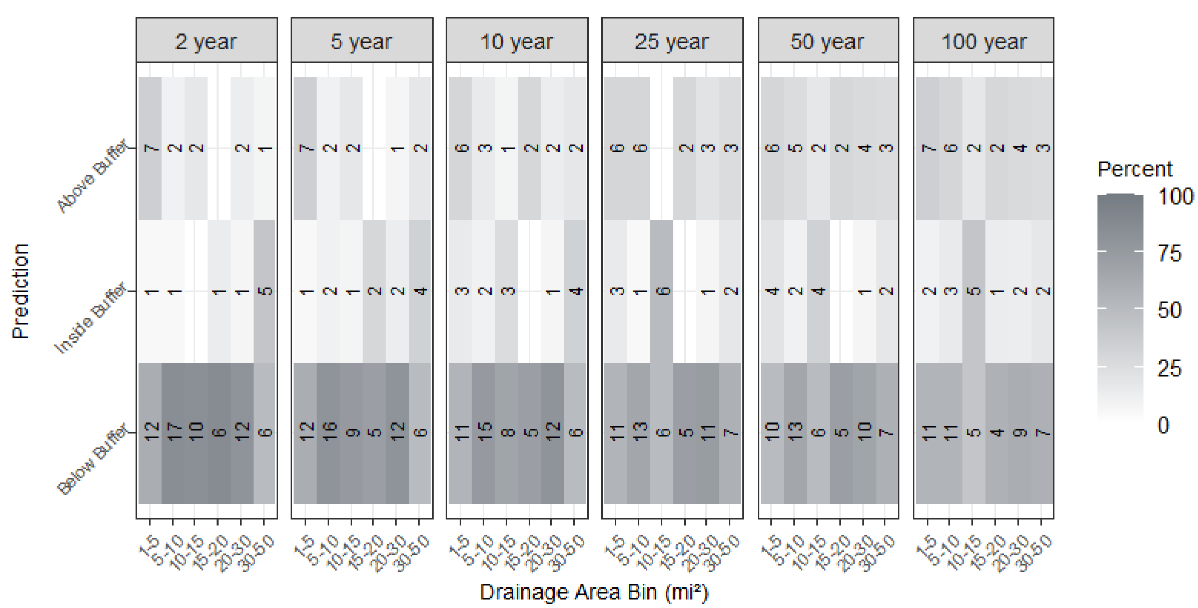

Figure C.3 Percent National Water Model Predictions Above, Inside, or Below ±30% Buffer

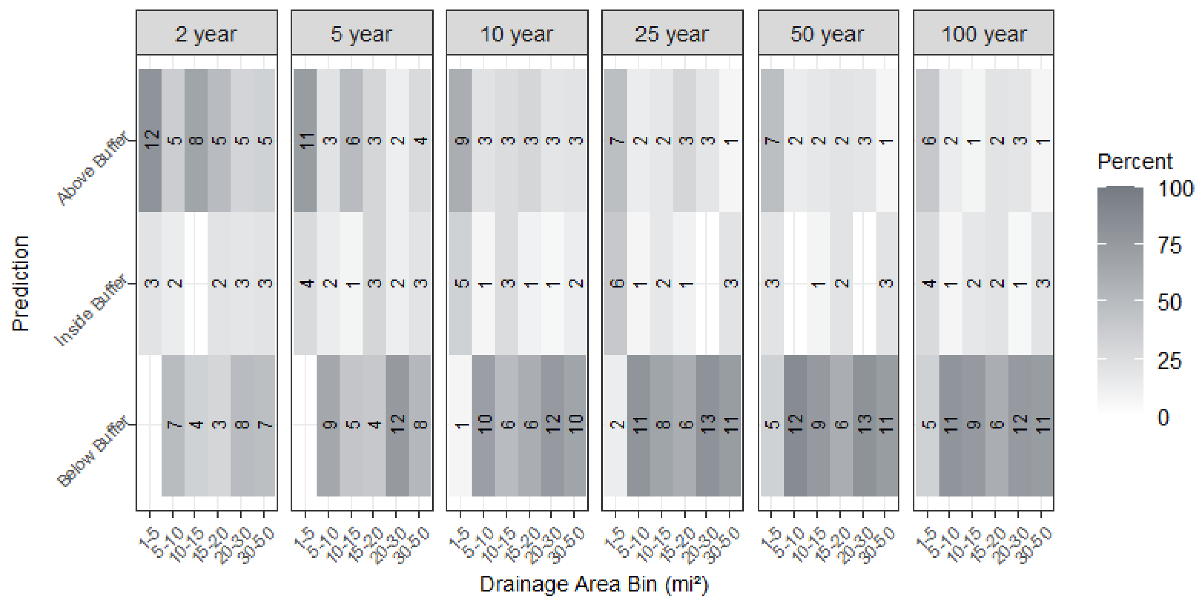

Figure C.4 Percent GEOGloWS Predictions Above, Inside, or Below ±30% Buffer

C.4 Discussion

From Figure C.3 and C.4, we see that using simulated NWM and GEOGloWS datasets for flow frequency analyses most often results in underpredicted peak discharges. There is no consensus in recent literature explaining this bias. Models of this nature are relatively new and most publications describing validation or applications of their data have focused on early flood warnings and analyzing patterns in river flows over time.

A significant limitation of the retrospective simulations from GEOGloWS and NWM is the resolution of the grids, which calculate runoff depths. In the case of GEOGloWS, the retrospective simulation's meteorological forcings come from the European Centre for Medium Range Weather Forecasts' ERA5 product. ERA5's grid resolution is one quarter (0.25) degree. At the latitude of Omaha, Nebraska, a representative area of a grid cell is about 225 square miles meaning that the city fits within about two grid cells. Runoff depths calculated over that grid cell are assumed to occur uniformly across the entire area. No downscaling occurs. Small watersheds investigated in this report are often less than five square miles, or only about 2% of a grid cell. The runoff volumes which would get routed through streams in small catchments are determined overwhelmingly by much larger areas surrounding the areas. One reason for the coarseness of the grid used to calculate runoff depths is the coarseness and infrequency of historical hydrometeorological measurements.

The coarseness of the grid supports published findings that the model shows large bias in the vicinity of Nebraska for uncorrected historical simulation values (Sanchez Lozano, 2023). One grid cell, which encompasses both urban areas and agricultural areas, provides only one runoff depth for both areas and ignores the differences in runoff generation processes between both sites. A map in Figure C.5 shows the size of the grid cell boundaries in black lines with a labeled topographic basemap showing the metropolitan areas of Omaha and Lincoln, Nebraska for size reference.

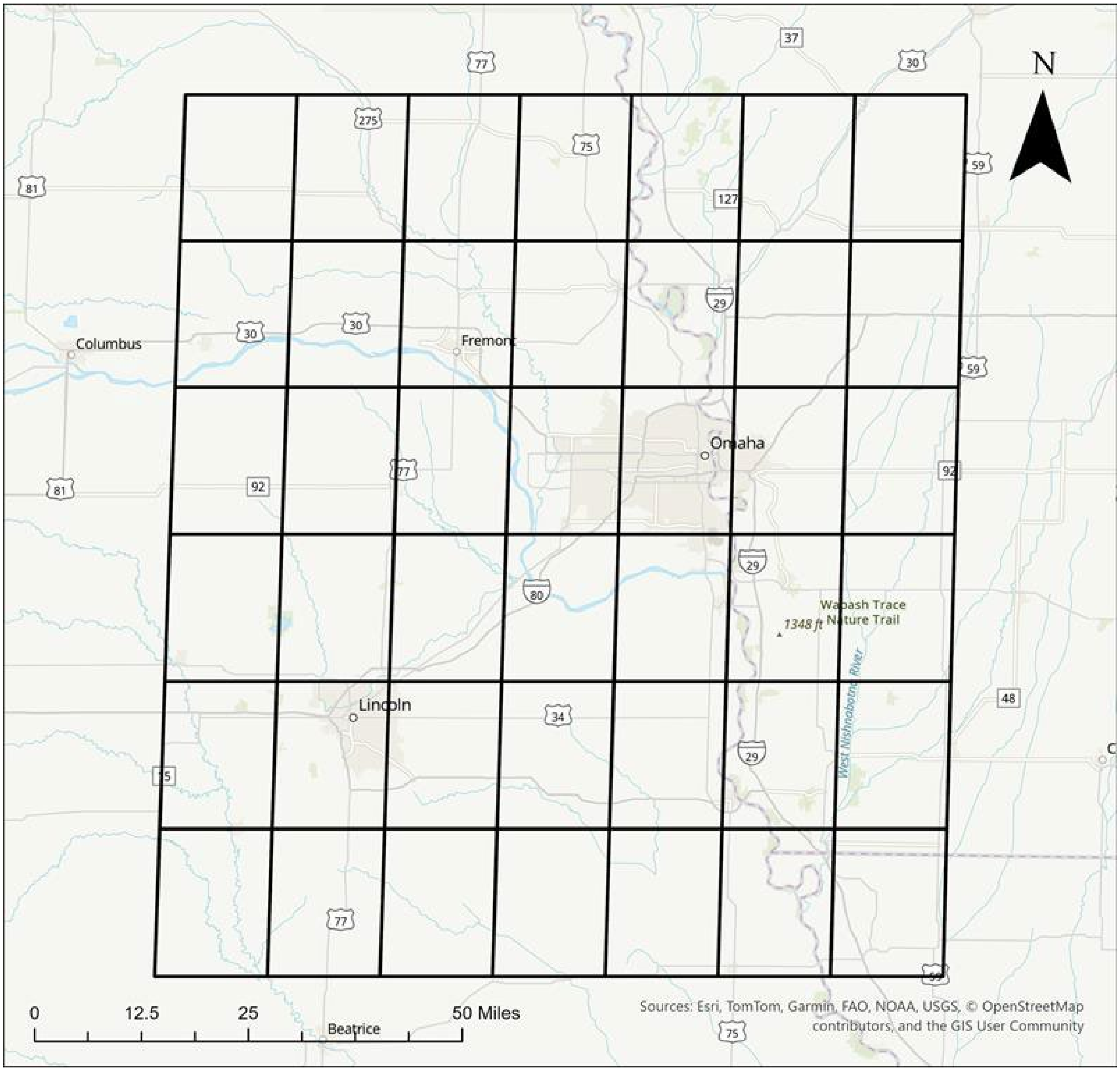

Figure C.5 National Water Model and GEOGloWS Cell Size

Modern observation and modeling systems for real time and forecasting of hydrometeorological variables operate on higher resolution grids. For instance, a leading global precipitation dataset, CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data https://doi.org/10.1038/sdata.2015.66), provides precipitation depths at one twentieth degree (0.05) grids or twenty-five times higher resolution than ERA5. A retrospective simulation using the same system is available as early as 1981. A successor to ERA5 is currently in development which is anticipated to have resolutions approaching four times greater (https://climate.copernicus.eu/sites/default/files/custom-uploads/7th%20GA%20C3S/Presentations/Day%202/S3/02-18062024_Reanalysis_Hersbach_v1.pdf). Future iterations of GEOGloWS and NWM using higher resolution grids for land surface calculations should increase their ability to skillfully predict forsmaller catchments.

Possible explanations of why the NWM frequently unpredicts stream flow include bias by region, bias by time of year, model parameterization, inaccurate land cover data, and underestimating soil moisture, snow water equivalent, and precipitation amounts (Abdelkader et al., 2023; Agnihotri et al., 2023; Duan, 2019; Kim et al., 2022). Oppositely, evidence that the center of the continental U.S. is typically biased wet rather than dry also exists (Cosgrove et al., 2024). The NWM's poor performance is also likely influenced by a similar coarseness of gridded data issue elucidated for the GEOGloWS data.

Appendix D TR-55 Limitations

Table D.1 Graphical Method Limitations as Found in TR-55 (NRCS, 1986)

Limitation	Chapter-Page
"The Graphical method (chapter 4) is used only for hydrologically homogeneous watersheds because the procedure is limited to a single watershed subarea."	1-4
"The approximate storage-routing curves (chapter 6) should not be used if the adjustment for ponding (chapter 4) is used."	1-4
"The Graphical method was developed from hydrograph analyses using TR-20, 'Computer Program for Project Formulation.'"	4-1
"The Graphical method provides a determination of peak discharge only."	4-2
"The watershed must be hydrologically homogeneous, that is, describable by one CN. Land use, soils, and cover are distributed uniformly throughout the watershed."	4-2
"The watershed may have only one main stream or, if more than one, the branches must have nearly equal TC' s."	4-2
"The method cannot perform valley or reservoir routing."	4-2
"The Fp factor can be applied only for ponds or swamps that are not in the Tc flow path."	4-2
"Accuracy of peak discharge estimated by this method will be reduced if Ia / P values are used that are outside the range given in exhibit 4. The limiting Ia / P values are recommended for use."	4-2
"This method should be used only if the weighted CN is greater than 40."	4-2
"When this method is used to develop estimates of peak discharge for both present and developed conditions of a watershed, use the same procedure for estimating Tc."	4-2
"Tc values with this method may range from 0.1 to 10 hours."	4-2

Table D.2 Tabular Method Limitations as Found in TR-55 (NRCS, 1986)

Limitation	Chapter-Page
"The Tabular method (chapter 5) can be used for a heterogeneous watershed that is divided into a number of homogeneous subwatersheds."	1-4
"If a hydrograph is needed or watershed subdivision is required, use the Tabular Hydrograph method (chapter 5). Use TR-20 if the watershed is very complex or a higher degree of accuracy is required."	4-2
"This method approximates TR-20, a more detailed hydrograph procedure."	4-9
"Exhibit 5 (5-I, 5-IA, 5-II, and 5-III) shows tabular discharge values for the various rainfall distributions... The exhibit was developed by computing hydrographs for 1 square mile of drainage area for selected Tc's and routing them through stream reaches with the range of Tt's indicated."	5-1
An assumption in development of the tabular hydrographs is that all discharges for a stream reach flow at the same velocity. By this assumption, the subarea flood hydrographs may be routed separately and added at the reference point.	5-1
"The Tabular method is used to determine peak flows and hydrographs within a watershed. However, its accuracy decreases as the complexity of the watershed increases."	5-3
"If you want to compare present and developed conditions of a watershed, use the same procedure for estimating Tc for both conditions."	5-3
"Use the TR-20 computer program (SCS 1983) instead of the Tabular method if Tt is greater than 3 hours (largest Tt in exhibit 5)."	5-3
"Use the TR-20 computer program (SCS 1983) instead of the Tabular method if Tc is greater than 2 hours (largest Tc in exhibit 5)."	5-3
"Use the TR-20 computer program (SCS 1983) instead of the Tabular method if drainage areas of individual subareas differ by a factor of 5 or more."	5-3
"Use the TR-20 computer program (SCS 1983) instead of the Tabular method if the entire composite flood hydrograph or entire runoff volume is required for detailed flood routings. The hydrograph based on extrapolation is only an approximation of the entire hydrograph."	5-3
"Use the TR-20 computer program (SCS 1983) instead of the Tabular method if the time of peak discharge must be more accurate than that obtained through the Tabular method."	5-3

Table D.3 TR-55 Input Limitations as Found in TR-55 (NRCS, 1986)

Limitation	Chapter-Page
Normally a rainfall duration equal to or greater than Tc is used.	1-4
"Both the Graphical Peak Discharge and Tabular Hydrograph methods are derived from TR-20 (SCS 1983) output. Their accuracy is comparable; they differ only in their products."	1-4
"The use of Tc permits them to be used for any size watershed within the scope of the curves or tables."	1-4
"These storage-routing curves, like the peak discharge and hydrograph procedures, are generalizations derived from TR-20 routings."	1-4
"Curve numbers describe average conditions that are useful for design purposes. If the rainfall event used is a historical storm, the modeling accuracy decreases."	2-11
"Use the runoff curve number equation with caution when re-creating specific features of an actual storm. The equation does not contain an expression for time and, therefore, does not account for rainfall duration or intensity."	2-11
"Ia, which consists of interception, initial infiltration, surface depression storage, evapotranspiration, and other factors, was generalized as 0.2S based on data from agricultural watersheds (S is the potential maximum retention after runoff begins). This approximation can be especially important in an urban application because the combination of impervious areas with pervious areas can imply a significant initial loss that may not take place. The opposite effect, a greater initial loss, can occur if the impervious areas have surface depressions that store some runoff. To use a relationship other than Ia = 0.2S, one must redevelop equation 2-3, figure 2-1, table 2-1, and table 22 by using the original rainfall-runoff data to establish new S or CN relationships for each cover and hydrologic soil group."	2-11
"Runoff from snowmelt or rain on frozen ground cannot be estimated using these procedures."	2-11
"The CN procedure is less accurate when runoff is less than 0.5 inch. As a check, use another procedure to determine runoff."	2-11
"The SCS runoff procedures apply only to direct surface runoff: do not overlook large sources of subsurface flow or high ground water levels that contribute to runoff. These conditions are often related to HSG A soils and forest areas that have been assigned relatively low CN's in table 2-2. Good judgment and experience based on stream gage records are needed to adjust CN's as conditions warrant."	2-11
"When the weighted CN is less than 40, use another procedure to determine runoff."	2-11
"Manning's kinematic solution should not be used for sheet flow longer than 300 feet."	3-4
"The minimum Tc used in TR-55 is 0.1 hour."	3-4
"A culvert or bridge can act as a reservoir outlet if there is significant storage behind it. The procedures in TR-55 can be used to determine the peak flow upstream of the culvert. Detailed storage routing procedures should be used to determine the outflow through the culvert."	3-4

Appendix E 130 Selected USGS Gages

Table E.1 130 Selected USGS Gages

Site Number	Site Name	Drainage Area (mi2)	Years of Record
06396490	Warbonnet Creek near Harrison	24.5	10
06443200	White River tributary near Glen	8	18
06443300	Deep Creek near Glen	10.9	26
06443900	White River tributary No. 2 near Crawford	5.4	13
06445530	Chadron Creek tributary at Chadron State Park near Chadron	2.59	26
06445560	Chadron Creek at Chadron State Park near Chadron	15.4	26
06445590	Big Bordeaux Creek near Chadron	9.4	11
06456200	Pebble Creek near Esther	3.07	26
06456300	Pebble Creek near Dunlap	23.5	18
06457200	Berea Creek near Alliance	32.3	26
06457800	Antelope Creek tributary near Gordon	26.6	26
06463100	Bone Creek tributary near Ainsworth	0.39	13
06463200	Bone Creek tributary No. 2 near Ainsworth	2.18	11
06463300	Sand Draw tributary near Ainsworth	1.07	19
06465200	Honey Creek near O'Neill	2.54	11
06465300	Camp Creek near O'Neill	1.65	21
06465400	Blackbird Creek tributary near O'Neill	0.6	11
06465850	Bingham Creek near Niobrara	6.5	11
06466950	Weigand Creek near Crofton	3.5	11
06600600	South Omaha Creek tributary near Walthill	2.64	18
06600700	South Omaha Creek near Walthill	15.2	18
06600800	South Omaha Creek tributary No. 2 near Walthill	1.51	29
06607700	South Branch Tekamah Creek near Craig	2.54	18
06607800	South Branch Tekamah Creek tributary near Tekamah	4.08	29
06607900	South Branch Tekamah Creek near Tekamah	9.7	18
06608000	Tekamah Creek at Tekamah	23	40
06608600	New York Creek near Spiker	1.75	16
06608700	New York Creek tributary near Spiker	1.55	28
06608800	New York Creek north of Spiker	6.5	25
06608900	New York Creek east of Spiker	13.9	29
06609000	New York Creek at Herman	25.4	25
06610700	Big Papillion Creek near Orum	8.52	11
06610750	Little Papillion Creek at Irvington, Nebr.	32	13
06610788	South Papillion Creek at Chalco, Nebr.	30.4	18
06763200	Lodgepole Creek tributary near Sunol	15.6	11
06767100	South Fork Plum Creek tributary near Farnam	9.81	20
06767200	North Fork Plum Creek tributary near Farnam	1.83	27
06767300	Plum Creek tributary at Farnam	19.8	22

Site Number	Site Name	Drainage Area (mi2)	Years of Record
06767400	North Plum Creek near Farnam	38.3	20
06768050	Buffalo Creek tributary No. 1 near Buffalo	2.08	14
06768100	East Buffalo Creek near Buffalo	5.2	28
06768200	Buffalo Creek at Buffalo	33.5	17
06768300	Buffalo Creek tributary No. 2 near Buffalo	1.93	15
06768400	West Buffalo Creek near Buffalo	17.1	28
06769100	Elm Creek tributary near Overton	0.58	28
06769200	Elm Creek near Sumner	14.9	28
06769300	Elm Creek tributary No. 2 near Overton	5.6	28
06769500	Elm Creek near Overton	31	12
06770600	Wood River tributary near Lodi	2.02	27
06770700	Wood River near Lodi	12.9	27
06770800	Wood River near Oconto	26.4	22
06770900	Wood River at Oconto	44.8	25
06772775	Warm Slough near Central City, Nebr.	31.8	17
06777600	Lillian Creek tributary near Broken Bow	2.02	26
06777700	Lillian Creek near Broken Bow	4.77	27
06777800	Lillian Creek tributary near Walworth	2.04	27
06782600	South Branch Mud Creek tributary near Broken Bow	0.4	28
06782800	North Branch Mud Creek at Broken Bow	15.5	17
06782900	Mud Creek tributary near Broken Bow	5.9	29
06784300	Oak Creek near Loup City	41.9	14
06784700	Turkey Creek near Farwell	27.2	27
06789100	Davis Creek tributary near North Loup	2.29	17
06789200	Davis Creek tributary No. 2 near North Loup	6.8	20
06789300	Davis Creek near North Loup	21.1	17
06789400	Davis Creek southwest of North Loup	31.2	28
06790600	East Branch Spring Creek tributary near Wolbach	1.52	27
06790700	West Branch Spring Creek at Brayton	19.5	28
06790800	West Branch Spring Creek near Wolbach	36.9	17
06790900	Mary's Creek at Wolbach	7.6	16
06793995	Skeedee Creek tributary near Genoa	0.59	12
06794710	Bone Creek near David City	8.8	12
06799190	South Fork Union Creek tributary near Comlea	6.5	12
06799423	North Logan Creek near Laurel	25.3	13
06799850	Pond Creek near Schuyler	0.54	11
06800350	Elkhorn River tributary near Nickerson	6.5	11
06803200	Antelope Creek at 48th Street, Lincoln	7.1	22
06803300	Antelope Creek at 27th Street, Lincoln	10.6	33
06803400	Antelope Creek at Lincoln	12.5	21
06803510	Little Salt Creek near Lincoln	43.6	54

Site Number	Site Name	Drainage Area (mi2)	Years of Record
06803520	Stevens Creek near Lincoln	47.8	54
06803540	Dee Creek near Alvo	7.9	17
06803570	Dunlap Creek tributary near Weston	0.42	29
06803600	North Fork Wahoo Creek near Prague	15.4	28
06803700	North Fork Wahoo Creek tributary near Weston	8.9	18
06803900	North Fork Wahoo Creek at Weston	43.3	28
06804100	Silver Creek near Cedar Bluffs	7	29
06804200	Silver Creek near Colon	30.3	29
06804300	Silver Creek tributary near Colon	10.3	28
06804400	Silver Creek tributary at Colon	17.6	28
06804900	Johnson Creek near Memphis	21.5	19
06805510	Buffalo Creek near Gretna	4.29	11
06806400	Weeping Water Creek at Elmwood	20.8	19
06806420	Stove Creek near Elmwood	5.2	19
06806440	Stove Creek at Elmwood	10.3	29
06806470	Weeping Water Creek tributary near Weeping Water	0.73	29
06810060	Honey Creek near Peru	3.43	10
06810100	Hooper Creek tributary near Palmyra	8	29
06810300	Wolf Creek near Syracuse	25.4	18
06810400	Little Nemaha River tributary near Syracuse	0.71	29
06815510	Temple Creek near Falls City	2.99	11
06824000	Rock Creek at Parks	23.6	82
06828100	North Branch Indian Creek near Max	4.76	10
06829700	Thompson Canyon near Trenton	9.1	13
06835100	Bobtail Creek near Palisade	30.2	13
06837100	Ash Creek near Red Willow	18.32	7
06838550	Dry Creek at Bartley	42	38
06839200	Elkhorn Canyon near Maywood	6.7	27
06839400	Elkhorn Canyon southwest of Maywood	13.4	19
06839600	Frazier Creek near Maywood	11.3	19
06839700	Frazier Creek tributary near Maywood	0.72	27
06839850	Fox Creek north of Curtis	13.8	19
06839900	Fox Creek above Cut Canyon near Curtis	31.8	28
06839950	Cut Canyon near Curtis	25.6	28
06840500	Dry Creek near Curtis	21.6	20
06849600	Turkey Creek near Hoidrege	22.9	12
06850200	Cottonwood Creek near Bloomington	15.6	26
06851300	West Branch Thompson Creek tributary near Hildreth	11.5	26
06852000	Elm Creek at Amboy	39.2	40
06853100	Beaver Creek near Rosemont	0.75	40
06879850	Big Blue River tributary near Hordville	4.07	11

Site Number	Site Name	Drainage Area (mi2)	Years of Record
06880590	North Branch West Fork Big Blue River tributary at Giltner	7.5	11
06880710	School Creek tributary near Harvard	14.6	19
06880730	School Creek tributary No. 2 near Harvard	16.4	26
06880775	Beaver Creek tributary near Henderson	1.16	11
06881250	South Fork Swan Creek tributary near Western	0.07	11
06883540	Spring Creek tributary near Ruskin	2.11	12
06883600	South Fork Big Sandy Creek near Edgar	15.2	18
06883700	South Fork Big Sandy Creek near Davenport	28.1	28
06883955	Little Sandy Creek near Ohiowa	11.6	11
06884005	Dry Branch tributary near Fairbury	4.51	11

Appendix F Segmental and Lag T_c Estimates

Table F.1 Segmental Time of Concentration Compared to Lag Time of Concentration

Site Number	Segmental T_c (hrs.)	Lag T_c (hrs.)	Site Number	Segmental T_c (hrs.)	Lag T_c (hrs.)	Site Number	Segmental T_c (hrs.)	Lag T_c (hrs.)
6396490	2.8	5.3	6769200	5.7	4.9	6804100	5.1	4.2
6443200	2.2	2.7	6769300	5.1	3.3	6804200	16.8	9.6
6443300	3.8	3.3	6769500	9.6	6.7	6804300	11.2	7.8
6445530	2.8	1.9	6770600	0.9	2.3	6804400	7.7	14.2
6445560	2.0	2.7	6770700	7.0	5.9	6804900	4.1	9.5
6445590	1.6	2.6	6770800	4.8	6.3	6806400	2.3	5.2
6456200	3.4	3.7	6770900	5.8	7.6	6806420	1.4	2.3
6456300	6.6	9.4	6772775	17.3	39.3	6806440	1.3	3.3
6457200	9.4	18.6	6777600	2.1	1.6	6806470	0.6	1.2
6457800	3.6	11.8	6777700	3.4	2.6	6810060	1.0	1.9
6463100	4.5	4.0	6777800	1.1	2.5	6810100	2.6	3.5
6463200	2.2	5.2	6782600	2.1	2.1	6810300	1.6	5.0
6463300	3.2	3.4	6782800	3.0	5.0	6810400	0.6	1.3
6465200	4.7	5.4	6782900	1.6	4.0	6815510	0.8	2.1
6465300	4.0	6.3	6784300	3.5	8.1	6828100	2.0	3.1
6465400	2.9	2.9	6784700	4.9	7.5	6829700	2.2	3.7
6465850	2.6	5.6	6789100	1.5	1.5	6835100	6.9	6.4
6466950	0.9	2.5	6789200	1.1	3.8	6837100	4.1	6.3
6600600	0.9	1.7	6789300	4.4	5.3	6838550	10.3	11.0
6600700	3.3	3.0	6789400	7.9	8.5	6839200	1.7	2.1
6600800	0.7	1.6	6790600	1.4	2.1	6839400	1.4	3.8
6607700	2.6	1.7	6790700	6.2	7.3	6839600	1.6	3.1
6607800	2.6	2.4	6790800	9.3	9.4	6839700	1.0	1.2
6607900	2.3	2.9	6790900	3.9	3.4	6839850	1.1	3.3
6608000	3.9	4.9	6793995	1.4	1.5	6839900	1.6	6.0
6608600	1.6	1.9	6794710	2.2	6.5	6839950	2.9	6.4
6608700	1.0	1.8	6799190	13.2	4.5	6840500	2.7	4.8
6608800	2.1	2.8	6799423	4.9	8.4	6849600	9.2	6.7
6608900	2.5	3.8	6799850	0.4	0.8	6850200	6.8	7.4
6609000	2.6	6.2	6800350	4.8	5.6	6851300	5.3	9.2
6610700	2.2	3.3	6803200	1.9	3.5	6853100	3.3	1.8
6767100	6.5	6.1	6803300	1.2	4.7	6880590	7.7	9.2
6767200	1.8	2.8	6803400	1.7	5.6	6880710	19.1	16.7
6767300	6.5	7.5	6803510	4.6	7.8	6880730	11.3	10.4
6767400	7.0	8.1	6803520	4.8	8.3	6880775	3.1	4.9
6768050	1.8	1.7	6803540	3.0	3.1	6883540	4.4	3.9
6768100	5.3	3.7	6803570	0.8	0.9	6883700	18.3	17.5
6768200	7.8	6.4	6803600	1.0	3.2	6883955	8.3	7.4

Site Number	Segmental T_c (hrs.)	Lag T_c (hrs.)	Site Number	Segmental T_c (hrs.)	Lag T_c (hrs.)	Site Number	Segmental T_c (hrs.)	Lag T_c (hrs.)
6768300	3.7	2.7	6803700	1.6	2.8	6884005	1.6	2.7
6768400	6.2	4.9	6803900	3.1	6.4			