MODELING THE FLOW OF HALL CREEK, HUMBOLDT COUNTY, CALIFORNIA USING VISUALIZING ECOSYSTEM LAND MANAGEMENT ASSESSMENTS (VELMA) AND CALCULATING THE CHANNEL FORMING FLOW USING THE EFFECTIVE DISCHARGE CALCULATION

By

Ethan Abraham Luckens

A Thesis Presented to

The Faculty of Humboldt State University

In Partial Fulfillment of the Requirements for the Degree

Master of Science in Natural Resources: Environmental Science and Management

Committee Membership

Dr. James Graham, Committee Chair

Dr. Eileen Cashman, Committee Member

Dr. David Gwenzi, Committee Member

Dr. Jonathan Halama, Committee Member

Dr. Erin Kelly, Graduate Coordinator

December 2019

ABSTRACT

MODELING THE FLOW OF HALL CREEK, HUMBOLDT COUNTY, CALIFORNIA USING VISUALIZING ECOSYSTEM LAND MANAGEMENT ASSESMENTS (VELMA) AND CALCULATING THE CHANNEL FORMING FLOW USING THE EFFECTIVE DISCHARGE CALCULATION

Ethan Abraham Luckens

Due to wide spread stream degradation across the globe there is great potential for restoring stream and riverine habitat. Land managers often lack necessary information about the stream discharges of ungauged watersheds. This lack of data makes designing stream restoration projects in ungauged watersheds more difficult. This is especially true when trying to determine the channel forming flow (Q_{cf}), the discharge that will support a stable channel geometry. In this study, the channel forming flow was approximated using effective flow (Q_{ef}). Effective flow is the level of flow that transports to greatest amount of sediments. One method for calculating effective flow is to use stream discharge and sediment transportation data. Modeled annual discharge data was generated for Hall Creek, an ungauged watershed, by running the Environmental Protection Agency's Visualizing Ecosystem Land Management Assessments (VELMA) ecohydrology model. The modeled VELMA flow data for Hall Creek and bedload sediment data from a similar nearby creek was used as the inputs for the effective discharge calculation. The effective discharge of Hall Creek was found to be 2.52 cubic meters per second.

ACKNOWLEDGEMENTS

I would like to thank the California National Guard Education Assistance Award Program (CNG EAAP) for offsetting a good portion of my tuition fees.

I would also like to thank the VELMA 2.0 team at the Environmental Protection Agency Corvallis Oregon Office who put together the VELMA training day, showing incredible hospitality, and fielding my questions during my research and writing process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

INTRODUCTION

1. Importance and Degradation of Streams

Streams and riparian areas are important habitat for many species and provide critical ecosystem services. Despite the value that streams provide in terms of habitat to many species the, majority of the world's streams have been modified to control the flow of water for flood protection or to divert water for other land uses such as agriculture (Brookes and Shields 1996). Scientists have recently gained a greater understanding of the value of stream ecosystem services in terms of water quality and the integrity of aquatic ecosystems. Due to this greater appreciation of streams there is now potential for restoring stream and riverine habitats. Restoring the functional community in a degraded stream is difficult and often expensive (Brookes and Shields 1996). Due to this restoration burden, every action should be taken to ensure that projects are successful. Modeling the potential flow and streambed geomorphological processes during the planning phase of a restoration project can ensure that the project has a greater chance of providing long term restoration benefits (Kondolf et al. 2000, Kondolf et al. 1996).

1.1 The Importance of Streams

Worldwide, streams and adjacent riparian areas are used by a wide variety of species and provide an unusually high amount of ecosystem services compared to their limited spatial extent (Raedeke 1989). Streams and their adjacent riparian areas are less than 10% of the total land mass; yet despite their limited watershed footprint, they offer an unusually diverse array of ecological services far in excess of their geographical extent (Naiman, Decamps, and Pollock 1993). The riparian corridor encompasses the stream channel itself, plus the terrestrial landscape above the high water mark where vegetation is influenced by elevated water tables or flooding. It is thought that 70% of vertebrate species in a region will use riparian corridors in some significant way during their life cycle (Raedeke 1989).

1.2 Damage Done to Streams

The impacts of humans on floodplains, river channels, and streams have been extensive worldwide. Humans have been changing the flow of water bodies for over 4000 years, though it has been heavily accelerated in the last 250 years due to industrialization (Brookes and Shields 1996). The flow of streams and rivers was changed to drain areas for agriculture or urban development: control flooding, hydropower generation, create impoundments, or for irrigating crops. Due to humans' ability to modify streams, it is thought that 60% of the world's total stream flow has been regulated or moderated in some way (Brookes and Shields 1996, Brookes 1988). In North America, almost immediately following settlement, settlers began to make changes to riparian areas to improve them for production of agricultural products and protect their new communities (Apostal et al. 2006).

The banks of natural stream channels are often modified. Modifications include removing natural vegetation, clearing snags, deepening channels, constructing dikes and levees, rip-rapping banks, and building dams (Apostal et al. 2006). In some more developed places, such as cropland or urban areas, the streams have been engineered into culvert pipes so the land above them can be developed (Apostal et al. 2006).

Channelization of streams and draining riparian areas was one of the first tasks that settlers in North America undertook (Apostal et al. 2006). In the 150-year period following the European settlement in North America at least 320,000 km of rivers and streams were modified. This work was accomplished to drain land for agriculture, control flooding, and facilitate the movement of goods (Brookes 1988). It is estimated that greater than 80% of the riparian corridor area of North America and Europe has disappeared in the last 200 years (Decamps and Naiman 1989, Petts et al. 1989). To this day the modification of this important habitat is continuing on a global scale, with little attention being paid to the ecological or human consequences of these changes (Decamps and Naiman 1989, Petts et al. 1989).

The extent of river modification, as an example, can be seen with Oregon's Willamette River. Since European settlement the banks of the Willamette River have been modified from their natural state and 80% of the riparian vegetation that the Willamette had before this time is no longer present. It is also thought that the Willamette River has lost half of its channel complexity as it used to have many off-channel wetlands and side channel features. These changes to the river have decreased the amount of native plants that inhabit the river and the disturbed areas along the river are conducive habitat for non-native plants, resulting in the majority of the riparian plant life along the Willamette River being non-native species (Apostal et al. 2006). In the Oregon Coast Range, most of the virgin riparian forest have been disturbed and replaced with early seral stage forests, which are an inferior habitat for riparian species (Apostal et al. 2006). Human activities in many watersheds have simplified stream channels, separated streams from there flood plains, fragmented streams, altered flows, and introduced toxic contaminants (Stanford and Ward 1992; Frissell 1997). As a result of this, the overall quality of streams in the Pacific Northwest may have been degraded.

The main consequences of the channelization of streams is a reduction in the complexity of habitat by the elimination of side-channel pools, riffles, and overall heterogeneity of the channel geometry. Channelization has increased water temperatures due to removal of bank-side and in-stream vegetation caused bed and bank erosion, as well as downstream flooding and sedimentation (Brookes 1988). The combined effects of these changes produce a wide range of biological impacts such as reducing the diversity of stream bed invertebrates, fish, and aquatic vegetation. Channelization can also lower the water table in the adjacent floodplain, which can negatively affect natural vegetation and wildlife (Brookes 1988).

1.3 Damage Done to Local Streams

The negative effects of historic land management activities such as logging, stream channel modification, or the drainage of nearby wetlands has been identified in virtually every stream inventory report along the North Coast of California. The result has been a significant decrease in pool frequency, depth and shelter values, significant stream bank erosion, locally dysfunctional or poorly functioning riparian habitat, high values of substrate embeddedness, and channel geomorphology simplification (Farro 2014).

Within the coastal mountain ranges of California, farmers and ranchers straightened and enlarged streams with horse drawn slip-scrapers and laborers as early as the 1870s (Keller 1976; Brookes 1988). Stream modification was accomplished to drain land for agriculture and reduce the risk of flooding. In timber rich areas, stream beds were often used as skid roads. Logs were dragged down the stream beds; damaging the banks and stream beds in the process (Apostal et al. 2006).

Within Coastal Northern California, stream aggregation is a major problem. Due to historic land uses and the unstable, erodible underlying Franciscan uplift geology, the lower reaches of many streams in this area are becoming clogged with sediments from upstream headwaters areas (GEC 2011). For example, the upstream aggregation of the Salt River has filled in much of the Salt River's channel. "Modifications for grazing and timber harvest in upslope areas increased sediment loading to the main stem of the Salt River" (GEC 2011). In response to this, a large restoration effort has taken place involving both excavating the channel of the Salt River and efforts have been taken to reduce the sediments from upstream through actions such as decommissioning unused logging roads.

The Coastal Streams of Northern California, such as Hall Creek in Northern Humboldt County, are spawning areas for economically and culturally important anadromous salmonids, such as coho salmon (*Oncorhynchus kisutch*), king salmon (*Oncorhynchus tshawytscha)* and steelhead trout (*Oncorhynchus mykiss iridius)*. As a result of the negative effects of historic land management the populations of these salmonid species have declined. Due to this, there is interest and conservation money available for the restoration of these streams (Williams and Reeves 2006). The health of coastal streams is not just based on fisheries. These streams also provide high quality water to municipal users. As an example, the confluence of Hall Creek and the Mad River is just upstream from the Humboldt Bay Municipal Water District pumping stations that provides water for much of the population of Humboldt County. Healthy coastal streams also recharge aquifers and help reduce the risk of flooding (Williams and Reeves 2006).

1.4 Damage to Hall Creek

Hall Creek was channelized into the west side of the valley so the valley could be used to grow food and forage for the nearby timber industry and to reduce the risk of flooding for the mill community that lived in the lower parts of the Hall Creek Valley. Many of the upslope tributaries of Hall Creek were filled with logging debris, sediments, and used as skid trails during the first and second logging cycles (Farro 2014).

It is not known for certain, but the lack of legacy large woody debris in Hall Creek and corresponding streams suggests that they were cleared of woody debris in the 1970s to improve the drainage of the stream. Pacific Watershed Associates and California Department of Fish Wildlife surveys from 2014 revealed that minimal amounts of large woody debris were present. Pacific Watershed Associates concluded in 2014 that this lack of large woody debris has led to increased local channel aggregation and a simplification of channel geomorphology (Farro 2014).

A portion of Hall Creek is located in the bottom of a steep sided valley, where coarse sediments originating in the steeper upper reaches are deposited as the stream flow velocity slows when the Hall Creek reaches the flat valley floor. This has furthered the aggregation problem in the stream bed. In some places along Hall Creek, the stream bed level has risen at least 60 cm in recent years; demonstrated by streamside fences that are half buried in gravel (McAdams, personal communication, 2017; Farro 2014).

Despite the damage done to Hall Creek, it still supports a significant population of coho salmon (Farro 2014).

2. Stream Restoration

Stream restoration seeks to undo the damage caused by human activities by reversing or removing the main degrading factor to that stream system (Williams and Reeves 2006). The goal of stream restoration projects is not always to restore the stream to historical conditions since that is often not possible or the pre-settlement conditions of the stream may not even be known (Williams and Reeves 2006; Kondolf et al. 2001).

Geomorphic influences on a stream restoration project need to be accounted for during the planning process to ensure that an appropriate project is executed. If this is not accounted for, the restoration efforts may not lead to an enduring post project state. Items that need to be known are: stream channel form, distribution velocities in the project reach; changes in channel form; and sediment transport patterns anticipated after the project is completed (Kondolf 2000).

A degraded stream will eventually re-carve a stable natural channel if the geomorphic processes that determined the original channel are still functioning. If the same run-off and sediment regime that led to the creation of the original stream channel still occurs, it is thought that the stream will eventually return itself to its pre-disturbance state. This natural process could take tens to hundreds of years (Kondolf et al. 2001).

Less successful projects not only waste funds and time, but divert funds from projects that may have more impact. This waste often makes the public question the allocation of money and effort on stream restoration (Kondolf 2000). Uvas Creek project near Gilroy California is an example where restorationists attempted to channelize the wide aggraded stream bed into a single stable meandering channel. The stream was historically a braided stream flowing across the flood plain. After channelization, the stream soon flooded and meandering channels returned the stream back to the pre-project conditions (Kondolf et al. 2001).

2.1 Types of Stream Restoration Work

Stream restorationists often seek to reintroduce channel complexity, reconnect fragmented systems, restore natural flow regimes, re-vegetate areas, reduce sediments washing into the stream, and eliminate sources of chemical pollution (Williams and Reeves 2006). This is accomplished by several methods. Un-used road systems in head water areas can be removed to reduce sediments that flow into the stream (Humboldt County Resource Conservation District 2017). Vegetation can be planted in riparian areas adjacent to streams to reduce instream temperatures and filter out fine sediments (Apostal et al. 2006). Large instream objects (such as debris or boulders) can be strategically emplaced to manipulate current velocity and sediment deposition. These objects often scour deep pools that are beneficial to fish (Waters 1995). Stream crossings such as culverts can be improved or replaced with bridges (Apostal et al. 2006). New channels can also be designed to restore a natural flow regime (Brookes and Shields 1996).

3. Salmonid Restoration

Due to the economic and cultural value of anadromous salmonids in the Pacific Northwest, the likelihood of a stream restoration project being funded and executed greatly increases when it will benefit these species habitat. Within the Pacific Northwest, stream restoration projects are often based on improving the habitat of the coho salmon and the steelhead trout (Burnett et al. 2003). The type and productivity of fish populations in a watershed are related to the geomorphic features of the stream (Montgomery and Buffington 1997, Burnett et al. 2003). The most productive habitats for coho salmon are low-gradient watersheds with wide valleys and intermediate-sized streams (Burnett et al. 2003). Coho salmon prefer stream with more pools, slower velocities, and large accumulations of gravel. The most productive habitats for steelhead trout, an anadromous sub-species of rainbow trout, prefer steeper gradient (3-5%) medium sized streams with narrow valleys. Ideal steelhead habitat possess smaller pools with higher velocities.

The body type and behavior of these two fish are adapted to their preferred habitat types. Coho are surface oriented with bodies that can maneuver quickly. Steelhead are bottom oriented with large pectoral fins to help them hold position in the current and narrow laterally compressed bodies (Burnett et al. 2003, Bisson et al. 1988). Not all streams have the same capacity for salmonid habitat and the limits of individual streams need to be recognized so that restoration efforts are not wasted on streams of lower habitat potential.

4. Flow

Flow (aka discharge) refers to the mean daily stream water discharge. Discharge is the volume of water passing through a cross sectional plane in a stream per unit of time. This is typically expressed as cubic feet per second (CFS). Discharge is the product of the stream's velocity times depth of the water times width of the water. These values are collected at gauge stations located on a stream or river (Shaw, 1994).

$$Discharge = velocity\ of\ water * depth\ of\ water * width\ of\ water$$

4.1 Channel Forming Flow

Alluvial streams have the potential to adjust their channel dimensions to accommodate the wide range of flows that move the sediments that form their channels. In many streams it has been demonstrated that a single representative discharge can be used to determine a stable channel geometry that would produce the same bankfull dimensions that would result from natural processes. The use of a single representative discharge is the foundation of "regime" and "hydraulic geometry" theories for determining morphological characteristics of alluvial channels and rivers. This single flow level that determines the geometry of a stream's channel is referred to as the dominant discharge or channel forming discharge (Biedenharn et al. 2000).

Channel forming discharge is often abbreviated as Q_{cf} (Biedenharn et al. 2000). The concept of channel-forming flow Q_{cf} or dominant discharge has since been widely accepted by river channel restoration designers. Three measures of channel-forming discharge that are most commonly applied: effective discharge(Q_{eff}), bankfull discharge(Q_{bf}), and a discharge of a certain recurrence interval(Q_{ri}), which theoretically are similar in geomorphically stable channels (Doyle et al. 2007).

Proper use of effective discharge, bankfull discharge, or return interval discharge are debatable as being interchangeable as approximations of the channel forming discharge. Q_{ri} and Q_{bf} are much less time consuming and conceptually simpler to quantify, and as a result they are often used in restoration projects to approximate Q_{cf}. Assuming similarity among Q_{bf}, Q_{ri}, and Q_{eff} is often invalid despite the widespread use of Q_{bf} for Q_{cf} (Doyle et al. 2007). It is thought that deviation from equality among the three Q_{cf}measures is particularly strong in systems with high anthropogenic modification and divergence of the measures of Q_{cf} may be indicative of channel instability. Doyle called using only Q_{bf} or Q_{ri} during the channel design process "risky and unwise"(Doyle et al. 2007).

4.1.1 Bankfull Flow

Bankfull flow Q_{bf} is the maximum discharge that can be contained within the channel without over-topping the banks. Leopold et al. proposed that this flow is responsible for forming and maintaining the morphology of the channel (Leopold Wolman and Miller, 1964).

4.1.2 Return Interval Flow

The most commonly used return flow interval for determining channel forming flow is a 1.58 year return interval flow ($Q_{1.5}$). The 1.58 year return interval flow approximates the “most probable annual flood”. The most probable annual flood corresponds with a 1.58 year return interval calculated from annual maximum flow series data (Biedenharn et al. 2000; Hey 1975; Leopold Wolman and Miller 1964).

4.1.3 Effective Flow

Effective flow (Q_{eff})is the discharge or range of discharges which, over time, transports the greatest quantity of sediment. According to Doyle et al. 2007, both suspended (Wolman and Miller 1960; Nash 1994; Crowder and Knapp 2005; Simon et al. 2004) and bed load (Andrews and Nankervis 1995; Emmett and Wolman 2001) sediment rating curves have been used for Q_{eff} computation, and computational procedures are well established (Biedenharn et al. 2000) as are analytical procedures for approximating Q_{eff} (Goodwin 2004). For analyzing or designing a channel, Q_{eff} provides the greatest information on actual channel processes but requires greater data and analysis compared to Q_{ri} or Q_{bf}. Q_{eff} is thus a preferable approach for channel design (Doyle et al. 2007; Bidenharn et al. 2000). As Hall Creek is a gravel and cobble bedded stream, a bed load sediment rating curve will be used to calculate effective flow (Biedenharn et al. 2000).

5. Flow Modeling Software

There are several stream flow modeling software products available from both private and government sources. Some of the more commonly used flow modeling software products are United States Geological Survey's GSFLOW, the US Army Corps of Engineers' Hydraulic Engineering Center's models Hydraulic Modeling System and River Analysis System (HEC-HMS and HEC-RAS). A lesser known, but valuable, modeling software application is the Environmental Protection Agency's Visualizing Ecosystems for Land Management Assessments (VELMA) program.

5.1 GSFLOW

Groundwater and Surface-water FLOW (GSFLOW) is a combined groundwater and surface-water flow model created by the United States Geologic Survey (USGS). GSFLOW is "based on the integration of the USGS Precipitation-Runoff Modeling System (PRMS) and the USGS Modular Groundwater Flow Model (MODFLOW and MODFLOW-NWT)". GSFLOW was developed to simulate coupled groundwater/surface-water flow in one or more watersheds by simultaneously simulating flow across the land surface, within subsurface saturated and unsaturated materials, and within streams and lakes. Climate data consisting of measured or estimated precipitation, air temperature, and solar radiation, as well as groundwater stresses (such as withdrawals) and boundary conditions are the driving factors for a GSFLOW simulation." GSFLOW operates on a daily time step (Markstrom et al. 2008).

GSFLOW can be used to evaluate the effects of such factors as land-use change, climate variability, and groundwater withdrawals on surface and subsurface flow. GSFLOW can be used over watersheds that range in area from a few square kilometers to several thousand square kilometers and for time periods of a few days to several months (Markstrom et al. 2008).

5.2 HEC-HMS

The US Army Corps of Engineers' Hydrologic Engineering Center's Hydraulic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It can be applied to a wide variety of geographic areas from small to large natural watersheds for water supply or flood modeling, and even small urban watersheds; all simulated to calculate runoff. Hydrographs produced with HEC-HMS can be used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, wetlands hydrology, and systems operations

The main components of the HEC-HMS are the basin models, meteorological models, control specifications, and input data components. These components are brought together in a simulation that calculates the precipitation run-off response in the basin model given the input from the meteorological model. The control specifications define the time period and time step of the simulation run. Input data components such as time series data, paired data, and gridded data are often required as parameter or boundary conditions in basin and meteorological models (Flemming and Brauer 2016).

The basin model component represents the physical watershed. The user creates a basin model by adding and connecting hydraulic elements. The meteorological model calculates the precipitation input required by a sub-basin. The meteorological model can utilize both point and gridded precipitation as input driver data and model frozen and liquid precipitation and evapotranspiration. The Watershed Explorer feature is the Graphic User Interface (GUI) that allows you to access the components of the HEC-HMS project (Flemming and Brauer 2016).

5.3 HEC-RAS

The US Army Corps of Engineers' Hydraulic Engineering Center's River Analysis System (HEC-RAS) is a modeling program able to perform one and two-dimensional hydraulic calculations for a full network of natural and constructed channels. According to the US Army Corps of Engineers (USACE) website "The HEC-RAS system contains several river analysis components for: (1) steady flow water surface profile computations; (2) one- and two-dimensional unsteady flow simulation; (3) movable boundary sediment transport computations; and (4) water quality analysis. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. As well as the river analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed." (USACE 2018).

The steady flow water surface profiles module is intended for calculating water surface profiles for steady gradually varied flow. The system can compute a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow water surface profiles (USACE 2018). The one- and two-dimensional unsteady flow simulation component of the HEC-RAS modeling system is able to simulate one-dimensional, two-dimensional, and combined one/two-dimensional unsteady flow through a full network of open channels, floodplains, and alluvial fans (USACE 2018).

The sediment model is able to simulate long-term trends of scour and deposition in a stream channel that could result from modifying the frequency and duration of the water discharge and stage height, while modifying the channel geometry. This sediment transport system can be used to evaluate deposition in reservoirs, design channels required to maintain navigation depths, predict the influence of dredging on the rate of deposition, estimate maximum possible scour during large flood events, and evaluate sedimentation in fixed channels" (USACE 2018).

The water quality analysis component of HEC-RAS can allow the user to perform riverine water quality analyses of water quality affecting chemicals such as dissolved nitrogen, phosphorus, and oxygen. (USACE 2018).

5.4 VELMA

The Visualizing Ecosystems for Land Management Assessments (VELMA) is a spatially distributed, eco-hydrological model that integrates a land surface and four layer subsurface hydrology model with a terrestrial biogeochemistry model to simulate the combined responses of vegetation, soil, and water resources from spatial disturbances. VELMA simulates how patterns in climate and land use interact to affect soil water retention, surface and subsurface runoff, vertical drainage, evapotranspiration, vegetation and soil carbon and nitrogen dynamics, and transport of nitrate, ammonium, and dissolved organic carbon and nitrogen to water bodies (McKane et al. 2014). VELMA is different from most other flow modeling programs because VELMA can model the growth and loss of vegetation across the landscape through its Plant Soil Model (PSM), and how the vegetative state affects the movement of water through a watershed. VELMA can also model disturbances such as timber harvest or wildfire and how those will affect water and nutrient cycling though a watershed, though disturbances will not be modeled in this study (McKane et al 2014, Halama, personal communication, July 2018). In this study VELMA was used to model the daily flow of water through the Hall Creek valley. VELMA's daily driver data are historic precipitation and mean daily temperature data, as well as spatial data representing a flat processed digital elevation model, a soil raster, a land cover raster, and a vegetation age raster (McKane et al. 2014).

5.4.1 How VELMA Works

VELMA consists of multilayered soil column models that communicate with each other through the downslope lateral transport of water. Each pixel of the VELMA spatial model is an individual soil column. Each soil column consists of three coupled sub-models: a hydrology model, a soil temperature model, and a plant-soil model (Abdelnour et al. 2011).

The hydrology model tracks and updates daily the soil water storage for four layers of soil, surface standing water, and a snow layer. Snowmelt, soil infiltration, sub-surface lateral flow, surface water flow, and stream flow are all accounted for (Abdelnour et al. 2011). Precipitation falls either as rain or snow based on the air temperature. Snow accumulates at the top of each soil column until the air temperature warms to the melting point, after which a degree-day approach is used to determine the snow melt, which then enters the surface water layer, infiltrates into the soil column, and flows into adjacent downslope pixels. Evapotranspiration rates increase exponentially with increasing soil water storage and asymptotically approach a maximum evapotranspiration rate as the soil reaches its saturation point. The vegetation extracts water from the upper layers of soil until the soil water storage of the upper layers of soil drops below the wilting point. When this occurs, the vegetation will begin to draw water from the lower soil layers (Abdelnour et al. 2011).

The soil temperature model simulates the ground surface temperature and during snow-free times is equal to the air temperature. Sub-surface heat transfer is modeled with a one-dimensional heat conduction equation (Abdelnour et al. 2011).

The plant-soil model (PSM) simulates ecosystem carbon storage and the cycling of carbon and nitrogen between the plant biomass layer and the active soil pools. This model simulates the interaction among plant biomass, humus, detritus, and plant available soil nitrogen. The deposition of atmospheric nitrogen into the first soil layer occurs as a function of precipitation. Uptake of nitrogen by the vegetation increases with stand age in young stands then decreases and reaches an equilibrium value in mature stands. The plant mortality rate is simulated as a function of plant biomass. The plant mortality is assumed to increase exponentially with increasing biomass and reach a steady state in mature stands. Water stress is proportional to the soil layer water saturation and limits vegetation growth as the soil layer wetness approaches zero. The vertical transport of nutrients within the soil column is dependent on the downward movement of water. The soil organic carbon decomposition rate varies with environmental factors such as soil temperature and moisture. Nitrification and denitrification, the oxidation and reduction of nitrogen compounds, is also dependent on soil temperature and moisture. The lateral transport of nutrients downslope though the sub-surface soil layers or through the stream is based on the modeled flow of water downslope through the terrain (Abdelnour et al. 2011).

5.4.2 Streamflow Prediction of Ungauged Watersheds

Rainfall-runoff models, such as the rainfall-runoff component of VELMA, are useful tools that can be used to extrapolate streamflow time-series data for scientific purposes. These models allow researchers to simulate the flow of watersheds where little or no streamflow data is available. Model parameters calibrated on watersheds for which gauged stream flow data exists can be transferred to similar ungauged watersheds and used to model time-series streamflow data. Calibration is the process of adjusting the parameters of the model until the model behavior and the observed streamflow data show a sufficiently high-degree of similarity (Wagener and Wheater 2006). In VELMA, the similarity of the simulated and observed streamflow data is quantified with a Nash-Sutcliffe value (McKane et al. 2014). The suitability of the parameters calibrated on the gauged stream when applied to the ungauged stream are generally related to how similar the two streams are in regards to geographic location, climate, vegetation type, soil type, geology, and land use (Oudin et al. 2008, Patil and Stieglitz 2015, Wagener and Wheater 2006). This method is not perfect and applying parameters calibrated on gauged sites to ungauged sites can lead to inaccuracies in the simulated data due to the differences in physical properties and meteorological inputs between the gauged and ungauged watersheds (Wagener and Wheater 2006).

5.4.3 The Nash-Sutcliffe Equation

The Nash–Sutcliffe model efficiency coefficient (NSE) is used to quantify the predictive power of hydrological models. It is defined as:

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right]$$

where Y_i^{obs} is the *i*-th observation for the constituent being evaluated, Y_i^{sim} is the *i*-th simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated and *n* is the total number of observations. (Moriasi et al. 2007).

The NSE value quantifies the goodness of fit of the predicted flow values against the observed flow values. A Nash-Sutcliffe value can be from $-\infty$ to 1. An efficiency of 1 corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model" (Nash and Sutcliffe, 1970).

According to Dr. Jonathan Halama a Nash-Sutcliffe value of 0.6 is the base line for substantiating a VELMA model, though values closer to 1 are indicative of a stronger model (Halama J, personal communication, July 2018).

6. On-going Projects on Hall, Mill, and Noisy Creek on the McAdams K-Bar Ranch.

The landowners of the McAdams K-Bar Ranch are conservation minded. The property is primarily used for selective harvest of second growth redwood under a Non-industrial Timber Management Plan (NTMP). The primary management goal is to maintain a constant level of timber harvest. However, whenever possible they try to support wildlife or environmental service projects (McAdams, personal communication, 2017).

The three creeks located on the McAdams K-Bar Ranch north block are Hall, Mill, and Noisy creeks. They begin on the slopes of Liscom Hill and flow into the Hall Creek Valley. The streams are all spawning streams for threatened coho salmon (*Oncorhynchus kisutch*), king salmon (*Oncorhynchus tshawytscha)* and steelhead trout (*Oncorhynchus mykiss iridius)*. Due to the presence of threatened species and important wild stocks of sportfish, these streams are precious habitat (Farro 2014).

Hall Creek is a small tributary of the Mad River draining the west side of Liscom Hill in Northern Humboldt County California. Over the past decade the Hall Creek Valley has progressed from being a well-drained valley in which Hall Creek had been channelized into the west side of the valley, to a marshier area that spills out into the valley floor. Due to this new overland flow, the valley is wetter and takes longer in the dry season to dry out (McAdams, personal communication, 2017).

Figure 1: The overland flow of Hall Creek at an exceptionally high winter flow (25 February 2019). The stream channel follows the base of the alders in the background. The flood water is flowing through what is a typically wet meadow with a shallow ditch running through it.

Figure 2: The overland flow of Hall Creek at an exceptionally high winter flow (25 February 2019). The flood water is flowing from a seasonal wetland in a depression on the right side of the image though the valley floor. The stream channel is located behind the willow thicket in the left background.

The owners of the McAdams K-Bar Ranch believe that that the aggregation of the channelized portion of Hall Creek, and the places where the water is spilling into the valley from the channelized portions of Hall Creek, are the first steps of Hall Creek reverting to a braided alluvial stream. There is evidence that the valley floor was once a braided alluvial stream. This is demonstrated in the many layers of alluvial clays, silts, sands, and gravels that make up the soil structure of the Hall Creek Valley and that in places there are outcroppings of stream cobbles in currently upland areas (McAdams, personal communication, 2017).

Hall Creek and the other streams on the McAdams K-Bar Ranch north block are considered some of the most productive coho salmon habitat in the entire Mad River Watershed (Farro 2014). Several stream restoration projects have been completed within the McAdams K-Bar Ranch property since 2009. The projects have primarily dealt with fixing stream bed aggregation. This has been accomplished by either channelization or the installation of large woody debris structures that encourage the scouring of pools into the stream bed during high winter flows. All projects were completed by Pacific Watersheds Associates (PWA), a local environmental consultant firm that specializes in completing habitat restoration projects using grant money. Mill Creek, an eastern tributary of Hall Creek was re-channelized in the summer of 2009. It was re-channelized into a single channel with and features off-channel ponds for winter juvenile salmonid habitat. A set of seasonal ponds that go along the centerline of the Hall Creek Valley floor to improve habitat for amphibians and waterfowl were dug in 2015. In some places these seasonal ponds are connecting themselves during times of high flow and potentially they could connect together into part of a new channel (Grey, personal communication, 2017). In the summer of 2016 and 2017 large woody debris structures were added to the bed of Hall Creek. In the summer of 2017, the structures from the previous year were found to all be in-place and functioning as intended. Due to this gained structure serving its purpose, pools were being scoured into the stream bed and more gravel was exposed in areas that had previously been covered with sediment from a landslide upslope (McAdams, personal communication, 2017). A similar large woody debris installation project was conducted on Noisy Creek. Noisy Creek historically fed into Hall Creek, but it has since been diverted to an alternative route (McAdams, personal communication, 2016).

Objectives:

This research has two objectives; the first objective is to model the mean daily discharge of Hall Creek. The second objective is to use the results from the discharge modeling exercise and identify the effective discharge of Hall Creek.

MATERIALS AND METHODS

1. Site Descriptions

Hall Creek (Figure 3) is a small tributary of the Mad River which drains the west side of Liscom Hill in northern Humboldt County, California. Hall Creek occupies a narrow north-northwest-trending valley and is separated from the Mad River by a 0.5 mile wide strip of fluvial terraces and floodplain. The Hall Creek watershed is approximately 1,980 acres. The valley itself is very low gradient with subtle topography that appears to favor wetland development. The wetlands are fed by two unnamed tributaries on the western side of Liscom Hill. Hall Creek currently occupies the western edge of the valley. The Hall Creek watershed is primarily second growth redwood forest (Farro, 2014).

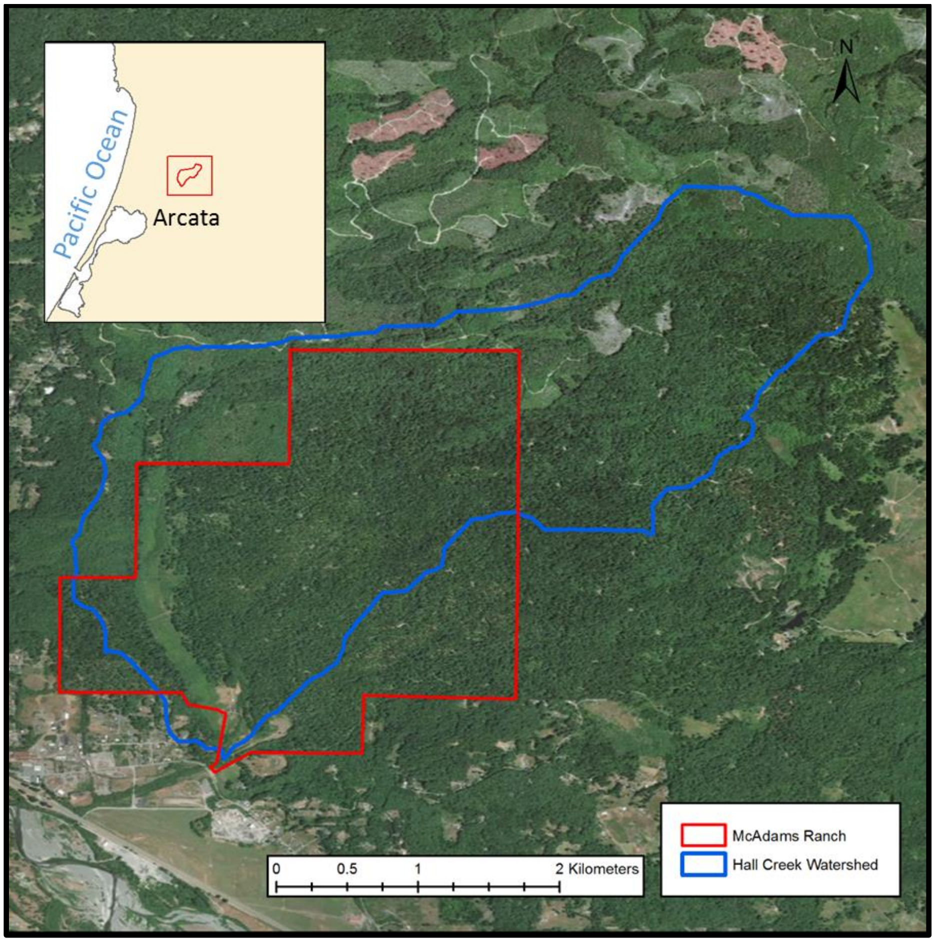

Figure 3: Map showing the Hall Creek Watershed and the McAdams Ranch North Block. Basemap imagery from Digital Globe, July 13, and September 19, 2018.

Hall Creek appears to have been subjected to some form of straightening in the past, as evidenced by several oxbow wetlands that are observed to the west of the active channel. The channel has also historically been subjected to accelerated sedimentation, as evidenced by bridges that are barely above the channel bottom (Figure 4), and half-buried culverts and fencing. The accelerated sedimentation in Hall Creek results in frequent discharge into the valley and its associated wetlands, and an abundance of flatwater habitat throughout the valley floor (Farro, 2014). The goal of this study was to use VELMA to model Hall Creek's daily flow, and to use that data to estimate the channel-forming flow, approximated by the effective flow, of Hall Creek.

Figure 4: Aggradation of the Hall Creek channel can be seen in this picture of the railroad car bridge across Hall Creek. There is little clearance from the gravel bar in the center of the stream to the bottom of the bridge. The creek has become noticeably shallower here in recent years (McAdams, personal communication, 2018). Photo by Ethan Luckens.

Hall Creek is an ungauged stream. A calibration model, using a gauged stream, was needed to calibrate the VELMA model and test the goodness of fit of modeling processes for the local ecosystem. Once the model was tested against a local system, those model parameters were used to create a Hall Creek simulation for estimating the flow of Hall Creek. Elder Creek was selected as the surrogate gauged stream because it was the closest small coastal stream to Hall Creek for which high quality daily average stream flow data was available from the United States Geologic Survey's (USGS) website (https://waterdata.usgs.gov/nwis). An unsuccessful attempt was made to use Jacoby Creek as the calibration stream.

Elder Creek (Figure 5) is a small tributary of the main-stem of the South Fork of the Eel River, located near the town of Branscomb in Mendocino County, California. Most of the Elder Creek watershed is located within the Angelo Coast Range Reserve, a research forest managed by the University of California (Angelo Coast Range Reserve, 2018). Due to Elder Creek's location in a research forest, its flow is measured by United States Geologic Survey gauge station number 11475560 (https://waterdata.usgs.gov/nwis). The Elder Creek watershed is approximately 4,135 acres. The riparian areas are primarily coast redwood groves (*Sequoia sempervirens*), while the upland areas are mixed forest of Douglas-fir (*Pseudotsuga menziesii*) and hardwoods such as tan-oak (*Lithocarpus densiflora*), live oak (*Quercus spp*.), California bay (*Umbellularia ealifornica*) and madrone (*Arbutus menziesii*). Thin bands of chaparral with manzanita (*Arctostaphylos sp*), *Ceonothus*, chamise (*Adenostoma fasciculatum*) and scrub oaks (*Quercus sp.*) occur at higher elevations on south-facing slopes, and along ridge tops (Angelo Coast Range Reserve, 2018).

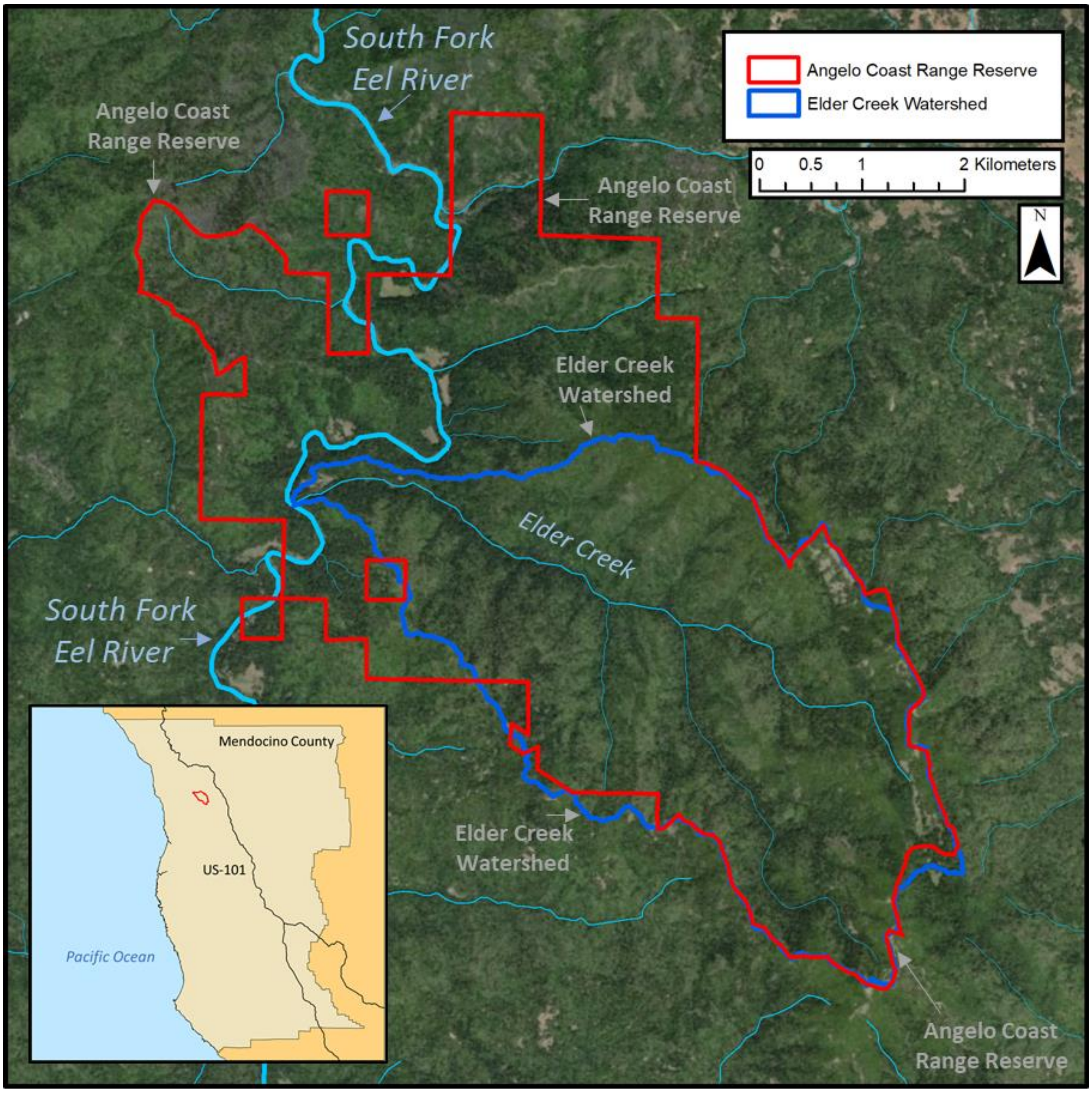

Figure 5: Map showing the Angelo Coast Range Reserve and the Elder Creek watershed boundaries. The Elder Creek watershed is almost entirely contained within the boundaries of the Angelo Coast Range Reserve. The locator map shows the Elder Creek watershed in relation to highway US-101. Map data from National Center for Earth-

Surface Dynamics, Caltrans, and ESRI. Basemap imagery from Digital Globe August 12, 2018

Jacoby Creek (Figure 6) is a coastal stream located south of Arcata. Jacoby Creek has a similar geology, climate, terrain, and land use history as Hall Creek, in that they are coastal streams in northern Humboldt County, California that have Franciscan complex bed rock and are covered with second growth coastal redwood forest. The Jacoby Creek watershed is approximately 8,708 acres. Jacoby Creek is located about 5 miles southwest of Hall Creek. Due to this proximity, it has very similar weather as Hall Creek. The bed of Jacoby Creek is mostly of poorly sorted gravel and small cobble substrate (Harvey et al. 2006; Farro, 2014). A bed load sediment transport curve calculated for Jacoby Creek was used to in lieu of sediment data for Hall Creek for the effective discharge calculation. Daily average discharge data and a bed load sediment transport curve for Jacoby Creek was provided by a local hydrologist (Klein et al. 2018).

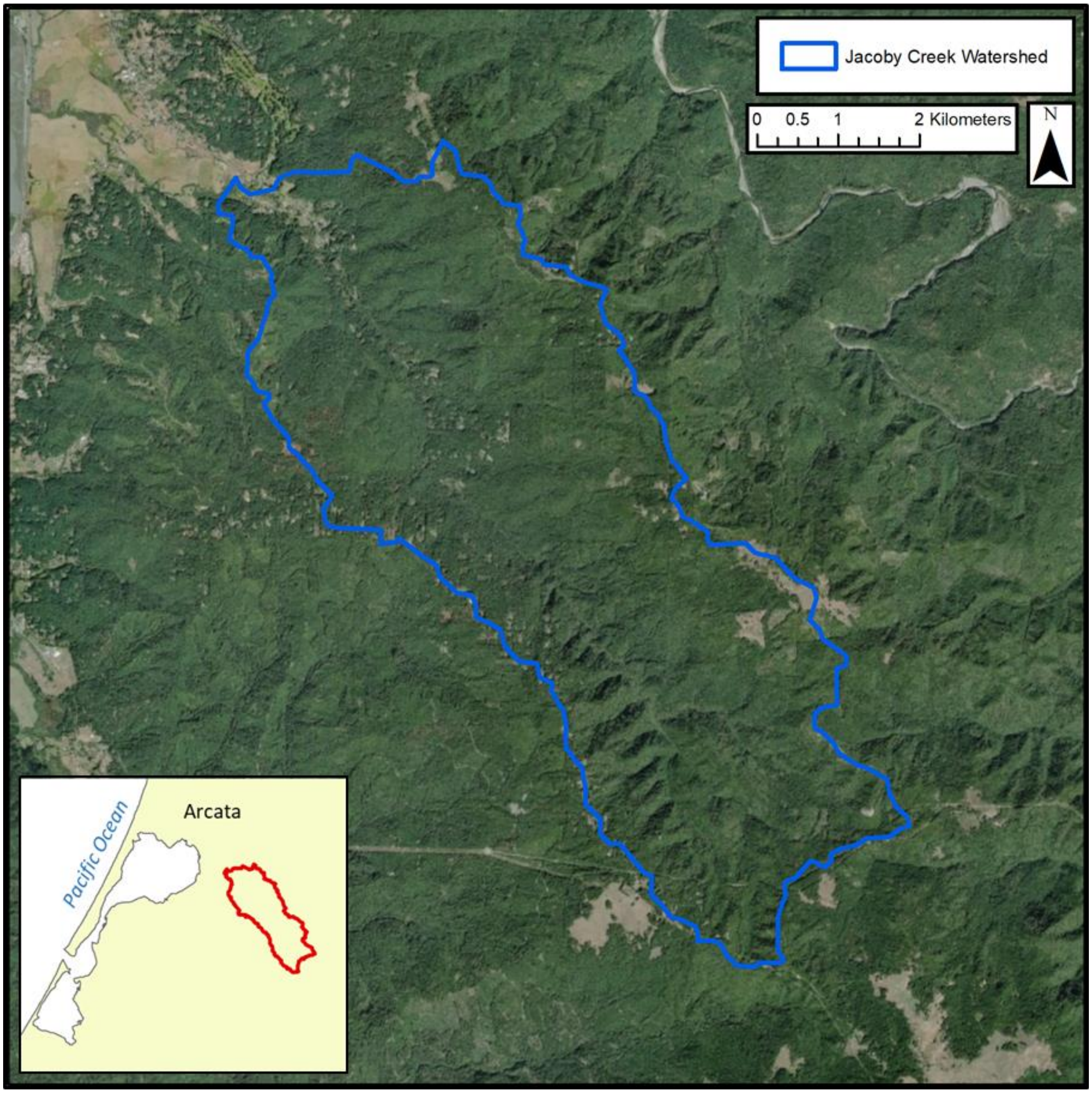

Figure 6: The Jacoby Creek watershed draining to the gauge station at Brookwood Bridge. Basemap imagery from Digital Globe, July 13, and September 19, 2018.

2. Modeling Overview

Initially, HEC-HMS was to be used to model flow in this project, but difficulties with pre-processing the data for entry to HEC-HMS occurred. Due to these limitations and the need for stream flow on ungauged systems, the switch was made to use the VELMA model. VELMA includes both a flow model and a vegetation model. The flow model portion of VELMA estimates the daily streamflow values in millimeters per day which flowed through the pour point (McKane et al. 2014). The PSM vegetation model "grows" trees for the duration of the simulation and the modeled vegetative structure influences the flow model through evapotranspiration. The VELMA model I used represented the watersheds as being covered with mature Douglas-fir forest on sandy loam soil (Halama, personal communication, July 2018).

A flat processed digital elevation model (DEM), the daily precipitation, and daily mean temperature were the inputs VELMA used to model the flow of water through a watershed. The modeled flow values were affected by cover type, tree age, and soil type data parameters. During the simulation, the modeled flow values were evaluated against the observed flow values using the Nash-Sutcliffe equation to produce a goodness of fit value.

In this study a calibration stream (Elder Creek) was used to test the goodness of fit of the VELMA model setup so that the model parameter set-up could be applied to an ungauged stream (Hall Creek). The resulting modeled flow of Hall Creek was used to calculate the effective flow.

It was recommended that the Elder Creek VELMA calibration parameter setup needed to yield a Nash-Sutcliffe value greater than 0.6 in order to proceed with confidence in applying the model to the ungauged Hall Creek (Halama, personal communication, July, 2018).

3. VELMA's Required Input Data

VELMA requires specific types of data inputs: a flat processed DEM, weather driver data, observed flow data, a land cover type map, a soil map, and a tree age map. A flat processed digital elevation model is a DEM that was modified so that water from all cells in the DEM flow through a single pour point. The weather driver data consists of daily mean air temperature and daily precipitation data. The land cover type map is a raster in which an integer represented the land cover type. In this study there was a single value raster that represented conifer forest. The tree age map was extracted from the 1990 LandTrendr forest age map of the North American west coast in which each pixel represented the stand age for every 30 square meters grid square (Kennedy, R.E. et al. 2012). The soil map was a single value raster representing sandy loam. The observed flow data was daily average flow data downloaded from the United States Geological Survey (USGS) Surface-Water Historical Instantaneous Data for the Nation: Build Time Series website (https://waterdata.usgs.gov/nwis/). Flat processing was accomplished using BlueSpray's "Water Tools" All other GIS data pre-processing tasks were accomplished with ESRI ArcMap 10.6.

This information was input into VELMA in two different file types. ASCII files were used to store raster data such as the terrain model, vegetation map, vegetation age map, and soil map. Tabular data was saved as comma separated value (CSV) files and was used to store the daily precipitation, daily mean temperature data, and observed daily flow data.

3.1 Flat Processed Digital Elevation Model (DEM):

The most important input into VELMA was a flat processed rectangularly cropped 30 meter resolution DEM of the modeled watershed areas projected into North American Datum 1983 Universal Transverse Mercator Zone 10 North (NAD 83 UTM Zone 10 North). Due to VELMA's requirement that all spatial data spatially match in terms of both extent and resolution, all other spatial layers are created using the flat processed DEM.

3.2 Weather Driver Data:

The daily mean temperature and daily precipitation data are collectively called the weather driver data. Weather driver data was downloaded for each modeled stream. The daily mean air temperature in degrees centigrade and daily precipitation in millimeters per day, for the modeled time period, January 1, 1991 through December 31, 2017, was downloaded from PRISM Climate Group as tabular data (CSV) files (http://prism.oregonstate.edu/).

3.3 Observed Flow Data:

The observed daily streamflow data, in cubic feet per second (CFS), for the Elder Creek calibration model for the desired time period, was downloaded from the United

States Geological Survey (USGS) Surface-Water Historical Instantaneous Data for the Nation: Build Time Series website (https://waterdata.usgs.gov/nwis/). These data were then converted from CFS to VELMA's mm/m^2/Day hydrology unit.

3.4 Cover Type and Soil Data:

The land cover type and the soil map were single value rasters comprised only of the integer value 1. These raster files represent categorical data; therefore had to be integer values or VELMA would fail during initialization. These single integer maps represented conifer forest and sandy loam respectively (McKane et al. 2014). The single value rasters were created in ArcMap.

3.5 Tree Age Data:

Tree age data was used to initiate VELMA's vegetative spatial pools. The vegetation data significantly affected PSM processing, which affected the amount of discharge flowing through the watershed model. The most realistic option for tree age data was to create a tree age coverage using the LandTrendr data. This resulted in an ASCII file map of the estimated forest age for each cell within the simulation. LandTrendr is a spatial-temporal trend analysis derived from Landsat imagery and Forest Inventory Analysis plot data. LandTrendr interpolates a continuous raster of tree ages for portions of the United States. For this study the West Coast LandTrendr image representing the vegetation ages in the year 1990 was used. This added a greater level of realism to the model, because it added heterogenetic realism of the forest age and biomass.

Hypothetically, if LandTrendr data could not have been located, a continuous raster representing the average age of the modeled watershed would have been created in the same fashion as the cover type and soil raster. This method was used to create a continuous age raster representing 80 year old forest before I acquired LandTrendr data (Halama, personal communication, January 10, 2019).

4. Preparing Data for Input into VELMA

VELMA required input data to be in specific file formats with specific characteristics. VELMA required tabular data to be saved as CSV files and raster data to be saved as ASCII grid files (ASC). Tabular data files were used to input the daily mean temperature, daily precipitation, and observed daily flow. Raster files were used to input the flat processed DEM, soil, land cover, and tree age data. A diagram showing the work flow used to process the VELMA input data is shown in Figure 7.

The primary raster was a flat processed DEM. A flat processed digital elevation model is a DEM that was modified so that water from all cells in the DEM flows through a single pour point. All rasters in the model had to match the row and column dimensions of the flat processed DEM. The cover type and soil rasters were prepared by creating single value masks from the flat processed DEM. The tree age raster was extracted from LandTrendr data. The daily mean temperature, daily precipitation, and observed flow data were prepared into separate header-free tabular files consisting of a single column containing the data. All three tabular files had the same number of rows, representing the days to be modeled. Details on preparing data for input into VELMA can be found in appendix A.

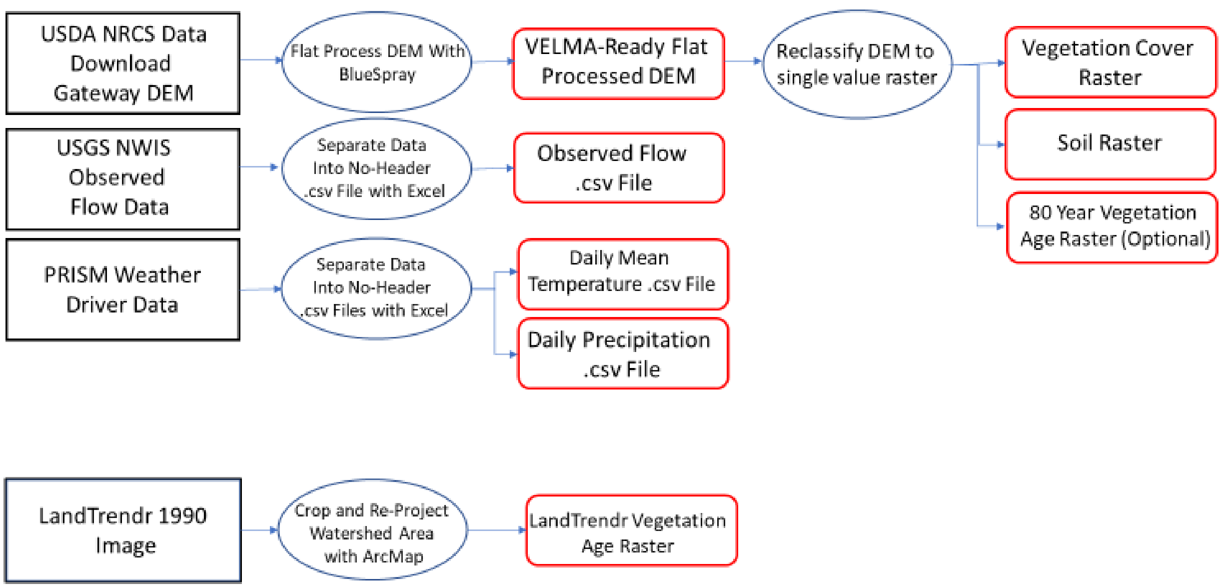

Figure 7: Flow chart displaying the work flow used to process the data from various sources into a complete set of VELMA-ready input files. Input data sources are shown as black rectangles, processing actions are shown in blue ovals, and VELMA-ready products are shown as red rounded ovals.

5. Building a Working VELMA Model

VELMA is an involved model that requires numerous inputs with numerous associated parameters. Due to this fact, an already functioning VELMA model setup originally built for the H.J. Andrews Long-term Ecological Research Forest was used as a template for both learning VELMA and developing a setup for the Elder Creek watershed. This setup and training was provided by Dr. Halama (Halama, personal communication, July 2018). This model included a full file structure and an XML configuration file that integrated the input files and parameter settings into the model. To adapt the existing Elder Creek XML setup into functioning Hall Creek XML setup, I setup and substituted the input files and parameters using the graphic user interface (GUI). The changes were saved as a new XML configuration file. Then new Hall Creek XML could then be tested for functionality and run. Details on building a working VELMA model can be found in appendix B.

6. Modeling Flow With VELMA

In this study VELMA was used to model the flow of Hall Creek, an ungauged stream. A calibration model was created for Elder Creek, a gauged stream that was similar to Hall Creek. Both streams are small coastal tributaries with coniferous vegetation and Franciscan uplift geology.   After each configuration run that included an observed flow component, VELMA calculated a Nash-Sutcliffe efficiency coefficient (value) to assess the goodness-of-fit between the observed and simulated flow and reported the results in a simulation output file named “NashSutcliffeCoefficients.txt”. (McKane et al. 2014). According to Jonathan Halama, a Nash-Sutcliffe value of at least 0.6 provided confidence in the calibration setup. A Nash-Sutcliffe value greater than 0.6 was considered a good fit between simulated and observed discharge (Halama, personal communication, July, 2018). Once the calibration setup for a the gauged watershed setup met the Nash-Sutcliffe goal of at least 0.6   Hall Creek data (the ungauged stream) could be substituted into the Elder Creek setup. The modeled flow of Hall Creek must then be presumed to have similar Nash-Sutcliffe value as the calibration model, even though there was no gauged flow to compare against (Halama, personal communication, July 2018).

6.1 The Calibration Model of Elder Creek

The Elder Creek calibration model was opened and run in VELMA. The Nash-Sutcliffe value for the calibration model was checked to ensure that it was higher than 0.6. Initially Jacoby Creek was to be used for the calibration model. The Jacoby Creek calibration model observed flow data had accuracy problems due to multiple month gaps in the summer dry season and instrument errors in almost every year of data. As a result, this setup would not yield a sufficient Nash-Sutcliffe value and was rejected in favor of the Elder Creek model.

6.2 Modeling Hall Creek and the Creating Modeled Flow Data

Once the Elder Creek calibration model was run and validated, Hall Creek data was substituted for the Elder Creek data. The observed flow data was removed from the Hall Creek model as Hall Creek is an ungauged stream. Without observed flow data, a Nash-Sutcliffe value was not produced for the Hall Creek model. The simulated flow values for Hall Creek were still valid because the model parameters were tested against the similar Elder Creek watershed (Halama, personal communication, July 2018). The simulated daily discharge data for Hall Creek was then extracted from the output file containing reported daily data at the simulation pour point.

7. Calculating the Effective Discharge of Hall Creek

The effective discharge was calculated according the methods described in Chapter 2 of *Effective Discharge Calculation: A Practical Guide* (Biedenharn et al. 2000). According to Biedenharn and others, the recommended procedure to determine the effective discharge was executed in three steps. In step 1, the flow-frequency distribution was calculated. In step 2, sediment data was used to construct a bed-material load rating curve. In step 3, the flow-frequency distribution and bed-material load rating curve were combined to produce a sediment-load histogram, which displayed sediment load as a function of discharge for the period of record. The sediment-load histogram peak indicated the effective discharge (Biedenharn et al. 2000). Twenty five years of flow data was used in this effective flow calculation to ensure the flow frequency curve was representative of the natural variation of flows (Biedenharn et al. 2000).

7.1 Converting VELMA Outputs to Cubic Meters Per Second

The simulated daily discharge data from the VELMA output file had to be converted from millimeters per square meter per day (mm/m^2/day) into cubic meters per second to be used in the effective flow calculations. This was accomplished by dividing the millimeters per day values by the conversion factor calculated for Hall Creek, using the same steps from Part 3.4. Dividing the VELMA modeled flow values by the conversion factor yielded daily flow values in cubic feet per second. Cubic feet per second values were converted to cubic meters per second by multiplying by a conversion factor of 0.02832.

7.2 Applying the Bed-load Sediment Transport Equation to the Flow Data

The bed-load is the proportion of sediments that travel by rolling, sliding, or bouncing along the bed of a stream. The bed-load is made up of larger and heavier sediment particles such as gravel and cobbles (Swartz 2006). In most alluvial streams, the major features of channel morphology are formed in bed load sediments. Due to this, bed-load sediment transportation data was used in the effective discharge calculation (Biedenharn et al. 2000). Bed-load data is more difficult to collect than suspended sediment data, so it is not as commonly available. Due to the less common nature of this data, the bed-load sediment transport equation was derived from data collected on Jacoby Creek in 1978, 1979, 2004, and 2005. Tom Lyle, a researcher at by the United States Forest Service Redwood Science lab collected the Jacoby Creek bed load sediment data and created a bed-load sediment transport rating curve (Klein et al. 2018). The bed-load sediment transport rating curve is a relationship between flow and bed-load transport and was used to model the transportation of bed-load material in Hall Creek. This curve was used to find the bed-load sediment transport values and to create the bed material load histogram.

In gravel-bed streams, such as Hall Creek, stream bed material primarily moves as bed load. Only discharge values high enough to move at least 0.1 grams of bed-load sediment per second were used in the effective discharge calculation (Biedenharn et al. 2000). The discharge needed to move 0.1 grams of bed-load sediment per second was approximately 0.24 cubic meter per second. All flow entries with a discharge less than 0.237 cubic meters per second were eliminated, because these values were below the threshold for bed-load transport initialization. The bed load transport values were calculated by applying the bed load sediment transport equation for Jacoby Creek; where x is the flow in cubic meters per second (cms), and y is bed load sediment transport in grams per second (g/s).

$$y = .5148x^{2.7388}$$

This bed-load transport threshold of 0.1 g/s corresponded with the threshold used to create the Jacoby Creek bed load data (Klein et al. 2018). Over 90% of the modeled flow and corresponding sediment transport entries for Hall Creek were removed as they were below the bed-load transport threshold.

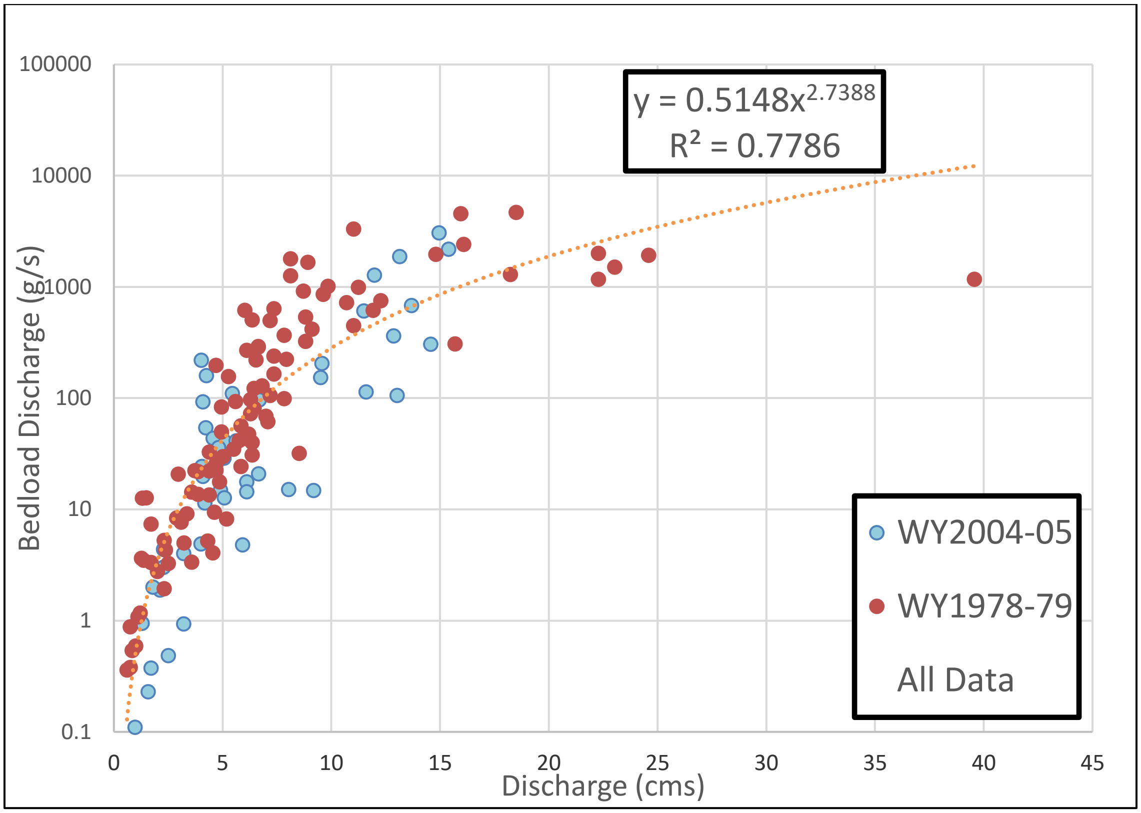

Figure 8: The bed-load sediment transport curve for Jacoby Creek showing the relationship between bedload sediment transport and discharge. The bed load sediment transport curve was provided by Randy Klein and was created by Tom Lyle et al. at the USFS Redwood Science Center (Klein et al. 2018). The bed-load sediment transport curve was used to find the bed load sediment transport values corresponding with discharge values and was used to create the bed material load histogram.

7.3 Finding the Flow Frequency Distribution

The discharge range (4.58 cms) was found by subtracting the smallest discharge value from the greatest discharge value (Biedenharn et al. 2000). The discharge range was then divided by 25 to find the initial flow class bounds. For hydrological applications, the literature suggested that the number of classes start at 25 and be adjusted as needed depending on the sample size (Biedenharn et al. 2000, Yevjevich 1972). The discharge data was then grouped into equal arithmetic flow classes.

There were less than 1000 individual flow entries greater than the bed load sediment transport threshold. This manageable number of flow entries allowed the use of actual frequencies of flow occurrence instead of percentage frequencies as mentioned by Biedenharn et al. The flow frequencies were determined by creating a histogram that separated all 995 flow entries into their corresponding equal flow classes.

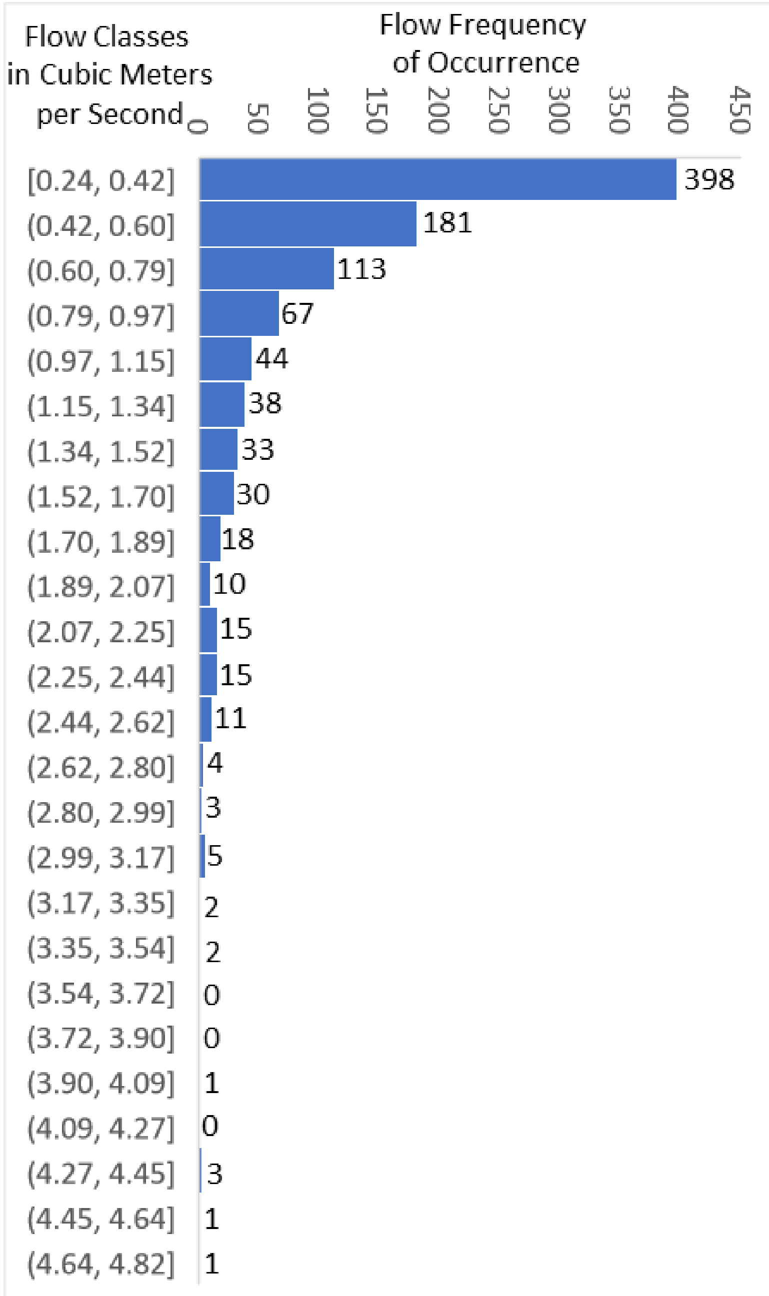

Figure 9: The initial flow frequency distribution histogram for the modeled flow of Hall Creek with Biedenharn et al.'s recommended 25 equal arithmetic flow classes.

After the initial flow frequency distribution was found, extreme flow events were identified. It was recommended by Biedenharn et al. that “all discharge classes display flow frequencies greater than zero and that there are no isolated peaks in individual classes at the high end of the range of observed discharges. If this is not the case, it is likely that either the class interval is too small for the discharge range, or the period of record is too short. Empty flow frequency classes and extreme flow events (outliers) can be eradicated by reducing the number of classes” (Biedenharn et al. 2000). Discharge class size and flow frequency distributions were recalculated until the flow frequencies in all classes were greater than zero and no isolated peaks existed in individual classes.

The flow frequency distribution histograms were recalculated according to Biedenharn et al.’s recommendations starting at 25 flow classes and working down. The initial flow frequency distribution histogram with 25 flow classes is shown in Figure 8. All the histograms with more than 13 classes had empty flow classes and the distribution with 25 classes had an isolated peak at the high end of the flow distribution. A flow frequency histogram of 13 classes maximized the number of flow classes, but did not contain empty flow classes or an isolated peak in a single class at the high end of the flow distribution (Figure 9) (Biedenharn et al. 2000).

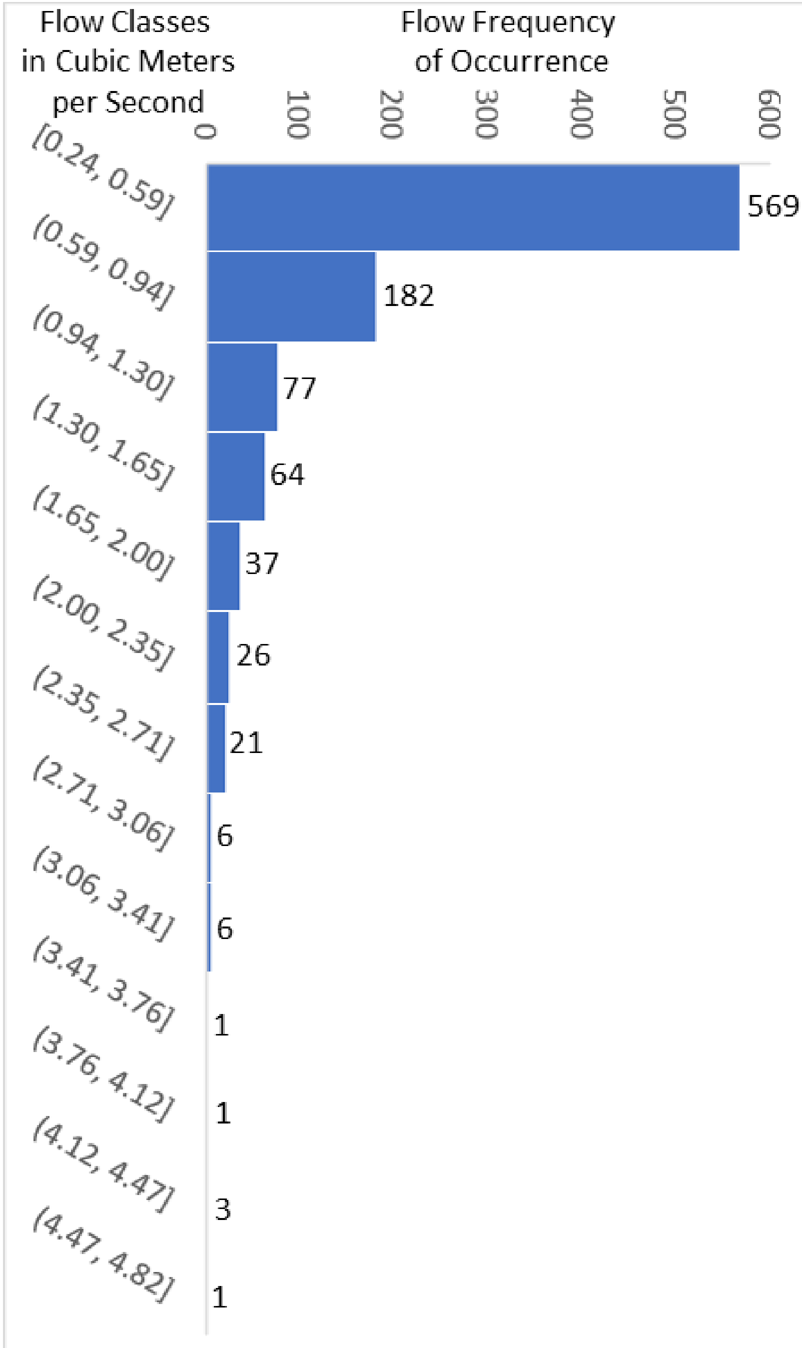

Figure 10: Final flow frequency distribution histogram for the modeled flow of Hall Creek with 13 classes. This histogram had the greatest number of classes while also lacking isolated peaks in a single class or empty classes as specified by Biedenharn et al.

7.4 Making the Bed Material Load Histogram

The final flow-frequency distribution histogram (Figure 11) and bed-material load rating curve (Figure 9) were combined to produce a sediment-load histogram, which showed the sediment load as a function of discharge for the period of record.

Representative discharges were used to calculate the bed material load histogram. The representative discharges used to create the bed-material load histogram were the average discharges for each class in the flow frequency distribution histogram. The bed material load histogram was generated by using the representative discharges and the bed-material load rating curve to find the bed-material load value for each discharge class. The bed material load rating curve value for the average discharge of each flow class was multiplied by the number of frequencies in each flow class. The results of this were plotted as a histogram representing the total amount of bed-material load transported by each representative discharge class during the period of record (Biedenharn et al. 2000).

The effective discharge corresponded to the mean discharge of the peak of the bed material load histogram. According to Biedenharn et al., the bed-material load histogram should display a near continuous distribution with a single peak. The peak of the histogram should not be in the lowest discharge class as this is an indication of error (Biedenharn et al. 2000). The calculated bed-material load histogram for Hall Creek displayed a single well-defined peak in a central discharge class representing a flow of

2.52 cubic meters per second. This defined a discharge of 2.52 cubic meters as the effective discharge.

After the effective discharge was calculated, the calculated effective discharge was evaluated to see if it was reasonable. The effective discharge's return interval was used to verify the calculated effective flow. The return interval of the effective discharge regardless of the type of river found was found by Hey to typically between 1 and 3 years, with the majority possessing an effective discharge return interval of between 1.01 and 1.2 years (Hey 1997).

RESULTS

The Elder Creek calibration model produced a Nash-Sutcliffe value of 0.65. The Nash-Sutcliffe value quantifies the predictive power of a hydrologic model by comparing the goodness of fit between the observed and predicted flow values. A model was considered sufficient if the Nash-Sutcliffe value was greater than 0.6. The tested Elder Creek model parameters were then leveraged to model the flow of Hall Creek.

The Jacoby Creek watershed is more similar to the Hall Creek watershed in flora, land use history, location, and weather than Elder Creek. However, the Jacoby Creek calibration model did not yield a Nash-Sutcliffe value high enough to validate the model. The Jacoby Creek calibration model was discarded in favor of the Elder Creek calibration model.

The modeled flow of Hall Creek was used as the input for the effective discharge calculation. The effective discharge for Hall Creek was identified as a flow of 2.62 cubic meters per second.

1. Elder Creek

The Elder Creek model yielded a Nash-Sutcliffe value of 0.65. This value was greater than the goal Nash-Sutcliffe value of 0.6 and was high enough to proceed with the VELMA calibration setup for the purposes of this study (Figure 12).

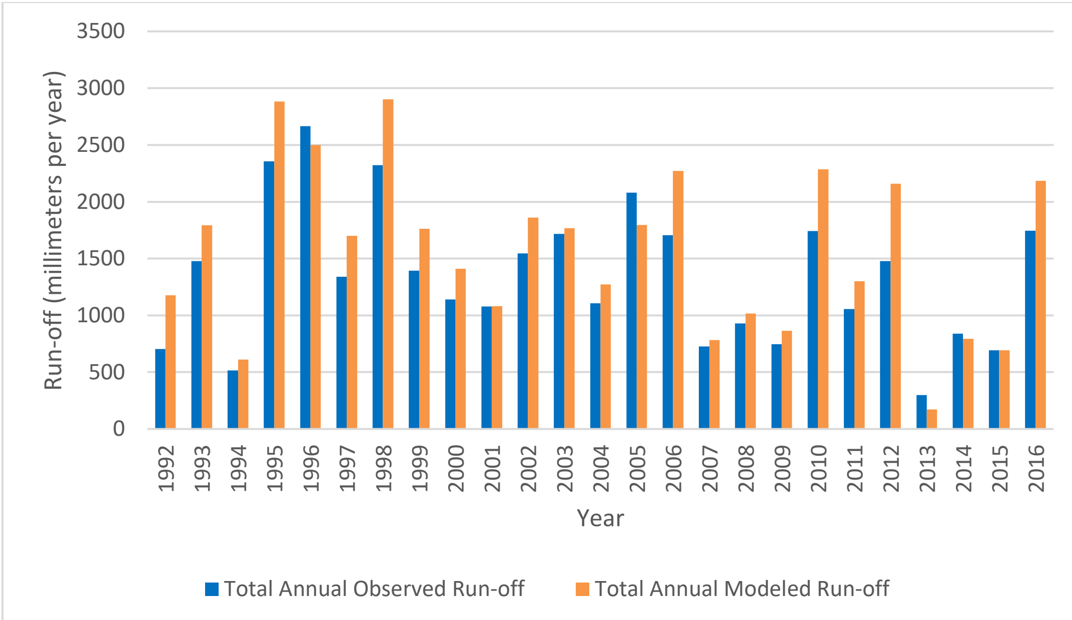

Figure 11: Elder Creek's yearly observed and modeled run-off values for the Elder Creek calibration model. This model yielded an overall Nash-Sutcliffe value of 0.65. In almost every year the modeled run-off was greater than the observed run-off values.

Figures 13-16 highlight the core spatial and temporal modeling that VELMA produces. The soil moisture maps (Figures 14-16) were included as they show how VELMA simulated run-off through the watershed in response to precipitation data, as well as soil parameters and evapotranspiration due to tree species type and tree age.

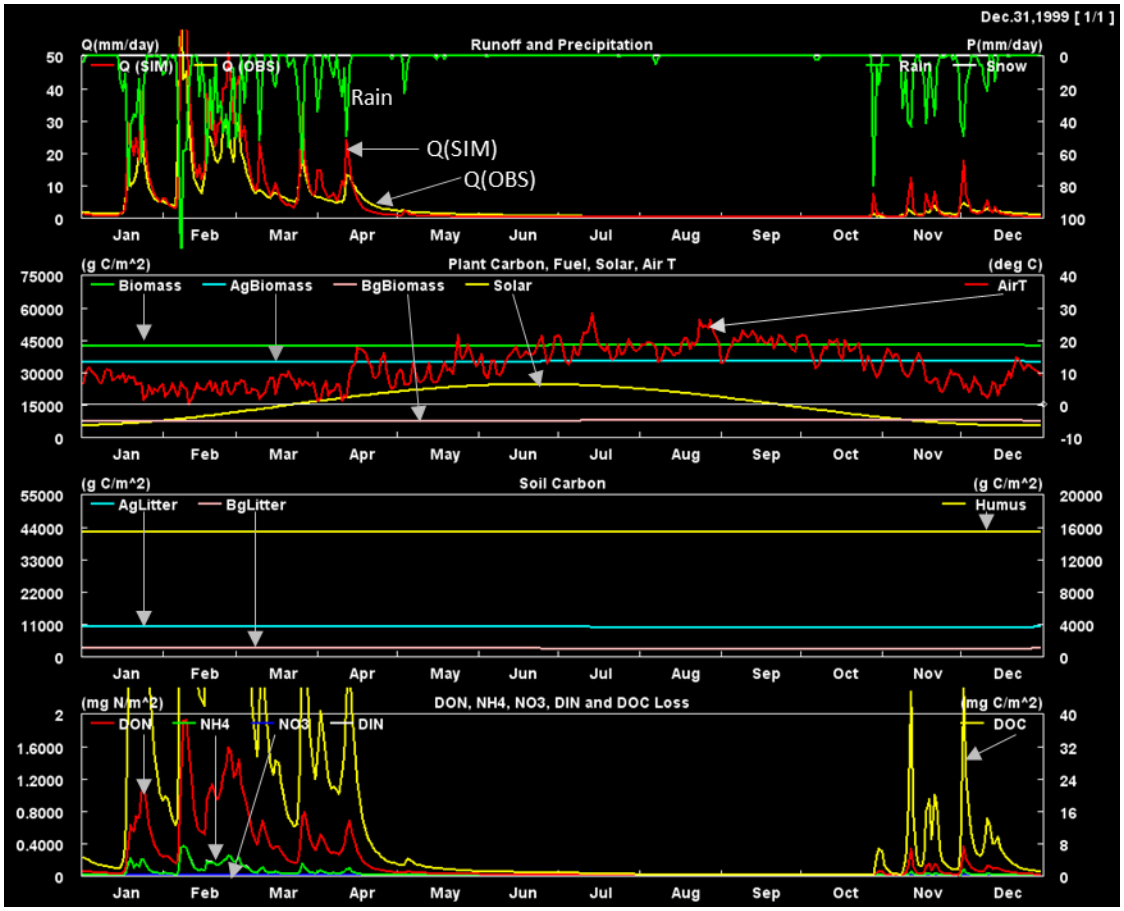

Figure 12: The yearly VELMA output summary display for the Elder Creek calibration model. The top graph displays runoff and precipitation in (mm/m^2/day); the yellow line shows observed discharge, the red line shows modeled discharge, the inverted green line shows the amount of precipitation that fell as rain. The second from top graph displays biomass accumulation, air temperature, and solar radiation. The mean daily air temperature and clear sky solar radiation values respond to seasonal changes. The biomass values are near constant (unnoticeable biomass accumulation) within a single year but will noticeably accumulate over the length of a multi-year study. The bottom

two graphs were not used in this study. The second from bottom graph shows soil carbon accumulation; this value is relatively constant in a single year but also accumulates as a multi-year study progresses. The bottom graph displays the loss of water-soluble nutrients flowing out the watershed. If vegetation disturbances (e.g. forest harvest, fire, plantings, etc.) were included in this VELMA model the biomass, soil carbon, and water soluble soil nutrient values would have changed to reflect the disturbance (McKane et al. 2014; Halama, personal communication, January 2019).

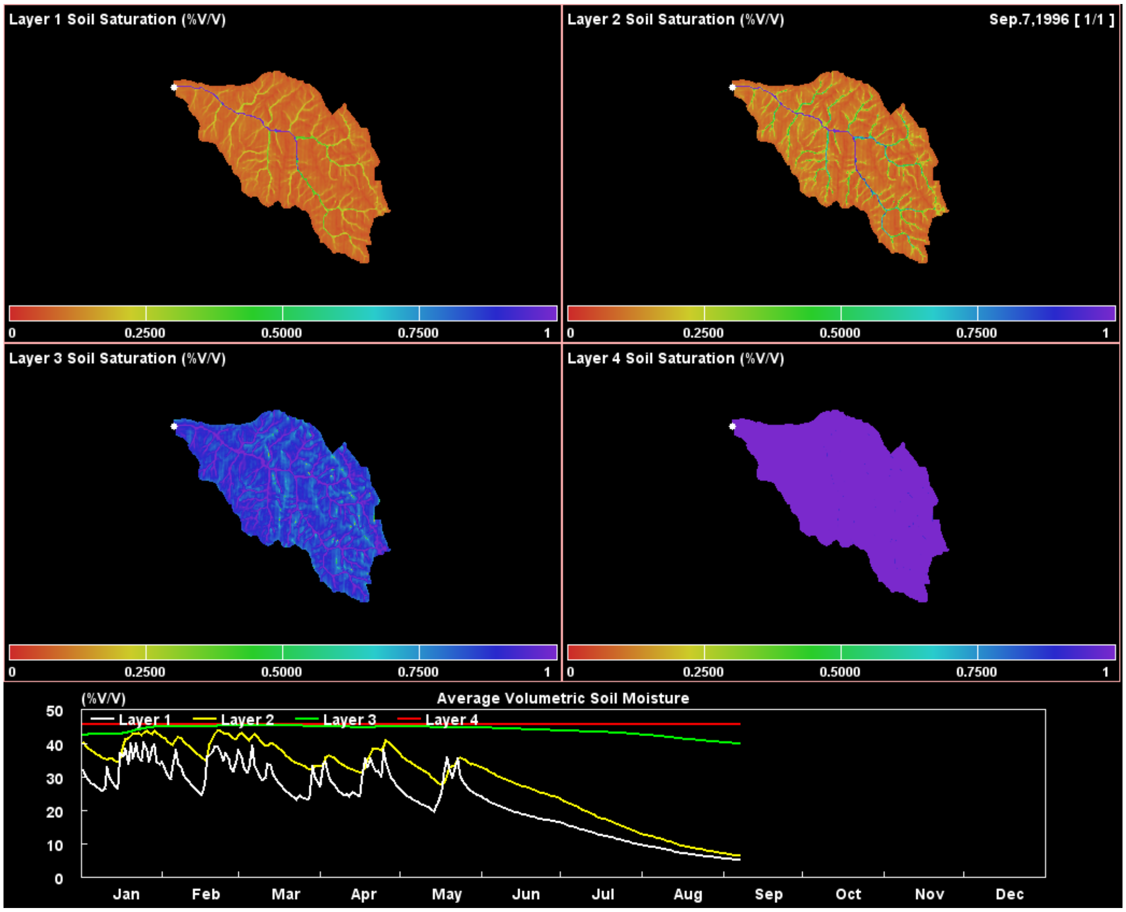

Figure 13: Elder Creek Soil Moisture Map: September 7, 1996. The soil moisture map spatially shows the modeled movement of water though the soil layers of the watershed. Figure 14 displays the conditions of late summer, the driest time of year. The first and second layers of the soil are very dry except for low-lying areas and stream beds. The lower soil layer moisture levels are usually not as dynamic as the upper soil layers throughout the year. The numbered color ramp represents the level of soil saturation, where %V/V is the percentage of water volume space occupying the total available water volume space.

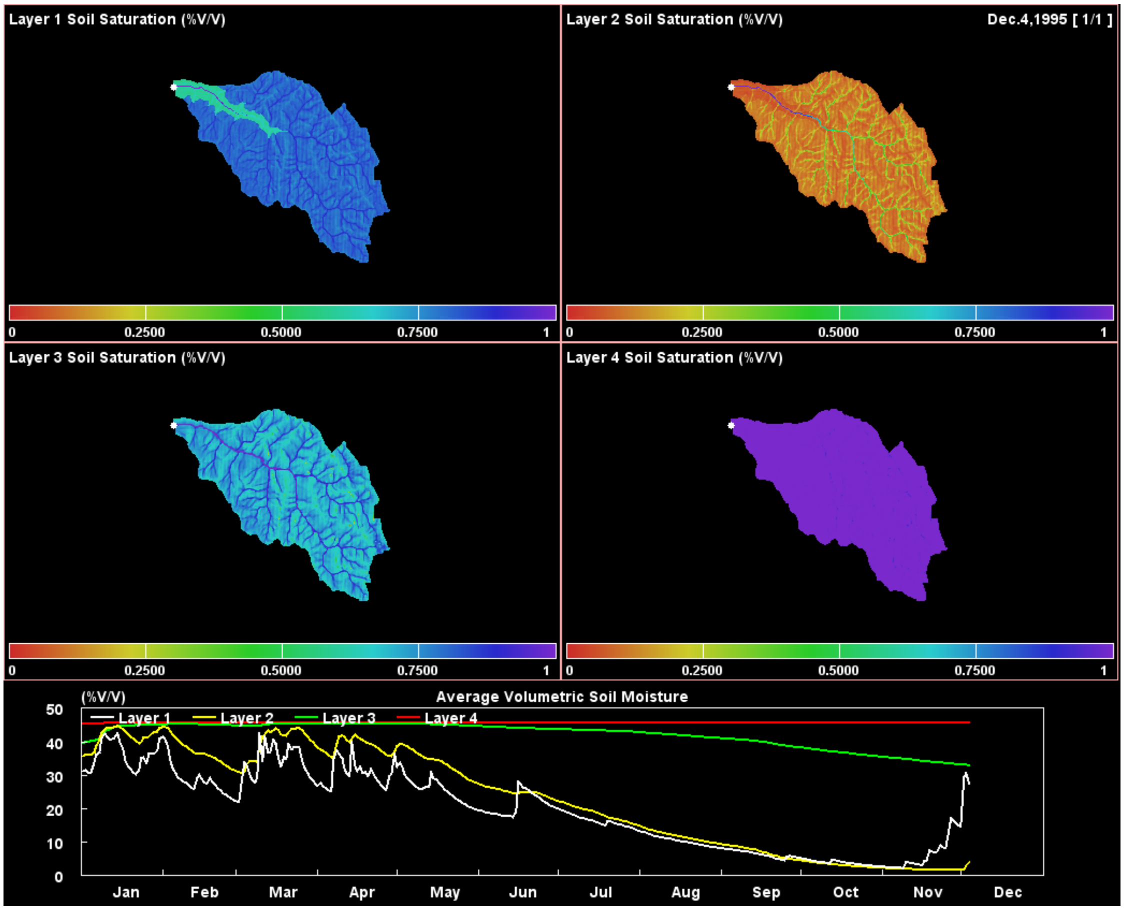

Figure 14: Elder Creek Soil Moisture Map: December 4, 1995. The soil moisture map spatially shows the modeled movement of water though the soil layers of the watershed. Figure 15 displays the conditions of one of the first winter storms of the year. The first layer of soil in the headwaters is very moist but the moisture has not yet fully infiltrated into the soil of the lower reaches. The winter storm water has not yet infiltrated into the second layer of soil which is still fairly dry except for the low-lying areas and stream beds. The lower soil layer moisture levels do not vary as much as the upper layers and stay fairly moist throughout the year.

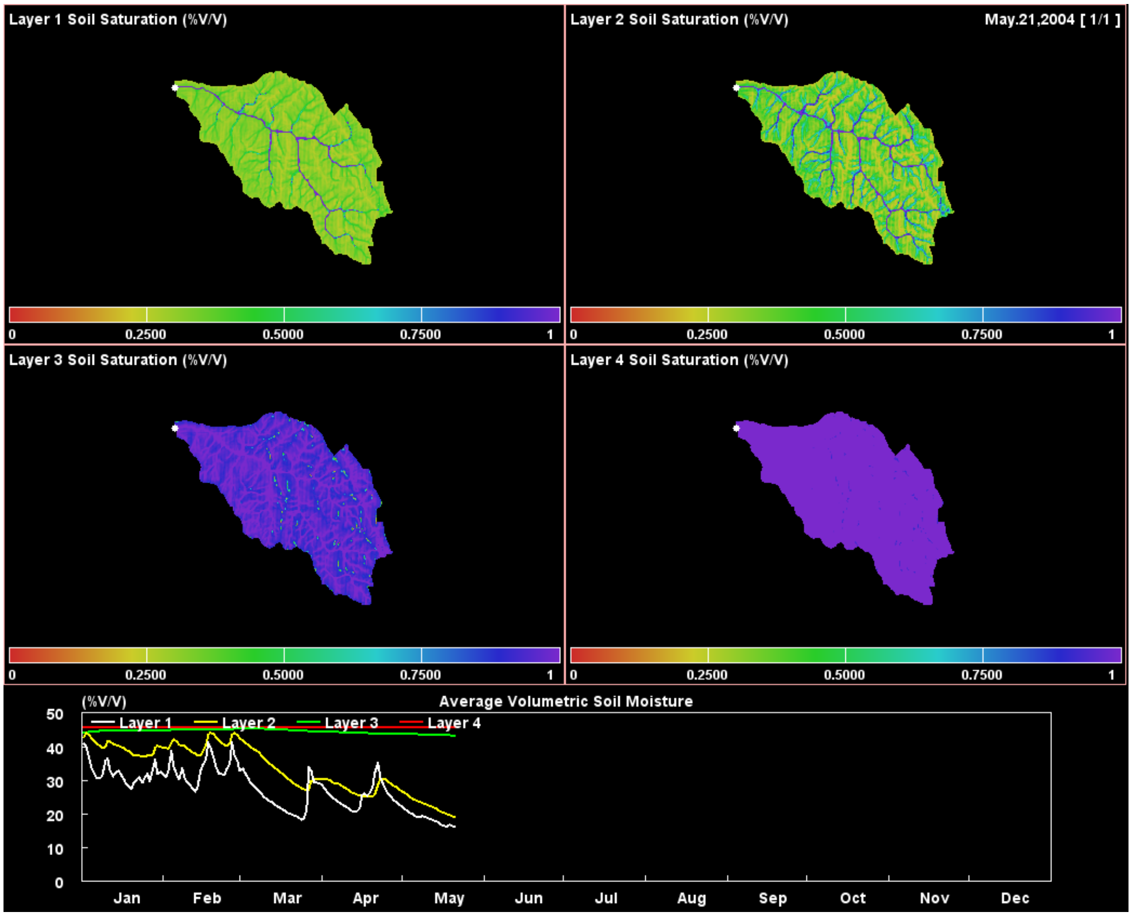

Figure 15: Elder Creek Soil Moisture Map: May 21, 2004. The soil moisture map spatially shows the modeled movement of water though the soil layers of the watershed. Figure 16 displays the conditions of late spring. The first and second layers of soil in the upland areas are beginning to dry out, while there is still a lot of moisture in the lower lying areas. The lower soil layers are still saturated with infiltrated winter rain water, though their moisture levels not have as much seasonal variation as the upper soil layers.

2. Jacoby Creek

The Jacoby Creek calibration model yielded a Nash-Sutcliffe coefficient of 0.28 which was not high enough to validate the model. The Jacoby Creek model was rejected in favor of the Elder Creek model. However, the Jacoby Creek bed load sediment transportation curve was used in place of Hall Creek bed load sediment data.

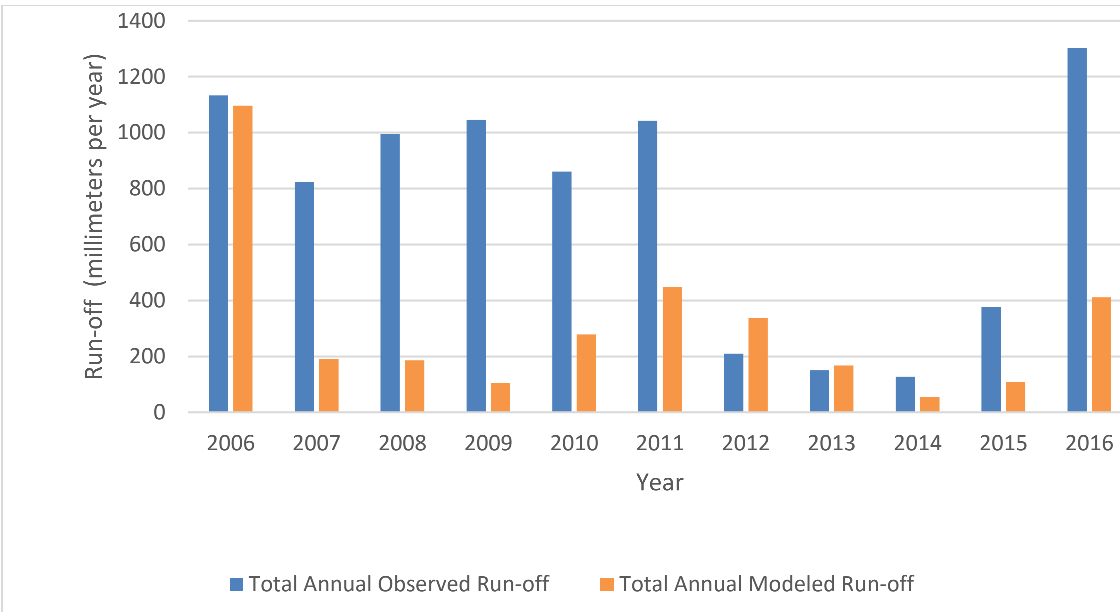

Figure 16: Jacoby Creek's yearly observed and modeled run-off values for the Jacoby Creek calibration model. Due to differences between the observed and modeled run-off values the model yielded an overall Nash-Sutcliffe value of 0.28. As the Nash-Sutcliffe value was not greater than 0.6 the Jacoby Creek calibration model was thrown out. In almost every year the observed run-off value of Jacoby Creek was higher than the modeled value.

3. Hall Creek

Data for Hall Creek was used to replace the Elder Creek data in the VELMA model. The resulting modeled flow data for Hall Creek was assumed to have the same predictive value as the Elder Creek calibration model. The Hall Creek modeled flow values were then used in the effective flow calculations.

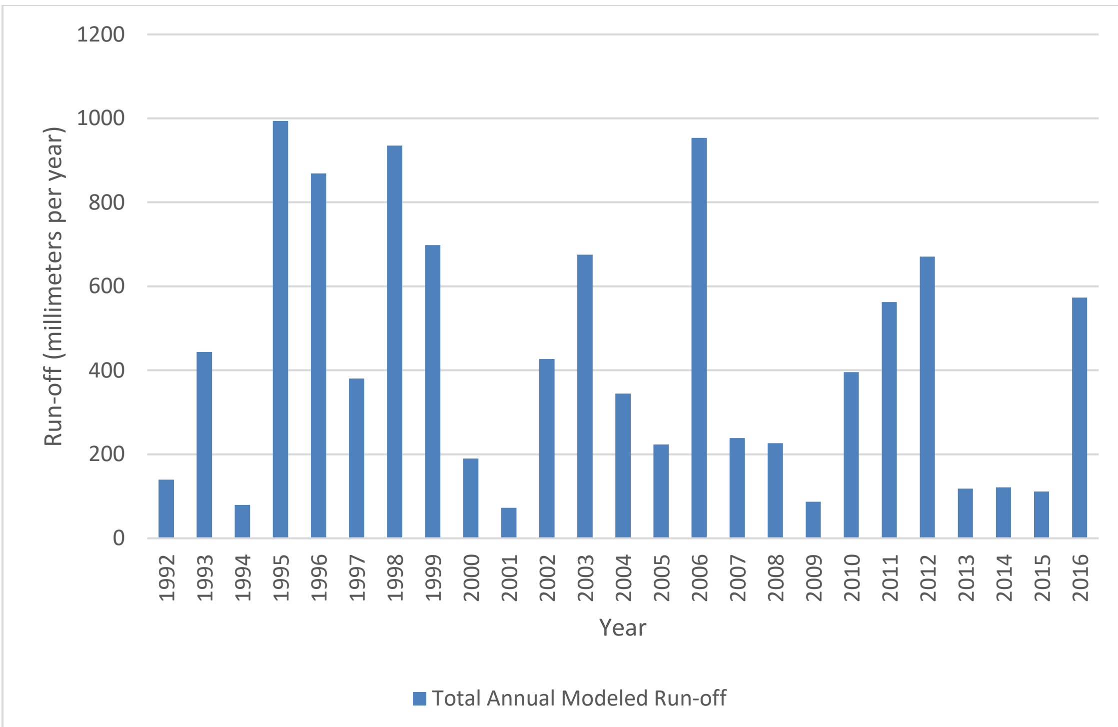

Figure 17: Hall Creek's total annual modeled run-off values generated by VELMA. There are no observed run-off values as Hall Creek is an ungauged stream. Due to the lack of observed run-off values for Hall Creek, a Nash-Sutcliffe efficiency calculation was not possible.

4. Calculating the Effective Discharge of Hall Creek

The effective flow calculation was executed as described in "Effective Discharge Calculation: A Practical Guide" (Biedenharn et al. 2000). The effective discharge was found to be approximately 2.52 cubic meters per second, the discharge associated with the peak of the bed-material load histogram (Figure 19). This discharge of 2.52 cubic meters per second represented the flow level that transported the greatest fraction of bed-material load sediment during the study time period. As the effective flow was used as a proxy for the channel forming flow it can be inferred that the channel forming flow for Hall Creek is 2.52 cubic meters per second.

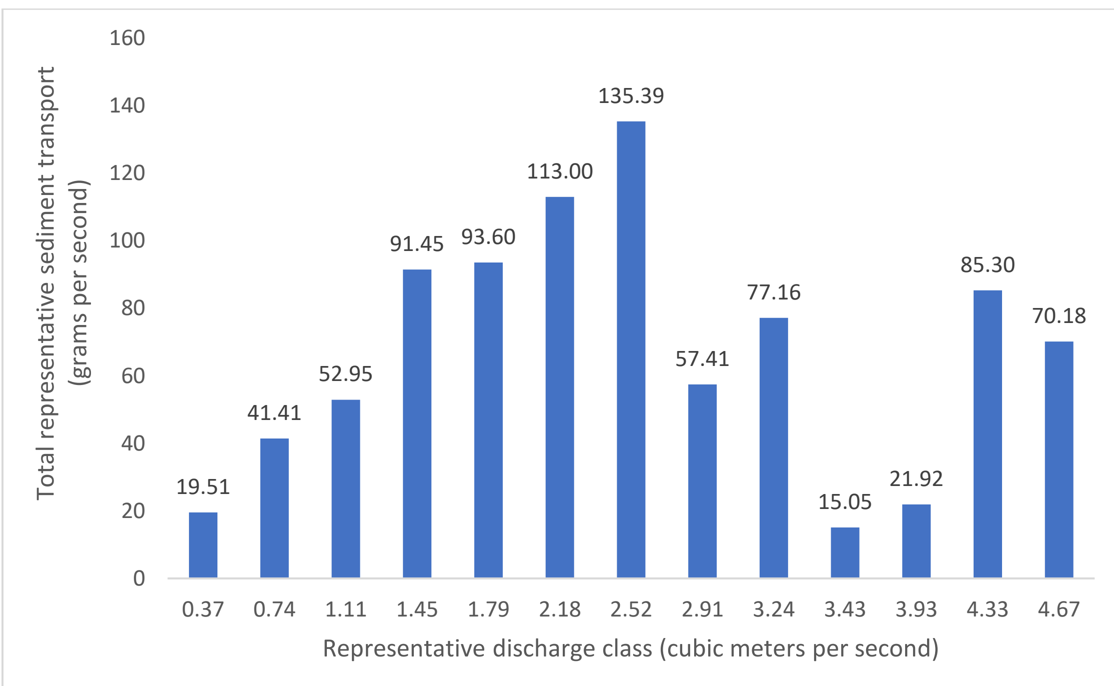

Figure 18: The total amount of bed-material load transported by representative discharge class for Hall Creek from 1992-2016. The representative discharge class that moved the

greatest fraction of bed load sediment during the study period was the class representing a flow of 2.52 cubic meters per second.

The effective discharge of Hall Creek was found to have a return interval of about 0.83 years. In the 25 modeled years there were 30 instances where flows equaled or exceeded the calculated effective flow of 2.52 cubic meters per second (Figure 9). Hall Creek's effective discharge return interval was supported by the findings of Crowder and Knapp, who found that the return interval of the effective discharge was typically greater than the mean flow of a stream but less than the 1.1 year flood event (Crowder and Knapp 2005). The recurrence interval of 0.83 years was slightly lower than Hey's findings; who found the return interval of the effective flow was typically between 1 and 3 years with the majority between 1.02 and 1.2 years in all river types (Hey 1997, Biedenharn et al. 2000).

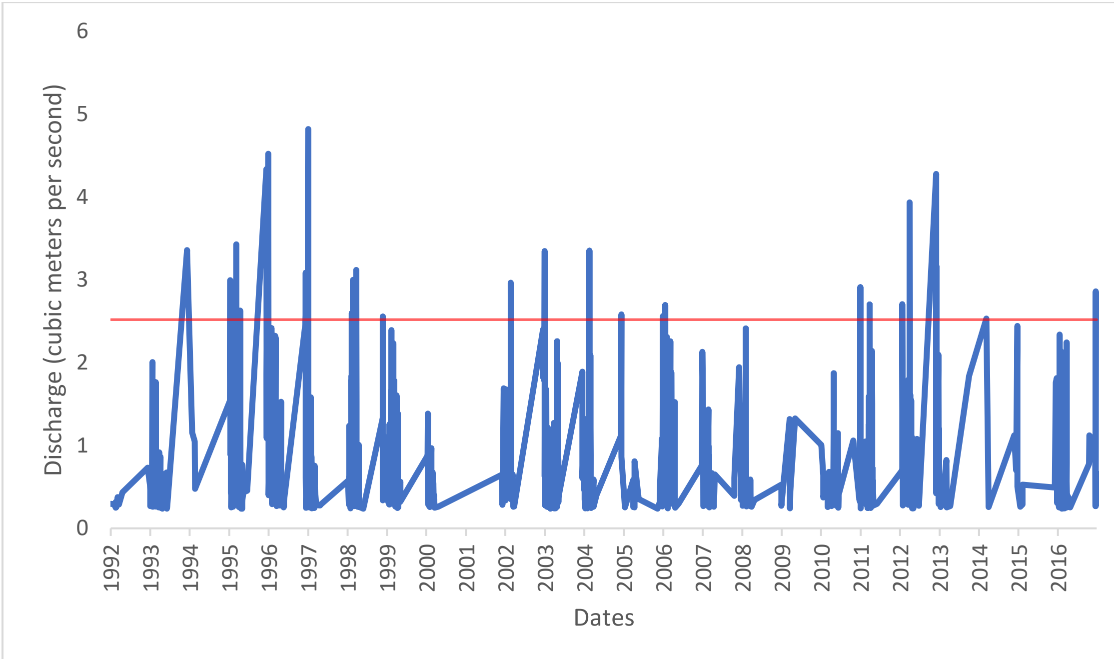

Figure 19: Modeled continuous discharge of Hall Creek from 1992-2016. The return period for the effective discharge of 2.52 cubic meters per second was calculated to be 0.83 years. The red line represents the effective discharge of 2.52 cubic meters per second.

DISCUSSION

VELMA is an eco-hydrologic model that incorporates the upland terrestrial soil and biomass through its PMS biogeochemistry model. VELMA can model the complex interactions of vegetation, soil, and water resources to disturbances (McKane et al. 2014). I only used the eco-hydrology model and did not model disturbance. I used VELMA as a flow model that included a vegetation model to calculate discharge. This type of flow modeling is commonly accomplished with HEC-HMS, which does not include a vegetation model (Ford et al. 2002). As my study site locations are heavily forested, I may have created more realistic flow results by using VELMA than if I had used the more conventional HEC-HMS as VELMA accounts for the vegetation on the landscape. Though the effective discharge of 2.52 cubic feet per second and the effective discharge return interval of 0.83 years were identified, there are still other pieces of information that should be explored in order to validate my results.

1. Difficulties Encountered While Executing the Research

During the first stage of my research, I was unable to flat process the DEMs using HEC-GeoHMS, for later entry into HEC-HMS. As a result I chose to switch modeling programs from HEC-HMS to VELMA. I initially struggled to use VELMA and the Java Processing Digital Elevation Model (JPDEM), the flat processing tool that was provided with VELMA. I opted to not use JPDEM and instead used BlueSpray's "Water Tools" to flat process my DEMs. I was also surprised with how time consuming it was to prepare the various VELMA input files. I overcame VELMA's steep learning curve with practice until I could identify and correct the errors that made VELMA crash. I was unable to achieve a sufficient Nash-Sutcliffe value for the Jacoby Creek calibration model. I substituted Elder Creek as the calibration model due to high-quality observed flow data was available for this site.

After the flow of Hall Creek was modeled, I had difficulty using the effective flow calculation as described in Biedenharn et al.'s manual. I overcame this by taking several weeks to read and re-read Chapter 3 of Biedenharn et al.'s manual and experimented with how to apply the manual's instructions to the modeled flow data using MS-Excel.

1.1 Problems Projecting and Flat Processing DEMs for HEC-HMS and the Pivot to VELMA

Prior to using VELMA an attempt was made to use HEC-HMS to model the flow of Hall Creek. HEC-HMS is a better-known program than VELMA and is part of the US Army Corps of Engineers Hydraulic Engineering Center's (HEC) modeling suite commonly used in the civil engineering field (Ford et al. 2002). Similarly, to VELMA, HEC-HMS requires a "flat processed" DEM to be input. To create the flat processed DEM and other input files for HEC-HMS the US Army Corps of Engineers created an ArcMap extension called HECGeo-HMS. Updated versions of HECGeo-HMS for versions of ArcMap later than ArcMap 10.5.1 are available for download from the ESRI website.

HECGeo-HMS required projected DEMs with a projection such as UTM Zone 10 North. I used DEMs from the USGS Earth Explorer site which I attempted to project before inputting them into HECGeo-HMS. DEMs from the USGS Earth Explorer site downloaded unprojected in the World Geodetic System 1984 Geographic (WGS 84 Geographic) coordinate system. These DEMs needed to be projected into UTM Zone 10 North. I had problems projecting the DEM without ruining its surface with grid-patterned artifacts. The only way to create a usable projected DEM from this data was to heavily smooth the projected DEM. This had the unfortunate side effect of obscuring much of the real and artifactual relief on the DEM. Due to the grid artifacts, I was unable to pre-process DEMs using HECGeo-HMS. This resulted in the project switching from using HEC-HMS to VELMA.

After switching the flow modeling software to VELMA, it came to light that the USDA's "NRCS Data Download Gateway" website distributed DEMs that downloaded native to the local UTM projection. These DEMs were in a projected coordinate system in meters. The NRCS-sourced DEMs also could be downloaded at 30-meter resolution, the recommended cell size for VELMA (Halama J, personal communication, July 2018). If the NRCS-sourced DEMs had been initially used as the input for HECGeo-HMS, I think DEMs could have been pre-processed for input to HEC-HMS. HECGeo-HMS creates a suite of HEC-HMS input files so it must be used to pre-process DEMs for input into HEC-HMS.

1.2 Flat Processing Issues with JPDEM and the Pivot to BlueSpray Water Tools

Prior to inputting the DEM into VELMA, the DEM must be "flat processed" so that all cells flow into a single pour point. The flat processing software that downloads with VELMA, called the Java Processing Digital Elevation Model (JPDEM), is problematic. JPDEM needs sloped terrain to function. Flat areas and cells with elevation values of zero cause it to malfunction. If the DEM has flat areas, such as marsh or tidal areas, JPDEM will struggle to flat-process, resulting in long processing times (Halama J, personal communication, July 2018). The challenges of using JPDEM were overcome by instead using the "Water Tools" suite in BlueSpray. The "Water Tools" can be used to quickly and efficiently create flat processed DEMs for all types of terrain and elevations.

The "Water Tools" suite in BlueSpray was created by Dr. James Graham partially for this project.

1.3 VELMA's Learning Curve

VELMA was fairly difficult for me to operate initially and it had a steep learning curve. VELMA was a fragile model in which each input files had to be entered correctly or the entire model would not run. VELMA's debugger is rudimentary, meaning Java I/O errors are output to the GUI with limited guidance. Users must decode the limited reporting in order to correct the parameters within the GUI. The most common errors I identified were raster files that had different dimensions of rows and columns, and incorrectly copied file names. The recommended way to build a working VELMA model was to start with an already working VELMA model and methodically replace files until the desired model was achieved. To start with an empty XML configuration file would be a time consuming and frustrating process for most users.

1.4 Issues with the Nash-Sutcliffe Equation

The Nash-Sutcliffe Equation greatly penalized data sets in which the observed flow data was greatly higher or lower than the modeled flow results. This was important, as the observed flow data from Jacoby Creek was generally higher than the modeled flow. Due to this, the Nash-Sutcliffe value for Jacoby Creek was never higher than 0.3, far under the 0.6 cutoff value needed to have confidence with the watershed setup. As a result, Jacoby Creek was rejected as the calibration site, though it was a much closer analog to Hall Creek than Elder Creek.

1.5 Observed Flow Data Quality

Due to the peculiarities of the Nash-Sutcliffe Equation, the most appropriate observed flow data was fully continuous and accurate for the duration of the model. The preferred source for this type of data was the USGS National Water Information System (NWIS). The NWIS flow data for Elder Creek was fully continuous for the entirety of the study period; therefore provided VELMA sufficient data resulting in acceptable Nash-Sutcliffe for the Elder Creek simulation. The flow data for Jacoby Creek was provided by a local US Forest Service researcher and proved to be problematic. The Jacoby Creek flow dataset had numerous temporary instrument calibration issues that resulted in inaccuracy and gaps in the data. These problems made the Jacoby Creek flow data difficult to use, compared to the fully continuous USGS NWIS sourced data, and prevented me from being able to achieve a sufficient Nash-Sutcliffe value with the Jacoby Creek calibration.

1.6 Difficulty Calculating the Effective Flow

Biedenharn's guide *The Effective Discharge Calculation: A Practical Guide* was at times difficult to understand. The guide did not always break complex tasks up into several simpler linear tasks with commonly understood language. The guide explained the theory of what tasks needed to be accomplished but did not describe in much detail how to accomplish these tasks. To overcome this, I broke up the steps described by Biedenharn into smaller tasks I understood how to accomplish using Microsoft Excel.

1.7 Processing the Data for Input into VELMA

I was surprised how much time it took to prepare the various specific files in the correct format to create the input files for a single VELMA model. It took up to an entire working day per site to download and process the different types of data into a set of VELMA input files. In the future parts of the data pre-processing could be automated to reduce the time needed to create a VELMA set-up and automatically enter the pre-processed files into the correct lines of the GUI.

2. Concerns Before Applying the Modeled Discharge or Effective Flow to Project Design

Though the effective discharge of 2.52 cubic feet per second and the effective discharge return interval of 0.83 years were identified, there are still other pieces of information that should be explored to validate my results. The modeled discharge and calculated effective flow should be compared to discharge data from comparable streams in the region. Morphological data for Hall Creek should also be used to confirm the validity of my results. The calculated effective flow for Hall Creek is a modeled product, thus it has inherent levels of inaccuracy. The inherent inaccuracy of the model was mitigated by validating the model using the Elder Creek calibration but not eliminated.

There were sources of uncertainty provided by each of the input data sources. The 30 square meter DEM added uncertainty as micro-terrain features present on the actual landscape may not have been represented in the 30 square meter resolution DEM. Sub-surface flow features such as culverts are also not represented in the DEM.

LandTrendr sourced tree age data may not have been accurate as LandTrendr is an interpolated product based on United States Forest Service Forest Inventory and Analysis (FIA) data. LandTrendr may provide an overgeneralized model of the tree age and species composition of a specific modeled area due to the distance from the FIA plots to the modeled area and number of FIA plots used in the interpolation of the LandTrendr data of the modeled area (Kennedy, R.E. et al. 2012). The soil and vegetation rasters assumed that all modeled areas were forested and had sandy loam soils. This was an overgeneralization for sake of simplicity of the model and added uncertainty. The precipitation data and mean daily air temperature data from PRISM were interpolated products based on existing weather station data. In an area such as Humboldt County where there are numerous microclimates interpolated weather data may not be accurate and could contribute to model uncertainty. The observed flow data could have errors due to faulty instruments was experienced with the Jacoby Creek observed flow data. The modeled Hall Creek discharge values were created using historical daily mean temperature and daily precipitation values for the past 25 years. To use modeled data created using historical weather data is to assume that weather patterns will not change in the future. Data created using historic weather patterns may not be as informative to future conditions as climate change begins to affect California.

In this study the channel-forming flow was approximated with the effective discharge (flow). The return interval discharge was an approximation that was less complicated to calculate flow than the effective discharge. The effective discharge, however, was a more holistic approximation of the channel-forming flow, as it accounted for the hydrologic and sediment transport regime of the individual stream, and provided a single well-defined discharge value.

2.1 Further Verification of the Modeled Effective Flow

The modeled effective flow identified in this study should also be compared to discharge data of nearby comparable streams as well as morphological data for Hall Creek in order to verify the validity of the modeled effective flow. Biedenharn et al. recommended that the duration of the effective discharge should be compared with basin area-flow duration curves. He also recommended that a morphological check should be performed to compare the effective discharge to the bankfull discharge. This can be accomplished by identifying the bankfull stage at a stable cross-section of the stream and calculating the corresponding discharge either from the stage-discharge relationship at a nearby gauging station, or by using the slope-area method (Biedenharn et al. 2000).

2.2 Bedload Sediment Size Comparison Between Hall Creek and Jacoby Creek

It was assumed that Hall Creek and Jacoby Creek had similar bedload sediment sizes due to their geographic, geologic, and climatic similarities. As Jacoby Creek bedload sediment data was used to calculate the effective discharge of Hall Creek the similarity between the bedload sediments in the two creeks needed to be verified. A Wolman pebble count procedure was used to quantify the sediment sizes between the bedload sediments of Hall Creek and Jacoby Creek. In this procedure 100 random pieces of stream bed gravel collected by transecting the stream bed were measured into size classes with a gravelometer and the distribution of sediment particle sizes was determined (Kondolf and Li 1992,Wolman 1954).

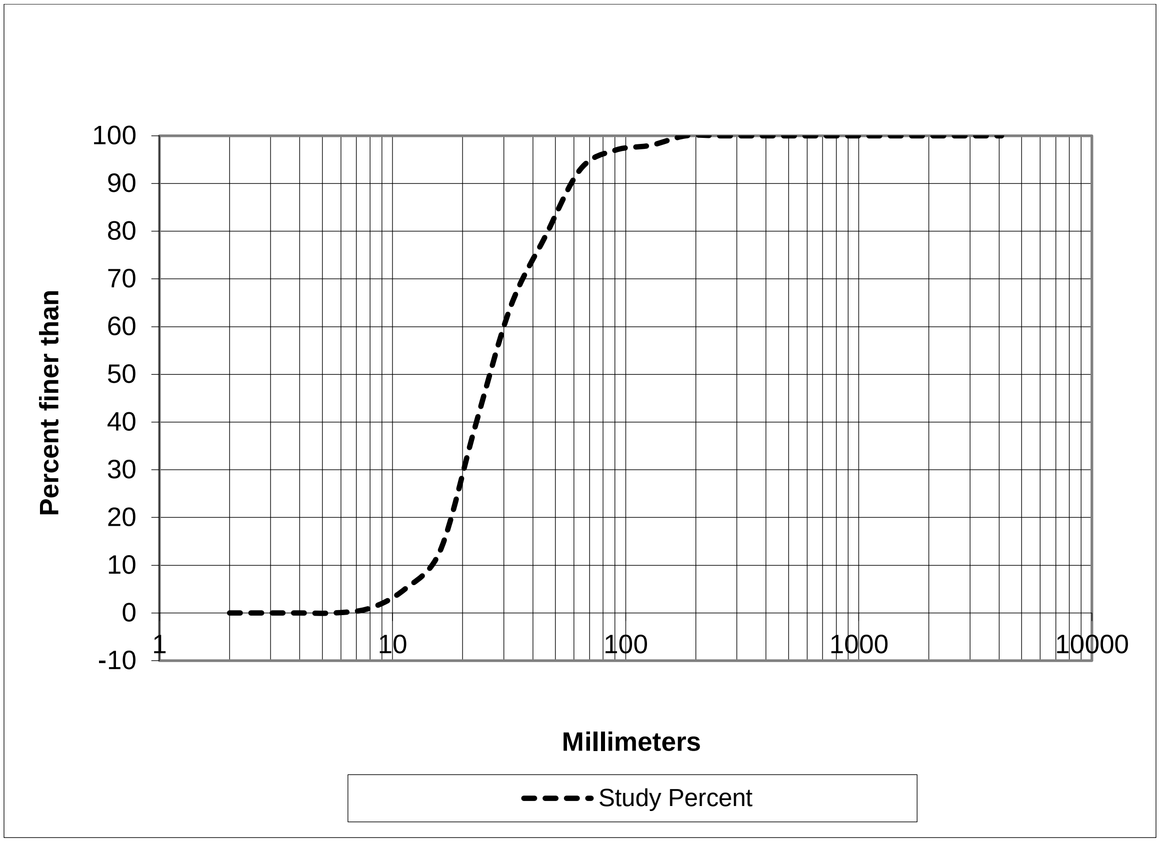

Figure 21: Cumulative particle size distribution of Jacoby Creek determined using the Wolman pebble count method. The average sediment particle was determined to be 27mm.

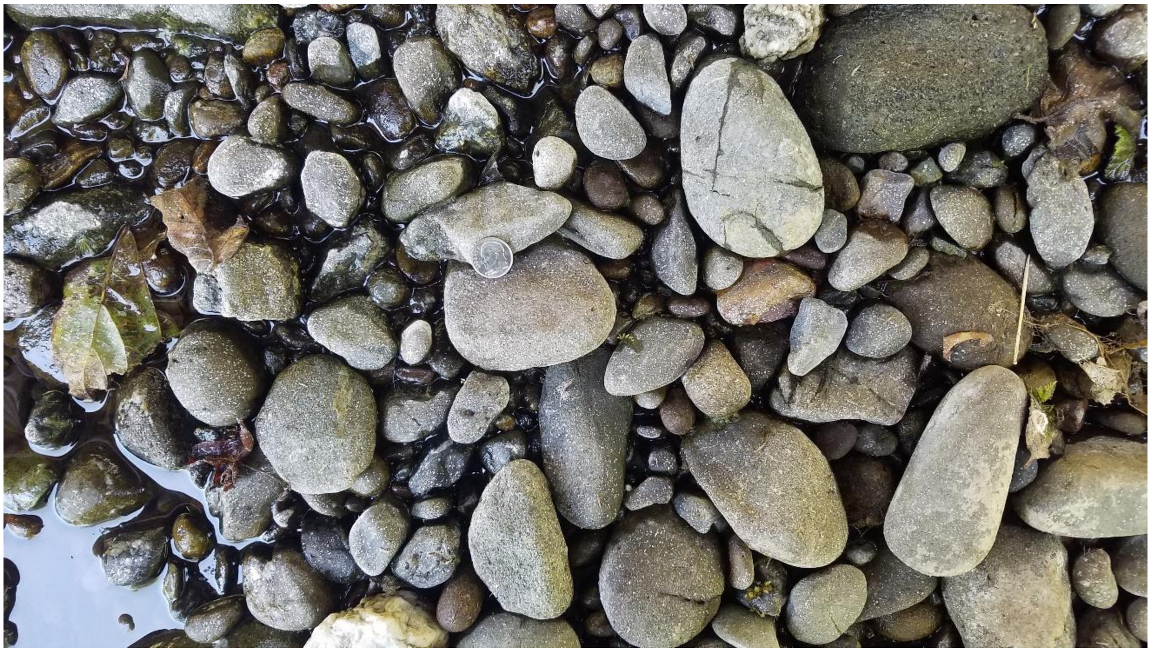

Figure 22: Jacoby Creek bedload sediments. A dime is shown for scale.

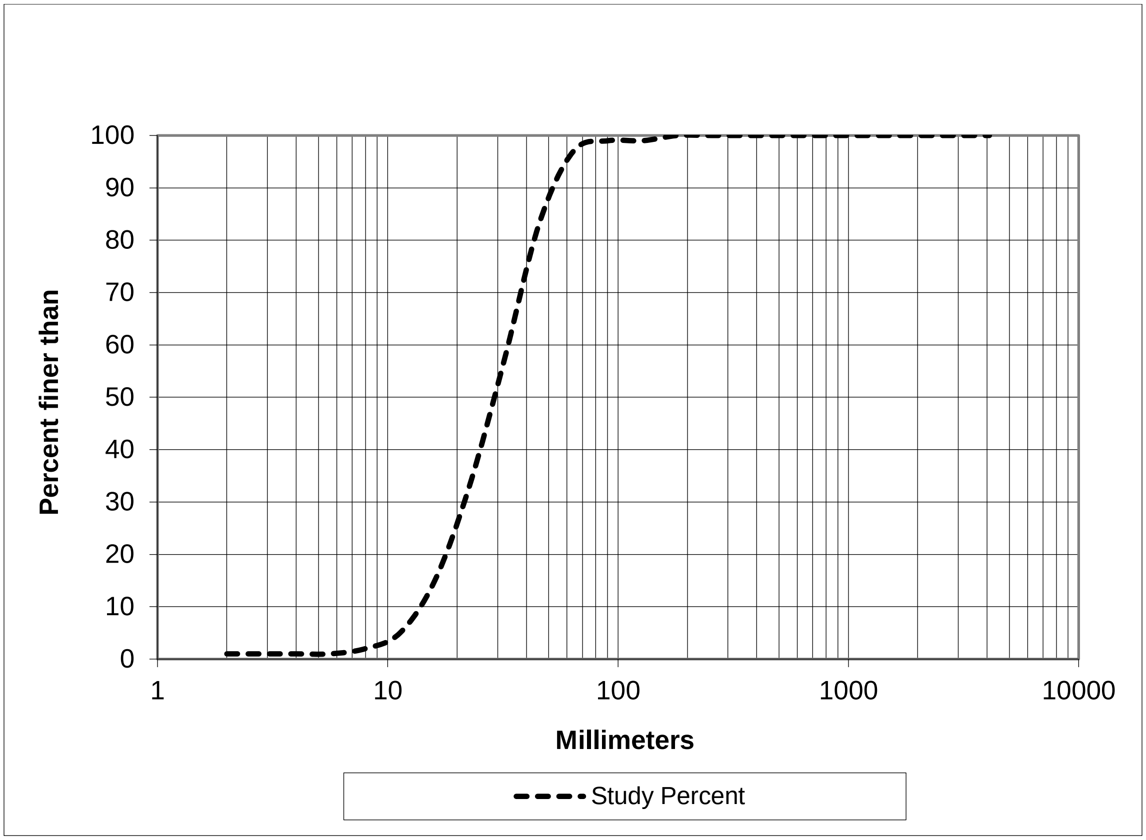

Figure 23: Cumulative particle size distribution of Hall Creek determined using the Wolman pebble count method. The average sediment particle was determined to be 29mm.

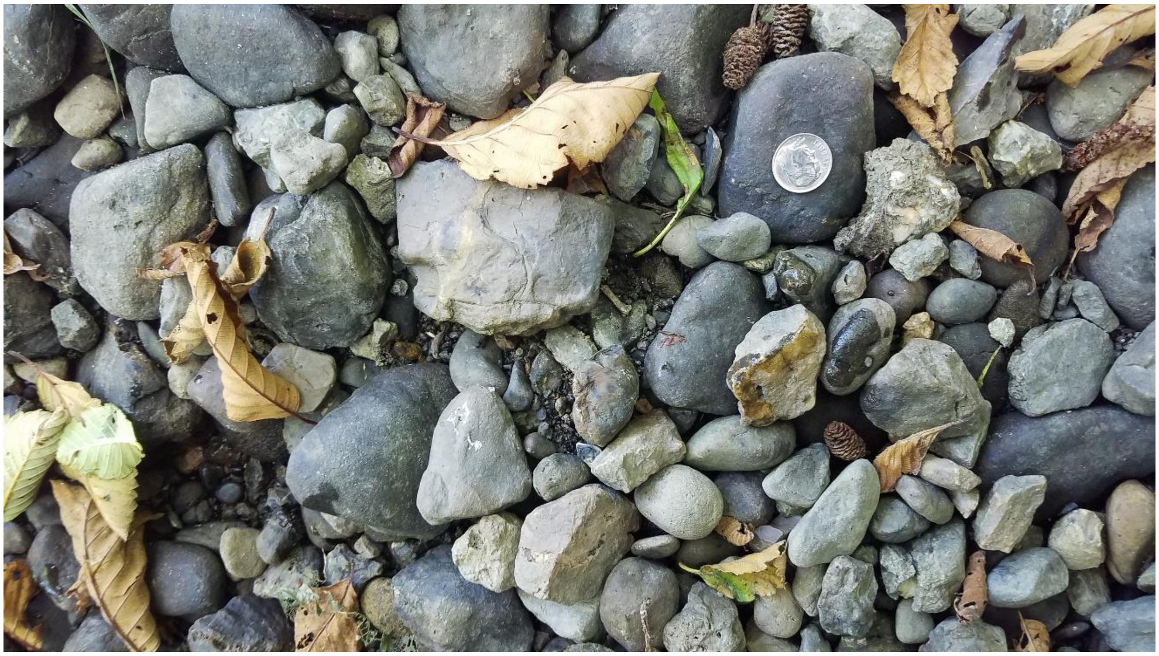

Figure 24: Hall Creek bedload sediments. A dime is shown for scale.

It was determined that the average sediment particle of Jacoby Creek was 27mm and the average sediment partible of Hall Creek was 29mm. Both average sediment sizes fall under the Wolman size class of coarse gravel. This confirmed that both streams have similarly sized coarse gravel bed load sediments.

2.2 Overestimation of Modeled Discharge by VELMA

In every year of the study except for 1996, 2005, 2013, 2014, and 2015 VELMA overestimated the modeled discharge compared to the observed discharge values of Elder Creek. In years with higher than average observed discharge values the overestimation was particularly pronounced. Overestimation of discharge however did not occur in all years in which there was a higher than average observed discharge but it was more likely than the years which had lower than average observed discharge. For the duration of the Elder Creek model the simulated discharge value was overestimated by 17% compared to the observed discharge values. It can be assumed that a similar level of overestimation would apply to the discharge model of Hall Creek, though it does not have observed discharge values to compare against.

This information is useful for future land managers who wish to use VELMA to model the discharge of ungauged streams. They should take steps to quantify the degree of overestimation of their modeled watershed using their calibration watershed model to ensure they do not over allocate water or make plans that include overestimated flow models.

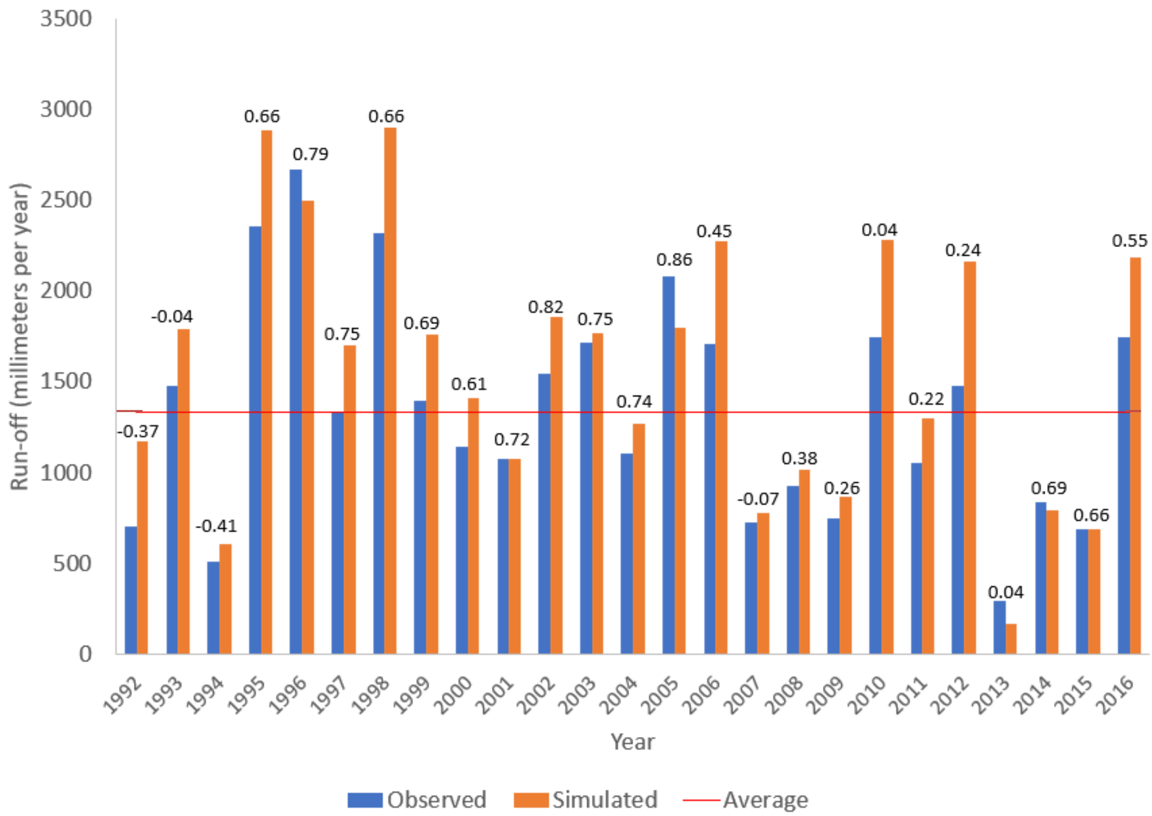

Figure 25: In almost every year VELMA overestimated the run-off produced by the Elder Creek watershed compared to the observed run-off data. The number above the paired bar charts are the Nash-Sutcliffe values produced for each year. The overall Nash-Sutcliffe value for this model was 0.65.

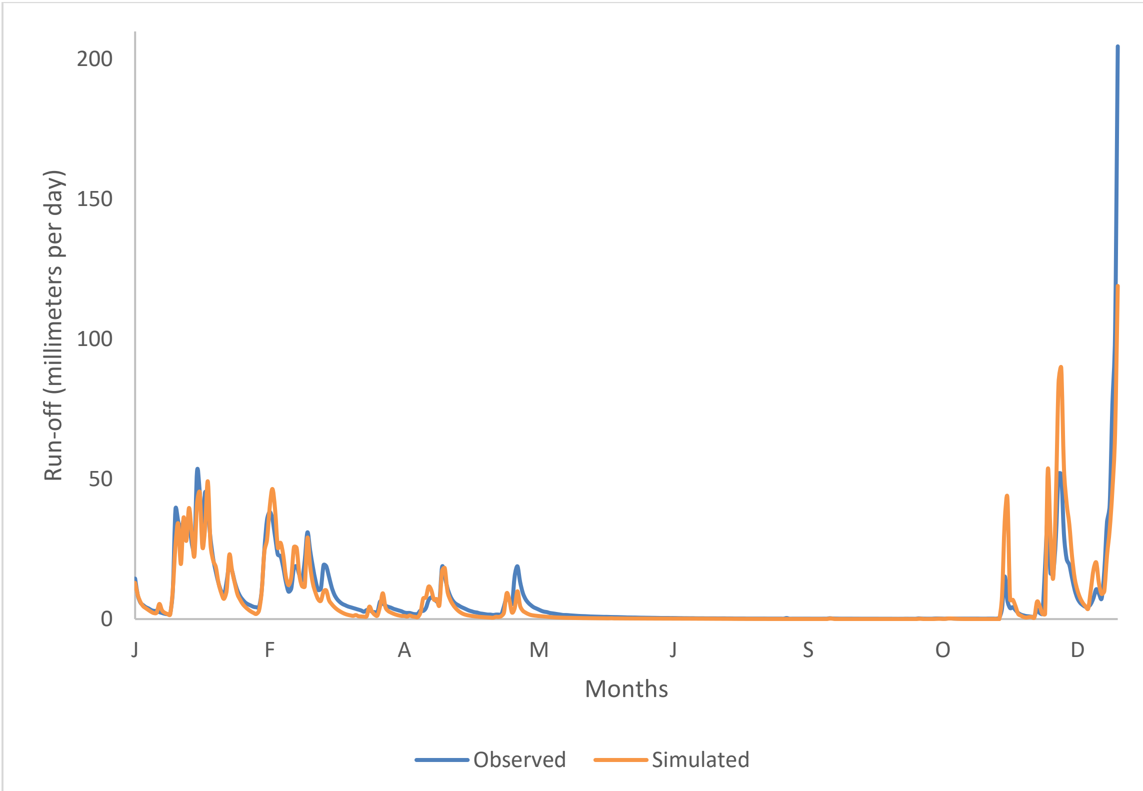

Figure 26: Hydrograph of the observed and modeled discharge values of Elder Creek in 1996, a wet year.

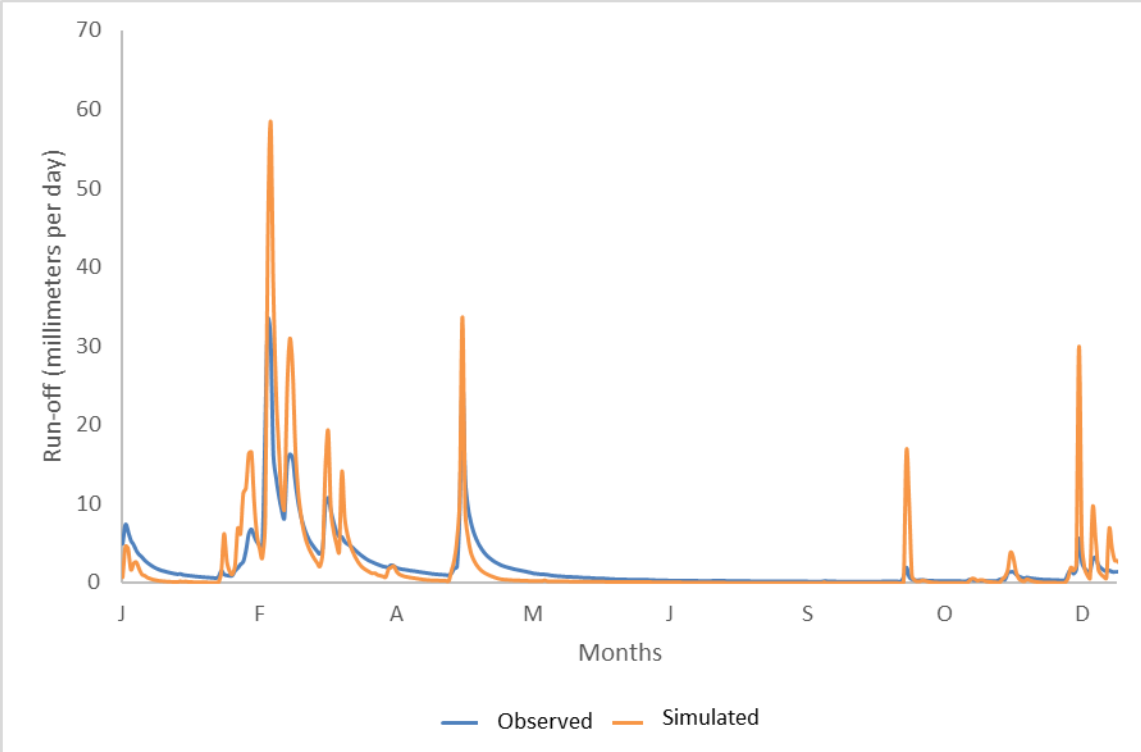

Figure 27: Hydrograph of the observed and modeled discharge values of Elder Creek in 2009, a dry year.

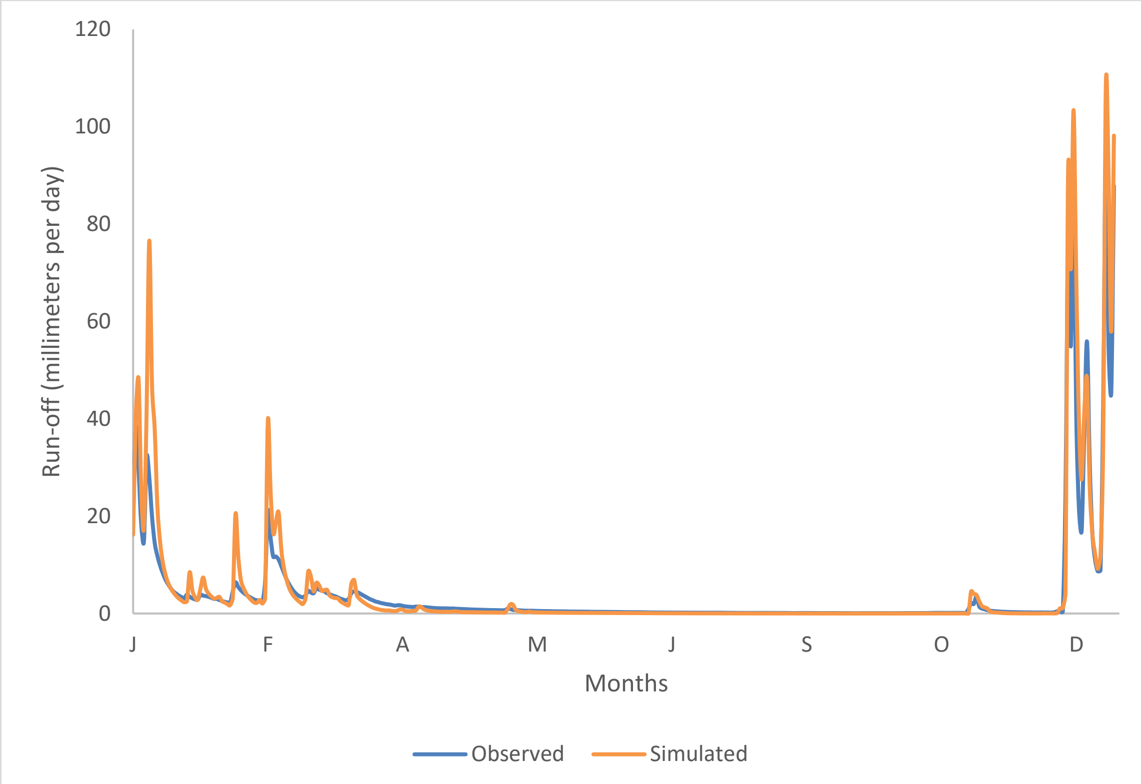

Figure 28: Hydrograph of the observed and modeled discharge values of Elder Creek in 2002, an average year.

In the hydrographs for the wet, dry, and average years there was overestimation of run-off during high flow events. This overestimation of run-off during high flow events was most pronounced in the hydrograph of the dry year and least pronounced in the hydrograph of the wet year. There appears to be a trend that in drier years VELMA over-estimated the run-off of high flow events more than in wetter years.

VELMA's overestimation of discharge could have had an effect on the calculated effective discharge for Hall Creek. The effective discharge of Hall Creek was found to have corresponded with a flow that had a return interval of 0.83 years. In the annual hydrographs an approximately yearly flow was one of the most overestimated points on the hydrographs. VELMAs overestimation of high flows could have resulted in a significantly overestimated effective discharge value for Hall Creek.

2.3 Inherent Inaccuracy in the Modeled Discharge and Calculated Effective Flow

Because the calculated effective flow of Hall Creek and modeled discharge of Hall Creek were modeled products, they had inherent levels of inaccuracy. The inaccuracy in the modeled Hall Creek discharge data was mitigated by calibrating the model using the Elder Creek data in order to quantify the accuracy of the VELMA modeled data with the Nash-Sutcliffe coefficient value. It was then assumed that the modeled discharge values produced for Hall Creek had the same level of accuracy as the calibration model for Elder Creek. It was found that VELMA had a tendency to overestimate discharge.

Elder Creek is a more inland system that is dominated by Douglas-fir and chaparral systems compared to Hall Creek which is more coastally influenced and almost completely covered with second growth redwood forest. Elder Creek is also located over 100 miles south of Hall Creek so Elder Creek may not be as good a calibration stream as Jacoby Creek even though it yielded a better Nash-Sutcliffe value. To use the VELMA created discharge values for Hall Creek or products derived from them, such as the calculated effective discharge, without further verification would be unwise.

The Hall Creek discharge values, modeled using VELMA, were created using historical daily mean temperature and daily precipitation values for the past 25 years. If the modeled discharge values are used for planning a future Hall Creek channel restoration project, an assumption will be made that the future weather patterns will remain stable. As California enters the Anthropocene and begins to experience the effects of climate change, historic weather patterns could be less informative of the future. This could be especially true if yearly precipitation and weather patterns continue to be as variable as they have been in the past 5 years, which were characterized by drought and extreme weather events.

2.4 Sources of Uncertainty for the VELMA Modeled Discharge Data

There are numerous sources of uncertainty in hydrological models such as VELMA. These sources of uncertainty can be grouped into two types model based uncertainty and input data uncertainty (Demargne et al. 2014). There is uncertainty in the model due to simplification in the conceptual model, parameters, or due to processes unknown and not included in the model. An example of this type of uncertainty is the overestimation of discharge during high-flow events. The overestimation likely occurred due to parameter settings or a component model of VELMA, not due to inaccuracy in the input data. The other type of uncertainty is due to inaccuracy of input data. For a model to yield accurate results it requires accurate inputs. An example of this would be the error filled Jacoby Creek gauge data that resulted in the failure of the Jacoby Creek model. Another example could be the PRISM air temperature and precipitation data. PRISM yields an interpolated product and in an area such as Humboldt County, California which has numerous microclimates it could yield inaccurate data due to the interpolation. The precipitation differences of microclimates could have a significant effect on the modeled discharge produced by VELMA. At the VELMA user level there is much more control over the input based sources of uncertainty than the model based sources of uncertainly. Input uncertainty is best managed by using input data from reliable sources and preforming quality assurance checks on all input data before inputting it into VELMA.

2.3 Why Approximate the Channel Forming Flow with Effective Flow?

Though the channel-forming flow can be approximated with bankfull flow, it is not recommended. There are numerous definitions of bankfull flow that currently exist (Williams, 1978). Depending on the definition of bankfull flow chosen, bankfull flow could correspond to a 1, 1.5, 2, or 3 year return interval (Biedenharn 2000; Richard 1982; Leopold 1994; Ford et al. 2002). The effective discharge is a more holistic approximation of the channel-forming flow, since it accounts for the hydrologic and sediment transport regime of the individual stream, while also providing a single well-defined discharge value.

The return period for channel-forming flows depends on the flow and sediment transport regime for each stream or river. By calculating the effective flow of a stream, a restorationist has a more tangible and justifiable discharge value to use as a starting point for the hydrologic design of a restored channel. This is preferable to the wide range of a 1-3 year return interval flow or a single arbitrary flow level as is found in one of the various definitions of bankfull flow.

3. Broader Impacts

This study only utilized the eco-hydrological modeling component of VELMA to model the discharge of a small watershed. The type of continuous flow modeling accomplished in this study can also be accomplished using HEC-HMS, a basin based rainfall run-off model (Anderson et al. 2002). VELMA could be more accurate in modeling watershed level run off in natural systems because it incorporates the biotic component of the watershed into its modeled results while HEC-HMS does not (Abdelnour et al. 2011; Hoghooghi et al. 2018). The vegetation model (PSM) of VELMA in this study was configured to model Douglas-fir forest. The Douglas-fir model was used to model the growth of redwood forest and its effects on watershed flow.

3.1 The Full Capabilities of VELMA

According to McKane et al., "VELMA is a spatially distributed, eco-hydrologic model that combines a land surface hydrology model with a terrestrial biogeochemistry model in order to simulate the integrated responses of vegetation, soil, and water resources to interacting stressors" (McKane et al. 2004). VELMA had the capacity to model the effects of changes in climate, disturbance (harvest, fire, etc.), and land cover on hydrological, ecological, and biogeochemical processes within watersheds. This capability was demonstrated in Abdelnour et al.'s study that used VELMA to model the losses of carbon and nitrogen to both run-off and increased decomposition after timber harvest (Abdelnour et al. 2013).

3.2 Justification for How VELMA was Used in This Study

This study only utilized the eco-hydrological modeling component of VELMA to model the discharge of a small watershed. Using VELMA to model the run-off produced by a forested watershed was not without precedence. Abdelnour et al's study "Catchment Hydrological Responses to Forest Harvest Amount and Spatial Pattern" used VELMA to quantify the impact of different levels of timber harvest on the run-off produced by a watershed in the H.J. Andrews research forest in Western Oregon (Abdelnour et al. 2011). VELMA was also used to model vegetated watershed run-off in Hoghooghi et al.'s study "Cumulative Effects of Low Impact Development on Watershed Hydrology in a Mixed Land-Cover System" in which they investigated low impact development practices (rain gardens, permeable pavement, and riparian buffers) on the run-off of a suburban watershed in Ohio (Hoghooghi et al. 2018).

HEC-HMS included land cover type data and an evapotranspiration co-efficient in its model, but did not incorporate a vegetation model to grow for the modeled time period (Ford et al. 2002). The inclusion of the vegetation model in VELMA may create a more accurate watershed model than HEC-HMS in vegetated systems. Due to the heavily forested condition of the Hall Creek watershed it is possible that the modeled discharge results created in this study with VELMA are more realistic than if I had used HEC-HMS or another modeling system that did not contain a vegetation model (Abdelnour et al. 2011; Hoghooghi et al. 2018). Vegetation slows the flow of water though a watershed and causes some of the water to be taken up by vegetation and transpired into the atmosphere (Dunne et al. 1991). This would result in VELMA's flows being more buffered against major spikes after rain events and the flow amount being slightly reduced due to transpiration by the vegetation compared to the results from a model that did not have a vegetation component.

3.3. The Use for VELMA Created Modeled Discharge Data

There are numerous streams and rivers that are either too isolated or small to justify being gauged. VELMA can be used to create modeled discharge data for these streams. This data can be used for various applications, such as operational forecasting to determine streamflow, as planning tools for resource management, for impact assessment of past and proposed land use changes, and for assessing climate change effects. Modeled discharge data can be used to model seasonal changes in water supplies, and even the availability of hydroelectric power. It can be used to help determine water quality and for allocating water by resource managers. It is also needed for modeling aquatic habitat, especially that of anadromous salmonids (Bourdin et al. 2012). In this study VELMA was found to overestimate the modeled discharge, especially the discharge of high flow events in dry years. Due to this resource managers should be aware of this tendency so that they do not over-allocate water.

CONCLUSIONS

1. Use for this Research

There are many small ungauged streams for which discharge data has never been collected. The method that I have described in my study is a fairly simple way to model daily stream flow for ungauged watersheds using commonly used GIS packages, modeling programs, and data sets. All these items, except for ESRI ArcMap, are accessible at no charge to anyone with an internet connection. A free open source GIS package such as QGIS could have been used in lieu of ESRI Arcmap.

Though no modeled product is perfect, it is better for stream restoration projects that occur on ungauged streams to have at least a modeled flow regime and effective discharge than no data to inform the designers. VELMA’s flow modeling application can also be used to model waterflow through the year for smaller ungauged tributaries. This has relevance for land managers, such as helping managers allocate seasonal water drafting by landowners in headwater regions, and other tasks that would require average daily flow values for ungauged streams. Like all modeled products, the modeled flow and products created using the modeled flow should always be tested and scrutinized before they are used for real-world planning purposes.

2. Application of the Findings

This project was executed with the ultimate goal of informing the land managers of the Hall Creek watershed of the flow level that a stream channel restoration should be constructed to accommodate. The modeled effective flow, a proxy for channel forming flow, was identified; however, the effective flow by itself is not enough information upon which to base a stream restoration. The modeled effective flow still needs to be further validated.

3. The Need for Sensitivity Analysis on VELMA

Sensitivity analysis should be conducted on VELMA so that the inputs or parameters that contribute the greatest amount of variance to the discharge model output can be identified. When the parameters and inputs that have the greatest contribution to the modeled discharge are identified, these inputs and parameters can be further calibrated and refined. The performance of the model with re-calibrated inputs and parameters can then be evaluated using performance criteria like the Nash-Sutcliffe coefficient of efficiency value (Holvoet et al. 2005). In this way the performance of VELMA discharge models can be improved.

4. Other Information Needed Prior to a Stream Channel Restoration

An effective stream channel restoration project requires other information aside from the effective flow. A set of clearly defined objectives for the channel restoration project is needed so that the purpose and end state of the project is established. This is necessary, as not all objectives are compatible: for instance, preventing further bank erosion by armoring the banks may not be compatible with creating a natural aesthetic. The current and desired ecological state needs to be defined. The relationship of the stream to the rest of the hydrologic and geomorphologic factors acting within the watershed needs to be established so that the stability of the stream, and stages of geomorphic evolution, can be assessed (Biedenharn et al. 2000).

The width of the designed channel needs to be determined. This can be accomplished by using the measured average width of a reference reach. The reference reach is a similar section of the stream or an analog stream that has a similar channel-forming flow as the project reach. Hydraulic geometry relationships can also be used to determine the channel width if a reference reach is not available (Biedenharn et al. 2000). The stable slope and depth of the channel needs to be determined to calculate a hydraulic geometry relationship. Biedenharn et al. recommends an analytical approach to calculate the design variables of width, slope, and depth from the independent variables of discharge, sediment inflow, and bed-material composition (Biedenharn et al. 2000; Hey and Thorne 1986). The stable channel planiform which is derived from meander length of the channel should also be determined (Leopold, Wolman, and Miller 1964).

A sediment assessment should be conducted to assess the long-term stability of the restored reach in order to identify future aggradation or degradation issues and try to estimate how much future maintenance will be needed to maintain the restored channel reach (Biedenharn et al. 2000).

5. Further Steps to Improve VELMA

The VELMA model required significant time to collect and process the raw data into a complete set of input files. In the future, tools could be created to automate the collection and processing of VELMA input files. Automation would greatly simplify and speed the processing of input data. In this study redwood forest was modeled using Douglas-fir vegetation model parameters. Species specific vegetation model parameters could be created to improve the overall performance of VELMA.

5.1 Automation of VELMA Input File Creation

Python could be used to automate the creation of VELMA input files. A georeferenced polygon could be used to determine the desired study area, extract the spatial data inputs such as the DEM, LandTrendr vegetation age data, soil type, and vegetation type rasters from their various online sources, and save the extracted files in a VELMA readable format. As the creation of these items would be automated, the cell sizes, raster dimensions, and data projection would automatically match. The extracted DEM and a pour point could then be run through an automated version of BlueSpray Water Tools to create a flat processed DEM with a designated pour point. The tabular data collection for temperature, precipitation, and observed flow data could also be automated by using the location of the watershed pour point and the desired time frame to extract weather driver data from PRISM and observed flow data from NWIS. As this tabular data collection would also be automated the resulting files would all have matching numbers of rows in the single column header-free format required by VELMA. The automatically created VELMA input files could then be input automatically into their correct locations in the VELMA GUI. By automating the creation and input of VELMA input files much of the difficulty associated with using VELMA could be removed.

5.2 The Need for Species Specific Vegetation Models

The vegetation model of VELMA was configured to the existing Douglas-fir parameters. For VELMA's purpose here, Redwood and Douglas-fir were similar species, yet for many aspects of VELMA's PSM Redwood and Douglas-fir are dissimilar species. The Douglas-fir parameters will not accurately model redwood growth, moisture uptake, or other functions as well as a Redwood species specific parameters. A redwood specific calibration should be created in the future so that VELMA models in the redwood region are more accurate. Similar species specific calibrations would also be beneficial for other common forest types that may not be well represented by Douglas-fir parameters.

REFERENCES OR LITERATURE CITED

Abdelnour, A., Stieglitz, M., Pan, F., & Mckane, R. (2011). Catchment hydrological responses to forest harvest amount and spatial pattern, *47*(July), 1–18.

Abdelnour, A., Mckane, R. B., Stieglitz, M., Pan, F., & Cheng, Y. (2013). Effects of harvest on carbon and nitrogen dynamics in a Pacific Northwest forest catchment, *49*(March), 1292–1313.

Anderson, M. L., Asce, M., Chen, Z., Asce, M., Kavvas, M. L., Asce, M. (2002). Coupling HEC-HMS with Atmospheric Models for Prediction of Watershed Runoff, *7*(4), 312–318.

Andrews, E. D., and Nankervis, J. M. (1995). "Effective discharge and the design of channel maintenance flows for gravel-bed rivers." Natural and anthropegenic influences in fluvial geomorpholgy, AGU Monograph Series No. 89, Washington, D.C., 151–164.

Angelo Coast Range Reserve. (2018). Retrieved February 21, 2019, from http://angelo.berkeley.edu/

Apostol, D., Sinclair, M., & Higgs, E. (2006). *Restoring the Pacific Northwest The Art and Science of Ecological Restoration in Cascadia*. Washington: Island Press.

Biedenharn, D. S., Copeland, R. R., Thorne, C. R., Soar, P. J., Hey, R. D., & Watson, C. C. (2000). Effective Discharge Calculation : A Practical Guide.

Bisson, P.A., K. Sullivan, and J.L. Nielson. (1988). Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead trout, and cutthroat trout. Transactions of the American Fisheries Society 117: 262-273.

Bourdin, D.R., Fleming, S.W., & Stull, R.B. (2012) Streamflow Modelling: A Primer on Applications, Approaches and Challenges, Atmosphere-Ocean, 50:4, 507-536, DOI: 10.1080/07055900.2012.734276

Brookes, A., (1988). Channelized Rivers: Perspectives for Environmental Management. John Wiley and Sons, Chichester: Wiley.

Brookes, A.,& Shields, F.D.,JR. (1996). River channel restoration: guiding principles for sustainable projects. John Wiley and Sons, Chinchester.

Brunner, Gary W. (2016). HEC-RAS River Analysis System User's Manual. Hydrologic Engineering Center, US Army Corps of Engineers. Davis California.

Burnett, K.M., G. Reeves, D. Miller, S. Clarke, K. Christiansen, and K. Vance-Borland. (2003). A first step toward broad-scale identification of freshwater protected areas for Pacific salmon and trout in Oregon, USA.

Collin, M., Flemming, S. (2018). *Obtaining a DEM and Pour Point for VELMA.* Internal Report: THE INSTITUTE FOR SPATIAL ANALYSIS, MODELING, AND MONITORING at Humboldt State University. Unpublished.

Crowder, D. W., & Knapp, H. V. (2005). Effective discharge recurrence intervals of Illinois streams. Geomorphology, 64(3–4), 167–184. https://doi.org/10.1016/j.geomorph.2004.06.006

Decamps, H., and R. J. Naiman. (1989). L'ecologie des fleuves. La Recherche 20:310-318.

Demargne, J., Wu, L., Regonda, S. K., Brown, J. D., Lee, H., He, M. & Schaake, J. (2014). The science of NOAA's operational hydrologic ensemble forecast service. *Bulletin of the American Meteorological Society*, *95*(1), 79-98.

Doyle, M. W., Shields, D., Boyd, K. F., Skidmore, P. B., & Dominick, D. (2007). Channel-Forming Discharge Selection in River Restoration Design. *Journal of Hydraulic Engineering*, *133*(7), 831–837.

Dunne, T., Zhang, W., & Aubry, B. F. (1991). Effects of rainfall, vegetation, and microtopography on infiltration and runoff. *Water Resources Research, 27*(9), 2271-2285.

Emmett, W. W., and Wolman, M. G. (2001). "Effective discharge and gravel-bed rivers." Earth Surf. Processes Landforms, 26, 1369–1380.

Farro, M. (2014). *2014 FRGP Proposal Application Form: Hall Creek Coho Habitat Improvement Project*. Arcata, CA: Pacific Coast Fish, Wildlife and Wetlands Restoration Association.

Fleming and Brauer. (2016). Hydrologic modeling system HEC-HMS Quick Start Guide. Hydrologic Engineering Center, US Army Corps of Engineers, Davis, CA.

Ford, D., Pingel, N., & DeVries, J. J. (2002). *Hydrologic modeling system HEC-HMS: applications guide*. US Army Corps of Engineers, Hydrologic Engineering Center.

Frissell, C.A. (1997). Ecological principles. Pages 96-115 in J.E. Williams, C.A. Wood, and M.P. Dombeck (eds.), Watershed Restoration: Principles and Practices. American Fisheries Society, Bethesda, MD.

GEC (Grassetti Environmental Consulting). (2011). "Final environmental impact report: Salt River ecosystem restoration project." SCH# SD2007-05-6 Accessed December 2017

Goodwin, P. (2004). "Analytical solutions for estimating effective discharge." J. Hydraulic. Engineering., 130(8), 729–738.

Graham, James. (2016). "Learning Module: Streams and Watersheds." GSP 510: Streams and Watersheds, Humboldt State GSP. http://gsp.humboldt.edu/OLM_2017/Activities/GSP_270/06_MusicFestival_Attributes/Lab6_Part2_510.html

Grey, Greg. (2017). Personal Communication during field visit to McAdams Ranch. January 2017.

Harvey, B. C., Nakamoto, R. J., & White, J. L. (2006). Reduced streamflow lowers dry-season growth of rainbow trout in a small stream. *Transactions of the American Fisheries Society, 135*(4), 998-1005.

Halama, Jonathan. (2018). Personal Communication at VELMA training seminar July 2018.

Halama, Jonathan. (2018) Personal Communication by email August- December 2018.

Halama, Jonathan. (2019) Personal Communication by telephone January 10, 2018.

Hey, R. D. (1975). "Design discharge for natural channels," Science, Technology and Environmental Management. R. D. Hey and T. D. Davies, eds., Saxon House, 73-88.

Hey, R. D. (1997). "Channel response and channel forming discharge: literature review and interpretation," Final Report, U.S. Army Contract Number R&D 6871-EN-01.

Hey, R. D., and Thome, C. R. (1986). "Stable channels with mobile gravel beds," Journal of Hydraulic Engineering 112(8), 671 -689.

Hoghooghi, N., Golden, H. E., Id, B. P. B., Barnhart, B. L., Brookes, A. F., Djang, K. S., Pettus, P. P. (2018). Cumulative Effects of Low Impact Development on Watershed Hydrology in a Mixed Land-Cover System, 1–21.

Holvoet, V. G., Seuntjens, & Vanrolleghem. (2005). Sensitivity analysis for hydrology and pesticide supply towards the river in SWAT. *Physics and Chemistry of the Earth, 30*(8-10), 518-526.

Keller, E.A. (1976). Channelization: Environmental, geomorphic and engineering aspects. In *Geomorphology and Engineering* (ed. Coates, D.R.). George Allen & Unwin, London, pp.115-140.

Kennedy, R.E., Yang, Z., Cohen, W.B., Pfaff, E., Braaten, J. and Nelson, P., (2012). “Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan.” Remote Sensing of Environment, 122, pp.117-133.

Klein, R., Lyle T., et al. (2018). Bed Load Sediment Transport Curve for Jacoby Creek at Brookwood Bridge. USFS Redwood Science Lab, Arcata California. Unpublished.

Kondolf, G. M. (2000). Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. *Restoration Ecology*, *8*(1), 48–56.

Kondolf, G. M., Smeltzer, M. W., & Railsback, S. F. (2001). Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. *Environmental Management*, *28*(6), 761–776.

Kondolf, G. M., J. C. Vick, and T. M. Ramirez. (1996). Salmon spawning habitat rehabilitation on the Merced River, Cali- fornia: an evaluation of project planning and performance. Transactions of the American Fisheries Society 125: 899-912.

Kondolf, G. M., & Li, S. (1992). The pebble count technique for quantifying surface bed material size in instream flow studies. *Rivers*, *3*(2), 80-87.

Leopold, L. B. (1994). A view of the river. Harvard University Press, Cambridge.

Leopold, L. B., & Wolman, M. G. Miller. (1964). Fluvial processes in geomorphology. *San Francisco, California, Freeman*, *522*, 135-163.

Luckens, Ethan. (2018) "An Attempt to Use HEC-GeoHMS to Pre-Process Digital Elevation Models for Entry into HEC-HMS". Unpublished.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., (2008). GSFLOW-Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1, 240 p.

McAdams D.C., Luckens, B.J. Personal Communication Sept-Dec 2017.

McKane, Robert. et al. (2014). VELMA Version 2.0 User Manual and Technical Documentation. U.S. Environmental Protection Agency Office of Research and Development.

Montgomery, D.R. and J.M. Buffington. (1997). Urbanization, flood frequency, and salmon abundance in Puget Lowland streams. *Journal of the American Water Resources Association* 33: 1289-1297.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900.

Nash, D. B. (1994). "Effective sediment-transporting discharge from magnitude-frequency analysis." J. Geol., 102, 79–95.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I- A discussion of principles. *Journal of hydrology*, *10*(3), 282-290.

Naiman, R.J., T.J. Beechie, L.E. Benda, D.R. Berg, P.A. Bisson, L.H. MacDonald, M.D. O'Connor, P.L. Olson, and E.A. Steel. (1992). Fundamental elements of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. Pages 127-188 in R.J. Naiman Watershed Management: Balancing Sustainability and Environmental Change. Springer-Verlag, New York.

Naiman, R. J., Decamps, H., & Pollock, M. (1993). The Role of Riparian Corridors in Maintaining Regional Biodiversity. *Ecological Applications*, *3*(2), 209–212.

Oudin, L., Andre, V., Perrin, C., & Michel, C. (2008). Spatial proximity , physical similarity , regression and ungaged catchments : A comparison of regionalization approaches based on 913 French catchments, *44*, 1–15. https://doi.org/10.1029/2007WR006240

Patil, S. D., & Stieglitz, M. (2015). Comparing spatial and temporal transferability of hydrological model parameters. *JOURNAL OF HYDROLOGY*, *525*, 409–417. https://doi.org/10.1016/j.jhydrol.2015.04.003

Petts, G.E., H. Moller, and A.L. Roux, editors. (1989). Historical change of large alluvial rivers: western Europe. John Wiley & Sons, Chinchester, England.

Raedeke, K., editor. (1989). Streamside management: riparian wildlife and forestry interactions. Contributuin Number 59. Institute of Forest Resources, University of Washington, Seattle, Washington, USA.

Richards, K. S. (1982). Rivers: form and process in alluvial channels. Methuen, London, 361.

Shaw, E. (1994). *Hydrology in practice* (3rd ed.). London ; New York: Chapman & Hall.

Simon, A., Dickerson, W., and Heins, A. (2004). "Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: Transport conditions at the bankfull and effective discharge?" Geomorphology, 58, 243–262.

Stanford, J.A. and Ward J.V. (1992). Management of aquatic resources in large catchments: recognizing interactions between ecosystem connectivity and environmental disturbance.

Swartz, Maurice. (2006). *Encyclopedia of Coastal Sciences.* Springer Science and Business Media. The Neatherlands.

USACE Hydraulic Engineering Center (2017). HEC-RAS Features. US Army Corps of Engineers. Retrieved January 16, 2018, from http://www.hec.usace.army.mil/software/hec-ras/features.aspx

Wagener, T., & Wheater, H. S. (2006). Parameter estimation and regionalization for continuous rainfall-runoff models including uncertainty, *320*, 132–154. https://doi.org/10.1016/j.jhydrol.2005.07.015

Waters, T.F. (1995). Sediment in streams: sources, biological effects, and control. American *Fisheries Society Monograph* 7, Bethesda, MD.

Williams, G. P. (1978). "Bankfull discharge of rivers," Water Resources Research 14(6), 1141-1154.

Williams, J. E., & Reeves, G. H. (2006). Stream Systems. In *Restoring the Pacific Northwest*(pp. 298-318). Washington: Island Press.

Wolman, M. G. (1954). A method of sampling coarse river-bed material. *EOS, Transactions American Geophysical Union, 35*(6), 951-956.

Wolman, G., and Miller, J. (1960). “Magnitude and frequency of forces of geomorphic processes.” J. Geol., 68, 54–74.

Yevjevich, V. (1972). Probability and Statistics in Hydrology, Water Resources Publications, Fort Collins, CO, USA.

APPENDIX A: PREPARING DATA FOR INPUT INTO VELMA INSTRUCTIONS

Appendix A.1 : Creating a Flat Processed DEM and Defining the Pour Point

The following steps were used to create a flat processed DEM and the pour point used to define the watershed boundaries using BlueSpray's "Water Tools." This process started with cropping a projected DEM. Possible sinks in the cropped DEM were filled. The filled DEM was used to create the initial flow direction raster. The initial flow direction raster was used to create the pour point data set. The pour point data set and the initial flow direction raster were used to create the initial watershed raster. The new watershed raster was created by correcting sinks and flat areas on the initial watershed raster so that all pixels flowed into a pour point. The new watershed raster was used to create the accumulation raster. The stream network was created by using the pixel accumulation values to identify the stream network. The watershed pour point was created at the bottom of the watershed. The watershed pour point and the new watershed raster were used to create the flat processed DEM.

A.1.1 Downloading the Original DEM and Extracting the Cropped DEM for Flat Processing

DEMs projected into NAD 83 UTM Zone 10 North were available from the United States Department of Agriculture ('USDA') Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/). These DEMs did not need to be re-projected. Re-projecting DEMs can create artifacts that distort the modeled flow (Luckens, 2018).

The original DEMs were downloaded from the USDA Geospatial Data Gateway site as a zipped file containing images in a tagged image file format (TIFF). If the watershed was located within a single image, the area containing the watershed can be cropped from the original image. The Hall Creek watershed was located along an image boundary, so two images had to be mosaiced together before clipping. Generous overestimation of the watershed area by at least 1 kilometer on all sides was recommended when cropping the DEM (Halama, personal communication, 2018). The overestimation is to ensure all the watershed is captured; VELMA is a spatially complete watershed simulation model.

A.1.2 Finding the Initial Flow Direction Raster

The cropped watershed DEM could have contained sinks or holes. Holes or sinks are cells where all the surrounding pixels are higher, which prevents water from flowing out of the sink. Before the watershed DEM could be flat processed, any sinks and holes needed to be filled. The “Fill Sinks” option within “Water Tools” was used to accomplish this task (Collin and Flemming, 2018). Filling sinks will be automatic in future versions of BlueSpray (Graham, Personal Communication, March 2019).

The initial flow direction raster identified the direction of flow for each pixel, with an integer from 1 to 8 representing a cardinal direction. The initial flow direction raster in BlueSpray displayed the cardinal direction of each pixel with a direction arrow. Sink pixels were shown as circles. Two or more adjacent pixels that had the same value were represented as squares, meaning that they were “flat”. Flat areas were corrected in the next steps, so that the direction raster had no flat areas, and the only remaining sinks were pour points on the edge of the raster (Collin and Flemming 2018). The initial flow direction raster was created by using the filled DEM as the input for the “Find Flow Direction” option within “Water Tools”.

A.1.3 Finding the Initial Pour Points

The initial pour point dataset was a necessary input for the initial watershed raster as it set the points into which the initial watersheds flow. The initial pour point dataset may contain many pour points, as the smaller watersheds at the edges of the raster were each assigned a pour point. In this study the initial pour point dataset contained many pour points on the edges of the raster. The numerous pour points on the edges of the map were desirable because they kept the water on the edges flowing off the map, instead of into the modeled watershed. The initial pour point dataset was created by using the filled DEM as the input for the "Find Pour Points" option within "Water Tools" (Collin and Flemming 2018).

A.1.4 Finding the Initial Watershed Raster

The initial watershed raster flowed all the pixels in the initial flow direction raster through the initial pour points. Each pixel within a watershed was given a value greater than 0 to identify the watershed in which it was located. Pixels that did not reach a pour point appeared with a value of 0. The great majority of the pixels would not flow to a pour point. The initial watershed raster was created by using the pour point raster and initial flow direction raster as the inputs for the "Find Initial Watershed Raster" option within "Water Tools" (Collin and Flemming 2018).

A.1.5 Finding the New Watershed Raster

The new watershed raster was a modified version of the initial watershed raster in which all pixels flowed to a pour point. This was done by "filling" sinks and "sloping" flat areas so that all pixels in the raster drained into a watershed. This was one of the few BlueSpray transformations that modified an existing watershed raster, rather than creating a new raster. The new direction raster was created by using the initial watershed raster, the initial flow direction raster, and the filled DEM as the inputs for the "Add Pixels to Watershed Raster" option within "Water Tools" (Collin and Flemming 2018).

A.1.6 Finding the Accumulation Raster

The accumulation raster was a raster in which each pixel was a count of the number of pixels that flowed into it. The accumulation raster contained very large numbers at the end of the paths. As a result of this, the accumulation raster was given a special color ramp to compensate for the large range of values. The accumulation raster was created by using the new direction raster as the input for the "Find Accumulation" option within "Water Tools" (Collin and Flemming 2018).

A.1.7 Finding the Stream Network

The stream network was identified by using the pixel accumulation values from the accumulation raster and the minimum accumulation value to identify the stream network and create a vector layer in which each stream reach was a feature. The "minimum accumulation value" set the value that was required for an accumulation pixel to be designated as part of a stream reach. If the minimum accumulation value was set too low, an overly complex stream network was created. Higher minimum accumulation values would reduce the complexity of the stream network but might not include reaches in headwater areas. The created stream network was compared against aerial imagery or other GIS files of the actual stream system. The stream network was created by using the accumulation raster and new direction raster as the input for the "Find Stream Network" option within "Water Tools." It was recommended to initially use the pre-set minimum accumulation value of 100 when using "Water Tools" in BlueSpray. Changes could be made based on the initial performance at the minimum accumulation level of 100 (Collin and Flemming 2018). In this study the pre-set minimum accumulation value of 100 was used.

A.1.8 Placing the Watershed Pour Point

The watershed pour point was placed at the location of a gauge station or where a gauge would be located on an ungauged watershed. The watershed pour point was placed using the accumulation raster as a reference for the location of the stream. VELMA required that the watershed pour point be specified as an X,Y pixel coordinate within the flat processed DEM (Collin and Flemming 2018).

A.1.9 Create the Flat Processed DEM

A flat processed DEM was created by using the watershed pour point and the new direction raster as inputs for the "Find Initial Watershed Raster" option in "Water Tools." This resulted in a flat processed watershed. In BlueSpray, the resulting flat processed

DEM was labeled “Flowing Elevations”, which was a more accurate description than the more common term of “flat processed.”

The flat processed DEM can be cropped if extraneous areas need to be removed. The flat processed DEM was cropped to include a 10% buffer surrounding the entire desired watershed as recommended by Jonathan Halama (Halama, July, 2018). A minimum of a three cell border is required by VELMA. The cropped flat processed DEM was then saved as an ASCII grid file. Once saved as an ASCII file, the final flat processed DEM version was ready for input into VELMA.

The “Identify” tool was used to find the pixel coordinate of the watershed pour point within the final flat processed raster. The pour point coordinates were written down, and a text file was created in which to store the pour point coordinates with the VELMA ready flat processed DEM (Collin and Flemming 2018).

A.1.10 Saving the Desired Intermediate Files.

BlueSpray does not save files automatically. If intermediate files are not saved manually, they will be lost when BlueSpray is closed. I always ensured to save at least the pour point, the created stream network, and the new watershed raster.

Appendix A.2 Creating Soil, and Land Cover Type Rasters

A reclassified DEM, made up entirely of the integer of 1, was needed for the soils layer and the land cover type layer. A reclassified DEM comprised of only the value 80 was useful as a placeholder tree age raster until Landtrendr tree age rasters could be produced. This represented an 80 year old second growth forest covering the entire watershed. The reclassified single value rasters were saved as ASCII files, to ensure that they were saved as whole numbers, not decimal values (Halama, personal communication, December 2018).

Appendix A.3 Creating the Tree Age Raster

To create a LandTrendr tree age raster, an area of interest shapefile was created from the flat processed DEM. A single integer raster was used to create an area of interest shapefile of the perimeter of the raster. A 500 meter buffer was created around the area of interest shapefile. The buffered area of interest was projected into LandTrendr's Albers projection, and the projected 500 meter buffer shapefile was used to clip out the desired tree age data from the Landtrendr raster. The clipped LandTrendr raster was then projected into the UTM Zone 10 North projection to match the rest of the VELMA input raster files. The UTM Zone 10 North projected LandTrendr raster was then clipped to the extent of the original single integer raster as VELMA requires all reasters to be for the same extent and resolution (Halama, personal communication, December 2018).

Appendix A.4 Downloading and Formatting the Weather Driver Data.

The mean daily air temperature data (in degrees Celsius) and precipitation data (in millimeters per day) for the modeled time period were downloaded from PRISM Climate Group (http://www.prism.oregonstate.edu/). The weather driver data for each modeled location downloaded as a single tabular data file with a heading. The temperature and precipitation values were extracted into separate CSV files without heading information.

Appendix A.5 Downloading and Formatting the Observed Flow Data for VELMA.

Mean daily flow (cubic feet per second) data for Elder Creek was downloaded from the USGS "Surface-Water Historical Instantaneous Data for the Nation: Build Time Series" website for the modeled time period. The flow data was downloaded as a zipped folder. After unzipping, this tabular data was opened in Excel and a new blank CSV file was created. In the new CSV file, the observed flow data was copied without headers or column names. The observed flow file and weather driver files represented the same days and contained the same number of rows.

The observed flow data (cubic feet per second) must be converted into millimeters per square meter per day ($mm/m^2/day$) for input to VELMA. The millimeters per square meter per day conversion factor was found with the following steps. I converted the number of cells within the watershed to the square footage of the watershed. Given that the cells were 30 meters on a side and there were 18,595 cells, the resulting watershed area was 180,139,248 square feet. The inverse of this area was multiplied by the number of seconds in a day. This value was then multiplied by 12 to convert to inches per day. The inches per day value was converted to millimeters per day by multiplying by 25.4. This yielded the millimeters per square meter per day conversion factor. The discharge data in cubic feet per second was then multiplied by the millimeters per square meter per day conversion factor to transform it into the VELMA compatible millimeters per square meter per day (Halama, personal communication, November 2018).

The conversion factor for Hall Creek was determined using the same methods. The Hall Creek conversion factor was required to transform the VELMA created simulated flow ($mm/m^2/day$) values into cubic feet per second by dividing the millimeters per day per square meter per day values by this conversion factor.

Appendix A.6 Preparing the Folder Structure for VELMA

A folder structure was used to organize the various input and output files of a VELMA model. Each stream model had its own folder containing a subordinate file structure. The subfolders were for the (eXtensible Markup Language) XML configuration files, the input data files, and the output data files. The Java file containing the VELMA program and the batch file used to launch VELMA were also stored in the same folder as the VELMA model folder structure. A diagram of the folder structure used for this project is shown in Figure A1.

The configuration folder was used to hold the individual XML configuration files. The XML configuration files were used to save input file paths and parameters set using the graphic user interface (GUI) (Halama, personal communication, November 2018).

The input data folder held the data that was input into VELMA to create the model. All raster files within a VELMA model must have the same dimensions and pixel size as the flat processed DEM. The input data folder was further broken down into subfolders that held the various input file by type. This included sub-folders for the DEM, weather drivers, vegetation age, vegetation cover type, soils, and observed flow (Halama, personal communication, November 2018).

The output data folder was where the output files, created during each VELMA run were stored. Each VELMA output folder contained a CSV file of the daily simulated and observed flow values, a CSV of the yearly simulated and observed flow values, a text file (TXT) of the Nash-Sutcliffe value, and other files.

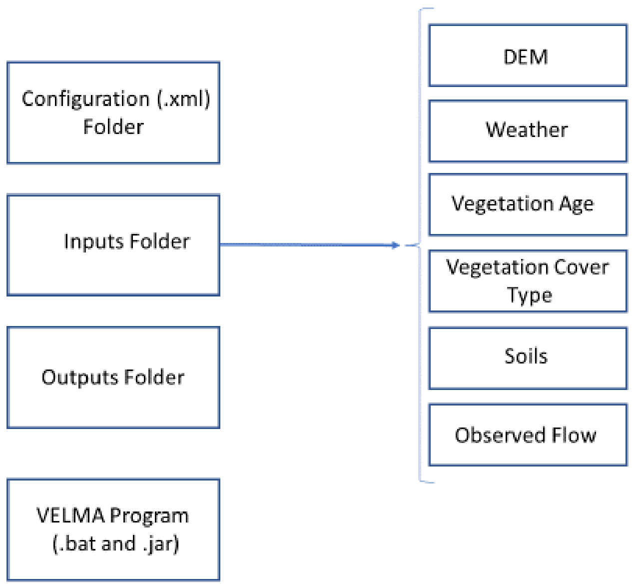

Figure A1. The diagram shows the recommended folder structure for a VELMA model. The XML configuration files, inputs, and outputs are the primary folders. The files containing the VELMA program are stored at the same level as the primary folders. The inputs folder is further broken down into sub-folders for the different types of inputs (Halama, email communication, November, 2018).

APPENDIX B: DETAILS ON BUILDING A WORKING VELMA MODEL

Appendix B.1 Creating a VELMA Model XML Configuration File

The VELMA software provides a GUI to input file paths and set parameters such as the initialization date, termination date, latitude, and longitude. Input file paths were added to the configuration by opening the "All Parameters" tab within the GUI and scrolling to the desired parameter line. The "Replace Value" button was used to add the new input file paths and parameters to the VELMA model configuration. The input file paths, output file paths, and parameter settings were saved to an XML configuration file.

Appendix B.2 Launching VELMA and Testing the Elder Creek Model.

The Java file containing the VELMA program was stored in the same folder as the VELMA model folder structure. VELMA was launched using the executable Java file. To run the VELMA model on a new computer, I had to change the input data location root name, input data location directory name, and output data location root names to the locations of these files on my computer. The input data location root name was changed to the entire file path of the Elder Creek VELMA model. The input data location directory name was changed to the file name of the Elder Creek VELMA model's input subfolder. If the input data location root name and input data location directory name was entered correctly, the number of columns and rows in the DEM automatically populated within the "Run Parameters" tab of the GUI; a built in VELMA clue to assist with setup. The output data location root name was changed to the name of the output subfolder of the Elder Creek VELMA model. A new version of the XML configuration file, in which the inputs and output folders of the Elder Creek VELMA model were connected, was saved. The Elder Creek VELMA model was tested by running it to completion. The output files such as daily modeled flow values and the Nash-Sutcliffe value were reviewed to see if it was greater than 0.6 (Halama, personal communication, July, 2018). The Elder Creek VELMA model produced a Nash-Sutcliffe value of 0.65, which was high enough to allow us to apply the model to Hall Creek.

Appendix B.3 Inputting Hall Creek Files to the Elder Creek VELMA Model

The working and tested for goodness of fit Elder Creek VELMA model configuration was modified by replacing the existing files with files for the Hall Creek watershed. The input data files for the Hall Creek watershed were copied into their corresponding sub-folders within the Elder Creek VELMA model file structure. The tabular files containing the Hall Creek weather driver data were updated first. This was done by replacing the Elder Creek precipitation and temperature data file paths with the Hall Creek precipitation and temperature data file paths. This is edited using the “air temperature” and “precipitation drivers” parameters within the “All Parameters” tab “weather” option within the GUI. The changes were saved as a new version of the XML configuration file and the new XML configuration file was run to test functionality.

The Hall Creek flat-processed DEM and all corresponding raster files were added to the VELMA model at the same time. VELMA would not run if there were raster files with dimensions that did not agree. Within the “All Parameters” tab “Calibration” option, the parameters labeled “input_dem”, “CoverSpeciesIndexMapFileName”, “coverAgeMapFileName” “soilParametersIndexmapFileName”, were changed to the Hall Creek data for the flat processed DEM, cover type raster, Landtrendr tree age raster, and soils raster file names. The changes were saved as a new XML configuration file and VELMA was run to test for functionality.

Appendix B.4 Running the Hall Creek Model

After all the component input files and parameters of the Hall Creek watershed model were input into a working XML configuration file, the model was run to completion. If all items were entered correctly the “chart” tab of the GUI initialized and displayed a graph of the daily inputs and outputs of the model as it ran. The GUI displayed daily values for modeled flow, precipitation, temperature, and values tied to the vegetation model. After the model was run to completion the produced output files could be opened. If the XML configuration file had an error the model would fail to run. Most models that did not run successfully to completion failed to initialize. If VELMA populates all parameters and transfers all spatial raster data into “spatial pools” during initialization, therefore if VELMA runs for 30 seconds past initialization the XML configuration setup was correct and VELMA has a high likelihood of running to completion. If the model failed, the lines of java script executed prior to crashing were displayed on the “console” tab to assist with trouble-shooting the simulation setup.

Appendix B.5 Troubleshooting VELMA Crashes

When the model crashed, I checked that the input file paths and parameters were all correct, and that the dimensions of all the rasters agreed. After identifying the problem, I reverted to the last working XML configuration file and correctly re-enter the input file paths and ensured that I changed the correct parameters. If the raster dimensions were wrong, new rasters with proper dimensions were created to replace the spatially mismatching rasters.