MODELS FOR EVALUATING SUMMER STREAM TEMPERATURES IN COHO REARING STREAMS

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Abstract

Stream temperature is an important water quality focus for many riparian and stream ecosystem management agencies and organizations, especially for coho streams in the Pacific Northwest. Consequently, this management emphasis creates the need for data and techniques to model and analyze stream and species requirements. Capturing these relationships is dependent upon the quantity and quality of the data and tools available to researchers. Different types of data, modeling tools, and data collection methods are supported by various organizations and agencies. Some of these agency-supported data and models are better suited for certain stream parameters. Therefore, understanding the model capabilities and specific project goals facilitates better model and data selection for specific conditions within a management area. Likewise, understanding the typical coho habitat parameters, in addition to their biological limits, can also assist with appropriate model and data selection. The goal of this study is to identify the relationships among riparian vegetation, coho, and stream temperatures and present available research and information that can be used to more effectively evaluate and analyze coho rearing streams. This study also analyzes the available models and determines the most appropriate models for understanding these relationships.

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List of Multimedia Objects

List of Abbreviations

7DADM	7 Day Average of the Daily Maximum
BASINS	Better Assessment of Science Integrating Point and Nonpoint Sources
BIOS	Biogeographical Information and Observation System
Cal EPA	California Environmental Protection Agency
BLM	US Bureau of Land Management
CalFish	California Cooperative Fish and Habitat Data Program
CDFG	California Department of Fish and Game
EPA	US Environmental Protection Agency
GAO	US Government Accountability Office
GIS	Geographic Information System
MWAT	Mean Weekly Average Temperature
MWMT	Mean Weekly Maximum Temperature
NCDC	National Climatic Data Center
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NSIP	National Streamflow Information Network
NWIS	National Weather Information System
ODEQ	Oregon Department of Environmental Quality
ODFW	Oregon Department of Fish and Wildlife
OSU	Oregon State University
OWEB	Oregon Watershed Enhancement Board
PHABSIM	Physical Habitat Simulation system model
SALMOD	SALmonid Population MODule
SNTEMP	Stream Network Temperature Model
SSTEMP	Stream Segment Temperature Model
STORET	STOrage and RETrieval
TIR	Thermal Infrared Radiometry
TMDL	Total Maximum Daily Load
COE	US Army Corps of Engineers
USDA	US Department of Agriculture
USFS	USDA Forest Service
USGS	US Geological Survey
WASP	Water quality Analysis Simulation Program
WDFW	Washington Department of Fish and Wildlife
WDOE	Washington Department of Ecology

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INTRODUCTION

Coho salmon (*Oncorhynchus kisutch*), also commonly known as Silver salmon, need rearing stream habitats that meet specific water temperature requirements (Laufle et al. 1986). Riparian vegetation is important to regulating stream temperatures. Making necessary stream temperature management decisions requires appropriate stream and riparian vegetation data and models. While low stream temperature is a critical component of juvenile coho viability, as stated by Poole et al. (2001:3) “water temperature alone cannot save native fish populations” In light of this fact, it is important to note that factors creating low stream temperature also help create other beneficial conditions to native fish such as lower sediment and more woody debris. Beschta (1997:27). stated “while temperature is a ‘stand alone’ variable with regard to water quality and aquatic habitat, it is also an important indicator of numerous other ecological processes and functions of healthy aquatic/riparian ecosystems” Applying management practices to achieve lower stream temperatures will likely have other positive stream quality improvements that will benefit coho and other stream species.

Research and information need to be available to help researchers choose the most appropriate data and models to effectively communicate the connection between these complex systems. Models serve as a tool to quantify, predict, and explain these relationships, and are invaluable in helping not only researchers, but decision makers as well. Models help researchers and decision makers understand the impacts that riparian and stream management decisions have on the viability of juvenile coho salmon rearing streams.

Relationships among coho habitat, stream temperatures, and riparian vegetation have been thoroughly studied for more than fifty years. Various organizations and government agencies study, monitor, and collect data. Then, they develop modeling tools to better understand one or more of these relationships. Each government agency and organization has a specific purpose for studying these relationships, and this often shapes the way data are collected and models are developed. Government regulations and guidelines also significantly shape available data and models. Additionally, each of these agencies and organizations supports it own models and data, and there are no central locations for models or information. Likewise, there are no comprehensive analyses of the differing models and data to help researchers select the most appropriate model for their project.

The goal of this paper is to identify and analyze the relationships between riparian vegetation, coho, stream temperatures, and the resources available for researching these areas. Presenting the findings and analysis of this research should help future researchers and decision makers more effectively evaluate and analyze these relationships. This paper will analyze the tools, data, and models currently available to determine the most appropriate models and data for modeling summer stream temperatures in coho rearing streams.

REVIEW OF LITERATURE

The influence of riparian vegetation on stream temperature has become an important issue in the last few decades. As more is learned about the importance of stream temperatures, riparian and stream management has become a focus for many organizations and government agencies and this is especially true in the Pacific Northwest’s coho streams. Consequently, this new management emphasis has created a need for data and techniques to model and analyze stream and species requirements and the effectiveness of management practices and activities. Capturing these relationships is dependent upon the quantity and quality of the data and tools available to research and analyze the conditions. Different types of data, modeling tools, and data collection methods have been developed to help capture and explain specific occurrences by various types of organizations, government agencies, and independent researchers. The US Geological Survey (USGS), US Environmental Protections Agency (EPA), US Army Corps of Engineers (COE), National Oceanic and Atmospheric Administration (NOAA), Washington Department of Ecology (WDOE), and Oregon Department of Environmental Quality (ODEQ), among others, all provide assistance, models, techniques, and data for use in making stream and riparian area management decisions. Some of these agency supported data and models are better suited for certain circumstances. Therefore, understanding the parameters and logic behind the creation of these tools and data can help make tool and data selection more effective for specific conditions within a management area. Understanding the typical coho habitat parameters and biological limits can assist with selecting appropriate models and data.

Coho Salmon

Coho salmon are an anadromous fish species found throughout North America’s Pacific Northwest. Coho distribution in the US currently ranges from the San Lorenzo River in Monterey Bay, California, to the Aleutian Islands and Point Hope, Alaska, in the US (Pacific Fishery Management Council 2005). Coho are additionally located as far south as Korea on the Asian side of the Pacific Ocean (Pacific Fishery Management Council 2005). More so than other salmonids, coho are almost always anadromous (Quinn 2005). Coho lead a relevantly simple lifecycle when compared to other anadromous salmonid species. Most coho spawning within the continental US spend approximately one year of life in freshwater and eighteen months in the ocean (NOAA 1999:A-24).

During each life cycle, coho are highly migratory (NOAA 1999:A-26). Coho enter freshwater to spawn from July through December (NOAA 1999:A-31). Spawning normally occurs between November and March. The majority of coho, however, spawn during the months of November, December, and January (Weitkamp et al. 1995). Unlike other anadromous salmonid species, such as the chinook salmon, coho generally spawn in smaller streams rather than larger rivers and streams (Pacific Fishery Management Council 2005). Egg incubation can be from 38 to 137 days, largely depending on temperature (Koski 1965).

Most fry emerge from March to May, but can emerge as late as July, depending on certain habitat conditions, including water temperature (Koski 1965).

Coho salmon require specific habitat conditions during different stages within their lifecycle. For example, juveniles rearing conditions enabling them to prepare for the smolt stage of development and their journey to the ocean. This paper focuses on the habitat needs and challenges facing coho during their juvenile phase. This phase requires certain physical habitat features, many of which are highly linked to streamside vegetation.

Summer is also an important period of juvenile coho development. Riparian vegetation near coho rearing streams has significant effects on the stream’s water quality and coho habitat. One major influence of riparian vegetation on stream water quality is stream temperature. Riparian vegetation shades streams from solar radiation, which is at its strongest during the summer. Land use and vegetation management in riparian areas is critical, and therefore, can have significant impacts on water quality and juvenile coho. Because of this interrelationship, understanding the influence of the surrounding land and vegetation is essential to understanding how to manage coho populations.

The Juvenile Stage of the Coho Lifecycle

The juvenile stage is critical in the coho lifecycle where they grow and prepare for smoltification (smoltification is the changes freshwater juvenile salmon undergo to be able to survive in saltwater habitat (Quinn 2005)) and their journey to the sea. According to studies conducted by Neave and Wickett in 1953, the survival rate from egg to smolt is usually less than 2 percent (Laufle et al. 1986). Juvenile salmonid predators consist primarily of fishes (other salmonids, sculpins, squawfish, and others), birds (kingfishers, herons, loons, mergansers, and others), and mammals (river otters) (Quinn 2005, Laufle et al. 1986). Juvenile coho feed primarily on aquatic and other insects, crustaceans, and other fish (Laufle et al. 1986). The highest summer rearing densities typically occur in areas with structural habitat elements and an abundance of prey (NOAA 1999:A-28). When adequate spawning escapement exists, summer habitat carrying capacity is the juvenile coho population limiting factor (NOAA 1999:A-28), thus making adequate stream habitat all the more important. Some small numbers of coho migrate to the sea shortly after emergence, while the majority of juvenile coho (south of central British Columbia) spend a year in freshwater before migrating to the ocean as smolts (Laufle et al. 1986). Size, age, and stream conditions are all factors that induce smoltification (Laufle et al. 1986).

Rearing Habitat

Juvenile coho take refuge in a very diverse range of habitats, including: streams, wetlands, lakes, sloughs, tributaries, estuaries, and large river tributaries (NOAA 1999:A-28). Coho, steelhead, and cutthroat trout commonly share habitat; however, coho are typically the most numerous salmonids in streams they inhabit (Quinn 2005). Reeves et al. (1989) found that coho preferred habitat elements including: undercut banks, pools, glides, riffles with large woody debris, and overhanging vegetation (NOAA 1999:A-28). According to Chapman (1965), the most productive rearing habitat was determined to be streams smaller than fourth order (The Horton-Stahler Method of stream ordering is the most common method in the US. Headwater streams are first order streams, two merging first order streams create a second order stream, and so forth. Two merging third order streams create a fourth order stream (EPA 2000)) with pools formed by large woody debris, with low alluvial channels (NOAA 1999:A-28). Young coho also need rearing habitat with a water velocity less than 1 meter per second (m/sec) (Laufle et al. 1986). Ideally, juvenile coho prefer riffles with a water velocity between 0.31 and 0.46 m/sec and a pool water velocity range between 0.09 and 0.24 m/sec (Laufle et al. 1986). Furthermore, juveniles over a year in age need 2.4 to 5.5 square meters of space per fish (Laufle et al. 1986). Coho also prefer streams with a one to one riffle to pool ratio (Laufle et al. 1986). Juvenile coho prefer water between the depths of 0.3 and 1.2 meters (Laufle et al. 1986). They also prefer highly oxygenated water: juvenile's swimming speeds were at their fastest at 100 percent saturation (Laufle et al. 1986). As fish become larger, they often move to deeper and faster water (Quinn 2005), possibly seeking cover that accommodates their growing size. Salmonid juveniles' rearing space and food typically limit the production of smolts rather than spawning space (Quinn 2005). This indicates that changes to juvenile rearing space will more likely affect smolt production than changes to spawning space. The coho's habitat preference changes with the seasons and stream conditions. Temperature cycles often trigger fish migration (EPA 1986). Increased flows due to fall rains often provide a cue for coho to move to off-channel areas such as sloughs, ponds, tributaries, and wetlands (Quinn 2005).

A study conducted in southeast Alaska determined that coho entered smaller tributaries in the fall as water temperatures dropped (Bramblett et al. 2002). Conversely, the coho then moved out of these smaller streams as temperatures increased in the spring (Bramblett et al. 2002). Nickelson et al, (1992,) found that these off-channel rearing serve as winter rearing habitat for coho and these diminishing habitats are considered to be the primary limiting factor for salmon in many coastal streams (NOAA 1999:A-29). Additionally, Nickelson et al. (1992) found coho prefer a less diverse array of habitat during the winter compared to summer preferences (NOAA 1999:A-29). Territorial behavior lessens as coho aggregate in habitat that provides stable depth, velocity, and water quality during the winter (NOAA 1999:A-29). Fry typically school at the stream's edge in early spring, most likely to avoid predatory fish and high water flows (Quinn 2005). Coho prefer summer rearing habitats in areas with abundant drifting aquatic invertebrates and terrestrial insects that serve as food and are near structural habitat elements (NOAA 1999:A-28). A slowing in growth often occurs in early summer with an onset of territorial behavior (Quinn 2005). Summer time is the critical development period for the juvenile coho, and is also a time when high stream temperatures are of greatest concern.

Effects of High Summer Stream Temperatures

Summer stream temperatures follow winter rearing habitat as most critical to coho salmon (NOAA 1999:A-28). Temperature is a very important and influential characteristic and, as stated in the 1967 Federal Water Pollution Control Act, temperature can act as a "catalyst, a depressant, an activator, a restrictor, a stimulator, a controller, and a killer" (EPA 1986: not numbered). Both aquatic species composition and activities are both regulated by water temperature (EPA 1986). "Water temperature affects the distribution, health, and survival of native salmonids and other aquatic organisms by influencing their physiology and behavior" (Poole et al. 2001:1).

The exact range of optimum temperatures for juvenile coho varies slightly according to different studies. Brett (1952) determined optimal temperatures to be between 12° and 14° C. In 1973, Bell estimated optimum temperatures to be between 11.8° and 14.6° C (Laufle et al. 1986). The National Marine Fisheries Services (NMFS) estimates juvenile coho growth best in temperatures between 10° and 15° C (NOAA 1999, A-28). Studies however have shown that juvenile coho can withstand temperatures between 0° and 26° C (Brett 1952). Even though juveniles can withstand temperatures up to 26° C, it is also true that higher non-optimal temperatures can induce additional stress from heat (EPA 2003:19).

Heat stress in aquatic communities can "increase incidence of disease and parasitism (Sinderman 1965); reduce or block sexual maturation (Thorhaug et al. 1971, deVlaming, 1972); inhibit or block embryonic cleavage of larval development (Calabrese 1969); reduce feeding and growth of juveniles and adults (Olla and Studholme 1971); result in increased predation (Gonzalez 1972); and reduce productivity of macroalgae and seagrasses (South and Hill 1970, Zieman 1970)" (EPA 1986: not numbered).

High water temperatures influence metabolic processes in aquatic organisms and can cause direct mortality of salmonids (Poole et al. 2001). One study demonstrated that juvenile lethal temperatures (one week exposure) were at 23° to 24° C (Poole et al. 2001). Moreover, EPA studies determined that swimming speed rates were reduced at 20° C. Disease rates also increased to "severe" at 18° to 20° C, and were "elevated" between 14° and 17° C (Poole et al. 2001). Welsh et al. (2001) conducted a study that suggests Mean Weekly Maximum Temperatures (MWMT) greater that 18.1° C or Mean Weekly Average Temperatures (MWAT) greater than 16.8° C may completely eliminate the presence of coho in the Mattole River in northern California.

Unsuitable temperatures impair feeding, growth, resistance to disease, competitive ability, and predator avoidance in salmonids (Poole et al. 2001). High thermal temperatures can also create thermal barriers to juvenile migration (Poole et al. 2001). Evidence suggests that increases in temperature as small as 2-3° C above the biologically optimal range can reduce salmonid fitness during some life stages (Poole et al. 2001). Additionally, EPA has determined that the toxicity levels of toxic materials generally increases with temperatures, while organisms with stress from toxic materials are less tolerant of temperature extremes (EPA 1986). Thomas et al. (1986) determined that increased stream temperatures caused increased metabolic rates in juvenile coho salmon. Dramatic increases in temperature were also associated with increased mortality in juvenile coho (Brett 1952). EPA has also found that, generally, fluctuating water temperature has a positive affect on growth rates when mean temperatures are below the optimal growth temperature, but will reduce growth when the mean temperature exceeds the optimal growth temperature (EPA 2003:19). High temperatures also cause changes to juvenile coho behavior (EPA 2003:19).

Changes in Behavior Due to Temperature

Fish usually regulate their body temperatures by moving to locations of different temperature, and according to Coutant (1975) have been found to avoid areas 1° to 3° C above preferred temperatures (EPA 1986). Aquatic community balance can be drastically altered by changes in temperature. Changes in temperature can alter reproduction rates, recruitment, and growth of each component population, which can lead to altered inter-species relationships (EPA 1986). Slow growth and potential weight loss in salmonids in late summer can be attributed to low water levels, less habitat, higher temperatures, and less food (Quinn 2005). “Pool depth was second only to temperature in its importance as a factor in site selection by coho salmon” (Hines and Ambrose 1997:9).

Bjornn and Reiser (1991) determined that increased stream temperatures caused changes to juvenile coho distribution (Hines and Ambrose 1997). A California study conducted in Mendocino County found that maximum weekly average stream temperature exceeding 17.6° C was one of the strongest variables in predicting the location of juvenile coho salmon (Hines and Ambrose 1997). Additional studies conducted by Nielson and Lisle (1994) in northern California found juvenile salmonids preferred pools as habitat when thermally stressed (Hines and Ambrose 1997). Poole et al. (2001)found that during times of high stream temperature, salmonids often sought cold water . Pools often contain cooler water than shallow water, due to groundwater seeps and stream upwelling cooled by moving through the streambed substrate (Beschta et al. 1987). Groundwater entering streams help offset high summer stream temperatures and provide thermal refuge for salmonids; however groundwater is often lower in dissolved oxygen than the stream water (Matthews and Berg 1997, Quinn 2005). When this occurs salmonids must either endure the stresses of low dissolved oxygen or high stream temperatures (Quinn 2005).

Studies conducted on different salmonids species can offer clues to behavioral changes can also provide insights coho responses caused by stream temperature increases. For example, Reeves et al. (1989) indicated that steelhead dominated redside shiners at low temperatures; however, at higher temperatures, the shiners were more active and out competed steelhead for food (Quinn 2005). Reese and Harvey (2002) found similar results on studies between steelhead and the pikeminnow. Reeves et al. (1989) also found that minimum summer water temperatures exceeding 20° C for two weeks may give advantages to non-game species competing with salmonids. These behavioral relationships found in salmonid species may suggest that coho have similar behavior correlated to temperature increases.

Riparian Vegetation Shade

Riparian areas are transition zones between areas strongly influenced by freshwater and drier upland areas (Naiman et al. 2005). Successful riparian area planning and management requires a “robust understanding of riparian ecology” and thorough, scientifically sound monitoring and evaluation (Naiman et al. 2005). The characteristics of these transitional areas have tremendous influence both land and water ecology (Naiman et al. 2005).

Stream Temperatures Effects

While many human activities have immediate and deadly impacts on salmon, successful riparian vegetation management is critical to the long-term viability of wild salmon populations. The Pacific Northwest stream-dwelling species have evolved over recent geologic times in habitat dominated by coniferous forests (Quinn 2005). Riparian habitat within these forests is typically cool and humid, barring major disturbances (Quinn 2005). These forests could provide up to 99 percent shade to small streams (Naiman 1992). Riparian vegetation is integral to the physical habitat needed by juvenile coho and countless other species.

Stream temperature regulation is only one of the benefits that riparian vegetation provides; all of which are highly intertwined and interdependent. Riparian vegetation can increase the woody debris recruitment, create current-sheltered water, create cover for stream fishes, provide greater stream diversity, create higher atmospheric humidity levels, and control sediment and nutrient input (Naiman et al. 2005, EPA 2003). It also reduces storm surge size, filters runoff, creates higher ground water levels, shades solar radiation, creates nocturnal heat radiation, provides organic matter for insects and other detritivore (detritivores are a class of consumers who gain energy from organic wastes and dead organisms (EverythingBio 2006)) and provides insect habitat, and improves water quality (Naiman et al. 2005, EPA 2003:2). This paper only focuses on riparian vegetation's influence on stream temperature. However, all of these benefits are significant, because they are interrelated and need to be considered with stream temperature when planning stream, salmon, land, or riparian management and/or restoration.

Johnson et al. (2002:5) stated "air temperature is the single most important regulator of water temperature". In a study conducted in the Six Rivers National Forest in California, air temperatures above streams exponentially increased in relationship to riparian buffer width (Ledwith 1996). Ledwith found that mean air temperature increases averaged 1.6° C every ten meters in areas where buffers were zero to 30 meters wide, and 0.2° C every ten meters in streams with buffer widths between 30 and 150 meters (1996). Additionally, the study found that relative humidity was inversely proportional to air temperature – decreasing 19 percent in mean relative humidity between a 150 meter buffer and a no buffer (Ledwith 1996). Riparian buffers that allow increased solar radiation into riparian zones raise air temperatures and decrease relative humidity (Ledwith 1996). Stream temperatures tend to mimic air temperatures, but do not increase or decrease as drastically as air temperatures (Beschta et al. 1987) Shallow streams more closely mimic air temperature (Quinn 2005). A study in Ontario determined that desirable trout water temperatures were positively correlated to the proportion of banks covered by vegetation (Naiman et al. 2005).

Riparian vegetation management that reduces the amount of stream shade will likely increase temperatures, especially in the summer time.

Streams receive the most solar radiation in the summer, which is the time of greatest concern for high stream temperatures (Moore and Miner 1997). Summer is also the time of year that stream volumes are at their lowest, reducing water quantity which requires heating (Moore and Miner 1997). Additionally, streams with smaller water volumes may be preferred coho habitat, and are of concern, because they experience rapid and greater stream temperature fluctuations (Moore and Miner 1997). Wide, shallow streams will heat up faster than narrow deep streams of the same volume (Moore and Miner 1997). The Oregon Department of Fish and Wildlife (ODFW) considers western Oregon streams smaller than 12 meters in width, “undesirable” if they have less than 60 percent shade over the stream (Coast Range Association 2005). This number lowers, to 50 percent, for stream widths greater than 12 meters (Coast Range Association 2005). Since the Pacific Northwest was predominantly dominated by coniferous forests in the past, natural conditions usually provided beneficial stream shading through riparian vegetation. The need to analyze riparian vegetation and stream shading is primarily a result of human activities within these sensitive areas.

Human Activities Affecting Stream Water Temperature

Human activities in the summer months generally cause the greatest water temperature impacts on salmonids rearing areas (EPA 2003:18). Mortality, disease prevalence, and increased interspecies competition have all been linked to temperature increases caused by land use changes (Naiman et al. 2005). Stream shade comes in three forms - macrotopographic shade, bank shade, and vegetative shade (Davies et al. 2004). Of the three forms of stream shade, riparian vegetation is the one form that humans have the greatest control over and have also manipulated the most (EPA 2003:13).

Four human activities, i.e., urbanization, agriculture, logging, and grazing, substantially influence the riparian vegetation found near juvenile coho streams. These land management activities, common in the Pacific Northwest, can cause considerable landscape disturbances and impact the associated streams and rivers. Until very recently, little thought was given to riparian vegetation or the streams that ran through areas of human activity. An emphasis on establishing riparian buffers along Oregon streams in urban and agricultural areas only began in the mid 1990s (Nicholas et al. 2005). An analysis conducted by Oregon State University (OSU) and the United States Department of Agriculture (USDA) Forest Service (USFS) Pacific Northwest Research Station indicated that over the last 3,000 years, the coastal forest contained an average of 48 percent old growth forest and forests with trees greater than 80 years old covered an average of 71 percent of the land (Wimberly et al. 2000). Old growth forests now average 5 percent of the coastal forestland, and only 11 percent have trees greater than 80 years old (Coast Range Association 2005). The loss of mature forests may not be directly related to stream temperature increases; however it is an indicator of the coastal landscape changes. It is likely that some of the riparian forests were converted to areas with little forest canopy such as urban areas, agricultural fields, grazing pastures, or were clear cut when it was an accepted logging practice. Loss of riparian canopy can result in increased maximum stream temperatures and increased daily stream temperature fluctuations (Quinn 2005). The loss of old growth forest and riparian areas are primarily a result of these human activities.

Urbanization

Urban areas often contain significant impervious cover and few trees (NOAA 1999:A-84). Areas with more impervious cover and fewer trees can be 5.6 to 6.7° C warmer than agricultural or forested areas, and have fewer trees to offset solar radiation (Metro 1997, cited by NOAA 1999:84). Government agencies and other organizations provide a substantial amount of research, literature, and other resources to implement better management practices to these urban areas. Additionally, riparian area management is often now regulated by local, state, and federal agencies, especially when the riparian area is for salmonid species.

Agriculture

Agriculture can take place in flood plains and can alter the riparian functions, and include creating higher stream temperatures (NOAA 1999:A-78). Riparian vegetation removal is often an agricultural practice (NOAA 1999:A-78). Riparian vegetation disturbances can reduce stream shade, therefore increasing stream temperatures (NOAA 1999:A-78). Additionally, the lack of riparian vegetation can allow higher temperature run-off from the bare soil (from agriculture usage) and flow directly into the stream without a riparian buffer (NOAA 1999:A-78).

Logging

Timber production (i.e. growing and harvesting timber) is the most dominant land use in the Pacific Northwest (NOAA 1999:A-93). Logging can alter stream environments in a manner that does not support native species (Brosofske et al. 1997). The Oregon Coastal Coho Assessment Report stated that riparian buffers along forestland streams were rare until the 1960s (Nicholas et al. 2005). Before riparian buffering, early unregulated timber harvests took little consideration of their impacts on streams and riparian areas. Logging in riparian areas and splash dams (timber transport method where a temporary dam on a river or stream is exploded, creating a surge of water that carries timber suspended in the dammed water downstream) were accepted logging practices in early Pacific Northwest logging operations that had significant impacts on riparian vegetation. Naiman et al. (2005) found riparian area timber harvests can increase summer stream temperatures and decrease winter stream temperatures. Today, different public and private land charters, as well as different company practices create different timber logging or harvesting methods throughout the Pacific Northwest. Needless to say, logging practices have significantly altered the riparian vegetation over the years.

Grazing

Livestock grazing occupies approximately 41 percent of the land base in the Pacific Northwest and is the second largest land use in the region next to timber production (NOAA 1999:A-93). Grazing can change riparian environments by reducing or eliminating vegetation, widening stream channels, encouraging increases in non-native plant species, and lowering water tables (Platts 1999, cited by NOAA 1999:A-93). Livestock grazing can also reduce productivity or eliminate streamside shrubs, causing increased solar radiation to streams and higher stream temperatures (NOAA 1999:A-93). For better and worse, riparian vegetation responds to changes in grazing practices at a relatively quick rate (NOAA 1999:A-93). While the resiliency of riparian vegetation is a plus for implementing restoration and improved management practices, it also indicates that unwise practices quickly alter the positive attributes of established riparian vegetation.

Human activities in riparian areas have a significant influence on water quality, to include temperature in juvenile coho streams. The EPA came to the conclusion that modification of thermal degrading human actions, such as industrial discharge and riparian vegetation removal, will need to be modified to be able to restore appropriate stream and river temperatures (Poole et al. 2001). The National Marine Fisheries Service suggests creating riparian buffers wide enough to support important riparian functions such as shading, large woody debris input, leaf litter inputs, sediment and nutrient control, and bank stabilization functions (NOAA 1999:A-80).

Modeling, Measurement, and Data

Knowledge about decreased riparian vegetation and increased stream temperatures effects without area-specific data and modeling of past, present, and future conditions is required for more effective management decisions. Numerous data collection, analysis, and modeling methods currently exist. However, knowing where to find existing resources and determining the most appropriate choices of data and analysis requires a thorough understanding of the area and species-specific information, as well as how and why the data and modeling techniques were developed, and which of these data and models best fit the specific area and species parameters. This section describes the laws and agencies that have shaped the current models and data, model availability, and analyses of their suitability for modeling shade and stream temperatures in juvenile coho rearing streams.

Governmental Influence

Data are collected and maintained for different reasons by a variety of groups, governments, and organizations. The federal government is a particularly good data source. While this paper is not intended to go into great detail about governmental roles, it is worth noting that government entities provide vital tools, research, resources, incentives, assistance, standards, and regulations. This support helps shape the way data are collected, managed, and assessed, as well as the way research and models and tools are used. While other federal agencies also provide excellent research, studies, and analyses, the Environmental Protection Agency (EPA), US Geologic Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and the US Army Corps of Engineers (COE), provide research information, modeling, and have a regulatory role in water quality standards, coho management, and/or water data. An example of how government has shaped data collection and analysis can be seen in a study where Hines and Ambrose (1997:4) found that “daily maximum temperatures are better able to discriminate temperature changes likely to be detrimental to salmonids”. Hines and Ambrose (1997) also found that existing Mean Weekly Average Temperature (MWAT) thresholds (a measurement used by the EPA) using temperature magnitude limits are not the most biologically relevant approach because they do not effectively account for the length and frequency of threshold exceedences. Despite these findings, MWAT information, studies, and analysis were commonly because the EPA recommended States use the MWAT as one of the two measurements of temperature water quality standards in 1986 guidelines (EPA 2003:4). In this light, many other government mandated measures influence the types of data collected, the models available, and the manner in which they are analyzed. Understandably, one of the biggest contributors to water quality regulation is the Federal Water Pollution Control Act, also known as the Clean Water Act.

The Clean Water Act contains statutory language that created water quality standards. The relevant water temperature data standards of the Act are sections 303(c), 303(d), 304(a). Section 303(c) requires all states and tribes to adopt water quality standards, designated uses, and water quality criteria for state water bodies (33 USC 1251). Water quality standards establish water quality goals for specific waterbodies (EPA 2003:3). Section 303(d) of the Clean Water Act requires waters not meeting the established water quality standards to be listed on an “impaired water bodies list,” and create Total Maximum Daily Loads (TMDLs) for the identified impaired water bodies) (Federal Water Pollution Control Act 1972). Section 304(a) requires water quality criteria are established based on available scientific information regarding specific parameters and aquatic life protection (Federal Water Pollution Control Act 1972). EPA’s criteria recommendations for stream temperature are in the Quality Criteria for Water 1986 publication (EPA 2003:4). EPA uses/recommends two temperature-based indicators for fish habitat monitoring – the first consists of calculations to protect fish from short-term exposure to high temperatures, the second provides protection from maximum weekly average temperature exposure (EPA 2003:4).

1. Protective Short Term Temperature Exposure is simply 2° C below the upper incipient lethal temperature (the temperature at which 50 percent of the sample dies) (EPA 2003:4). This formula determined that Short Term Exposure Temperature limits for Coho are 24° C (EPA 2003:4).

Short Term Temperature Exposure Formula is defined by:

$$\mathit{Log}^{10}\,(\mathit{time}^{\,(\mathit{minutes})}) = a + b\,(\mathit{Temperature}\,(^\circ\,C))$$

Where: Log^{10} *= logarithm to base 10 (common logarithm)*

a = intercept on the “y” of the logarithm axis of the line fitted to experimental data and which is available from some species from Appendix II-c, of the National Academy of Sciences document (1972)

> *b = slope of the line fitted to experimental data and which is available for some species from Appendix II-c, of the National Academy of Sciences document (1972).* - EPA 1986

2. Mean Weekly Average Temperature (MWAT) - protective Weekly Average Temperature Exposure calculations determine the MWAT. Protective Weekly Average Temperature Exposure is calculated by adding 1/3 the difference between the optimal growth temperature and the upper incipient lethal temperature to the optimal growth temperature (EPA 2003:4). This formula determined that the MWAT for coho is 18° C (EPA 2003:4). However, EPA has determined through more recent scientific studies that many chronic and sub-lethal effects can occur to salmonids exposed to this MWAT (EPA 2003:5). Therefore, temperature recommendations in the 1986 304(a) criteria recommendations may not sufficiently protect salmonids (EPA 2003:4).

After discovering the inaccurate information in their 1986 guidance, EPA published additional stream temperature guidance in 2003. EPA's 2003 Water Quality Standards guidance recommends that States and Tribes incorporate the three following elements into salmonid water quality standards:

> 1. *Coldwater Salmonid Uses and Numeric Criteria to Protect Those Uses*
> 2. *Provisions to protect water temperatures that are currently colder than the numeric criteria*
> 3. *Provisions to protect salmonids from thermal plume impacts*
>
> - EPA 2003:15

Considerations one and two have the most relevance to this paper's focus. Rather than using the two temperature formulas mentioned in the 1986 guidance, consideration one recommends temperature consideration for each life stage for salmon and trout (EPA 2003:15).

The 2003 EPA Guidance also suggests that it is generally appropriate to designate water quality standards based on life stages because Pacific Northwest salmonids have different temperature thresholds and requirements during different life stages (EPA 2003:17). Poole et al. (2001:5) states that "salmonid populations will require a variety of cold water temperatures that are well distributed over space and time". EPA also recommends use of the 7 day average of the daily maximum (7DADM) because it provides focus on the maximum temperature within a stream without being overly influenced by single-day maximum temperatures (2003). This method can be used for acute, sub-lethal, and/or chronic effects (EPA 2003:19).

In addition to the EPA guidance, the US Geological Survey also provides various types of water quality data and information through various programs. The USGS has a few relevant programs; most relevant are the National Streamflow Information Program (NSIP) and the National Water Information System. (NWIS) The NSIP maintains stream gages (USGS 2006b). USGS information is water volume focused. The data collected by the USGS is used by the COE, the National Weather Service, and the Bureau of Reclamation for flood and drought forecasting and dam management (USGS 1999). These customers frequently use USGS information to create river conditions reports for flood, drought, and dam management (USGS 1999). This focus on flood, drought, and dam management, therefore, has allowed the USGS to create and collect a significant amount of water volume data. It is also a good indicator of models' purposes that are created or supported by these agencies.

Together, the Clean Water Act and the USGS mission have influenced much of the stream data that is available today. The following sections list the types and sources of data relevant to stream temperature modeling.

Data Collection, Availability, and Support

A fundamental element to better understanding temporal and spatial trends and occurrences in riparian ecosystems is data - particularly water quality data. Various individual monitors and researchers, government agencies, and organizations collect data in watersheds throughout North America. Equally abundant are the reasons why and the manner in which people and organizations collect information. This abundance of methods and stream data sources makes determining data validity, suitable analysis methods, and interpreting study results challenging. Differences even exist between similar State water quality programs. For example, the Government Accountability Office (GAO) pointed out that meaningful comparison of National Water Quality Inventory data could not be accomplished between States due to the number of variables that exist between state programs (GAO 2000). Griffith et al. also point out that neither a comprehensive standard data analysis nor a standard interpretation method has been established by any major entity (2001). Agencies focus on stream shade when developing the temperature TMDLs because of the direct relationship and the ease of gathering data and developing shading models as compared to actual temperatures (Johnson et al. 2002). Without established national standards, or consistency among States, researchers need to closely evaluate specific stream conditions, the existing data, available resources, and location specific information, to determine appropriate modeling and measurement techniques.

Government Agency Resources

The agencies and organizations listed in this proceeding section offer data and/or data storage service for any citizen or group to use free of charge. The quality and quantity, and data relevance may vary, but these agency and organization resources can provide an invaluable source of information, conserving limited resources when assessing riparian vegetation and stream temperature relationships.

EPA

The EPA has created several tools and data sets to help accomplish their goals. These tools and data can be used by anyone. They are available online or can be distributed on a CD-ROM. Listed below are some of the most relevant tools for stream temperature and riparian vegetation assessment in juvenile coho streams.

STORET (STOrage and RETrieval), www.epa.gov/STORET, is a "database of ambient environmental data relating to water quality", and is EPA's principal repository for freshwater monitoring data (EPA 2004). STORET serves as a database system for agencies and organizations to share data, and to search and retrieve large volumes of specific data quickly (EPA 2004). EPA also provides an assistance hotline for help retrieving data (EPA 2004).

EPA also provides public access to a suite of their environmental tools and models at a watershed and water quality technical support center website: http://www.epa.gov/athens/wwqtsc/index.html. Furthermore, this center also provides technical support and training on the different tools and models they support (EPA 2006b). This website offers access to a number of models and data that can be used for stream temperature, riparian vegetation and related studies, to include BASINS (Better Assessment of Science Integrating Point and Nonpoint Sources), WASP (Water quality Analysis Simulation Program), and QUAL2K (EPA 2006a).

BASINS (Better Assessment of Science Integrating Point and Nonpoint Sources), http://www.epa.gov/waterscience/basins/, was created to help regional, state, and local agencies examine environmental information, systems, and alternatives (EPA 2004). It is a multipurpose environmental analysis system for performing watershed and water quality based studies (to include TMDL studies) (EPA 2004). BASINS software consists of multiple Geographic Information System (GIS)-based tools, a series of models, and custom databases (EPA 2004).

USGS

NSIP and NWIS are both parts of the USGS. The NSIP maintains stream gages throughout the nation that provide two primary sets of data – Stage and Streamflow (USGS 2006b). In 2001, approximately 7,000 stream gages throughout the US were operated by the USGS (USGS 2006b). Most data available through the USGS is focused on water volume measurements, an essential piece of stream temperature modeling.

NWISWeb (http://waterdata.usgs.gov/nwis) provides access to water-resources data collected at approximately 1.5 million sites in all 50 States. Online access to this data is organized in different categories.

NOAA

NOAA is home to two key organizations of significant importance to riparian and stream temperature management in juvenile coho streams – the National Climatic Data Center (NCDC) and the NMFS. NOAA has been mandated to manage many of the Pacific Northwest salmon; as a fishery through the Magnuson Stevens Act and as listed Threatened or Endangered Species, as required by the Endangered Species Act (NOAA 2006a). Part of NOAA's responsibility is to distinguish and protect salmon critical habitat (NOAA 2006a). Critical habitat is defined as: "specific areas within the geographical area occupied by the species at the time of listing, if they contain physical or biological features essential to conservation, and those features may require special management considerations or protection; and specific areas outside the geographical area occupied by the species if the agency determines that the area itself is essential for conservation" (NOAA 2006a). Four of the seven coho Evolutionarily Significant Units (an Evolutionarily Significant Unit is a "Pacific salmon population or group of populations that is substantially reproductively isolated from other conspecific populations and that represents an important component of the evolutionary legacy of the species" (NOAA 2006c)) in the Pacific Northwest (California, Oregon, and Washington) are currently either listed or under consideration for listing und the Endangered Species Act, and therefore, NMFS have data, research, and analysis on coho to some extent throughout these units (NOAA 2006c).

The NCDC (http://www.ncdc.noaa.gov/oa/ncdc.html) maintains climatological data from throughout the world (NOAA 2006b). This data, which includes precipitation, temperature, wind, pressure, clouds, solar, and visibility information, can be retrieved at hourly, daily, monthly, or annual increments (NOAA 2006b). In California, Oregon, and Washington, there are 401, 94, 125 NCDC weather station respectively (NOAA 2006b). Some of this information can be used in all models compared in this paper, and Bartholow (1989) states that this may be the best organized climatological data available.

Other Federal Agencies

Several other federal agencies play significant roles in the research, analysis, and management of riparian vegetation and stream temperatures. While not all of these agencies collect relevant data, provide regulation, or modeling software. They are still invaluable resources for research and analysis.

The US Army Corps of Engineers (COE) is a federal agency with a significant mission in water quality issues. The COE is "the other" federal agency charged with executing statutes within the Clean Water Act. Additionally, the COE's Water Resources mission entails navigation, flood damage reduction, recreation, hydroelectric power, shore protection, dam safety, and water supply

(COE 2006a). Much of the COE's work deals with navigable waters and dams, both of which tend to be larger, slower moving bodies of water not often associated with juvenile coho stream habitat, although coho may select these types of locations as rearing habitat. Therefore, many of the COE's modeling and analysis tools deal with precipitation runoff and drainage, watershed planning, dynamic water flow, and for large, stratified, slow moving water bodies (COE 2006b).

The Natural Resources Conservation Service (NRCS) has been authorized through the Watershed Protection and Prevention Act to work with state and local agencies to improve soil conservation, flood prevention, effective and efficient water use, and land utilization (NRCS 2006). The NRCS supports this Act through three programs: watershed surveys and planning, watershed protection and flood prevention operations, and watershed rehabilitation (NRCS 2006).

Additionally, the Bureau of Land Management (BLM) and USDA Forest Service (USFS) both provide outstanding research and invaluable case studies. As land management agencies, their mission and work keeps most of their studies and assistance on public lands. The benefit from their research and studies is essential to all parties involved in stream management. Federal and state land management agencies provide invaluable research and studies related to riparian habitat, stream temperatures, and coho; however, they have little regulatory impact or control over data and management outside of their respective land management charters.

State Agencies

Despite the coho's large geographical dispersion, this paper primarily focuses on data currently available for areas within the lower forty eight states. In the continental US, California, Oregon, and Washington are the only states which have remaining runs of native coho salmon (NOAA 2006). Because they have recognized the importance, all of these states are heavily involved in riparian vegetation, stream temperature, and coho salmon studies. The various agencies that are directly involved in these types of studies include Departments of Environmental Quality, Departments Fish and Wildlife/Game, the Oregon Watershed Enhancement Board, the Washington Department of Ecology, and Calfish.

California

Department of Fish and Game (CDFG) developed and maintains a system called Biogeographical Information and Observation System (BIOS): http://bios.dfg.ca.gov/. It is designed to enable the management, visualization, and analysis of biogeographic data collected by the Department and its partner organizations (CDFG 2006). The BIOS system has successfully created a statewide, integrated information management tool (CDFG 2006).

California Cooperative Fish and Habitat Data Program (CalFish), (http://www.calfish.org/DesktopDefault.aspx, is a "multi-agency cooperative program designed to gather, maintain, and disseminate fish and aquatic habitat data and data standards" (CalFish 2006). They have a "Two-Fold Mission: To create, maintain, and enhance high quality, consistent data that are directly applicable to policy, planning, management, research, and recovery of anadromous fish and related aquatic resources in California; and to provide data and information services in a timely manner in formats that meet the needs of users" (CalFish 2006). This website has an abundance of data, studies and other useful materials.

Environmental Protection Agency (Cal EPA) is responsible for establishing TMDLs for the state's waters.

Oregon

Department of Environmental Quality (ODEQ), http://www.deq.state.or.us/wq/TMDLs/WQAnalTools.htm, sponsors the use of TTools 7.0 and Heat Source to conduct stream temperature studies. TTools is a GIS extension or add-on that contains tools designed to automatically sample spatial data sets used in water quality monitoring (Boyd and Kasper 2004). ODEQ is responsibly for creating TMDLs for the State of Oregon.

Department of Fish and Game (ODFW) provides studies of salmon, and was a primary contributor to the Oregon Plan – a plan that focuses on salmon recovery. Many studies are available through the ODFW, and they house their data in the Stream Net database. The ODFW also supports and aquatic inventories project: http://oregonstate.edu/Dept/ODFW/freshwater/inventory/.

Oregon Watershed Enhancement Board (OWEB) is charged with maintaining watersheds within State of Oregon (OWEB 2006). They assist in maintaining watersheds by coordinating, collecting, sorting, and analyzing stream and watershed data (OWEB 2006). Two programs that are important assets to stream shade and temperature modeling are the Oregon Watershed Restoration Inventory, and the Volunteer Water Quality Monitoring Program (OWEB 2006).

Washington

Department of Ecology (WDOE) – Among other things, the Washington Department of Ecology's Stream Hydrology Unit provides stream flow data for the State of Washington (WA Dept. of Ecology 2002). The Stream Hydrology Unit uses two types of temperature measurement probes – an internal thermistor and separate thermistor probes (WDOE 2002). Nominal accuracy of the probes are ± 0.2° C (WDOE 2002). Washington's Department of Ecology is also responsible for creating the State's TMDLs.

Department of Fish and Wildlife (WDFW) provides studies and research on salmon and salmon habitat management. They also have a comprehensive list of salmon recovery, conservation, and management agencies and organizations within the State (WDFW 2006).

Other Data Resources

Stream Net (http://www.streamnet.org/index.html) is a project supported by the Pacific States Marine Fisheries Commission that consolidates, standardizes, and distributes fisheries related information from the Pacific Northwest states (ID, MT, OR, and WA) (Stream Net 2006). These States as well as the Tribes and federal fisheries organizations all consolidate information into the Stream Net database (Stream Net 2006). Depending on the study, some of Stream Net's data may currently be useful for conducting stream temperature modeling or riparian vegetation studies on a juvenile coho stream. However, Stream Net does not currently have water temperature information available online, although it is available upon request (Stream Net 2006). Stream Net indicated on their website that they plan to make stream temperature data available online in the near future (Stream Net 2006).

There are numerous sources of data available throughout the Pacific Northwest. Researchers conducting stream temperature surveys should contact or look up agencies and information that may have relevant information for their particular area of study. These agencies may also have historical knowledge of previous local stream temperature modeling activities and may have recommendations as to the most effective data and models to use. However, when data are not available or are unsuitable for a particular study, researchers may need to collect their own data, which can be accomplished in a number of methods.

Data Collection Methods

Agencies and organizations frequently collect stream measurements such as volume, velocity, temperature, etc. through the use of data loggers. These data collection devices can collect temporal temperature census data through continuous recording; they can also collect spatial census data by using remote sensing techniques to map the distribution of water temperatures along an entire river (Pool et al. 2001). Stream data collected through data loggers is often more readily available than stream shade data because of its relatively low manpower needs.

Stream shading and riparian vegetation can be collected in three ways – (1) on-site physical stream assessments, (2) aerial photography, and (3) GIS software. This type of data is not usually readily available and typically requires some type of analysis or interpretation. Stream shade comes in three forms - macrotopographic shade, bank shade, and vegetative shade (Davies et al. 2004). Different techniques of measuring stream shade can capture different types of shading, or focus on a specific source. It is common to use multiple assessment methods to ensure valid data.

On-site assessments usually require measurements of these shade producing elements. The common tools for these physical measurements are:

Ceptometer - a specialized scientific instrument, not readily available, that measures the amount of diffuse non-interceptance (DIFN) of a specific area (Davies et al. 2004),

Clinometer - an inexpensive optical device for measuring elevation angles above horizontal (requires the use of traditional or built in compass) (Calvert 2003)

Densiometer – a mirrored optical device that measure the amount of overhead canopy cover (UWSP 2006),

Solar Pathfinder TM - measures a site's solar potential for the year (Solar Pathfinder 2006)

Solarimeter - measures the flux of solar radiation through a surface (Alam 2006)

As with many other analysis and data collection tools, these tools have different advantages and disadvantages that must be reviewed and analyzed before a selection is made. There are also different measurement techniques and strategies for taking measurements.

An example of a relatively simple technique developed to physically measure stream shade is a method that measures three angles using a clinometer and compass (Davies et al. 2004). The three parameters are: (1) the angle to the top of the stream bank measured from the centerline of the stream, (2) the angle to the top of the riparian vegetation canopy, and (3) the average shade factor of riparian vegetation. The measures, when connected to the sun's path, determine the amount of sun that reaches a stream throughout the day.

Aerial photographs are frequently used to assess riparian conditions. The advantages of using aerial photographs are: (1) the ability to see the terrain by stereoscopically viewing the photos, (2) acquiring photos for a specific time period, and (3) access to historical aerial photos for assessing trends through time (Clark et al. 2004). Aerial photographs come in various scales and resolution. Aerial photography interpretation expertise and ground truthing is recommended when using this method.

Geographic Information System (GIS) has revolutionized the abilities that land and water resources managers have to view and manipulate data. Using GIS in addition to field methods data is essential for the correct interpretation of digital imagery or aerial photography (Clark et al. 2004). GIS and associated tools have even been found to be useful for determining which watershed contains coho salmon (NOAA 1999:A-31). However, the use of GIS to identify specific stream reaches that are inhabited by coho is not effective because coho distribution will change to accommodate fluctuations in the physical characteristics of the stream (NOAA 1999:A-31). Many federal agencies and other organizations have developed GIS "add-ons" or extension tools that enhance the capabilities of GIS for a specific purpose (i.e. vegetation mapping). These extensions are created for various reasons and purposes, but almost always in concert with the mission and goals of that agency or organization. It is therefore important to analyze the capabilities of the systems and look into the agency's purpose and mission to better understand why a tool was created. For example, EPA's BASINS add-on can be linked to their Clean Water Act mandated rules for water quality standards and creating TMDLs. Ground truthing, in conjunction with GIS analysis is a common practice.

Even though collecting and verifying data often end up being the most labor intensive and time consuming portion of a study, it is imperative that adequate time and resources are expended to ensure the data is the appropriate data for the particular modeling and analysis to be conducted.

Natural Background Temperatures

Little can be done in current stream temperature studies without first determining natural background temperatures. Natural background temperatures enable the determination of temporal changes to stream temperatures. However, historical thermal regime data is often scarce (Poole et al. 2001). EPA recommends five strategies to establish this information:

1. ***Demonstrate That Current Temperatures Reflect Natural Background Conditions.*** *This method is most applicable to non-degraded*

watersheds. Under this approach, past and present human activities with potential to alter stream temperatures are collected and a technical demonstration is used to demonstrate that humans do not currently impact temperatures. These streams often serve as reference streams.

2. ***Comparisons to a reference Stream**. Streams of similar size and characteristics, but with different levels of anthropogenic uses can often be compared under that assumption that temperatures would be similar without human disturbance. This technique is most applicable to smaller streams.*
3. ***Historical Data**. A data analysis can be conducted on streams with historical temperature data to determine human influences on the temperature regime. Limitations to this method include lack of data, uncertainty of data quality.*
4. ***Temperature Models**. Models are often used for streams with little data or similarities to reference streams. Two types of models are primarily used:*
    a. *Statistical or Empirical models – based on observed relationships between variables (often used in conjunction with measurements from a reference location). These models estimate thermal stream conditions by using statistics to find correlations between temperatures and landscape characteristics.*
    b. *Process or Simulation models – based on mathematical characterizations of scientific understanding of critical processes*

> *affecting water temperatures in streams and rivers. Generally a two step process – 1. Estimate current river or stream temperatures with input variables, and 2. changing the model input parameters to represent natural conditions. Since, process modes do not rely on reference points; they can be used for rivers and streams that have no suitable reference points available.*
>
> 5. ***Historical Fish Distribution**. Historic salmonid distribution can provide general estimates of natural background temperatures based on known salmonid temperature requirements.*
>
> - EPA 2003:41

EPA acknowledges that all of the above methods have uncertainty, and therefore recommends using multiple methods to reduce uncertainty (2003). Temperature modeling not only serves as a tool for determining background temperatures, but also as a useful tool for modeling various types of temporal and spatial studies of current and alternate future scenarios in streams and rivers.

Stream Temperature Modeling

Stream temperature models help quantify assumptions in mathematical representations of stream processes (Rounds 2001). The two types of model methodology are generally used in water temperature modeling – empirical models and process models (Krause 2002). While available empirical models should also be considered, this paper focuses on the use of process models. Additionally, there are three basic categories of stream temperature models:

reach (models a stream segment), basin (models a network of stream segments), and dynamic (basin models with the ability to account for unsteady water flows) (Krause 2002). Krause points out that reach models are generally more accurate predictors of temperature because they pertain to small sections with less stream diversity and fewer compounding influences (Sullivan et al. 1990). While reach models may be more accurate, basin models are often more appropriate because management usually occurs in stream networks rather than in single segments (Krause 2002). Dynamic models are often necessary due to hydropeaking caused by dam water releases (Bartholow 1997). The primary disadvantage to dynamic modeling is the large data requirement (Krause 2002). Large data requirements often lead modelers to approximate some parameters, due to a lack of time and money to gather sufficient data, which can then decrease the accuracy of the temperature predictions (Krause 2002).

Many different types of stream temperature models are available from a variety of organizations or agencies. The challenge natural resources managers and researchers face is selecting the most appropriate model. The key to successful model selection is to understand the model’s capabilities and limitations, the specific research situation, to include research goals, parameters, and resources available. Unfortunately, there is little information on temperature modeling for specific and actual management issues (e.g. coho fishery management) (Krause 2002). Krause points out that when selecting a temperature model, natural resources managers are often limited to user manuals, research papers, and limited model evaluation studies that provide little comparative analysis of models to make an accurate choice (2002). Finding the available modeling options is even a challenge since very few of them are found together; most models are listed in separate publications or on separate websites. A variety of water quality and stream temperature models are publicly available throughout the United States. However, only seven published process models were found during this study that could measure both shade and stream temperatures. Each of these seven models has their own advantages and disadvantages.

Available Process Models

2D CE-QUAL-W2 - recommended for deep, narrow estuaries. Often referred to as W2, this model is a “2 dimensional laterally averaged flow and water quality model” best used for bodies of water with negligible lateral differences in water quality, but where vertical variations are important – often reservoirs and lakes are ideal (Rounds 2001). This method was successfully used on Oregon’s Tualatin River because of its lake-like characteristics (Rounds 2001). The model simulated water temperatures accurately in the Tualatin River (Rounds 2001), but would not be an appropriate model for free flowing streams.

CE-QUAL-ICM was developed for the Chesapeake Bay. This model involves a 2 dimensional or 3 dimensional hydrodynamic model and using the output for transport terms. Because of this models’ focus on 2d and 3d modeling, it is more likely suited for larger more stratified water bodies than juvenile coho streams.

EPD Riv1 (http://www.epa.gov/athens/wwqtsc/html/epd-riv1.html) was designed by the EPA to model one-dimensional dynamic waterbodies (EPA 2006a). The emphasis of this model is on TMDLs, wasteload allocations, and other regulatory decision making factors (EPA 2006a). This model is based on the COE's CE-QUAL-RIV1 model (EPA 2006a), and it accounts for up to sixteen variables to include stream temperature. The advantages of this model are its ability to incorporate dynamic changes to streams, and its ability to "provides defensible results for regulatory decision making" (EPA 2006a:1). A disadvantage is that it does not accommodate stream shading.

Heat Source (http://www.heatsource.info/) simulates stream and river water temperature through dynamic heat and mass transfer (Heat Source 2006). The use of spatial data makes this method unique when compared to other models. This model uses data collected from thermal imaging to map a stream's temperature. Cost and complexity of methods are two of the biggest downsides of Heat Source (Heat Source 2006). Thermal infrared technology and an aircraft are required to acquire Thermal Infrared Radiometry (TIR) data for model validation (Heat Source 2006). TIR validation is optional, but highly recommended; Boyd and Kasper even mention that TIR data is often more informative than other modeling efforts in assessing spatial distribution of stream temperatures (2004). However, Heat Source performs poorly when input data are assumed or inaccurate (Heat Source 2006). While Heat Source is good candidate for juvenile rearing stream temperature modeling, costs, additional data requirements, and model complexity should be taken into consideration before selecting this model.

QUAL2K (Q2K), http://www.epa.gov/QUAL2E_WINDOWS/, is a river and stream water quality model that is an updated version of the QUAL2E model (EPA 2006b). Updates include the use of a Microsoft Windows environment (EPA 2006b). Q2K is one dimensional, and does not analyze dynamic or stratified systems well (Chapra, Pelletier 2003). Attributes of the model include a diurnal heat budget simulated as a function of meteorology on a diurnal time scale, diurnal water-quality kinetics, heat and mass inputs, and simulated point and non-point loads and abstractions. All water quality variables are simulated on a diurnal time scale. Additionally, the QUAL2K framework includes model segmentation, and uses unequally-spaced reaches. The older QUAL2E was more tedious than RQUAL and the Stream Network Temperature model (SNTEMP) (both discussed later) because it was not able to predict for multiple days within one run of the model (Krause 2002). The user's manual for Q2K indicates that it still lacks to ability to predict for multiple days within one run (Chapra, Pelletier 2003). Furthermore, QUAL2E could not predict temperatures under alternative shade levels or predict maximum temperatures (Krause 2002), and QUAL2K still does not have the capabilities to measure alternative shade levels. However, the QUAL2K Users Manual suggests using *Shade.xls* (http://www.ecy.wa.gov/programs/eap/models/) from the Washington Department of Ecology to input shade elements (Chapra, Pelletier 2003). With the addition of stream shade data from Shade.xls, QUAL2K could be a viable modeling option.

RQUAL (http://www.loginetics.com/agpm.html) is available and supported by a private company call Loginetics. ADYN, another Loginetics program, provides hydrodynamic data for RQUAL. Because ADYN is a necessity to run RQUAL, this paper will refer to the combination of RQUAL and ADYN simply as RQUAL. RQUAL simulates temperature (among other qualities) over time at multiple model nodes throughout a simulated river system (Loginetics 2006). User-specified temperature and water quality for the main channel and tributaries serve as boundary conditions (Loginetics 2006). The model uses a full heat budget that includes atmospheric heat exchange, channel shading by trees and barriers, channel bottom heat exchange, and heated discharges to the river (Loginetics 2006). RQUAL outputs can provide temperature and water quality inputs to FISH, which could be useful in additional studies of temperature affects on coho. A downside to RQUAL is that the software is not shareware, and currently costs $295 (Loginetics 2006).

Stream Network Temperature Model and Stream Segment Temperature (SNTEMP/SSTEMP),

http://www.fort.usgs.gov/products/software/SNTEMP/sntemp.asp, models are based off of Thuerer's Stream Network Temperature Model Instream Flow Incremental Methodology (IFIM) (Bartholow 1989). SNTEMP is a bit more complex and has not been updated to use a Windows platform, whereas SSTEMP runs from windows (USGS 2006a). However, the tradeoff of using SNTEMP is that it can be applied to a stream network of any size or order, while SSTEMP only applies to a stream segment or reach (USGS 2006a). SNTEMP/SSTEMP predict the solar radiation penetrating unshaded water as a function of latitude and time of year and the riparian and topographic shading of that radiation (USGS 2006a). They correct air temperature, relative humidity, and atmospheric pressure as functions of elevations within the watershed. SNTEMP/SSTEMP fills and optionally smoothes missing observed water temperature measurements (USGS 2006a). They also provide statistical "goodness-of-fit tables" to help judge the model's power of estimation. SNTEMP/SSTEMP does not allow multiple-day simulations (USGS 2006c). SNTEMP/SSTEMP does not predict minimum temperatures – it gives a heuristic guess (USGS 2006c). Additional limitations to SNTEMP/SSTEMP are their inability to deal with rapidly fluctuating flows, their empirical approach to predicting maximum daily water temperatures, and the fact that these programs assume turbulence is thoroughly mixed in the stream both vertically and transversely (i.e., no microthermal distributions) (USGS 2006a). Bartholow stated that SSTEMP/SNTEMP's strengths are: their shading algorithm, the statistical tools for filling, smoothing, and goodness-of-fit calculations, and the requirement for mean daily values only (USGS 2006a). He also stated that SSTEMP/SNTEMP's weaknesses are the estimation of maximum daily temperatures and lack of minimum daily temperature calculation, and the non-Windows user interface for SNTEMP (USGS 2006a). Krause found air temperature to be more sensitive for SNTEMP than QUAL2E (Krause 2002). Johnson et al. successfully used SSTEMP to support the temperature TMDL of the Mattole River (2002). USGS also provides the most comprehensive set of publications, training, and technical support of all models reviewed. The Survey has other models that assess physical habitat (PHABSIM) and fish population modeling (SALMOD). These additional instruments could be an advantage to selecting one of these models.

Stream Temp (http://www.northcoast.com/~trpa/sindex.html) was developed by Thomas Payne and Associates. It is based off of the USGS' SNTEMP model (Thomas Payne and Associates 2006). This model uses SNTEMPs foundations and converts them to a more user friendly Microsoft version. The software is relatively new and untested (Thomas Payne and Associates 2006). Payne stated that while the software was not fully tested, a number of groups were using it with no negative feedback (Payne 2006). Payne offers technical assistance to the users of his program (Thomas Payne and Associates 2006). There is normally a nominal $20 fee for the software to cover shipping and materials (Payne 2006). While this model has not been fully tested, initial assumptions of performance, strengths and weaknesses could be made from critiques of SNTEMP (Payne 2006).

TEMP-86 model was developed in Oregon by Beschta and Weatherred in 1987 (Belt et al. 1992). Temp-86 is designed to evaluate the effects of buffer strips on stream temperature (Belt et al. 1992). The model is based on a stream reach heat energy budget, with solar radiation as prime energy source (Belt et al. 1992). The model allows the comparison of different riparian buffer design effects on water temperature (canopy height and density are variables) (Belt et al. 1992). Different widths and canopy heights or densities predict hourly water temperatures for any given day and geographical location (Belt et al. 1992). Different riparian buffer scenarios can easily be compared using this model (Belt et al. 1992). Belt et al. stated that model data requirements are relatively extensive (1992). This model is not readily available; however Dr. Beschta can still be contacted at Oregon State University to discuss the model.

Water Quality Analysis Simulation Program (WASP), http://www.epa.gov/athens/wwqtsc/index.html, helps users “interpret and predict water quality responses to natural phenomena and manmade pollution for various pollution management decisions” (EPA 2006b:1). WASP is a dynamic model that accommodates analyses of 1D, 2D, and 3D systems (EPA 2006b). The model results can also be linked with hydrodynamic and sediment transport models that can provide flows, depths, velocities, temperature, salinity and sediment fluxes (EPA 2006b). The model has primarily been used in larger water bodies to include Florida’s Tampa Bay and Lake Okeechobee, and the Neuse River in North Carolina (EPA 2006b). WASP does not have a method to incorporate stream shading into the model.

Unavailable Process Models

CE-QUAL-RIV1 is a one dimensional water quality model for streams that is currently only available for Corps engineers (COE 2006). Fortunately, EPA created EPD Riv1, which is based on CE-QUAL-RIV1.

TEMPEST model was developed by Adams and Sullivan in 1990. This model is unpublished (Belt et al. 1992). The model is a computer simulation that estimates the effects of buffer strips on water temperature, based on an assessment of the heat energy budget for a stream reach (Belt et al. 1992). This model uses multiple simplifying assumptions that reduce the number of input data required (Sullivan et al. 1990). The data required for the model includes geographic location, elevation, percent shade, and stream depth, and it predicts hourly stream temperature over any specified interval (Belt et al. 1992). Reliability tests found that the model predicted average water temperature within plus or minus 2° C 95 percent of the time (Belt et al. 1992). The SNTEMP Frequently Asked Questions website listed Kate Sullivan, a Senior Scientist at Sustainable Ecosystems Institute as a contact person. However Dr. Sullivan was unresponsive to email inquiries about Tempest.

In addition to the above models, I found reference to and researched the following named models with minimal success: WQstat plus – Mann-Kendall Test/Sen Slope estimator, Seasonal Kendall Test, Heat transfer, Model Y, WQRRS, ORIS, RipTopo – works with SSTEMP (Johnson) UC Davis, Brown's Model, and SHADOW – USFS 1993.

Other Models Worth Mentioning

Some of the stream temperature models have other related models that can help interpret temperature and other variables' effects on salmon, fish, or physical habitat. PHABSIM and SALMOD work with SNTEMP and SSTEMP data, while FISH works with RQUAL data.

PHABSIM (Physical Habitat Simulation System model) - The purpose of the PHABSIM is to simulate a relationship between streamflow and physical habitat for various life stages of a species of fish or a recreational activity (USGS 2006a). The basic objective of physical habitat simulation is to obtain a representation of the physical stream so that the stream may be linked, through biological considerations, to the social, political, and economic world (USGS 2006a). The modification of physical habitat by temperature and water quality is analyzed separately from the physical habitat simulation contained in PHABSIM (USGS 2006a). Temperature in a stream varies with the seasons, local meteorological conditions, stream network configuration, and the flow regime; thus, the temperature influences on habitat must be analyzed on a stream system basis. (USGS 2006a)

SALMOD (http://www.fort.usgs.gov/products/software/salmod/salmod.asp) is a model with stream flow, water temperature, and habitat type as the physical state variables included in this model (USGS 2006a). The stream can be divided into flow and temperature segments either by distance or by computational unit numbers (USGS 2006a). Flow and temperature data are organized by river segments and by time steps for each segment (USGS 2006a). Habitat is defined by a flow versus habitat relationship for each habitat type (USGS 2006a). Currently, SALMOD only "sees" a linear stream, with no tributaries or branches possible (USGS 2006a). However, various options control what happens to fish moving out of the collection of computational units defining the study area, either upstream or down (USGS 2006a). SALMOD is unique simulation model because it is integer based, i.e., only whole animals are ever born, die, or even exist (USGS 2006a).

FISH (http://www.loginetics.com/agpm.html) models fish rather than stream or shade qualities. Developed by researchers from the Tennessee Valley Authority and EPA, FISH models fish biomass over time "resulting from bioenergetic exchanges during food consumption and respiration processes” (Loginetics 2006:1). The variables of Growth in this model are temperature, dissolved oxygen, and food availability (Loginetics 2006). This model, supported by Loginetics, requires the use of RQUAL outputs for stream temperature and dissolved oxygen data (Loginetics 2006).

Table 1 – Modeling and Data Resources by Supporting Agency/Organization

Agency	Service Provided	Type of Service	Description
Robert Beschta	Temp-86 Model	Model	Stream segment process model
CDFG	BIOS	Data	California biogeographic data
Corps of Engineers	2D CE-QUAL-W2	Model	Process model recommended for estuaries
	CE-QUAL-ICM	Model	2 or 3 dimensional process model designed for the Chesapeake Bay.
	CE-QUAL-RIV1	Model	One dimensional model for dynamic water bodies
EPA	BASINS	GIS extension	System for performing watershed and water quality based studies
	EPD Riv1	Model	1 dimensional model for dynamic water bodies based on CE-QUAL-RIV1
	QUAL2K	Model	River and stream water quality model (updated version of QUAL2E)
	STORET	Data	Ambient environmental data related to water quality
	Toolbox	Portal	Various EPA supported models and support center
	WASP	Model	Water quality response process model
Loginetics	RQUAL	Model	Water quality process model
	FISH	Model	Models fish biomass over time.
NOAA	NCDC	Data	Climatological data from throughout the world
ODEQ	TTools	GIS	Samples spatial data sets used in water quality monitoring
	Heat Source	Model	Dynamic heat and mass transfer is used to simulate stream and water temperature
Pacific States Marine Fisheries Commission	Stream Net	Data	Fisheries related data from ID, MT, OR, and WA.
Kate Sullivan	Tempest	Model	Water quality process model
Thomas Payne and Associates	Stream Temp	Model	Windows-based stream temperature process model based on SNTEMP
USGS/NSIP	Waterwatch	Data	Stage and Stream flow data for certain US water bodies
USGS/NWIS	NWISWeb	Data	Online water resources data
USGS	SNTEMP	Model	Stream network temperature process model
	SSTEMP	Model	Stream segment temperature process model
	PHABSIM	Model	Streamflow and physical habitat process model
	SALMOD	Model	Fish simulation model that evaluates stream habitat variables.

Analysis of Data, Models and Other Tools

Water temperature and riparian vegetation are critical to juvenile coho salmon; however, understanding the best way to analyze and model these relationships is not always clear. Miner and Moore wrote that “although monitoring the temperature of a stream is relatively easy, it is the much more difficult to interpret the data” (1997:5). The numerous tools and models available to help assess the conditions and trends of streams and riparian vegetation are confusing when determining the most appropriate tool to achieve different goals. Some tools and models may be more appropriate and useful for the characteristics of juvenile coho habitat in Pacific Northwest streams and rivers. Additionally, ensuring the model is an appropriate fit, with the right parameters for the habitat type, is another key consideration when selecting a model. Likewise, these tools may not have features needed for the juvenile coho's specific circumstances and measuring their optimal conditions.

Choosing the correct model is dependent upon multiple factors, which include: (1) knowledge of the models’ limitations (Krause 2002), (2) the specific objective(s) of the study (Bartholow 1997), and (3) the species of interest specific characteristics (physical habitat, biological limits, etc.). This paper can serve as a starting point for answering these three critical pieces of information for juvenile coho salmon.

Specific Stream Habitat Parameters

Knowing essential information about juvenile coho habitat and coho biological limitations is an essential first step in determining what data and tools to pursue for analysis of riparian vegetation and stream temperatures in juvenile coho streams. Krause noted that “modeling stream temperatures under altered conditions become most useful when coupled with thermal tolerance data for the stream’s fish species” (2002:3). The essential information mentioned in the preceding sections has been captured in the following table.

Table 2 – Salmonid and Coho Stream Habitat and Temperature Characteristics

Salmonid Stream Temperature Characteristics	
Salmonid Optimal growth Limited Food	10-16° C (constant) [a]
Rearing Preference Temp.	10-17° C (constant) [a]
Impairment to Smoltification	12-15° C (constant) [a]
Coho Preferred temperature range	11.8° to 14.6° C [3]
Disease Risk (lab studies) High	>18-20° C (constant) [a]
Elevated	14-17° C (constant) [a]
Minimized	12-13° C (constant) [a]
Lethal Temperature	4-14° C (daily average) [a]
Coho Upper Lethal Temperature	25.8° C[3]
Salmonid uses during summer maximum conditions	
Salmon/Trout core juvenile rearing	16° C (7DADM) [a]
Salmon/Trout non-core juvenile rearing	18° C (7DADM) [a]
Summer water temperature – min water temp (may limit the production of presmolts)	20° C > 2 weeks
Coho-specific Preferred Stream Habitat Characteristics	
Early juvenile rearing habitat depth in shallow areas	< 30 cm [b]
Early juvenile rearing habitat quiet areas water velocity	< 10 cm/s [b]
Rearing habitat average gradient	< 3% [2]
Riffle water velocity	.31 to .46 m/sec [c]
Pool water velocity	.09 to .24 m/sec [c]
Pool to riffle ratio	1:1 [c]
Preferred spawning stream size	< 4th order [c]
Water depth	.3 to 1.22 m[c]
Desired Dissolved oxygen level	Near saturation [c]

[a] Temperature considerations for juvenile rearing salmon and trout (except Bull Trout) (EPA 2003:16-25, [b] Reeves et al. 1989, [c] Laufle et al. 1986

These stream and temperature characteristics can be used when determining the most appropriate data and analysis methods to ensure that coho specific data and analysis is conducted.

Selecting the most appropriate model for a specific use requires the comparison of study-specific information to the models' capabilities, parameters, and requirements. Initial decisions should be made on coho-specific information (such as in table 1), stream specific (e.g. size, dynamic, non-dynamic etc.), known time, data, and financial resources, as well as the goals of the study. This information should then be compared with a model's data parameters, input, capabilities (dynamic stream modeling, stream shade analysis, etc.), ease of use, and technical support. Some of the models can be immediately eliminated for use in juvenile coho stream temperature modeling because they were not designed to model smaller bodies or water or because of their inability to measure stream shading.

Modeling Streams and Stream Shade

Understanding the relationship between salmon, stream temperatures, and riparian vegetation requires the model to accommodate stream shading and smaller stream dynamics within the modeling. Some models were not designed to model smaller streams (2D CE-QUAL-W2 and CE-QUAL-ICM), while others were not equipped to model stream shade (WASP, EPD Riv1, 2D CE-QUAL-W2 and CE-QUAL-ICM). QUAL2K (QUAL2E's replacement) has many positive attributes for modeling water quality; however, it is not understanding the relationship between riparian vegetation and stream temperatures. The QUAL2E model would also be an unacceptable choice for shade evaluation as there is no shade component to this model. However, as previously mention, the QUAL2K handbook recommends using *Shade.xls* to provide shading data to supplement the QUAL2K stream temperature model (Chapra, Pelletier 2003). SNTEMP vegetation density parameter allows assessment of alternative shade scenarios as well as vegetation height, offset, and crown width (Krause 2002). Shade assessment may be possible with RQUAL, but because there is no vegetation density parameter the differences in water temperature under alternative shade scenarios may be indiscernible (Krause 2002). The RQUAL model contains both vegetation offset and height parameters and a parameter that accounts for the fraction of solar radiation absorbed by shaded water for which a relationship with vegetation density might be developed. However, unlike SNTEMP, which allows different vegetation densities at multiple longitudinal locations on each side of the river, RQUAL only allows one value for the entire modeled system and offset and height must the be same for both sides of the river. Table 2 lists the capability of the models to assess small streams and dynamic water conditions.

When comparing juvenile coho stream habitat with the capability and design purpose of the models, the COE's 2D CE-QUAL-W2, CE-QUAL-ICM would likely be ineffective because they were designed to model larger, estuary- and lake-type bodies of water. While many streams preferred by juvenile coho for rearing do not have dynamic water conditions caused by discharge of water from dams or other point sources, this would be a definite consideration if the stream in question did have such a dynamic quality. Heat Source, WASP, and

EPD Riv1 were the only models suited for small streams that were also capable of handling dynamic flow conditions.

Table 3 – Model Stream Characteristics Measuring Capabilities

Model	Small non-stratified Streams	Measures Stream Shading	Dynamic Water modeling	Stream Network
2D CE-QUAL-W2			X	
CE-QUAL-ICM			X	
EPD Riv1	X		X	
Heat Source	X	X	X	X
QUAL2K (Q2K)	X	X*		X
RQUAL	X	X		X
SNTEMP	X	X		X
SSTEMP	X	X		
Stream Temp	X	X		X
TEMP-86	X	X		
WASP	X		X	

* With the use of WA Dept. of Ecology’s Shade.xls program.

Data Requirements/Inputs

Data requirements are a key consideration when selecting a model because the amount, difficulty, and time required for data collection and input is not only a resource issue, but can also affect the accuracy of the outputs as well. The more inaccurate and estimated the data, the more likely it is that outputs will be inaccurate. The RQUAL model requires the most data collection (out of SNTEMP and QUAL2E) because it is a dynamic model and creates hourly predictions (Krause 2002). SNTEMP and QUAL2E/QUAL2K have similar data requirements (excluding SNTEMP’s shade requirements). The creators of Heat Source “strongly recommend using TIR data to validate the [Heat Source] model” (Boyd, Kasper 2004:117). This creates not only an additional data obstacle, but also creates the financial obligation of hiring a helicopter with TIR to acquire the data, which can be quite costly. Knowing model data requirements and the associated cost and resource to acquire the data is an important consideration when selecting a model.

Data requirements are another area to analyze. Some models may require either extraneous amounts of data, unattainable data, or parameters that are better suited for a particular study.

Table 4 – Data Requirements for Models Appropriate for use in Streams*

	Heat Source	**QUAL2K**	**RQUAL**	**SNTEMP**	**SSTEMP**	**Stream Temp**
Stream Geometry and Time Parameters						
Mean Basin elevation		X				
Reach Elevations		X	X	X	X	X
Mean Basin Latitude	X	X	X	X	X	X
Mean Basin Longitude	X	X	X			
Standard meridian		X				
First and last day of simulation period	X	X	X	X	X	X
Distance of modeled reaches		X	X	X	X	X
Stream width coefficient				X	X	X
Stream width exponent				X	X	X
Manning’s N		X	X	X	X	X
Travel Time				X	X	X
Cross-section area at anodes			X			
“Full channel” depth			X			
Shade Parameters						
Stream width	X	S**	X	X	X	X
Channel azimuth per stream reach			X	X	X	X
Topographic altitude		S		X	X	X
Vegetation height		S	X	X	X	X
Vegetation offset		S	X	X	X	X
Vegetation crown				X	X	X
Topographic Shade		S				
Minimum and Maximum vegetation density	X	S		X	X	X
Time of morning fog lift			X			

	Heat Source	QUAL2K	RQUAL	SNTEMP	SSTEMP	Stream Temp
Meteorological parameters						
Air temperature	X	X	X	X	X	X
Web bulb temperature		X				
Relative humidity	X			X	X	X
Solar radiation			X	X	X	X
Percent possible sun or cloudiness		X	X	X	X	X
Wind speed	X	X	X	X	X	X
Ground reflectivity				X	X	X
Dust coefficient		X		X	X	X
Evaporation coefficient		X	X			
Mean annual air temperature				X	X	X
Barometric pressure		X	X			
Dewpoint temperature			X			
Fraction of drybulb /dewpoint depression by which drybulb is cooler over shaded water			X			
Flow Parameters						
Depth exponent		X				
Depth coefficient		X				
Velocity exponent		X				
Velocity coefficient		X				
Discharge		X	X	X	X	X
Water/Streambed Temperature Parameters						
Water temperature at the modeled reach start-point		X	X	X	X	X
Streambed thermal gradient or diffusivity			X	X	X	X
Ground temperature (surrogate for lateral inflow temperature)			X	X	X	X
Effective channel bed thickness (upper layer) for bed heat conduction			X			
Effective channel be thickness (deep layer) for bed heat conduction			X			
Bed heat storage capacity			X			
Fraction of solar radiation absorbed in surface .6 m of water			X			
Albedo of bed material			X			
Fraction of solar radiation absorbed by shaded water			X			
Thermal Infrared Radiometry	X					

*This table is a modified version of Krause's table (2002), **"S" indicates Qual2K is capable of this measurement with input from Shade.xls.

Training, Support, and Costs

While training, support, and costs have nothing to do with model's ability to accurately measure stream temperature and shading, it is a vital question for a manager or researcher to review. Considering these questions prior to model selection will help ensure that a researcher or manager does not overstep his or her expertise, resources, or time boundaries. Newer dynamic models such as Heat Source require finer meteorology (USGS 2006a). In addition, they require substantial computer time and much more detail on the hydraulic cross section (USGS 2006a). SNTEMP and SSTEMP models have the most documentation, provide technical assistance, and offer a self-study course (Bartholow 1997, 1989). Krause found the RQUAL user's guide was the most simplified of the assessed models [QUAL2E and SNTEMP were the others] (Krause 2002). However, while RQUAL offers technical assistance, it does not provide training (Krause 2002). Krause had to contact experts on the SNTEMP and RQUAL model, and used the listserv for the QUAL2E to effectively run all three programs (Krause 2002).

Table 5 – Model Training, Support, and Costs

Model	Training Provided	Technical Assistance	User's Manual	Model Cost	Complex Model*	Data Collection*	
						Cost	Complexity
EPD Riv1		X		Free			
Heat Source		X	X	Free	X	High	High
QUAL2K		X	X	Free			
RQUAL		X		$295			
SNTEMP	X	X	X	Free	X		
SSTEMP	X	X	X	Free			
Stream Temp		X		$20			
TEMP-86				Free			
WASP		X		Free			

* based on proclamations provided by the model literature or studies conducted on models.

Accuracy

The research conducted on these models was intended to identify potential models that could assess stream temperature and riparian vegetation in juvenile coho streams. No model testing, formula or methodology analysis was conducted in this research. While accuracy is a primary consideration in the selection of a model, this paper does not attempt to answer the question of "which is the most accurate model?" Still, the following section includes information from other studies and publications that address accuracy.

Several stream water temperature simulation models were analyzed by Washington's Timber, Fish, and Wildlife "Temperature Work Group" (Sullivan et al. 1990). The Temperature Work Group used accuracy, reliability, and practicality in estimating the impacts of timber harvest on stream temperature as their criteria (Sullivan et al. 1990). The analysis they conducted found that the TEMP-86 model had the greatest accuracy, while the TEMPEST model ranked highest when other criteria were also considered (such as data requirements), and Brown's model (Brown contributed to the QUAL2K model) ranked third (Sullivan et al. 1990). The USGS Frequently Asked Questions database stated that Tempest was more accurate especially for maximum temperature prediction, than SSTEMP (2006). TEMPEST and TEMP-86 may be better on small, forested headwater streams where a substantial portion of the flow is actually sub-surface than SSTEMP or SNTEMP (USGS 2006a). These findings highlight the fact that individual circumstances will usually dictate the most appropriate model.

Krause’s studies concluded that there was no “best” model between QUAL2E, SNTEMP, and RQUAL because of their similar predictive abilities (2002). Krause found that all three of the models he assessed were capable of predicting temperature well (2002). He suggested that, between the three, selection should be made based on unique model capabilities that best fit the individuation situation (Krause 2002). Krause also concluded that it was inadvisable to use the three models he reviewed in dynamic flow conditions (2002). These comparisons of different models, while they provide good information, still need to be taken in account only as part of a larger assessment of the tools. Accuracy is likely to vary from location to location. Krause, who provides one of the primary comparison studies, conducted his research on streams in Virginia, which likely had significant stream characteristic differences than those of the Pacific Northwest.

CONCLUSIONS

The interrelationships of riparian vegetation, stream temperature, and the health of juvenile coho rearing streams are vast and complex. Coho require specific habitat conditions throughout their lifecycle, to include the very critical juvenile stage, where they are most vulnerable to affects of poor riparian vegetation management. Their specific needs, such as streams with low temperatures and high dissolved oxygen, were historically created by natural conditions. Human activities have altered these natural conditions over time as activities have increased within these areas. Understanding the effects of these human activities on the health of riparian and stream areas is vital to making sound management decisions. Riparian vegetation is the greatest stream temperature-changing element that humans influence and have control over. Analysis of human activity in riparian areas helps determine the effects of these activities on the vegetation, the stream temperatures, and juvenile coho. Data collection, modeling, and analysis help ensure effective natural resources management, and ensure a better understanding of the effects human activities have on these ecosystems.

Knowing the best stream modeling instrument for specific situations is key to performing the most accurate analyses. No one model stands out as the “best” model for modeling stream temperature in coho streams. Instead, knowing the different model capabilities, their data requirements, methodologies, and modeling support, in addition to the specific study area characteristics, are all keys to effective modeling. A tremendous amount of data is available on both water quality and coho; stream shade data is also available in many situations. In addition to reviewing models and data appropriateness for assessing juvenile coho streams, selecting the most appropriate model and data also depends on stream and resources specific information.

This analysis creates a logical starting point for selecting a stream temperature model with shading capability. The different models examined have their own specific attributes that make them either unsuitable for consideration, or preferable for specific study conditions. Because typical juvenile coho streams are small and not stratified, CE-QUAL-W2, CE-QUAL-ICM are not viable options. WASP and EPD Riv1 are also not viable options because they are incapable of measuring stream shade. The remaining models reviewed are all viable options for measuring juvenile coho streams. However, each model has its own distinct characteristics and project specific analysis is necessary when determining the most appropriate model. Predominant distinctions between viable models include the capability to model dynamic water conditions, stream networks, shade, and model complexity.

Studies that have the most model options available are non-dynamic stream segment studies. This type of study can choose between all seven remaining models (see Table 6). However, Temp-86 model was the most accurate in a study conducted by Washington State's Timber Fisheries and Wildlife Taskforce (Sullivan et al. 1990). SSTEMP may also be a preferred option because of its user friendly Windows platform and abundant training resources. Stream networks studies are limited to 5 models - QUAL2K, RQUAL, Heat Source, SNTEMP, and Stream Temp. Krause's (2002) study may be beneficial to select from RQUAL, QUAL2K, and SNTEMP. While Heat Source is the only option available to model dynamic water conditions, its high complexity and demanding data requirements may make it undesirable for non-dynamic conditions where other options are available. These suggestions are based on model limitations. Additional stream specific information and, if possible, accuracy comparisons of the models should still be considered no ensure the model selected is the most appropriate for the situation.

Table 6 – Model Suitability

Model	**Non-dynamic juvenile coho streams Segments**	**Stream Networks**	**Dynamic Streams**
Heat Source	X	X	X
QUAL2K	X	X	
RQUAL	X	X	
SNTEMP	X	X	
Stream Temp	X	X	
SSTEMP	X		
TEMP-86	X		

Previous research and analysis, users manuals, and available training are all good resources to learn more about a model or data. Currently, there is not sufficient information to compare and contrast the accuracy of differing models or their performance as compared to other models. Although, this document provides some assistance and a starting point to making the selection of a temperature model, more research should be conducted before selecting a model.

Krause mentions in his paper that more effort should be invested in comparisons of temperature models (2002). He found very little data to compare and contrast the advantages to different models. Like Krause's study, this study found a deficit in comparison studies, and relied on model user manuals and training to evaluate the fit of models to the specific modeling requirements of juvenile coho streams. Comparative analyses of Shade.xls, QUAL2K, Heat Source, and the Stream Temp model, to other models could not be found during this study. Additionally, if TEMP-86 and Tempest proved to be some of the most accurate models in the University of Idaho study and in the Washington’s Timber, Fisheries, and Wildlife report, effort should be made to make them more widely available to all stream temperature and shade researchers. More in depth research and comparisons of these models could prove invaluable to future stream modeler’s selection of models and data, and to a more accurate assessment of the stream.

SUMMARY

Coho require certain stream temperatures for optimal growth, and have temperature thresholds can cause death when exceeded. Temporal and spatial changes to temperatures significantly affect the coho’s lifecycle, behavior, and viability. Therefore, effectively managing stream water temperatures is critical to this species’ success. Understanding the behavior modifications coho undergo during different temperatures reminds us that salmonids are very sensitive to habitat changes. Examining water temperature data is critical when planning watershed, stream, riparian area, and fisheries management activities. Of these management activities, the one that offers the most control over stream temperatures by humans is riparian vegetation.

Streamside vegetation removal reduces solar radiation-blocking shade and increases solar heating of streams (EPA 2003:6). Lack of streamside vegetation also increases stream bank erosion and sedimentation, which increases stream surface area, solar radiation exposure and heat exchange with the air (EPA 2003:6). Temperatures elevated through anthropogenic causes can adversely effect juvenile coho salmon during the summer months and early fall, and may create unsuitable rearing habitat, thereby reducing the amount of rearing habitat available and potentially, overtime, the coho population (EPA 2003:13).

The increasing human population has created an increased demand for urbanization, timber, cattle, and agricultural products. For these reasons, effective stream and riparian vegetation management will continue to be critical for ensuring the viability of juvenile coho streams. The only way to determine whether riparian management practices are accomplishing desired results is through collecting and analyzing data to better understand the past present and future of these critical areas. A common method to measure the effects that riparian vegetation has on water temperatures is by measuring stream shade. Shade often serves as a surrogate for more complex hydraulic stream models because it is the temperature-influencing factor most likely altered from natural conditions. Additionally, riparian vegetation is the primary factor that can be managed by humans (EPA 2002, Johnson et al. 2002).

Stream temperature and shade models and supporting data are abundantly available through different government agencies and other organizations. Models are usually aligned with their supporting agencies' purposes. Most models are free and the supporting agency frequently provides some form of technical support or model assistance. Determining the most appropriate model and data requires a thorough understanding of the available models' capabilities, project specific resources, the study's purpose, and species and habitat qualities. There are advantages and disadvantages to each model. Models that measured stream segments or reaches, such as Temp-86, were found to be more accurate, and can be more user friendly (e.g. SSTEMP). However, these models are not capable of measuring stream networks, which is often where management decisions are made. Stream network models, such as SNTEMP, Stream Temp, RQUAL, and QUAL2K) are capable of modeling networks, but are not as accurate or user friendly as stream segment models. Of all the models mentioned, dynamic streams can only be modeled by the Heat Source model. Choosing the right model therefore depends on criteria specific to each project.   Understanding coho, stream, project, data, and model specifics will greatly assist selecting the most appropriate model.   Appropriate model selection, in turn, should then provide the most appropriate results to help make coho stream management decisions and improve juvenile coho stream habitat.

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Vita

Jeffery W. McPherson

Jeff McPherson focused his studies in marketing and management at Western Oregon University where he obtained a BS in Business in 1996. While at WOU, Jeff also participated in the Reserve Officer's Training Corps, and received his commission as a second lieutenant in the US Army. During his four year long tour of duty, Jeff was stationed as a Field Artillery Officer in the Republic of Korea and in Fort Sill, OK. In 2000, while at Fort Sill, he obtained an MA in Communications from the University of Oklahoma. In 2001 Jeff left the Army as a captain and began a new career in the US EPA's Office of Research and Development in Washington DC. After three years of organizational development work at ORD, Jeff transferred to the EPA's Office of Water were he still works as a Drinking Water State Revolving Fund program coordinator. Some recent highlights in Jeff's work are serving as a team member for a multi-agency Hurricane Katrina and Rita wastewater and drinking water recovery team, working on an Energy STAR certification initiative for drinking water and waste water facilities, and participating in the revision of EPA's National Environmental Policy Act regulations. Additionally, he participated in the National Capital Region's Natural Resources Program strategic planning. In his free time, Jeff volunteers as a Fairfax County Stream Monitor and assists the Reston Association's natural resources program.