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Stream Dynamics in the Headwaters of Post-Glacial Watershed Systems

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STREAM DYNAMICS IN THE HEADWATERS OF POST-GLACIAL WATERSHED SYSTEMS

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An Abstract of the Dissertation Presented
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This dissertation summarizes research examining watershed processes across Northern New England, with an emphasis on the Central and Coastal regions of Maine. The research presented here focuses on the linkages between watershed geomorphic conditions, climate, and surface flow regimes driving stream channel hydraulic conditions and bed dynamics governing channel geometry. The geologic and human history of the landscape provides the context in which earth surface processes are examined within the dominant physiographic settings in Maine to describe vulnerabilities to climate change. Results are summarized to support the development of sustainability solutions for forecasted watershed management problems by natural resource management agencies and communities.

The research components of this dissertation were developed through stakeholder engagement to identify regional water resource sustainability problems. Physical watershed processes affecting stream flow and sediment transport conditions are fundamental to stakeholder concerns. This research examines the influence from human activities, climate, and earth surface processes associated with erosion from ice and water

flows on modern surface hydrology and fluvial geomorphology in the region. Research targets are organized relative to scientific principles and contemporary watershed management approaches relevant to stakeholder interests related to water quality, aquatic habitat, recreation, and coastal fisheries.

This research is framed by geo-spatial analyses organized to examine Northern New England landscape conditions linked to patterns of surface water flow. The approach uses dominant geologic, soil, topographic, and land cover conditions as independent variables, providing a tool for scaling observations in reference watersheds and evaluating the transferability of information guiding selection of watershed management practices across the region. River discharge measurement data within representative assemblages are analyzed to evaluate the implications of varied landscape conditions to surface water flow regimes. Stream channel hydraulic geometry is quantified to relate surface flows, stream channel conditions, and the history of glaciation and human activities affecting watershed processes.

Flow regime responses to forecasted climate change in varied landscape settings are estimated using numerical watershed hydrologic simulations. Modeling results suggest that changes to annual snow pack conditions will have the most substantial influence on surface flows. Base, mid-range, and peak flows have varied responses governed by surface water storage, snow pack dynamics, and rainfall patterns. The impact of the predicted surface flow changes on stream channel sedimentary environments are quantified by coupling simulated flow time series with a sediment transport model. Results indicate that changes to sediment dynamics affecting stream hydraulics and channel stability may result from forecasted climate changes in the region.

Research objectives and outcomes are framed to support the development of sustainability solutions to watershed management challenges related to public safety, water quality, and aquatic habitat conservation. The process of designing the project approach with input from stakeholders and evaluating outcomes from quantitative analyses improves understanding of how multiple factors governing earth surface processes operating over varied time scales combine to create varied hydrologic and geomorphic responses to watershed land use and climate changes in the Northern New England region. The prediction of measurable alterations to streams in evaluated settings provide rationale for development of watershed management strategies in response to future land use and climate changes. Varied vulnerabilities to changes suggest that customized management approaches will be necessary as some stream systems will be more responsive than others. The development of an approach for parsing the landscape into Geomorphic Response Units (GRUs) demonstrated by this research provides a basis for designing a statewide approach for implementing strategies for watershed management that considers varied vulnerabilities to land use and climate changes in the region. This work provides tools for the stakeholder community to evaluate the applicability of management techniques across the region and knowledge of water resource vulnerabilities as they relate to landscape conditions and climate.

DEDICATION

To Dad, for the inspiration to learn.

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ATTRIBUTIONS

This dissertation is composed of chapters which have been compiled from manuscripts, with the exception of chapter one which presents a review of introductory material relevant to the core of this research. Some information, primarily introductory and discussion material, may appear repetitious because of this structure. Pagination, figure and table labels, and the bibliography have all been formatted to conform to the University of Maine Graduate School dissertation guidelines.

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$$k = \frac{dQ}{dW} = \frac{\frac{dQ}{dt}}{\frac{dW}{dt}} = \frac{\frac{dQ}{dt}}{P-ET-Q} = \left.\frac{-\frac{dQ}{dt}}{Q}\right|_{P \ll Q, ET \ll Q}$$

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LIST OF ABBREVIATIONS AND NOTATIONS

$\propto$	Momentum distribution coefficient
a, c, j	Denotes variable coefficients
b, f, m, r	Denotes variable exponents
A	Cross sectional area
BCSS	Between Cluster Sums of Squares
C	Chezy's resistance coefficient
Conc.	Constituent concentration
CCSM	Community Climate Systems Model
D	Grain size
d	Channel depth
DA	Drainage Area
E_t	Expected (Modelled) discharge at time t
NSE	Nash-Sutcliffe Efficiency criteria
EPA	Environmental Protection Agency
EPSCoR	Established Program to Stimulate Competitive Research
ET	Evapotranspiration
ET_{can}	Evapotranspiration from the vegetation canopy
ET_{pon}	Evapotranspiration from ponds and other sources of surface water storage
ET_{snow}	Evapotranspiration from snow
ET_{sz}	Evapotranspiration from the saturated zone
ET_{uz}	Evapotranspiration from the unsaturated zone
g	Acceleration due to gravity
GIS	Geographic Information System
GRU	Geomorphic Response Unit
h	Hydraulic head
I	Infiltration
IPCC	Intergovernmental Panel on Climate Change
J_T	Degree-day factor for snow melt
J_{Rad}	Radiation melting factor for snow melt
J_E	Energy snow melting coefficient for the energy of liquid rain
K	Hydraulic conductivity
k	Sensitivity Parameter (Chp. 2), variable coefficient (Chp. 4)
K_s	Saturated hydraulic conductivity
l	Variable loading
LAI	Leaf Area Index
LGM	Last Glacial Maximum
LULC	Land Use/ Land Cover

M_T	Temperature snow melting
M_R	Radiation snow melting
M_E	Energy snow melting
MeSSI	Maine's Sustainability Solutions Initiative
μ	Fluid viscosity
n	Manning's roughness coefficient
n_D	The partitioned Manning's roughness coefficient for sediment
NOAA	National Oceanographic and Atmospheric Administration
$\overline{O}$	Observed average discharge
O_t	Observed discharge at time t
P	Precipitation
P_b	Surface ponding
PC	Principal Component
PBIAS	Percent Bias
Q	Discharge
Q_s	Sediment transport rate
Q_{Load}	Mass flux of constituent
q	Discharge per unit width
q_s	Sediment transport rate per unit width
q_s^*	Dimensionless sediment transport rate
R	Hydraulic radius
R_{sw}	Incoming solar radiation
RD	Rooting Depth
ρ_f	Density (fluid)
ρ_s	Density (sediment)
RMSE	Root Mean Square Error
S	Slope
s	Relative grain density ($^{\rho_s}/_{\rho_f}$)
STDEV	Standard Deviation
T	Temperature
T_0	Freezing temperature of snow
t	Time
θ	Soil water content
TSS	Total Sums of Squares
τ	Shear stress
τ^*	Dimensionless shear stress
τ_c	Critical shear stress
τ_c^*	Dimensionless critical shear stress
τ_{ci}	Critical shear stress for sediment of size i
τ_g	Partitioned shear stress acting on sediment, or grain shear stress
U	Reach segment averaged velocity
V_s	Volume of water at saturation
v	Velocity

W	Water storage
w	Channel width
X	Denotes a variable
x, y, z	Denotes cartesian coordinates
WCSS	Within Cluster Sums of Squares

CHAPTER ONE

INTRODUCTION

1.1 Research Questions

The rates and magnitudes of watershed hydrologic processes in Northern New England are dominantly influenced by climate, the post-glacial terrain, and landscape modifications by humans following European colonization of the area in the early 1600's (Maine Historical Society 2014). The influence that human activities, climatic conditions, and past glaciation exert on surface hydrology and fluvial geomorphology in the region is the focus of this research. This dissertation summarizes analyses that identify and quantify watershed geomorphology, climate conditions, surface flow regimes, and stream channel dynamics. The study area extends through Central and Coastal Maine where local economies and cultural identities have close ties to surface water resources and water quality conditions affecting rivers, lakes, and coastal estuaries.

The core components of this dissertation were developed with input and collaborative interactions with local stakeholder communities to define research objectives relevant to water resource sustainability in the region. Three research questions framed around processes governing water resource conditions in the study region are pursued using a combination of field measurements, spatial data analysis, and numerical watershed modeling. These research questions provide the organizational structure for the dissertation:

1. How do watershed geomorphic conditions vary (e.g. geology, soils, relief, and land cover) and how do the dissimilarities relate to stream flow characteristics?

2. What are the implications of climate change to the surface flow regimes of headwater stream systems in the region?

3. How do watershed conditions and flow regime alterations from climate change affect stream channel dynamics?

Observations and research results are summarized throughout this document to address the watershed management and sustainability challenges described by local communities, environmental organizations, and government agencies charged with managing environmental conditions and natural resources in Maine.

1.2 The Sediment-Water Proportionality

The research questions inspiring this project are related to watershed management and fundamentally framed around relations between the availability of mobile sediment and the capacity of surface flows to transport this sediment supply through and from headwater streams (Wilcock et al. 2009). The fundamental proportionality between water and sediment is an important consideration linked to management of nonpoint source pollution, aquatic habitat, and drinking water supplies, particularly as it relates to watershed and stream conditions, surface water discharge, and climate. The relation between water discharge, sediment supply, and sediment transport provides an underlying basis because of the direct associations with watershed alterations, human activities, climate changes, and stakeholder water resource interests and concerns.

The transport of sediment in the modern Maine landscape is driven by surface water discharge (Q), which is a function of watershed drainage area (DA):

$$Q = f(DA) \qquad [1]$$

The rate at which sediment is transported (per unit width of stream) is a function of flow strength (τ, i.e. shear stress), depth (h), sediment grain size (D), the density of the sediment (ρ_s) and water (ρ), fluid viscosity (μ), and gravity (g):

$$q_s = f(\tau, h, D, \rho_s, \rho, \mu, g) \qquad [2]$$

Stream channel dynamics are governed by the relation between components of equation 2, with channel cross section area and bottom substrate conditions responding to alterations in water and sediment supplies. This proportionality between sediment and water is conventionally framed by the Lane/Borland Balance in figure 1 (Borland 1960) and the sediment-water proportionality:

$$Q_s D \sim QS \qquad [3]$$

where Q_s is the sediment transport rate and S is the channel slope. Changes to terms on either side of the proportionality function produce a change in channel conditions.

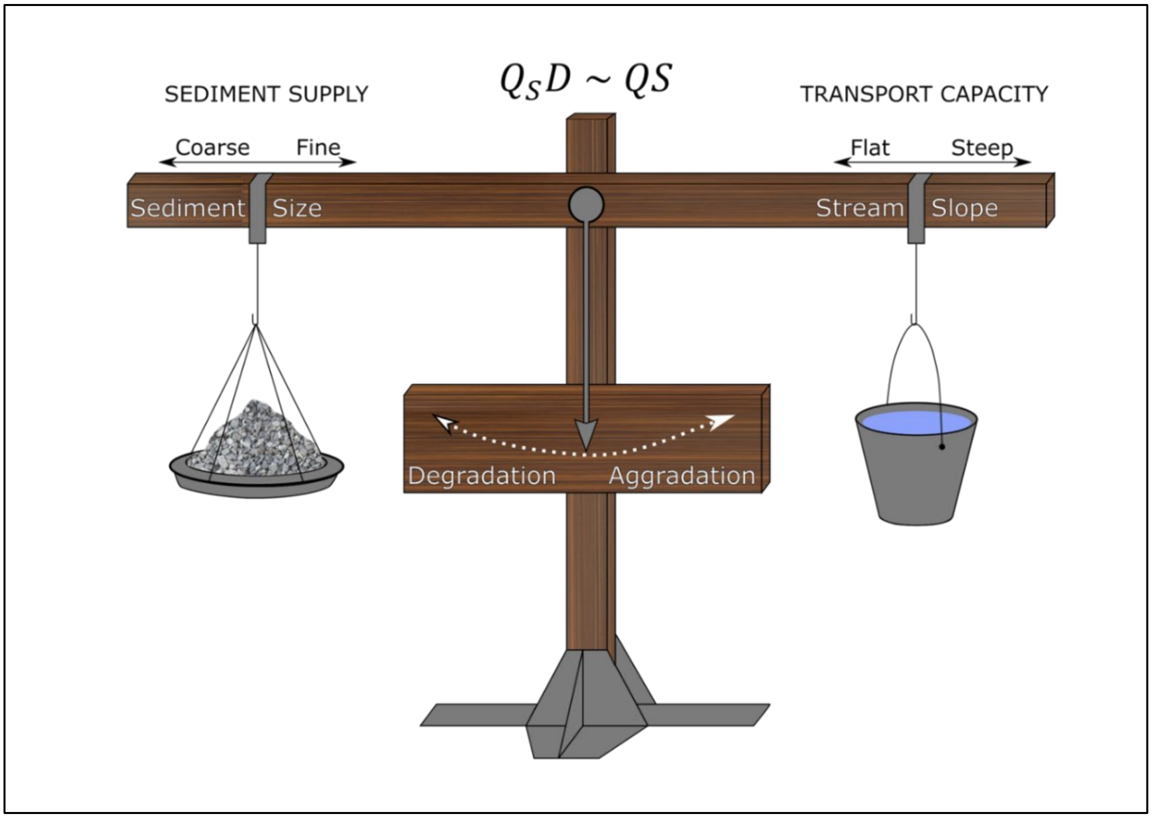

Figure 1:The Lane/Borland channel stability relation. Adapted from Lane (1955).

The sediment-water proportionality in Maine's deglaciated landscape presents a condition of relatively low watershed sediment supply compared to locations south of the limit of glaciation (USDA 2009). Sediment inputs from upland areas to streams are low with the exception of locations where glacial features such as eskers and moraines are present and in close proximity to waterways (Snyder et al. 2009). The historic glacial activity in this landscape "reset" the geomorphology ~15 Kya as the Laurentide Ice Sheet retreated from the region (Borns Jr. et al. 2004). The relatively thin veneer of young soils and regolith present over bedrock today is an artifact of mechanical work by the overburden of ice during glaciation and outwash during retreat. The glacial history produced a limited modern supply of sediment, particularly grain sizes smaller than sand, in large areas of the state with the exception of coastal areas that have fine-grained sediments on the surface deposited during the transgression of the Atlantic Ocean prior to isostatic rebound of the region.

The right-hand side of the sediment-water proportionality (Equation 3), transport capacity, is influenced by all components of watershed hydrologic systems, including types of precipitation, timing and rates of runoff production, and pathways of routing through drainage networks. Although Maine has an average annual precipitation depth (114 cm, NOAA 2007) similar to the Mid-Atlantic, the monthly hydrologic budget is very different due to climate effects on snowfall and snowpack, vegetation, and evapotranspiration. Surface routing pathways conveying excess precipitation as runoff are also substantially modified by a multitude of lakes, ponds, and wetlands that were created from glacial ice sheet dynamics. These reservoir features store surface water and regulate the downstream movement of both water and sediment. Northern New England is forecast to become increasingly wetter due to climate changes (Fernandez et al. 2015). The effects of the hydrologic changes in the region on sediment transport competence and capacity in headwater stream channels have not been quantified in most of the settings in the region. The implications to stakeholder interests related to water resources and aquatic habitat are therefore poorly understood, limiting the development of responsive watershed management strategies for sustainability solutions.

1.3 Background: Sustainability Solutions Research in Maine

This research project grew out of two National Science Foundation (NSF) projects as part of the Established Program to Stimulate Competitive Research (EPSCoR). The projects focused on connecting knowledge with action, bridging the gap between academic research and sustainability solutions through stakeholder-driven and scientifically defensible management strategies. The project initially began in 2013 as part of research activities included in the project portfolio of Maine's Sustainability Solutions Initiative (MeSSI) (National Science Foundation award EPS-0904155). A component of the MeSSI project focused on the Sebago Lake watershed in southern Maine, inspired by concerns around the vulnerability of the lake to future watershed modifications from land development. This project sought to develop decision support tools for water resource sustainability in this and other Northern New England lake systems. Much of the landscape in the Sebago Lake watershed is dominated by private forestland, but socio-economic projections have indicated increased land cover alterations in the region. Projected regional population growth and the transition of the landscape to include more suburban development over the next thirty years (U.S. EPA 2009) may have adverse impacts on downstream water quality. These pressures and the use of Sebago Lake as a drinking water resource for much of southern Maine's population has made the watershed one of the most at risk in the northeastern United States (Barnes 2009).

The geographic scale of the sustainability-focused research was expanded in 2015 as part of the New England Sustainability Consortium (NEST) (National Science Foundation award IIA-1330691). This project was centered on strengthening the link between science and decision making, primarily as related to rules for beach closures to shellfish harvesting areas in response to pollution problems. Many coastal Maine community economies are linked to tourism, aquaculture, industrial fishing, and shellfish harvesting industries that are dependent on good water quality in nontidal streams and rivers, tidal estuaries, and coastal beach areas. Community culture and wellbeing are in many ways connected to near and offshore water quality. Degradation in water quality has begun to threaten these communities as the population along Maine's coastline increases and the effects from climate change become more prevalent (Evans et al. 2016; Taylor 2018; Fernandez et al. 2015). Quantification of land-sea connections was at the heart of the NEST research effort, with the goal of comparing the vulnerability of varied coastal Maine landscape settings to water pollution problems.

The research summarized in this dissertation is an extension of these two projects focused on sustainability solutions to water resource and aquatic habitat problems, examining coupled social-biophysical systems in the Central and Coastal Maine region. The earth science questions examined were inspired by stakeholder engagement, primarily state and regional resource management agencies (e.g., Maine Department of Marine Resources and the Portland Water District) during the MeSSI and NEST projects. This research seeks to address research gaps related to management that are directly related to sustainability solution goals. The research uses information gathered from previous research and monitoring activities, knowledge of stakeholders, and data collected during these projects to advance analyses of watersheds draining Maine's landscape to support management needs linked to water resources. The MeSSI and NEST project activities included deployment and operation of a stream monitoring network. The NEST project also synthesized new coastal Maine watershed delineations derived from high resolution topographic (LiDAR) datasets that have only recently become available for the coastal Maine region.

1.4 Study Region

The region of focus for this dissertation is Central and Coastal Maine. For the purposes of this dissertation, the extent of Central and Coastal Maine will be broadly defined by the White Mountains and the Piscataqua River to the south, the "Maine Highlands" to the west, the Maine coastline to the east, and the Saint Croix River to the north/northeast (Figure 2). The study region spans a range of elevations and geologic conditions. The areas of highest relief and elevation are found along the Appalachian Range to the west, and the landscape generally loses elevation and relief moving eastward. An exception to this general trend is the coastline of Mid-Coast Maine where the expression of the Acadian Orogeny produces some of the highest relief in the state. The entire region is predominantly underlain by schistose bedrock with increasing metamorphism from south to north (Osberg et al. 1985). However, several granitic plutons are present, most notably throughout the high relief regions around the Mid-Coast and the Sebago Pluton that underlies Sebago Lake and much of its contributing rim watershed.

A well-documented geomorphic boundary approximating the separation of Maine's Central and Coastal sub-regions is the demarcation of the extent of marine transgression following the retreat of the Laurentide Ice Sheet (Woodrow and Borns 1985). West of the marine transgression the surficial geology is mostly dominated by till with a scattered mix of wetland, glacio-fluvial, and glacio-marine deposits. East of the marine transgression the surface is largely dominated by fine grained marine deposits, although the deposit thickness is relatively small or absent in portions of the Mid-Coast and Downeast areas.

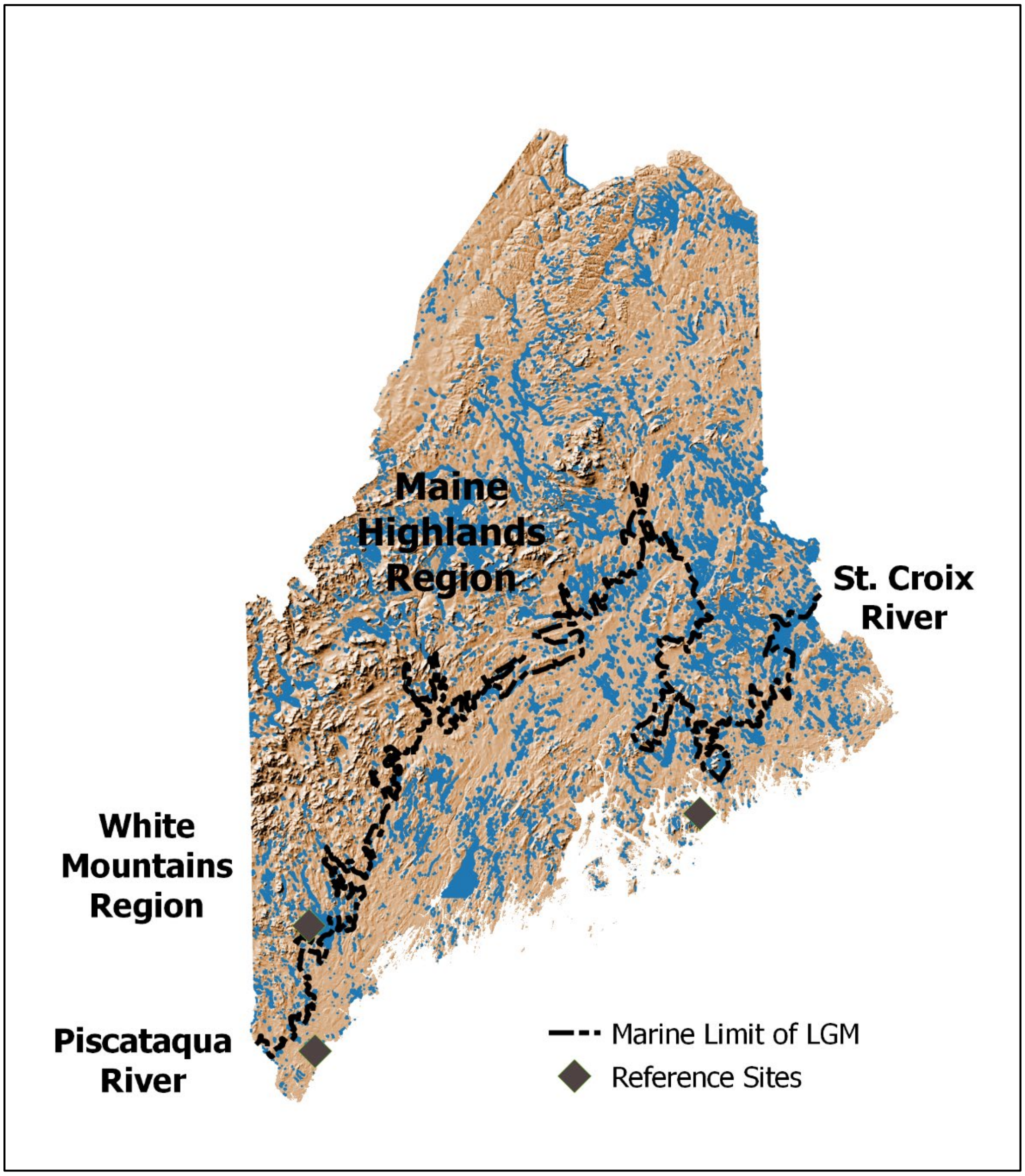

Figure 2: Study region site map.

Climatically, the coastal regions experience some moderating effects from the Gulf of Maine relative to the central regions of the state. However, these difference between regions is minimal. Averaged between 1895 and 2007, yearly temperature in the Central and Coastal Maine region was ~6 °C and the region received approximately 114 cm of precipitation (NOAA 2007). This precipitation falls as snow in winter months, producing median seasonal snowpack depths between 500 and 800 mm (Cember and Wilks 1993). The melting of this snow often results in large runoff events and seasonally high spring stream flows (Dudley and Hodgkins 2002; Dudley and Hodgkins 2005).

Phase three of the Coupled Model Intercomparison Project (CMIP3) indicates an increase in regional temperatures of around 6-7 °C over the next 100 years, with the largest increase occurring during winter months (Jacobson et al. 2009). Over this same period, precipitation is expected to increase. These simulations indicate an increase in winter precipitation of approximately 8-14%, a 9-10% increase in spring precipitation, and an increase of about 6% in the fall. Summer precipitation is forecasted to experience minimal change.

1.5 Reference Watersheds

To quantify processes linked to overland runoff and stream responses in the region, reference watersheds were selected to describe the range of geomorphic conditions in the watershed headwaters of Central and Coastal Maine. Three watersheds were chosen for more detailed examination of hydrologic and geomorphic processes. These three sites are the Northwest River watershed in the South-Central Maine Lakes region, the Webhannet

River watershed along the Southern Coast, and the Cromwell Brook watershed in Mid-Coast Maine.

The Northwest River watershed is a sub-basin of the Presumpscot River watershed that drains directly into Sebago Lake. The watershed is of modest relief, and with the exception of the geographic center which has substantial wetland deposits, the surficial geology is dominated by glacial till as is most of the Sebago Lake watershed. The basin is mostly rural like most of Central Maine, and land cover is dominated by forestland with scattered pockets of development clustered along road corridors and lake perimeters (Pavri et al. 2013).

The Webhannet River watershed has physiographic and land use characteristics similar to many locations in the Southern Coastal region. The watershed has relatively low topographic relief and is moderately developed (~11%). Much of this development is concentrated along the coast. The region is one of the earliest inhabited areas in Maine and has a long history of human interventions. The Webhannet River drains into a tidal estuary that is part of the Wells National Estuarine Research Reserve. The watershed is well east of the inland limit of the marine transgression that followed deglaciation. As such, its surficial geology is dominated by marine clays and sands (Smith 1999a; Smith 1999b).

Cromwell Brook watershed is located on Mount Desert Island adjacent to Bar Harbor. Much of the watershed is within Acadia National Park. This watershed has modest to relatively high topographic relief and has large granitic exhumations in the majority of the watershed's headwaters. Soils are absent or thin throughout much of the watershed except for areas within the lowland valleys where the lowermost reaches of the waterway traverse a landscape mostly covered by fined grained marine deposits, including clay layers (NRCS 2016). The watershed is moderately developed, approximately 19%, much of which is within Bar Harbor at the downstream end of the watershed.

1.6 Research Summary

This dissertation examines watershed dynamics across a range of spatial and temporal scales within the study region. Primary data was collected between 2013 and 2017. In a general order of succession, data were collected from the Sebago Lake, the Webhannet River, and the Cromwell Brook watersheds. The structure of data collection and analysis activities matches the progression of the project as described in Section 1.3. The following chapters address the three research questions outlined above using a combination of first-person observations, statistical techniques, and numerical modeling.

CHAPTER TWO

HEADWATER DRAINAGE AREA SETTINGS IN MAINE

2.1 Chapter Abstract

Watershed hydrology across Northern New England is responsive to the region's history of glaciation and human activities. Knowledge of surface flow characteristics and the extent to which geomorphic features in a landscape influence watershed hydrology is important for the development of sustainable water resource management strategies across the region. This research evaluates landscape conditions relative to surface flow characteristics in Maine to provide a basis for examining the transferability of water resource management strategies in the state's varied physiographic settings. A high density of watershed measurements is ideal for adaptive management, but the capacity for data collection is limited. A solution to the problem presented by the limited capacity for continuous monitoring of surface water conditions in all places is to prescribe management strategies relative to watershed settings defined by landscape conditions affecting surface water hydrology and stream channel dynamics. The approach focuses on landscape attributes governing the generation of excess precipitation and the routing of runoff through watershed drainage networks. While not every relevant characteristic driving watershed hydrology is captured at high resolution, watershed attributes most prominently affecting surface water flow regimes and fluvial processes in headwater stream drainage networks are considered. The watershed scale of evaluation is conceptually similar to the "statistical and essential realism" examples of landscape

modeling presented by Dietrich et al. (2003), placing focus on prominent characteristics that relate to contemporary earth surface processes.

Geomorphic characteristics of Maine's landscape are examined, and dominant attributes are grouped at the grain scale of moderately sized (third order) watersheds to describe and compare landscape conditions with a focus on hydrologic variability in headwater stream systems. The approach considers a range of time scales and processes affecting contemporary landscape conditions, ranging from modern hydrology and surface erosion, to deposits formed during deglaciation ~15 Kya, to continental scale processes shaping the terrain millions of years ago.

Watershed conditions influencing surface water flows and stream dynamics in Maine are grouped into nine statistically definable clusters referred to as Geomorphic Response Units (GRUs) using geospatial data analysis. The clusters are assembled from a set of attributes that govern headwater stream flows and morpho-dynamics. Analysis of flow time series from USGS river gauging stations across the region are used to compare hydrograph characteristics across GRUs. The comparisons provide a basis to quantify surface hydrology and correlate them with geomorphic settings defined by the GRUs. These analyses identify watershed "types" based on the collection of attributes and establish a framework to evaluate the responses and vulnerabilities of varied watershed settings to land use and climate changes in the region.

2.2 Introduction

The retreat of the Laurentide Ice Sheet ~15 Kya from the Northern New England region exposed a landscape sculpted and carved by glacial process (Borns Jr. et al. 2004). The landscape's generally thin soils, till dominated surficial geology, and numerous lakes were produced from the advancement and retreat of the ice sheet. These conditions which describe the fundamental properties of the regional sediment-water proportionality (Equation 3), produced a drainage network with a relatively small sediment supply and a large volume of surface water storage as compared to other parts of North America below the southern extent of glaciation (Kelley et al. 2011; Smith and Wilcock 2015). While sediment transport is small compared to non-glacial environments, variability from the regional conditions of the sediment-water proportionality are present where high sediment supply exist from glacial deposits (e.g. eskers) in close proximity to stream channels (Snyder et al. 2009).

While extensive investigation of runoff, stream conditions, and nonpoint source pollution have been conducted in other regions in the Eastern USA, glaciated regions of the Northeastern USA have received less examination (Leopold et al. 1964). The modern drainage network in this deglaciated landscape has not been described in terms of its morphometry or process of development by mechanical erosion driven by ice and surface water flows. Locations and alignments of large rivers in the region are known to correspond to prominent geologic features; however, the influence of Maine's glacial history on the characteristics of upland drainage networks is not well understood. This information gap exists despite the fact that headwater streams are the most extensive components of watershed drainage networks and are important to the sustainability of public water supplies and aquatic habitat in the region. More information is necessary to identify and clarify the processes that influence tributary water flow regimes, as well as the physical and chemical connections between the upland landscape and downstream rivers, lakes, and estuaries. The information gap related to headwater drainage networks limits the ability for natural resource managers and environmental regulators to develop strategies to respond to water quality, aquatic habitat, and safety problems linked to watershed land use and climate changes.

This research provides a foundation to address this knowledge gap by focusing on headwater watershed conditions that govern surface water hydrology, quantifying watershed variability and relating identified watershed types to surface flow regime characteristics. Clustering of headwater basins based on landscape characteristics provide a means to identify settings more vulnerable to land use and climate changes and develop decision tools for adaptive watershed management strategies.

Delineations of physiographic regions have been previously completed at various scales to include the continental United States and Maine (Fenneman 1938; Toppan 1935). Researchers in other regions of the United States have used similar approaches to guide hydro-chemical sampling, interpretation of water quality information, and classify hydrologic flow regimes for public policy claims (Preston 2001; Lipscomb 1998). Within the study region, previous work has been performed to identify both biophysical and climatic regions for natural resource management purposes (Briggs and Cornelius 1998; Krohn, et al. 1999). This research expands these previous efforts, focusing on geomorphic variables influencing surface water flows, stream channel conditions, and related to water resource sustainability concerns.

2.3 Methods

2.3.1 Watershed Characterization

Data Collection: 8,274 drainage divides are delineated within the State of Maine by the Maine Geologic Survey. These basins are sub-units of HUC-12 watersheds that have been delineated based on USGS 1:24,000 scale topographic maps, averaging ~ 10 km^2 in size. Geospatial data for each watershed were assembled from GIS Databases available through the Maine Office of GIS (http://www.maine.gov/megis/) and the USDA (https://datagateway.nrcs.usda.gov/). Variables considered in the analysis were selected based on their relevance to watershed hydrology, geomorphic watershed properties, and data availability (Table 1).

Table 1: Variables used to characterize Maine's landscape for PCA and cluster analysis.

Variable	Description
Bedrock Geology	Percent of watershed underlain by Granoblastic, Metasedimentary, Chemical, Melange, Carbonate, Clastic, Volcanic, Plutonic, Magmatic, or Metaigneous bedrock.
Surficial Geology	Percent of watershed surficial geology that is Bedrock (Exposed), Gaciofluvial, Glaciomarine, Moraine, Till, Alluvium, Beach, Eolian, or Lake Bottom.
Land Cover/Use	Percent of watershed that is Developed, Agricultural Land, Forested, Storage, or Low Vegetation.
Hydrologic Soil Group	Percent of watershed that is classified as either A, B, C, or D soils by the State Soil Geographic database (STATSGO) (NRCS 2016).
Representative Slope	The estimated slope from STATSGO soil data.

Bedrock geology units, surficial geology units, and land cover types were grouped into categories and the percent cover of each category was defined for the 8,274 watersheds. Tables 8 and 9 in Appendix A summarize the categorization of surface geology and land cover types. Information for bedrock geology classification and grouping is provided by the USGS Mineral Resources On-Line Spatial Database, https://mrdata.usgs.gov. Variable selection and categorization produced a dataset of 8,274 samples (watersheds) by 34 variables.

Analysis: A Principle Component Analysis (PCA) was performed to find linear combinations of variables that captured the maximum variation across Maine watersheds (Harris 2001). The methodology of a PCA can be represented as:

$$\begin{aligned} PC_1 &= l_{1,1}X_1 + l_{1,2}X_2 + \ldots + l_{1,n}X_n = \boldsymbol{X l_1} \\ PC_2 &= l_{2,1}X_1 + l_{2,2}X_2 + \ldots + l_{2,n}X_n = \boldsymbol{X l_2} \\ &\vdots \\ PC_n &= l_{n,1}X_1 + l_{n,2}X_2 + \ldots + l_{n,n}X_n = \boldsymbol{X l_n} \end{aligned} \quad [4]$$

where *PC* is a principal component, *X* is a variable, and *l* is a loading or weight applied to a variable as a coefficient when calculating the principal component. Weights are defined for each variable in order to maximize the total variation while requiring that the squares of the coefficients involved in any PC sum to one. As PCs are defined for as many variables as are used in the analysis, each successive PC explains less variation in the dataset.

In finding principal components which maximize variation, the analysis is sensitive to differences of scale between variables. Variables with larger values are more likely to be identified as principal components. For this reason, variables were translated to normalized z-scores (each data point was transformed to represent the number of standard deviations it appeared from the mean value of the variable). Following PCA analysis, the Rule N-criterion was used to determine which principle components to retain (Lipscomb 1998; Preisendorfer et al. 1981). This technique compares the resulting PC eigenvalues, which define the variance described by each principal component, to PC eigenvalues derived from analysis of a random data matrix of equal dimensions (i.e. the 8,274 samples by 34 variables). Principal components are only retained if the ratio of $\frac{PC_{actual}}{PC_{random}}$ exceeds one, that is, the PCs are only retained if they describe more variance in the actual dataset than they would in a random dataset.

A k-means cluster analysis was performed to identify GRUs across the study region. A k-means cluster analysis is an iterative multivariate technique used to identify natural groupings in data by minimizing Within Cluster Sums of Squares (WCSS) relative to k user specified points (Crawley 2012; Harris 2001; SAS Institute Inc. 1985; Sokal and Rohlf 1995) (Figure 3). The principal components retained based on the Rule-N criterion, and their scores, were used in the analysis to describe watershed characteristics in place of the original variables.

Identification of the most suitable k user specified points often relies on a priori knowledge of the dataset population and/or underlying causes that might drive natural groupings within the data. The associated complexity of geomorphic data defining watershed conditions causes ambiguity for determining the number of k points used in this cluster analysis. Therefore, to identify the most suitable number of k points for categorizing these watersheds, cluster analyses were run with a range of k points from two to fifty. For each of these analyses the variation in the data explained by clustering was analyzed (Equation 5):

$$\frac{BCSS}{TSS} \quad [5]$$

where BCSS is the Between Cluster Sums of Squares and TSS is the Total Sums of Squares. BCSS is the sum of squared residuals for the k-points relative to the cluster mean, and TSS is the sum of squared residuals of all data points from the mean of the entire dataset. As the number of k-points increases, the clusters describe more variance in the dataset, and this ratio approaches one. When this ratio equals one, the clusters describe all the variance in the dataset because the number of k-points, or clusters, equals the number of samples (i.e., watersheds). As the number of clusters increases the results become less significant for the original purpose of finding a small number of clustered watersheds that behave similarly. Sum of squares values within clusters can be analyzed relative to the number of clusters to identify "natural breaks" and identify a suitable number of k points.

Considerations were also made for the non-deterministic nature of a k-means cluster analysis. The outcome of this analysis can be variable due to the stochastic nature of the "starting locations" of the k points, although the variability of the outcome decreases as the within cluster sums of squares increases. To reduce some of the uncertainty associate with this component of the analysis, the final cluster analysis using the selected number of k-point was performed 10,000 times. Of these 10,000 runs, the analysis that produced the highest $\frac{BCSS}{TSS}$ (i.e. described the most variation of all the runs) was selected to describe Maine GRUs.

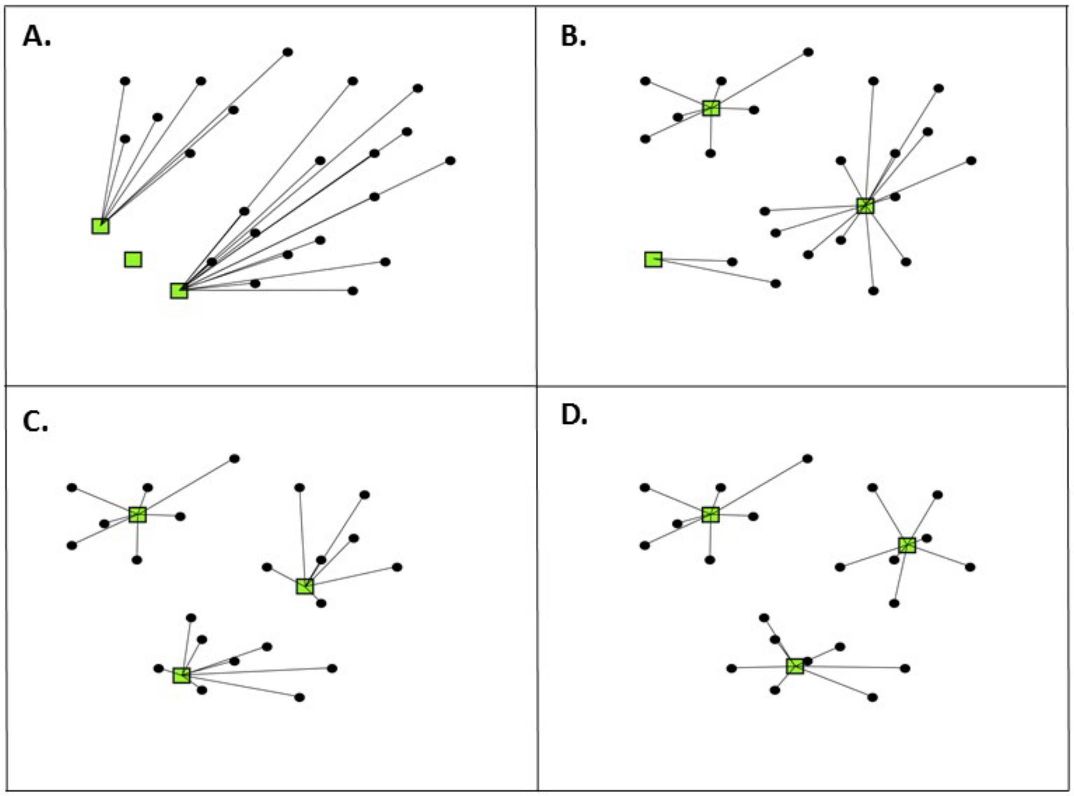

Figure 3: Example of the iterative procedure for a k-means cluster analysis in two dimensions, where k equals 3 user specified clusters. A through D are sequential representations of iterations.

2.3.2 Hydrologic Characterization

Data Collection: Hydrograph flow records from USGS monitoring stations located in Maine were used to characterize flow conditions relative to geomorphic settings. USGS stations were selected based on two criteria: 1) The availability of a continuous flow record from 2010 to 2016; and 2) A drainage area less than 100 km^2, ten times the average size of the drainage divides used in the GRU analysis. These criteria were used to limit the influence of climate variation and to minimize the influence from multiple GRUs on a discharge time series. Fourteen stations that met these criteria were used in the analysis (Table 2).

Table 2: USGS monitoring stations from which hydrograph analyses were performed and the corresponding sensitivity function results.

Name	**USGS ID**	**Contributing Area (km^2)**	**Sensitivity Function**
East Bear Brook	01022294	0.11	1.01
Otter Creek	01022840	3.50	1.43
Ducktrap River	01037380	37.29	0.88
Libby Brook	01021470	20.18	1.10
Branch Brook	01069700	27.71	1.13
Stoney Brook	01063310	2.10	0.88
Old Stream	01021480	75.37	0.81
Kennebunk River	01067950	69.15	0.95
East Branch Wesserunsett River	01048220	50.50	0.93
Black Stream	01031510	67.34	0.81
Pearce Brook	01018009	20.69	0.95
Williams Brook	01017550	9.89	1.22
Hardwood Brook	01017060	14.76	1.23
Sandy River	01047200	65.53	1.11

Analysis: Analysis focused on the sensitivity parameter, k, that describes the sensitivity of discharge in a stream to changes in storage within a landscape (Kirchner 2009). A large k indicates less storage and a smaller k indicates more storage. An example of this is shown in Figure 4. The steeper recession limb associated with watershed A (red), indicates that this watershed has less storage than watershed B (black).

The sensitivity parameter can be solved for by starting with a simple water balance:

$$\frac{dW}{dt} = P - ET - Q \qquad [6]$$

where W is storage, t is time, P is precipitation, ET is evapotranspiration, and Q is discharge. Using the linear reservoir theory, discharge can be defined as a function of storage.

$$Q = f(W) \qquad [7]$$

Through differentiation and substitution, we can define discharge over time as:

$$\frac{dQ}{dt} = \frac{dQ}{dW}\frac{dW}{dt} = \frac{dQ}{dW}(P - ET - Q) \qquad [8]$$

The relation can then be rearranged to derive the sensitivity parameter using only the discharge hydrograph when precipitation and evapotranspiration are relatively small. That is, we can estimate the amount of storage in the watershed using only the hydrograph.

$$k = \frac{dQ}{dW} = \frac{\frac{dQ}{dt}}{\frac{dW}{dt}} = \frac{\frac{dQ}{dt}}{P - ET - Q} = \frac{-\frac{dQ}{dt}}{Q}\Bigg|_{P \ll Q, ET \ll Q} \qquad [9]$$

Periods of the hydrograph during which precipitation and evapotranspiration terms are small were selected by this method. Conditions were assumed to be adequately met when the slope of the hydrograph was negative, an assumption considered reasonable based on the relatively small size of the watershed systems. Through trial and error, averaging the data over a three-hour time step was found to best fit the measurement resolution of the gauge data. Hydrograph slope and discharge at a three-hour time-step were calculated and a power function was fit through the relation. The slope of the power function is the sensitivity parameter describing the water storage properties.

2.4 Results and Discussion

2.4.1 Watershed Characterization

Rule-N criterion of the Principal Component Analysis resulted in the retainment of the first ten principal components. Loadings for PC1, which describe the most variation, are dominated by the contrast between developed and forested landscapes, glaciomarine and till dominated surficial geologies, and well drained soils versus those which are more moderate to poorly drained. These results conform with estimated outcomes based on observations across this landscape. Maine is a predominantly rural state with isolated developed zones along the southern coast near Portland, ME, the largest city in the state. Unlike more populated parts of the U.S.A. that have extensively distributed urban development, the transition from the largely rural land cover conditions to the urban coastal area is one of the strongest transitions affecting watershed conditions in the state.

Another important feature that broadly partitions the state is associated with the marine transgression limit (Borns et al. 2004). The retreat of the Laurentide Ice Sheet approximately 15 Kya was accompanied by the ocean inundation of the Maine coast, causing a thick deposit of marine sediment over areas east of marine transgression (Kelley et al. 1992). The transgression limit that coincides with the extent of

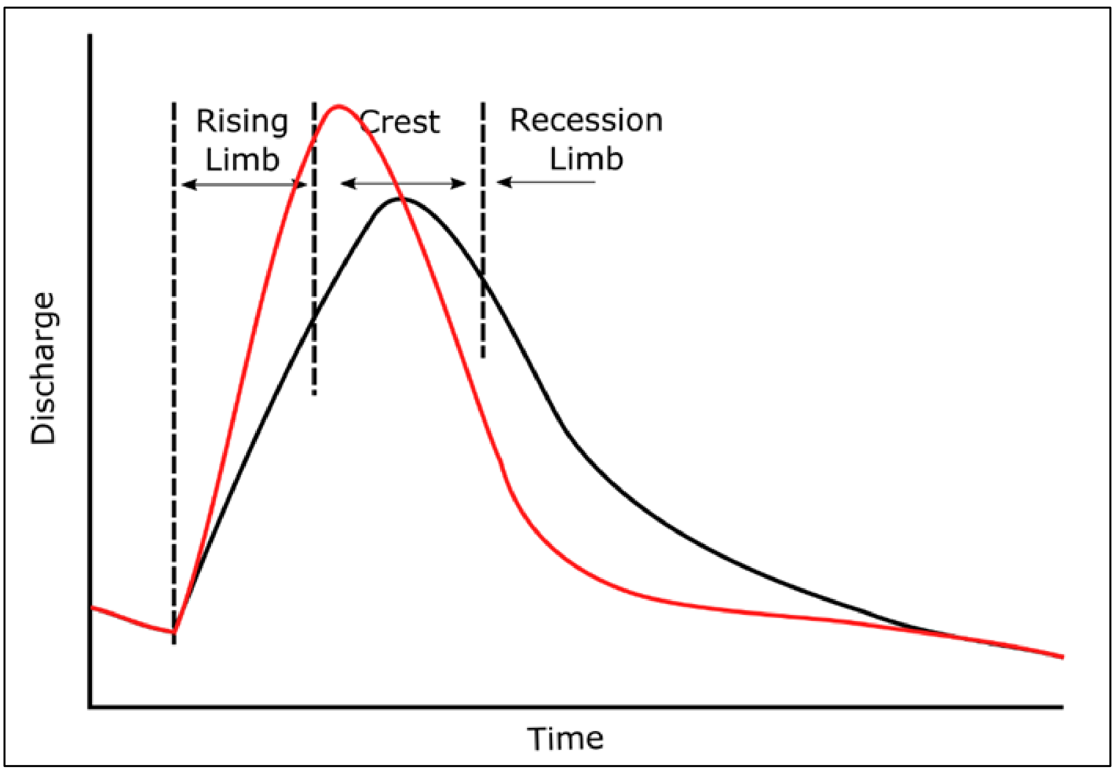

Figure 4: Characteristic hydrographs of a "flashier" system with a high sensitivity function (red) and a watershed with a lower sensitivity function (black). Adapted from Gupta (2008).

widespread marine deposits runs perpendicular to the coast and partitions the state into two distinct regions. In contrast to the coastal marine deposits, regions northwest of the marine transgression limit are predominantly covered by glacial till deposits (Thompson 1985). These distinct surficial geologic conditions provide varied environments for the development of soil conditions, producing extensive distributions of well drained soils in the northwest regions of the state and more poorly drained soils in coastal areas.

Visual analysis of $\frac{BCSS}{TSS}$ indicates a steep rise with increasing k points up to approximately k = 15, at which point the rate of increase was substantially reduced (Figure 5). A k =15 cluster analysis revealed that five clusters contained less than 5% of the watersheds, and one cluster contained less than one percent of the watersheds in the state. These clusters are "outliers", providing rationale to reduce fifteen clusters to nine. The nine clusters explain the variation in watershed characteristics half as well as considering each watershed individually ($\frac{BCSS}{TSS} \sim 50\%$), supporting the choice to proceed with a k = 9 cluster analysis.

Within HUC-12, HUC-10, and HUC-8 watersheds, the cluster at the scale of the drainage divide polygons that covered the greatest area was selected to define each watershed. This spatial averaging across HUC watersheds was done to reduce the number of isolated drainage divides that are characterized by GRUs, i.e. those that are different from the surrounding region. Because of the spatial resolution of the data, it is unclear whether these locations are truly distinct from the surrounding region or are anomalies because of data limitations and spatial averaging. Averaging across HUCs was chosen as a compromise given this uncertainty and the usefulness of HUC based GRUs for providing a more workable framework for watershed management applications. Based on visual analysis and field observations, averaging drainage divide clusters into HUC-10 based GRUs was found to be the most appropriate "grain scale" for identifying GRUs in the state. Averaging into HUC-12 watersheds produced little change, and details from the drainage basins were lost when averaging across the large HUC-8.

The nine defined GRUs across HUC-10 watersheds span a range of conditions that can be broadly categorized by the dominant variables in each unit (Table 3).

Table 3: Attributes defining each Geomorphic Response Unit.

Geomorphic Response Unit	Primary Location	Dominant Attributes
GRU 1	Mid-Coast and Central Region	Metasedimentary bedrock, C soils (poorly drained), and a surficial till
GRU 2	Northern Maine	Clastic bedrock and surficial till
GRU 3	Inland southern Maine	A soils (well drained) and glaciofluvial deposits
GRU 4	Downeast Region	Poorly drained soils
GRU 5	Kathadin Region	C soils (poorly drained) and a moraines
GRU 6	Inland Downeast Region, Lakes Region, and the Appalachian Mountains of Southern Maine	High relief, till, and plutonic bedrock
GRU 7	Mount Desert Island and surrounding area	High relief and exposed bedrock
GRU 8	St. John watershed in Northeastern Maine	B soils (moderately well drained), carbonate bedrock, and agriculture
GRU 9	Southern Coast	Urban development and glaciomarine clay

Figure 5: BCSS/TSS results plotted against the number of clusters for each analysis.

2.4.2 Hydrologic Characterization

Hydrograph analysis of the fourteen USGS gauge stations across Maine suggests a quantifiable geospatial relation between flow characteristics and watershed settings defined by GRUs. Monitoring stations along the coast that are within more poorly drained, developed, and/or higher relief GRUs have higher sensitivity parameter values. These geomorphic settings are more conducive to increased surface runoff, producing flashier flow regimes. These flashier systems are more responsive to precipitation, with quickly increasing flows as rain falls within the drainage area. This contrasts with hydrographs analyzed throughout the central region that have lower sensitivity parameter values. These monitoring stations are situated in GRUs with surficial geologies dominated by till. Till throughout the region is generally well drained, resulting in higher infiltration, less surface runoff, and more storage throughout the watershed system. Transitioning further west, monitoring station hydrographs begin to have sensitivity parameter values more consistent with those along the coast. These monitoring stations have higher relief than the central locations and more agricultural land cover.

These results provide support for the defined GRUs through a quantifiable relation between hydrographs and the watershed characteristics that govern the surface flow of water through these systems. Within the limited extent of Maine, this analysis displays the variability of current flow conditions due to a combination of historic and ongoing landscape modification by humans and geologic processes, both glacial processes on the order of ~15 Kya and endogenic processes on the order 50 to 350 Mya.

2.5 Conclusions

Results indicate that variation across Maine watersheds is most prominently represented by the contrast between developed and forested landscapes, followed by the division between the glaciomarine and the till dominated surficial geology. Watersheds with extensive urban development in Maine's mostly rural landscape are unique and the dissimilarities impact the surface watershed hydrology. Landscape dynamics driven by Maine's glacial history also creates a notable geologic partition along the marine transgression limit. The boundary coincides with a change in the dominant surface materials with well drained till to the Northwest and poorly drained marine deposits along the coast. The partition is the cause of substantial variation in watershed conditions driving surface water flows in the state.

This analysis led to the division of HUC-10 watersheds across Maine's post-glacial landscape into nine statistically distinct GRUs with predictable variations in stream flow conditions. The objective of this research was developed around regional stakeholder concerns about water resource sustainability and vulnerabilities. The quantification and classification of watershed conditions presented here through GRU development provides a basis for stakeholder communities to customize regional watershed management strategies in response to land use and climate changes affecting water quality, aquatic habitat, and other ecosystem services provided by nontidal headwater streams. This information also provides groundwork and an organizing framework for investigations of surface runoff, nonpoint source pollution, and stream channel dynamics that can inform adaptive strategies for water resource sustainability solutions in Maine.

2.6 Acknowledgements

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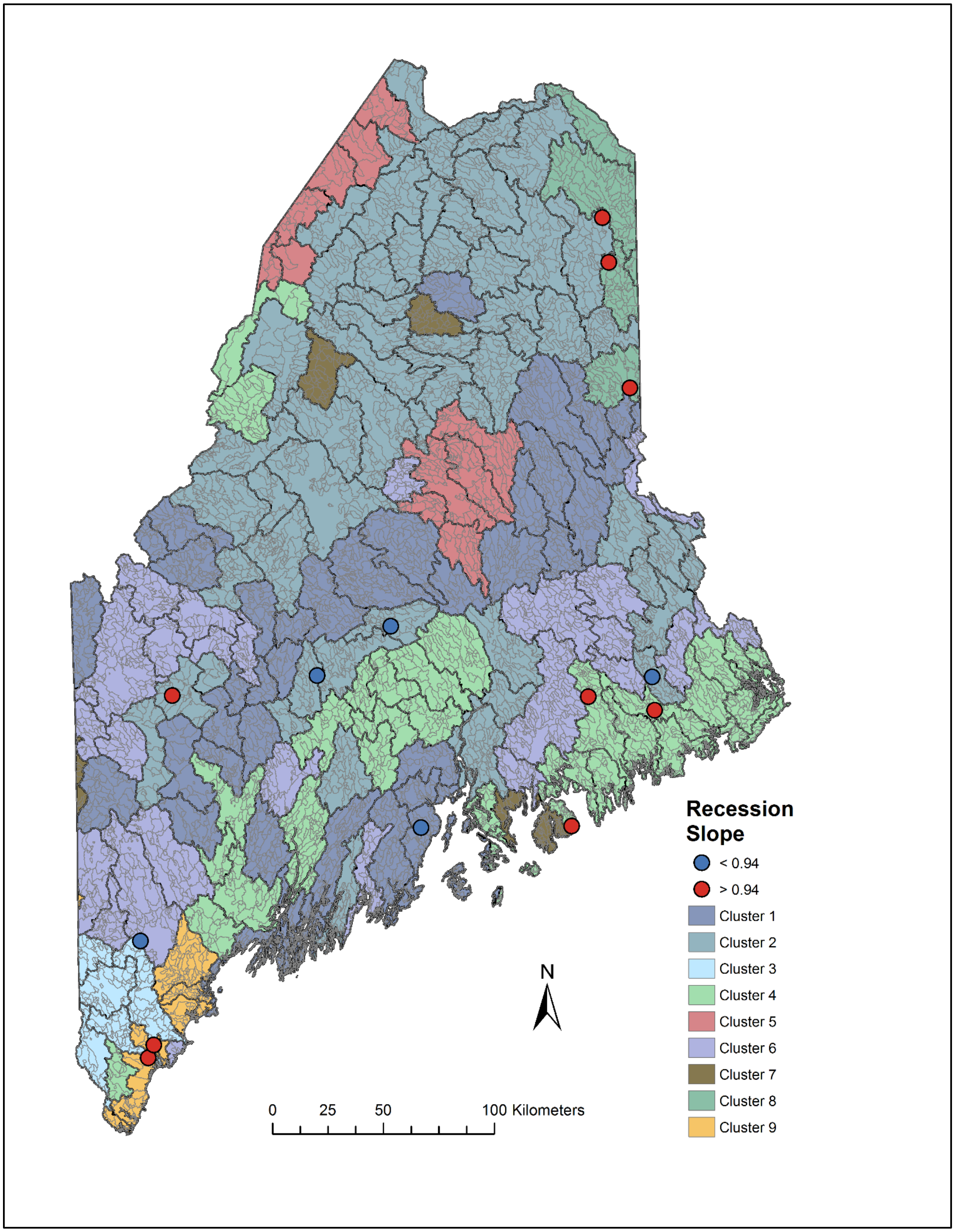

Figure 6: Sensitivity function values for Maine USGS watersheds plotted across GRUs.

CHAPTER THREE

THE HYDROLOGIC SIGNATURE OF NORTHEASTERN HEADWATER BASINS

3.1 Chapter Abstract

This research uses watershed simulations to evaluate the impact of projected climate modifications on hydrologic conditions in three Central and Coastal Maine watersheds, quantifying surface flows in three dominant physiographic settings in the region. A series of watershed hydrology scenarios were developed using climate information derived from the Coupled Model Intercomparison Project (CMIP5) to examine the effects of climate change on snow melt, watershed hydrology, and surface flow regimes within settings represented by the study watersheds. Research objectives were defined through engagement with regional stakeholders and identification of concerns related to water resource sustainability in the region and capacity to respond to problems from forecasted land use and climate changes. Results are framed to address these concerns and to provide information relevant to water resource planning in the post-glacial Northeast (USA) region.

Scenario simulation results indicate a substantial decrease in total snow water equivalent across all watersheds and a shift in the seasonal termination of snow melt ranging from ten to twenty days. The snowpack changes produce alterations in the timing and magnitude of surface flows dominated by snow melt contributions in late winter and early spring months. Surface flow rates during the remainder of the year are generally predicted to increase except where low flows are dominantly regulated by outflows from

surface water storage locations in ponds or wetlands. Low (base) flows are predicted to decrease slightly in locations with relatively high storage capacity due to increased evapotranspiration rates in response to forecasted temperature increases. These modeling outcomes present the range and variability of flow condition modifications the region may experience over the next century. Results from this research provide a basis for regionally and locally focused climate change adaptation strategies in varied post-glacial settings defined by topography, surface geology, land cover, surface water storage, and local climatic conditions.

3.2 Introduction

A river's flow regime is described by patterns of discharge over time, including the magnitude, frequency, duration, timing, and rate of flow change over annual periods of record (Poff et al. 1997). These patterns are governed by the climate, biota, surface geology, and landscape history that govern runoff production (e.g., infiltration rates) and surface flow hydraulic conditions (e.g., hydraulic roughness and surface water storage in ponds and wetlands). Alterations to these conditions produces flow regime modifications, which directly impacts a system's sediment-water proportionality. Increases or decreases in the magnitude or frequency of moderate to high flows can alter sediment transport, leading to channel adjustment and changes in the transport rate of constituents downstream. These modifications present major challenges to water resource sustainability because of the water budget implications to the water supply, the impact of altered transport of constituents to water quality, and the effect of channel morphology dynamics that affect aquatic habitat (Sparks 1995; Ward and Stanford 1995; Poff et al. 1997).

Humans commonly modify flow regimes through direct and indirect changes to drainage patterns and watershed conditions (Poff et al. 1997). Direct modifications include channel straightening, dredging, channelization, damming, and network expansion through the connection of urban storm drain systems to the “natural” drainage system. Indirect hydrologic modifications are produced by land use and cover (LULC) changes, topographic modifications (Jones 2013), and the effects of climate change on stream flows.

Knowledge of the associations between physiographic settings defined by climate and watershed characteristics and surface flow regimes can provide a basis for forecasting the effects of land use and climate changes on aquatic habitat and pollution related to watershed runoff. This research defines these associations to address stakeholder concerns related to instream habitat and downstream water quality. Stakeholders groups engaged within the Lakes Region, Southern Coast, and Mid-Coast settings of Maine (Toppan 1935) highlighted the strong tie between socio-economic conditions and the sustainability of these resources. Increasing development pressure (U.S. EPA 2009) within the predominantly rural and forested Lakes Region is a concern for downstream water quality, particularly in the Sebago Lake watershed that provides municipal water for 200,000 Maine residents (Portland Water District 2012). Within the Southern Coast and Mid-Coast regions, both similar in the greater extent of urban development compared to other parts of the state, the demand to address water resources sustainability is derived primarily from tourism and seafood industries. These industries and local communities are adversely affected by beach closures and water quality problems related to non-point source pollution that result in shellfishing area closures. The demands on these water resources and the uncertainty of non-point source pollution makes these systems high priority locations for coupled climate-landscape-hydrology research in the New England region.

This research supplements previous documentation of decadal time scale changes in surface water resources in the region (Collins 2009). Building on this work, stakeholder concerns are addressed using a distributed numerical watershed model to examine the regional associations of climate, landscape, and watershed hydrology at the century time scale. This approach has previously been utilized in a range of geographic conditions and scales to examine the outcomes of multiple watershed processes and to evaluate a variety of watershed conditions affecting surface water flows (Chu et al. 2013; Sahoo et al. 2006; Wijesekara et al. 2012). The simulations of hydrologic processes governing surface flow rates provides a basis to compare the effects of predicted climate change modifications to aquatic habitat and water quality among dominant watershed settings in Maine.

3.3 Methods

3.3.1 Study Sites

Areas selected for evaluations were chosen based on geomorphic setting and watershed size. Emphasis was focused on quantifying hydrologic conditions in three watersheds that span a range of conditions but are comparable in size. All of the watersheds were modest in size, reducing variability of physiographic and land use conditions, allowing calibration with limited weather data, and requiring decreasing computational requirements over the multiple calibration, validation, and scenario runs.

The Northwest River watershed was selected to represent landscape conditions in the Lakes Region. The Northwest River is a sub-basin of the Sebago Lake watershed. This watershed is the largest of the three study sites with a drainage area of 58 km^2. Like much of the Sebago Region, relief in the watershed is modest, and the bedrock is predominantly associated with the Sebago pluton. The watershed's surficial geology is dominated by till deposits, although wetland deposits cover large areas in the center of the watershed (Thompson et al. 1985). Characteristic of the region, numerous lakes and ponds are present, producing a large storage signature in the hydrology and water budget. Land cover throughout the watershed is predominantly rural with pockets of higher development along the lake perimeter.

The Webhannet River watershed sits along the Southern Maine Coast, covering 27 km^2 of mostly low relief terrain. The area is moderately developed (~11%), much of which is concentrated along the coast, and has a long history of human interventions. The surficial geology of the watershed is predominantly composed of marine clays and sands (Smith 1999a; Smith 1999b) corresponding to its location east of the line of marine transgression.

The Cromwell Brook watershed is in Mid-Coast Maine on Mount Desert Island, just outside of Acadia National Park. The watershed is ~18 km^2 and has moderate to high relief. The location is dominated by the presence of shallow granites with thin or absent soils. It is moderately developed (19%, mostly outside of Acadia National Park), and much like the Webhannet River watershed this development is concentrated along the coast.

Climatic conditions in the three watersheds are similar, although coastal areas are affected by maritime climate conditions (Jacobson et al. 2009; Vose et al. 2014). Between 1895 and 2007 the central Maine region received an average of 114 cm of precipitation annually and the average annual temperature was 6.19 °C (National Climate and Data Center). The Coastal Region received slightly more precipitation during this period, 118 cm annually, and was slightly warmer, 6.83 °C. In the winter months most precipitation falls as snow in all physiographic sub-settings. Southern regions experience earlier seasonal melts and generally smaller total annual snow water equivalent. Snowpack melting in the late winter and early spring month produces seasonally predictable and sustained high flow conditions called the "freshet" (Hodgkins et al. 2003).

3.3.2 Model Parameterization and Calibration

The distributed watershed modeling platform, MIKE SHE, was parameterized for all three watersheds using a combination of literature, spatial data, and field measurements (Table 4). The computational approaches for various phases of the water cycle included lumped and distributed approaches based on available data, data quality, and data resolution. These approaches are standardized for all watershed simulations (Figure 9). Domain resolutions were variable and based on the contributing areas for the basin monitoring sites. The resolution of both the Cromwell Brook and Webhannet River watershed models was 30m^2 while the Northwest River model resolution was 50m^2. Models were calibrated using a multi-objective approach; The primary objective was the matching of observed and modeled discharge, the secondary objective was the matching of observed and modeled snow water equivalent, and the third objective was to evaluate modeled water budget components relative to expected values.

Observed flow data in the Northwest River watershed was recorded by collaborators near the confluence of the Northwest River and Sebago Lake (Reeve et al. 2013). A pressure sensor was deployed to continuously measure water flow stage at 15-minute intervals that was converted to a surface flow time series based on a rating curve assembled from periodic manual discharge measurements (Rantz 1982a, 1982b). The rating curve derived for the site was tested and verified by the deployment of an Acoustic Doppler Profiler (Sontek-IQ) from mid-2015 to mid-2016. This instrumentation provided continuous automatic discharge measurement comparison with recorded stage measurements from the deployed pressure transducer. These methods produced nearly five years of flow data from mid-2011 to early 2017.

Acoustic sensors (Teledyne ISCO, Submerged Probe Flow Module 720) were deployed within the Cromwell Brook mainstem from mid-2015 through 2016. Construction activities in Cromwell Brook in mid-summer 2016 disturbed the latter portion of the dataset. Data was recorded at 10-minute intervals and coupled with periodic manual flow measurements to develop rating curves, the same methodological approach that was applied at the Northwest River.

The third study location, the Webhannet River watershed, was also monitored using instrumentation deployed in the Webhannet River and a tributary, Depot Brook. Periodic flow measurements were collected to construct rating curves. Hydraulic measurements and time series data indicate that flows at these two locations can be correlated with a

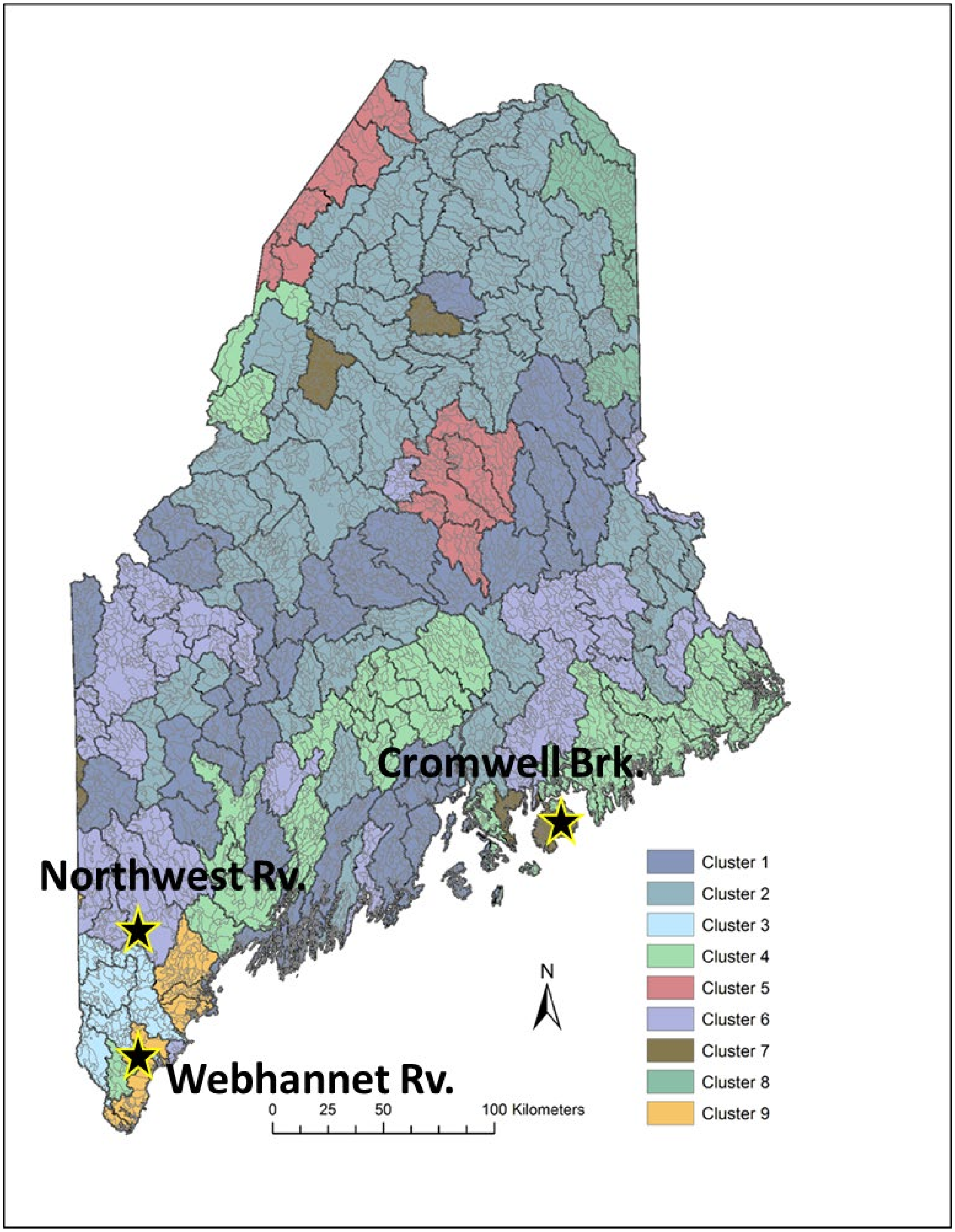

Figure 7: Location map of watersheds respective of Maine GRUs.

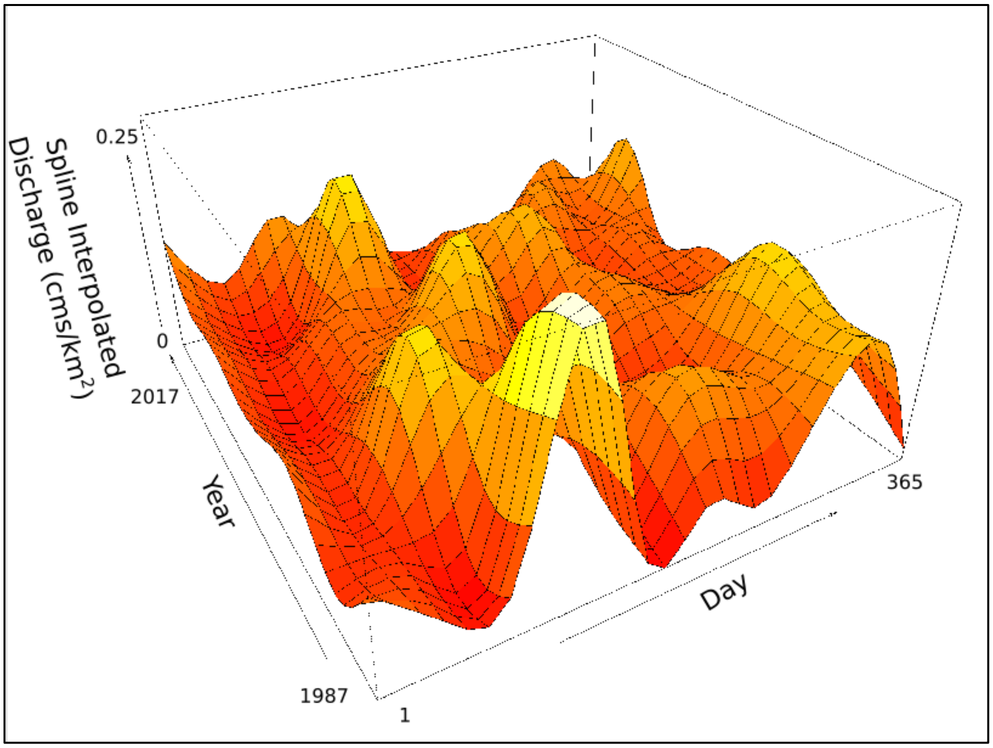

Figure 8: Hydrologic signature for the Northwest River. This presents the characteristic flow regime structure for the river system over the ten-year period of "current conditions."

nearby USGS gauge station (Kennebunk River, USGS 01067950) using standard approaches for flow normalization by drainage area (Gupta 2008). This approach produced continuous flow time series for the Webhannet River and Depot Brook from 2012 through 2016.

All watersheds and river monitoring sites were dominated by ice over conditions in winter months. These conditions limited flow measurements for approximately three months each year, resulting in less reliable flow data between December and March. Observed flow datasets were omitted from the datasets during this time from all monitoring stations for this reason.

Evaluation of model accuracy relied on multiple lines of evidence from a combination of statistical measures to include the Nash-Suttcliffe Efficiency criteria (NSE), Percent Bias (PBIAS), and the Root Mean Square Residual (RSR). NSE is a dimensionless, normalized statistic that compares the residual variance of a simulation dataset relative to the observed (measured) data variance (Moriasi et al. 2007; Nash and Sutcliffe 1970). NSE values vary between negative infinity and one, with lower values indicating a poorer fit, zero indicating a fit that would be achieved through assuming the average observed value at each time step of the dataset, and a value of one indicating a perfect fit between the model and observed data. NSE can be expressed as:

$$NSE = 1 - \frac{\sum_{t=1}^{n}(O_t - E_t)^2}{\sum_{t=1}^{n}(O_t - \bar{O})^2} \quad [10]$$

where O_t and E_t are the observed and predicted discharge at time t, respectively, and $\bar{O}$ is the average observed discharge.

PBIAS is an error index which measures the tendency of a model to over or underpredict relative to the observed dataset (Gupta et al. 1999; Moriasi et al. 2007). A PBIAS of zero indicates no bias in the modeled data set, while negative values indicate persistent over prediction and positive values indicate underprediction. PBIAS is expressed as:

$$PBIAS = \frac{\sum_{t=1}^{n}(O_t - E_t) * 100}{\sum_{t=1}^{n}(O_t)} \quad [11]$$

RSR is the ratio of the Root Mean Square Error ($RMSE$) to the standard deviation of the observed data ($STDEV_{obs}$). The form of this statistic differs from the NSE only in that the square root of both the numerator and denominator are taken, making the RSR less influenced by the correct or incorrect prediction of large values in the time series. The RSR ranges from 0, which is optimal, to positive infinity. RSR is expressed as:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{t=1}^{n}(O_t - E_t)^2}}{\sqrt{\sum_{t=1}^{n}(O_t - \bar{O})^2}} \qquad [12]$$

Acceptable values for these parameters vary relative to the research objective, but generally NSE > 0.5, RSR < 0.6, and PBIAS < ± 15 are considered satisfactory (Moriasi et al. 2007). Depending on the ultimate use of the model as well as data availability and associated uncertainties, higher values may be necessary or lower values may be acceptable.

Total snow water equivalent was evaluated using the same objective parameters. Simulated snow pack was evaluated in comparison to observed measurements made by the Maine Cooperative Snow Survey (Maine River Flow Commission), which takes monthly measurements at stations across the state. Point measurements made within the study watersheds were averaged over the entire domain of the corresponding watershed. Simulated water budget values were also compared to statewide estimates derived in previous investigations (Caswell 1987; Dudley, Hodgkins, and Nielsen 2001; Gupta 2008; NOAA; Stewart et al. 2004).

3.3.3 Climate Scenarios

Future climate scenarios were based on projections from Phase 5 simulations of the Coupled Model Intercomparison Project (CMIP5) using the Intergovernmental Panel on Climate Change's (IPCC) A1B conditions (IPCC 2007a, 2007b; WCRP 2014). The A1B emission scenario represents rapid economic growth with the global population peaking mid-century and declining thereafter. This scenario includes rapid introduction of new and more efficient technologies balanced across all sources.

For each of the twenty CMIP5 simulations, precipitation and temperature were averaged across the state. Simulated monthly conditions during the last 30 years (1987- 2017) were compared to simulated monthly conditions between 2070 and 2100. Using the minimum, median, and maximum simulated monthly changes, five scenarios were created utilizing a "delta method" approach (Hamlet et al. 2010; Prucha et al. 2011). This method evaluates the range of possible climate change scenarios. However, it is limited in that it does not account for modifications in storm frequency or duration, nor does it account for any changes to the sequence of weather patterns in the study area. The "control" condition representative of the current climate was based on observed precipitation and temperature in Augusta, Maine (44.3188° N, 69.7955° W). This location was selected based on its approximately central location to all three study watersheds. The "delta method" scenarios involved systematic adjustment of this precipitation and temperature data for each month of record.

Table 4: Data sources for watershed model parameters.

Data	Primary Sources	Application
Precipitation	NWS Southern Regional Headquarters Hourly Precipitation Analysis	Averaged across the watershed at 1hr intervals and applied uniformly.
Temperature	Local stations in Wunderground network	Uniform application based on nearest stations hourly data.
Topography	LiDAR from Maine Office of GIS (MEGIS)	2m resolution bare earth digital elevation model was used to define watershed topography.
Manning's M (Roughness)	Wijesekara et al. 2012	Values are defined respective of land cover.
Leaf Area Index (LAI)	NASA's Moderate Resolution Imaging Spectro-radiometer (MODIS).	Values were averaged respective of land cover using data from 2007 to 2010.
Rooting Depth (RD)	Literature Review: (Schenk and Jackson 2002)	Values were averaged per land cover.
Soil	USDA SSURRGO Dataset	Soil properties were averaged per soil texture.
River Network Extent	National Hydrography Dataset (NHD)	NHD networks were used to define the river network extent with some modification based on LiDAR or field observations.
River Network Geometry	Dudley 2004	Regional hydraulic geometry relations were used to estimate channel geometry with some modifications based on field observations.

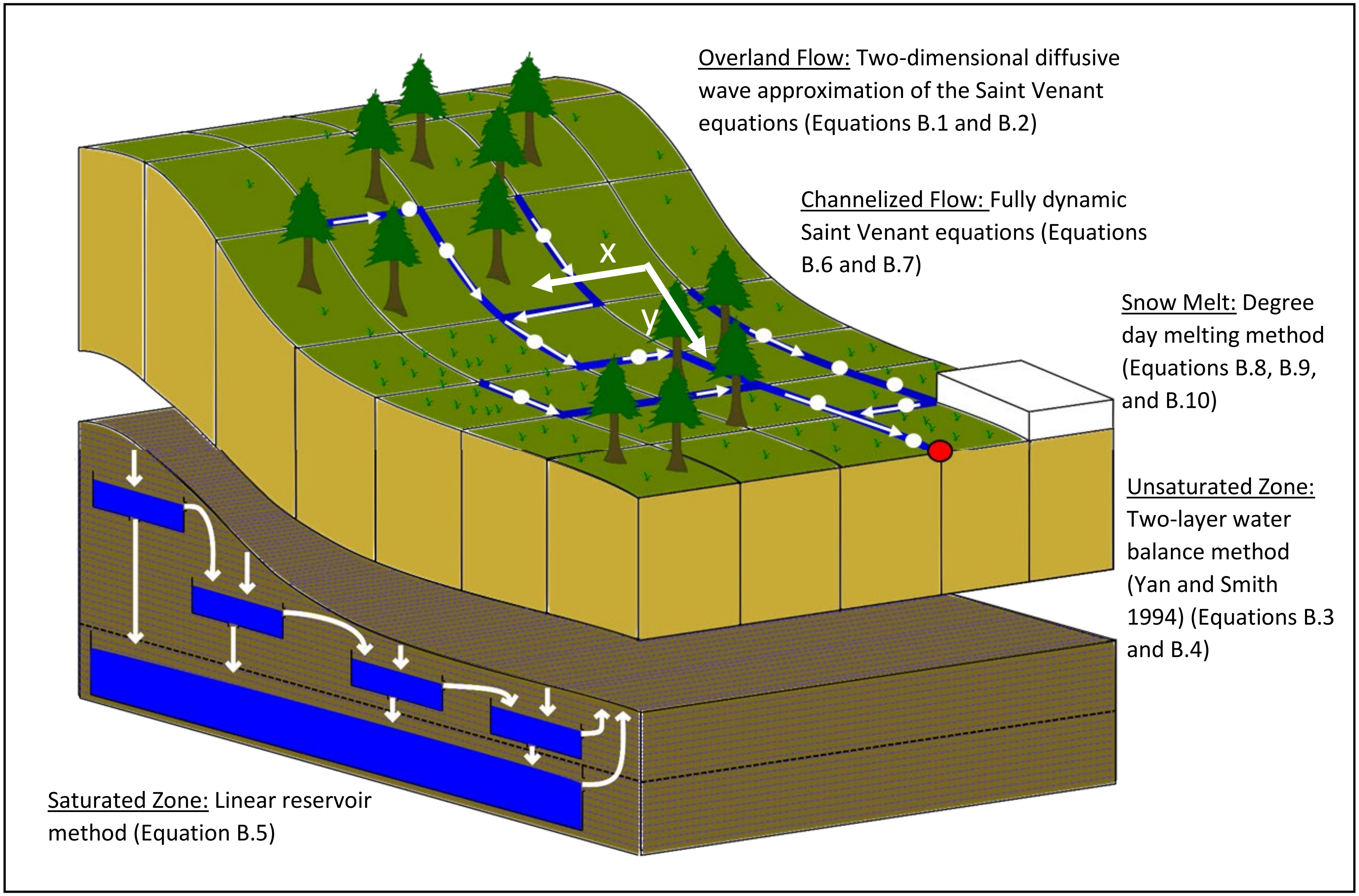

Figure 9: Diagram of the MIKE SHE model platform and the associated principles used to calculate the movement of water for various process.

Table 5: Summary of scenario conditions developed from CMIP5 projections used in the hydrologic simulations.

Scenario	Description
0	Current climate conditions
1	Median temperature (T_50) and median precipitation (P_50)
2	Minimum temperature (T_Min) and minimum precipitation P_Min)
3	Maximum temperature (T_Max) and minimum precipitation (P_Min)
4	Maximum temperature (T_Max) and maximum precipitation (P_Max)
5	Minimum temperature (T_Min) and maximum precipitation (P_Max)

Potential evapotranspiration was specified for each scenario based on simulated temperature values. No adjustment was made to the parameterization of land cover (i.e. change in vegetation), leaf area index, or rooting depth due to limited knowledge of how vegetation distributions might shift under varied climate conditions. Changes in climate will affect the vegetation and ultimately hydrology, but the coarse resolution of the land cover and vegetation parameters rationalize the use of static estimates in the simulations.

3.4 Results and Discussion

3.4.1 Calibration Results

Each model was manually calibrated following a preliminary, exploratory sensitivity analysis to evaluate model response to selected hydrologic simulation functions. Climate and water discharge datasets for the Northwest and Webhannet Rivers were split into calibration and validation time periods, however, the shorter flow record within the Cromwell Brook watershed was prohibitive to this approach. Primary optimizing parameters (saturated hydraulic conductivity, degree day coefficient, and time constants for interflow and baseflow) were incrementally adjusted until the models performed acceptably for both snow water equivalent and river discharge (Table 6 and Figures 30-

32 in Appendix B). Uncertainties associated with water discharge measurements, limited resolution of snow pack estimates, and spatial variability of precipitation and temperature estimates affect evaluations of model performance.

3.4.2 CMIP5 Analysis

Analysis of the CMIP5 simulations indicated an increase in temperature across all months of the year (Figure 10). These climate simulations indicated a 2 to 3 °C rise across Maine, which is in line with previous analyses of CMIP3 simulations across Maine (Jacobson et al. 2009). Increased temperature projections appear most pronounced during the winter and fall months and less so in the spring and summer. Simulated changes in precipitation differ across the seasons, but there is a general increase. Winter and spring months are forecasted to experience the largest increase in precipitation, and moderate increases are forecasted for summer and fall months with a slight decrease in August and September.

Table 6: Calibration statistics for the modeled watersheds.

Watershed	Metric	NSE	PBIAS	RSR
Northwest River Watershed	Northwest River Discharge	0.64; 0.55	4.65; 1.56	0.60; 0.67
	Snow Depth	0.43; 0.65	-32.41; -22.74	0.76; 0.6
Cromwell Brook Watershed	Cromwell Brook Discharge	0.64; NA	4.34; NA	0.6; NA
	Snow Depth	0.51; NA	18.45; NA	0.7; NA
Webhannet River Watershed	Webhannet River Discharge	0.63; 0.45	8.19; -22.43	0.6; 0.74
	Depot Brook Discharge	0.63; 0.51	8.77; -22.3	0.61; 0.70
	Snow Depth	0.85; 0.65	-5.15; -21.92	0.38; 0.59

3.4.3 Watershed Scenario Analysis

Flow duration curves were used to compare simulated scenarios for each monitoring site (Figure 34 in Appendix B). Subtracting the current surface flow rate values from flow rate values produced by Scenario 1 illustrates patterns of response to climate change forecasts in the region (Figure 11). Surface water flow changes can be partitioned into low flow (80- 100% exceedance probability), moderate flow (20- 80% exceedance probability), and high flow (0- 20% exceedance probability) adjustments.

Simulated low flow discharge rates are predicted to increase within the Webhannet River and Depot Brook watersheds. The simulated increase in baseflow is a direct result of the scenario-imposed precipitation increase. This increased precipitation is accompanied by increases in temperature and evapotranspiration, which leads to a slight decrease in the very low flow conditions within Northwest River and Cromwell Brook. The effects of increased evapotranspiration are more pronounced within these systems because of the greater volume of surface water storage. Examining the water balance reveals that scenario 1 predicts a 2.5% increase in evapotranspiration within the Webhannet River, 7.5% increase in the Northwest River, and 6.5% increase in Cromwell Brook. In the Webhannet River watershed, low flows are dominantly supplied by groundwater and not as effected by the predicted increase in evapotranspiration.

Moderate flows within all three systems are predicted to increase as a results of Scenario 1 climate change conditions. These predicted increases in moderate flow rates are produced by rainfall events that are modest in depth and intensity compared to historic records. During these events, precipitation outpaces evapotranspiration and the effect of increased temperature is minimal. The magnitude of change is greatest in Cromwell Brook, followed by the Northwest and Webhannet Rivers and Depot Brook. This order correlates with the total surface water storage in each system. These lakes and ponds are continuously at or near capacity and have limited ability to dampen downstream flows, acting instead as flow through systems able to sustain these simulated moderate flows. As these medium sized storms move through the watershed systems, the Great Meadow in the Cromwell Brook Watershed and the many lakes and ponds throughout the Northwest River fill above capacity and then slowly drain, producing these moderate flows at that increase in magnitude with increasing storm intensity.

High flow conditions in all three systems are driven by spring snow melt and/or large, intense summer storms. CMIP5 analysis predicts that summer precipitation will minimally increase and simulations in all three watersheds indicate a consistent and substantial decrease in total snow water equivalent. Accordingly, high flow conditions appear to remain the same in the Webhannet River watershed, and slightly decrease in the Northwest River watershed and the Cromwell Brook watershed.

Simulations of snow water equivalent in the Webhannet River produced a unique result as compared to the Northwest River and Cromwell Brook watersheds. Observed snow water equivalent in the Webhannet River watershed was comparably less and melted earlier in the year, likely influenced by the Southern Coastal Maine setting. The calibration procedure and observed snow dynamics indicate a lower significance of snow melt contributions to surface flows. Instead, high flows are more related to summer storms compared to the other watersheds. High flows in the Webhannet River and Depot Brook are predicted to experience less change under simulated climate conditions for this reason. The effects from climate change remain important in those settings, however, because small changes to the flow regimes can result in large changes in stream water discharge volumes and sediment transport.

The Northwest River watershed and the Cromwell Brook watershed experience a some decrease in peak flows under Scenario 1, a result coupled with reduced snow pack and warmer weather. However, simultaneous increases in coastal low-pressure systems resulting from climate change conditions could alter this outcome. A limitation of the CMIP5 simulations is that they do not account for changes in the frequency of these low-pressure storm systems moving into the study region from the Mid-Atlantic or Northern Atlantic Ocean. These weather systems can produce thunderstorms, tropical depressions, tropical storms, and hurricanes that produce high stream discharge events.

All of the examined watersheds are predicted to experience a decrease in total snow water equivalent (Figure 12). The magnitude of change is larger for the Webhannet River watershed, but the pattern of snowpack depletion is similar across all three locations with a median change for Scenario 1 between 60- 70% of current conditions. This is a substantial change in total snow water equivalent resulting from increased temperatures expected through CMIP5 simulations. It should be noted that the delta method does not account for any change in temperature variance (e.g. warmer days but nighttime temperature remaining nearly unchanged) which may change total snow water equivalent.

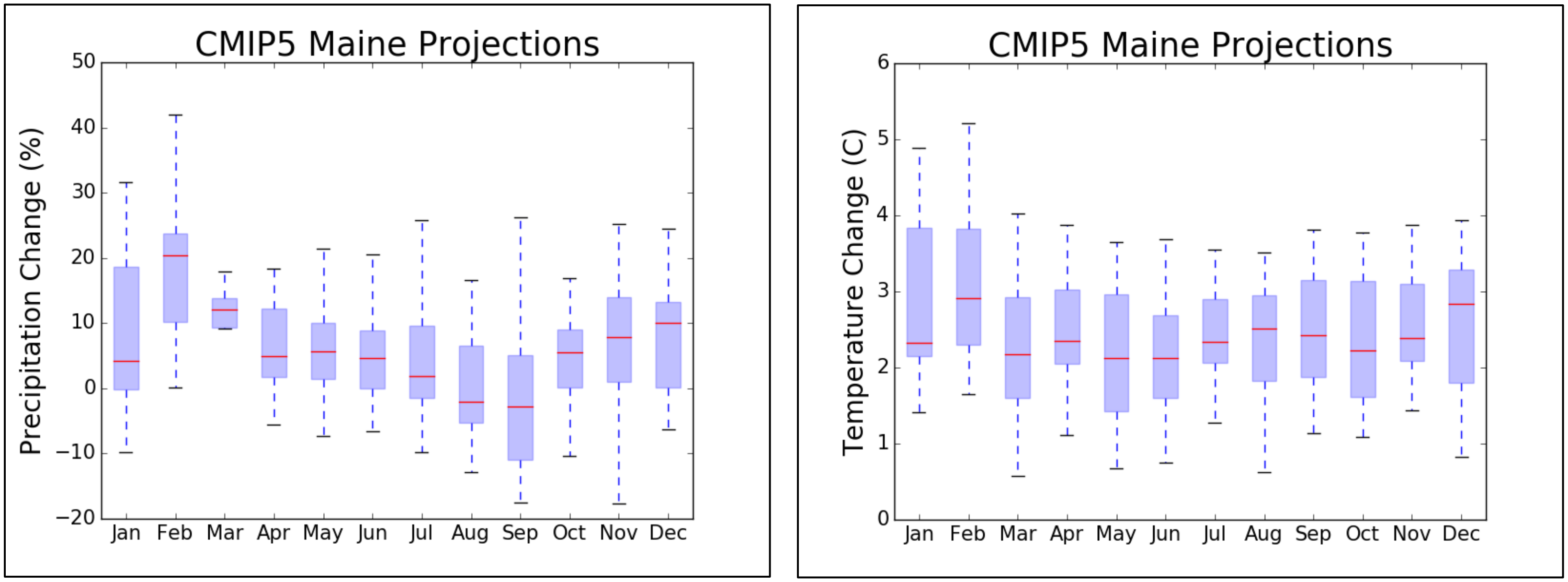

Figure 10: CMIP5 projections of Maine's future climate conditions, comparing current modeled conditions (1985 – 2015) to future modeled conditions (2070- 2100).

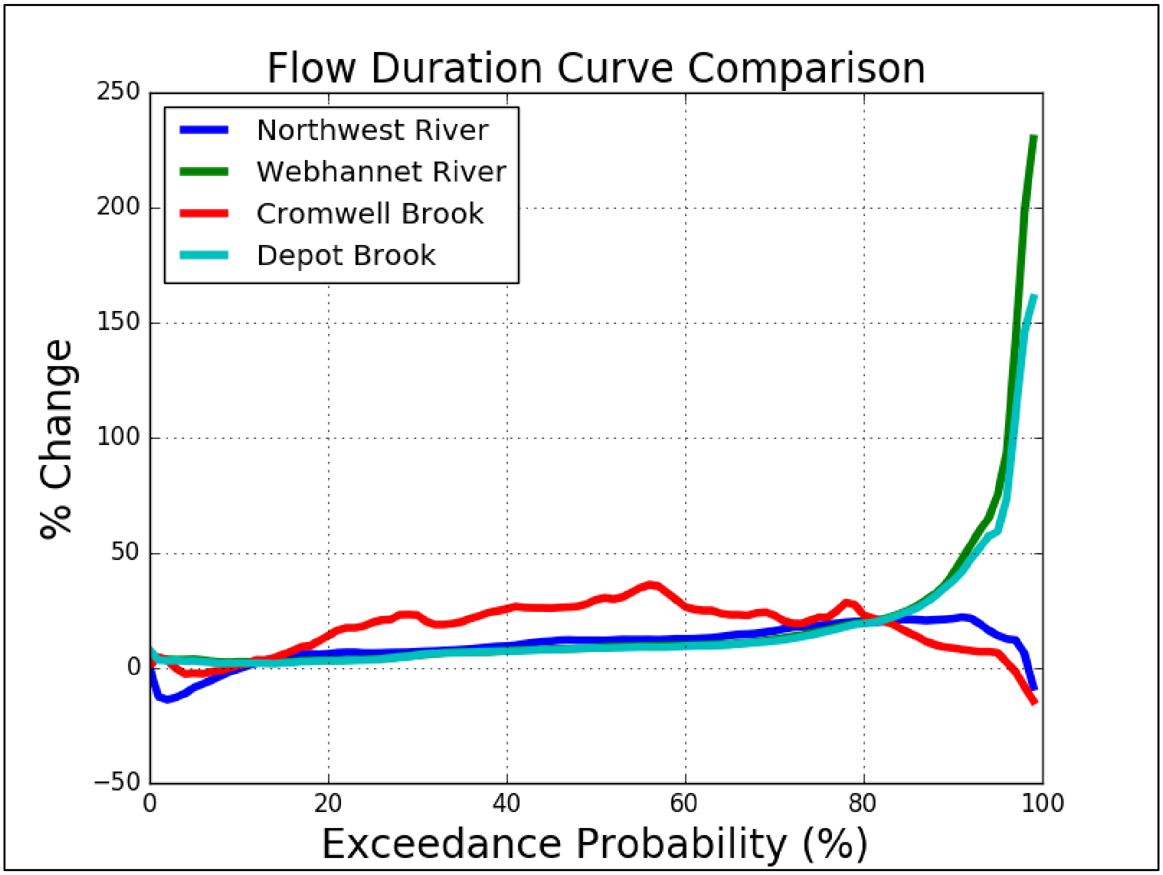

Figure 11: Flow duration curve percent change comparisons between current conditions and Scenario 1 (median change in temperature and precipitation) for the Webhannet River, Depot Brook, the Northwest River, and Cromwell Brook.

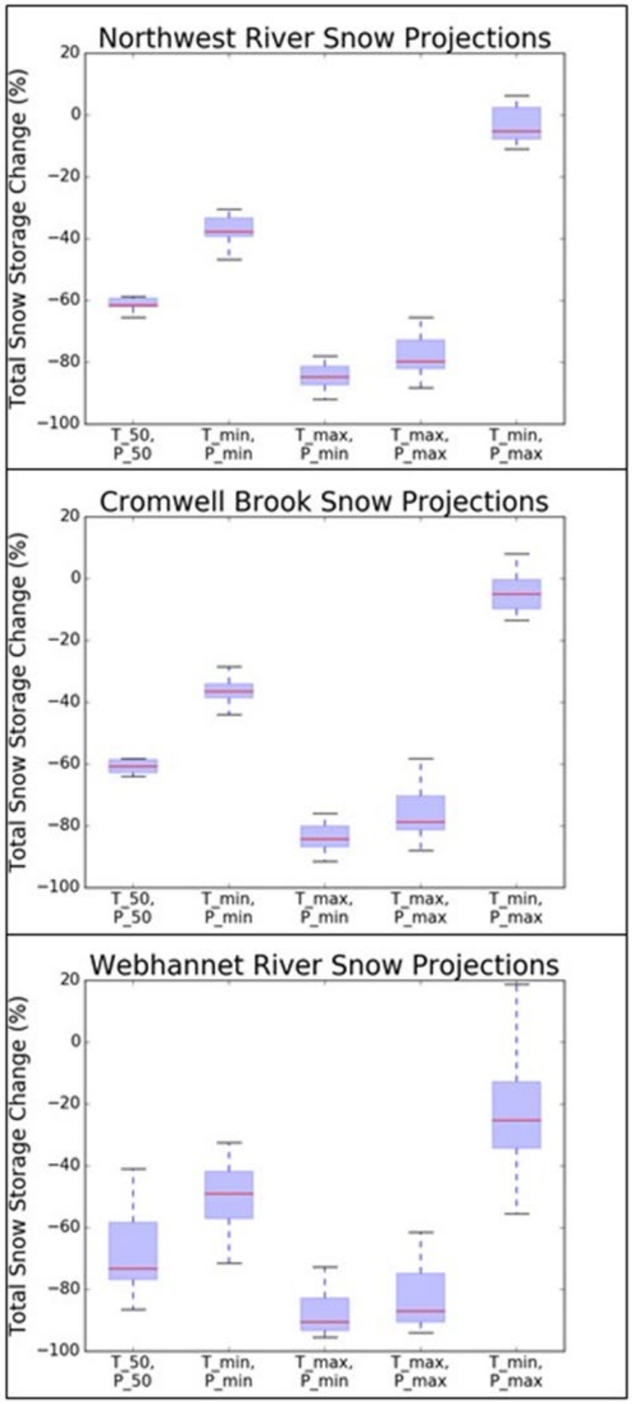

Figure 12: Box and whisker plot presenting the yearly change in total snow water equivalent.

Reduced total snow water equivalent is accompanied by a reduction in the number of days snow is present in the landscape, and the timing of the freshet is consistently earlier in the year (Figure 13). The simulated increases in temperatures produce similar patterns in snow melt timing across all three watersheds, with the largest change occurring in the Webhannet River watershed. Once again, this is a result of the differing snow conditions along the southern coast of Maine in comparison to the Lakes Region and Mid-Coast. Based on the median expected shift in temperature and precipitation from CMIP5 simulations, these model results indicate a potential shift in the timing of snow melt termination of between 10 and 20 days for the Central and Coastal Maine region.

The combined outcome of the projected climate conditions is a shift in the characteristic flow regime for the three watersheds (Figure 14). The most prominent change to the flow regime is a shift in the seasonally high flows resulting from the melting of the winter snow pack. Scenario 1 climate conditions result in these seasonally high flows occurring earlier in the year, and throughout the remainder of the year we see less change, although some decreases in flow are more notable in the Northwest River system (Figure 14).

3.5 Conclusions

The parameterization and calibration of three Coastal and Central Maine watershed models provided a tool for the examination and comparison of climate change conditions in varied watershed settings. Although hydrologic simulation results have limited ability to predict future conditions with high accuracy, the results describe the magnitude and characteristics of stream flow regime alterations linked to climate conditions. The

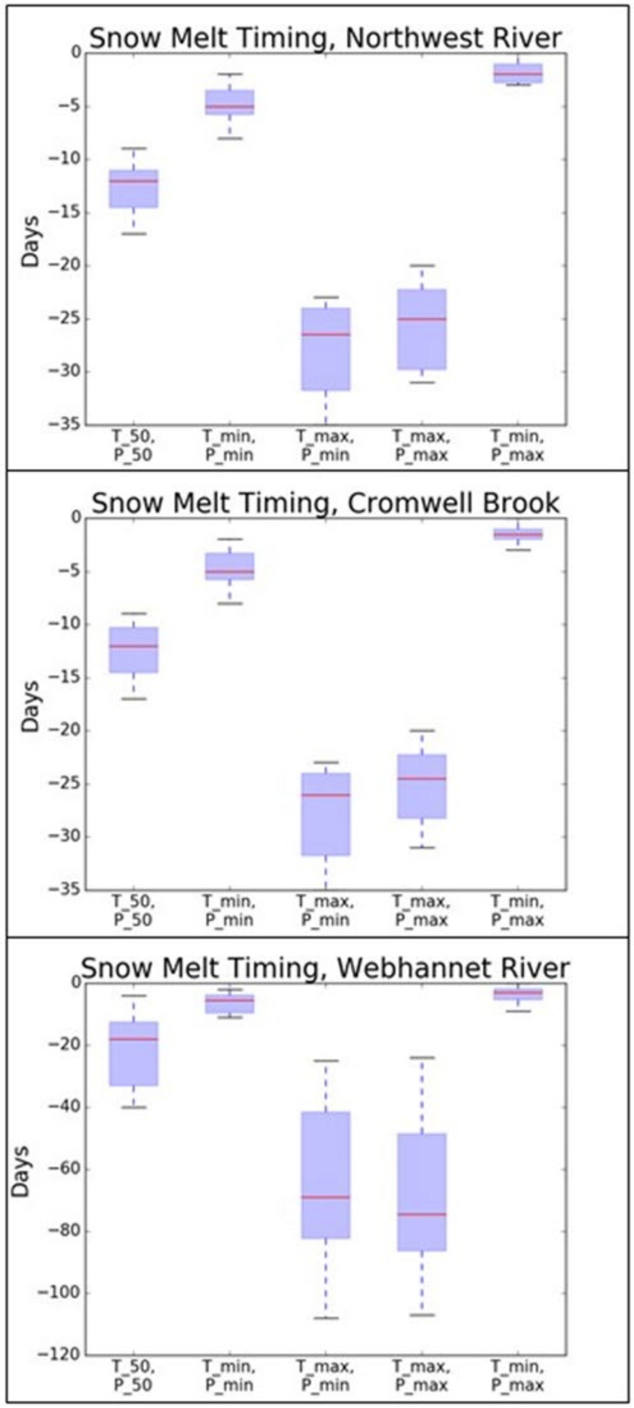

Figure 13: Box and whisker plot presenting the change in timing of yearly snow termination.

analytical outcomes quantify how surface flow patterns associated with climate change forecasts vary relative to the collection of watershed processes controlling watershed runoff production and routing. Although some generalizations can be made in the region, the varied responses predicted from the simulations show how the effects from climate change effects will differ relative to local watershed conditions in the Northeast. The observations highlight the varied vulnerability of stream system and associated biophysical-ecological processes to the effects of climate change. Localized responses of stream systems will be dependent on the physiography, landscape history, human activities, surface water resource management activities, and modern land uses.

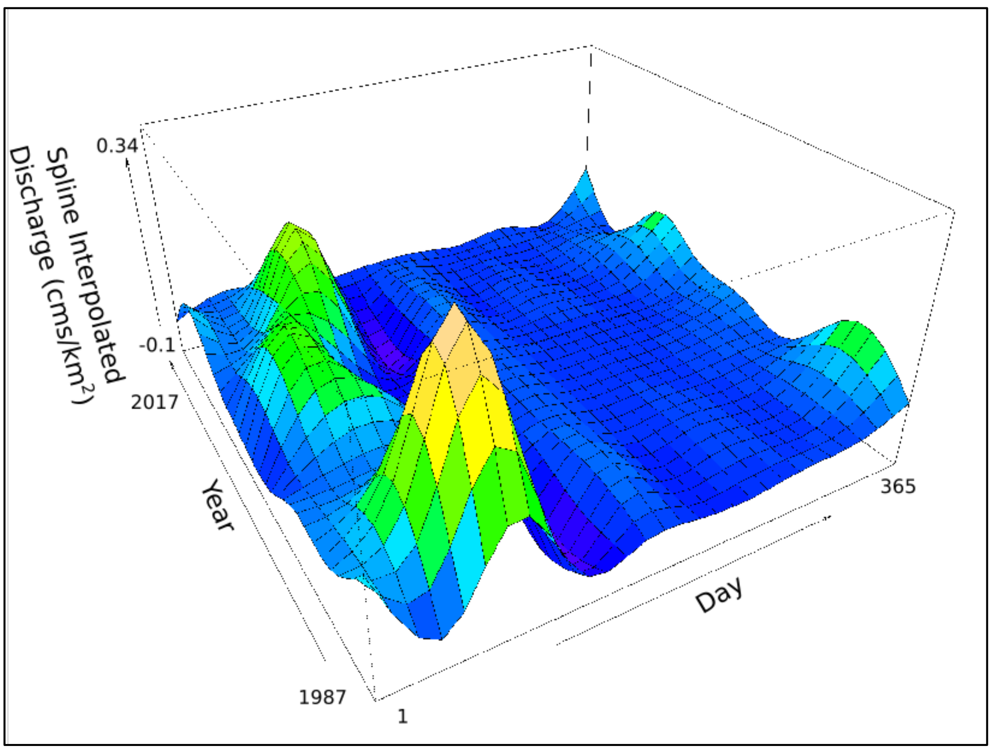

Figure 14: Hydrologic signature for Northwest River representing the change in timing and magnitude of flow between current conditions and Scenario 1 (median precipitation and temperature change).

CMIP5 climate simulations indicate a continuing increase in annual temperature and increases in winter, spring, and fall precipitation over the next century. The forecast conditions shift the total average snow water equivalent and snow melt timing. Total snow water equivalent decreases and the timing of snow melt occurs ten to twenty days earlier in the year. This causes the characteristically high spring flows to change in terms of timing (earlier) and magnitude (lower), supporting similar results found through historical analysis by Hodgkins and Dudley (2006). Other flow regime modifications resulted from increased precipitation and evapotranspiration with variability related to upland water storage capacity.

The findings suggest that biophysical-ecological process closely tied to snowpack and snowmelt processes are the most vulnerable to climate change in the region. The observed relevance of surface water storage to stream flow conditions highlights that drainage routing dynamics in lakes and ponds should be an important consideration when deciding where and how water resource sustainability efforts should be focused. The potential effects of surface water storage in the landscape increases moderate flows but appear to "buffer" the highest of flows, suggesting that locations downstream of these features may be less vulnerable to scour from high flow events resulting from projected increases in runoff from altered precipitation and snowpack inputs.

The research outcomes provide a foundation for identifying a strategy for surface water resource management in the post-glaciated Northeast region. The predicted changes to flow regime have important implications to ecosystem services provided by natural waterways that govern water quality conditions (Arthington et al. 2010). Changes to surface flow regime will alter terms in the sediment-water proportionality governing stream system dynamics and nonpoint source pollutant transport into large rivers, lakes, and estuaries in Maine. Results from this work suggest that water resource management strategies should consider the local physiographic and land use conditions.

3.6 Acknowledgements

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CHAPTER FOUR

NORTHEASTERN HEADWATER STREAM BED DYNAMICS UNDER VARIED CLIMATE CONDITIONS

4.1 Chapter Abstract

The geomorphology of Northern New England is a product of geologic, glacial, and anthropogenic processes operating over a range of time scales. Better knowledge and information about the impact of these processes, particularly the effects of human activities, on the physical condition of modern stream systems is necessary for the development of watershed management and restoration strategies. Research on coupled human-climate-stream systems in the region is limited despite the importance to sustainability solutions for surface water quality and aquatic habitat problems. Information gaps persist on headwater stream channel dimensions and dynamics in varied settings of Maine even though they compose the majority of drainage network lengths.

This project responded to the information gap by focusing on headwater stream hydraulics and geomorphology in fluvial systems of variable landscape characteristics across Central and Coastal Maine to support the development of watershed management decision tools. Research results improve characterization of upland stream channel dimensions and expand the capacity to predict stream responses to physiography, land use, and climate changes. Comparison of upland channels to those in lowland “alluvial” valley settings improves information customizing management responses to multi-objective stream management and engineering problems.

The analyses describe and quantify regional relations between in-channel conditions and watershed processes linked to deglaciation processes, land cover, and human activities in the region. The approach combines field measurements of stream channel dimensions with surface flow time series derived from watershed hydrologic simulations in multiple settings defined by relief, surficial geology, and land uses. Hydraulic geometry measurements describing upland channel dimensions are compared to predictive geometry measurements derived from previous measurements of lowland stream channels in the region (Dudley 2004).

The analysis shows relatively greater variability in upland channel dimensions compared to streams in lowland valleys that were measured by others to develop predictive relations. Predictive hydraulic geometry relations developed from streams set in lowland valleys differ minimally from those in upland settings but do generally under-predict the dimensions of upland streams surveyed as part of this project. The difference in the hydraulic geometry relations indicates the operation of a unique set of processes governing stream dimensions in modern upland and lowland settings.

Analyses of channel bed sediment transport using sediment grain size measurements, upland stream channel dimension data, and surface flow time series derived from watershed simulations provide another means to evaluate stream responses to watershed and climate conditions. Watershed hydrology simulations included climate change scenarios to compare stream responses to forecasted conditions impacting stream flows in the region. Sediment bedload transport analyses indicated changes which varied across watershed settings and climate conditions. Streams receiving flows from watersheds with relatively low surface water storage capacity responded with a measurable increase in sediment mobility, and a decrease in mobility was detected in stream reaches downstream from locations with relatively large amounts of surface water storage capacity. Overall, the results present the range of stream system responses to forecasted climate changes and demonstrate the relevance of watershed conditions to those responses.

4.2 Introduction

Surface runoff dynamics and the supply of sediment in the modern topography of Maine are influenced by the historical advance and retreat of the Laurentide Ice Sheet approximately 15 Kya (Borns Jr et al. 2004). The conditions of the modern landscape partly defined by this glacial history govern the sediment-water proportionality within watersheds across the region. The competence of surface flows to transport the relatively large clast sizes deposited during deglaciation of the region and now observed in stream channels is inadequate, resulting in a low frequency of sediment transport events in many drainage network locations (Snyder et al. 2009). The capacity of headwater stream flows is also often high relative to the supply of fine sediment in the landscape due to mechanical erosion of regolith by glacial processes. Local conditions exhibit some inconsistencies with these regional characteristics where glacially derived landforms such as eskers produce locations of elevated sediment supply. The region also exhibits a prominent transition in surficial geology related to the submergence of the eastern portion of Maine as the Laurentide Ice Sheet retreated (Borns et al. 2004). This marine transgression produced a till dominated surficial geology in central and inland portions of the state and a marine dominated surficial geology with finer grained sediment along the coast. These conditions have created both localized and regional variations in the supply of sediment to streams.

Modern drainage network conditions in the region are additionally a product of subsequent European colonization of the region starting in the early 1600's (Maine Historical Society 2014). Colonization introduced large-scale and small-scale industrial activities (e.g. agriculture, forestry, mills, etc.) that involved physical alterations to streams and river valleys (e.g. run-of-the-river dams, splash dams, and channelization of stream channels, etc.) (Allen 2013). These activities further impacted Maine's watershed systems by indirectly changing the supply of water and sediment. Many of the physical effects from these activities are less apparent today, but their impacts on the modern drainage network persist.

These activities occurring over a range of time scales define the sediment-water dynamics of the landscape and govern modern stream dimensions, slope, water discharge, and sediment load. Channel conditions are responding to the balance between the sediment supply and stream flow capacity to transport that supply through a reach given the associated hydraulic conditions (Lane 1955) (Figure 1 and Equation 3). This relation is described by the proportionality given by Henderson (1989):

$$q_s D^{\frac{3}{2}} \propto (qS)^2 \qquad [13]$$

where *D* is sediment size, *S* is channel slope, and q_s and q are the sediment transport rate per unit width and discharge per unit width, respectively. Rearranging Equation 13 expresses the relation of q_s, q, and D to changes in channel dimensions through aggradation or degradation over time $(\frac{S_1}{S_2})$ (Wilcock et al. 2009):

$$\frac{S_1}{S_2} = (\frac{q_{s2}}{q_{s1}})^{\frac{1}{2}}(\frac{q_1}{q_2})(\frac{D_2}{D_1})^{\frac{3}{4}} \qquad [14]$$

Stream dynamics driven by the sediment-water proportionality are of significant interest to multiple stakeholders in the region, particularly as they relate to future conditions and responses to watershed land use and climate changes. A prominent focus is the sustainability of in-stream habitat and downstream water quality because of the association with ecosystem services. Examples of sustainability solutions to related problems include stream restoration projects, multi-objective stream culvert designs, stormwater management for control of surface water discharge rates, and the management of nonpoint source pollutants such as sediment and nutrients.

The research summarized here examines the modern sediment-water dynamics governing stream channel conditions and evaluates the effects of forecasted climate changes to provide information and decision tools in support of modern stream system management challenges in the Northeast. This research leverages the conventions developed to quantify channel hydraulic geometry (Leopold and Maddock 1953) and builds on more recent regional observations describing channel conditions in Coastal and Central Maine watersheds by Dudley (2004). Existing channel geometry information derived from measurements by Dudley (2004) in lowland streams is compared to new measurements collected from headwater streams, providing valuable information for water resource management applications such as stream restoration and culvert design in upland headwater drainage networks. Sediment dynamics within headwater stream systems under projected climate conditions are examined to quantify the impact of altered flow conditions on channel hydraulics and dynamics. The analyses of dynamics focuses on sediment transport in varied landscape settings, examining the magnitude and spatial variability of future adjustment to predicted discharge time series. The outcomes inform and guide implementation of water resource management strategies in locations that have been impacted by modern human interventions or that are vulnerable to forecasted climate change effects on watershed surface runoff.

4.3 Methods

4.3.1 Data Collection

Geospatial data was assembled, and channel measurements were collected from 45 stream reaches within five watersheds in Central and Coastal Maine. These watersheds are the Sebago Lake watershed in the Maine Lakes Region (n = 34), the Webhannet River watershed along the Southern Coast (n = 6), the Cromwell Brook watershed in Mid-Coast Maine (n = 3), the Damariscotta Estuary watershed between the Southern Coast and Mid-Coast (n = 1), and the Bear Brook watershed in the Downeast Region of Maine (n = 1). Stream measurements included topographic surveys of channel cross sections and water surface slopes at baseflow conditions. Pebble counts were conducted to estimate bed grain size distributions (Wolman 1954) and corresponding watershed drainage areas were estimated using digital elevation data from available online sources (Maine Office of GIS 2017).

Headwater stream reaches in the study watersheds were selected to consider a range of stream conditions described by channel dimension (size), profile (slope), bottom sediment composition (grain size), riparian corridor conditions (vegetation), watershed conditions (land cover, soils, and topography), and history of disturbance from humans (e.g., presence of dams and culverts). These primary data collection sites were coupled and compared to information from previous investigations by the USGS (Dudley 2004) and results from the Instream Flow Incremental Methodology (IFIM) evaluations in the region (Kleinschmidt 1999a, 1999b).

4.3.2 Hydraulic Geometry

Hydraulic geometry addresses the fundamental relations between discharge, flow velocity, and channel dimensions in alluvial settings (Leopold and Maddock 1953). The relations can be expressed for a single station over a range of discharge rates (and corresponding flow stages) with an "at-a-station" geometry approach; or, for multiple stations representing upstream to downstream increases in bankfull discharge and corresponding flow dimensions with progressively larger contributing drainage area. The relations are expressed as the following functions with either approach:

$$w = aQ^b \quad [15]$$

$$d = cQ^f \quad [16]$$

$$v = kQ^m \quad [17]$$

where Q is streamflow, w is channel width, d is channel depth, v is flow velocity, and a, c, and k are derived coefficients, while b, f, and m are derived exponents. Because discharge is a function of cross section area (depth × width) and velocity, the exponents of these relations sum to one and the product of the coefficients equal one.

Downstream hydraulic geometry was evaluated relative to the channel bankfull dimensions, boundaries of which are determined in the field using features such as the top of the bank, outer edges of point bars, depositional deposits (benches), and/or changes in substrate and vegetation (Williams 1978; Harrelson et al. 1994). The relations were evaluated longitudinally in portions of drainage networks traversing through upland hillslopes sculpted by glacial processes and lowland alluvial valleys with floodplain deposits. At-a-station relations were defined using a meta-data analysis incorporating primary survey sites and four IFIM study sites from larger streams. Because of incomplete flow records for many of these locations, this research used a modified approach to examine at-a-station geometry focused on the ratio of the channel width to depth as a function of discharge or drainage area (DA).

$$\frac{w}{d} = j(DA)^r \qquad [18]$$

While this relation does not fully express how a channel accommodates increasing flows at a given cross-section, principally because it does not consider stream flow velocity, it does provide useful information regarding channel shape, dimensions, and the relative change in channel width and depth as flows increase at a cross-section.

4.3.3 Sediment Entrainment Frequency

Observations suggest that rates of sediment transport in the study region are generally low compared to non-glacial landscapes of the U.S.A. (Leopold et al. 1995; Snyder et al. 2009; Wilcock et al. 2009). Much of the sediment that is transported in the Central and Coastal Maine landscape is dominated by bedload with a majority of the grains moving along or near the streambed. Suspended and wash loads transported within the water column are a less significant portion of the total load in the region (Leopold et al. 1995; Wilcock 2009). The dominance of bed-material transport is largely driven by the limited supply of fine material resulting from limited fine-grained regolith in the landscape following the most recent advance and retreat of the Laurentide ice sheet (Ferwerda et al. 1997). For this reason, this research focuses specifically on bed-material transport.

Channel bed dynamics in coarse-bedded stream systems similar to those in Maine are largely controlled by the initiation of motion of the surface layer (Wilcock and Crowe 2003). This is because the vertical sorting of bed sediments produces a surface layer coarser than the substrate, causing high rates of transport be associated with movement in the surface layer. The approach used here is thereby focused on the flow competence problem to evaluate the frequency of bed material motion.

Incipient motion conditions, at which bed material becomes mobile, was evaluated from sediment transport calculations. Incipient motion conditions were considered to have been met once a small fraction, 1%, of the sediment quantile's mass was transported in one unit (minute) of time. The discharge at which these conditions were met or exceeded was compared to current and projected flow conditions from previous research (Chapter 3). Calculations were made for the Northwest River, Webhannet River, Cromwell Brook, and Depot Brook.

At each location and for each climate scenario flow condition, fractional transport rates of sediment within each grain size range (phi interval) were calculated using the surface-based Wilcock and Crowe (2003) (Equation 19) transport model implemented through the Bedload Assessment in Gravel-bedded Streams (BAGS) program:

$$W_i = \frac{\tau_g}{\tau_{rsg}} (\frac{D_{sg}}{D_i})^{\chi} \quad [19]$$

where W_i is the dimensionless fractional transport rate, τ_{rsg} is the reference shear stress for the mean grain size, D_{sg} is the mean grain size for the gravel portion of the bed, and χ varies relative to grain size ratio D_i/D_{sg}. The use of this surface-based model decreased the logistical difficulties of sub-surface sampling, particularly in deeper rivers, and its explicit treatment of sand is well suited for the sandy nature of many streams throughout the study region.

Calculated transport rates were compared to channel geometry measurements, measurements of channel bed sediment composition, and modeled flow conditions to estimate the frequency at which the D_{50} (median), D_{16}, and D_{84} grain sizes in each stream are mobile, the latter two of which represents the smallest and largest portions of the measured grain size distributions. The mass of each sediment quantile (i.e. D_{16}, D_{50}, and D_{84}) was estimated within a unit length of each stream using the observed channel width, the sediment distribution, an estimated depth equal to the sediment quantile's value, and the density of granite (2.65g/cm^3).

4.4 Results and Discussion

4.4.1 Hydraulic Geometry

A log-log plot of drainage area versus channel slope shows a visual inflection of the relation at approximately 1 km^2 for primary and secondary study sites (Figure 15). Montgomery and Buffington (1997) presented a similar inflection in this relation at approximately the same drainage area for mountain streams of the western USA, suggesting that this presented the transition from threshold to alluvial channels. Field observations generally support the occurrence of stream channel transitions from threshold to alluvial channels at drainage areas of approximately 1 km^2 in Maine. However, the primary driver of the relation and inflection in the trend may be unique to the Maine landscape and related to processes associated with landforms created by glacial advance and retreat in the region.

Field measurements of bankfull channel dimensions generally conform to downstream geometry relations developed on larger, lowland channels in the Central and Coastal Maine region (Dudley 2004). However, while the previously published relations provide reasonably accurate predictions of geometry in the largest channels of our dataset, the relations result in progressively greater under-prediction of channel width and depth with smaller contributing drainage areas. Under-prediction is most observed for channel depth (Figure 16). Observations of low sediment supply in the landscape lead to the assumption that the hydraulic geometry of the upland headwater channels can be attributed to the imbalance between sediment supply and flow capacity, producing incised channels that do not recover from erosion events through subsequent infill with new sediment from upslope sources.

At-a-station geometry calculations reveal a gradual transition from more confined, v-shaped channel conditions to more unconfined, rectangular shaped channels with increasing drainage area (Figure 17). Results also indicate that headwater streams exhibit much greater variability in channel shape. Localized structural (geologic) controls and

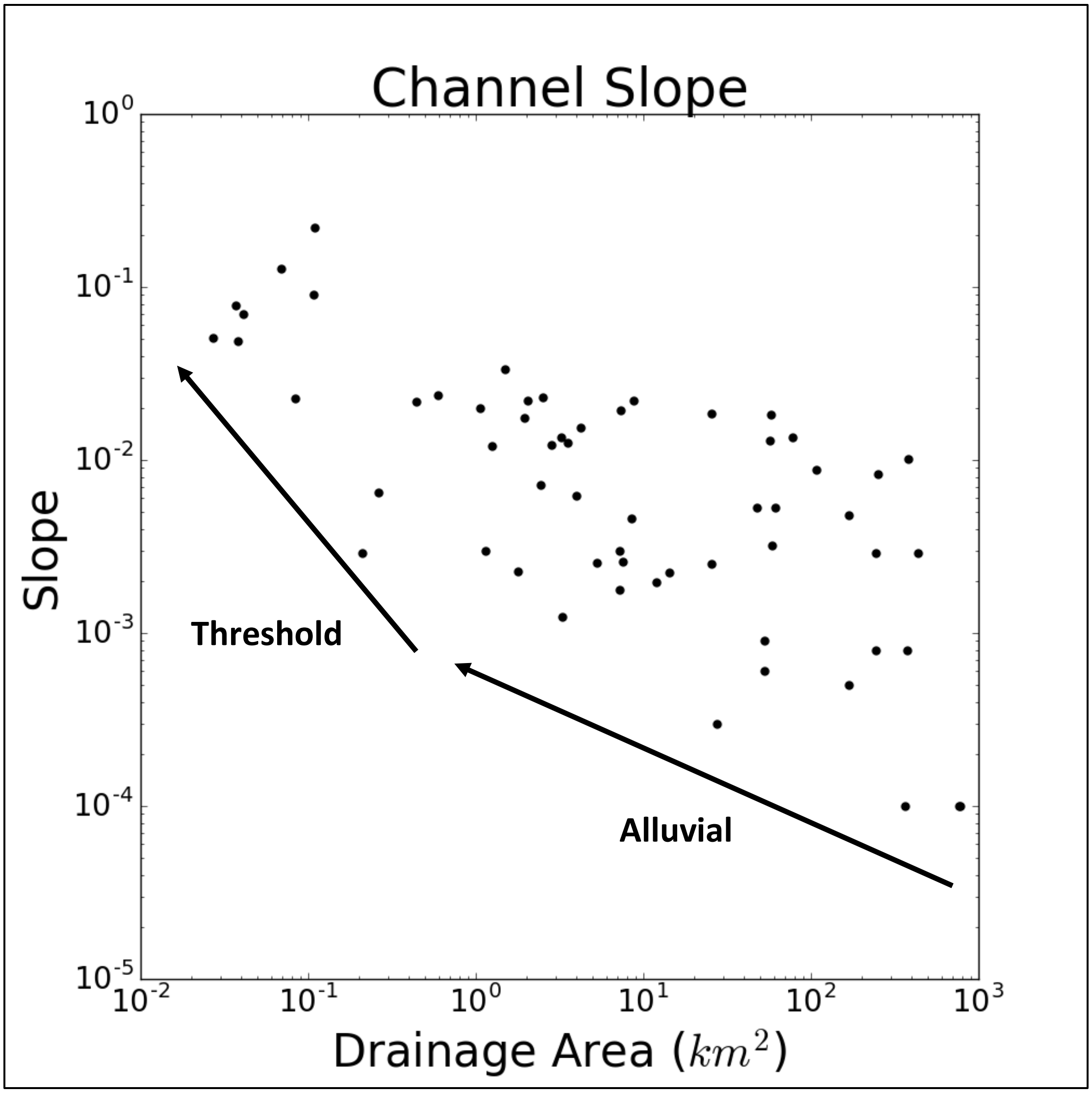

Figure 15: Channel slope plotted against drainage area for study sites investigated in this research and locations from previous channel research in the Central and Coastal Maine region (Dudley 2004).

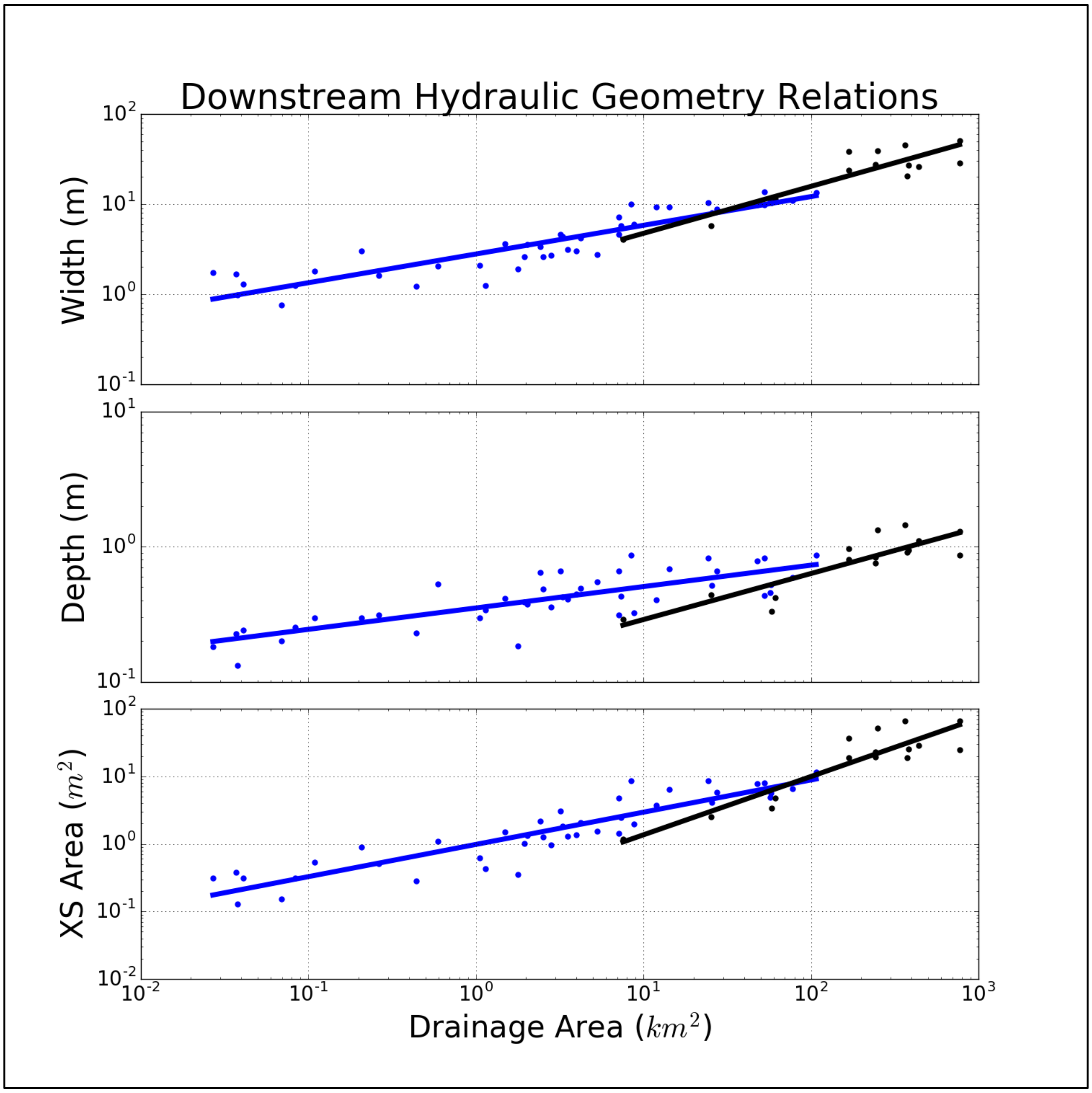

Figure 16: Downstream hydraulic geometry relations from this study, in blue, plotted against previous results from the region, in black (Dudley 2004).

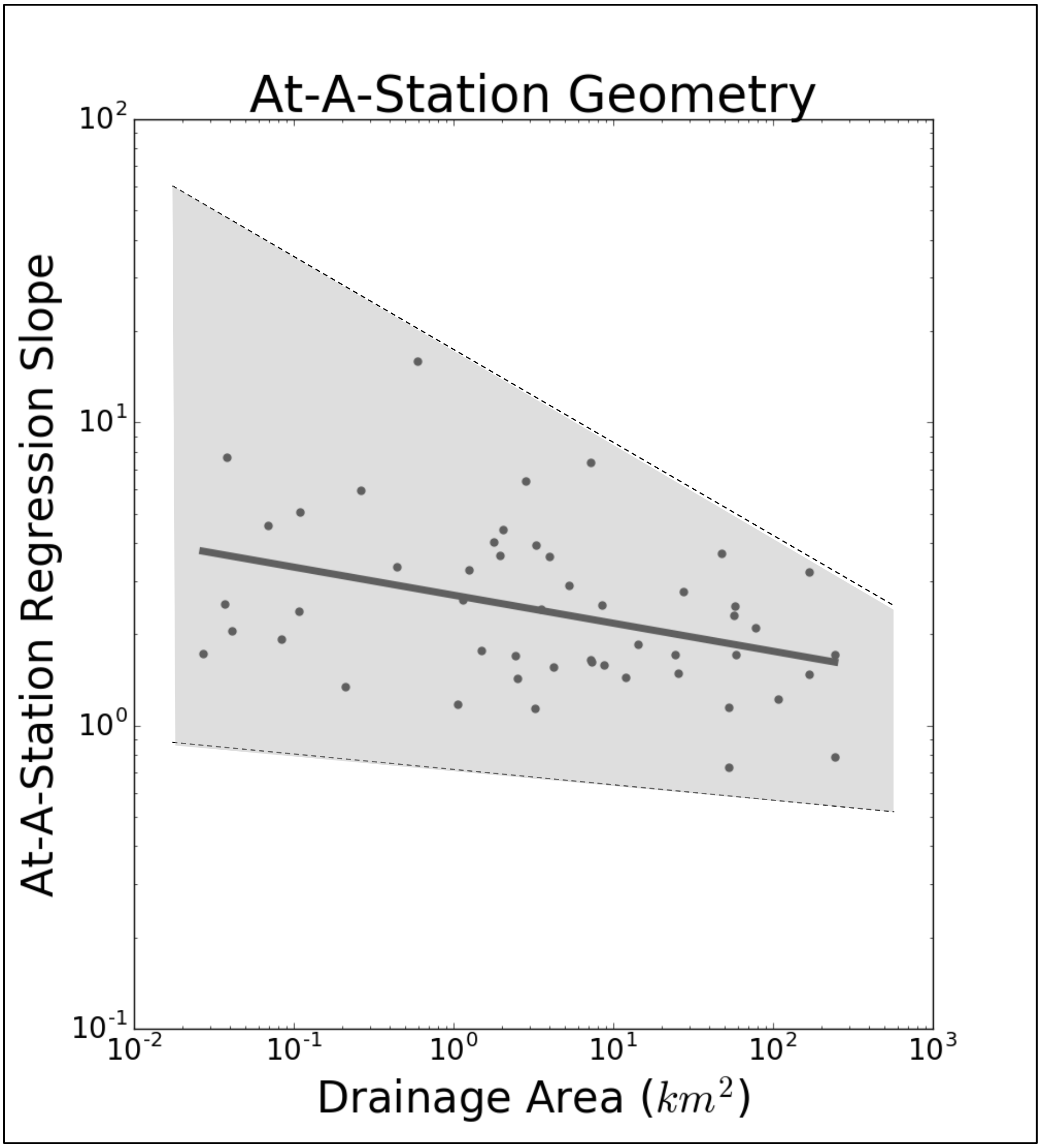

Figure 17: Rate of increase in channel width relative to increasing depth (y-axis) plotted against drainage area.

changes to channels and their contributing drainage areas by humans offer plausible explanations for the observed inconsistencies in the dimensions and shapes. Field and watershed reconnaissance observations support the conclusion that localized features and disturbances have considerable influence on modern headwater stream conditions.

4.4.2 Sediment Entrainment and Load Estimation

Estimated changes in the frequency of bed sediment entrainment generally align with the imposed climate conditions used to derive the flow regime scenarios (Table 7; Where Scenario 1 represents the median forecasted changes in temperature and precipitation; Scenario 2 represents the minimum forecasted changes in temperature and precipitation; Scenario 3 represents the maximum forecasted changes in temperature and minimum forecasted changes in precipitation; Scenario 4 represents the maximum forecasted changes in temperature and precipitation; Scenario 5 represents the minimum forecasted changes in temperature and maximum forecasted changes in precipitation). Across all four locations, Scenarios 2 and 3 produce a substantial decrease in the frequency of sediment mobility. These scenarios were developed using the lowest forecasted monthly average precipitation from CMIP5 ensembles. Across all months, the minimum projected precipitation was lower than current conditions, resulting in lower simulated stream flows. Scenarios 4 and 5, which forecast the maximum average monthly precipitation from CMIP5 projections, produced a significant increase in the frequency of sediment transport across all four locations. Precipitation in these scenarios is substantially higher than current conditions and this effect is propagated to the sediment entrainment estimates.

Scenario 1 flow conditions, produced from the median forecasted precipitation and temperature changes indicated by the CMIP5 ensemble, results in varied outcomes across the study sites. Predicted increases in precipitation drives greater frequency of bed material mobilization for all size classes at Depot Brook and the Webhannet River. More variable outcomes were observed in the Northwest River and Cromwell Brook locations. Flow conditions that initiate particle motion of smaller grain sizes (represented by D_{16} sizes) remain nearly unchanged in the Northwest River and decrease slightly for Cromwell Brook. The D_{50} sediment particle sizes show a slight decrease and no change for the Northwest River and Cromwell Brook, respectively (movement of the D_{80} in the Northwest River is very small in comparison to other size classes, and the increase in Table 7 would have relatively little effect on channel bottom conditions). These observations in the mobilization frequency for the Northwest River and Cromwell Brook are likely a function of decreasing snow melt contributions to flow and related to the substantial surface water storage in these watersheds. Watershed model calibration procedures and observed snow dynamics indicated a higher significance of snow melt contributions to surface flows at these watersheds as compared to the Webhannet River watershed. Furthermore, both locations have substantial surface water storage in wetlands and ponds that may moderate surface flow rates produced from increases in precipitation and temperature. Increased temperatures drive up evapotranspiration, which increases available storage capacity and may buffers storm flows. However, observations of static or decreases in transport frequency may be affected by weaknesses in the climate change scenarios. Climate change scenarios were developed using the delta method in conjunction with projected shifts in temperature and precipitation from CMIP5 projections. This method uses historical climate data and adds or subtracts the projected change in each variable, it does not factor into account possible changes in the frequency of rainfall events. Furthermore, CMIP5 projections are limited in their representation of tropical storm events, which could influence future summer climate conditions in the study region. Those locations and size classes most frequently mobilized during summer storm events are not well represented by the climate scenarios used for the hydrologic simulations.

Table 7: Predicted percent change in the frequency of bed material entrainment relative to current conditions. Dash indicates mobilization not estimated under current conditions.

	Northwest River			Webhannet River			Cromwell Brook			Depot Brook		
	D_{16}	D_{50}	D_{84}	D_{16}	D_{50}	D_{84}	D_{16}	D_{50}	D_{84}	D_{16}	D_{50}	D_{84}
Grain Size (mm)	*50*	*114*	*256*	*2*	*30*	*91*	*8*	*20*	*40*	*4*	*42*	*82*
Scenario 1	0%	-33%	80%	11%	7%	-	-17%	0%	-	5%	25%	100%
Scenario 2	-43%	-61%	-100%	-39%	-52%	-	-75%	-100%	-	-40%	-75%	-100%
Scenario 3	-60%	-81%	-100%	-43%	-50%	-	-75%	-100%	-	-42%	-63%	-100%
Scenario 4	61%	29%	600%	110%	117%	-	208%	350%	-	109%	163%	300%
Scenario 5	89%	85%	1020%	117%	124%	-	233%	400%	-	107%	200%	200%

4.5 Conclusions

Downstream hydraulic geometry relations constructed from upland headwater steams in the study region are generally similar to those developed from larger regional lowland river channels, with the primary exception of channel depth. The relation developed by Dudley (2004) under-predicts channel depth for the smallest streams measured in this study, likely due to the low sediment supply relative to the transport capacity in these headwater upland stream channels. As in other physiographic settings, headwater channels in Maine do not recover from scour events because of inadequate upstream sediment supply. This contrasts with stream channels within lowland alluvial valleys, some of which have a limited capacity to transport sediment in small to moderate flow conditions because of their low gradient (Smith et al. 2003).

Comparisons of upland and lowland stream at-a-station hydraulic geometry relations show greater channel variability in upland headwater portions of drainage networks. Localized geomorphic features, bedrock controls, and watershed modifications by humans are assumed to be causes of this irregularity in stream channel conditions. These observations are in accordance with previous explanations of landscape conditions and drainage networks, particularly the relevance of bedrock controls on consequent and subsequent streams described by Davis (1899). The advancement provided by this research is the highlighting of the headwater stream conditions in locations shaped by glacial erosion and deposition processes. As is the case with other physiographic settings, upland channels in Central and Coastal Maine are highly susceptible to direct modification from activities such as dredging, filling, damming, and straightening. While direct modifications have occurred throughout Maine’s drainage networks, modifications to upland streams are more pervasive and many of the modifications, particularly those related to the history of forest harvesting activities, are less apparent in rural areas.

Stream sediment transport analyses predict that projected increases in precipitation related to forecasted climate changes in the region will result in increased mobilization of sediment in streams conveying surface flows from watersheds without substantial upstream surface water storage capacity. Stream reaches in watersheds with relatively high surface water storage capacity, usually in large ponds and lakes, or where high flows are driven by snow melt events may experience no change or potentially a decrease in the frequency of stream bed mobility. The varied responses among the evaluated landscape settings is driven by the projected rise in air temperature that accompanies the precipitation increase. Rising temperatures decrease the snow melt volumes that drive spring freshets and increase storage capacity in lakes and wetlands as evapotranspiration rates increase.

These observations suggest that the response of upland channels to climate modifications over the next 100 years will be varied by settings in Central and Coastal Maine defined by land use, water storage capacity, and physiography. Water resource management efforts should account for this variability when evaluating the vulnerability of headwater streams to land use, drainage network, and climate changes. Streams where high flow events are less related to spring snow melt, or where there is relatively little upland surface water storage capacity may experience more increased sediment transport and possibly channel degradation and alterations to in-stream process and habitat conditions linked to channel bed dynamics.

4.6 Acknowledgements

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CHAPTER FIVE

DECISION SUPPORT FOR SURFACE WATER RESOURCE SUSTAINABILITY IN POST-GLACIAL LANDSCAPES

5.1 Chapter Abstract

The implementation of adaptive management strategies for water resource sustainability in the Northeastern USA requires an understanding of the dynamic interactions between the region's post-glacial landscape and headwater stream systems. The majority of stream network length is comprised of these headwater systems that provide important ecological functions and govern the conditions in downstream lowland rivers, lakes, and estuaries. Regional stakeholder concerns focused on the sustainability of potable drinking water quality, safe civil infrastructure, economically important recreation and tourism activities, resilient aquatic habitat conditions, and viable coastal fisheries are ultimately influenced by the inseparable and dynamic interactions between the landscape and upland surface flows and stream bed conditions. Accordingly, this research targeted hydrologic and sediment dynamics governing headwater stream conditions to provide information to guide the development and implementation of adaptive management strategies.

The questions and objectives of this research, which have been addressed as individual research components relating to watershed conditions, channel hydrology, and channel morphology, were organized to provide a framework to support water resource sustainability solutions. The organization of this research was developed through the identification of problems and co-generation of knowledge with stakeholder communities, reviews of a diverse collection of background information, and assembly of

data. Research results are summarized and organized here to provide decision support tools for state and local organizations tasked with developing management strategies to sustain ecosystem services related to surface water resource sustainability in the Northeast.

5.2 Research Development

The development of sustainable water resource management strategies is ideally comprised of several key components: 1) Collection and interpretation of scientific information; 2) Development of knowledge systems; and 3) Framing of adaptive management strategies with continuous stakeholder involvement. The research summarized here was framed to address these components as part of two larger NSF funded sustainability focused research projects, Maine's Sustainability Solutions Initiative (MeSSI) that included a focus on watershed connections to freshwater lakes (National Science Foundation award EPS-0904155) and the New England Sustainability Consortium (NEST) (National Science Foundation award IIA-1330691) that examined land-sea connections along the Maine coast. The components of these projects which comprise this dissertation focused on the collection and interpretation of information regarding watershed processes controlling surface water flow routing and in-channel conditions within the post-glacial landscape of the Northern New England region.

The framework and objectives of this research were organized to address three research questions:

1. How do watershed geomorphic conditions vary (e.g. geology, soils, relief, and land cover), and how do these variations relate to stream flow characteristics?

2. What are the implications of climate change to the surface flow regimes of headwater stream systems in the region?

3. How do watershed conditions and flow regime alterations from climate change affect stream channel dynamics?

These questions were developed through continuous stakeholder engagement and were organized around the relation between the freshwater flow regime (Poff, et al. 1997) and stream channel dynamics via the sediment-water proportionality given by $Q\,S \propto Q_s\,D$, where S is slope *(Length/Length)*, Q_s is sediment supply (*Length^3/time*) and D is sediment grain size (*Length*) (Lane 1955). While sustainability concerns and interests varied across stakeholder groups, a focus on this relation provided research targets related to processes governing multiple water resource sustainability interests. A scaled-up framework was also necessary to consider stakeholder concerns regarding nonpoint source pollution in the modern landscape, leading to consideration of surface water and pollutant source, delivery, and residence time categories. The breakdown of these categories provides a conceptual framework for development of decision support tools with a focus on the freshwater flow regime affecting stream channel conditions and water quality loads. The research summarized here focuses the mechanisms governing these time categories and informs on the applicability of management strategies based on the setting and relation of source, delivery and routing in the landscape. Maine watersheds have variable relations between these categories (as shown by the examples in Figure 18) and, accordingly, water resource sustainability benefits from adaptive management strategies.

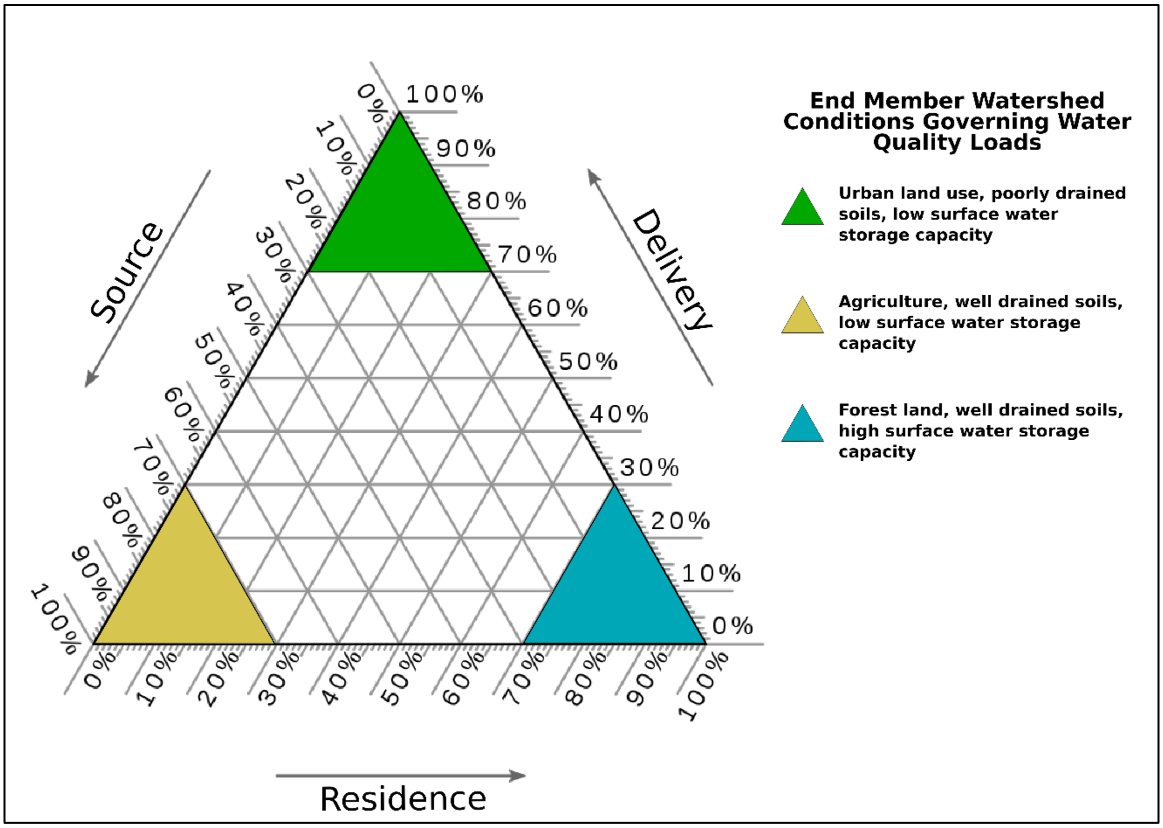

Figure 18: Source, delivery, and routing ternary diagram with end member examples.

5.3 Place-Based Research

Watershed management focused on water resource sustainability does not entail the preservation of every drainage area and stream, but it does require place-based research to provide knowledge of how landscape conditions relate to processes governing runoff production, pollutant movement, and dynamics associated with human activities and climate changes that can propagate spatially and temporally (Kates et al. 2001).

The approach fostered by sustainability science directs the development of adaptive watershed management strategies through research framed around stakeholder concerns, knowledge co-generated by academic and stakeholder collaborations, and implementation of solutions to water resource problems using formats that stakeholders are comfortable using. Clearly parsing problems into relevant spatial and temporal scales and evaluating vulnerability relative to that organizational structure is a substantial front end of water resource sustainability solutions work. The initial question guiding this research address the place-based aspect of sustainability research by examining landscape heterogeneity related to the mechanics of runoff production and routing in headwater drainage networks.

The region's geomorphology and history of alteration by humans has created a complex array of watershed conditions and settings in which communities, environmental organizations, and government organizations such as the Portland Water District (PWD) and the Maine Department of Marine Resources (MEDMR) implement water resource management strategies targeting stream ecosystem services. Stakeholder engagement at the beginning of this project guided a systematic delineation of locations with relatively high susceptibility to water resource problems linked to stream flows, hydraulics, and sediment-water dynamics.

While there is a general interest in watershed management strategies customized relative to specific conditions and settings, two groups of stakeholders had substantial influence on the approach. Communities and organizations concerned with Maine's largest public drinking water supply, Sebago Lake, inspired the examination of locations in the Presumpscot River watershed with relatively greater vulnerability to climate and land use changes affecting in-stream processes linked to surface water quality conditions. Communities, industries, and government agencies along the coast similarly expressed interest in identifying locations with elevated vulnerability to pollution; however, the concern was associated with the movement of bacteria from land areas into tidal estuaries that host shellfishing industries important to the state's economy. Connections between climate, landscape conditions, surface water flows, channel hydraulics, and pollution are the heart of the natural resource problem in each case. Both require the simultaneous consideration of multiple watershed factors influencing surface water flows.

Research and stakeholder engagement resulted in the decision to design a strategy based on Geomorphic Response Units (GRUs) delineated at an intermediate watershed scale (~3rd to 4th order) to provide stakeholders with a framework to identify unique settings relevant to watershed processes and evaluate vulnerability to modern and future watershed conditions. The approach framed around GRUs provides a tool for developing research targets to expand the knowledge base related to surface water hydrology, stream hydraulics, and nonpoint source pollution. It provides a basis for planning monitoring of surface flows, transferring information among similar settings, and avoiding inappropriate extrapolations to dissimilar settings. Outcomes from the research also advance the capacity to customize watershed management strategies relative to the localized processes governing runoff production and stream dynamics. The analysis identified nine defined settings delineated at the scale of the HUC-10 watersheds standardized by the USGS in Maine.

5.4 Surface Water Flow Regimes

Quantification and characterization of a stream's flow regime, defined by patterns of discharge over time (Poff et al. 1997), is a consideration fundamental to the sustainability of water supply, water quality, and aquatic habitat conditions in modern lotic systems (Sparks 1995; Ward and Stanford 1995; Poff et al. 1997). Observations suggest that regional surface flow patterns are changing due to shifting climatic conditions (Collins

2009) and forecasts predict an increasingly wetter and warmer climate which may further alter regional flow regimes. These observations and projections are a primary concern for many of the stakeholder groups that were engaged in the development of this research, including the Maine Lakes Environmental Association, Acadia National Park, and the Maine Department of Transportation. The interests of these stakeholders are inspired by concerns related to water quality and instream habitat conditions, both of which are governed by processes described by the sediment-water proportionality and the coupled dynamics of the channel bed, sediment transport, and nutrient flux in modern streams.

The second component of this research summarized in Chapter 3 of this dissertation addresses stakeholder concerns related to regional flow regime characteristics and modifications from climate change. This research focuses on runoff production and watershed drainage patterns relevant to surface water routing and storage to estimate the magnitude and regional variability of flow regime modifications from projected climate conditions. Results suggest that stream flows produced from the spring snow melt are most substantially impacted in terms of timing and magnitude. Modeling results show that surface watershed storage, which is substantial in Maine's drainage networks, impacts the stream flow regime response to climate changes. Simulations provide estimates of the relative magnitudes of surface flow responses to forecast climate changes, indicating that surface water storage will likely impact climate change response in headwater drainage basins in the region. The research outcomes provide a basis for identifying the watershed systems most vulnerable to land use and climate changes and clarify the role of background and human-augmented surface water storage within modern drainage networks in regulating increases in excess precipitation in varied landscape settings. The importance of these findings is relevant to the prediction of civil infrastructure performance (e.g. road culverts and dams), aquatic habitat, and water quality loads because of the association of all of the related ecosystems services to surface water flow rates.

5.5 Channel Dynamics

Channel geometry and channel bed sediment conditions are a product of the sediment-water proportionality, and modifications to surface water flows or sediment supply can result in aggradation, degradation, and/or changes in the bed-surface sediment composition (Surian and Cisotto 2007; Wolman and Schick 1967, Wilcock et al. 2009). These changes can produce deleterious effects to downstream water quality and directly impact instream ecological conditions through development of channel instabilities or indirectly through alterations to hyporheic exchange, the exchange of water between the stream and a fluctuating layer of unconsolidated sediment beneath or adjacent to the stream (Arntzen et al. 2006; Boulton et al. 1998; Buffington and Tonina 2009; Hatch et al. 2010; Kasahara and Wondzell 2003; Mutiti and Levy 2010; Packman and Salehin 2003; Triska et al. 1993; Westhoff et al. 2011).

The focus of this research on quantification of stream channel conditions and dynamics related to the sediment-water proportionality was inspired by discussions with stakeholder groups, including the Maine Department of Inland Fisheries and Wildlife and local Trout Unlimited and Salmon Clubs concerned about channel bottom conditions for the sustainability of recreationally, economically, and culturally significant fisheries in the region (Southwick 2014).

Stream channel hydraulic geometry surveys conducted as part of this project extend the domain of predictive relations that relate stream flows to channel dimensions in the deglaciated drainage networks of the Northern New England (Dudley 2004). The domain extension is relevant to headwater portions of the networks, primarily streams of 1st through 3rd order. The headwater stream channel measurements are important to the development of criteria for engineering streams, culverts, and bridges in the most substantial and spatially varied portion of modern drainage networks in Maine's landscape.

The analysis of stream channel hydraulic geometry was coupled with results that show the spatial heterogeneity of climate change effects on channel bottom conditions. Headwater channels where high flow events are less related to spring snow melt and that had limited surface water storage capacity will experience increased perturbations to channel bottom sediment over the next 100 years in response to the predicted climate changes. Important to stakeholders concerned about the sustainability of stream channel conditions in diverse and ecologically valuable headwater channels, the research outcomes suggest increased management focus on locations with limited surface water storage.

5.6 Water Resource Sustainability Solutions and Future Work

Traditional water resource management strategies generally seek to "control" major changes to water quality through end-of-pipe solutions (Pahl-Wostl et al. 2008). These point source solutions are not able to address many of the stakeholder concerns and research results show that a "one size fits all" approach to watershed management can have uncertainty in Maine's complicated landscape. Water resource sustainability solutions framed relative to first principles and the physical system are essential even at the watershed scale resolution (Portland Water District 2012). The results compare watersheds affected by mechanical sculpting by glacial processes, human interventions, and climate changes. Research summarized by this dissertation creates a workbench for environmental and natural resources managers to further develop adaptive management strategies to protect water quality and aquatic habitat in the region (Figure 19).

The link between landscape conditions, freshwater flows, and water quality loads is at the root of many stakeholder concerns in Maine. This dissertation research focused on the physical processes governing freshwater flows as they relate to stakeholder interests, all of which were fundamentally connected to the proportionality between water and sediment in streams. The results close knowledge gaps related to coupled watershed-hydrology-stream systems in regions with a history of glaciation by evaluating multiple factors affecting surface flows and stream channel responses. The observations and outcomes provide a basis for developing watershed management approaches tailored to the region's physiographic settings related to glaciation, climate, and direct human perturbations.

These measurements, simulations, and spatial data analyses have uncertainties, but relative comparisons provide a basis for designing and implementing responses to land use and climate changes to protect water resources and related ecosystem services (Table 8). Quantification and prioritization of uncertainty analyses will advance knowledge supporting future management approaches. In evaluating and characterizing physiographic settings, limitations exist due to the granularity and inconsistencies of sourced spatial data, some of which is estimated over broad regions based on sampling and transects (e.g. soil data). The analysis and results are delineated at a scale (HUC-10) which minimizes some of these issues, but the use of GRUs should consider unique local conditions not represented in the data sets assembled for this research.

In examining surface flow regimes by numeric simulations, uncertainties associated with spatial data are also present. The coarse resolution of some spatial data (up to $30m^2$) coupled with computational limitations requires that simulations be carried out at a resolution of 30 to 50 m^2. Additional limitations are caused by uncertainties in the weather and discharge data used to parameterize and calibrate the watershed hydrology models. The lack of proximal weather stations during the period of study and error associated with stage-discharge measurements in reference watersheds, particularly during high flow events, limits the capacity to calibrate the watershed models used to evaluate the flow regime characteristics. Interpretation of the analytical outcomes for climate change scenarios tested also requires review of uncertainty associated with the CMIP5 projections. One important consideration is the limited accountability for changes in the frequency of precipitation events or low-pressure storm systems from the Mid-Atlantic or Northern Atlantic Ocean.

Uncertainties associated with the watershed model output and field measurements propagate to the predictions of sediment transport and inferred stream bed dynamics. Furthermore, while commonly used by geomorphologists, sediment distributions derived from pebble counts and estimates of Manning's roughness from field observations are imperfect summaries of channel conditions. Limitations of sediment transport estimates would benefit from field measurements of sediment transport (i.e, bedload and suspended load) in representative headwater streams.

Table 8: The primary sources of uncertainty associated with each component of the dissertation research.

Primary Sources of Uncertainty
Chapter 2: Headwater Drainage Area Settings in Maine
▪ Coarse reslolution of some landscape attributes (e.g. land cover at 30m^2) ▪ Inconsistencies in attributes mapped through sampling (e.g. soil data mapped by transecting or sampling efforts across multiple agencies)
Chapter 3: The Hydrologic Signature of Northeastern Headwater Basins
▪ Coarse model resolutions used due to data limitations and computational capacities ▪ Uncertainties associated with stage-discharge relationships used to estimate observed discharge ▪ Limited weather data in close proximity to modeled watersheds ▪ Associated uncertainties from CMIP5 climate projections and limitations to incorporate changes in precipitation frequency
Chapter 4: Northeastern Headwater Stream Bed Dynamics Under Varied Climate Conditions
▪ Uncertainties associated with pebble count sampling to estimate sediment distribution ▪ Uncertainties associated with estimates of channel roughness conditions ▪ Limited/absent field observations of sediment transport

Future research building on the work presented here should be guided towards quantification and characterization of the following: 1) Impacts of direct human modifications to hydrologic conditions in modern terrain and drainage networks to quantify the cumulative impact of small privately-owned dams on regional flow regime conditions; 2) Relations between glacial processes, bedrock conditions, and other watershed process on upland channel dynamics; and 3) Implications of changes in bed sediment dynamics on hyporheic exchange and water quality. The work presented here provides a foundation to address these topics and additional knowledge gaps related to sediment-water dynamics underlying stakeholder concerns throughout Maine's post-glacial landscape.

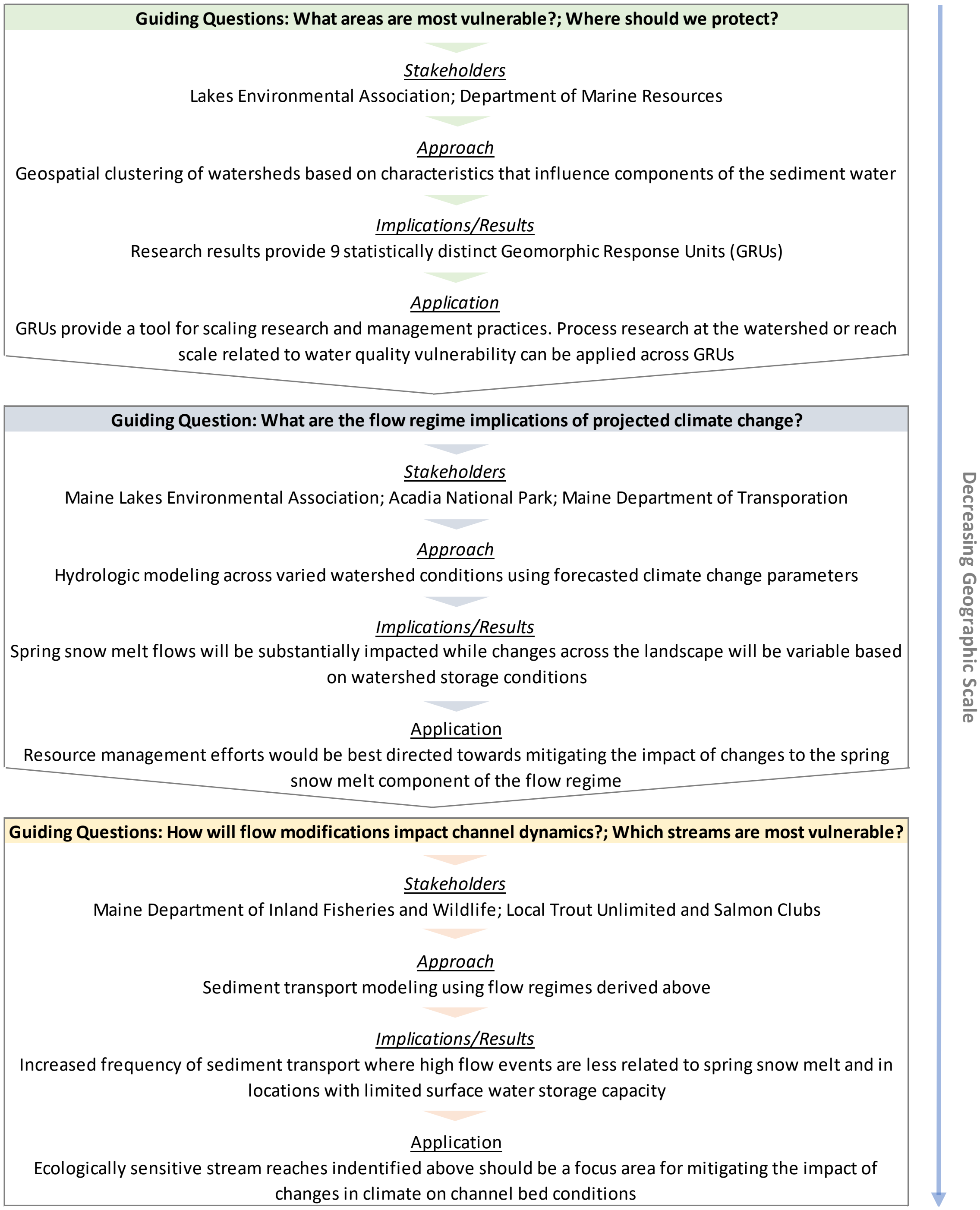

Figure 19: Summary of headwater stream sustainability solutions research and applications across spatial scales in post-glacial landscapes of the Northeast USA.

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APPENDIX A

CHAPTER TWO SUPPLEMENTAL MATERIAL

A.1 Supplemental Tables

Table 9: Pre-analysis categorization of surficial geology units used in the PCA and cluster analysis.

Categories	Units
Bedrock (Exposed)	Exposed rock and thin drift deposits
Glaciofluvial	Eskers, ice contact deposits, and glacial outwash deposits
Glaciomarine	Fine grained and medium grained glaciomarine deposits
Moraine	End moraine, ribbed moraine, and stagnation moraine deposits
Till	Till
Alluvium	Alluvium
Beach	Beach deposits and emerged beach deposits
Eolian	Eolian deposits
Lake Botton	Lake bottom deposits

Table 10: Pre-analysis categorization of land cover types used in the PCA and cluster analysis.

Categories	Land Cover Types
Developed	Developed open space and low, medium, and high intensity development
Agriculture	Hay, pasture, and cultivated crops
Forested	Deciduous, evergreen, and mixed forest
Storage	Open water, woody wetlands, and emergent herbaceous wetlands
Low_Vegetation	Barren land, and shrub/scrub

Table 11: Variables and corresponding PC loadings for each of the retained PCs used in the cluster analysis.

	Loadings									
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**
Mean Slope	0.14	0.35	0.18	0.19	0.10	0.09	-0.02	-0.25	0.15	-0.06
A Soils (%)	-0.30	0.08	0.24	-0.27	0.00	-0.33	0.22	-0.08	-0.06	0.04
B Soils (%)	-0.10	-0.19	0.32	0.47	0.06	0.19	-0.01	-0.04	0.03	-0.01
C Soils (%)	0.43	-0.07	0.00	-0.24	-0.01	0.16	0.08	0.16	0.16	0.16
D Soils (%)	-0.24	0.13	-0.39	0.23	-0.01	-0.05	-0.25	-0.11	-0.17	-0.23
Developed (%)	-0.30	-0.06	-0.16	-0.11	0.24	0.09	0.17	-0.19	0.27	0.03
Agriculture (%)	-0.26	-0.26	0.17	0.24	0.19	0.07	-0.11	0.10	0.10	0.01
Storage (%)	-0.18	-0.01	0.01	-0.23	-0.29	0.03	-0.47	0.20	-0.11	0.14
Forested (%)	0.37	0.25	0.07	0.08	0.21	-0.24	0.14	0.17	-0.07	-0.07
Low Vegetation (%)	0.06	-0.14	-0.11	0.02	-0.45	0.22	0.19	-0.40	-0.13	-0.08
Bedrock (%)	0.02	0.40	-0.06	0.35	0.13	0.24	0.05	0.11	0.00	0.07
Glaciofluvial (%)	-0.17	0.07	0.31	-0.20	-0.16	-0.34	0.31	-0.01	-0.17	-0.04
Glaciomarine (%)	-0.35	0.08	-0.30	-0.10	0.17	0.02	0.05	0.11	0.05	0.01
Moraine (%)	-0.03	0.06	0.14	-0.09	-0.33	0.44	0.09	0.33	0.07	-0.16
Till (%)	0.34	-0.34	0.05	-0.01	0.13	-0.18	-0.33	-0.26	-0.12	0.04
Alluvium (%)	-0.08	-0.07	0.07	0.03	-0.11	0.06	-0.09	0.23	0.27	0.08
Beach (%)	-0.05	-0.01	-0.05	-0.09	-0.01	0.16	0.02	-0.41	0.16	0.10
Eolian (%)	-0.03	-0.01	-0.02	-0.03	0.05	-0.02	0.06	0.10	0.19	-0.28
Lake_Bottom (%)	-0.02	0.00	0.01	-0.02	-0.11	-0.02	-0.06	0.07	0.05	0.05
Granoblastic (%)	-0.02	-0.03	0.00	-0.05	-0.07	0.06	-0.07	-0.06	0.00	-0.41
Metased. (%)	0.04	-0.13	0.03	-0.31	0.46	0.35	0.08	0.04	-0.18	-0.26
Chemical (%)	0.01	0.01	-0.03	-0.09	0.09	0.06	0.17	0.00	0.00	-0.14
Melange (%)	0.03	-0.05	0.06	-0.21	0.19	0.19	-0.20	-0.26	0.00	-0.09
Carbonate (%)	-0.17	-0.20	0.41	0.23	0.03	-0.02	0.06	0.03	-0.11	0.11
Clastic (%)	0.08	-0.29	-0.30	0.20	-0.27	-0.36	0.19	0.11	0.34	-0.05
Volcanic (%)	-0.03	0.14	-0.23	0.18	0.03	0.07	0.07	0.16	-0.55	0.40
Plutonic (%)	-0.03	0.45	0.23	-0.11	-0.12	-0.02	-0.39	-0.19	0.20	0.24
Migmatite (%)	0.00	0.02	-0.01	0.01	0.03	-0.02	-0.09	-0.04	-0.08	-0.34
Metaigneous (%)	-0.04	-0.02	-0.05	-0.12	0.06	0.11	0.15	-0.19	0.18	0.46

Table 12: Variable means for the Maine clusters/GRUs.

	Cl.1	Cl.2	Cl.3	Cl.4	Cl.5	Cl.6	Cl.7	Cl.8	Cl.9
Slope Mean	9.46	8.08	7.72	5.96	8.79	13.63	18.27	6.33	4.99
A Soils (%)	2.09%	0.90%	80.50%	3.09%	1.64%	5.44%	0.31%	1.58%	40.97%
B Soils (%)	3.63%	3.26%	1.07%	0.89%	2.40%	2.58%	12.57%	86.05%	1.07%
C Soils (%)	91.95%	89.46%	15.96%	16.84%	92.42%	87.51%	60.45%	11.53%	29.32%
D Soils (%)	2.09%	5.82%	1.78%	77.84%	2.24%	3.11%	26.67%	0.84%	28.16%
Developed (%)	3.11%	1.78%	6.92%	5.26%	0.82%	1.99%	2.73%	7.40%	35.68%
Agriculture (%)	2.52%	1.90%	4.22%	5.93%	0.42%	1.26%	0.16%	35.11%	9.93%
Storage (%)	75.22%	73.54%	65.05%	61.51%	63.94%	76.98%	82.00%	37.25%	36.09%
Forested (%)	11.20%	10.73%	18.54%	19.38%	17.28%	13.35%	8.18%	16.32%	11.31%
Low Vegetation (%)	6.44%	10.18%	4.63%	6.38%	15.21%	5.20%	5.71%	2.54%	5.31%
Bedrock (%)	2.14%	2.98%	0.43%	3.02%	0.86%	3.90%	76.62%	0.51%	1.11%
Glaciofluvial (%)	2.15%	2.46%	44.62%	1.69%	4.04%	3.06%	0.82%	3.89%	1.17%
Glaciomarine (%)	5.02%	3.70%	14.61%	36.95%	0.33%	3.98%	2.91%	0.70%	70.63%
Moraine (%)	0.78%	1.02%	0.83%	0.84%	71.46%	1.05%	0.59%	15.66%	0.45%
Till (%)	89.46%	89.24%	37.64%	56.41%	22.03%	87.44%	19.00%	73.00%	22.25%
Alluvium (%)	0.33%	0.39%	1.29%	0.60%	1.05%	0.28%	0.06%	5.89%	0.67%
Beach (%)	0.01%	0.00%	0.00%	0.00%	0.00%	0.06%	0.00%	0.00%	2.63%
Eolian (%)	0.02%	0.04%	0.06%	0.03%	0.00%	0.03%	0.00%	0.00%	0.50%
Lake_Bottom (%)	0.07%	0.17%	0.52%	0.22%	0.23%	0.14%	0.00%	0.35%	0.00%
Granoblastic (%)	0.00%	0.00%	0.08%	0.04%	0.00%	0.00%	0.00%	0.00%	0.01%
Metased. (%)	75.08%	3.75%	10.26%	11.47%	27.45%	3.39%	8.20%	7.64%	43.82%
Chemical (%)	0.00%	0.01%	0.00%	0.00%	1.09%	0.00%	0.00%	0.00%	0.00%
Melange (%)	1.75%	0.62%	1.23%	0.02%	12.66%	0.08%	0.61%	0.62%	0.00%
Carbonate (%)	2.68%	0.69%	24.11%	0.24%	0.09%	1.10%	0.02%	66.82%	1.40%
Clastic (%)	7.52%	87.52%	17.03%	42.51%	14.49%	6.18%	26.35%	21.77%	28.78%
Volcanic (%)	8.88%	4.13%	0.51%	22.27%	1.50%	0.94%	20.64%	0.75%	3.73%
Plutonic (%)	3.58%	3.01%	46.77%	23.18%	42.55%	88.24%	44.05%	2.39%	16.16%
Migmatite (%)	0.08%	0.00%	0.00%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%
Metaigneous (%)	0.40%	0.25%	0.02%	0.05%	0.17%	0.07%	0.13%	0.00%	6.09%

Table 13: Z-scored variable means for the Maine clusters/GRUs.

	Cl.1	Cl.2	Cl.3	Cl.4	Cl.5	Cl.6	Cl.7	Cl.8	Cl.9
Slope Mean	0.05	-0.28	-0.36	-0.78	-0.11	1.04	2.14	-0.69	-1.01
A Soils (%)	-0.47	-0.52	2.36	-0.44	-0.49	-0.35	-0.54	-0.49	0.93
B Soils (%)	-0.32	-0.34	-0.42	-0.42	-0.37	-0.36	0.00	2.64	-0.42
C Soils (%)	1.02	0.95	-1.08	-1.05	1.03	0.89	0.15	-1.20	-0.71
D Soils (%)	-0.57	-0.42	-0.58	2.41	-0.56	-0.53	0.40	-0.62	0.46
Developed (%)	-0.38	-0.51	-0.03	-0.19	-0.60	-0.49	-0.42	0.01	2.61
Agriculture (%)	-0.39	-0.45	-0.24	-0.08	-0.58	-0.50	-0.60	2.56	0.28
Storage (%)	0.70	0.60	0.09	-0.12	0.03	0.81	1.11	-1.58	-1.65
Forested (%)	-0.71	-0.83	1.14	1.35	0.82	-0.17	-1.48	0.58	-0.69
Low Vegetation (%)	-0.11	0.89	-0.59	-0.13	2.24	-0.44	-0.30	-1.15	-0.41
Bedrock (%)	-0.32	-0.29	-0.39	-0.29	-0.37	-0.25	2.66	-0.39	-0.36
Glaciofluvial (%)	-0.35	-0.33	2.66	-0.38	-0.22	-0.29	-0.44	-0.23	-0.42
Glaciomarine (%)	-0.44	-0.50	-0.03	0.91	-0.64	-0.48	-0.53	-0.62	2.33
Moraine (%)	-0.41	-0.40	-0.40	-0.40	2.61	-0.39	-0.41	0.23	-0.42
Till (%)	1.12	1.11	-0.57	0.04	-1.08	1.05	-1.18	0.58	-1.08
Alluvium (%)	-0.47	-0.43	0.06	-0.32	-0.07	-0.49	-0.61	2.61	-0.28
Beach (%)	-0.33	-0.34	-0.34	-0.34	-0.34	-0.28	-0.34	-0.34	2.67
Eolian (%)	-0.35	-0.22	-0.12	-0.26	-0.47	-0.29	-0.47	-0.47	2.65
Lake_Bottom (%)	-0.70	-0.10	1.95	0.21	0.26	-0.29	-1.14	0.96	-1.14
Granoblastic (%)	-0.52	-0.52	2.29	1.04	-0.52	-0.52	-0.52	-0.52	-0.19
Metased. (%)	2.24	-0.73	-0.46	-0.41	0.26	-0.74	-0.54	-0.56	0.94
Chemical (%)	-0.34	-0.31	-0.34	-0.34	2.67	-0.33	-0.34	-0.34	-0.34
Melange (%)	-0.05	-0.33	-0.18	-0.48	2.64	-0.46	-0.33	-0.33	-0.48
Carbonate (%)	-0.36	-0.45	0.59	-0.47	-0.48	-0.43	-0.48	2.50	-0.42
Clastic (%)	-0.82	2.38	-0.44	0.58	-0.54	-0.87	-0.07	-0.25	0.03
Volcanic (%)	0.21	-0.34	-0.76	1.77	-0.64	-0.71	1.58	-0.73	-0.39
Plutonic (%)	-0.93	-0.95	0.59	-0.24	0.44	2.05	0.49	-0.97	-0.49
Migmatite (%)	0.58	-0.45	-0.45	2.51	-0.45	-0.41	-0.45	-0.45	-0.45
Metaigneous (%)	-0.20	-0.28	-0.39	-0.38	-0.31	-0.37	-0.34	-0.40	2.66

A.2 Supplemental Figures

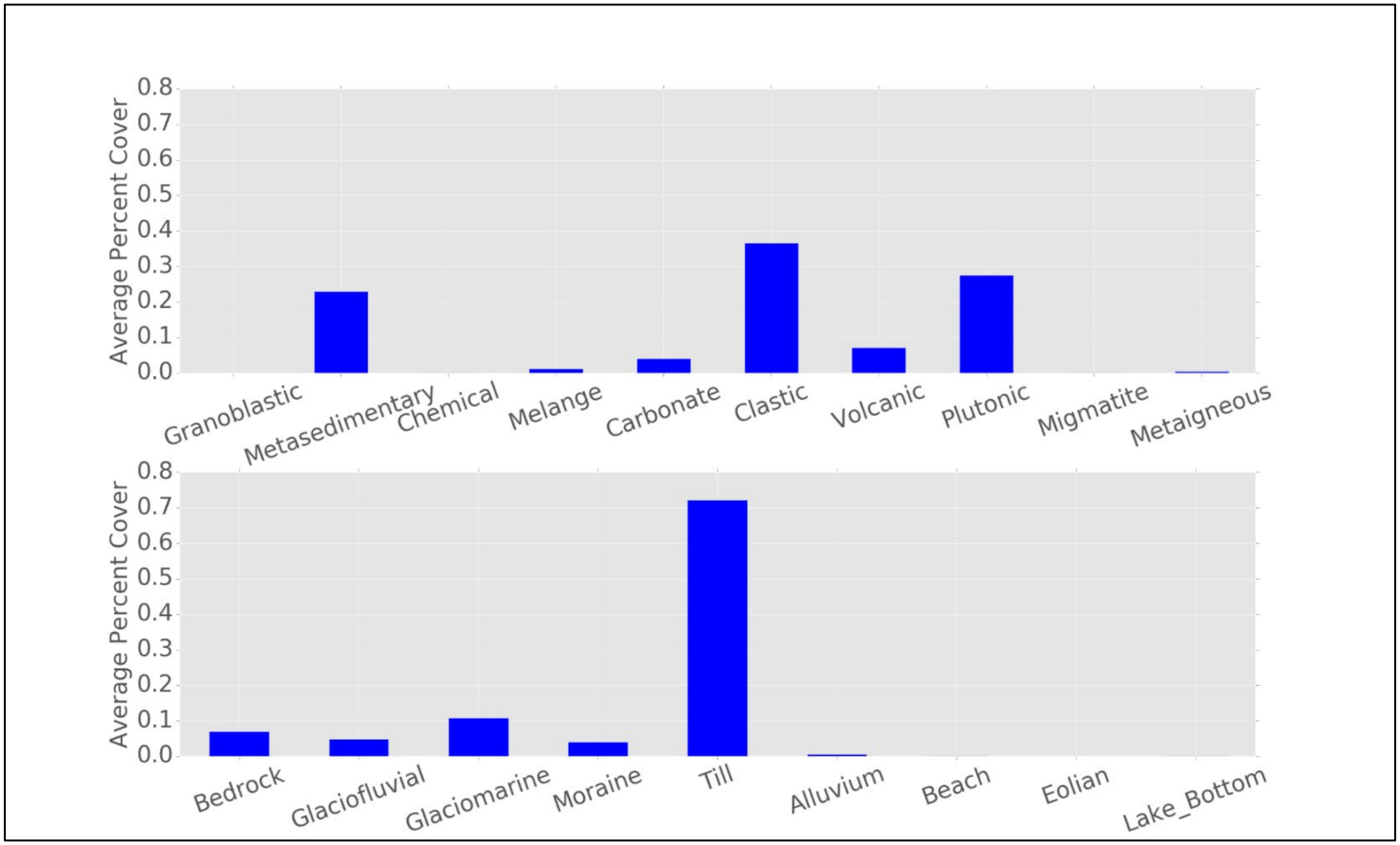

Figure 20: Drainage divide averages for the percent occupied by bedrock geology (top) and surficial geology (bottom) categories.

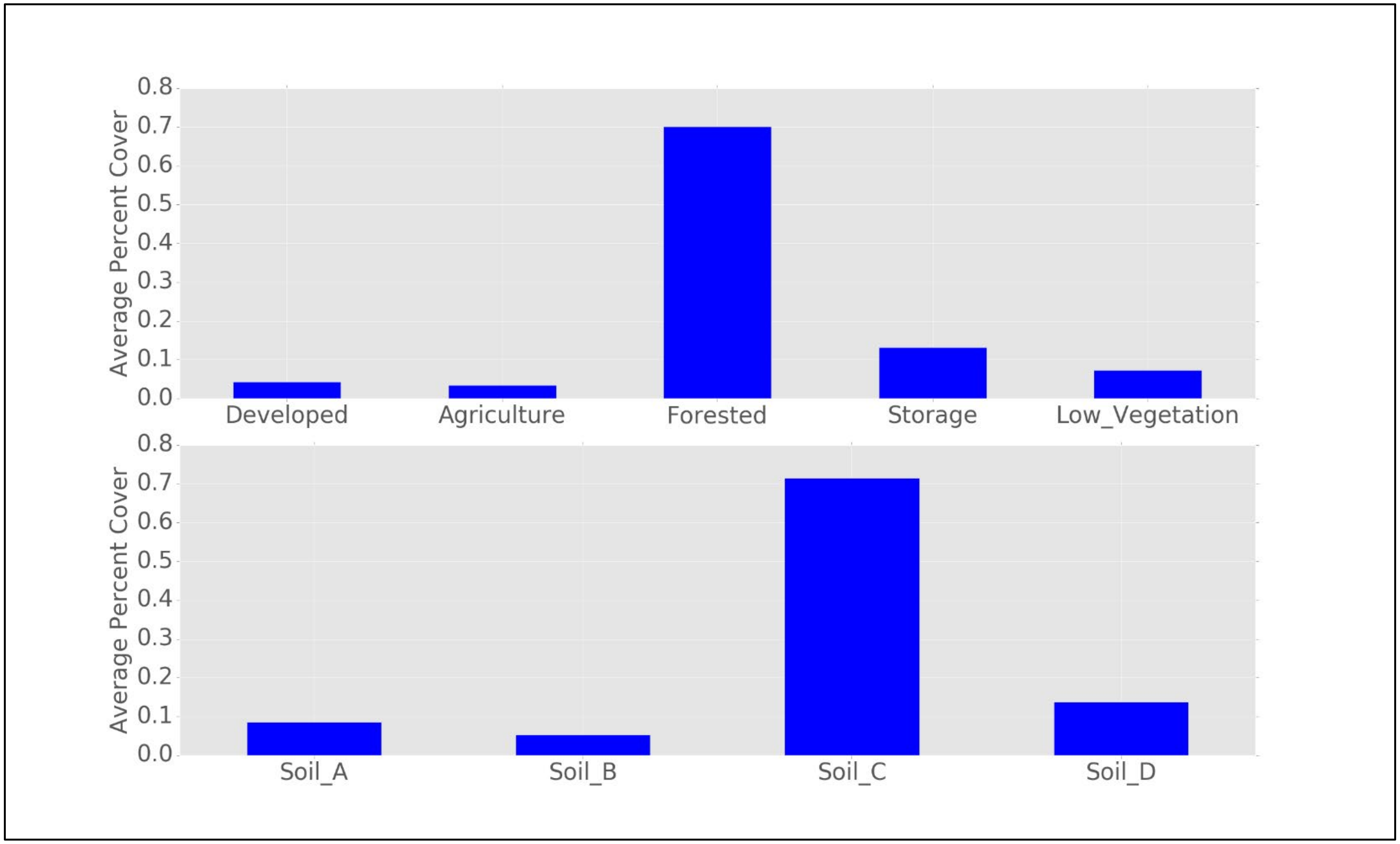

Figure 21: Drainage divide averages for the percent occupied by land cover (top) and hydrologic soil group (bottom) categories.

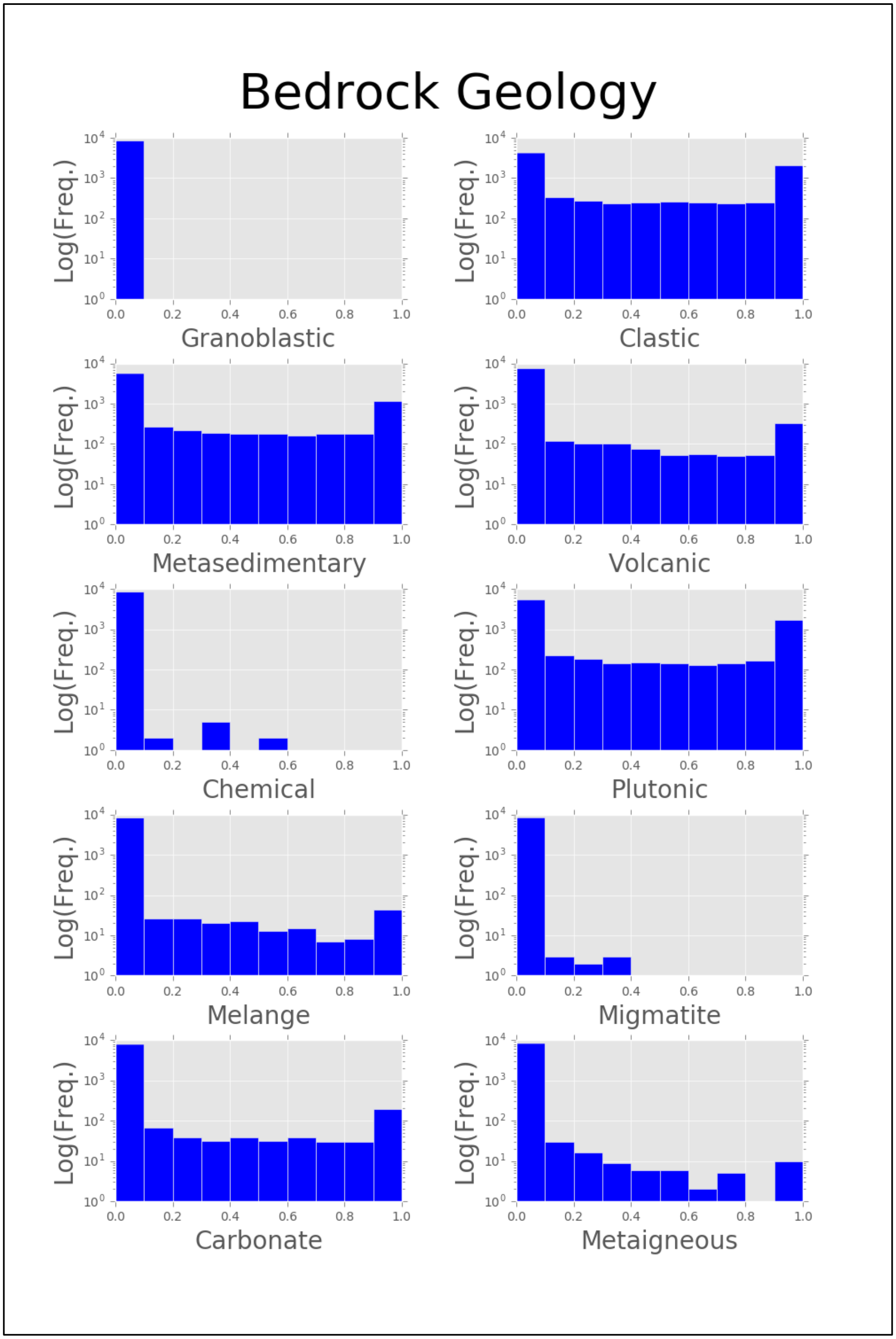

Figure 22: Histograms for the frequency of percent cover across all Maine drainage divides for each of the bedrock geology categories.

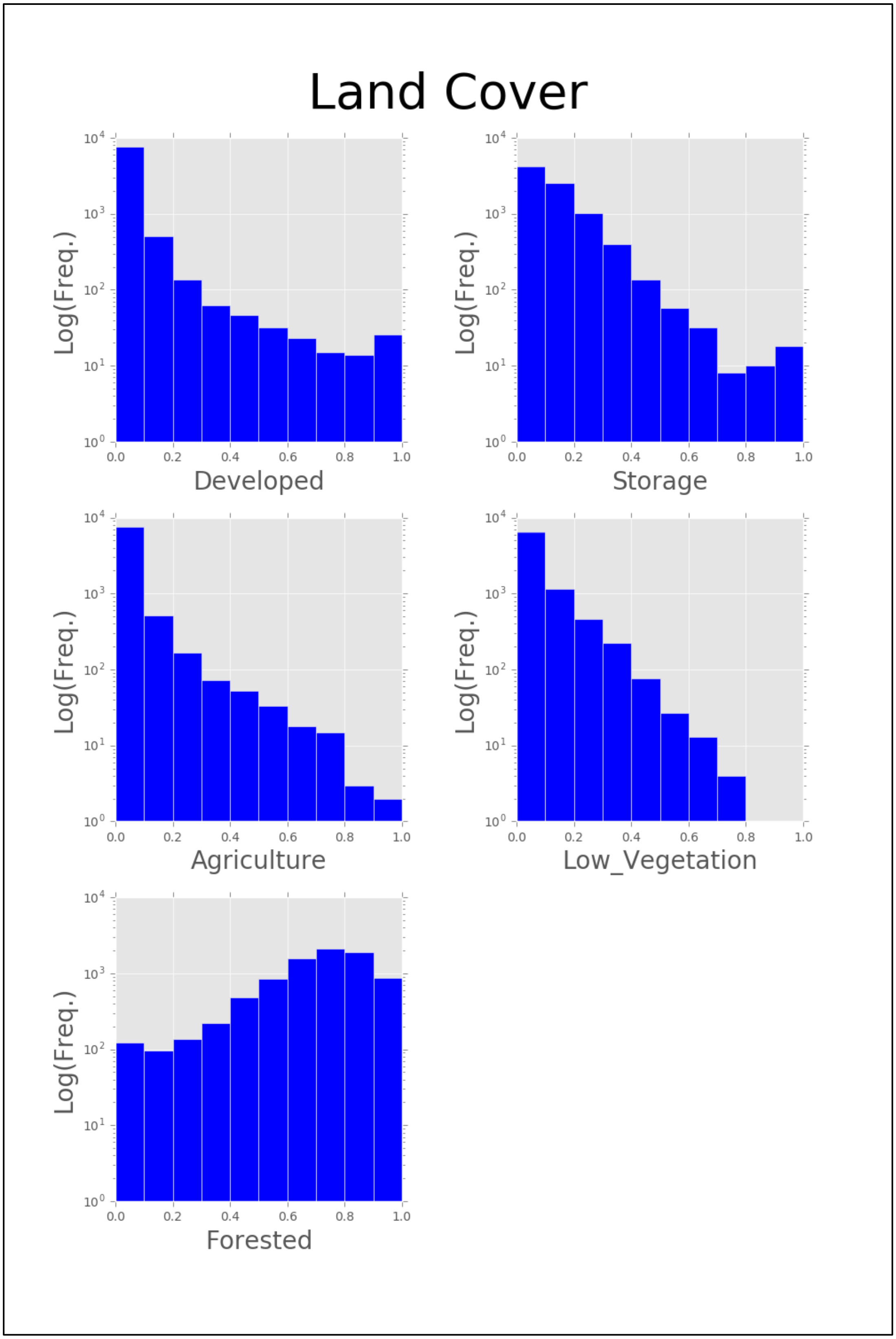

Figure 23: Histograms for the frequency of percent cover across all Maine drainage divides for each of the land cover categories.

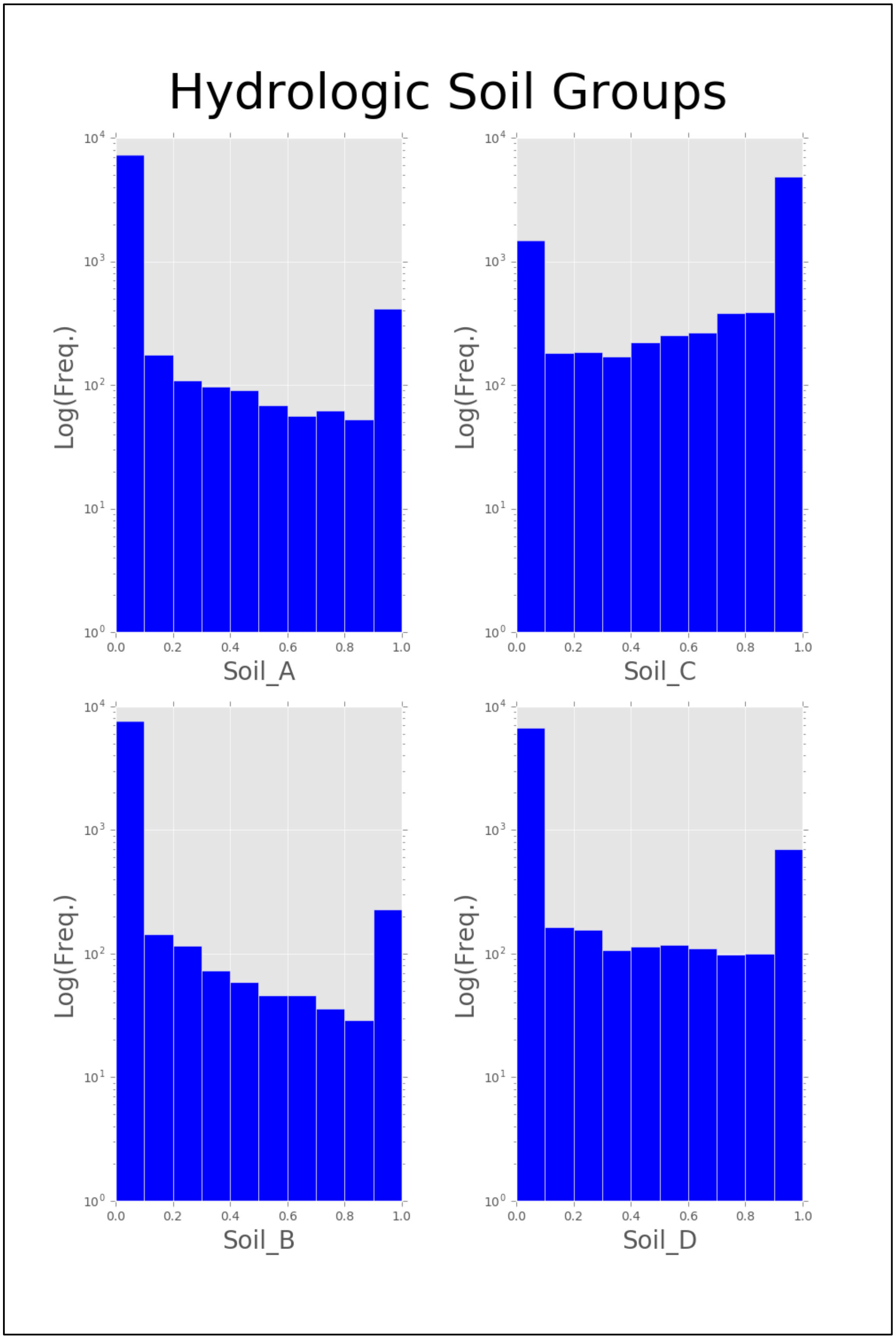

Figure 24: Histograms for the frequency of percent cover across all Maine drainage divides for each of the hydrologic soil group categories.

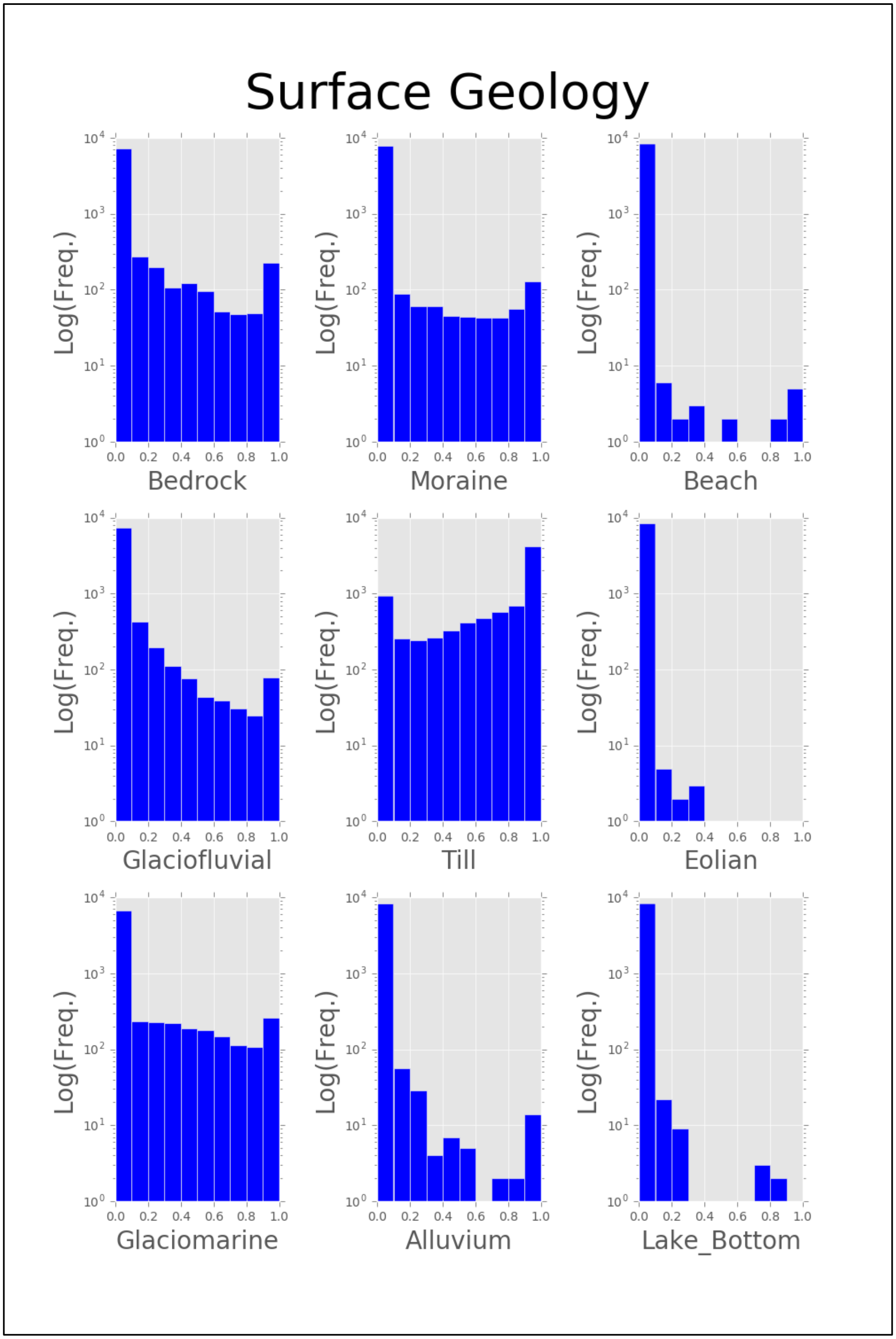

Figure 25: Histograms for the frequency of percent cover across all Maine drainage divides for each of the surficial geology categories.

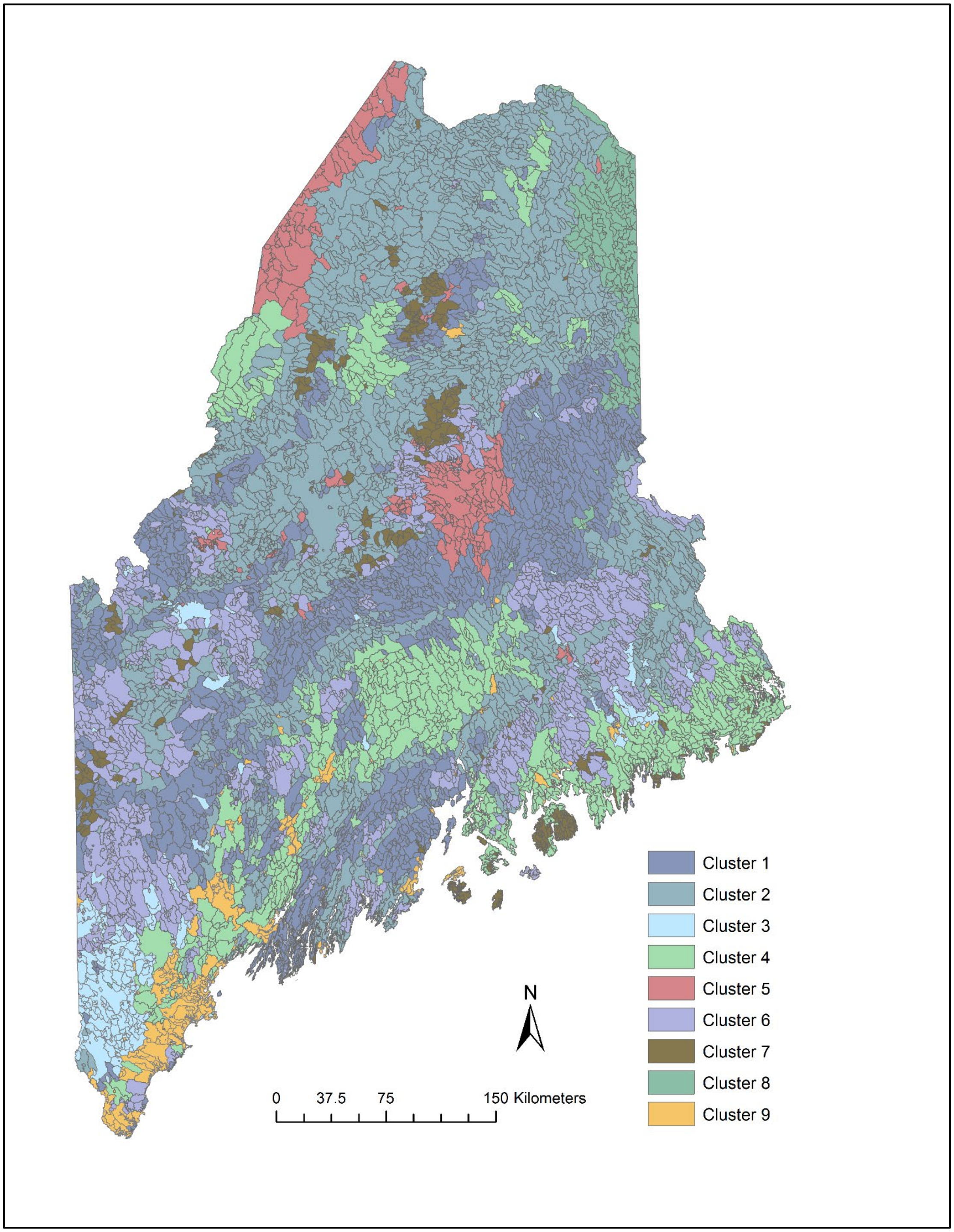

Figure 26: Maine GRUs derived from PCA and cluster analysis.

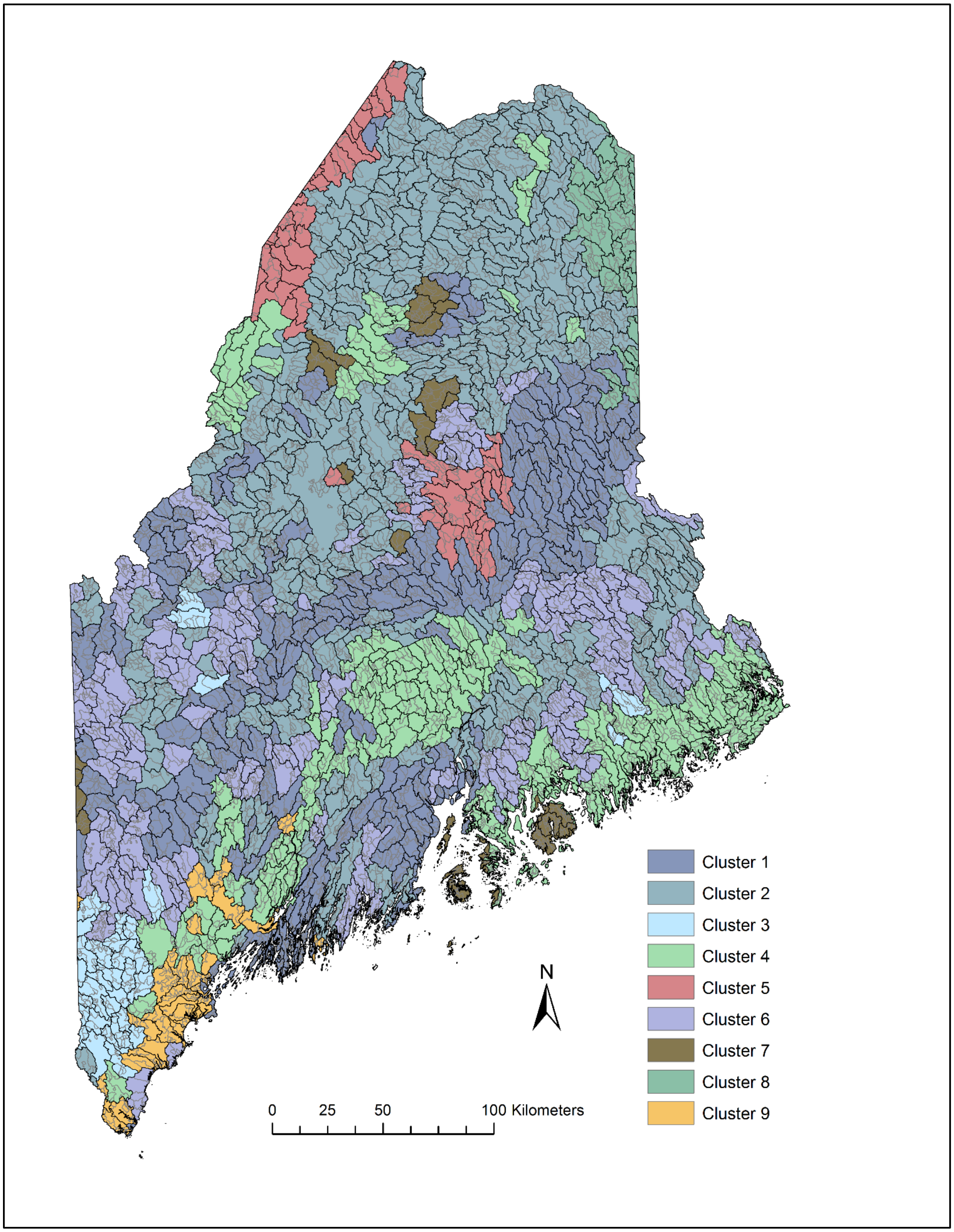

Figure 27: Maine GRUs averaged across HUC-12 watersheds.

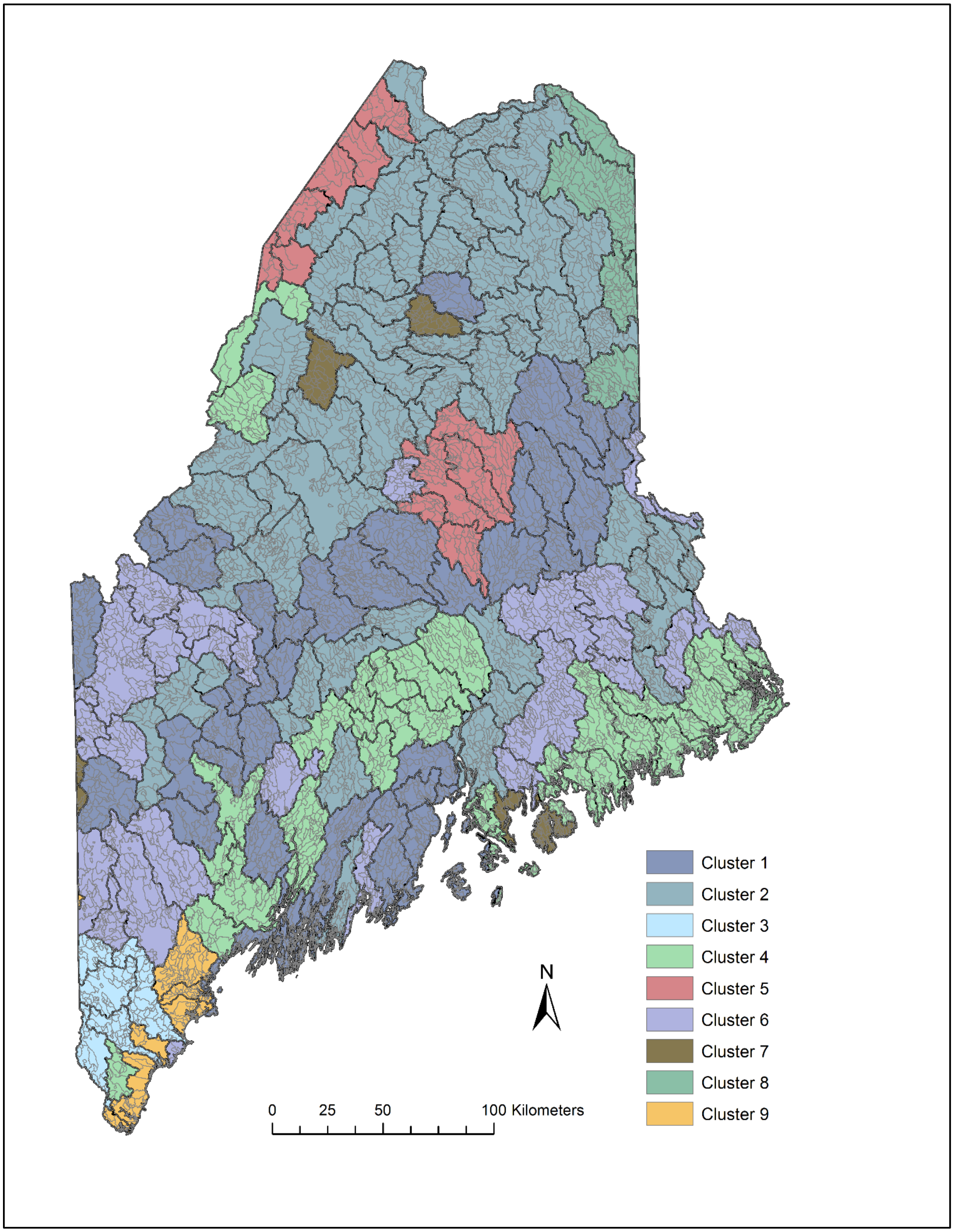

Figure 28: Maine GRUs averaged across HUC-10 watersheds.

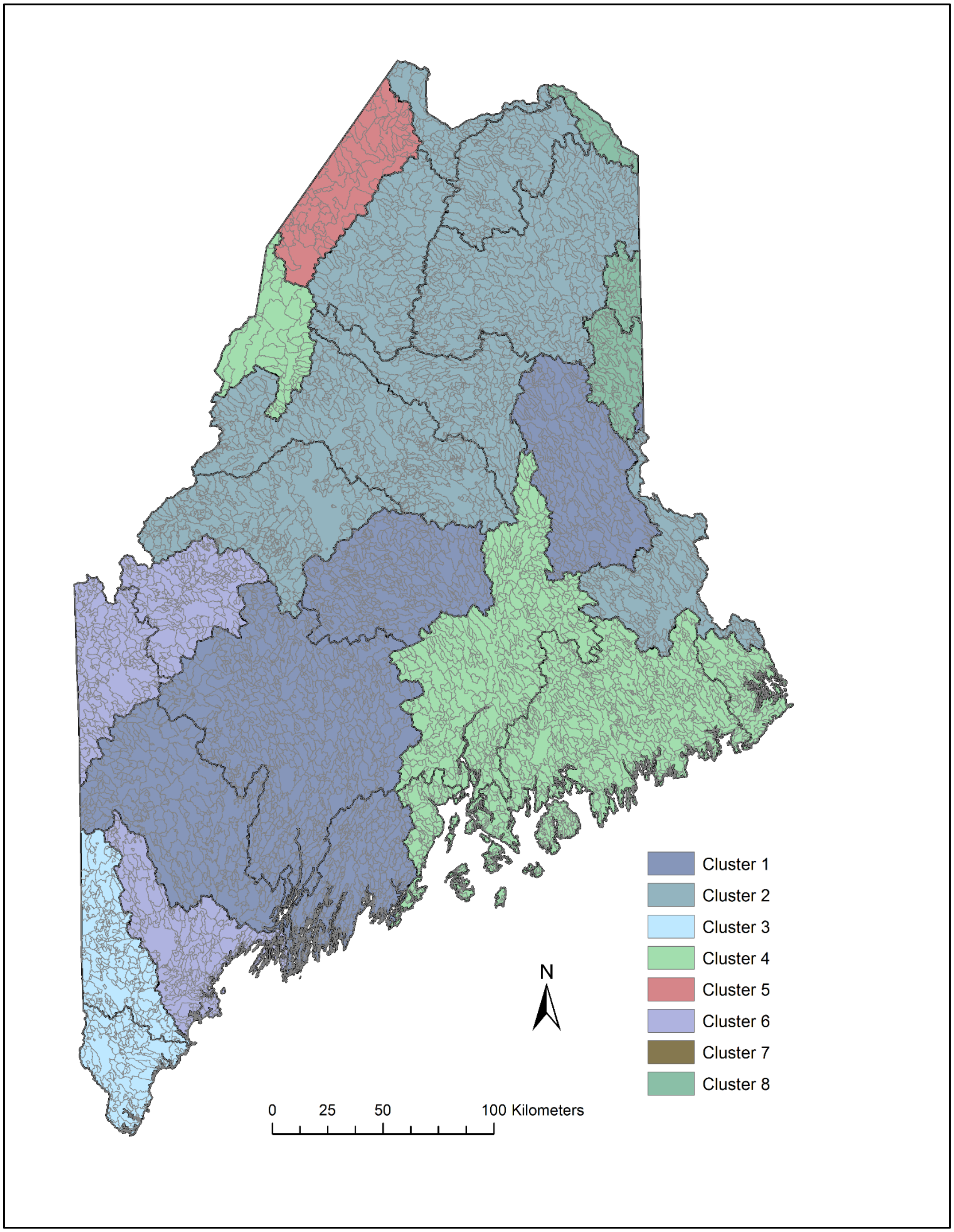

Figure 29: Maine GRUs averaged across HUC-8 watersheds.

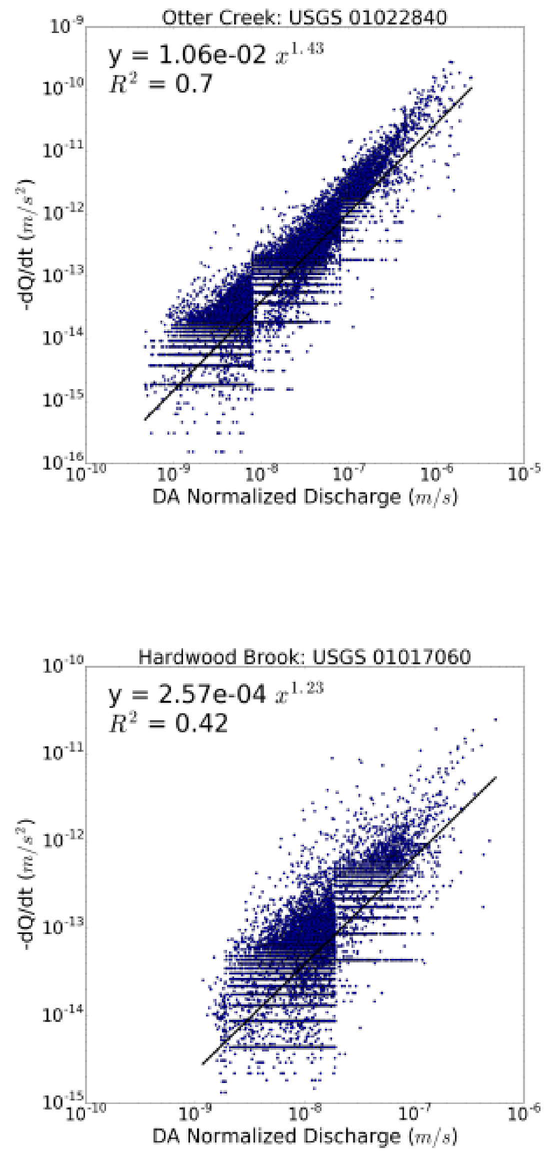

Figure 30-A: Sensitivity function plots for selected USGS monitoring stations. The x-axis is drainage area normalized discharge during periods of receding flows. The y-axis represents the rate (slope) of flow decrease at each instance.

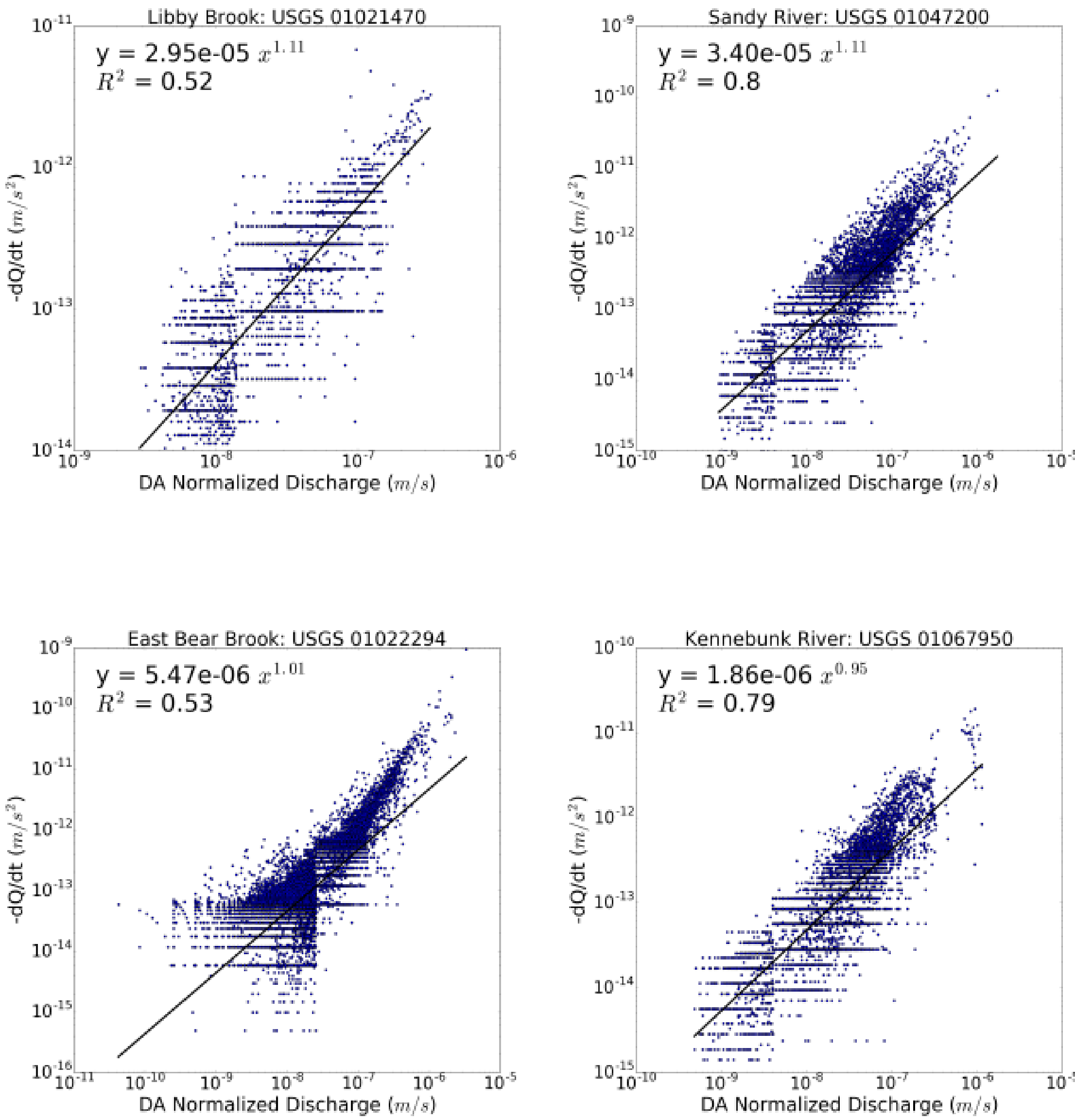

Figure 30-B: Sensitivity function plots for selected USGS monitoring stations. The x-axis is drainage area normalized discharge during periods of receding flows. The y-axis represents the rate (slope) of flow decrease at each instance.

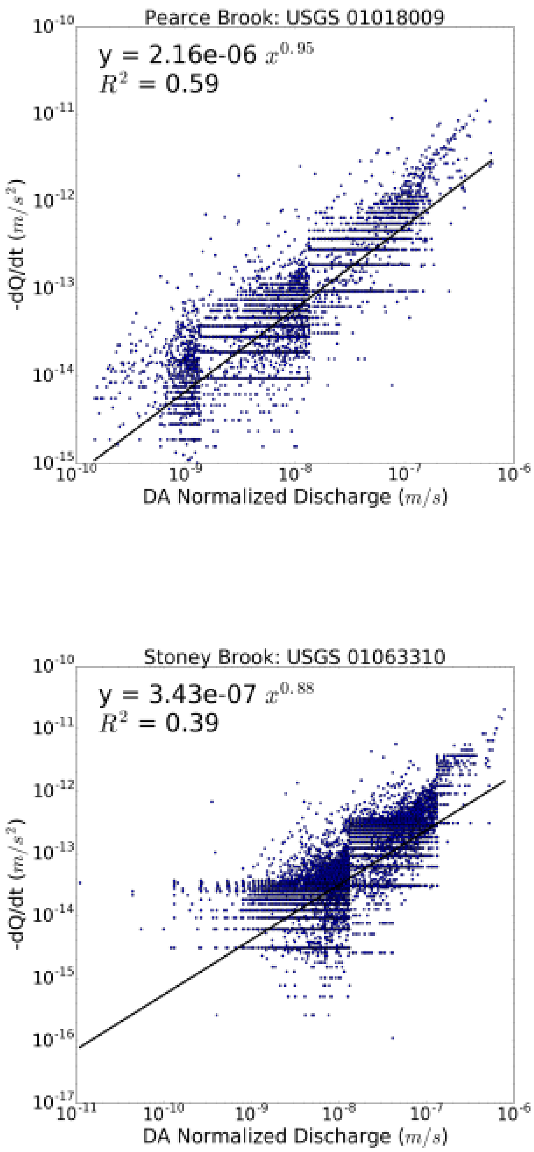

Figure 30-C: Sensitivity function plots for selected USGS monitoring stations. The x-axis is drainage area normalized discharge during periods of receding flows. The y-axis represents the rate (slope) of flow decrease at each instance.

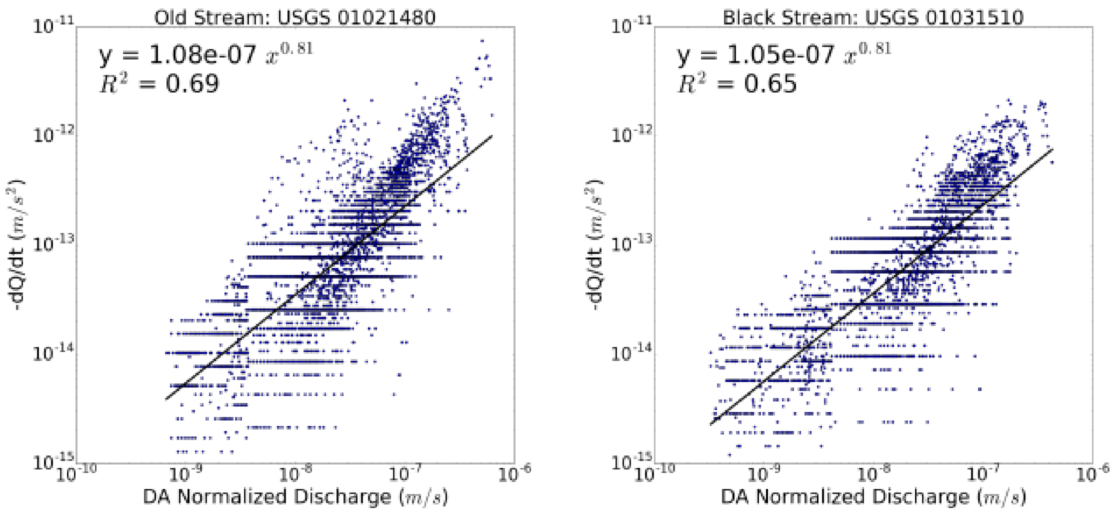

Figure 30-D: Sensitivity function plots for selected USGS monitoring stations. The x-axis is drainage area normalized discharge during periods of receding flows. The y-axis represents the rate (slope) of flow decrease at each instance.

APPENDIX B

CHAPTER THREE SUPPLEMENTAL MATERIAL

B.1 Supplemental Figures

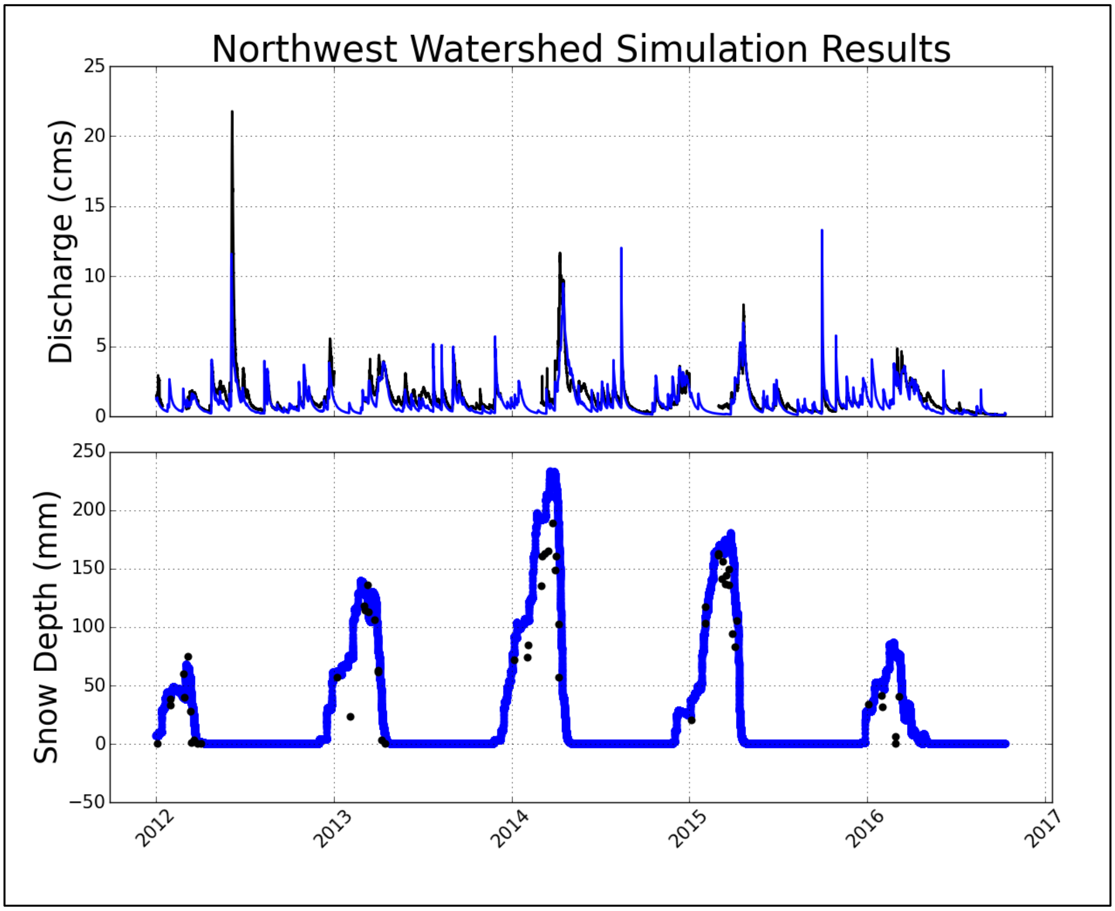

Figure 31: Modeled (blue) and observed (black) discharge and snow depth (in water equivalence) for the Northwest River Watershed.

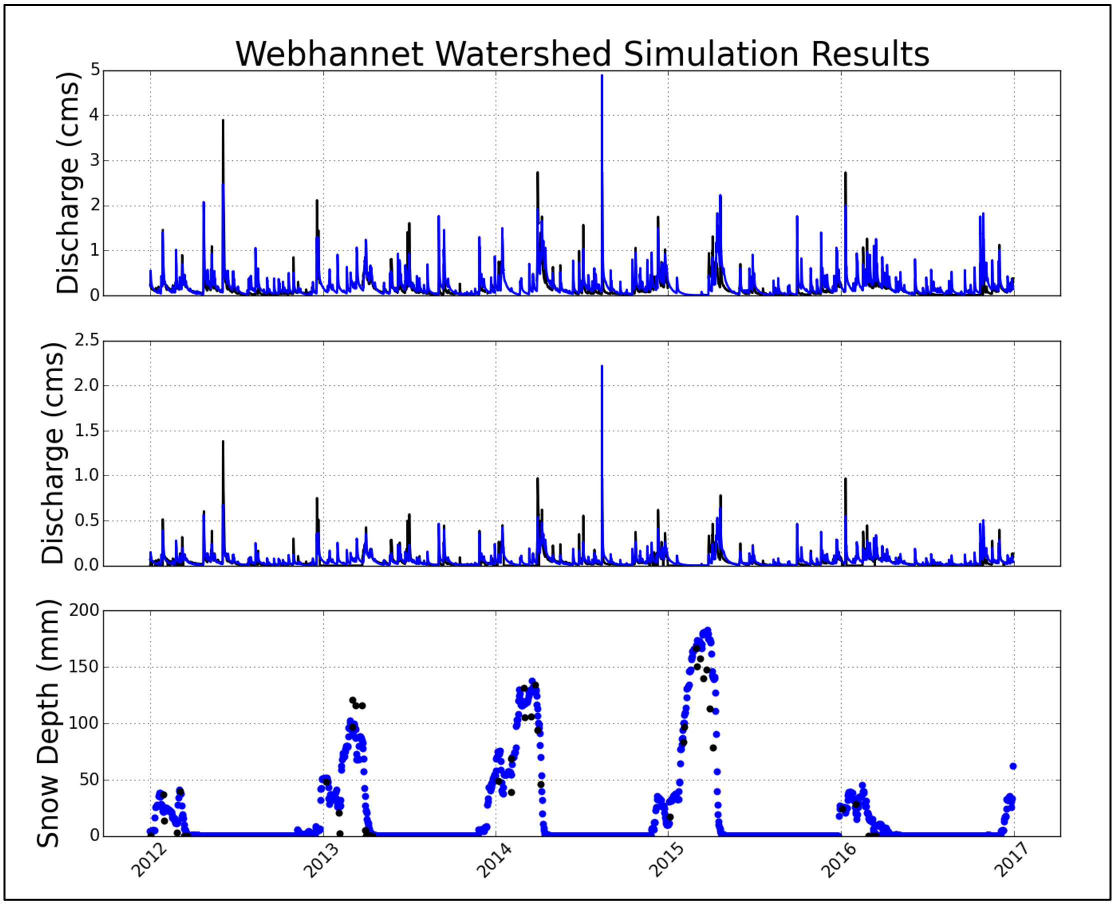

Figure 32: Modeled (blue) and observed (black) discharge and snow depth (in water equivalence) for the Webhannet River Watershed.

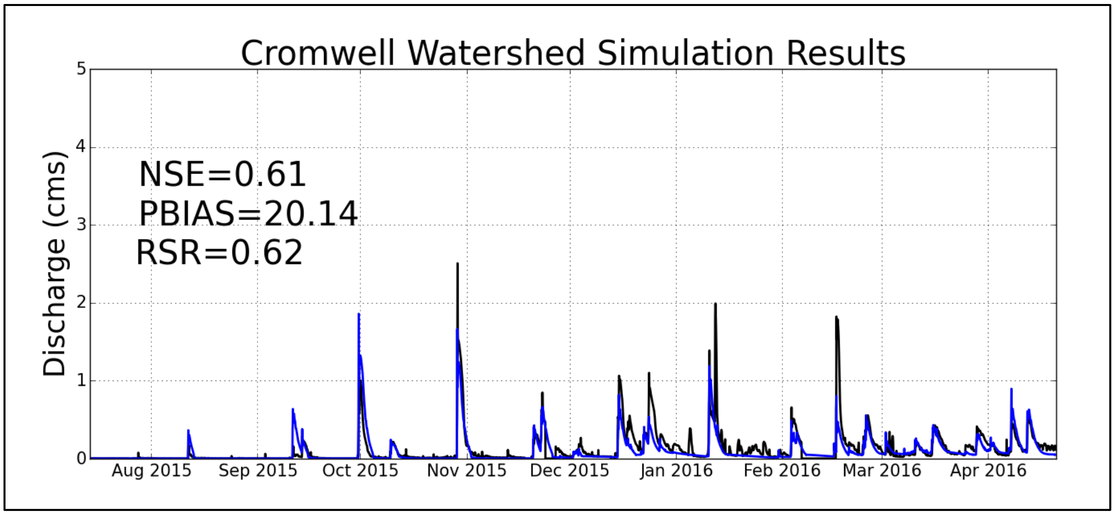

Figure 33: Modeled (blue) and observed (black) discharge and snow depth (in water equivalence) for the Cromwell Brook Watershed.

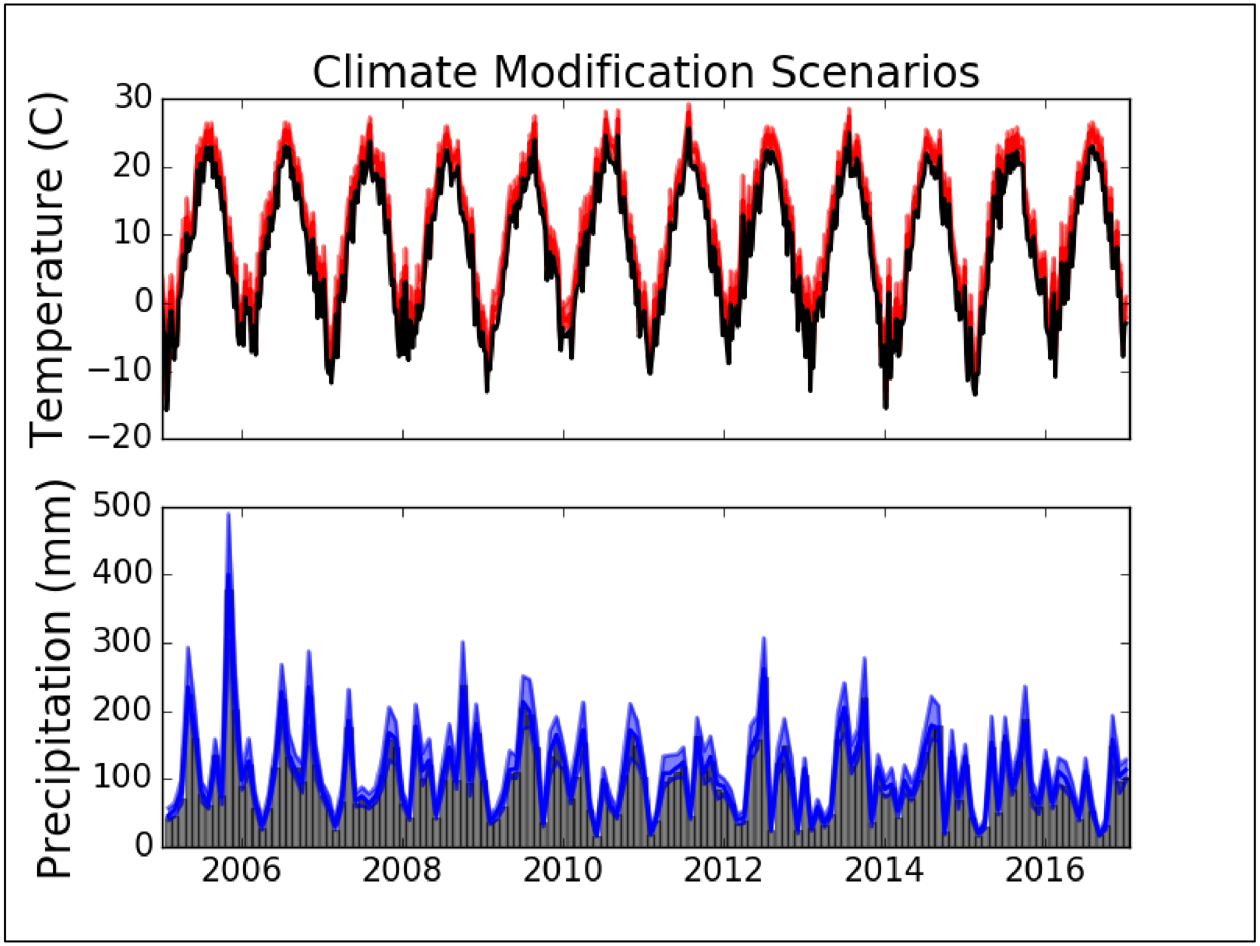

Figure 34: Observed precipitation (gray) and temperature (black) measured in Augusta, ME. The range of modifications to these variables for climate scenarios based on CMIP5 data are plotted in red (temperature) and blue (precipitation).

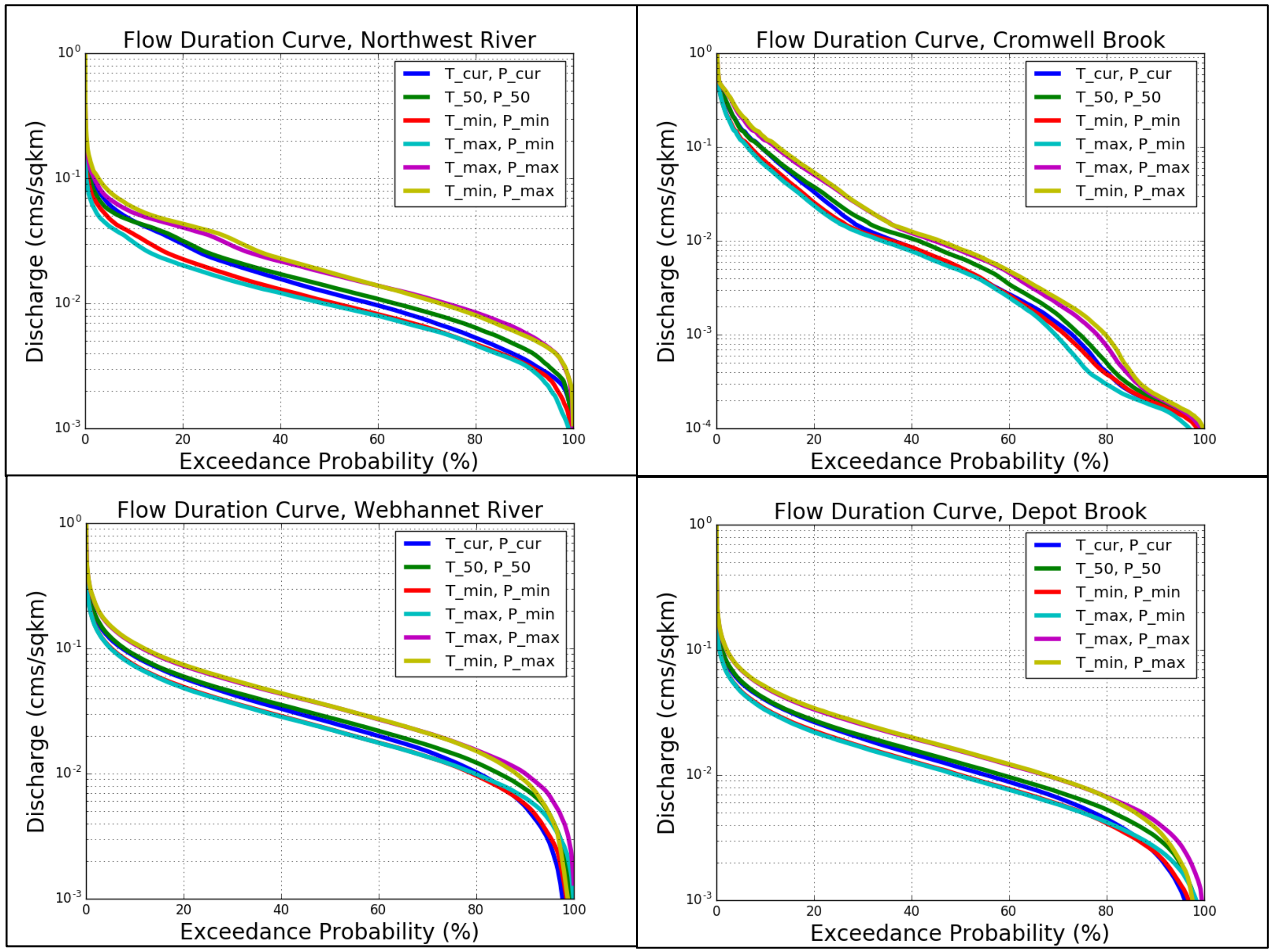

Figure 35: Flow duration curves for the Northwest River, the Webhannet River, and Cromwell Brook under the five scenario conditions compared to current climate conditions.

B.2 Supplemental Equations

B.1: Equations solving for the overland flow discharge per unit area along a cell boundary in the x direction.

$$v_x h = K_x(-\frac{\partial z}{\partial x})^{\frac{1}{2}} h^{\frac{5}{3}}$$

v_x = Velocity in the x direction
h = Depth of water
K_x = Manning's M in the x direction
z = Elevation above the datum

B.2: Equation solving for the overland flow discharge per unit area along a cell boundary in the y direction.

$$v_y h = K_y(-\frac{\partial z}{\partial y})^{\frac{1}{2}} h^{\frac{5}{3}}$$

v_y = Velocity in the x direction
h = Depth of water
K_x = Manning's M in the x direction
z = Elevation above the datum

B.3: Equation for total evapotranspiration (ET) using the two-layer water balance method.

$$ET = ET_{can} + ET_{pon} + ET_{uz} + ET_{sz} + ET_{snow}$$

ET_{can} = Evapotranspiration from the canopy
ET_{pon} = Evapotranspiration from ponded water
ET_{uz} = Evapotranspiration from the unsaturated zone
ET_{sz} = Evapotranspiration from the saturated zone
ET_{snow} = Evapotranspiration from the snow

B.4: Equation for determining infiltration (I) using the two-layer water balance method.

$$I = min(P_b, K_s * \Delta t, (V_s - \theta) * (z - h)$$

P_b = Surface ponding
K_s = Saturated hydraulic conductivity
Δt = Time step length
V_s = Volume of water at saturation
θ = Actual water content
z = Height of cell top above the datum
h = Hydraulic head in the cell

B.5: Linear reservoir method equation for the storage of a reservoir (W).

$$W = k * Q$$

k = Storage constant
Q = Discharge outputs (i.e. interflow and baseflow)

B.6: The vertically integrated equation of the conservation of mass.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

Q = Discharge
A = Flow area
t = Time
q = Later inflows

B.7: The vertically integrated equation of the conservation of momentum.

$$\frac{\partial Q}{\partial t} + \frac{\partial (\propto \frac{Q^2}{A})}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0$$

Q = Discharge
A = Flow area
t = Time
q = Later inflows
C = Chezy's resistance coefficient
R = Hydraulic radius
g = Acceleration due to gravity
$\propto$ = Momentum distribution coefficient

B.8: Equation for temperature melting of snow (M_T).

$$M_T = J_T(T - T_0)$$

J_T = Degree-day factor for snow melt
T = Air temperature
T_0 = Freezing temperature of snow

B.9: Equation for radiation melting of snow (M_R).

$$M_R = -J_{Rad}R_{sw}$$

J_{Rad} = Radiation melting factor for snow melt
R_{sw} = Incoming solar radiation

B.10: Equation for energy melting of snow (M_E).

$$M_E = J_E P(T - T_0)$$

J_E = Energy snow melting coefficient for the energy of liquid rain
P = Precipitation
T = Air temperature
T_0 = Freezing temperature of snow

APPENDIX C

CHAPTER FOUR SUPPLEMENTAL MATERIAL

C.1 Supplemental Figures

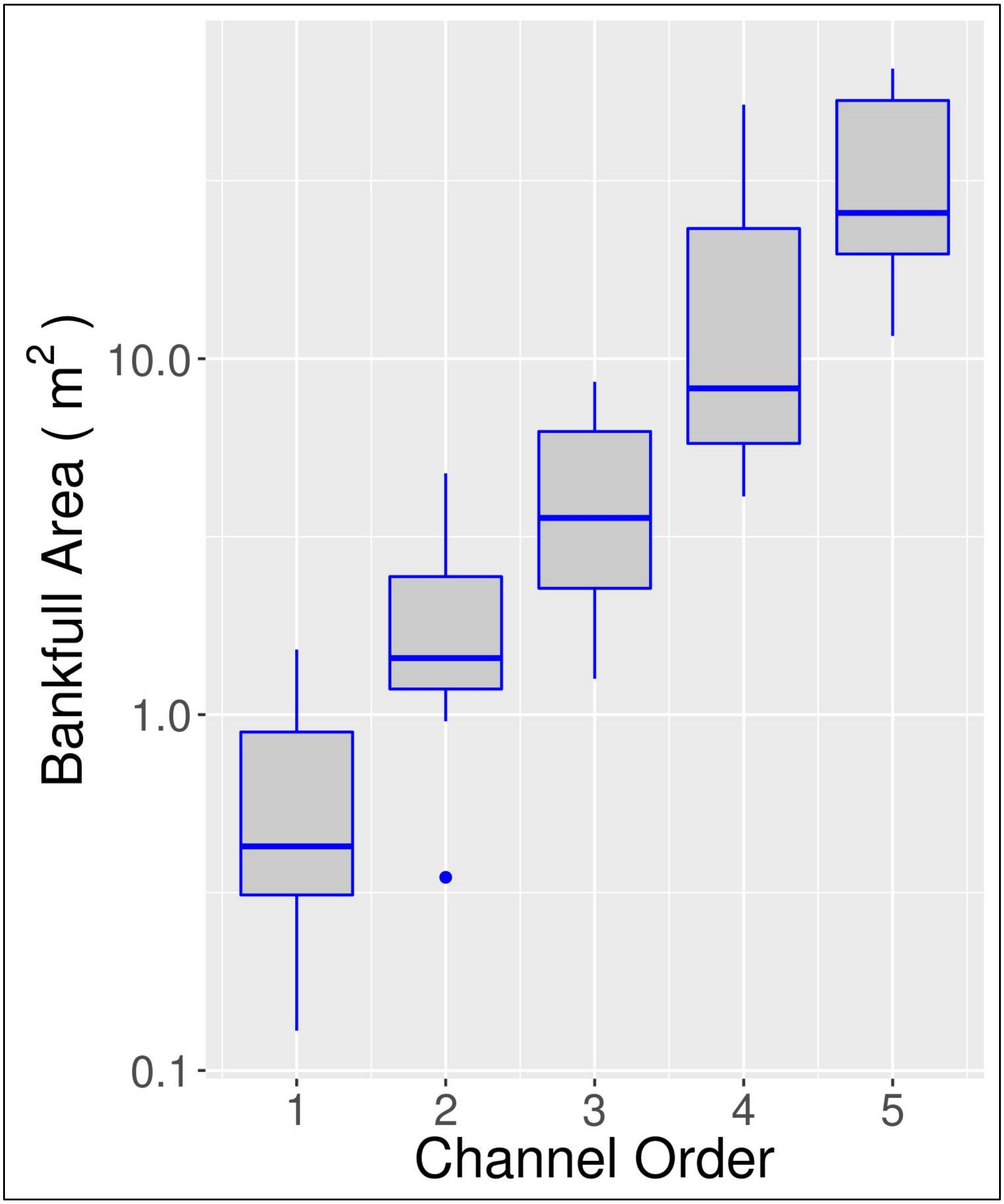

Figure 36: Box and whisker plot of bankfull area vs channel order.

BIOGRAPHY OF THE AUTHOR

Brett Gerard was born in Lafayette, Louisiana. He is the son of Brian and Terrell Gerard. Brett graduated of The Woodlands High School (2005) and Texas State University (B.S. in 2010; M.S. in 2012). He began pursuit of a Ph.D. at the University of Maine in January 2013.

In 2004 he met the woman that in now his wife, Adele Gerard. On November 29, 2016 they welcomed Braxton Raymond Gerard into their family.

He is a candidate for a Doctor of Philosophy degree in Earth and Climate Science from the University of Maine in December 2018.