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An Investigation of Spatial and Temporal Variability in Stream Temperature in Several of Montana's Reference Streams: Working Toward a More Holistic Management Strategy

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Committee Chair: Dr. Vicki Watson

Water temperature is a physical property that fundamentally affects stream ecology and is considered an important water quality parameter from scientific and legal view points. On global, catchment and reach scales, anthropogenic activities have substantially altered natural stream temperature regimes, impairing these systems' ability to maintain ecological integrity. Thermal degradation often can be attributed to a variety of human activities, and global climate change, which has been accelerated by the demands of an exponentially expanding human population, will play a central role in defining stream temperature regimes in the future. Natural spatial and temporal variability in stream temperatures adds to the complexity of regulating thermal pollution and restoring natural conditions of stream ecosystems. As such, managers would benefit from a comprehensive understanding of the thermal dynamics and primary drivers, including air temperature, of the thermal energy budgets in unaltered, or reference, streams.

In this study, a random coefficient regression model was developed and used to analyze variability in summer daily average water temperatures and the relationship between summer daily average air and water temperatures of thirty-six of the Montana Department of Environmental Quality's reference streams. These streams represent four of Montana's seven Level III ecoregions: Middle Rockies, Northern Rockies, Northwestern Glaciated Plains, and Northwestern Great Plains. Variability in stream temperatures between ecoregions, between streams within ecoregions, and the air-water temperature relationship were primary considerations. This model indicates that there *is not* significant variability between ecoregions in Montana's reference stream temperatures and in the air-water temperature relationship. Alternately, the model indicates that there *is* significant variability between streams within each ecoregion in reference stream temperatures and the air-water temperature relationship. Equations representing the expected daily average water temperatures of reference streams, given values of daily average air temperature with zero and one-day lag, are also presented. Finally, the management implications of this predictive model are discussed, and a holistic approach is recommended for developing thermal regime-based stream temperature standards, which are critical for the restoration and maintenance of ecological integrity, based on 'natural' conditions in reference streams.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Stream temperature regimes are the result of dynamic interactions between fluvial system *structures*, including the channel, riparian zone, and alluvial aquifer, and the *processes* that drive or influence water temperatures, including climatic factors, stream flow, groundwater/surface water interactions, solar radiation and shading by riparian vegetation (Poole and Berman 2001; Theurer *et al*. 1984; Bartholow 1989; Johnson 2004; Moore *et al*. 2005). On global, catchment and reach scales, anthropogenic activities have substantially altered natural stream temperature regimes (Poole and Berman 2001; US EPA 2003; Webb 1996; Webb and Crisp 2006; Krause *et al*. 2004; Reeves *et al*. 1998). Global climate change, in particular, has been accelerated by the growing demands of an exponentially expanding human population (IPCC 2007) and will likely play a central role in defining stream temperature regimes in the future (Schindler 1997; Bates *et al*. 2008; Hauer *et al*. 1997; Durance and Ormerod 2008). Natural and anthropogenically-induced fluctuations in stream temperature will interact and may induce a wide array of novel, and potentially detrimental, behavioral and physiological responses in aquatic organisms and can render formally suitable habitat unsuitable for native species assemblages (Poole and Berman 2001).

Unfortunately, as of 2006, thermal impairment is already documented in 2,393 miles of rivers and streams in Montana, or about 13% of those that have been assessed for beneficial use support (United States Environmental Protection Agency (US EPA) 2006). Although legislation is in place to address the deleterious impacts of changing stream temperature regimes, growing concern for the ecological integrity of stream ecosystems and the native aquatic species assemblages they support has led to mitigation and regulation of human activities that cause thermal degradation. However, research and monitoring programs that do not account for spatial and temporal patterns of stream temperature, the relative influence of various drivers, and the expected response of stream temperature to anthropogenic influences will not provide sufficient or useful answers to scientific or management questions about the temperature requirements of stream communities (Poole and Berman 2001; Johnson 2003). A holistic and adaptive approach to understanding and restoring natural variability (in space and time) in ecological processes that acknowledges the tremendous uncertainty that is inherent in attempting to model and restore stream ecosystems is necessary for effective stream management (Franklin 1993; Poff *et al*. 1997; Wohl *et al*. 2005).

A conceptual understanding of the processes and structures that influence stream temperature in *unaltered* systems can provide a framework for understanding the breadth of human activities that may substantively influence stream temperature and provide the basis for development of “spatially explicit management prescriptions” (Poole and Berman 2001). The “reference condition concept” asserts that there exist for any group of similar waterbodies (such as streams) relatively undisturbed (reference) examples that can represent the natural biological, physical, and chemical integrity of a region (Montana Department of Environmental Quality (MT DEQ) 2006). Montana's narrative temperature standards require that water quality be compared to "naturally occurring", and the DEQ uses reference sites to help interpret what naturally occurring is (MT DEQ 2006; Suplee *et al*. 2005) and thus relies on accurate empirical study, description and analysis of reference stream data. Reference streams are also a useful tool for conducting comparative analyses between "reference" and "degraded" systems (Bailey *et al*. 2004; Hughes 1995). Hence, an investigation of spatial and temporal variability in reference stream temperature regimes, coupled with a discussion of the human activities most likely to affect the primary determinants of these regimes, may provide stream managers with a framework for understanding and managing the issue of thermal impairment. This analysis may also be useful for making predictions about expected stream temperature conditions, and for developing or changing Montana's water quality temperature standards in the future.

The overall **purpose** of this study is to improve our understanding of natural spatial and temporal variability in water temperature in Montana's reference streams and to use that information to guide efforts to restore and maintain the temperature integrity of Montana's streams. The **first objective** is to provide a critical review of scholarly literature on natural variability in, and the ecological significance of, stream temperatures (especially in Montana's ecoregions), and on factors that drive and buffer stream temperature variability. The **second objective** is to provide a critical review of legal approaches to restoring and maintaining stream temperature integrity, including EPA guidance on temperature standards and temperature Total Maximum Daily Loads (TMDLs) and Montana's current temperature standards and TMDL practices, and to discuss the current status of stream thermal impairment and management in Montana.

The Level III ecoregion is the geographical unit often used to study and describe ecosystem parameters in different regions of Montana (Woods *et al*. 2002). However, high spatial variability across Montana's landscapes suggests that the ecoregion scale may be too coarse to usefully develop reference stream temperature monitoring schemes or to capture natural variability in reference stream temperature regimes, affirming the need for more site-specific analysis. If reference stream data is to be used to determine 'spatially explicit characteristic' stream temperatures and develop ecologically meaningful water quality temperature standards, it is useful to first determine how much variability in stream temperatures is natural, or considered acceptable, between ecoregions and between streams within ecoregions. Also, air temperature is a primary driver of natural variability in stream temperature (Crisp and Howson 1982; Stefan and Preud'homme 1993; Johnson 2004), and analysis of the air-water temperature relationship over time in Montana's reference streams will improve managers' understanding of natural stream temperature variability.

Thus, the **third objective** of this study is to develop a random coefficient regression model that allows Montana's stream managers to: (1) analyze if water temperatures and the air-water temperature relationship in reference streams varies significantly between ecoregions; (2) analyze if water temperatures and the air-water temperature relationship in reference streams varies significantly between streams within ecoregions; (3) develop a general equation representing the air-water temperature relationship for *all* reference streams (the population average) in four of Montana's ecoregions; (4) construct a similar equation for each individual reference stream included in this analysis that deviates significantly from the population average; and (5) reliably predict reference stream water temperatures given air temperature values. This type of model may provide a framework for the development of predictive models of stream water temperature change over time, and may also be useful in addressing global climate change concerns and other human impacts on future temperature regimes.

Unfortunately, Montana's reference stream temperatures are typically sampled throughout only one summer season; this may result in unrepresentative reference data. The **fourth objective** of this study is to determine whether or not the reference streams included in the model were sampled during a year when air temperature conditions were typical of long-term averages.

Finally, the natural flow regime paradigm calls for restoring the full range of the natural flow regime (Poff *et al*. 1997; Lytle and Poff 2004). However, particularly in the western United States, stream management often focuses on maintaining minimum low flows during the hottest time of the year, primarily for maintenance of cold-water fisheries and anthropogenic water demands (Poff *et al*. 2007; Larson 1981). This management approach ignores: (1) other extreme conditions with respect to temperature and discharge that are critical in shaping the nature of the stream system and its biological communities; (2) the consideration of spatial and temporal stream temperature variability in the creation of regionally-specific water quality standards; (3) the impacts of thermal degradation on the greater ecosystem form and processes; and (4) the impacts of thermal degradation on aquatic organisms besides fish. There are also limitations in the collection and summary of stream temperature data in Montana which complicate efforts to research and analyze stream temperature regimes. Hence, the **fifth objective** of this paper is to recommend and describe a more holistic approach to developing summertime temperature standards to restore and maintain stream temperature integrity, and to discuss meaningful ways to collect and summarize reference stream temperature data for easier comparison between streams and years and for greater ease in relating temperature to driving variables (such as air temperature).

SECTION 1 - REVIEW OF STREAM TEMPERATURE REGIME DYNAMICS, ECOLOGICAL SIGNIFICANCE, AND ANTHROPOGENIC DEGRADATION

Stream Temperature Basics: Thermal Energy Budgets and Heat Flux

Energy exchange is described by the First and Second Laws of Thermodynamics, which explain that energy can be transformed but neither created nor destroyed, and that the direction of energy exchange will occur from areas of higher to lower concentration (Halliday and Resnick 1988; Larson and Larson 1996). Understanding heat flux in streams is increasingly important as anthropogenic influences, including climate change, alters stream thermal regimes, often leading to shifts in aquatic species composition and changing rates of biogeochemical processes (Evans *et al*. 1998; Poole and Berman 2001). Stream heat budgets are complicated because temperature is controlled by multiple factors; as the relative magnitude of each factor varies among sites with differing biotic and geophysical properties, the impact of individual components can be difficult to distinguish (Johnson 2004; Sinokrot and Stefan 1993; Burkholder *et al*. 2008). A more comprehensive understanding of thermal dynamics will make stream managers less apt to study stream temperatures in the wrong way, at the wrong location, or at the wrong time, and will help them to describe the expected response of stream temperatures to such disturbances (Poole and Berman 2001; Johnson 2003).

The temperature of streams draining a landscape represents an integration of energy inputs from diverse sources, including solar radiation, and transfers of latent and sensible heat between the atmosphere and stream channel environment (Tague *et al*. 2007). However, water temperature is not simply a measure of the *amount* of heat energy in water but is instead proportional to heat energy divided by the volume of water (discharge) and can thus be conceptually understood as a measure of the *concentration* of heat energy in a stream, which varies daily, seasonally, and along latitudinal and altitudinal geographic gradients (Poole and Berman 2001; McClain *et al*. 1998; Kim 2007).

Five basic thermal processes are recognized by heat flux relationships in streams: (1) radiation; (2) evaporation; (3) convection; (4) conduction; and (5) conversion of energy from other forms to heat (Theurer *et al*. 1984; Brown *et al*. 2005; Hondzo and Stefan 1994; Silliman *et al*. 1995). Each is considered mutually exclusive but, when added together, they account for the thermal energy budget of a given column of water (Theurer *et al*. 1984). This budget determines the amount of energy available to modify stream water temperature (Webb 1996). Several of these gradients and the major heat flux relationships are depicted in Figure 1.

An understanding of the basic heat flux components of energy budgets is helpful when developing stream temperature studies and restoration plans. **Radiation** is an electromagnetic mechanism which allows energy to be transported at the speed of light through regions of space that are devoid of matter (Theurer *et al*. 1984). The heating of a natural body of water is governed by two primary sources of radiation: the sun (solar), and the ambient back radiation emitted from the water surface, atmosphere, riparian vegetation and topographic features; this distinction is necessary because surfaces (i.e., water, rock, vegetation, road) absorb, emit and reflect radiation differently and can thus have site-specific effects on stream heat budgets (Satterlund and Adams 1992; Larson and Larson 1996). **Evaporation**, though second in importance to radiation, is a significant form of heat exchange, and the rate of evaporation is a function of the circulation (**wind speed)** and vapor pressure (**relative humidity**) of the surrounding air (Theurer *et al*. 1984). Evaporation requires an exchange of thermal energy for the isothermal conversion of liquid water to vapor (heat of vaporization); its counterpart, **condensation,** requires an equivalent amount of energy released through condensation as vapor is converted to liquid (Theurer *et al*. 1984). **Convection** is often an important form of heat exchange at the air-water interface as the ability of air to circulate, either due to wind or temperature differences, leads to the constant exchange of air and affects the rate of evaporation (Theurer *et al*. 1984). **Conduction** occurs when a temperature gradient exists in a material medium in which there is molecular contact, and occurs both at the air-water surface and along the streambed interface (Theurer *et al*. 1984; Poole and Berman 2001). Streambed conduction, for example, is a function of the difference in temperature between the streambed at the water-streambed interface and the streambed at an equilibrium ground temperature at some depth below the streambed elevation (the equilibrium depth) and the thermal conductivity of the streambed material (Theurer *et al*. 1984). Finally, as water flows downstream, **fluid friction** generates heat from the portion of the potential energy that is not converted to other uses, although this is the least significant source of heat flux (Theurer *et al*. 1984).

Variables that affect lotic water temperatures can be categorized into drivers (i.e., solar radiation, air temperature), insulating and buffering processes (i.e., channel morphology, shading, groundwater inflow). Several of these variables are depicted in Figure 2 and are discussed in more detail below.

Drivers of Stream Temperature

The heat load of streams is derived from solar radiation, which transfers heat energy from the sun to the stream; alternately, discharge**,** which is derived entirely from precipitation and whose pathways for entering the stream are determined by the interaction of climatic and geographic drivers, determines the stream temperature response to a given heat load (Poole and Berman 2001). For a given rate of solar radiation, in-channel water temperature increase is directly proportional to stream surface area and inversely proportional to stream discharge (Poole and Berman 2001; Sullivan *et al*. 1990; Brown 1972; Beschta 1997). The larger the water volume, the greater the capacity for heat storage and the less responsive the stream will be to alterations in the energy budget (Webb 1996).

Any process that influences heat load or discharge will influence water temperature and can be considered a natural “driver” of stream temperature (Poole and Berman 2001). Drivers are *external* to the stream system, help form the physical setting, and control the rate of heat and water delivery, therefore raising or lowering stream temperatures; they include: wind speed, phreatic groundwater temperature and discharge, solar angle, cloud cover, relative humidity, precipitation, topographic shade, upland vegetation, and tributary temperature and discharge (Poole and Berman 2001; Sullivan and Adams 1991).

Consideration of variation in the relative importance of stream temperature drivers within and among streams and over time may help explain discrepancies in stream temperature literature (Johnson 2004). Fluctuations in these drivers and changing water source contributions, all of which vary markedly in space and time, have been used to explain distinct annual, seasonal, and diurnal fluctuations in stream temperature (Brown *et al*. 2005; Constantz 1998; Malard *et al*. 2001; Brown and Hannah 2007). Many believe the thermal regimes of small streams are affected *most* by solar radiation and ambient-air temperatures (Isaak and Hubert 2001).

Solar radiation

Solar radiation, when corrected for atmospheric conditions and cloud cover, represents the total amount of solar energy per unit area, often as projected onto a level surface over 24-hours (Theurer *et al*. 1984). At a specific site, as related to sunrise-to-sunset duration, solar radiation is a function of latitude, general topographic features, and time of year: **latitude** is a measure of the angle between horizontal surfaces along the same longitude at the equator and the site; average solar **altitude** at **sunrise/sunset** is the measure of obstruction by topographic features; and the **time of year** directly predicts the angle of the sun above or below the equator (declination) and the distance between the earth and the sun (orbital position) (Theurer *et al*. 1984; Poole and Berman 2001). Deviations from the zenith position reduce the intensity of radiation by spreading energy over a larger surface area, causing solar radiation to vary in intensity from zero at night to a maximum at noon when the sun is directly overhead (Trewartha 1968; Satterlund and Adams 1992; Larson and Larson 1996).

Increased solar input results in higher maximum summer temperatures and larger diurnal fluctuations, especially in small streams (Sullivan *et al*. 1990). It has been suggested that a representative value for daily incoming radiation in the temperate zone on a clear summer day is 332 W/m^2 of solar radiation and 330 W/m^2 of ambient radiation (Satterlund and Adams 1992; Larson and Larson 1996). As seen in Figure 2, solar radiation is attenuated on its path through the atmosphere by scattering and absorption when encountering gas molecules, water vapor, and dust particles; this is a function of cloud cover which significantly reduces direct solar radiation and somewhat reduces diffused solar radiation (Theurer *et al*. 1984). An average of 19% of the solar radiation striking the atmosphere actually reaches the surface of the earth as direct radiation; an additional 28% will arrive at the earth surface as diffuse and scattered radiation (Trewartha 1968; Larson and Larson 1996).

Water is transparent to (does not absorb), visible solar radiation (violet to red 400-700nm) and is least likely to absorb energy contained in blue (400 nm) and green (500 nm) color bands (Hollaender 1956). Approximately 95% of visible radiation will penetrate a column of clear water to a depth of 3ft and over 75% will penetrate to a depth of 30ft (Hollaender 1956, Sellers 1974; Larson and Larson 1996). In contrast, water is opaque to (absorbs) near-infrared (700-1,000 nm) and ambient (>1,000 nm) radiation, with nearly 90% of this radiation absorbed in the top 0.5 inch of a water column and 100% absorbed within the top 4.0 inches (Hollaender 1956, Sellers 1974). The absorption of this energy warms the top 4 inches of the water column without directly warming the water at greater depths and these interactions vary with the season of the year, time of day, water turbidity, and surface turbulence (Larson and Larson 1996).

Ambient Air Temperature

While incoming solar radiation is the main source of thermal energy for streams (Brown and Krygier 1970; Sinokrot and Stefan 1993; Webb and Zhang 1999), air temperature is also considered a major driver of stream temperature (Smith and Lavis 1975; Sullivan and Adams 1990; Johnson 2004). As described above, air temperature plays a part in most of the heat flux components (especially atmospheric radiation, evaporation, and convection) and is the most important, or sensitive, parameter affecting stream temperature and thus deserves special attention (Bartholow 1989). Air temperature, which is influenced by solar radiation, is a primary factor affecting the amount of long-wave atmospheric radiation entering the water, along with atmospheric vapor pressure, cloud cover, reflection at the water surface, and interception by vegetative canopy (Johnson 2003; Theurer *et al*. 1984). Because high correlations exist between air and stream temperature in diurnal and seasonal patterns of temperature fluctuations, air temperature is occasionally used as a ‘surrogate’ for predictions instead of complex heat flux equations (Webb 1987; Johnson 2003). For example, Crisp and Howson (1982) found that they could explain 86-96% of the variance in water temperature by regressions containing solely mean air temperatures, and several others have found similar correlations (Stefan and Preud’homme 1993; Smith and Lavis 1975).

While analyses of the air-water temperature relationship may prove useful for some management applications, it must be noted that solar radiation remains the major factor influencing both air and stream temperature and, while correlations can be helpful in predicting patterns for a future time or a nearby location, they do not imply causation (Johnson 2003). Ideally, comprehensive heat budget analyses should be used to model stream temperature regimes since convection at the air-water interface is, in fact, only one component of otherwise complex heat flux relationships (Sinokrot and Stefan 1993; Webb and

Nobilis 1997). However, as resources for stream management and restoration are often limited, air temperature can serve as a useful parameter for modeling stream temperature variability in space and time.

Another complicating factor in correlating air and water temperature is that complex environmental gradients occur over very short distances away from the stream, and air temperature and other climate-related factors (wind speed, relative humidity, subsurface saturation and soil) are very responsive to variations in landscape features and riparian vegetation distribution (Chen *et al*. 1993). Measurement of these parameters close to the stream may reveal very different conditions than if measured several meters away, and variability can increase with greater distance from the stream. Due to limited availability of site-specific air temperature data, data from the nearest climatic station, which is often kilometers away from the study stream, is commonly used to represent environmental conditions for modeling; this data can provide useful information about the air-water temperature relationship but may not be accurate input for sensitive models (Johnson 2003).

Insulating and Buffering Processes of Stream Temperature

Unlike drivers, the stream's physical structure exerts *internal* control over water temperature and determines resistance to warming or cooling as well as the means and rates of heat and water entry into, flow through, storage within, and release from the stream system and its components (Poole and Berman 2001). Insulating characteristics, such as channel geometry and shading, influence the rate of heat flux into and out of a stream (Poole and Berman 2001). Buffering processes either heat or cool a stream channel but differ from drivers in that they store heat already in the system rather than adding or removing any additional thermal energy, and they also integrate variation in discharge and temperature over time (Poole and Berman 2001). The two-way exchange between the alluvial aquifer and stream channel is perhaps the most important stream temperature buffer (Poole and Berman 2001).

Channel Geometry

Channel width determines the surface area available for heat flux activities, all of which take place at either the air-water interface or water-ground interface (Bartholow 1989). Since wider streams are shaded less by riparian vegetation (Naiman and Sedell 1980) it is thought that stream width would exhibit a direct relationship with temperature. However, the influence of channel width on temperature is often negated, at least in part, by the likeliness that increasing stream width would also be accompanied by an increase in the total thermal capacity of a stream, thereby decreasing the responsiveness to solar inputs (Isaak and Hubert 2001). As described above, **channel depth** affects the absorption capacity of a channel, with narrower, deeper channels absorbing less heat than shallow, wide channels (Poole and Berman 2001).

Watershed aspect is thought to influence stream temperatures on the premise that orientation relative to the path of the sun will alter the amount and intensity of sunlight that a stream receives (Isaak and Hubert 2001; Johnson 1971; Smith and Lavis 1975). Accordingly, streams in the northern hemisphere that have northerly aspects are generally believed to be coldest and those with southerly aspects are warmest; however, it can be argued that if streams with northerly and southerly aspects are oriented similarly relative to the path of the sun but simply flow in opposite directions, watershed aspect would have the same effect on the temperatures of streams with northerly and southerly aspects and a different effect on streams with easterly and westerly aspects (Isaak and Hubert 2001).

Channel elevation influences atmospheric pressure with respect to heat convection, the depth of the atmospheric pathway of solar radiation, and helps to determine channel slope which results in heat from friction (Bartholow 1989). Elevation may have the largest effect on maximum stream temperature in small streams, and mean basin elevation tends to correlate more strongly with stream temperatures than point elevations probably by better characterizing the spatially distributed effect of air temperature on stream temperature. As such, mean basin elevation could also be a ‘surrogate’ when stream temperature data are unavailable (Isaak and Hubert 2001; Sloat *et al*. 1999).

Stream Shading

Shading affects stream temperature by screening the water surface from direct solar radiation, reducing the amount of the back radiation from water at night, and by producing its own long wave thermal radiation which tends to moderate minimum stream temperatures at night (Bartholow 1989). Stream shade comes largely in two forms: riparian vegetative shade and topographic shade from valley walls, cliffs and streambanks, although in-stream shade from woody debris, vegetation and other structures should also be considered (Bartholow 1989; Davies-Colley *et al*. 1998). For an unshaded stream during clear-sky conditions in mid-summer, over 90% of the incoming energy would become available to that stream (Beschta 1997). Low flow, high width streams are especially sensitive to stream shading in midsummer (Bartholow 1989).

Topographic shade is a function of the: (1) time of year; (2) stream reach latitude; (3) general stream reach azimuth; and (4) topographic altitude angle. R**iparian vegetation shade** is a function of the topographic shade plus several riparian vegetation parameters: (1) height of vegetation; (2) crown measurement; (3) vegetation offset; and (4) vegetation density (Theurer *et al*. 1984). As such, the effect of shade on water temperature varies due to the continually changing spatial relationship between the sun, the canopy of riparian vegetation, and the amount of solar energy reaching a stream from day-to-day during the summer (Beschta 1997; Larson and Larson 1996). The greatest reduction in direct radiation by shade occurs at the time of the greatest solar angle (Larson and Larson 1996). In general, riparian vegetation helps regulate the microclimate of stream-riparian ecosystems, and streams with adequate shade are cooler in summer and warmer in winter than those without, although the effectiveness of these zones decreases with increasing stream size (Welch *et al*. 1998; Brown and Brazier 1972; Larson and Larson 1996; Sand-Jensen and Pedersen 2005). Additional discussion of the importance of shading on stream temperatures can be found under "Reduction of Riparian Shading" in the "Anthropogenic Causes of Thermal Degradation in Streams" section of this report.

Groundwater-Surface Water Interactions (Hyporheic Exchange)

Groundwater can be defined as the water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer (Fetter 2001). The interface where stream- and groundwater mixing occurs is typically referred to as the hyporheic zone, which has been defined as "the subsurface region of streams and rivers that exchanges water with the surface" (Valett *et al*. 1993). Hyporheic exchange has been previously thought to have little impact on stream temperature (Brown 1969), but a number of recent studies show that hyporheic exchange plays an important role in the thermal dynamics of some streams and preserving these interactions is critical to maintaining their ecological health (Burkholder *et al*. 2008; Story *et al*. 2003; Johnson 2004; Loheide and Gorelick 2006). For example, the presence of cooler patches of water within rivers can act as thermal refugia for fish and other aquatic organisms, reaffirming the importance of maintaining natural groundwater interactions when restoring the thermal regime of rivers (Burkholder *et al*. 2008).

Groundwater tends to have more stable temperatures than surface water (Ringler and Hall 1975; White *et al*. 1987; Evans and Petts 1997; Johnson 2004), and thus generally forms the baseline from which stream temperature deviates, with channel water temperature often trending away from groundwater and toward atmospheric temperatures in a downstream direction (Sand-Jensen and Pedersen 2005; Edwards 1998; Sullivan *et al*. 1990). As such, during warm periods, groundwater-surface water interactions have two primary effects on stream temperature: (1) cool groundwater discharging as baseflow lowers stream temperature, and (2) hyporheic exchange buffers diurnal stream temperature variations (Loheide and Gorelick 2006).

The mechanism for hyporheic heat exchange is streambed conduction, which is a function of the thermal gradient at the streambed interface; rates of heat exchange depend on the thermal conductivity of the bed material as well as the thermal gradients within the substrate (Johnson 2004). The **thermal gradient** between ground and surface water temperature determines the rate of heat lost or gain by the water from the streambed; the larger the difference, the greater the potential heat transfer (Bartholow

1989). Conduction occurs while the water is in contact with the subsurface substrates, transferring heat energy from warmer to cooler surfaces (i.e., water warmed during the daytime and flowing over cooler rocks in the subsurface would transfer heat to the substrates, whereas during the night, cooler stream water entering the subsurface and passing over warmer rocks would absorb heat) (Johnson 2004). Hyporheic exchange may also buffer stream temperature over time as, for example, stream temperature in autumn is buffered probably as a result of progressive heating of the ground during the summer in both summer-warm and summer-cool streams (Edington 1965).

Because hyporheic exchange occurs more readily through more permeable alluvial substrates than bedrock, silt or sand, with alluvial sediments often acting as a preferential groundwater pathway (Stonestrom and Constantz, eds. 2003; Burkholder *et al*. 2008; Fetter 2001), alluvial streams are more likely to be buffered by hyporheic exchange (Johnson 2004). Also, hyporheic flowpaths lengthen the residence time of water in a given reach of stream, thereby likely moderating diurnal fluctuations in downstream temperatures (Poole and Berman 2001; Haggerty *et al*. 2002). Stream size also influences the effect of hyporheic exchange on stream temperatures, with smaller streams experiencing a greater groundwater buffering effect than larger rivers due to diminishing opportunities for hyporheic exchange as channel size increases (Johnson 2004; D'Angelo *et al*. 1993; Boulton *et al*. 1998; Burkholder *et al*. 2008).

Because streambed temperature is suggested to reflect the nature and extent of groundwater–surface water interactions (Malcolm *et al*. 2004; Brown *et al*. 2005; Brown and Hannah 2007), temperature is increasingly being used as a tool in quantitative studies of these processes (Oxtobee and Novakowski 2002; Johnson *et al*. 2005; Conant 2004; Silliman *et al*. 1995; Kulongoski and Izbicki 2008). However, similarly to surface water temperatures, hyporheic exchange is sensitive to biogeographical conditions of the upland (including geology, climate, vegetation and land use) (Hayashi and Rosenberry 2002), and varies in the vertical, lateral and longitudinal directions (Woessner 2000), and so any study designed to quantify the influence of hyporheic exchange on water temperatures must take spatial variability into account at multiple scales.

Ecological Significance of Stream Temperature

Human use of streams may be affected by water temperature, with the efficiency of water purification and treatment methods, the palatability of domestic supplies, the effectiveness of irrigation, the economics of commercial aquaculture and of industrial processes requiring cooling water, and the suitability of water courses for recreation, including swimming and angling, all related to river temperatures (Webb 1996). However, stream temperature is an ecologically significant parameter that affects the *entire* stream ecosystem and, as such, maintaining or restoring the natural thermal regime beyond human utility should be a primary goal in stream management (Webb 1996).

A stream's summertime temperature regime is often a *critical* characteristic of habitat quality (Beschta 1997). By directly influencing aquatic species' geographical distribution, growth and metabolic rates, physiology, reproduction and life histories, movements and migrations, behavior, and tolerance to parasites, diseases and pollution, water temperature is arguably the most important physical property fundamentally affecting the stream ecology and is thus considered an important water quality parameter (Johnson 2004; Webb 1996; Isaak and Hubert 2001; Welch *et al.* 1998; US EPA 1986). Undoubtedly, the ratio of heterotrophy to autotrophy in stream ecosystems is controlled, in part, by temperature (Cummins 1974). Stream water temperature also governs in-stream processes, including metabolism, organic matter decomposition, and solubility of gases (Johnson 2004), and helps to determine rates of other important community processes such as nutrient cycling and productivity (Poole and Berman 2001).

Various aspects of the ecological significance of stream temperature are described in greater detail below with the hope that those charged with managing and restoring thermal regimes of streams will approach management of stream temperature regimes with a more holistic system perspective, rather than an anthropo- or fish-centric perspective.

Physical and Chemical Characteristics of Stream Water

Temperature exerts a strong influence on many physical and chemical characteristics of water, including gas solubility, surface tension, density and viscosity, sediment concentrations and transport, denitrification and other chemical reaction rates, and the persistence and growth of pathogens (Stevens *et al*. 1975; Webb 1996; Pfenning and McMahon 1996). Increases in the concentration of dissolved organic carbon (DOC), an important source of carbon for stream bacteria, are associated with changes in water temperature (Bernhardt and Likens 2002). Additionally, the toxicity of many substances is intensified as the temperature rises (Theurer *et al*. 1984). Temperature also affects the solubility of gases in water, particularly dissolved oxygen, which is critical to the survival of aerobic biota, with higher temperatures diminishing the solubility of dissolved oxygen so warm water holds less oxygen than cold (Johnson 2004; Welch *et al.* 1998). Since the rate of oxygen consumption and organic decomposition tends to increase with higher temperatures, elevated temperatures stress stream ecosystems by creating an increased oxygen demand and decreased oxygen supply (Sand-Jensen and Pedersen 2005; Theurer *et al*. 1984). In addition, sorption of chemicals to particulate matter and volatilization rates are influenced by changes in water temperature, with sorption often decreasing with increasing temperature and volatilization increasing with increasing temperature (US EPA 2007). This may affect the response of the system to chemical pollutants.

Metabolism and Nutrient Cycling

Temperature increases accelerate the rates of production, metabolism and respiration of algae and other microorganisms, plants, invertebrates, fishes, and other cold-blooded stream animals (Welch *et al*. 1998). Respiration approximately doubles with a 10^{o}C temperature increase (Theurer *et al*. 1984), thereby increasing overall nutrient uptake, nutrient assimilation, and elimination of waste products (McClain *et al*. 1998 Sobczak and Findlay 2002; Sinsabaugh 1997). Microbial activity and other processes that govern nutrient cycling in stream systems also increase with higher temperatures, leading to faster rates of organic matter decomposition (i.e., leaf breakdown) and redox reactions, further increasing both nutrient mineralization and uptake (McClain *et al*. 1998; Theurer 1984; Suberkropp 1998). Research has shown, for example, that temperature influences uptake lengths for important elements like phosphorus (P) and nitrogen (N) (Butturini and Sabater 1998; Valett *et al*. 2002).

Fish (Especially Salmonid Species)

Temperature is critical to the survival of cold-water organisms, particularly salmonid fishes (Welch *et al.*1998; Crisp 1996; Malcolm *et al*. 2008). Due to their ectothermic nature, stream temperature inevitably shapes the physiology (Lund 2003; Nicola and Almodovar 2004), life history (Staurnes *et al*. 1994, Dunham *et al*. 1999), and distribution (Rahel and Hubert 1991; Zweifel *et al*. 1999; Martin 2004) of stream fishes. Over the non-lethal range, temperature plays a key role in the rates of species additions (and thus community diversity) (Reeves *et al*. 1998), location and time of spawning (Webb and McLay 1996; Reeves *et al*. 1998), rates of embryo development and timing of emergence (Crisp 1988; Elliot and Hurley 1998), food intake (Ojanguren *et al*. 2001; Flodmark *et al*. 2004), growth (Meeuwig *et al*., 2004; Bacon *et al*., 2005), species distribution (Lessard and Hayes 2003; Richter and Kolmes 2005; Wherly *et al*. 2007), density (Lessard and Hayes 2003; Isaak and Hubert 2004), biomass (Isaak and Hubert 2004), smolting (Crisp 1996), migration (Hall 1972; Richter and Kolmes 2005) and resistance to disease (Malcolm *et al*. 2008).

The most serious potential effect of solar heating is that it can produce lethal stream temperatures for these cold-water fish, leading to increased concern over summer high temperature extremes that may cause fish mortality (Quigley 1981; Malcolm *et al*. 2008). For example, at least two major fish kills occurred due to excessive heating of lakes and rivers in Montana in July of 2007, in the Firehole River (Associated Press 2007a) and in Roger's Lake (Associated Press 2007b). Thermal metabolic stress, competition for cold-water refugia, and reduced DO levels can also influence juvenile mortality (Bisson *et al*. 1988). Higher-than-normal winter water temperatures can also cause more rapid egg development and emergence, thus subjecting emerging fry to potentially lethal late-winter and early-spring high flows (Holtby 1988). Thermal tolerance varies depending on species (Elliot and Elliot 1995; Richter and Kolmes 2005), duration of exposure (Elliot 1991; Elliot and Elliot 1995) and local adaptation (Richter and Kolmes 2005; Malcolm *et al*. 2008).

Salmonids respond to an uncomfortable water temperature by moving from one spot to another because of a discrepancy between the temperature of the surrounding water and a "set point" in their brains that registers thermal comfort, a response known as behavioral thermoregulation (Sauter *et al.* 2001). Besides behavioral thermal regulation, evolutionarily adaptive non-thermal ecological factors can be immediately cued by thermal stimuli, including habitat selection, intraspecies size segregation, interspecies niche differentiation, isolating mechanisms, predator avoidance, prey location, escape reactions, and migrations (Sauter *et al.* 2001). Interestingly, the choice of spawning sites by salmonids is often tied to the presence of groundwater discharge since it provides a thermal buffer, in both winter and summer, that incubates eggs within proximity of the water table, even during periods of low flow, and prevents redds from freezing (Woessner and Brick 1992; Power *et al.*1999; Malcolm *et al*. 2002).

Natural resource managers often refer to thermal guild classifications which are developed to consolidate fish species of similar thermal suitabilities into practical categories (e.g. cold-water, cool-water, and warm-water) (Eaton *et al*. 1995, Wehrly *et al*. 2003). While these guilds can be useful, they are often developed based on examination of the consequences of thermal variability at both relatively small spatial scales within individual stream reaches, as well as regional variability among stream reaches (Martin 2004). However, an improved understanding and quantification of thermal dynamics across entire watersheds may greatly enhance our understanding of large-scale fish dynamics (Webb 1996, Young 1999, Gardner *et al*. 2003).

Macroinvertebrates

Temperature serves partially to synchronize invertebrate life cycles, with egg incubation, overwintering and emergence tied directly to temperature cues (Brittain 1983; Butler 1984; Hershey and Lamberti 1998). Temperature also fundamentally constrains macroinvertebrate physiology, with some (cold *stenotherms)* preferring a narrow range of temperature, whereas others (*eurytherms*) are able to tolerate a broader range (Hershey and Lamberti 1998). For several species of stoneflies (Plecoptera), Brittain (1983) found that nymphal growth rate increased with temperature and growth rates changed markedly in connection with the rise and fall of temperatures associated with ice-break and ice formation. This underscores the need for year-round stream temperature measurements.

It has also been suggested that temperature may be a limiting factor in species distribution and diversity, although contradictions in research findings exist (Edington 1965). Since water temperature is a primary physical habitat factor influencing the life history characteristics, distribution and diversity of macroinvertebrate taxa in lotic ecosystems (Vannote and Sweeney 1980; Ward 1985; Sweeney and Vannotte 1986), and particularly in alpine streams (Milner and Petts 1994), an understanding of the processes driving thermal variability is fundamental for assessment and prediction of stream ecological response (Brown *et al*. 2005). Variability in the water column and streambed temperatures provides a range of thermal habitat available for colonization of benthic communities over relatively small areas (Brown *et al*. 2005).

Primary Producers

Many riparian trees, such as poplar and willow, are phreatophytes which acquire water from the saturated zone below the water table (Fetter 2001), and the effects of shading by these ground water-dependent plants can significantly reduce the diurnal fluctuations in stream water temperatures (Beschta 1997). As human activities alter groundwater availability and riparian canopy cover, stream ecosystems are at risk of losing the temperature regulating qualities of this vegetation. Temperature increases can also stimulate algae growth, leading sometimes to nuisance levels (Welch *et al.* 1998, Watson and Gestring 1996). Periphyton, benthic algae that typically attach themselves to substrate and plants, are often distinctly segregated, in part, by temperature (Stanford and Ward 1993). Optimal temperatures for photosynthesis were determined for natural populations of algae inhabiting cold mountain streams in the Beartooth Mountains in Montana and Wyoming, where temperatures from 20 to 30^{o}C were optimal for all the samples, regardless of site temperature and the organisms present in the sample (Mosser and Brock 1976).

Fungus, Bacteria, and Disease Organisms

Many disease organisms proliferate at higher temperatures, and fish are more susceptible to disease when stressed by higher temperatures (Theurer *et al*. 1984). For example, the emergence of Whirling disease *(Myxobolus cerebralis)*, first discovered in Montana in 1994, and the bottom-dwelling aquatic worm that is the whirling disease protozoa’s secondary host (*Tubifex tubifex)*, is delayed by cold water temperatures, reducing its ability to infect trout (Palmer 2002).

Temperature has been correlated with bacterial growth and production doubling rates of unicellular and filamentous populations in sediments of forested streams (Bott and Kaplan 1985; Suberkropp 1998; Bott 1975). Temperature can also affect microbial mineralization directly during leaf breakdown, with greater breakdown rates often found in environments with higher temperatures (Cummins 1974, Suberkropp 1998). Aquatic hyphomycetes, which are decomposers commonly found growing on leaves and wood in flowing waters, have temperature- specific growth adaptations (Suberkropp 1998; Suberkropp 1984). For example, those commonly found on leaves in temperate streams during autumn and winter grow optimally at 15 to 20^{o}C but can grow at 1^{o}C (Suberkropp 1984); in contrast, species common in summer (or in tropical streams) grow optimally at temperatures as high as 25 to 30^{o}C, but typically do not grow at temperatures below 5^{o}C (Suberkropp 1998).

Anthropogenic Causes of Thermal Degradation in Streams

Stream temperature regimes have been substantially altered by various human activities on global to reach scales and over time despite their ecological significance (Poole and Berman 2001). Stream temperatures in many regions have increased as a result of land use practices (Beschta and Taylor 1988; Sugimoto *et al*. 1997), resulting especially in undesirable impacts on cold-water species (i.e., salmonids) (Beschta *et al*. 1987; Bisson *et al*. 1992; Li *et al*. 1994; Johnson 2004; Khangaonkar and Yang 2008). Stream temperature degradation can often be attributed to multiple anthropogenic causes (Webb 1996; Wang and Kahnel 2003). As such, an understanding of the mechanisms of human-induced stream temperature change, and the expected ecological response in individual stream systems, is critical to accurately identify sources of thermal degradation, prioritize restoration efforts, and to prevent further decline in ecosystem integrity.

Direct sources of thermal degradation, such as the discharge of heated effluents (Langford 1990), are referred to as "point sources". Indirect, "nonpoint" sources of thermal pollution human activities which tend to result in elevated stream temperatures due to excessive atmospheric heat loading (Khangaonkar and Yang 2008), include riparian vegetation removal and streamside logging (Beschta 1997; LeBlanc and Brown 2000; Crisp *et al*. 2004; Webb and Crisp 2006), impoundment with dams (Petts 1984; Khangaonkar and Yang 2008), human-induced wildfire (Brown and Krieger 1970; Dwire and Kauffman 2003), urbanization (Krause *et al*. 2004; Kim 2007; Herb *et al*. 2008), and other forms of channel modification. While the following discussion describes several main anthropogenic factors driving thermal degradation, it is recommended that, for individual streams, the causes of thermal degradation be evaluated on a site-specific basis to ensure appropriate and adequate restoration goals are developed.

Point Sources: Heated Effluent Discharge

The discharge of heated effluents, especially in the form of the cooling water used in the generation of electrical power, results in a direct alteration of stream and river thermal regime (Parker 1974; Webb 1996). Leaking sewer pipes, industrial and wastewater treatment effluents, and irrigation return flows often add heat to streams (Walsh 2000; US EPA 2003), particularly in urban areas (Kim 2007). Heated discharge from industrial facilities often have particularly negative effects because they tend to be long term, excessive, and are often associated with toxic chemicals (Brown and Brazier 1972; Welch *et al.* 1998). Fortunately, with the passage of the Clean Water Act (CWA) in 1972, and the implementation of source control through the National Pollutant Discharge Elimination System (NPDES), point sources of thermal pollution have largely been rather strictly and successfully regulated

(Khangaonkar and Yang 2008). Whereas point sources are often overtly visible and more readily identified, the following non-point sources may prove to be more elusive causes of stream degradation and targets for restoration.

Reduction of Riparian Shading

As mentioned previously, preventing stream heating with riparian shade is an important function of streamside vegetation (Brown and Krygier 1970; Feller 1981; Isaak and Hubert 2001; Fleming et al. 2001; LeBlanc and Brown 2000; Webb and Crisp 2006). One of the most common causes of elevated stream temperatures is excess solar heat loading due to the absence of riparian shading (LeBlanc and Brown 2000; Moore *et al*. 2005; Caissie 2006). A relatively continuous border of riparian trees located along the streambank and beyond can significantly ameliorate this problem (Beschta 1997), and riparian shading can help to moderate daily minima and daily maxima, especially during the summer period (Webb and Crisp 2006).

Unfortunately, the shading functions of riparian vegetation along many streams in the western US has been diminished by a wide variety of human activities with serious effects on water and habitat quality (Quigley 1981; Beschta 1997; Welch *et al.* 1998). While the loss of vegetation may cause summer base flows to increase slightly (Ziemer 1964; Jones and Post 2004), thereby increasing the stream's thermal capacity, thermal degradation from riparian canopy removal persists. This results from a variety of historical land use practices, including harvesting of riparian trees, shrub removal along streams, ditching and straightening of channels, and season-long grazing in riparian areas (Mclntosh *et al*. 1994, Wissmar *et al*. 1994, National Research Council 1996; Beschta 1997; Isaak and Hubert 2001). A reduction in stream shade is the dominant mechanism by which forestry activities can increase stream temperature (Teti 2003), and has been shown to have short-term negative effects on aquatic biota (Jobling 1981; Brownlee *et al*. 1988; Hicks *et al*. 1991; Mellina *et al*. 2005; Moore *et al*. 2005). Also, given the ubiquity of cattle across western North America, grazing may be a particulary problematic cause of thermal degradation in streams across very broad geographic areas (Isaak and Hubert 2001).

It is important to note that the efficacy of using riparian vegetation to remediate thermal degradation may have variable or limited application depending on responsiveness of the stream site in question to shading (Larson and Larson 1996; Pollack *et al*. 2009). Small streams, with low flow rates and high width-to-depth ratios, are at greatest risk from temperature problems but are also the easiest to shade (Welch *et al.* 1998). The type of vegetation that is effective in providing shade varies among riparian zones and size of stream, ranging from mature trees to sedges, rushes, and other herbaceous plants along streambanks (Beschta 1997). Because trees provide more shade than other forms of riparian vegetation such as shrubs or grasses, stream temperatures can be predicted to be colder in those watersheds where trees make up a large proportion of the riparian vegetation (Isaak and Hubert 2001).

Given the increasing interest in managing semi-natural riparian woodland for salmonids, there is an urgent need to understand the influence of riparian shading on the spatiotemporal variability of stream temperatures and the impact that this has on salmonids (Malcolm *et al*. 2008). Specifically there is a need to understand over what distances stream temperatures change in response to riparian tree cover, the magnitude of that response, the aspects of the thermal regime that are most heavily influenced (e.g. mean, maximum, minimum temperatures), and the time periods over which these changes occur (Malcolm *et al*. 2008).

Dams/Hydroelectric Power Production

Dam impoundment and regulation might have an immediate effect on downstream water temperature by eliminating freezing conditions, depressing summer maxima, delaying the annual cycle of variation and reducing diel fluctuations in temperature (Webb 1996; Imbert and Stanford 1996; Dare and Hubert 2003; US EPA 2003), although the magnitude or severity of these impacts may vary considerably on an annual basis and over the long term (Webb 1996; Murchie *et al*. 2008). Modified discharge regimes in regulated streams also influence their thermal capacity (Webb 1996). The thermal characteristics of water issuing from a reservoir typically differ from ambient conditions in an unregulated water course because of the greater thermal inertia of the impounded water mass, thermal stratification of the reservoir, or alteration of groundwater circulation downstream of the dam (Webb 1996). Some dams release cold, hypolimnetic water that produce colder ecological conditions downstream (Lessard and Hayes 2003). The effect of warm water discharge from small, surface release dams on downstream thermal regimes is also a major habitat concern for many cold-water systems across the country (Lessard and Hayes 2003).

As such, dams can be detrimental to the natural temperature regimes of streams and can alter the community structure, reproductive success and survival of native aquatic species, particularly macroinvertebrate and salmonid fish species (Reeves *et al*. 1998; Imbert and Stanford 1996; Dare and Hubert 2003). Not surprisingly, there is considerable pressure on regulators and dam operators to implement operational changes and in-stream flow control to modify water temperatures (Khangaonkar and Yang 2008).

Diversion of Flow (Dewatering)

Off-stream diversion of stream water for industrial, agricultural or domestic purposes, or out of basin diversion of flow in transfer schemes, may cause changes in water temperature by altering the discharge, and thus thermal capacity, of the stream without necessarily modifying the actual components of the heat budget (Webb 1996). Diversion of flow can impact water temperatures over long distances of stream channels and in-stream withdrawals may exacerbate maximum temperatures, particularly during summertime periods (Beschta 1997).

Urbanization (Imperviousness) and Channel Modification

Urbanization often elevates stream temperature through changes in shading, channel geometry, groundwater input, and inflows of stormwater and point source loading (Pluhowski 1970; Welch *et al.* 1998; Krause *et al*. 2004; Kim 2007; Herb *et al*. 2008). Stream temperatures often experience the "urban heat island effect" (Booth and Jackson 1997; Kim 2007), whereby urban areas tend to be warmer as a result of paved and other heat absorbing surfaces. Shallow, wide, low-flow stream channels typical of urban areas are especially susceptible to thermal degradation due to larger inputs of solar energy and the smaller heat capacity due to their physical structures (Booth and Jackson 1997). Increased and warmer runoff from impervious surfaces into streams can also lead to degradation of habitat for cold-water species assemblages (Herb *et al*. 2008; Wang and Kahnel 2003). Thermal pollution from stormwater runoff is more severe when (1) atmospheric air and dew point temperatures are higher than stream temperature, e.g. for streams that are fed by groundwater that is colder than the ambient air, (2) rainfall events are short, intense and preceded by full or partial sun, and (3) watersheds have a high percentage of impervious, particularly paved, surfaces (Herb *et al*. 2008). Urban development schemes that minimize the total amount of impervious areas and that avoid development in areas where major ground water recharge occurs should reduce the impact of urbanization on cold-water stream integrity (Wang and Kahnel 2003).

Furthermore, human-imposed channel modifications that simplify localized habitat structure (dredging, diking, bank hardening, etc.) reduce temperature variability, leading to loss of thermal refugia and general decline in habitat quality for stream organisms (Poole and Berman 2001). In addition, widening channels causes greater exposure to solar radiation (Swanson 1981). Overall, it appears that channel widening and other channel disturbance will result in a net increase in stream temperatures (Dunham *et al*. 2007).

Wildfire

Wildfire is a major source of *natural* disturbance in stream ecosystems (Gresswell 1999), although human activities have altered the natural fire regime and have increased the frequency and severity of wildfires (IPCC 2007c). Wildfire and associated channel disturbance may influence a number of processes that contribute to the heat budget of streams, and a large number of thermal responses are possible (Beschta *et al*. 1987; Johnson 2003; Moore *et al*. 2005; Dunham *et al*. 2007). However, wildfire tends to result in elevated summer maximum water temperatures (Brown and Krieger 1970; Dwire and Kauffman 2003), a phenomenon that can persist for at least a decade following wildfire, particularly in streams with severe channel reorganization (Dunham *et al*. 2007). During wildfire, intense heating can lead to short-term (<1 day) increases in stream temperatures of several degrees (Hitt 2003). However, over longer timeframes and broader spatial scales, changes to terrestrial vegetation and stream channel morphology related to wildfire may lead to substantially altered water temperatures across stream networks. In turn, such changes in stream temperature can lead to loss and fragmentation of suitable habitats and increased risk of local extinction for cold-water aquatic species (Bury 2004; Burton 2005; Sestrich 2005; Dunham *et al*. 2007).

Climate Change and Stream Temperature

Earth's natural greenhouse effect makes life as we know it possible; however, scientific consensus suggests that human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming (IPCC 2007a). This occurs when these and other human activities increase the planet's atmospheric concentrations of greenhouse gases (GHGs), aerosols, and cloudiness, affecting climate by altering components of the planet's basic energy balance, namely incoming solar radiation and outgoing thermal radiation (IPCC 2007a). Since the start of the industrial era (about 1750), anthropogenic emissions of four principal GHGs (carbon dioxide, methane, nitrous oxide and halocarbon gases), as well as water vapor and ozone, have *significantly* increased concentrations beyond their natural range (IPCC 2007a). Given the driving relationship between air and water temperatures, climate change is poised to have serious and irreversible impacts on natural stream temperature regimes.

Global climate change has now widely been recognized as the most important issue of our time. Altogether, there is probably no other effect of climatic warming that will approach crisis proportions as quickly as the diminution of freshwater resources (Schindler 1997) and, globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits (Bates *et al*. 2008). North America's already overallocated water resources will be strained further, increasing competition among agricultural, municipal, industrial, and ecological uses (Bates *et al*. 2008; Grimm *et al*. 1997; Schindler 1997).

In light of the severity of this issue, it is becoming increasingly important for natural resource managers to understand the causal linkages between anthropogenically-driven climate change and thermal degradation of surface waters, as well as the ecosystems' projected sensitivity and response in the future. While climate change will certainly have an impact, it is useful to bear in mind that the effects of land use practices on regional climate may overshadow larger-scale temperature changes commonly associated with observed increases in greenhouse gases (Stohlgren *et al*. 1998). An understanding of the processes driving stream temperature dynamics is fundamental for assessment and prediction of thermal response to climatic variability and change (Caissie 2006; Brown and Hannah 2007). Human-induced climate change itself may ultimately be considered a major driver of stream temperature degradation as it affects the flow regimes and many of the basic heat flux components of the thermal budgets of streams. Models that help to explain the influence of climatic drivers on stream temperature regimes and other ecological parameters may help managers to predict the severity of impacts of climate change on stream ecosystems. Several examples of ecologically-detrimental effects of climate change on thermal regimes are already evident across Montana, and management approaches will have to take the effects of climate change on stream temperatures into consideration as these trends continue.

Rising Air temperatures

On the global scale, warming of the climate system is unequivocal. Eleven of twelve years between 1995 and 2006 rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850) (IPCC 2007b), and the second half of the 20th century was likely the warmest 50-year period in the Northern Hemisphere in the last 1300 years (IPCC 2007a). For the next two decades, global warming of about 0.2°C per decade is projected and, even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected (IPCC 2007b). In general, analyses from central Rocky Mountains suggest that the climate has been steadily warming since ca. 1850 (Luckman 1990; Hauer *et al*. 1997). As seen in Figure 3, from 1895 to 2008, summer (June-August) air temperatures in Montana have been steadily increasing at a rate of approximately 0.11^{o}F per decade (NOAA 2009a). More recently, in the past 50 years (1958-2008), summertime air temperatures have been rising at a rate of 0.24^{o}F per decade (see Figure 4) (NOAA 2009a). Streams that are most sensitive to changes in air temperatures are at the greatest risk from climate change (Hauer *et al*. 1997). Stefan and Preud'homme (1993) found that stream temperatures increased by an average of approximately 0.98^{o}C for every degree increase in air temperature. An exception appears to be where groundwater is the major water source for small streams (Schindler 1997).

Alterations to the Natural Flow Regime

Snowmelt/runoff

Observed warming over several decades has been linked to changes in the large-scale hydrological cycle (Bates *et al.* 2008). The hydrology of the Rocky Mountain region is dominated by snow accumulation and melt (Poff and Ward 1989), where summer stream hydrographs are typically driven by melting snow that has accumulated throughout the winter and, by late summer and autumn, streamflow is predominately supported by groundwater discharge (Hauer *et al*. 1997). Therefore, seasonal distribution of streamflow is, in general, more sensitive to air temperature changes than elsewhere in the US (Adam *et al*. 2009). Projected warming in the western US produces strong decreases in winter snow accumulation and spring snowmelt over much of the affected area (Hamlet *et al*. 2007; Mote *et al*. 2005; Stewart *et al*. 2005; Adam *et al*. 2009). For example, Mote *et al*. (2005) evaluated trends in the entire reconstructed snow water equivalent (SWE) records for 1915–2003 for the western US, and found that, over the nearly 90-year period, there was a general downward trend in snow water equivalent (SWE) over most of the region (Adam *et al*. 2009). Increasing temperatures by even a few ^{o}C may dramatically affect the timing of runoff in mountainous watersheds in the western US (Gleick 1987; Lettenmaier and Gan 1990), and the timing of the center of mass of annual runoff has shifted consistently over the last half century towards earlier dates in areas affected by snowmelt (Stewart *et al*. 2005; Adam *et al*. 2009), increasing runoff in the cool season, decreasing runoff in the warm season, and moving peak flows associated with snowmelt earlier in the water year (Adam *et al*. 2009). These alterations to the natural flow regime of streams in the western US, specifically in the Rocky Mountain region, that result from climate change are likely to substantially influence stream temperatures and thermal capacity in Montana.

Flow years like those seen in 2007 on Montana's Blackfoot River are becoming more common: an early pulse of runoff after a warm spell in March, followed by peak flows in early May—weeks ahead of the historic average peak flow (Brick *et al*. 2008). Flow data from the Clark Fork Basin and from around the northern Rockies all point toward earlier runoff in the spring (Brick *et al*. 2008), followed by a long period of below-average flow from late-June through September as a result of limited snowpack (Brick *et al*. 2008). Some have suggested that 60% of the climate-related trends seen in flow, snowpack, and winter air temperatures over the past 50 years are attributable to human-caused release of greenhouse gases to the atmosphere (Brick *et al*. 2008).

Precipitation

Climate change has also influenced precipitation, the primary driver of the land surface hydrologic system (Adam *et al*. 2009). Although the average annual precipitation remained steady or even increased slightly in the Clark Fork basin over the past 50 years, more of that moisture came down as rain instead of snow, especially at lower elevations (Brick *et al*. 2008). In its Climate Change 2007 report, the IPCC predicts no significant change for western Montana's total precipitation over the next century; however, the timing and type of precipitation may shift: the report predicts a 10% increase in precipitation during the winter months, and a 10 to 15% decrease in summer precipitation (Brick *et al*. 2008; IPCC 2007c). Also, for western North America, Revelle and Waggoner (1983) conclude that declining precipitation would amplify the effect of increasing evapotranspiration (Schindler 1997).

Drought

Montana has experienced several years of prolonged, and sometimes severe, drought (National Weather Service 2009). As depicted in Figure 5, much of Montana has experienced prolonged deficit from normal precipitation levels during five years in this decade. As of June 16, 2009, the U.S. Drought Monitor shows that abnormally dry conditions are now found in the northeastern corner and spans across much of western Montana and along much of the western half of the Montana-Canada border. Fortunately, moderate to extreme drought conditions only exist in a small region along the Canadian border in several Mid- to Western-central counties (see Figure 6) (Tinker 2009). Higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality, exacerbate thermal pollution, and negatively affect ecosystem integrity and human use of streams (Bates *et al*. 2008; Lettenmaier *et al*. 2008; Hogg and Williams 1996).

Groundwater Interactions

Climate warming may significantly alter groundwater temperatures (Hauer *et al*. 1997). With climate change, availability of groundwater is likely to be influenced by three key factors: withdrawals (reflecting development, demand, and availability of other sources), evapotranspiration (increases with temperature) and recharge (determined by temperature, timing and amount of precipitation, and surface water interactions) (Bates *et al*. 2008). Groundwater-dominated watersheds that are transitioning between transient and seasonal snow regimes will be the most affected by projected climatic change, particularly in terms of late summer and fall streamflow (Jefferson *et al*. 2008). As a result, water resource managers in the mountainous western USA, particularly in groundwater-dominated watersheds and those perched at the transient/seasonal snow transition, must anticipate and address the elevated temperatures that climate change is likely to bring (Jefferson *et al*. 2008).

Melting Glaciers

The melting of glaciers could have serious implications for temperatures in streams that rely on these glaciers for summer base flow, particularly in northwestern Montana. The mean annual summer temperature in Glacier National Park has increased three times more than the global average and only 27 of an estimated 150 glaciers remain since it was founded in 1910 (Brick *et al*. 2008). According to Hall and Fagre (2003), Montana's glaciers are in serious decline and all glaciers in the Blackfoot-Jackson Glacier Basin of Glacier National Park, when modeled to include carbon dioxide-induced global warming, are projected to disappear by as soon as the year 2030.

Temperature-Related Ecological Threats to Stream Integrity by Climate Change

Native Species Resilience

The major effect of climate warming on stream fishes will probably be mediated through changes in maximum summer temperatures and minimum winter temperatures (Keleher and Rahel 1996). The potential impacts of climate change on biological diversity at all levels of biological and ecological organization have been of concern to the scientific community for some time (IPCC 1990; Lovejoy and Hannah 2005; Janetos *et al.* 2008). As Montana's climate changes, native species assemblages remain at great risk and closures of recreational fisheries are likely to become more common. In the Rocky Mountain region, global warming is likely to induce a noticeable reduction in habitat suitable for salmonids and an increase in population fragmentation as coldwater fish become separated from main river channels and restricted to headwater streams at increasingly higher elevations (Keleher and Rahel

1996; Hauer *et al*. 1997). Consequently, a substantial number of fish species endemic to this region could face extinction unless they were able to adapt behaviorally or genetically (Keleher and Rahel 1996; Flebbe 1993).

It has been estimated that, due to warmer temperatures alone, western Montana could lose between 5 to 30% of native trout habitat over the next century, and temperature-sensitive native species are particularly at risk (Brick *et al*. 2008). For example, as lower elevation streams warm up during the summer, a loss of 27 to 99% of habitat patches that are large enough to sustain populations of bull trout, listed as "threatened" under the Endangered Species Act, by the end of the century has been predicted (Brick *et al*. 2008). Some mid- to late-summer temperatures in Montana have been lethal for even more temperature-tolerant non-natives, such as rainbow and brown trout (Brick *et al*. 2008).

Invasive/ Non-Native Aquatic Species

Direct effects of climate change, including range expansions of pathogens and habitat changing invasive plants, will likely be some of the most noticeable changes seen in aquatic ecosystem communities (Janetos *et al*. 2008). Interactions between increasing global temperature and pests and pathogens are of particular concern because of the rapid and sweeping changes these taxa can render (Janetos *et al.* 2008). The rise in global temperature will tend to extend polewards the ranges of many invasive aquatic plants, posing a major threat to native biodiversity in aquatic ecosystems (Bates *et al.* 2008). Climate warming may also affect native stream salmonids, such as native cutthroat and bull trout, by exacerbating biotic interactions with non-native species that may gain a competitive advantage as a result of climate change (Hauer *et al*. 1997). For example, in the western mountains, native bull trout (*Salvelinus confluentus*) are threatened by the introduction of the eastern brook trout (*Salvelinus fontinalis*), which has already taken over much of the bull trout's habitat in montane areas (Schindler 1997). Whereas brook trout appear to be prevented from invading high altitude bull trout habitats by cold water temperatures, this limitation would be likely be reduced by climatic warming, causing further extirpation of the threatened bull trout (Schindler 1997).

Declining Riparian condition

A warmer climate is also predicted to have a substantial effect on riparian plant communities, particularly in arid regions in the western US, as the competitive balance shifts in favor of non-native plants, such as Salt cedar and Russian olive, promoting displacement of native plants, like willows and cottonwoods, in riparian zones (Ryan *et al*. 2008; Janetos *et al.* 2008). Also, shallow groundwater, which plays an important role in structuring riparian plant communities (Stromberg *et al*. 1996), will likely decline as human depletions and intensified drought in a changing climate lowers the water table (Ryan *et* *al*. 2008). Structural changes in the riparian canopy may compromise its ability to provide adequate shade for regulation of stream temperatures.

Future Outlook on Climate Change Preparedness

One of the challenges of understanding changes in biological diversity related to variability and change in the physical climate system is the adequacy of the variety of monitoring programs that exist for documenting those changes (Janetos *et al.* 2008; Mulholland *et al*. 1997). Essentially no aspect of the current hydrologic observing system was designed specifically for purposes of detecting climate change or its effects on water resources and are thus in many cases unable to predict all the challenges of a rapidly changing climate (Lettenmaier *et al*. 2008). Regardless of the cause of recent climate warming trends, it is essential to anticipate the consequences for aquatic ecosystems and the human endeavors that depend on them (Schindler 1997). The predictive model discussed in Section 3 of this report may serve as a useful tool for anticipating the effects of climate change on natural stream temperatures in Montana's reference streams, particularly by facilitating the application of more readily available air temperature data to supplement more extensive on-site monitoring of stream temperatures.

SECTION 2 – REVIEW OF THE LEGAL MADATE FOR MANAGING STREAM TEMPERATURES: MOTIVATIONS FOR RESTORING NATURAL THERMAL REGIMES

Managing Temperature as a Water Quality Parameter

The federal government, specifically the United States Environmental Protection Agency (US EPA), has provided states with a legal mandate and guidance to protect the thermal regimes of streams. Given the complexity, natural variability, ecological significance, and impairment of thermal regimes in Montana's streams, the development of regulatory mechanisms for fulfilling this mandate presents a challenge to management agencies, primarily the Montana Department of Environmental Quality (MT DEQ), for several reasons.

The process of setting stream temperature standards must take into account the wide variety of human uses and values associated with Montana's surface waters while also preventing the decline in integrity of Montana's aquatic ecosystems that often results from those uses. Maintaining stream temperatures that support all human and ecosystem uses can be difficult since deleterious impacts can stretch across the entire ecosystem and their causes can be elusive. Also, because temperature management in streams and rivers is primarily driven by the need to provide temperatures in compliance with fish rearing and spawning needs (Khangaonkar and Yang 2008), the delineation of thermal tolerances across species and regions adds an additional layer of complexity to setting water quality standards. Furthermore, choosing the proper targets (i.e., reference condition) for maintaining and restoring "natural" temperatures is complicated by the natural variability in, and the multitude of factors that influence, stream temperature.

Not surprisingly, thermal degradation remains a substantial problem across the United States, particularly in Montana and the greater West. An understanding of the legal mandate and protocol for developing water quality standards may help determine the degree of flexibility that managers have within the law to expand and improve upon stream temperature management approaches.

Current Status of Stream Temperature Impairment in Montana

Nationally, temperature has been listed as one of the top ten impairments of water quality (Poole *et al*. 2004), with temperature recently cited as the cause of impairment for 3,015 waters (US EPA 2008). Montana has 677 waters on the "303(d) list" (see below) (US EPA 2008). As of 2006, 18,006 miles of the 176,750 total miles of rivers and streams (~10%) in Montana have been assessed for water quality and, of these, 15,221 miles (~85%) are considered impaired (US EPA 2006). Temperature is cited as the cause of impairment for 2,393 miles (~13% of those assessed) (US EPA 2006).

As of 2007, nonpoint source pollution accounted for 90% of stream impairments in Montana, with water temperature listed as one of four primary factors responsible for the greatest numbers of impaired stream miles in Montana, along with sediments, nutrients, and heavy metals (MT DEQ 2007). According to Montana's Nonpoint Source Management Plan, the five leading sources of water quality impairments for rivers and streams, all of which impact temperature directly or indirectly, are: (1) agriculture (including dryland farming, irrigated crop production and grazing); (2) hydrologic modification (i.e., channel straightening, channel relocation, dams); (3) resource extraction (mining); (4) habitat modification; and (5) construction (MT DEQ 2007).

Legal Mandate for Protecting Stream Temperature

The Clean Water Act (CWA)

The Clean Water Act of 1972 (33 U.S.C. §§1251 et seq.), provides the primary legal mandate for protecting natural stream temperatures. The CWA established an "interim" national goal of achieving fishable and swimmable water quality by July 1, 1983 to allow the propagation of fish and wildlife, and recreational uses of water, by that date "wherever attainable" (Plater *et al*. 2004; Murchinson 2005). The stated objectives of the CWA are to restore and maintain the chemical, physical, and biological integrity of the nation's waters and that the discharge of toxic pollutants in toxic amounts be prohibited (33 U.S.C.S. § 1251(a)(3); *Friends of Pinto Creek v. EPA* 2007). The phrase "restore and maintain" indicates that Congress sought to return water bodies to their natural conditions, not modify their natural conditions, and "integrity" refers to a condition in which the natural structure and function of ecosystems is maintained (*Sierra Club et al. v. Leavitt* 2007).

This statute provides a legal mechanism for regulating thermal pollution of our nation's "navigable" waters by imposing national, technology-based effluent limitations from point sources of pollution discharging to waters of the United States *and* more stringent in stream quality-based discharge limits for waters where technology-based limitations do not meet water quality standards based on fishable-swimmable criteria (Plater *et al*. 2004). While effluent limitations focus on the composition of the waste stream as it flows out of the discharge pipe, water quality limits focus on the waste assimilation capacity of the receiving water. These quality-based regulations are necessary to account for the fact that natural and human-induced variability in streams can mean that compliance with effluent limitations does not necessarily mean that water quality standards will be met. This is particularly true streams that receive discharge from multiple sources, streams with relatively low flows, or those with heavy use (Andreen 2004).

CWA's "303(d) list" and "305(b) List"

Section 303(d)(1)(A) of the CWA requires that each state identify "water quality limited segments" within its boundaries for which the technology-based point-source limits required by the CWA are not stringent enough to implement water quality standards applicable to such waters (33 U.S.C.S. § 1313(d)(1)(A); 40 C.F.R. §§ 130.2(j), 130.7(b)(1)). This list is often referred to as "the 303(d) list" (40 C.F.R. § 130.7(d)(1), (b)(4); Plater *et al*. 2004). Also, under section 305(b) of the CWA, states must provide an assessment on the overall state-wide water quality, the extent to which state waters protect their designated uses, a report on water pollution control programs; and a description of ground and drinking water programs (MTDEQ 2006). As such, Montana's Integrated 303(d)/305(b) Water Quality Report for Montana is the primary document for state-wide reporting of water quality (MT DEQ 2007).

Total Maximum Daily Loads (TMDLs)

According to §303 (d)(1)(C) of the CWA, for each waterbody on the list, states must establish the total maximum daily load (TMDL) for every pollutant, including temperature, suitable for calculation that prevents or is expected to prevent a waterbody from attaining applicable water quality standards (Plater *et al*. 2004; 40 C.F.R. § 130.7(c)(1)(ii)). A TMDL is a specification of the "maximum amount of a particular pollutant that can pass through a waterbody each day without water quality standards being violated" (33 U.S.C. §1313(d)(1)(c); Plater *et al*. 2004; Andreen 2004), and is essentially the same as the "waste assimilation capacity" of a water body. Such load shall be established at a level necessary to implement the applicable water quality standards, with acknowledgement of seasonal variations and a margin of safety which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality (Plater *et al*. 2004). TMDLs allocate those loadings among the various sources of pollution (Andreen 2004), and they are divided into two types: "load allocations" for nonpoint source pollution and "wasteload allocations" for point source pollution (40 C.F.R § 130.2(g)-(i)).

States are required to submit their lists of water quality limited water bodies, TMDLs, and priority rankings to the EPA every two years (40 C.F.R. § 130.7(d)(1)). Section 303(e)(3) of the Clean Water Act (CWA) additionally requires that each state include in its continuing planning process adequate implementation, including schedules of compliance, for revised or new water quality standards for all navigable waters within such State (*Pronsolino et al. v. Nastri et al.* 2002). A state may remove a waterbody from its impaired waters list if it is meeting all applicable standards, or is expected to meet them in a reasonable time frame, or if the original basis for listing is determined to be inaccurate (*Sierra Club et al. v. Leavitt* 2007).

These regulations apply whether a water body receives pollution from point sources only, non-point sources only, or a combination of the two (*Pronsolino et al. v. Nastri et al.* 2002). This ruling helped to secure the legal mandate for protection of streams from both direct and indirect causes of thermal degradation. Also, in *Friends of the Earth v. EPA et al*. (2006) when questioned whether the meaning of the word “daily” in TMDL was sufficiently pliant to mean a measure of time other than daily, the court held “daily means daily, nothing else.”

Montana’s TMDL Program Overview

The Watershed Management Section (WMS) within the Water Quality Planning Bureau is responsible for TMDL development for Montana. The goals for the section include the development of TMDLs that are consistent in the application and interpretation of state water quality standards and state law, and the development of TMDLs at a pace consistent with court ordered schedules. The WMS also provides a linkage to TMDL implementation by including implementation strategies and recommendations in TMDL documents, thus facilitating the transition from TMDL development to TMDL implementation (MT DEQ 2006). Of the 18,006 miles of streams and rivers in Montana that have been assessed for water quality, 12,533 miles (~70%) still require completion of TMDL(s) as of 2006 (US EPA 2006).

In Montana, TMDLs and watershed restoration plans are developed using a "watershed" approach in which TMDLs are developed for all streams impaired by a given pollutant or set of pollutants within a given watershed. The scale of the watershed used for TMDL development is based on USGS Hydrologic Unit Code (HUC - 4th code) boundaries where practical. These “watersheds” are called TMDL Planning Areas (TPAs) to distinguish the areas from USGS 4th code HUC watersheds, and can be seen in Figure 7 (MT DEQ 2006). In Montana, these watersheds usually have a size of more than 300,000 acres (MT DEQ 2007).

Within the TMDL process, the EPA draws a distinction between “pollutants” and “pollution.” The EPA only approves or disapproves TMDLs addressing *pollutant* impaired or threatened waterbodies, whereas p*ollution* impairment or threats may be addressed within the TMDL document but are not considered in EPA’s approval of the TMDL for a specific waterbody - pollutant combination (MT DEQ 2006). Temperature is considered a pollutant, while examples of pollution include “alteration in stream-side or littoral vegetative covers”, “low flow alterations”, and “fish barriers” (MT DEQ 2006). A large percentage of waters within Montana have impairments that fall within the “pollution” category (MT DEQ 2006). WMS staff develops water quality plans that include TMDLs for waterbodies impaired by *pollutants* and additional restoration goals and objectives for waterbodies impaired by *pollution.* This allows staff to identify and pursue water quality improvements via a comprehensive planning process that typically addresses all situations where water quality standards are not attained within a watershed. The comprehensive document is often referred to as a watershed or water quality restoration plan that includes required TMDLs within its scope (MT DEQ 2006).

Enforcement of the CWA

Unfortunately, states must implement TMDLs only to the extent that they seek to avoid losing federal grant money; there is no pertinent statutory provision otherwise requiring implementation of §303 plans or providing for their enforcement. 33 U.S.C.S. § 1319; 33 U.S.C.S. 1365 (*Pronsolino et al. v. Nastri et al.* 2002). Additionally, although the EPA has approval authority, it does not have a mandatory duty to monitor a state's waters under the CWA. §1313(d)(2) (*Sierra Club et al. v. Hankinson et al.* 1996). This lack of compliance and enforcement has heightened the challenge of maintaining natural thermal regimes necessary for healthy aquatic systems. Fortunately, the EPA may approve a state's continuing planning process only if it will result, for all "navigable waters" within the state, plans that include effluent limitations, TMDLs, area-wide waste management plans for non-point sources of pollution, and plans for "adequate implementation, including schedules of compliance, for revised or new water quality standards." §303(e)(3) (*Pronsolino et al. v. Nastri et al.* 2002). Also, to aid in enforcement of the CWA, section 505(a) authorizes citizens to bring suit in federal court against the EPA for failure to perform any act or duty under the CWA which is not discretionary with the Administrator. 33 U.S.C.S. § 1365(a). "The Supreme Court has held that the CWA citizen suit provision allows a district court to 'order the relief it considers necessary to secure prompt compliance with the Act'" (*Sierra Club et al. v. Hankinson et al.* 1996).

Stream Temperature (Water Quality) Standards: Guidance from the US EPA

Water quality standards are tailored to the uses and values of specific waters, for which states set technical criteria for water quality standards designed to protect those uses (33 U.S.C. §1313(c)(2)(A); Andreen 2004). The US EPA believes that water quality criteria should apply to all the river miles for which a particular use is designated, including the lowest point *downstream* at which the use is designated, whereby waters upstream of that point will generally need to be cooler in order to ensure that the criterion is still met downstream as water progressively warms (US EPA 2003). The EPA also believes that criteria should apply *upstream* of the areas of actual use because temperatures in upstream waters significantly affect the water temperatures where the actual use occurs and upstream waters are usually colder (40 C.F.R. § 131.11(a); US EPA 2003).

Montana's Beneficial Uses

As shown in Table 1, Montana's Water-Use Classification System (ARM 17.30.604-629) identifies the following beneficial uses: drinking, culinary use, and food processing; aquatic life support for fishes and associated aquatic life, waterfowl, and furbearers; bathing, swimming, recreation, and aesthetics; agriculture water supply; and industrial water supply (MT DEQ 2006). A waterbody is considered impaired when there is a violation of the water quality standards established to protect any of the applicable beneficial uses (MT DEQ 2006). The designated uses that have the highest water quality requirements are aquatic life, fisheries, recreation, and drinking water, culinary and food processing, and any waterbody that supports these beneficial uses should support all other existing and future designated uses (see Table 1) (MT DEQ 2006).

Montana Water Quality Standards: Numeric vs. Narrative

Montana law provides the authority to the DEQ and the Board of Environmental Review (BER) to adopt proposed water quality standards into the Administrative Rules of Montana (ARM), and the DEQ periodically reviews, updates, and modifies Montana's water quality standards, as necessary. Montana water quality standards include both use-specific components (ARM 17.30.621-629) and general provisions (ARM 17.30.635-646), and may be either narrative or numeric, and be specific to human health (i.e., drinking water, contact recreation), aquatic life support or other beneficial uses (MT DEQ 2006b).

Using guidance from the EPA, Montana has established numeric water quality temperature standards based on Water-Use Classifications (ARM 17.30.620-629; MT DEQ 2008). N*arrative* standards provide a minimum level of protection to state waters and may be used to limit the discharge of pollutants, or the concentration of pollutants in waters not covered under numeric standards (MT DEQ 2006). Montana narrative water quality standards also prohibit activities which would result in nuisance aquatic life, such as excessive biomass (e.g., alga growth) or the dominance of undesirable species (ARM 17.30.637), both of which have been tied to elevated stream temperatures. Narrative standards for temperature, as well as pH and sediment, are defined in terms of change from what would naturally exist and provide that "no increase above naturally occurring condition" shall occur (MT DEQ 2006). “Naturally occurring" refers to conditions or materials present from events over which man has no control, or from developed land where “reasonable” land, soil, and water conservation practices have been applied (although conditions resulting from reasonable operation of dams in existence since July 1, 1971, are considered natural) (75-5-306 MCA; MT DEQ 2006b). Montana’s current stream temperature standards are listed by ‘use classification’ in Table 2.

Cold- and Warm-Water Fisheries

Broad-scale distribution patterns of fishes in Rocky Mountain streams generally reflect the importance of temperature, with upstream reaches being dominated by cold-water species and downstream reaches by warm-water species (Rahel and Hubert 1991). In Montana, stream sites located in the level III ecoregions Canadian Rockies (41), Northern Rockies (15), Idaho Batholith (16) and Middle Rockies (17) were labeled as cold-water, and those in the Northwestern Glaciated Plains (42), Northwestern Great Plains (43) and the Wyoming Basin (18) were labeled as warm-water (Woods *et al*.

2002). Overall, the geographic location of warm- and cold-water sites based on ecoregions closely parallels the state's beneficial use classifications for warm- and cold-water fisheries (see ARM 17.30.607) (Suplee *et al*. 2005).

Cold-water streams are generally located in the western mountainous region of the state, and are expected to support salmonids — fish preferring temperatures lower than 65^{o}F. Warm-water streams are generally located east of the Rocky Mountain Front, and comprise prairie streams and rivers that support walleye, bullhead, bass and a variety of other fish that prefer temperatures 65^{o}F or greater (Holton and Johnson 1996). More specifically, a cold-water fish guild composed of four species of salmonids that are common throughout the Rocky Mountain region (rainbow trout (*Oncorhynchus mykiss),* brown trout (*Salmo trutta),* brook trout (*Salvelinus fontinalis*), and cutthroat trout (*Oncorhynchus clarki)* show optimal temperatures for growth of 14-18°C and upper thermal tolerance limits of 22-24°C (Eaton *et al*. 1995; Keleher and Rahel 1996).

These delineations of cold- and warm-water fisheries inform the creation of temperature standards in Montana. For example, Montana divides B and C classifications based on cold-water or warm-water aquatic life. B-1 and C-1streams support growth and propagation of cold-water organisms (i.e., salmonid fishes and associated aquatic life) and B-2 and C-2 streams support growth and *marginal* propagation of cold-water aquatic life, wheras B-3 and C-3 waterbody classes support warm-water aquatic life (i.e., non-salmonid fishes and associated aquatic life) (MT DEQ 2006). Most streams in Montana have a B (1, 2, or 3) classification (MT DEQ 2006).

Benefits and Challenges of Complying with the CWA in Montana

Humans and ecosystems co-benefit from Montana's compliance with the Clean Water Act's requirement to set and enforce water quality standards for stream temperature (MT DEQ 2006). For example, with fishing as one of the most popular and income-generating water-related activities in Montana, maintaining natural stream temperatures, especially in Montana's several Blue Ribbon Trout Rivers and streams, is beneficial to anglers *and* native fish species alike, particularly those that are endangered and threatened. However, setting water quality standards to support beneficial uses that adequately reflect "natural" conditions of stream temperature regimes is a complex task, as described above. As such, investigations of spatial and temporal variability in Montana's reference stream temperatures are imperative for water quality managers as they seek to preserve the natural condition and integrity of stream ecosystems across the state and into the future. Additionally, compliance with the CWA will likely become more difficult to achieve as the changing climate will likely amplify the importance of air temperature as a driver of stream temperature. Thus, further investigation of the air-water temperature relationship in these reference streams may also be an asset to stream managers as they develop predictive tools for modeling stream temperature regimes now and in the future.

SECTION 3 – ANALYSIS OF SPATIAL AND TEMPORAL VARIABILITY IN TEMPERATURE REGIMES OF SEVERAL OF MONTANA'S REFERENCE STREAMS

Introduction

This section aims to quantify spatial and temporal variability in Montana's reference streams and to investigate the air-water temperature relationship that influences their thermal regimes. The thirty-six streams included in this analysis are characterized as "reference" by the Montana Department of Environmental Quality (MT DEQ), and represent four of Montana's Level III ecoregions: Middle Rockies, Northern Rockies, Northwestern Glaciated Plains, and Northwestern Great Plains (see Table 3).

A brief discussion of the study streams chosen and the field study/characterization of MT DEQ's reference streams are followed with a brief literature review of the air-water temperature relationship and the availability of and collection methods for water and air temperature data. To achieve objective 3 of this study, data are analyzed through the development of a random coefficient regression model which allows stream managers to: (1) analyze if water temperatures and the air-water temperature relationship in reference streams varies significantly by ecoregion; (2) analyze if water temperatures and the air-water temperature relationship in reference streams varies significantly by stream within ecoregion; (3) develop a general equation representing the air-water temperature relationship for *all* reference streams (the population average), and (4) to construct a similar equation for each individual reference stream included in this analysis that deviates significantly from the population average. To determine if reference streams were sampled during a summer when air temperatures were typical of long-term averages, and to achieve objective 4 of this study, an analysis of air temperatures over an 11-year period is also described. This section concludes with a discussion of improvements that may be made to the collection and analysis of reference stream water temperature data, and the management implications of this model's application.

Purpose and History of Montana's "Reference Streams"

Until the early-1990's, the United States Environmental Protection Agency (US EPA) based water pollution controls primarily on the measurement of chemical constituents and laboratory tests of the toxicity of wastewater discharges to selected organisms. Recognizing that this was insufficient, they began to emphasize a more ecological approach to water pollution control in attempts to directly gauge the health of whole biological communities in aquatic ecosystems, most notably those subject to the cumulative effects of both point and nonpoint sources of pollution (Bahls *et al*. 1992). This paradigm change led to efforts by states, including Montana, to begin establishing baseline conditions of various biological components in aquatic reference systems (Bahls *et al*. 1992). The MT DEQ uses reference condition to determine if narrative water quality standards are being achieved (MT DEQ 2006b). The term "reference condition" is defined as the condition of a waterbody capable of supporting its present and future beneficial uses when all reasonable land, soil, and water conservation practices have been applied; in other words, reference condition should reflect minimum impacts from human activities and attempts to identify a waterbody's greatest potential for water quality given historic land uses activities (MT DEQ 2006b).

The Montana Water Quality Bureau presented three reasons for establishing benchmark or baseline biological conditions in least-impaired "reference" streams:

1. To provide a reference against which to compare conditions in other streams. Such a reference will help gauge the severity of pollution as well as progress in abating pollution. This will be particularly helpful in the Nonpoint Source Program- for ranking prospective watershed demonstration project streams and measuring the effectiveness of best management practices,
2. To provide the basis for narrative and numerical biological criteria and enforceable biological standards in streams, and
3. To describe the natural biodiversity and types of algal and macroinvertebrate communities found in Montana streams. The concept of biodiversity recognizes the intrinsic value of biological species and their functional importance in ecosystems. Little work of this type has been accomplished in aquatic ecosystems as compared to terrestrial ecosystems; and few studies of biodiversity have addressed invertebrates and nonvascular plants as compared to vertebrate animals and vascular plants (Bahls *et al*. 1992).

In response, in 1992 Bahls *et al.* released a report that documents the benchmark biology of several reference streams in Montana, marking early efforts to establish reference conditions in the state. This report describes the composition and structure of benthic macroinvertebrate (mostly insect), periphyton (algae), and fish communities inhabiting least-impaired reference streams in Montana's six major ecoregions in the summer of 1990. In addition the report provides supporting information on water chemistry, macroinvertebrate habitat, and overall stream condition (Bahls *et al.* 1992).

Montana Department of Environmental Quality's (MT DEQ) Reference Stream Project

In 2002, the Department of Environmental Quality re-initiated these earlier efforts with the Reference Stream Project in which data were collected at both existing reference sites (per Bahls *et al*. 1992) and at new sites that were identified around the state (Suplee *et al.* 2005). Recall that the reference condition concept asserts that there exist for any group of waterbodies relatively undisturbed examples that can represent the natural biological, physical and chemical integrity of a region; such reference stream sites serve to represent the reference condition (MT DEQ 2006). The MT DEQ is primarily interested in reference sites because they help the Department interpret narrative water-quality standards; as a number of Montana's narrative standards require that water quality be compared to "naturally occurring," reference sites serve to help interpret the meaning of this designation (Suplee *et al.* 2005). As of 2009, 159 documented reference streams exist in Montana (Suplee 2009).

MT DEQ's Reference Stream Site Criteria

Although some pre-established reference sites that had already been thoroughly reviewed were automatically classified as final reference sites, the MT DEQ uses an evaluation process to assess each candidate reference site. Quantitative watershed and water-quality analyses are performed for each site, as well as qualitative assessments of stream health and condition using a set of criteria and best professional judgment (BPJ) (Suplee *et al.* 2005). Each criterion evaluates some aspect of stream or watershed condition that could potentially impact water quality and aquatic life, with sixteen criteria used for cold-water streams in Montana's mountainous regions and thirteen criteria tailored for warm-water streams in prairie regions (Suplee *et al.* 2005).

To create the final list of reference sites, seven tests, or "screens", are then used which were constructed from the qualitative BPJ assessments and from numeric values identified as impact thresholds in the quantitative analyses (Suplee *et al.* 2005). These are: (1) cumulative impacts from multiple causes; (2) site-specific data sufficiency; (3) impacts from land-use based on the proportion of agriculture; (4) numeric water-quality standards exceedences for heavy metals; (5) impacts from mines; (6) road density; and (7) timber-harvest intensity (the latter two applicable to cold-water streams only). A site must pass each applicable screen to qualify as a general-purpose reference site and be considered to be in an un-impacted condition for all categories; these "screens" address factors operating at the watershed-scale, site-specific scale and, in many cases, both (Suplee *et al.* 2005).

Explaining Variability in Montana's Reference Stream Temperature Regimes

The complexity of stream thermal budgets and natural and anthropogenic variability adds to the challenge of applying the reference condition approach. Once reference sites are identified, they must be sufficiently characterized in a way that allows managers to choose a 'reference site' that is adequately representative of the 'degraded' or 'comparison' site parameters in question. For example, when developing reasonable restoration goals and expectations for a stream experiencing thermal degradation, the reference condition may be used to reflect appropriate standards of the "natural condition" that can be expected post-restoration. Ideally, to help heighten confidence that the proper reference condition is chosen, comprehensive studies of "reference" and degraded "comparison" streams that characterize every individual ecosystem parameter that contributes to streams' thermal heat budgets should be undertaken and used to facilitate this choice. These comprehensive stream energy balance studies are vital for understanding the heat transfer processes driving temperature variability (Hannah *et al*. 2008; Malcolm *et al*. 2008).

Unfortunately, these systems-oriented heat budget investigations are generally spatially limited due to associated costs and logistics and are normally of short duration (Webb and Zhang 1997). This is problematic for assessing larger spatial and temporal scale variability in stream temperature and, consequently, there is a need for studies that are capable of generating spatially distributed temperature data (through field measurement), which are more readily obtainable and resourced over longer time periods (Malcolm *et al*. 2008). The MT DEQ Reference Stream Project collects a wide array of data on physical, chemical and biological parameters of these stream ecosystems, but the study of temperature is currently rather limited in scope.

Particularly due to its large size, temperate climate, wide elevation gradient, and the different climatic regimes that occur on the eastern and western sides of the Rocky Mountain divide, Montana exhibits substantial variability in climate. Thus, it is expected that natural (reference) stream temperatures will vary significantly over space (i.e., region-to-region and stream-to-stream) and time (season-to-season and year-to-year). Given our growing understanding of the importance of thermal heterogeneity across multiple spatial scales, monitoring programs may be inadequate if they cannot capture expected changes in the spatial thermal variability of streams (Poole and Berman 2001). Also, owing to the flowing nature of streams, stream temperature at a point is controlled not only by immediate surroundings but also by upstream conditions (Johnson 2003). As such, while site-specific variability in stream temperature is important for determining community composition and other localized attributes, stream temperatures must also be measured on a sufficiently coarse scale to understand the influence of upstream thermal variability on chosen study sites. Facing resource limitations, the MT DEQ and others designing stream temperature studies in Montana would benefit from choosing an appropriate scale to use while designing efficient and effective sampling schemes.

Level III Ecoregions

The MT DEQ has, in general, found the Level III ecoregions presented by Omernik and others (Omernik 1987, 1995; Woods *et al*. 2002) to be an excellent tool for the initial partitioning of Montana reference streams (see map of Level III ecoregions in Figure 8) (Suplee *et al.* 2005). Ecoregions have been used to classify regions of the United States within which the ecosystems and the type, quality, and quantity of environmental resources are generally similar. They are designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components (Woods *et al.* 2002). They were first derived based on the premise that ecological regions can be identified through the analysis of the spatial patterns and the composition of biotic and abiotic phenomena that affect or reflect differences in ecosystem quality and integrity, including geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology (Wiken 1986; Omernik 1987; Woods *et al.* 2002). As a result, ecoregions were used as a major grouping variable while conducting this investigation of reference stream temperature variability in Montana. A more detailed description of Montana's ecoregions can be found in Appendix A.

Applicability and Limitations of Reference Data

The MT DEQ does, however, recognize that while it is likely that some water quality parameters and biological assessment metrics can be "referenced" at the fairly coarse ecoregion scale, others cannot. In certain cases, more specific geospatial characteristics may need to be determined for the reference site and the comparison site depending on the parameter of interest (Suplee *et al.* 2005). This notion reinforces the rationale for this study of spatial variability in reference stream temperature data between ecoreigons and between streams within ecoregions, to determine if the ecosystem-scale is useful for designing stream temperature studies and standards.

It should also be noted that most of the MT DEQ's Reference Stream Project sites are located in lower Strahler stream orders – mainly 1st through 4th but including a few 5th order sites – and thus the data are most applicable to "wadeable" streams and may not be appropriately applied to much larger waterbodies (Suplee *et al.* 2005). In the Strahler ordering scheme, stream order is 1 at the headwaters and increases toward the outlet of the watershed; when two n-th order streams come together, they form an (n+1)-th order stream, but the confluence with streams of lower order does not change the order of the highest order stream (Strahler 1957; Duscharne 2008).

The MT DEQ recognizes that reference streams are not necessarily pristine or perfectly suited to giving the best possible support to all possible beneficial uses. Reference condition does not reflect an effort to "turn the clock back" to water quality conditions that may have existed before human settlement, which is usually unattainable, but is instead intended to accommodate natural variations in ecosystem attributes (i.e., biological communities, water chemistry) due to natural physiochemical differences (i.e., climate, bedrock, soils, hydrology), and to differentiate between natural conditions and widespread or significant alterations of biology, chemistry or hydrogeomorphology due to human activity (MT DEQ 2006b).

Also, comparisons of conditions in a waterbody to reference waterbody conditions must be made during similar season and/or hydrologic conditions for both waters (MT DEQ 2006b), particularly when water temperatures that are driven by climatic and hydrologic variables are in question.

Air Temperature: A Primary Driver of Stream Temperature

As described in Section 1 of this report ("*Drivers of Stream Temperature*"), air temperature is considered a major driver of stream temperature (Smith and Lavis 1975; Sullivan and Adams 1990; Johnson 2004) and the air-water temperature relationship has often been used to predict or explain variability in stream water temperatures (Stefan and Preud'homme 1993; Smith and Lavis 1975; Crisp and Howson 1982). Investigations and mathematical models of the air-water temperature relationship in reference streams may provide useful information and tools for managers aiming, for example, to predict the response of natural water temperature regimes to climate change or other human-induced sources of thermal degradation. These models may also allow managers to more efficiently identify potential reference sites by allowing them to use widely-available air temperature data to accurately predict whether or not a potential reference stream's temperature appears to fall within its natural temperature range.

Linearity in the Air-Water Temperature Relationship

Using data from field studies, many authors have successfully used simple linear regression models to represent the air-water temperature relationship, and have shown that mean air temperature accounts for a high percentage (i.e., 86-96%) of the variation in corresponding mean water temperatures (Stefan and Preud'homme 1993; Crisp and Howson 1982; Jeppesen and Iversen 1987; Saffran and Anderson 1997; Eaton and Scheller 1996; Caissie *et al*. 1998; Duscharne 2008). According to Crisp and Howson (1982), this strong correlation exists even when the water and air temperatures were measured at stations some 50km apart. These simple linear regression models highlight air temperature as a surrogate for changes in heat fluxes that affect the water surface (Duscharne 2008). The strength of this association has led several researchers to describe local air temperature as the single most important parameter associated with daily mean stream temperature (Bartholow 1989, Sinokrot and Stefan 1994; Meays *et al*. 2005).

It is important to note that several observations of the subtleties and complexities of the air-water temperature relationship have led some to question the assumption that this relationship is linear (Webb *et al*. 2003). For example, a deviation from this linear relationship has been shown at very low temperatures ($<0^{o}$C) (Crisp and Howson 1982; Webb and Nobilis 1997), which can be ascribed to the release of latent heat with ice formation which prevents water temperatures falling much below 0^{o}C (Webb *et al*. 2003). More recently, it has been suggested that deviation from the linear relationship for weekly mean values occurs also at high air temperatures (> ca. 25^{o}C) (Webb *et al*. 2003); this likely occurs as increases in the moisture-holding capacity of the atmosphere promotes greater evaporation from the water surface and thus enhances evaporative cooling and, as water temperatures rise, back radiation is also enhanced (Mohseni *et al*., 1998, 1999, 2002). At both extremely high and low temperatures, a continuous S-shaped curve based on a non-linear logistic regression function has been used successfully to represent departures of the water–air temperature relationship (Webb *et al*. 2003; Mohseni and Stefan 1999).

The reference streams included in this study were sampled during the summer, negating (or greatly reducing) the effect of extreme low temperatures on linearity of the air-water temperature relationship. To ensure that extreme high temperatures during the sampling period did not have a substantial effect on linearity, scatter plots of each stream's air-water temperature relationship regressions were reviewed (see Figures 9-12). The green line in these figures represents the linear regression between daily average water temperature and daily average air temperature with various lag times, whereas the red line represents a slightly sigmoid regression relationship between these two variables. Since these two lines mostly overlap and the sigmoid relationship did not appear to be a substantially better "fit" for the data than a linear regression model is, the linear model was deemed appropriate for use in this analysis. These (green) regression lines suggested a linear pattern exists between daily average *summer* water and air temperatures for all streams included in this study. The scattered behavior of minima in some streams has been attributed to the fact that the higher thermal capacity of water prevents development of the low nocturnal minima characteristic of air temperature (Smith 1979). Daily means were the thermal variables (metrics) chosen for this study because several authors found that the use of daily average (or maximum) water and air temperature values tend to be less scattered than daily minimum values (Webb *et al*. 2003; Stefan and Preud'homme 1993), and because the available air temperature data was better suited to calculating means. Also due to the high thermal capacity of water, air temperatures would be expected to experience higher daily extreme temperatures than water temperatures, further suggesting that daily averages were suitable for comparison in this analysis. However, future studies, particularly those concerned with lethal thresholds for aquatic organisms, may consider including other metrics, including daily maxima, which may represent periods when aquatic organisms experience additional thermal stress.

Also, since water temperatures cannot be predicted from air temperature in periods with large amounts of melt water (Smith and Lavis 1975; Jeppesen and Iversen 1987), it is fortunate that reference streams were studied during the summer season so as to minimize the effects of spring high flows on the air-water temperature relationship.

Air Temperature Lag Time

Because of the high heat capacity of water, water temperature variations often tend to lag behind those of air temperature (Meays *et al*. 2005; Stefan and Preud'homme 1993, Mosheni and Stefan 1999; Duscharne 2008; Jeppesen and Iversen, 1987). As such, several authors have suggested that the correlation of water temperatures to air temperatures can be improved by imposing a lag time, often finding the current day and/or one day-lagged air temperature data is most appropriate for relatively small streams (Stefan and Preud'homme 1993; Saffron and Anderson 1997; Grant 1977; Webb *et al*. 2003). Analysis of the effect of time-lagged air temperature data discussed in this report supports this finding (see "*Determination of Appropriate Air Temperature Lag Times*" section below).

The lag effect has been shown to be more pronounced in larger, deeper rivers that have higher flow volumes and greater thermal capacities than in smaller streams (Webb *et al*. 2003; Stephan and Preud'homme 1993; Saffron and Anderson 1997). In this study, lagged air temperatures are defined as the daily average air temperatures measured one, two, and three days *prior to* the day reference stream water temperatures were measured, rather than the daily average air temperature averaged over multiple days. Because all of Montana's reference streams included in this analysis are located in lower Strahler stream orders and are thus relatively small streams (Suplee *et al*. 2005), the decision to limit the lag times included in this analysis to three days was assumed to be sufficient and later verified through statistical analysis.

Stefan and Preud'homme (1993) have also suggested that this lag time varies depending on catchment size, with 0 days for catchments 300 km^2 or less in size, but more than 8 days for basins in excess of 4 x 10^5 km^2. While catchment size data for the reference streams analyzed here was not available and thus not included, this relationship between lag time and catchment size may be helpful to consider when designing future studies of the air-water temperature relationship in Montana's streams and rivers.

Water and Air Temperature Data Availability: Temperature Data Loggers & Weather Stations

Water temperature can be measured with relative ease although data that are both detailed and long enough for rigorous assessment of trends are rare. Hence there is a dearth of long, reliable and unbroken river temperature records reflecting the later development of interest in quality monitoring, compared with quantity monitoring for rivers (Webb 1996). Fortunately, the advent of a new technology over the past several years has allowed examination of spatial dynamics of stream temperature at higher resolution than possible before (Johnson 2003; Dunham *et al.* 2005). This technology consists of small, inexpensive electronic temperature sensors coupled with data loggers which are relatively inexpensive, simple to deploy and capable of collecting large amounts of data. Also, long and detailed records of air temperature data are kept for many weather stations across Montana and are available online through the National Oceanographic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) (NOAA 2009b). Since complex environmental gradients occur over very short distances (and in a lateral, horizontal, or vertical direction) away from the stream, appropriate measures should be taken to capture site-specific data (Johnson 2003; Dunham *et al*. 2005). For example, wind speed, relative humidity, subsurface saturation and soil and air temperature are very responsive to variations in landscape features and riparian vegetation distribution (Chen *et al*. 1993; Johnson 2003). As such, it is ideal to measure air and water temperatures at the same stream site when the data is to be used to model the relationship between these two variables. However, logistical limitations sometimes necessitate the use of remote air temperature data. The air temperatures obtained from carefully-chosen weather stations for use in this analysis are assumed to be sufficiently representative of the stream sites at which water temperatures were measured.

Methods

Reference Stream Temperature Data (Source and Manipulation)

One electronic data logger, the Optic® StowAway developed by the Onset Computer Corporation (2009), was used to collect water temperature data in each of 36 of Montana's reference streams every 30 minutes throughout one summer (data logger identification numbers and period of record dates are listed in Table 4). The Optic StowAway is submersible, has a memory capacity of 32,520 observations, is reliable for a temperature range of –4°C to 37°C, and is accurate to 0.2 °C (Dunham *et al.* 2005). According to the MT DEQ Temperature Data Logger Protocols Standard Operating Procedure and others (Stermitz *et al*. 2005; Jones and Allin 2006), an accuracy check was performed on temperature data loggers in the lab and care was taken to place data loggers in a stream location that is: shaded from direct sunlight; away from obvious regions of warm or cool water sources such as side channel inflows or ground water; in a well-mixed portion of the stream that is most likely to remain flowing for the longest period of time (typically in or very near the thalweg); and is not susceptible to excessive scour. Temperature data loggers were typically secured using plastic zip ties to either a steel fencepost or a brick to avoid displacement or disturbance. Upon deployment during the first site visit (early summer), the date, time, and a descriptive narrative of the location, as well as the latitude and longitude collected using a handheld GPS unit, was recorded on a field form. Often, a digital photograph of the deployment location was taken as well. Each data logger was generally checked during a mid-summer site visit to ensure they were not "high and dry or buried in the substrate" and necessary adjustments were made and recorded on the field form (Stermitz *et al*. 2005). Data loggers were retrieved upon the third and final site visit (usually late-August to mid-September), and the date and time were recorded.

Continuous water temperature data and site identification information for 36 of Montana DEQ's reference streams were obtained from Rosie Sada de Suplee, Montana DEQ's Water Quality Monitoring Section Environmental Program Manager. These streams represent all reference streams for which *continuous* temperature data is available, and they represent 4 of the 7 total Level III ecoregions in Montana with 4 streams in the Middle Rockies Ecoregion, 11 in the Northern Rockies Ecoregion, 5 in the Northwestern Glaciated Plains Ecoregion, and 16 in the Northwestern Great Plains Ecoregion (see Table

3) (Woods *et al*. 2002). The period of record for each stream varied between June to September, with most streams sampled from July to August. Each stream was sampled during one summer between 2004 and 2008 (see Table 4).

For each stream, summer daily average water temperature (DAWT) (^{o}F) was calculated to summarize data and minimize the effect of diurnal temperature variability on this analysis. DAWT is defined as the average of 48 temperature measurements per day for the summer period of record. The first and last dates of the data logger period of record were removed from these calculations so that only water temperatures measured during an *entire* day were included. To begin exploring trends in temperature over time between ecoregions and between streams within ecoregions, reference streams were sorted by ecoregion, and a timeplot of DAWT (^{o}F) was created for each ecoregion (see Figures 13-16). Generally, as seen in Figures 13 through 16, over the course of the entire summer season there appears to be little variability in water temperatures in the Northern Rockies and Northwestern Great Plains ecoregions. In contrast, the trend lines of stream temperatures in the Middle Rockies and Northwestern Glaciated Plains ecoregions experience an observable drop from mid-July to September. It is likely that these trends are a result of the different sampling periods for streams. Most streams that experience an observable decline in temperatures near the end of their period of record were sampled later in the summer, with temperature measurements collected from mid-July to mid-September when air temperatures begin to decline rapidly (see Figures 13, 15). Alternately, those that appear to remain rather constant were sampled earlier, from mid-or late-June to early-September (see Figures 14, 16).

Air Temperature Data (Source and Manipulation)

A weather station was chosen that was thought to be most ‘representative of’ or ‘correlated to’ the air temperature conditions at each reference site. The choice of a weather station to correlate with each stream was prioritized, from most to least representative, by: (1) similarity in elevation to stream sampling site; (2) proximity to the stream sampling site; and (3) length of period of record. Each reference stream’s elevation was within 415 m of the weather station chosen to represent that stream. One exception to this is Rock Cr II (2007) which was prioritized by location rather than elevation (1117m difference) since few weather stations exist nearby. Specific methods for accessing, requesting and downloading weather station data can be found in Appendix B.

Hourly air temperature data sets from 14 weather stations (13 in Montana and one in Canada) were obtained from NOAA’s National Climatic Data Center (NCDC) (NOAA 2009b). Some weather stations were associated with multiple streams (see Table 4). Air temperatures for an 11 year period of record, from January 1998 to December 2008, were requested; it was important to ensure that this record includes data both for each summer day reference streams water temperatures were sampled *and* on an (almost) daily basis each summer month over the 11 years (see Appendix B).

For each day corresponding to each stream's summer period of record, four thermal variables were calculated: daily average air temperature (DAAT) (^{o}F), daily average air temperature with one day lag (DAAT1) (^{o}F), daily average air temperature with two day lag (DAAT2) (^{o}F), and daily average air temperature with three day lag (DAAT3) (^{o}F). DAAT is defined as the average of approximately 50 measurements per day that a reference stream's water temperature was measured. DAAT1, DAAT2, and DAAT3 are defined as the DAAT one, two and three days prior to the corresponding water temperature measurement, respectively; these variables are used to determine the appropriate lag time to include in the analysis of the air-water temperature relationship exhibited by Montana's reference streams.

DAWT, DAAT, DAAT1, DAAT2, and DAAT3 were compiled for each reference stream's period of record into a Microsoft Excel spreadsheet in a format compatible with SAS version 9 for Windows with the following columns: Ecoregion (E), Stream Name (SN), Stream (S), Time, Date (Month Day), Year, DAWT, DAAT, DAAT1, DAAT2, and DAAT3.

Model Specification

A (linear) relationship is known to exist between water temperature and air temperature both from the literature (Stefan and Preud'homme 1993; Crisp and Howson 1982; Jeppesen and Iversen 1987; Saffran and Anderson 1997; Eaton and Scheller 1996; Caissie *et al*. 1998; Duscharne 2008) and from initial analysis of the scatter plots between DAWT and DAAT for these reference streams (see Figures 9-12). As such, one objective with this model is to determine if this relationship varies significantly by ecoregion and by stream within ecoregions. An additional objective is to ensure that this relationship is established within the model for *all* reference streams, not just for the 36 reference streams included in this analysis. These factors were taken into account when specifying which model to use.

A random coefficient regression model (also referred to as a multilevel or hierarchical model) was built where both the intercept and slope are assumed to be random. The MIXED procedure in version 9 of SAS for Windows was used and two levels of randomness were included in the model: (1) at the across ecoregion level, and (2) at the across stream level within ecoregions. Essentially, the model allows for the effect of air temperature to vary between ecoregions and between streams within ecoregions. The within stream serial dependence of the daily air and water temperatures is accounted for by including an autoregressive order 1 type autocorrelation for the random errors.

This mathematical model can be expressed as follows:

$$\mathrm{DAWT}_{ijk} = \beta_0 + \beta_1\mathrm{DAAT1} + \beta_2\mathrm{DAAT2} + \beta_3\mathrm{DAAT3} + (b_{0i} + b_{0j(i)}) + (b_{1i} + b_{1j(i)})\mathrm{DAAT1} + (b_{2i} + b_{2j(i)})\mathrm{DAAT2} + (b_{3i} + b_{3j(i)})\mathrm{DAAT3} + \varepsilon_{ijk}$$

Where, i = i^{th} ecoregion (1,2,3,4); j = j^{th} stream within ecoregion (1,2,3,…,N_i); N_i = the number of streams in the i^{th} ecoregion; k = k^{th} day within j^{th} stream within i^{th} ecoregion (k = 1,2,3,…,n_{ij}); n_{ij} = the number of days observed for the j^{th} stream in the i^{th} ecoregion; β_0 = the overall population average intercept; β_1 = the overall effect of air temperature on water temperature; b_{0i} = the deviation in the slope for the i^{th} ecoregion; $b_{0j(i)}$ = the deviation in the slope for the j^{th} stream in the i^{th} ecoregion; b_{1i} = the deviation in the effect of air temperature on water temperature for the i^{th} ecoregion; $b_{1j(i)}$ = the deviation in the effect of air temperature on water temperature for the j^{th} stream in the i^{th} ecoregion; and ε_{ijk} = the random errors.

Fitting the Model: Determination of Appropriate Air Temperature Lag Times

It has been discussed that analyses of the air-water temperature relationship in streams can be improved by the addition of lag times between air and water temperature (Stefan and Preud'homme 1993; Saffran and Anderson 1997; Grant 1977; Webb *et al*. 2003). Thus, when constructing the model, it was important to determine the type of relationship experienced between DAWT and DAAT for reference streams, and to determine how much lag time (in days) is appropriate to include in the model. Initial exploratory analysis was performed by plotting, for each stream, DAWT vs. DAAT, DAWT vs. DAAT1, DAWT vs. DAAT2, and DAWT vs. DAAT3. These scatter plots indicated that, for all reference streams, a linear relationship exists between DAWT and all four DAAT variables, although DAAT and DAAT1 appear to display the least random statistical noise as compared to longer lagged air temperatures.

The initial model was run to determine the significance of the fixed effect, and the deviation from it for each stream and ecoregion, of daily air temperature with zero to three day lag times (DAAT to DAAT3) on daily average water temperature. The level of significance was set at $\alpha = 0.05$.

Improve and Run the Model

As will be shown in the Results section of this report, the Ecoregion, DAAT2 and DAAT3 variables were determined to have an insignificant effect on water temperature. Hence, these variables were removed from the model. The updated model was run and was used to analyze variability in Montana's reference streams as a result of stream and air temperatures with zero (DAAT) and one day (DAAT1) lag time, both of which were found to be able to explain a significant amount of variability in water temperature. Residual analysis was also conducted to assess the adequacy of the model. The basic code for this 'Proc Mixed' model can be found in Appendix C.

Longer-Term Representativeness of the Model given Air Temperature Change

A fifth air temperature variable, monthly average air temperature (MAAT), was calculated for each summer month (June through September) throughout the 11-year period of record, from 1998 to

2008, for each weather station. MAAT is defined as the average of approximately 700 to 1200 (and up to as many as 8000+) measurements per month. This variable is used to analyze whether reference stream temperatures appeared to be sampled during a summer season in which air temperatures were typical of long term averages. For each weather station, MAAT for June, July, August and September were plotted and analyzed to determine whether air temperatures at each weather station exhibit a significant trend (i.e., warming) (see Figure 17). The existence of such a trend would indicate that the summer season in which water temperature was sampled in each stream, associated with a given weather station, may not be truly representative of climatic conditions that may be expected in recent years or those to come, having implications for the applicability and predictive capacity of this model. Fortunately, this does not appear to be the case (see Figure 17).

Results and Discussion

Relating Stream Temperatures to Air Temperature with Various Lag Times

The solution for fixed effects resulting from running the initial model (1) indicates that the effect of DAAT and DAAT1 on DAWT is significant, with $p = 0.0170$ and 0.0470, respectively. However, the effect of DAAT2 and DAAT3 is not significant regardless of ecoregion or stream within ecoregion, with $p = 0.4055$ and 0.5900, respectively. This indicates that there is zero effect overall of two and three day lagged air temperature on the population average of reference stream water temperature. Likewise, the covariance parameter estimates indicate that DAAT2 and DAAT3 also do not have a significant effect on reference stream water temperatures of individual reference streams included in this analysis, with $p = 0.2920$ and 0.2115, respectively. This finding supports the decision to remove DAAT2 and DAAT3 from further analysis.

As described previously, Montana's reference streams are generally relatively narrow and shallow 1st through 4th order streams and so are likely affected more rapidly by changes in air temperature than would be larger streams, thereby negating the need for longer lag times. Also, because weather stations were relatively similar in elevation and proximity to the reference stream sites, they are considered to be adequately representative of the climatic conditions at the stream site itself. Longer lag times may have been needed if air temperature conditions from more distant weather stations had been used; temperatures at these stations are likely to exhibit very different conditions to those at the stream study sites.

Ecoregion-to-Ecoregion Variability in Stream Temperatures and their Relationship to Air Temperatures

The variance of the random intercept at the ecoregion level indicates that there is no significant variability in reference stream water temperatures between ecoregions, with $p = 0.2002$. Also, there is no significant variability in the effect of DAAT and DAAT1 on the air-water temperature relationship between ecoregions, with p = 0.1518 and 0.2116, respectively.

This finding suggests that the ecoregion, while useful when studying *some* ecosystem parameters, may not be the ideal unit for grouping reference streams when conducting stream temperature analyses, particularly those investigating the air-water temperature relationship. This is because a significant amount of variability in Montana's reference stream temperatures *cannot* be explained with the addition of ecoregion as a variable in this model. This has implications for natural resource managers developing water temperature standards, suggesting that the ecoregion scale is too coarse to usefully predict the degree and rate of temperature change that a particular stream ecosystem can withstand, as well as the tolerance of that system to thermal pollution. This also has implications for developing water temperature monitoring projects, whereby sampling schemes that choose monitoring sites according to ecoregion may not capture significant spatial variability occurring at another scale.

Stream-to-Stream (Within Ecoregion) Variability in Stream Temperatures and their Relationship to Air Temperatures

The variance of the random intercept at the stream level indicates that there is significant variability in reference stream water temperatures between streams within ecoregions, with p = 0.0047. Also, there is significant variation in the effect of DAAT and DAAT1 on water temperature in reference streams between streams within ecoregions, with p = 0.0003 and 0.0246, respectively.

Air temperature is shown to explain differing, and significant, amounts of variability on reference stream water temperature when considered at a more site-specific *stream* scale as opposed to the ecoregion scale. Factors that directly influence the air-water temperature relationship (i.e., riparian shading) may be more pronounced in some regions of the state than others, and care must be taken to investigate these changes in the temperature regime of streams at an appropriate scale. Global warming, for example, will likely have a more severe impact on (reference) stream ecosystems that are more sensitive to ambient air temperature than others. Analysis, using this model, of trends in expected reference stream temperatures as the climate warms in the future may help managers know what 'natural' conditions can be expected, and to prioritize which streams or types of stream ecosystems are at the greatest risk of thermal degradation, and set restoration goals accordingly.

Significant stream-to-stream variability also suggests that comprehensive investigation and monitoring of site-specific conditions is crucial for adequately understanding the temperature dynamics of a stream ecosystem. Reference stream monitoring projects would benefit from aiming specifically at investigating stream temperature regimes in light of those variables most influencing stream temperatures (i.e., degree of shading, groundwater exchange, etc.). Unfortunately, while fully comprehensive monitoring is the ideal scenario, it is not always a realistic goal for managers facing limited budgets, time and other resources. Thus, models such as this are useful in that they allow managers to make predictions about and better understand a stream system's thermal regime based on widely-available air temperature data before undertaking any extensive field research. Besides air temperature, other driving, insulating and/or buffering characteristics that control the temperature regimes of individual reference stream ecosystems may also exhibit significant variability when considered on a more site-specific scale. This model would benefit from the addition of other influential variables besides air temperature to conduct a more complete heat budget analysis.

In summary, the Level III Ecoregion scale is too coarse to capture the diverse landscapes in which Montana's streams exist; the landscape can be quite different within a short distance and thus ecosystem parameters that influence water temperature also exhibit site-specific characteristics, particularly as a result of human use of the land for agriculture, rangeland, and urban/suburban development, etc. Thus, managers should aim to sample many more streams grouped at a finer scale than Level III ecoregions to ensure reference streams are representative of all streams in Montana.

Air-Water Temperature Relationship: All Reference Streams

As seen in Table 5, based on the solution for fixed effects, the general equation representing the expected daily average water temperature for *all* reference streams in at least the four ecoregions represented in this analysis for given values of air temperature can be expressed as:

$$\text{Expected DAWT for Reference Streams} = 41.2586 + (0.2050)\text{DAAT} + (0.06295)\text{DAAT1}.$$

Air-Water Temperature Relationship: Individual Reference Streams

Statistically, most (23 of the 36) of the reference streams included in this analysis deviate significantly, in at least one variable, from the overall equation depicting the population average for "all reference streams." Those streams' equations are listed in Table 5, and the estimates and p-values for all streams and the population average are listed in Table 6. If this model is to be used for making predictions about or comparisons between streams (i.e., between "reference" and "degraded"), care should be taken to choose the proper reference equation. If, for example, a stream in question seems likely to exhibit characteristics similar to one of the documented reference streams included in this analysis (i.e., due to proximity or similar air temperature regimes/climatic conditions), the corresponding individual reference equation should be chosen. Otherwise, if there is little reason to believe that the stream in question may deviate significantly from the population average, the general reference equation should be chosen.

Considerations of Ecological Significance

Despite these statistically significant differences, the question remains of whether these individual stream equations produce expected DAWTs that deviate from the population average to a degree of *ecological* significance to influence water quality investigations. If these equations all predict temperatures that are similar (i.e., within 1^{o}F) to predictions from the population average equation, there may be little motivation for choosing a more specific individual reference stream equation with which to simulate the water (temperature) quality of the stream in question.

To assess the degree to which these predicted DAWTs deviate from the population average, the same air temperature value (60^{o}F) was entered into each equation discussed above and shown in Table 5 for both DAAT and DAAT1. As shown in Table 7, when the same air temperature value is input to solve each equation, the predicted water temperatures deviate at least 1.7^{o}F and at most 27.6^{o}F from the population average. This represents a 3% to 48% change between the population average and individual results. A majority (14 of 23) deviate by at least 6^{o}F and, on average, expected DAWT from the individual stream equations deviates 6.91^{o}F (either plus or minus) from the population average.

Some of the individual streams' temperatures are predicted to be higher (+) and some are predicted to be lower (-) than the population average (see Table 7). None of the four Middle Rockies streams deviate from the population average. However, all five Northern Rockies streams deviate from the population average. Water temperatures in these five streams are predicted to be generally cooler than the population average temperatures. This is very likely because these streams are all higher elevation, cold headwater streams in the Yaak region of northwestern Montana. The predicted water temperatures for most (4 of 5) of the Northwestern Glaciated Plains streams deviate from and are mostly warmer than the population average. This is likely because they tend to be low-flow prairie streams with little shade from riparian vegetation. An exception to this is Deer Creek-1which is located in the foothills of the Sweetgrass Hills, a small island mountain range in north central Montana. As such, Deer Creek-1 is at a much higher elevation and has substantially more riparian vegetation than the other streams in this ecoregion. Finally, most (9) of the twelve Northwestern Great Plains streams that deviate from the population average are predicted to be warmer, whereas only three are predicted to be warmer than the population average. Similarly, many of these streams are rather small and unshaded prairie streams. In contrast, Sweetgrass Creek and Rock Creek II (2007) are both located in the Crazy Mountains, have higher elevations than the rest and more shade, and are thus not surprisingly generally warmer than others within the ecoregion. The Unnamed Tributary to Little Deer Creek is also not surprisingly cooler than the rest since this stream is incredibly narrow and shallow but was *completely* shaded by mature woody vegetation (see Table 7). Although it is not possible based on this analysis to explain exactly why Lost Boy Creek is predicted to be so drastically warmer than the population average, it is likely because this is an ephemeral stream located in the (extremely hot and arid) Terry Badlands in far eastern Montana. It consists of isolated, shallow pools for much of the summer and appears to have little cool groundwater inflow, perhaps leading it to respond more rapidly to rising air temperatures experienced throughout the summer season. Overall, the individual reference stream equations appear to predict temperatures that deviate enough from the reference stream population average to have potentially ecologically significant implications for management applications of this model. This underscores the recommendation that the equations described here be chosen carefully according to the management goal/intent as well as the level of sensitivity of the system in question.

Model Adequacy (Diagnostics or Residual Analysis)

In checking the model's assumptions, the effect of non-normality on these data analyses can be assumed to be negligible because a very large data set is being used. Also, the autoregressive (AR) serial dependence term indicates that there is significant serial dependence between water temperature and air temperature *over time*, with $p = <0.0001$; this supports the model's inclusion of autoregressive type serial dependence and makes it more reliable.

Residual analysis did not identify anything that indicates the model's assumptions are invalid. As shown in Figure 24, when the residuals are plotted against the linear predictors of water temperature, no pattern (i.e., parabolic, linear, funneling) is apparent, suggesting confidence that the model was specified correctly.

Furthermore, boxplots depicting water temperatures for each stream within each ecoregion were created (see Figure 18). These generally display a symmetrical distribution. This further supports our confidence in the model and the findings presented above. Also, when compared between ecoregions, very little variation among boxplots is apparent and the interquartile ranges of all streams temperatures range between approximately 46^{o}F and 80^{o}F, whereas a substantial variance is apparent when compared for streams within ecoregions (see Figure 18). For example, it is apparent in Figure 18 that water temperatures in Deer Creek-1 differ substantially from water temperature in the other streams in the Northwestern Glaciated Plains ecoregion. As previously described, and unlike the other less shaded prairie streams, Deer Creek-1 is a high-elevation, substantially shaded steam in the foothills of the Sweetgrass Hills.

It is important to note that this model requires that air and water temperature data be entered in degrees Fahrenheit (^{o}F), and is applicable only to summertime temperatures.

Longer-Term Air Temperature Data Trends

To be useful for forming management prescriptions, particularly water quality standards, reference stream temperature data must be representative of the natural temporal variability in Montana's streams. Some concern arose throughout the development of this model regarding the fact that these reference streams are only sampled throughout a *single* summer. If the reference streams' water temperatures had been measured during an exceptionally hot or cool summer, the data used to fit and run the model would not necessarily be representative of the "typical" climatic conditions and stream temperatures for that given reference site. Although serial dependence in water and air temperature *over time* in the model, the potentially significant amount of natural year-to-year variability in Montana's stream temperatures suggests the need for reference streams to be studied for multiple consecutive years to obtain a more representative sample.

However, upon further investigation, no significant year-to-year variation in the summer (June-September) monthly average air temperatures (MAAT) exists for the previous 11 years (1998-2008) at any of the weather stations incorporated in this study (see Figure 17). On average, monthly air temperatures at each weather station paired with a reference stream are not exhibiting a significantly upward, downward, or other, trend, and instead remain rather consistent (horizontal) between 60-70^{o}F (see Figure 17). Accordingly, during the time the reference project has been conducted the air temperatures at these weather stations have been similar, so it is probably appropriate to compare stream temperatures across those years of study. This suggests that the model's findings, described above, and the model itself, may be reliably able to predict reference stream water temperatures and describe the air-water temperature relationship in future years, provided no major alterations are made to the stream or climatic system. In light of natural and human-induced climate change, forecasts of water temperature change over longer time scales must still, of course, remain tentative. While air temperatures during the summers that these streams were sampled, from 2004 to 2008, do not appear to be atypical of the long-term average from 1998-2008, air temperatures in the past 10+ years have been substantially warmer than those previous on record; warming trends over the past many decades coupled with projections of continued warming must be considered (see Figure 3).

Conclusion

The creation of water quality standards has serious implications for stream ecosystems, and the dynamic nature, and variability in space and time, of stream temperature makes this water quality parameter perhaps more difficult to regulate than others that can rely on more simplistic thresholds. The hierarchical nature of random coefficient regression models allows for the integration of multiple variables and provides for both the assessment of the individual effect of each variable as well as their combined effect on the dependent variable in question. As such, they lend themselves to the investigation of complex relationships inevitably found in natural ecosystems, in which all parameters interact with one another to produce the conditions that result. This provides some of the flexibility that is needed to approach stream temperature investigations with a systems perspective, and is particularly helpful for identifying those variables that can explain the most significant variability. Predictive models can be used and revised over time, as well, making them a useful tool for adaptive management schemes. However, it must be realized that predictive models are simplifications that are inherently limited in scope and cannot replace carefully designed and executed field investigations. Also, while the importance of the air-water temperature relationship has been well documented and is supported by the findings of this study, there remains the potential for improvement of this model for more accurate simulation of on-the-ground conditions. Several other variables may be of particular interest.

The inclusion of catchment size, for example, may allow for a more watershed-scale analysis of stream temperature variability and allow managers to better explain variability when upstream and downstream drivers/influences are taken into account (Stefan and Preud'homme 1993). Similarly, the integration of land-use factors may also help managers explain regionalized differences in stream temperatures, and identify regions particularly at risk of thermal degradation. It has also been suggested that mean basin elevation correlates well with stream temperature and that elevation may be used as a surrogate whenever stream temperature data are unavailable (Isaak and Hubert 2001; Meays *et al*. 2005). Thus, the model described here, or similar models, may be improved with the inclusion of elevation as a parameter beyond using it simply to prioritize the choice of associated weather stations. Solar radiation, in its role as the primary driver of stream temperature, may also be worthwhile to include, although it can be difficult to measure in the field. Also, since the volume of water flowing through a stream system, coupled with the shape of the channel itself, plays a major role in determining the stream's thermal capacity and sensitivity to climatic drivers, especially air temperature and incoming solar radiation, the inclusion of discharge and width-depth ratio and/or other measures of channel geometry may be beneficial. Likewise, groundwater-surface water interactions play a critical role in regulating temperatures in some streams and the adequacy of modeling these streams' temperatures may require the inclusion of hyporheic exchange. An analysis of soil slopes and permeability in the watershed may help to identify runoff- versus groundwater-dominated streams. Streams with steeper, less permeable soils are often dominated by runoff, whereas streams with flatter, more permeable soils are typically associated with a larger groundwater component. Some metric to relate the degree of shading, particularly by (relatively) undisturbed riparian vegetation, could also be incorporated in the future.

Unfortunately, stream sampling schemes often fail to adequately quantify the aforementioned variables, thus diminishing the ability to incorporate them into modeling and management scenarios. The MT DEQ Reference Stream Project does, however, involve the collection of data on many physical, chemical, and biological parameters, thereby enhancing reference streams' potential for use to understand natural variability in Montana's stream ecosystems. Given a clear and accurate understanding of *natural* variability in temperatures in *unaltered* streams, managers will be better equipped to identify, explain, and address unnatural changes experienced by these systems, and the model presented here begins to achieve this understanding.

SECTION 4: FINAL CONCLUSIONS AND RECOMMENDATIONS FOR STREAM TEMPERATURE MANAGEMENT

Limitations of the Current Stream Temperature Management Scheme

Biological integrity is defined as the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region (Karr and Dudley 1981; Apfelbeck 2007). Often, the focus of stream assessment is to evaluate biological integrity because it provides a direct measure of aquatic life beneficial use support, and the assessment of biotic communities can help identify water quality stressors, such as elevated temperatures, nutrients, toxic metals and sediment, that cause degradation (Apfelbeck 2007). Unfortunately, stream management scenarios too often focus solely on one, or few, indicator species and on protecting human uses of surface waters. Also, stream temperature restoration projects tend to assume that the manipulation of one, or few, physical stream characteristics (i.e., altering the width/depth ratio to narrow widened channels and change the thermal capacity, or enhancing shading with riparian vegetation) will be sufficient and will elicit similar responses in different streams.

Recently, however, a shift in the dominant paradigm of stream management has begun to take hold. The natural flow regime paradigm calls for restoring the full range of the natural flow regime (Poff *et al*. 1997; Lytle and Poff 2004). Whereas traditional stream restoration techniques often focus on making *structural* changes to stream channels, this new paradigm calls for a more *process*-based approach and considers major drivers of stream (flow) dynamics. Due to the strong relationship between stream temperature and discharge, maintenance and restoration of the natural flow regime will surely aid in maintenance of natural thermal regimes as well. Despite this shift, stream temperature management, particularly in the western United States, often continues to concentrate on maintaining minimum low flows during the hottest time of the year, primarily for maintenance of fisheries and anthropogenic water demands (Poff *et al*. 2007; Larson 1981). In Montana, for example, salmonid species in cold-water regions of the state often serve as the ultimate indicator of overall stream health and integrity. Our growing understanding of the complexities and ecological significance of stream temperatures has emphasized the need for a more holistic, systems-oriented approach to managing stream temperatures as thermal degradation persists.

Because the *complete* description and quantification of entire natural ecosystems is inherently beyond human comprehension and study, management and restoration of stream temperatures must inevitably rely on making assumptions. These include assumptions regarding the basic behavior, the major influential variables, and the expected response to human manipulation of stream temperatures.

Mathematical models, such as that presented here, can help to test the validity of these assumptions and can be an asset to managers seeking to efficiently and effectively measure and analyze stream temperatures at the proper spatial and temporal scales, and using proper methods. This model could be used for a variety of applications, several of which are described briefly below.

Furthermore, limitations in the collection and summary of stream temperature data in Montana complicates efforts to research and analyze stream temperature, leaving many of these assumptions untested. To ensure that these management and restoration assumptions are based on the best possible approximations of stream 'reference condition', it is critical that managers, and others, design stream temperature studies with thermal energy budget analyses in mind as much as possible. Achieving the ultimate goal of regulating stream temperatures such that all biotic and abiotic components are able to maintain their structure and function, and thus preserve *ecosystem* integrity, requires an understanding of stream heat flux components, as well as the collection and summary of comprehensive, accurate field data, and useful analytical tools. Based on realizations made throughout this study, several recommendations for improving upon current (reference) stream data collection and analysis are included below and will hopefully be considered during future efforts to achieve water quality goals.

Applications of the Model

Reference Stream Site Choice and Screening

As described in Section 2 of this report, the MT DEQ adheres to an intensive and time-consuming protocol for choosing potential reference streams, which is followed by additionally intensive site assessment and screening phases. The model developed and described in this study may also be helpful by allowing monitoring project planners investigating spatial variability of stream temperatures to determine, before doing fieldwork, if it seems likely the streams that have been chosen for sampling may actually exhibit significant differences in water temperatures. This may be helpful for strategizing which potential reference streams to choose in the future. For example, to save time, travel and money, prior to on-site visits, managers could choose either the 'reference population average' or a more closely-paired individual reference stream equation, "plug in" air temperature data, which is more readily-available and can be remotely accessed via the Internet, and run the model to determine the expected stream temperature. Then, once on-site measurements are taken upon the first site visit, managers could better determine if the potential stream is behaving 'as expected' for natural and local conditions. If the potential reference sites' predicted water temperatures do not appear to be in line with the expected values for other similar reference streams as projected from the model, this may be an indication that the site is experiencing some degree of thermal degradation. It is recommended that multiple (at least three) reference streams are chosen as opposed to a single reference. Also, the basis on which to choose which individual reference stream equation may differ depending on the region or need for comparison. It is recommended that, when temperature is the variable in question, reference streams are chosen or first prioritized according to similarities in the drivers of stream temperature (i.e., solar radiation, air temperature, wind speed, phreatic groundwater temperature and discharge, solar angle, cloud cover, relative humidity, precipitation, topographic shade, upland vegetation, and tributary temperature and discharge) (see *Drivers of Stream Temperature* in Section 1 of this report). Similarities in elevation and other insulating and buffering factors should be additional considerations when choosing a reference stream.

Stream Temperature Study Design

As previously discussed, Montana's size, beneficial use and cold- vs. warm-water fisheries delineations, climate, etc., seems to indicate that streams would exhibit significantly different temperatures in different ecoregions. Perhaps the most enlightening outcome of this study lies in the rather surprising finding that temperature in Montana's reference streams, at least those included in this study, does not vary significantly from ecoregion-to-ecoregion. Because of the role that the Level III ecoregion scale plays in the study design and sampling scheme of the MT DEQ Reference Stream Project, and other ecosystem investigations, those responsible for designing these monitoring plans should avoid basing site choice on which ecoregion it lies within. Furthermore, managers seeking to test other scales that may be more appropriate for studies intending to capture natural variability in stream temperatures, and investigating the air-water temperature relationship, may adapt this model to accommodate the grouping/descriptive variable of choice. Other variables that may be useful to test include the Level IV ecoregions (see Table 3 and Figure 22) (Woods *et al*. 2002), Montana's major drainage basins (see Figure 22) or the USGS 4th-code Hydrologic Unit Codes (HUCs) that delineate drainage basins and also delineate TMDL planning areas (see Figure 7)) (MT DEQ 2007).

Inform Restoration Goals/Objectives

Typically faced with the aforementioned resource limitations, restoration project planners could more efficiently plan and execute stream temperature restoration projects with clear knowledge of the precise causes of thermal degradation. While this study does not allow managers to identify caused of thermal degradation, and understanding of how stream temperatures can be expected to respond to changes in the air-water temperature relationship is helpful. Effective restoration of thermally impaired streams will require the human manipulation of multiple components of the thermal energy budget to achieve the purpose of restoring their natural thermal regimes. To set reasonable goals and expectations for restoration of a degraded stream, it is critical that an appropriate 'reference condition' is chosen. The findings of this study suggest that, when choosing a reference stream to represent a restored stream's desired outcome, it is not sufficient or useful to first choose a reference stream from within the same ecoregion as the degraded stream. Also, as previously mentioned, since considerable variability can be expected between streams within the same ecoregion, reference site choice must consider similarity in the primary driving, insulating and buffering factors influencing each stream's thermal energy budget. Once a documented reference stream is chosen, air temperature conditions from the degraded site could also be used to solve the respective reference stream equation to obtain an idea of the water temperatures that are considered 'natural' or 'acceptable' under given climatic conditions. Target temperatures for restoration could then be based, at least in part, upon these expectations.

Prediction of Future Impacts of Climate Change

Given the importance of water temperature to the quality, ecology, utility and sensitivity of streams, it is of considerable interest to understand how thermal regimes have changed in the past and how they may be modified in the future (Webb 1996). As discussed in Section 1, climate change is one major factor that is likely to influence stream temperatures in the future, and analyses of trends in expected future water temperatures over time rely on prediction. The model presented here may be useful to managers in predicting how much of an increase in temperature may be expected in Montana's reference streams as a result of a warming climate.

For example, Table 8 shows the expected daily average water temperature (DAWT) for the reference streams included in this study over five decades when the model-derived equations are solved using a baseline DAAT and DAAT1 of 60^{o}F for 2009 and assuming a climate warming rate of 0.11°F per decade (see Figure 3), as projected for Montana (NOAA 2009a). Expected reference stream temperatures increase only a very small amount, several hundredths of a degree per decade, indicating rising air temperatures on the state-wide scale may not be as ecologically significant. Even when these equations are solved for conditions that would exist 200 years from now (i.e., 62.2^{o}F in 2209), they predict water temperatures that are still less than one degree different than those predicted based on current conditions in 2009 (see Table8). These applications have interesting implications since reference streams theoretically depict temperatures that would have, except for climate change, remained otherwise unaltered. As such, these predictions require the assumptions that other influential factors on reference stream temperatures have not significantly changed in the short-term as climate change occurs, and that regional expectations of warming will be experienced similarly at each stream site. Unfortunately, this is not likely the case, and the long-term effects of climate change will realistically be amplified by other detrimental human activities in the short-term. Generally, the air-water temperature *relationship* is not likely to change substantially, and since many climate scenarios focus on predictions of air temperature changes, this model's the inclusion of air temperature seems ideal for generally predicting the effect of climate change on stream temperatures. However, even these slightly warmer air temperatures may cause changes in snowmelt, runoff, groundwater interactions and other hydrologic properties that will influence the air-water temperature relationship and so predictions made centuries into the future based on this relationship alone may not necessarily provide accurate results.

Management Recommendations

As discussed throughout this report, while stream temperature management and restoration have positive intentions of maintaining thermal integrity, management approaches tend to be limited in scope for a variety of reasons. Detailed expressions of spatial and temporal variability are sometimes replaced with "snapshot views" of the temperature conditions. Summer sampling periods may provide information about the upper range of thermal tolerances for aquatic organisms, but they fail to capture variability in, and response to, other extreme climatic and hydrologic conditions throughout the year that are critical in shaping the nature of the stream system and its biological communities. These include extreme low temperatures in the winter and other extreme periods of drought and flooding. Furthermore, while fish and other higher-order stream organisms can serve as useful indicators of biological integrity, management and restoration projects that focus exclusively on these without regard for overall ecosystem form and process may miss capturing the full impacts of thermal degradation on the system.

Although it was beyond the scope of this report to test the significance of these limitations, several recommendations for reference stream data collection and analysis are discussed below. These help to identify opportunities for future stream temperature investigations and improvements to this model.

Recommendations for Stream Temperature Data Collection/ Summary/Analysis

Spatial variability complicates stream management and restoration. The lotic nature of streams means the effects of activities that affect upstream discharge and temperatures will be felt downstream, and so management prescriptions must be made from a watershed-scale perspective. Also, since environmental (i.e. climatic) conditions that form boundary conditions for stream ecosystems vary throughout different regions of the state, ecologically-based classification of spatial regions can be useful when determining appropriate water quality standards.

Temporal variability also makes restoration of thermal regimes difficult. In the long-term, climate will exert a fundamental control on stream temperatures and, as global climate change accelerates, stream temperature issues will be increasingly challenging to address. Daily and seasonal variations are also important to overall thermal dynamics and, to form pragmatic and ecologically-sound restoration goals, it will be crucial to understand the natural constraints on temperatures of individual streams. Also, since thermal degradation tends to stem from several indirect sources, it is likely that restoration of thermal regimes may often be accomplished only over a longer time scale and immediate improvements will not be apparent. For example, riparian vegetation growth may eventually provide adequate shade but a newly planted riparian buffer cannot be expected to supply immediately the benefits that it will once fully established.

As a result of this variability, current water quality temperature standards (see Table 2) are inevitably quite confusing, particularly because they limit rates of change over short time periods and differ quite a bit according to beneficial uses and classifications. Current sampling schemes are sometimes insufficient to detect these changes in a manner that is detailed enough to be able to effectively identify impaired streams and enforce standards. Each stream assessment plan needs a comprehensive sampling strategy and clear goals with respect to stream temperature

To better capture spatial variability, temperature data loggers could be deployed in *more* streams throughout the state, and sampled at a scale that can be shown to explain enough variability in stream temperatures to allow setting stream-specific temperature standards. Currently, temperature data exists for only a small number of reference streams in each ecoregion. Consequently, and as shown in this analysis, this quantity of data is insufficient to allow for analysis of variability in stream temperatures within regions that are smaller than ecoregions. If temperature is measured in additional reference streams, reference streams may be grouped together at a finer scale which may better facilitate the analysis of variability in temperature. Then, once managers identify the scale at which significant variability in stream temperature is apparent between these regions, more spatially explicit temperature standards could be developed to reasonably reflect natural variability. Also, the placement of additional data loggers in each stream site would provide a more complete picture of reach-scale characteristics of the streams, particularly habitat heterogeneity with respect to maintenance of temperature requirements for aquatic organisms (i.e., at various depths, on both banks, in the hyporheic zone, in pools and riffles, in regions of variable shading by riparian vegetation, etc.). At a minimum, two temperature data loggers should be placed in each stream to avoid losing data due to instrument malfunctions, loss, or damage.

Since temperatures may vary significantly from year-to-year, a single season of reference stream temperature data may be insufficient to adequately determine “characteristic temperature regimes”. Therefore, stream monitoring plans that measure for a much longer period of record (i.e., over the course of multiple years, throughout multiple seasons of per year) are recommended. Although the summer air temperatures have not varied significantly from year-to-year at weather stations over the past 11 years (during which time the reference stream project has been conducted), significant variance may be apparent if considered over a longer that 11-year period of time. This suggests that further investigation into how reliably *one* summer period of record of reference stream temperatures, as analyzed in this report, can be used to represent 'natural conditions' in coming decades may help to ensure that truly representative reference data is being used to inform management actions.

In addition to the MT DEQ, many other state and federal agencies are involved with the collection of temperature measurements in streams (i.e., Montana Department of Fish, Wildlife, and Parks, U.S. Geological Survey). The science and management communities would benefit from a state-wide database in which stream temperature data could be compiled, coupled with site descriptions and quality assessments, and made publicly available. Similar databases already exist for a number f other water-related variables, such as the Ground Water Information Center (GWIC). Ideally, the data would be continuous, collected with similar data loggers and at the same granularity (i.e., every 30 minutes). These databases could also include site-specific records of air temperature or other stream temperature driving variables.

Stream temperature investigations would also benefit from the identification of thermal metrics (i.e., daily maximums, 7-day running average daily means, monthly or annual degree-days, cumulative days the maximum is above a certain threshold for aquatic species) that are the most useful for making ecologically-meaningful comparisons between streams, years and driving variables. Finally, particularly because stream temperature standards are complex and difficult for the "layman" to comprehend, public outreach and education about the ecological significance of stream temperature, its role as a critical water quality parameter, and the importance of regulating thermally degrading activities, may help to minimize thermal impairment.

Final thoughts on Management and Restoration of Stream Temperatures in Montana

Some have advocated for the development of water quality "regime" standards, which would describe desirable distributions of conditions over space and time within a stream network (Poole *et al*. 2004), rather than reliance on a single threshold value (Bisson *et al*. 1997, Poff *et al*. 1997). This approach recognizes the importance of the dynamics associated with healthy ecosystems and focuses the development of water quality standards on supporting and protecting important patterns of natural variability, and should be applied at coarse spatial scales (Poole *et al*. 2004).

A review of the boxplots produced for each reference stream's summer daily average temperatures may help to provide a framework for developing such regime-based standards. To begin, the boxplots help managers to describe the thermal conditions that could be expected over the summer season for individual reference streams. This may be particularly helpful for describing those streams that exhibit temperatures that differ substantially from other streams in the same ecoregion (or other scale), or that deviate significantly from the population average. For example, upon review of the boxplot for Deer Creek-1, it is apparent that this stream differs substantially from the other reference streams in the

Northwestern Glaciated Plains ecoregion (see Figure 18). Deer Creek-1 is also predicted to exhibit temperatures that are approximately 4°F cooler than the reference stream population average (see Table 7).

The boxplot for this stream can be used to discuss the expected thermal characteristics of Deer Creek-1 stream and could hence aid managers when describing the characteristics of other reference streams that are believed to be similar to this stream according to thermal driving, insulating and buffering characteristics. Upon review of the boxplot for Deer Creek-1, it may be reasonable to believe that maximum temperatures should not exceed 61°F, and minimum temperatures should not fall below 43°F, for any substantial period of time. Also, when monitoring temperatures, managers could assume that roughly half of the measurements should fall above, and half below, the median temperature of 53.5°F for this stream and those like it. Finally, with a lower quartile temperature of 49.5°F, temperatures should not fall below this value for any more than 25% of the time and, likewise, temperatures should not exceed the upper quartile temperature of 56.6°F any more than 25% of the time. These types of thermal guidelines can be referenced, for example, during monitoring to help determine if an existing reference stream has begun to experience ‘unnatural’ temperatures. They could also inform managers’ expectations of temperature regimes of streams that are similar to the existing reference stream.

Furthermore, and as discussed throughout this analysis, streams will not necessarily exhibit similar thermal regime characteristics simply because they are located within the same spatial region. As such, the boxplots in Figure 18 may help managers to group streams according to the thermal characteristics that they experience over the course of a summer season. This may then allow for the development of stream temperature standards based on similarities in stream characteristics that influence stream *temperatures* rather than over a defined spatial scale (ie., ecoregion, watershed). For example, it is apparent that the temperature regimes of Sweetgrass Creek and Rock Creek II (2007) differ substantially from the regimes of other reference streams in the Northwestern Great Plains ecoregion (see Figure 18). However, the interquartile ranges of these two streams are closely aligned with those of Grizzly Creek and White Creek in the Northern Rockies ecoregion. As such, a regime-based stream temperature standard could be based, in part, on the distribution of these streams’ boxplots and then applied to these and other similar streams. By mandating the protection and restoration of the aquatic ecosystem dynamics that are required to support beneficial uses in streams, well-designed regime standards would facilitate more effective strategies for management of natural water quality parameters (Poole *et al*. 2004). In such instances, managers and stakeholders would be charged with developing a restoration plan to comply with the regime standard (Poole *et al*. 2004).

One limitation of this approach is that streams that deviate, and those that do not deviate, from the model’s predicted population average cannot be easily distinguished by their boxplots of daily average water temperatures (see Figure 18). This is likely because streams that deviate from the population average tend to do so because of a difference in the effect of at least one of the daily average *air* temperature terms within the model (DAAT and/or DAAT1), and not necessarily because of a difference in *water* temperature itself. Thus, a stream that *does* deviate may exhibit a similar daily average water temperate boxplot as another stream that *does not* deviate, particularly if the effect of daily average air temperature (with zero or one day lag) is the only term by which this deviation from the population average is significant. As a result, reviewing the boxplots provides a relatively limited view of the air-water temperature relationship exhibited by these streams.

In conclusion, since a multitude of factors influence stream temperatures, there will often likely not be a simple solution to restoring natural temperature regimes. Restoration efforts must begin with a comprehensive investigation of the ecological community that is being adversely affected. Careful identification of the causes and severity of impairment should follow, upon which restoration goals can be based. Future monitoring schemes should also be included in stream temperature restoration and management plans to allow for evaluation of success and adaptive management purposes. Gaining a conceptual understanding of the processes and structures that influence stream temperature in *unaltered* systems is a challenge that will persist into the future. The reference condition approach provides a framework from which spatially-explicit “acceptable temperature ranges” based on reference stream data can be carefully developed and used to inform the creation of numeric and narrative water quality standards for stream temperature. As a result, long-term, comprehensive and thoughtfully-designed stream assessment projects like the MT DEQ Reference Stream Project are critical and should continue and be improved upon for the foreseeable future.

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Table 1 - Montana surface water beneficial use classifications

Classification	**Description**
A-CLOSED	Waters classified A-Closed, are suitable for drinking, culinary and food processing purposes after simple disinfection.
A-1	Waters classified A-1, are suitable for drinking, culinary and food processing purposes after conventional treatment for removal of naturally present impurities.
B-1	Waters classified B-1, are suitable for drinking, culinary and food processing purposes after conventional treatment; bathing, swimming and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.
B-2	Waters classified B-2, are suitable for drinking, culinary and food processing purposes after conventional treatment; bathing, swimming and recreation; growth and marginal propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.
B-3	Waters classified B-3, are suitable for drinking, culinary and food processing purposes after conventional treatment; bathing, swimming and recreation; growth and propagation of non-salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.
C-1	Waters classified C-1, are suitable for bathing, swimming and recreation; growth and propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.
C-2	Waters classified C-2, are suitable for bathing, swimming and recreation; growth and marginal propagation of salmonid fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.
C-3	Waters classified C-3, are suitable for bathing, swimming and recreation; growth and propagation of non-salmonid fishes and associated aquatic life, waterfowl, and furbearers. The quality of these waters is naturally marginal for drinking, culinary and food processing purposes, agriculture, and industrial water supply. Degradation which will impact existing or established uses is not allowed.
I	The goal of the State of Montana is to have these waters fully support the following uses: drinking, culinary and food processing purposes after conventional treatment; bathing, swimming and recreation; growth and propagation of fishes and associated aquatic life, waterfowl and furbearers; and agricultural and industrial water supply.

(MT DEQ 2006a; ARM 17.30.604-629)

Table 2 - Montana's stream temperature standards, 2009

Specific surface water quality standards, along with general provisions in ARM 17.30.635 through 17.30.637, 17.30.640, 17.30.641, 17.30.645, and 17.30.646, protect the beneficial water uses set forth in the water-use descriptions for the following classifications of water (17.30.620). SAMPLING METHODS (1) Water quality monitoring, including methods of sample collection, preservation, and analysis used to determine compliance with the standards must be in accordance with 40 CFR Part 136 (July 1, 2007) or other method allowed by the department. 17.30.641. Narrative temperature standards set for Montana's streams that have been deemed to support beneficial uses (A, B, C, & I) and specifically for classifications A-closed, A1, B1, B2, B3, C1, C2, C3, & I (from A.R.M. **17.30.601-17.30.629,** 2006).

Use Classification	Temperature Standards	A.R.M. Section
A-CLOSED	No increase above naturally occurring water temperature is allowed.	17.30.621
A-1	A 1ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 66ºF; within the naturally occurring range of 66ºF to 66.5ºF, no discharge is allowed which will cause the water temperature to exceed 67ºF; and where the naturally occurring water temperature is 66.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF. A 2ºF-per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF.	17.30.622
B-1	A 1ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 66ºF; within the naturally occurring range of 66ºF to 66.5ºF, no discharge is allowed which will cause the water temperature to exceed 67ºF; and where the naturally occurring water temperature is 66.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF. A 2ºF per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF. This applies to all waters in the state classified B-1 except for Prickly Pear Creek from McClellan Creek to the Montana Highway No. 433 crossing where a 2ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 65ºF; within the naturally occurring range of 65ºF to 66.5ºF, no discharge is allowed which will cause the water temperature to exceed 67ºF; and where the naturally occurring water temperature is 66.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF.	17.30.623
B-2	A 1ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 66ºF; within the naturally occurring range of 66ºF to 66.5ºF, no discharge is allowed which will cause the water temperature to exceed 67ºF; and where the naturally occurring water temperature is 66.5ºF or greater,	17.30.624

	the maximum allowable increase in water temperature is 0.5ºF. A 2ºF per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF.	
B-3	A 3ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 77ºF; within the naturally occurring range of 77ºF to 79.5ºF, no thermal discharge is allowed which will cause the water temperature to exceed 80ºF; and where the naturally occurring water temperature is 79.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF. A 2ºF per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF.	17.30.625
C-1	A 1ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 66ºF; within the naturally occurring range of 66ºF to 66.5ºF, no discharge is allowed which will cause the water temperature to exceed 67ºF; and where the naturally occurring water temperature is 66.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF. A 2ºF per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF.	17.30.626
C-2	A 1ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 66ºF; within the naturally occurring range of 66ºF to 66.5ºF, no discharge is allowed which will cause the water temperature to exceed 67ºF; and where the naturally occurring water temperature is 66.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF. A 2ºF per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF.	17.30.627
C-3	A 3ºF maximum increase above naturally occurring water temperature is allowed within the range of 32ºF to 77ºF; within the range of 77ºF to 79.5ºF, no thermal discharge is allowed which will cause the water temperature to exceed 80ºF; and where the naturally occurring water temperature is 79.5ºF or greater, the maximum allowable increase in water temperature is 0.5ºF. A 2ºF per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55ºF. A 2ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55ºF to 32ºF.	17.30.629
I	No increase in naturally occurring temperature is allowed which will or is likely to create a nuisance or render the waters harmful, detrimental, or injurious to public health, recreation, safety, welfare, livestock, wild animals, birds, fish, or other wildlife.	17.30.628

(ARM 17.30.621-629)

Table 3 – Reference stream site identification and location by Level III Ecoregion

Reference Stream by Level III Ecoregion	Year Sampled	Latitude	Longitude	Elevation (m)	Level IV Ecoregion	County
MIDDLE ROCKIES						
Cottonwood Creek	2004	44.9425	112.4294	2006	Dry Intermontane Sagebrush Valleys	Beaverhead
Willow Creek II	2004	45.483	112.7422	1612	Dry Intermontane Sagebrush Valleys	Beaverhead
Elk Springs Creek	2004	44.6444	111.6636	2031	Centennial Basin	Beaverhead
Willow Creek I	2004	45.4481	112.8277	1859	Pioneer-Anaconda Ranges	Beaverhead
NORTHWESTERN GLACIATED PLAINS						
Rock Creek II (state land)	2004	48.5858	106.9981	696	Glaciated Northern Grasslands	Valley
W.Fk. Poplar River	2004	48.4149	105.4954	769	Glaciated Northern Grasslands	Roosevelt
Wolf Creek at Wolf Point	2004	48.0866	105.6769	614	Glaciated Northern Grasslands	Roosevelt
Woody Island Coulee	2008	48.9227	108.3806	858	Glaciated Northern Grasslands	Blaine
Deer Creek-1	2008	48.9831	111.566	1281	North Central Brown Glaciated Plains	Toole
NORTHERN ROCKIES						
Cache Creek	2006	46.7979	114.6558	1168	Grave Creek Range - Nine Mile Divide	Mineral
N. Fork Canyon Creek	2006	48.4202	115.1918	1124	Salish Mountains	Lincoln
N. Fork Fish Creek	2006	46.9126	114.8181	1082	St. Joe Schist-Gneiss Zone	Mineral
Straight Creek	2006	46.9099	114.8188	1085	St. Joe Schist-Gneiss Zone	Mineral
White Creek	2006	46.7957	114.6607	1180	Grave Creek Range - Nine Mile Divide	Mineral
North Fork 17 Mile Creek	2008	48.6619	115.7623	942	Purcell-Cabinet-North Bitterroot Mountains	Lincoln
Flattail Creek	2008	48.6243	115.7142	1012	Purcell-Cabinet-North Bitterroot Mountains	Lincoln
Smoot Creek	2008	48.7203	115.6436	1014	Salish Mountains	Lincoln
East Fork Basin Creek	2008	48.8753	115.484	1276	Salish Mountains	Lincoln

Reference Stream by Level III Ecoregion	Year Sampled	Latitude	Longitude	Elevation (m)	Level IV Ecoregion	County
Independence Creek	2008	48.7056	115.8581	904	Purcell-Cabinet-North Bitterroot Mountains	Lincoln
Grizzly Creek	2008	48.7464	115.8188	1107	Purcell-Cabinet-North Bitterroot Mountains	Lincoln
NORTHWESTERN GREAT PLAINS						
Hart Creek	2006	47.5674	106.9657	705	River Breaks	Garfield
Hell Creek 1 - Lower	2006	47.3452	106.5778	724	River Breaks	Garfield
Snap Creek	2006	47.5566	106.2923	688	River Breaks	Garfield
Lost Boy Creek	2007	46.7998	105.4208	681	River Breaks	Prairie
Sweetgrass Creek	2007	46.1529	110.1815	1764	Non-calcareous Foothill Grassland	Sweet Grass
Rock Creek II (state land)	2007	47.2545	106.838	1817	Non-calcareous Foothill Grassland	Garfield
Crow Creek	2007	45.6788	105.1219	877	Montana Central Grasslands	Powder River
Little Powder River	2007	45.2001	105.3144	971	Montana Central Grasslands	Powder River
Milk Creek	2007	46.1673	104.6787	882	Montana Central Grasslands	Fallon
Boxelder Creek	2007	47.2714	104.4989	613	River Breaks	Dawson
Krug Creek	2007	47.0922	104.6102	643	River Breaks	Dawson
Little Beaver Creek	2007	46.0453	104.3728	954	Montana Central Grasslands	Fallon
Boxelder Creek	2008	47.339	109.0117	1095	Montana Central Grasslands	Fergus
Beaver Creek	2008	47.0834	109.5994	1159	Judith Basin Grassland	Fergus
Little Deer Creek	2008	47.2554	109.2689	1312	Non-calcareous Foothill Grassland	Fergus
Unnamed Tributary to Little Deer Creek	2008	47.257	109.2662	1319	Non-calcareous Foothill Grassland	Fergus

Table 4 – Reference stream site data logger number, period of record, and associated weather station

Water Body Name	**Period of Record**		**Year**	**Temp Logger Number**	**Stream Elevation**	**Weather Station Elevation**	**Difference in Elevation**
	Begin	**End**			**(m)**	**(m)**	**(m)**
Cottonwood Creek	27-Jul	12-Sep	2004	578049	2006	1591.7	414.3
Willow Creek II	17-Aug	10-Sep	2004	650635	1612	1591.7	20.3
Elk Springs Creek	20-Jul	14-Sep	2004	650640	2031	2076	-45
Willow Creek I	17-Jul	14-Sep	2004	650641	1859	1591.7	267.3
Cache Creek	13-Jul	8-Sep	2006	578177	1168	972	196
N. Fork Canyon Creek	11-Jul	3-Sep	2006	617397	1124	906.2	217.8
N. Fork Fish Creek	15-Jul	3-Sep	2006	650669	1082	972	110
Straight Creek	14-Jul	6-Sep	2006	650694	1085	972	113
White Creek	16-Jul	5-Sep	2006	584806	1180	972	208
North Fork 17 Mile Creek	29-Jun	29-Aug	2008	650648	942	906.2	35.8
Flattail Creek	1-Jul	29-Aug	2008	927375	1012	906.2	105.8
Smoot Creek	2-Jul	28-Aug	2008	759252	1014	906.2	107.8
East Fork Basin Creek	3-Jul	31-Aug	2008	759354	1276	906.2	369.8
Independence Creek	1-Jul	27-Aug	2008	759295	904	906.2	-2.2
Grizzly Creek	5-Jul	30-Aug	2008	759246	1107	906.2	200.8
Deer Creek-1	19-Jul	22-Sep	2008	759309	1281	1169.8	111.2
Rock Creek II (state land)	9-Jul	5-Sep	2004	650646	696	699.2	-3.2
W.Fk. Poplar River	8-Jul	3-Sep	2004	650658	769	635.5	133.5
Wolf Creek at Wolf Point	6-Jul	4-Sep	2004	650650	614	635.5	-21.5
Woody Island Coulee	18-Jul	8-Sep	2008	759254	858	785	73
Hart Creek	30-Jun	23-Aug	2006	418516	705	811	-106
Hell Creek 1 - Lower	30-Jun	23-Aug	2006	418532	724	811	-87
Snap Creek	28-Jun	23-Aug	2006	418529	688	811	-123
Lost Boy Creek	20-Jun	22-Aug	2007	584807	681	749	-68
Sweetgrass Creek	18-Jul	14-Sep	2007	530247	1764	1407.6	356.4
Rock Creek II (state land)	16-Jul	13-Sep	2007	650593	1817	699.2	1117.8

Crow Creek	12-Jul	4-Sep	2007	617334	877	802.8	74.2
Little Powder River	8-Jul	3-Sep	2007	650640	971	802.8	168.2
Milk Creek	7-Jul	2-Sep	2007	617357	882	902	-20
Boxelder Creek	5-Jul	23-Aug	2007	617311	613	749	-136
Krug Creek	4-Jul	22-Aug	2007	650694	643	749	-106
Little Beaver Creek	15-Jun	20-Aug	2007	530216	954	902	52
Boxelder Creek	15-Jul	6-Sep	2008	759328	1095	1263.7	-168.7
Beaver Creek	16-Jul	6-Sep	2008	759292	1159	1263.7	-104.7
Little Deer Creek	13-Jul	8-Sep	2008	759340	1312	1263.7	48.3
Unnamed Trib	14-Jul	5-Sep	2008	759256	1319	1263.7	55.3

Table 5 – Equations for estimating expected daily average water temperature (DAWT) for reference streams in four of Montana's ecoregions, given daily average air temperatures with zero (DAAT) and one-day (DAAT1) lag time

Stream Name	**Equation for Predicting DAWT**
All Reference Streams*	**= 41.2586 + (0.2050)DAAT + (0.06295)DAAT1**
N Fk Canyon	= 41.2586 + (0.3097)DAAT + (0.06295)DAAT1
Straight	= 41.2586 + (0.0890)DAAT + (0.06295)DAAT1
White	= 41.2586 + (0.12351)DAAT + (0.06295)DAAT1
Smoot	= 34.4227 + (0.2050)DAAT + (0.06295)DAAT1
E Fk Basin	= 34.3639 + (0.2050)DAAT + (0.06295)DAAT1
Independence	= 50.2291 + (0.0141)DAAT + (0.06295)DAAT1
Deer Cr-1	= 29.7817 + (0.3321)DAAT + (0.06295)DAAT1
Rock Cr II (2004)	= 41.2586 + (0.3208)DAAT + (0.06295)DAAT1
W Fk Poplar	= 41.2586 + (0.4405)DAAT + (0.01074)DAAT1
Wolf	= 41.2586 + (0.3239)DAAT + (0.06295)DAAT1
Woody Island Coulee	= 41.2586 + (0.3292)DAAT + (0.01132)DAAT1
Hart	= 50.4987 + (0.12981)DAAT + (0.06295)DAAT1
Hell	= 49.6540 + (0.13073)DAAT + (0.06295)DAAT1
Snap	= 41.2586 + (0.27025)DAAT + (0.06295)DAAT1
Lost Boy	= 58.5546 + (0.3762)DAAT + (0.06295)DAAT1
Sweetgrass	= 41.2586 + (0.0629)DAAT + (0.06295)DAAT1
Rock Cr II (2007)	= 41.2586 + (0.0508)DAAT + (0.06295)DAAT1
Crow	= 41.2586 + (0.3159)DAAT + (0.06295)DAAT1
Little Powder	= 49.0075 + (0.2050)DAAT + (0.06295)DAAT1
Milk	= 41.2586 + (0.2050)DAAT + (0.12554)DAAT1
Little Beaver	= 48.2854 + (0.2050)DAAT + (0.06295)DAAT1
Little Deer	= 41.2586 + (0.3111)DAAT + (0.06295)DAAT1
Unnamed Trib to Little Deer Cr	= 30.6453 + (0.3533)DAAT + (0.06295)DAAT1

*Streams that fit this equation are: Cottonwood, Willow II, Elk Springs, Willow I, Cache, N. Fk. Fish, N. Fk. 17 Mile, Flattail, Grizzly, Boxelder (2007), Krug, Boxelder (2008), and Beaver.

Table 6 – Model output estimates* and p-values used to develop equations in Table 5 for each reference stream

		Intercept		DAAT		DAAT1	
Ecoregion & Stream Name	**Stream Code**	**Estimate**	**p-value**	**estimate**	**p-value**	**estimate**	**p-value**
Middle Rockies (1)							
Cottonwood Creek	1	-6.2158	0.0699	-0.01903	0.6277	0.00099	0.9705
Willow Creek II	2	-5.1954	0.1606	0.000154	0.9972	0.01022	0.716
Elk Springs Creek	3	0.3657	0.9	-0.0404	0.1608	0.04006	0.0528
Willow Creek I	4	-6.0734	0.0615	-0.03012	-0.422	0.009387	-0.7161
Northern Rockies (2)							
Cache Creek	1	-3.1952	-0.3464	-0.03409	0.3428	-0.00538	0.8285
N. Fork Canyon Creek	2	-9.6033	0.0059	0.1047	0.0097	-0.02226	0.4108
N. Fork Fish Creek	3	-1.6486	0.6323	-0.05175	0.1533	-0.00404	0.8714
Straight Creek	4	4.1165	0.2296	-0.116	0.0014	-0.03431	0.1741
White Creek	5	-3.092	0.367	-0.08149	0.0248	-0.00194	0.9382
North Fork 17 Mile Creek	6	-2.3326	0.4696	-0.04004	0.2343	0.000594	0.9806
Flattail Creek	7	-3.4279	0.2938	-0.02261	0.5019	0.005354	0.827
Smoot Creek	8	-6.8359	0.0385	-0.04856	0.1806	-0.01152	0.6429
East Fork Basin Creek	9	-6.8947	0.0342	-0.04099	0.2277	-0.00851	0.7234
Independence Creek	10	8.9705	0.0079	-0.1909	<0.0001	-0.04208	0.0954
Grizzly Creek	11	-5.9987	0.0691	-0.02028	0.5588	0.000474	0.9844
Northwestern Glaciated Plains (3)							
Deer Creek-1	1	-11.4769	0.0001	0.1271	<0.0001	-0.00501	0.8145
Rock Creek II (state land)	2	2.4453	0.4458	0.1158	0.0009	0.005257	0.828
W.Fk. Poplar River	3	-3.5613	0.2718	0.2355	<0.0001	-0.05221	0.0473
Wolf Creek at Wolf Point	4	1.9399	0.5321	0.1189	0.0008	0.004083	0.8679
Woody Island Coulee	5	1.4301	0.6263	0.1242	<0.0001	-0.05163	0.0161
Northwestern Great Plains (4)							
Hart Creek	1	9.2401	0.008	-0.07519	0.023	0.005218	0.8209
Hell Creek 1 - Lower	2	8.3954	0.0157	-0.07427	0.0247	0.038	0.103
Snap Creek	3	-0.06196	0.9854	0.06525	0.0447	0.01414	0.5365

Lost Boy Creek	4	17.296	<0.0001	-0.1712	<0.0001	-0.00544	0.8088
Sweetgrass Creek	5	3.1346	0.3173	-0.1421	<0.0001	-0.0286	0.1992
Rock Creek II (state land)	6	2.2786	0.4814	-0.1542	<0.0001	-0.02661	0.2661
Crow Creek	7	-0.4455	0.8992	0.1109	0.0018	0.04464	0.0761
Little Powder River	8	7.7489	0.0284	-0.03699	0.2915	0.03849	0.1138
Milk Creek	9	2.0581	0.5347	-0.00259	0.935	0.06259	0.0072
Boxelder Creek	10	2.9837	0.4178	0.04646	0.1964	0.03134	0.2119
Krug Creek	11	5.8012	0.1203	0.02357	0.5116	0.01593	0.525
Little Beaver Creek	12	7.0268	0.0291	-0.02094	0.5181	-0.00155	0.9462
Boxelder Creek	13	4.0504	0.1811	-0.02249	0.4764	0.00377	0.8666
Beaver Creek	14	0.09724	0.9743	0.03527	0.2644	0.02194	0.3312
Little Deer Creek	15	-2.7068	0.3601	0.1061	0.0008	-0.02485	0.2654
Unnamed Trib to Little Deer Creek	16	-10.6133	0.0007	0.1483	<0.0001	-0.019	0.3958

*Shaded cells represent those coefficients that deviate significantly from the population average, where $p < 0.05$.

Table 7 - Deviation of expected DAWT predicted by individual reference stream equations from reference stream population average when DAAT=DAAT1=60

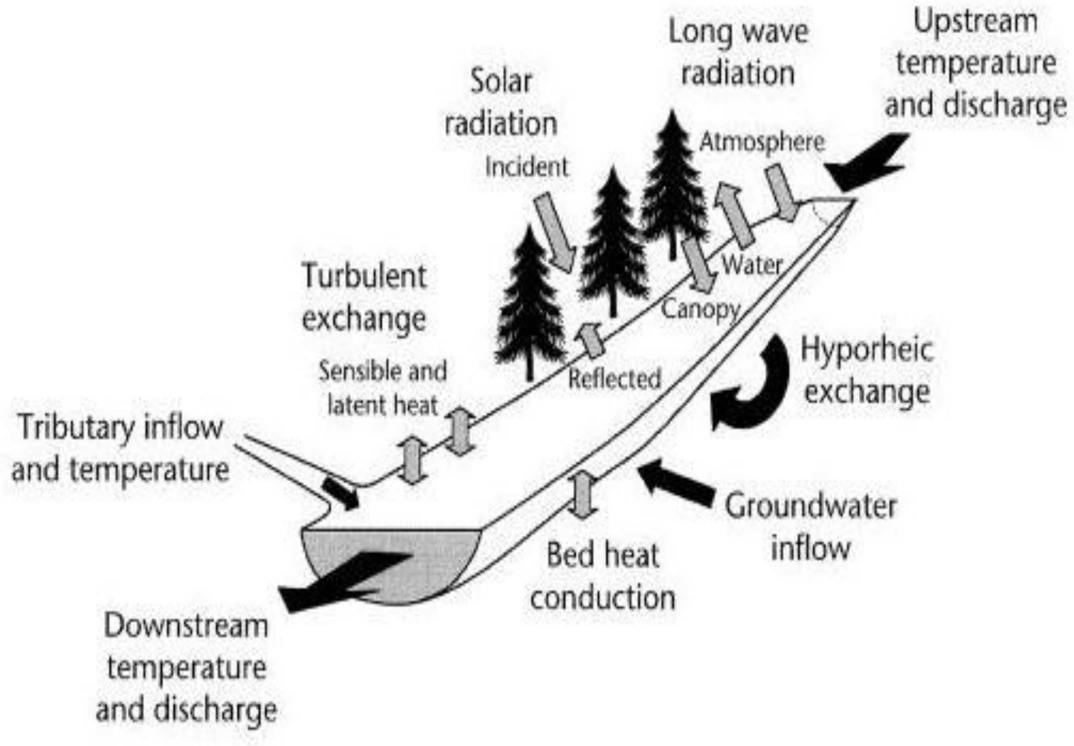
	Deviation from Average			
Reference Stream	**(^{o}F)**	**(%)**	**(+/-)**	**(Trend)**
Northern Rockies				
N Fk Canyon	6.3	11.0%	+	Mostly Cooler
Straight	7.0	-12.1%	-	
White	4.9	-8.5%	-	
Smoot	6.8	-11.9%	-	
E Fk Basin	6.9	-12.0%	-	
Independence	2.5	-4.3%	-	
Northwestern Glaciated Plains				
Deer Cr-1	3.9	-6.7%	-	Mostly Warmer
Rock Cr II (2004)	6.9	12.1%	+	
W Fk Poplar	11.0	19.2%	+	
Wolf	7.1	12.4%	+	
Woody Island Coulee	4.4	7.6%	+	
Northwestern Great Plains				
Hart	4.7	8.3%	+	Mostly Warmer
Hell	3.9	6.9%	+	
Snap	3.9	6.8%	+	
Lost Boy	27.6	48.1%	+	
Sweetgrass	8.5	-14.9%	-	
Rock Cr II (2007)	9.3	-16.1%	-	
Crow	6.7	11.6%	+	
Little Powder	7.7	13.5%	+	
Milk	3.8	6.6%	+	
Little Beaver	7.0	12.3%	+	
Little Deer	6.4	11.1%	+	
Unnamed Trib to Little Deer Cr	1.7	-3.0%	-	
Average	6.9	**4.3%**	+	

Table 8 – Predicted daily average water temperatures (DAWT) (°F) in Montana's reference streams for the next five decades, and in 200 years, assuming global warming rate of 0.11°F* per decade

	2009	2019	2029	2039	2049	2059	2209
Stream	**DAWT at 60°F**	**DAWT at 60.11°F**	**DAWT at 60.22°F**	**DAWT at 60.33°F**	**DAWT at 60.44°F**	**DAWT at 60.55°F**	**DAWT at 62.20°F**
Reference Streams that Fit the Average Model							
	57.34	57.37	57.39	57.42	57.45	57.48	57.93
Northern Rockies							
N Fk Canyon	63.62	63.66	63.70	63.74	63.78	63.82	64.44
Straight	50.38	50.39	50.41	50.43	50.44	50.46	50.71
White	52.45	52.47	52.49	52.51	52.53	52.55	52.86
Smoot	50.50	50.53	50.56	50.59	50.62	50.65	51.09
E Fk Basin	50.44	50.47	50.50	50.53	50.56	50.59	51.03
Independence	54.85	54.86	54.87	54.88	54.89	54.89	55.02
Northwestern Glaciated Plains							
Deer Cr-1	53.48	53.53	53.57	53.62	53.66	53.70	54.35
Rock Cr II (2004)	64.28	64.33	64.37	64.41	64.45	64.49	65.13
W Fk Poplar	68.33	68.38	68.43	68.48	68.53	68.58	69.33
Wolf	64.47	64.51	64.55	64.60	64.64	64.68	65.32
Woody Island Coulee	61.69	61.73	61.76	61.80	61.84	61.88	62.44
Northwestern Great Plains							
Hart	62.06	62.09	62.11	62.13	62.15	62.17	62.49
Hell	61.27	61.30	61.32	61.34	61.36	61.38	61.70
Snap	61.25	61.29	61.32	61.36	61.40	61.43	61.98
Lost Boy	84.90	84.95	85.00	85.05	85.10	85.15	85.87
Sweetgrass	48.81	48.82	48.84	48.85	48.86	48.88	49.09
Rock Cr II (2007)	48.08	48.10	48.11	48.12	48.13	48.15	48.33
Crow	63.99	64.03	64.07	64.11	64.16	64.20	64.82
Little Powder	65.08	65.11	65.14	65.17	65.20	65.23	65.67
Milk	61.09	61.13	61.16	61.20	61.24	61.27	61.82
Little Beaver	64.36	64.39	64.42	64.45	64.48	64.51	64.95
Little Deer	63.70	63.74	63.78	63.83	63.87	63.91	64.52
Unnamed Trib to Little Deer Cr	55.62	55.67	55.71	55.76	55.80	55.85	56.54

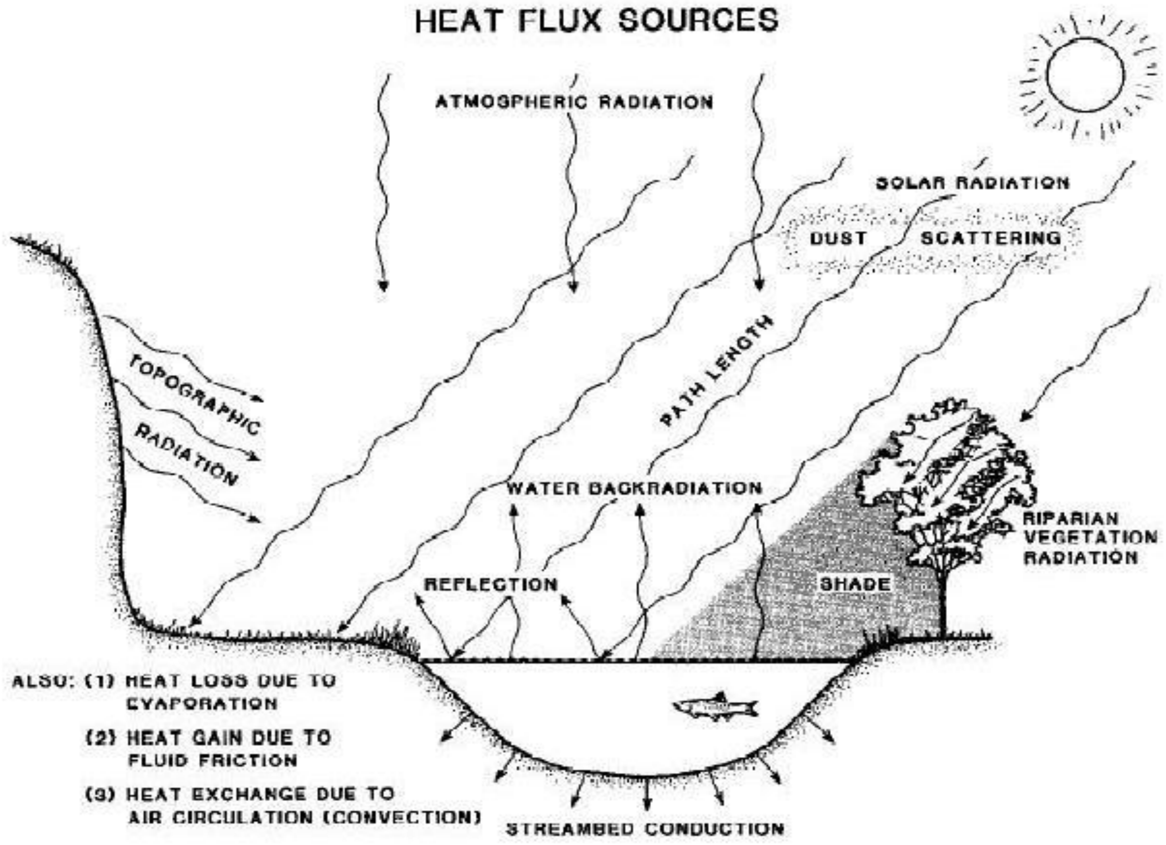
*See Figure 3

Figure 1 – Several factors controlling stream temperatures (energy fluxes associated with water exchanges are shown as black arrows)



(Moore *et al*. 2005)

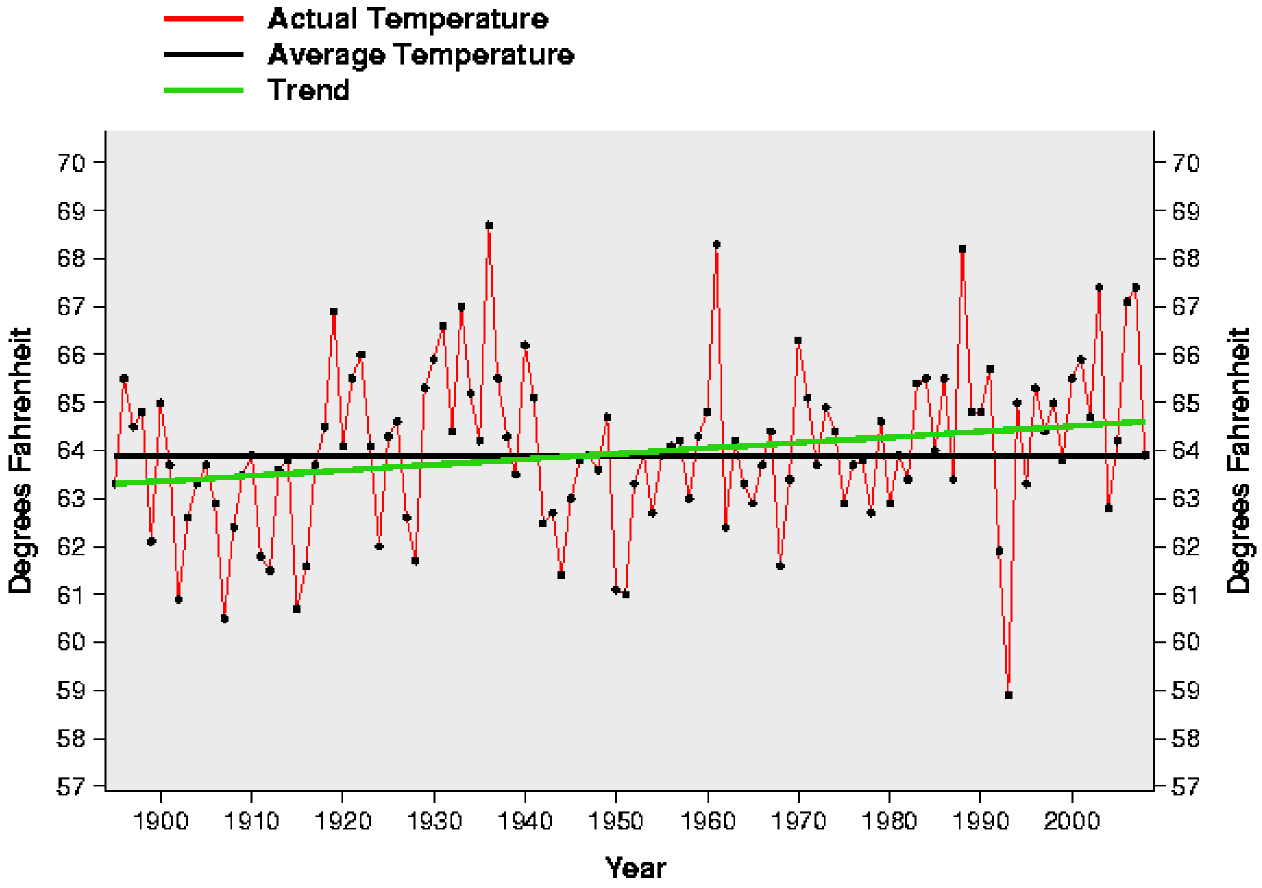
Figure 2 – Sources of heat flux that determine stream water temperature regimes



(from Bartholow 1989 as modified from Theurer *et al*. 1984)

Figure 3 – Summer (June – August) air temperatures from 1895 to 2008 in Montana (statewide)

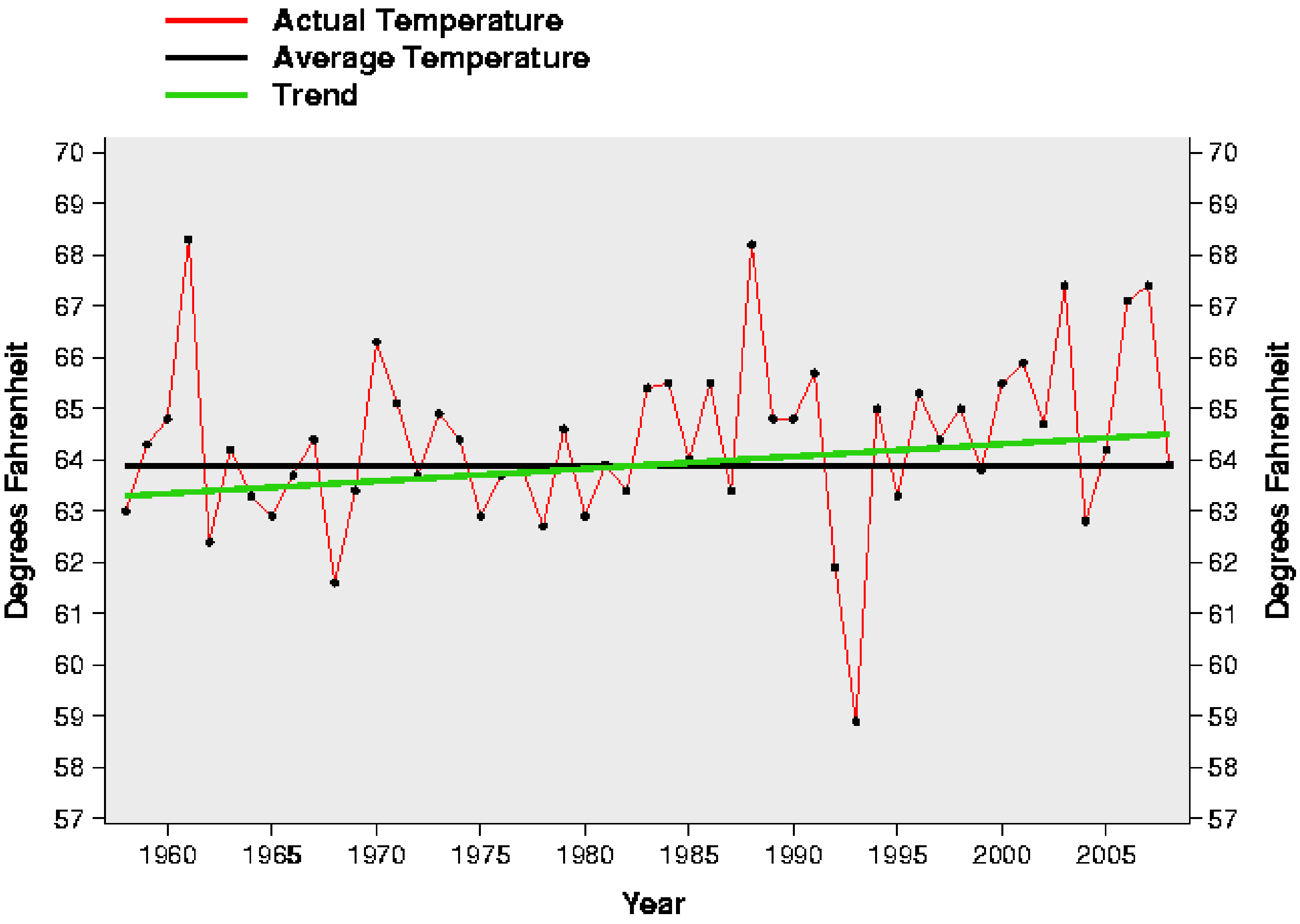
(Summer (Jun-Aug) 1901 - 2000 Average = 63.91 degF; Summer (Jun-Aug) 1895 - 2008 Trend = 0.11 degF / Decade)



(NOAA 2009a)

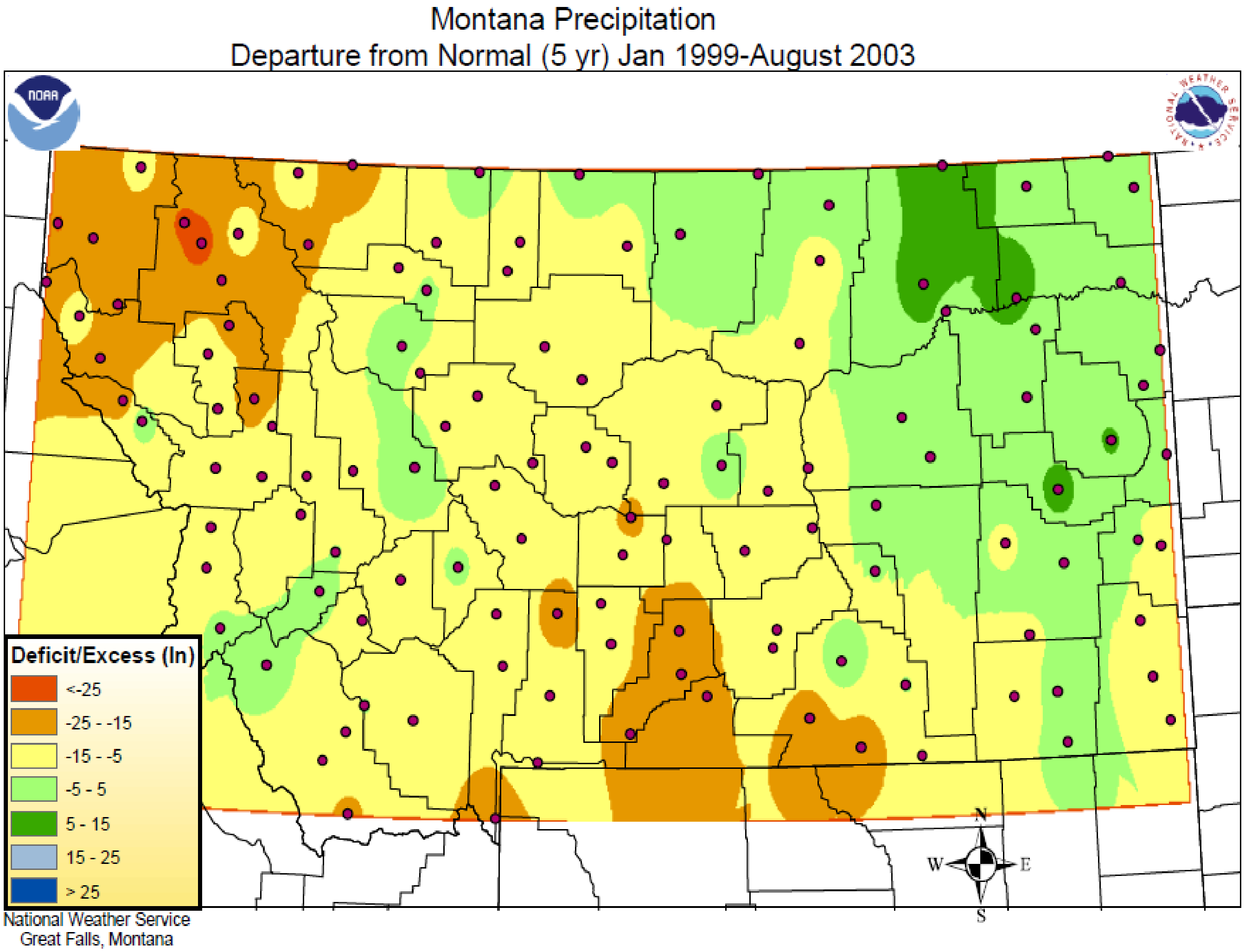
Figure 4 – Summer (June – August) air temperatures from 1958 to 2008 in Montana (statewide)

(Summer (Jun-Aug) 1901 - 2000 Average = 63.91 degF; Summer (Jun-Aug) 1958 - 2008 Trend = 0.24 degF / Decade)



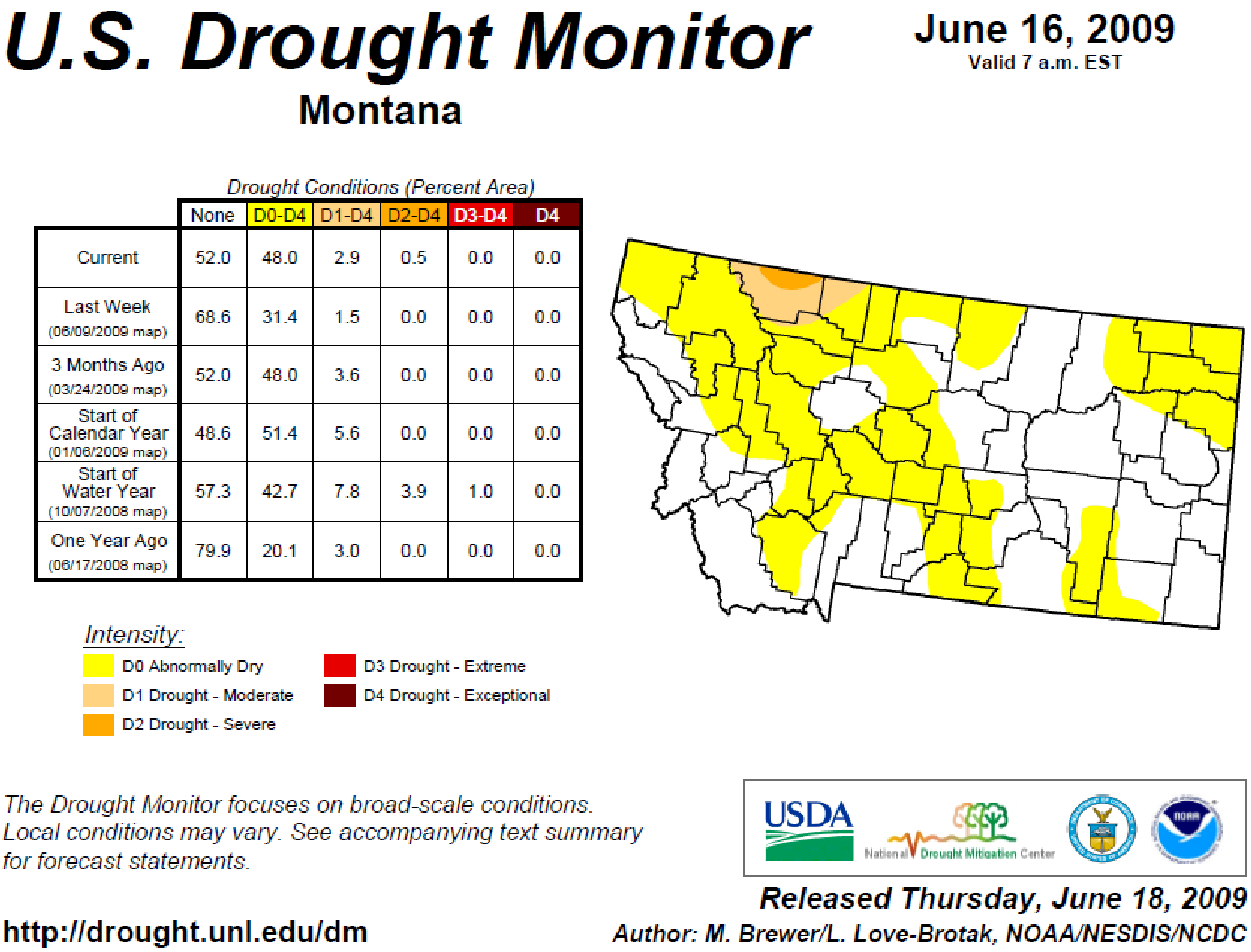
(NOAA 2009a)

Figure 5 – Departure from normal precipitation levels (inches) in Montana's recent past (Jan 1999-August 2003)



(National Weather Service 2009)

Figure 6 – Drought Conditions in Montana as of June 16, 2009



U.S. Drought Monitor

Montana

June 16, 2009
Valid 7 a.m. EST

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	52.0	48.0	2.9	0.5	0.0	0.0
Last Week (06/09/2009 map)	68.6	31.4	1.5	0.0	0.0	0.0
3 Months Ago (03/24/2009 map)	52.0	48.0	3.6	0.0	0.0	0.0
Start of Calendar Year (01/06/2009 map)	48.6	51.4	5.6	0.0	0.0	0.0
Start of Water Year (10/07/2008 map)	57.3	42.7	7.8	3.9	1.0	0.0
One Year Ago (06/17/2008 map)	79.9	20.1	3.0	0.0	0.0	0.0

Intensity:

- 🟨 D0 Abnormally Dry
- 🟧 D1 Drought - Moderate
- 🟧 D2 Drought - Severe
- 🟥 D3 Drought - Extreme
- 🟫 D4 Drought - Exceptional

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

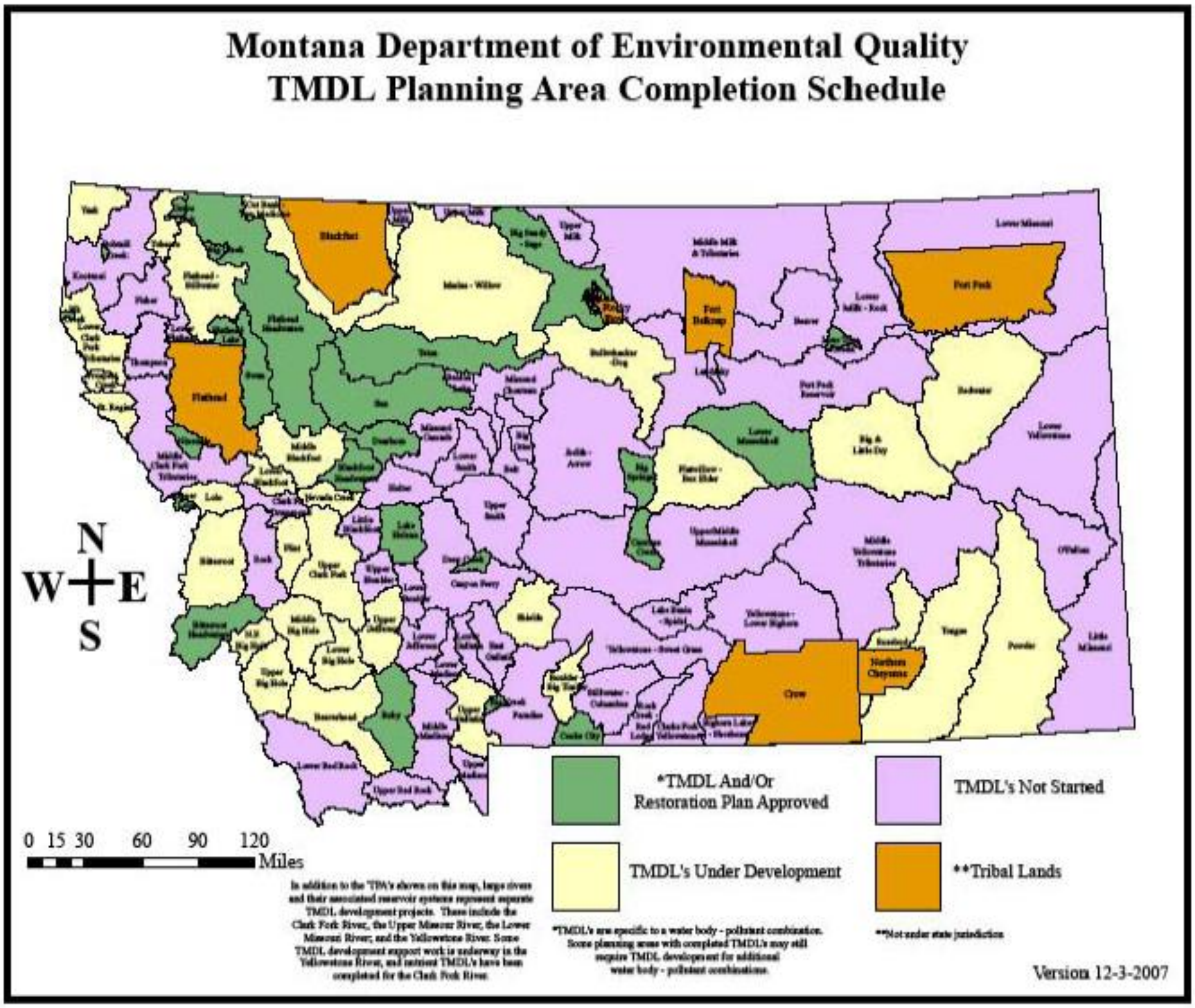
http://drought.unl.edu/dm

Released Thursday, June 18, 2009

Author: M. Brewer/L. Love-Brotak, NOAA/NESDIS/NCDC

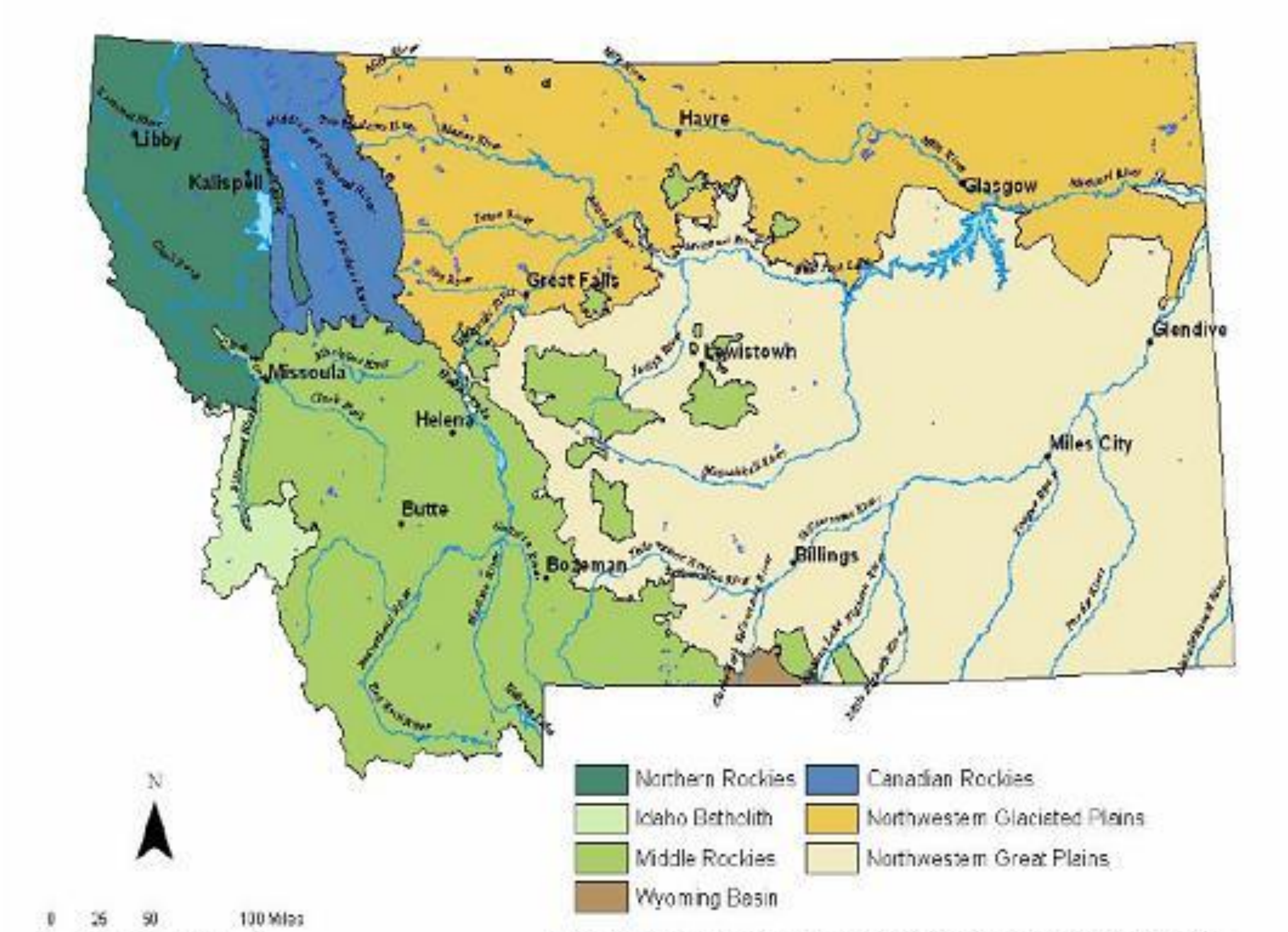
(Tinker 2009)

Figure 7 - Map of Montana Department of Environmental Quality's Updated Completion Schedule for TMDL Planning Areas (TPAs), 2007



(MT DEQ 2007)

Figure 8 - Map Depicting Montana’s Seven Level III ecoregions



Derived from: Woods, Alan J., Omernik, James, M., Nesser, John A., Shelden, J., and Azevedo, Sandra H., 1999, Ecoregions of Montana (color poster with map, descriptive text, summary tables, and photographs): Reston, Virginia, U.S. Geological Survey (map scale 1:1,500,000).

(Woods *et al*. 2002)

Figure 9 – Plots of Daily Average Water Temperature (DAWT) (^{o}F) versus Daily Average Air Temperature (^{o}F) with Zero Lag Time (DAAT)

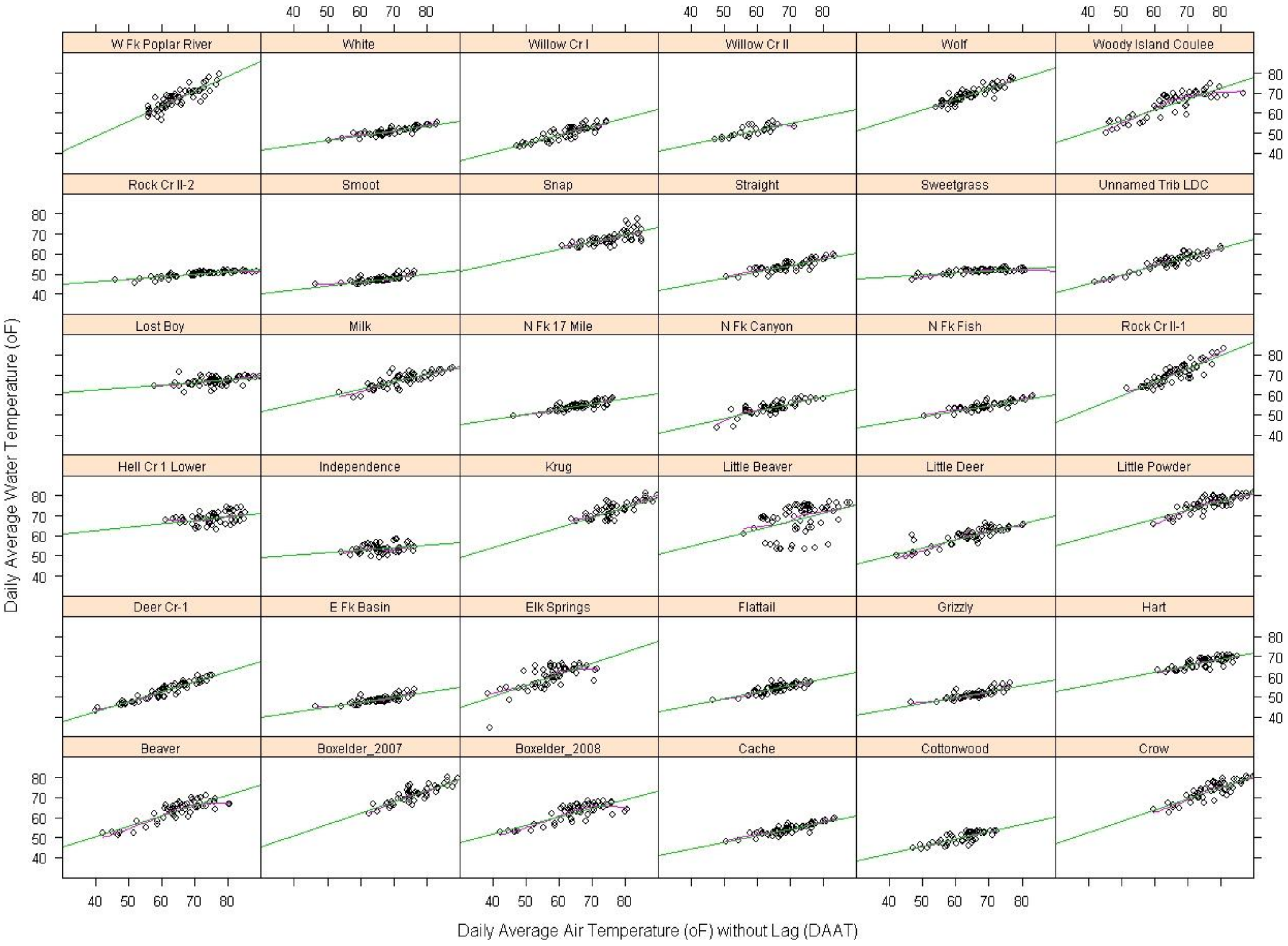


Figure 10 – Plots of Daily Average Water Temperature (DAWT) (^oF) versus Daily Average Air Temperature (^oF) with One-Day Lag Time (DAAT1)

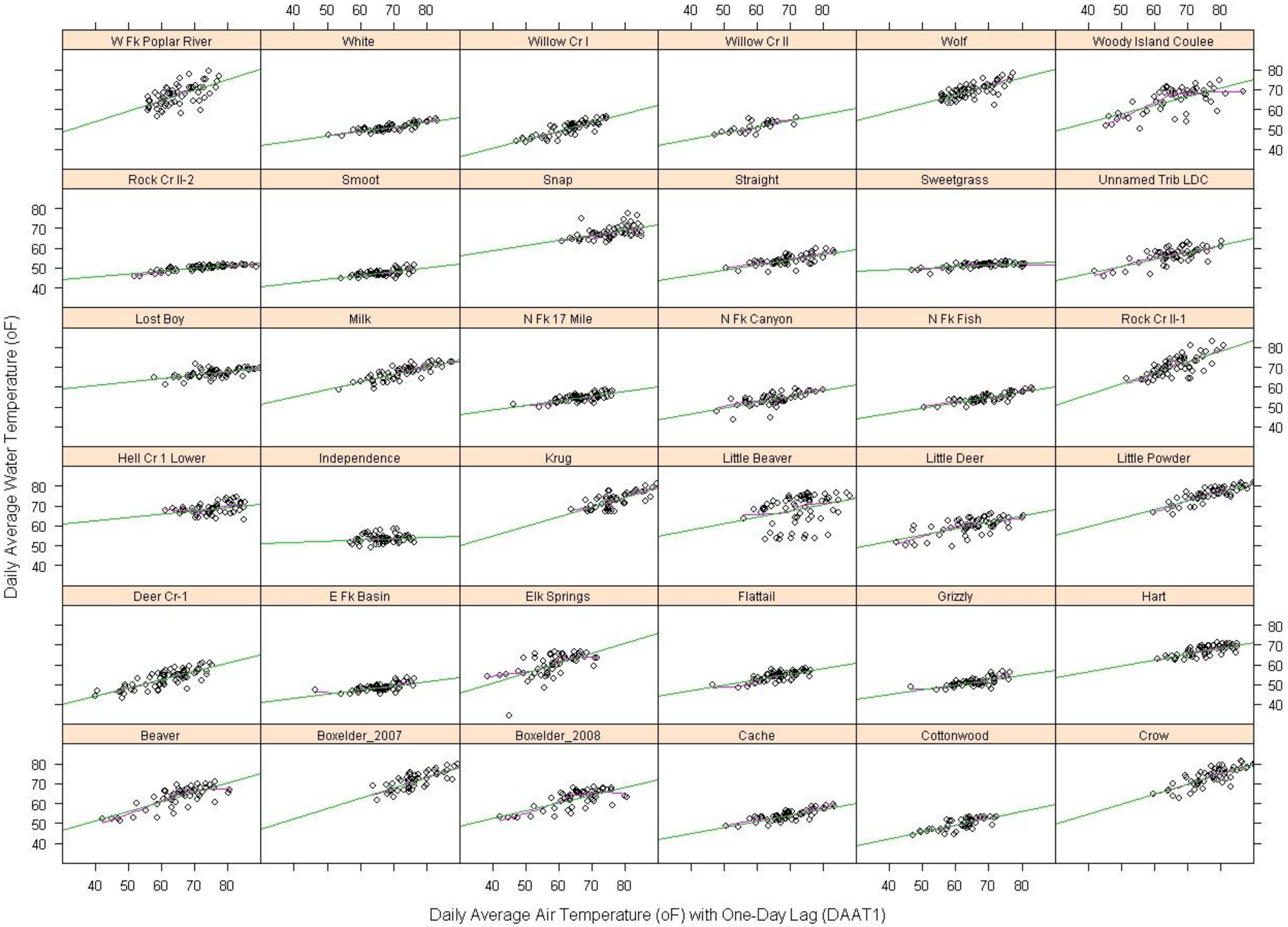


Figure 11 - Plots of Daily Average Water Temperature (DAWT) (^{o}F) versus Daily Average Air Temperature (^{o}F) with Two-Day Lag Time (DAAT2)

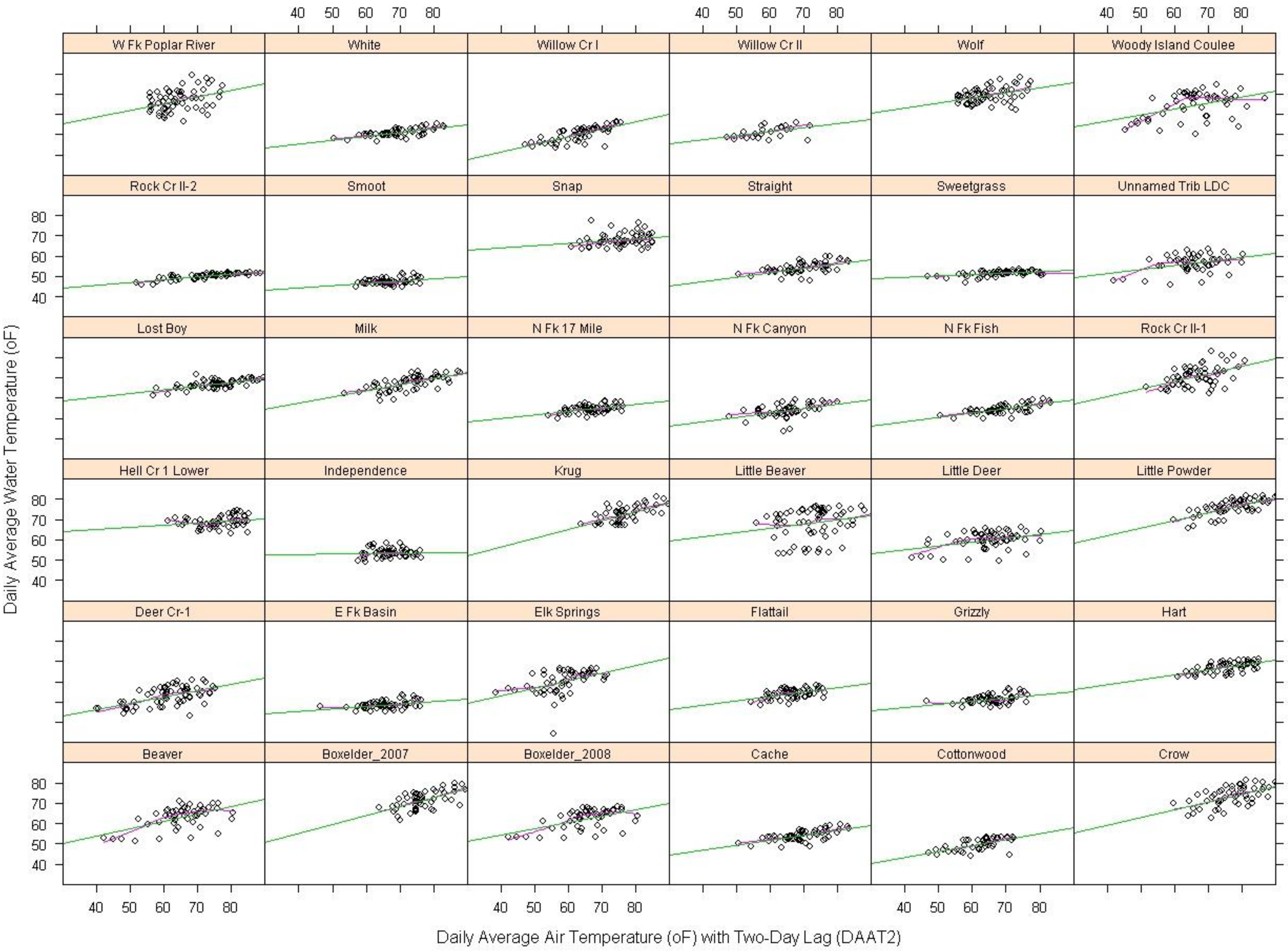


Figure 12 - Plots of Daily Average Water Temperature (DAWT) (^oF) versus Daily Average Air Temperature (^oF) with Three-Day Lag Time (DAAT3)

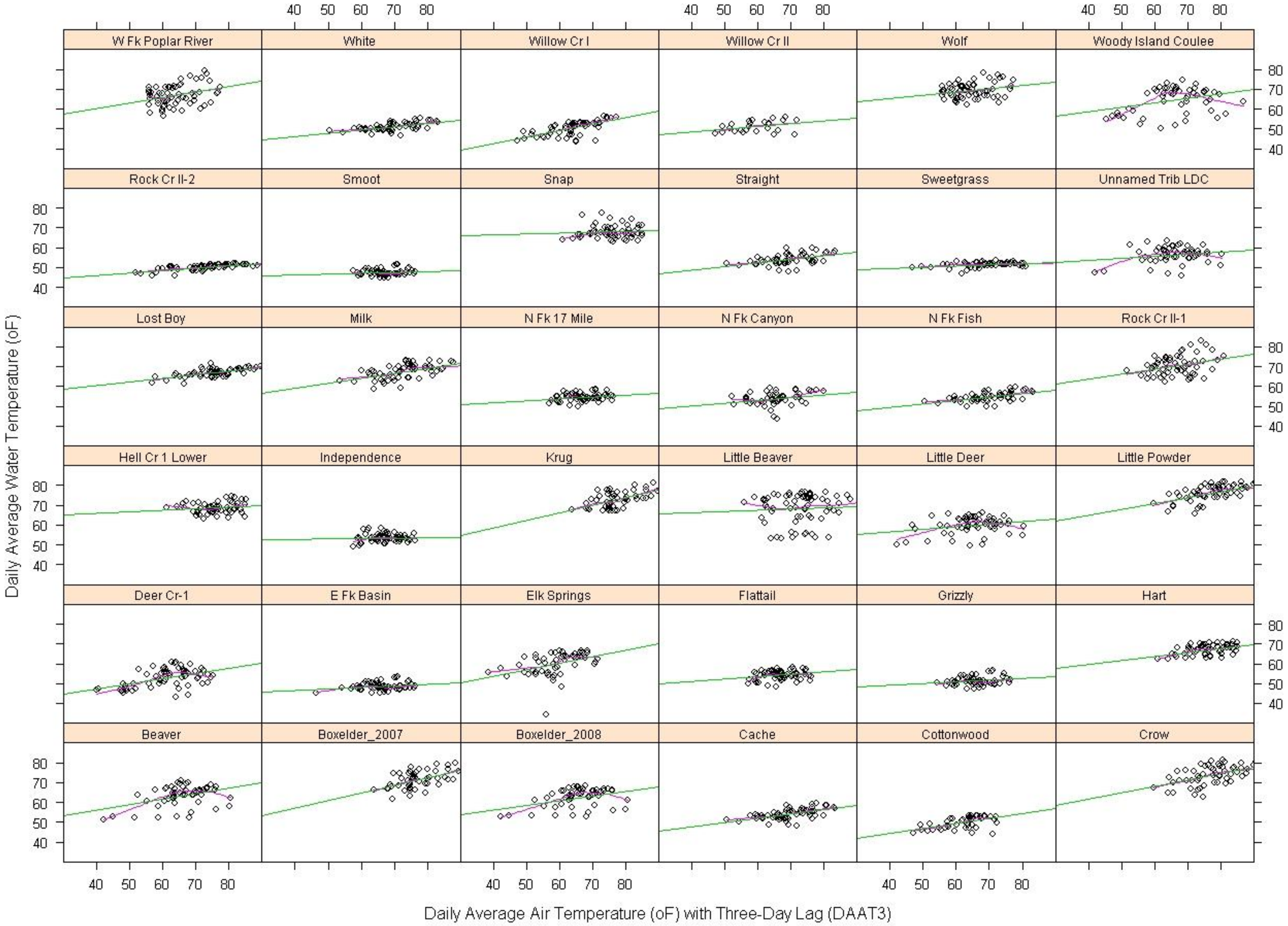


Figure 13 - Daily average reference stream temperatures (^{o}F) in the Middle Rockies ecoregion, 2004 - 2008

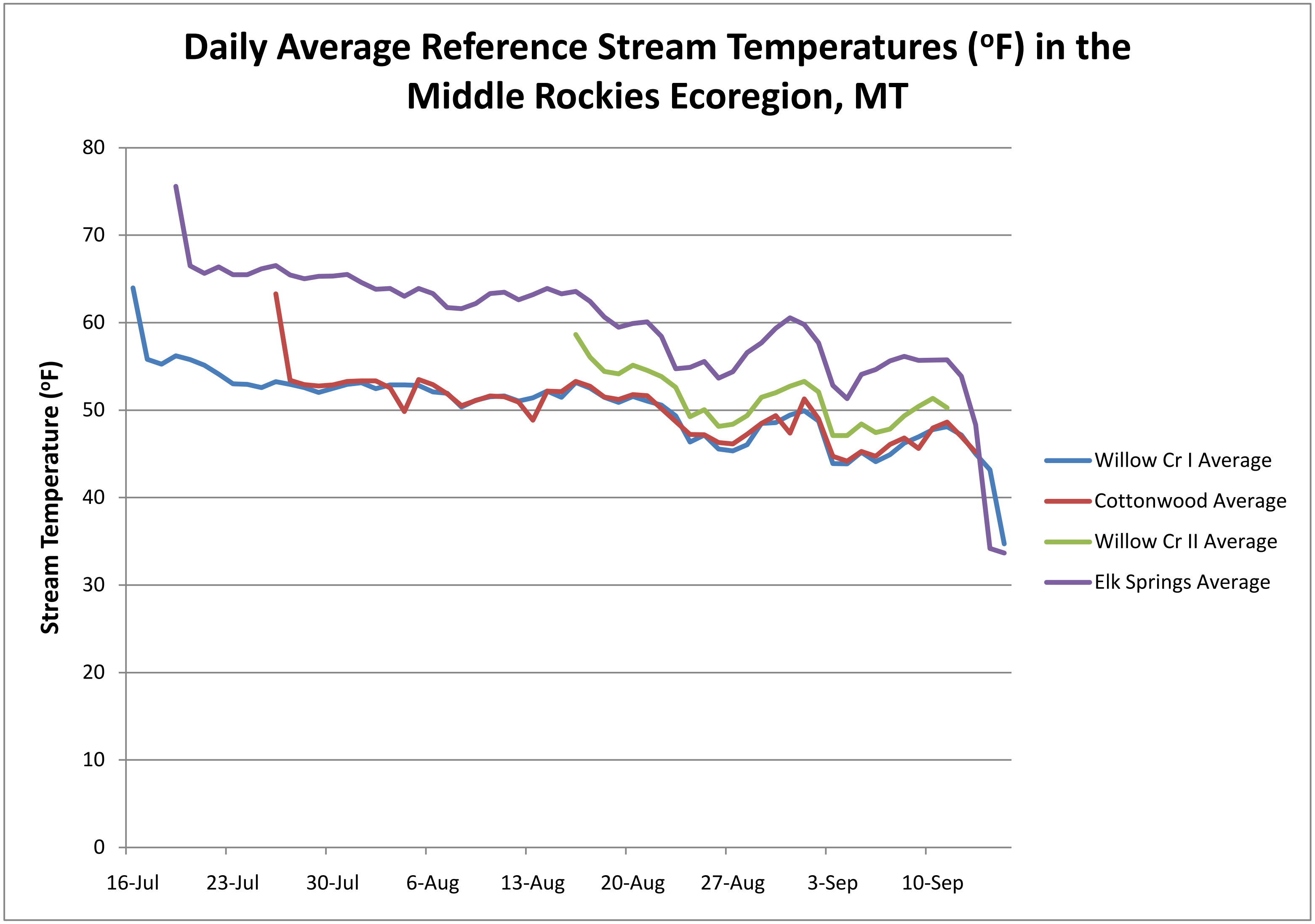


Figure 14 - Daily average reference stream temperatures (°F) in the Northern Rockies ecoregion, 2004 - 2008

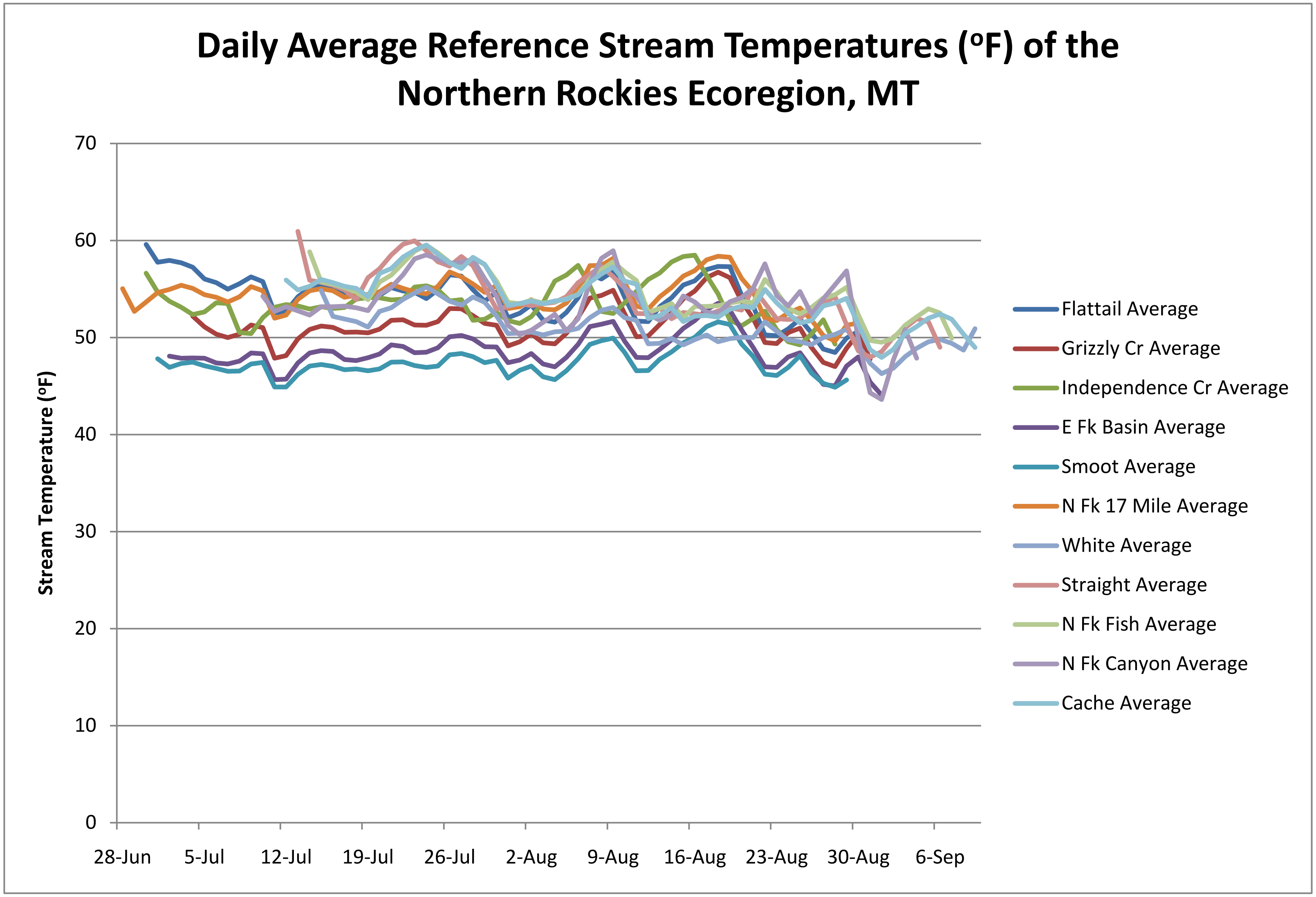


Figure 15 – Daily average reference stream temperatures (^{o}F) in the Northwestern Glaciated Plains ecoregion, 2004 - 2008

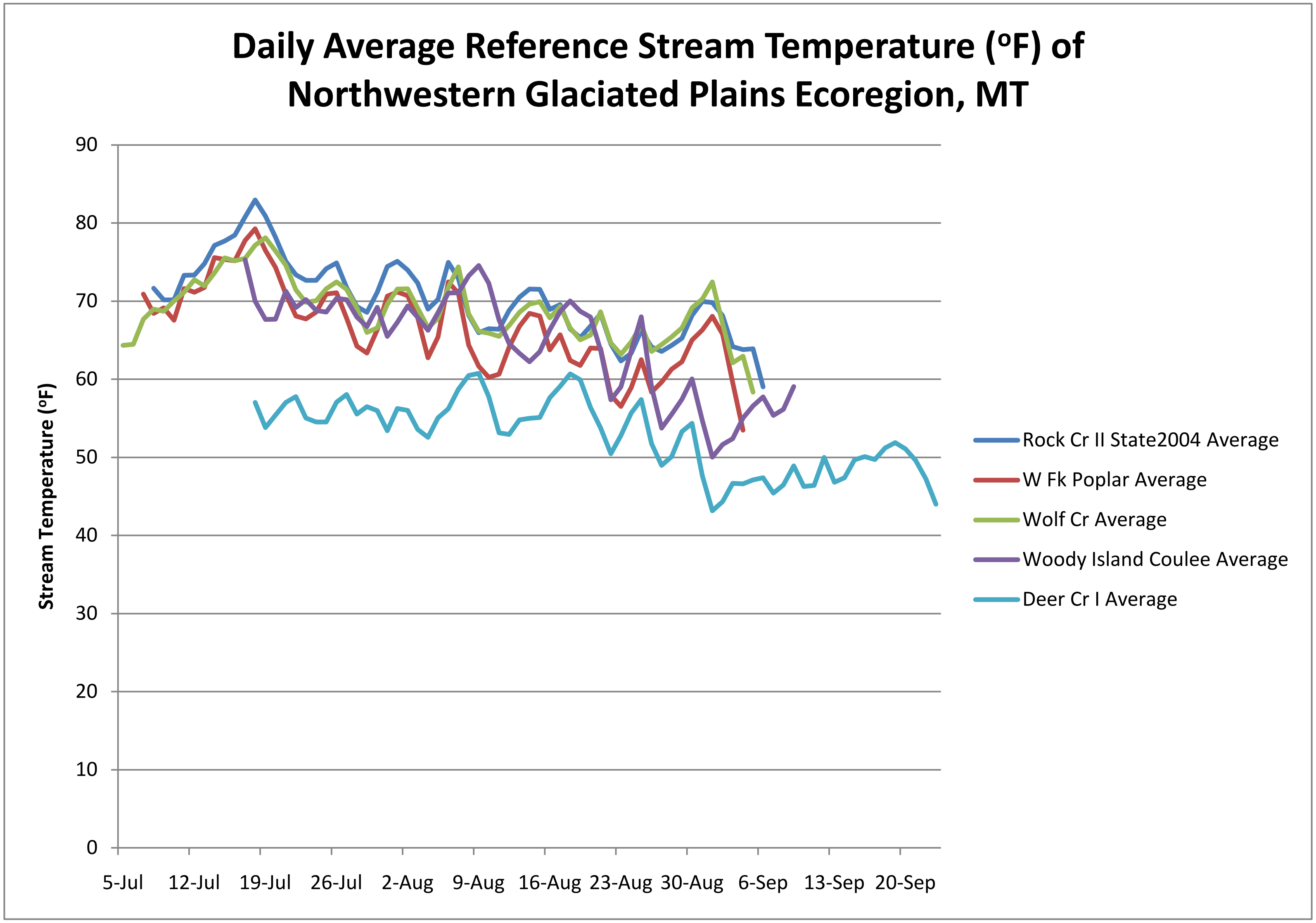


Figure 16 – Daily average reference stream temperatures (°F) in the Northwestern Great Plains ecoregion, 2004 - 2008

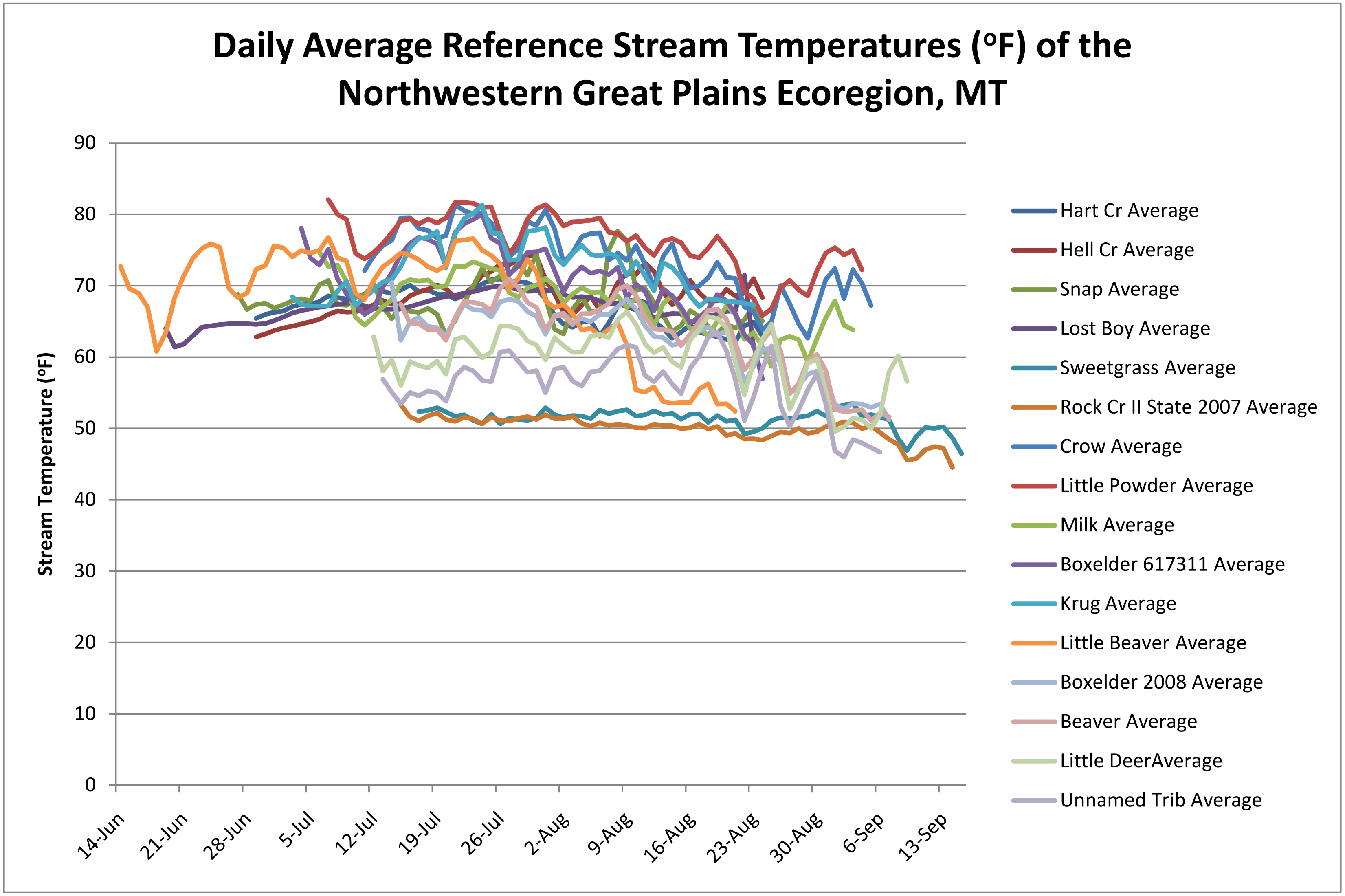


Figure 17 – Plots of summer (June – September) air temperature from fourteen weather stations in Montana, over an 11-year period (1998-2008)

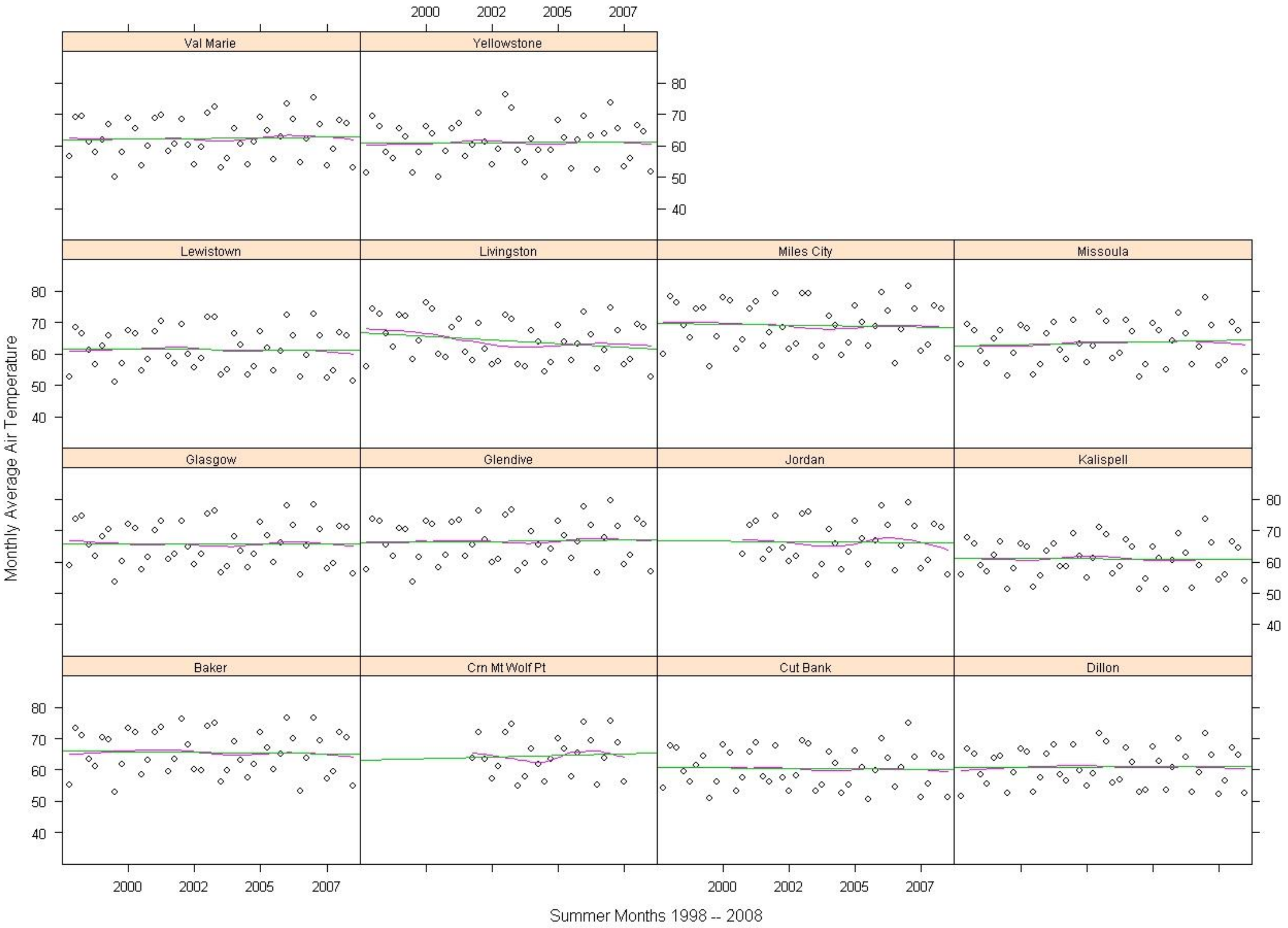
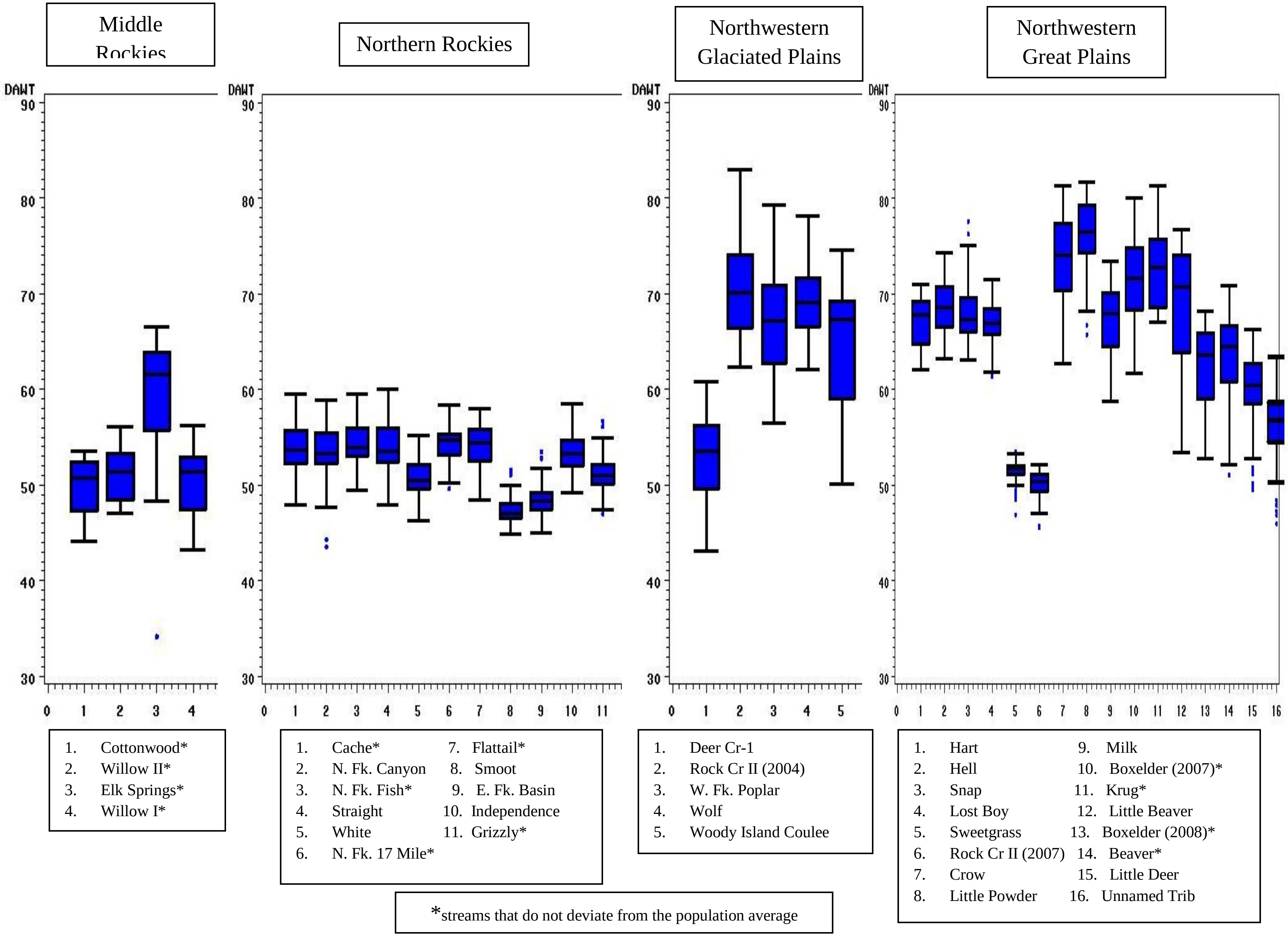


Figure 18 – Box plots for reference stream summer daily average water temperatures



Middle Rockies

1. Cottonwood*
2. Willow II*
3. Elk Springs*
4. Willow I*

Northern Rockies

1. Cache*
2. N. Fk. Canyon
3. N. Fk. Fish*
4. Straight
5. White
6. N. Fk. 17 Mile*
7. Flattail*
8. Smoot
9. E. Fk. Basin
10. Independence
11. Grizzly*

Northwestern Glaciated Plains

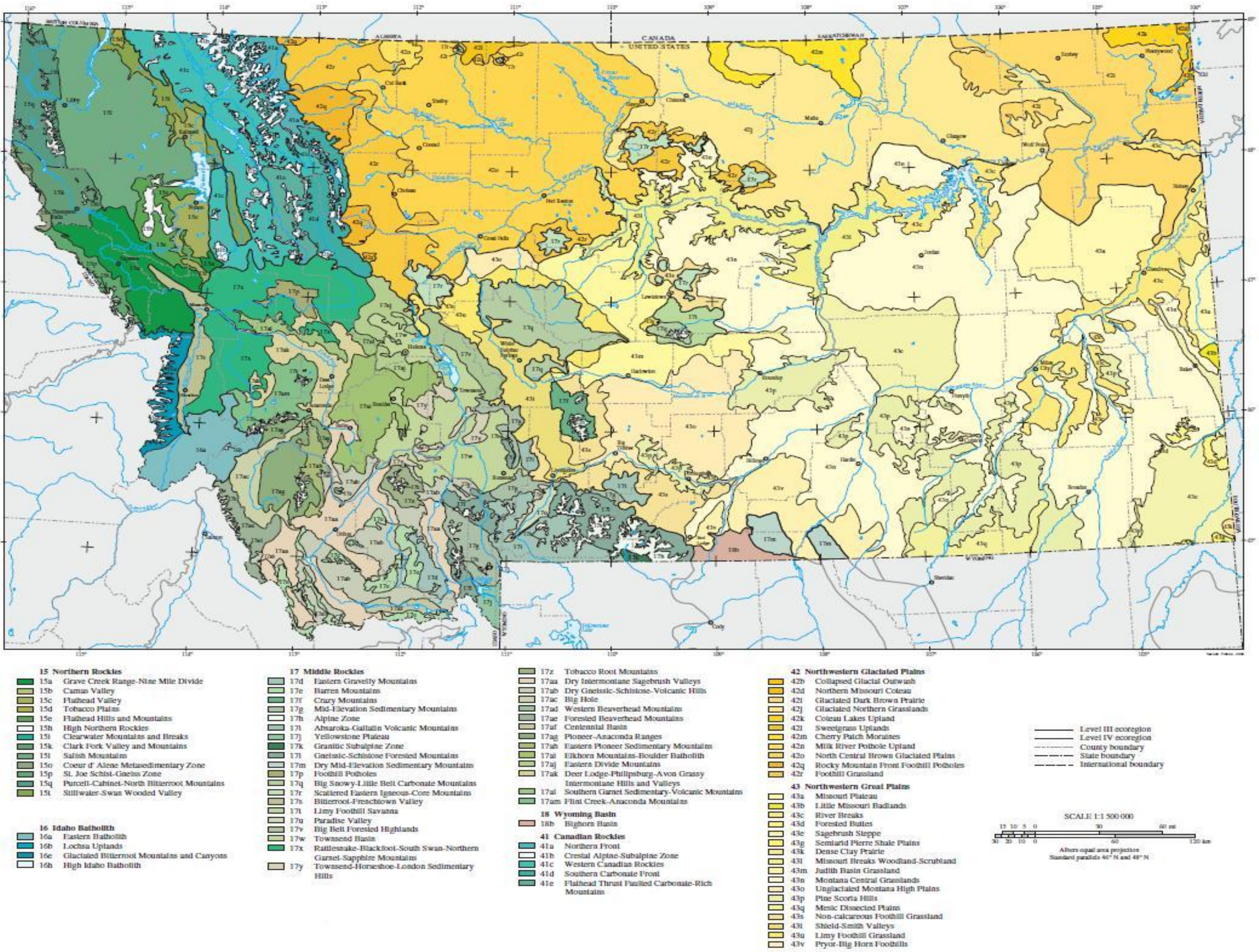
1. Deer Cr-1
2. Rock Cr II (2004)
3. W. Fk. Poplar
4. Wolf
5. Woody Island Coulee

Northwestern Great Plains

1. Hart
2. Hell
3. Snap
4. Lost Boy
5. Sweetgrass
6. Rock Cr II (2007)
7. Crow
8. Little Powder
9. Milk
10. Boxelder (2007)*
11. Krug*
12. Little Beaver
13. Boxelder (2008)*
14. Beaver*
15. Little Deer
16. Unnamed Trib

*streams that do not deviate from the population average

Figure 19 – Map depicting Level IV ecoregions of Montana



(Woods *et al*. 2002)

Figure 20 – Montana's major drainage basins and Montana DEQ administrative basins

State of Montana **2006 Integrated 303(d)/305(b) Water Quality Report**

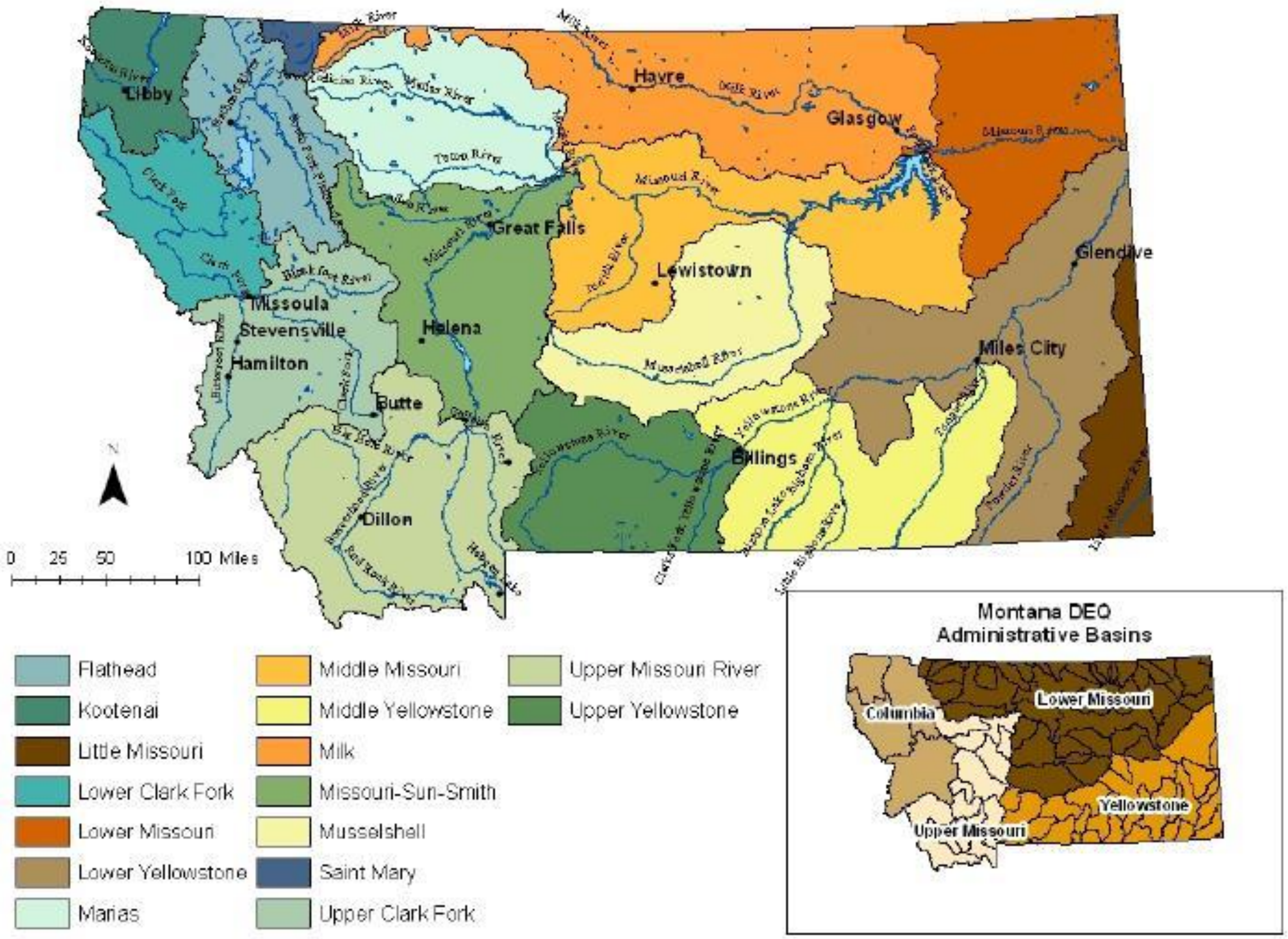
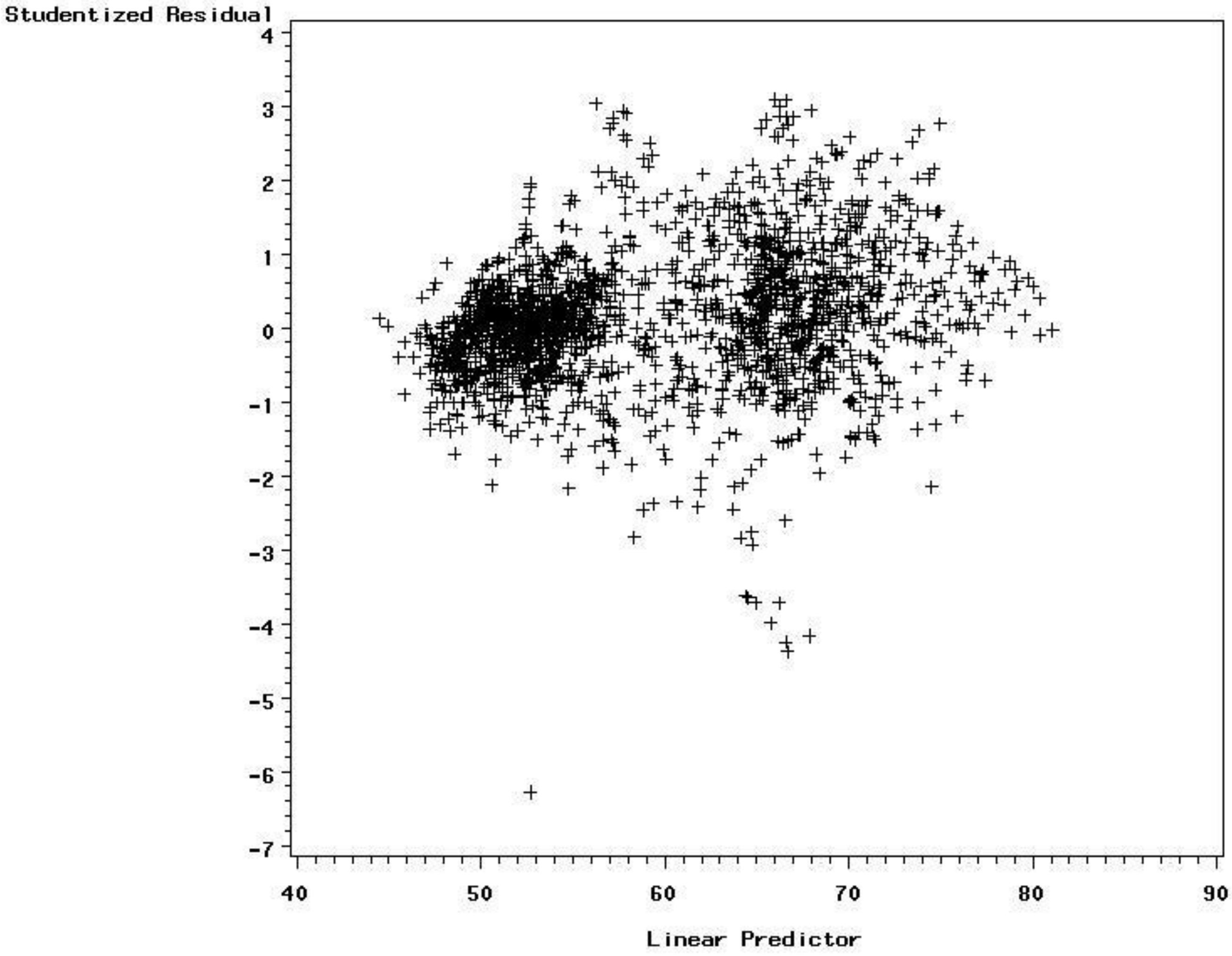


Figure 1. Montana's Major Drainage Basins and Montana DEQ Administrative Basins

(MT DEQ 2006a)

Figure 21 – Plot of Residuals versus Linear Predictors



APPENDICES

Appendix A – Descriptions of Montana's Ecoregions

Northern Rockies (15)

Ecoregion 15 is mountainous and rugged. Climate, trees, and understory species are characteristically maritime-influenced. Douglas-fir, subalpine fir, Englemann spruce, western larch, lodgepole pine, and ponderosa pine as well as Pacific indicators such as western redcedar, western hemlock, mountain hemlock, and grand fir occur. Pacific tree species are more numerous than in the Idaho Batholith (16) and are never dominant in the Middle Rockies (17). Alpine areas occur but, as a whole, the region has lower elevations, less perennial snow and ice, and fewer glacial lakes than the adjacent Canadian Rockies (41). Metasedimentary rocks are common; granitic rocks and associated management problems are less extensive than in the Idaho Batholith (16). Thick volcanic ash deposits are more widespread than in Ecoregion 16. Logging and mining are common and have caused stream water quality problems in the region. Recreational uses are also important (Woods *et al*. 2002).

Middle Rockies (17)

The climate of the Middle Rockies lacks the strong maritime influence of the Northern Rockies. Mountains have Douglas-fir, subalpine fir, and Engelmann spruce forests and alpine areas; Pacific tree species are never dominant. Forests can be open. Foothills are partly wooded or shrub- and grass-covered. Intermontane valleys are grass- and/or shrub-covered and contain a mosaic of terrestrial and aquatic fauna that is distinct from the nearby mountains. Many mountain-fed, perennial streams occur and differentiate the intermontane valleys from the Northwestern Great Plains. Granitics and associated management problems are less extensive than in the Idaho Batholith. Recreation, logging, mining, and summer livestock grazing are common land uses.

Northwestern Glaciated Plains (42)

Ecoregion 42 is transitional between the generally more level, moister, more agricultural Northern Glaciated Plains (46) to the east and the typically more irregular and drier Northwestern Great Plains (43) to the south. The southern boundary of the Northwestern Glaciated Plains (42) is near the limit of continental glaciation and its soils are derived from glacial drift. Hummocky moraines locally occur and are characterized by seasonal and semi-permanent ponds and wetlands. Land use is devoted to cattle ranching and farming (Woods *et al*. 2002).

Northwestern Great Plains (43)

Ecoregion 43 is largely an unglaciated, semiarid, and rolling plain that is underlain by shale, siltstone, and sandstone. It contains occasional buttes, badlands, ephemeral-intermittent streams, and a few perennial rivers. Low precipitation and high summer evapotranspiration rates restrict groundwater recharge rates. Rangeland is common, but spring wheat and alfalfa farming also occur; agriculture is affected by erratic precipitation and few opportunities for irrigation. Native grasslands persist, especially in areas of steep or broken topography (Woods *et al*. 2002).

Idaho Batholith (16)

Ecoregion 16 is mountainous, deeply dissected, partially glaciated, and characteristically underlain by granitic rocks. The lithological mosaic and related slope stability and water quality issues are different from Ecoregions 15 and 17. Soils derived from granitics are droughty and have limited fertility, and therefore provide only limited amounts of nutrients to aquatic ecosystems. They are highly erodible when vegetation is removed. Douglas-fir, ponderosa pine, and, at higher elevations, subalpine fir occur.

Maritime influence is slight. Pacific tree species are less numerous than in Ecoregion 15; western hemlock is absent. Overall, the vegetation is unlike that of Ecoregions 15 and 17. Land uses include logging, grazing, and recreation. Streams are likely to suffer from increased loads of fine sediments after disturbance by humans. Fish assemblage composition is similar to Ecoregion 15 (Woods *et al*. 2002).

Wyoming Basin (18)

The broad, xeric intermontane Wyoming Basin (18) is punctuated by high hills and low mountains and dominated by grasslands and shrublands. The region is somewhat drier than the Northwestern Great Plains (43) and is nearly surrounded by mountains. Livestock grazing takes place throughout the ecoregion even though many areas lack sufficient vegetation to adequately support this activity (Woods *et al*. 2002).

Canadian Rockies (41)

Ecoregion 41 extends into northern Montana from Alberta and British Columbia. The ecoregion is generally higher and more snow- and ice-covered than the Northern Rockies (15), and portions are strongly influenced by moist maritime air masses. Melting snow and rainfall are abundant at the higher elevations. Some surplus water is stored in glacial deposits, unconsolidated mountain valley fill, and permeable sedimentary rocks. However, areas underlain by crystalline rocks lack sufficient groundwater storage capacity to prevent overland runoff or to develop groundwater supplies; in these places, base flow is meager and high elevation streams generally flow only during rain and snow melt periods. The highest elevations are treeless, glaciated alpine areas. The potential natural vegetation is mostly subalpine fir, Douglas-fir, and Engelmann spruce. Soils are thin or absent on upper mountain slopes but become deeper and more developed below, especially west of the Continental Divide. Recreation, forestry, and mining are common land uses (Woods *et al*. 2002).

(Woods *et al*. 2002)

Appendix B – Methods used to access, request and download air temperature data from weather stations

Choice of weather station methods

To determine which weather station's air temperature data is most reliably correlated to each reference stream's water temperature, the National Climatic Data Center (NCDC) online mapping tool from the National Oceanographic and Atmospheric Administration (NOAA; US Department of Commerce) was used this tool to locate and display all weather stations that collect hourly air temperature data within the county and surrounding counties in which each stream is located.

- To search stations, go to website [http://www.ncdc.noaa.gov/oa/ncdc.html]
- Under "Data & Products", click on "Search by Map"
- http://gis.ncdc.noaa.gov/website/ims-entrymap/viewer.htm
- First drop-down box (NCDC Data/Products), select: Surface Data Hourly Global
- Click "Select Area" tab on right of screen
- Enter Country (US), State (Montana), and County (containing stream(s) in question)
- When map image is loaded, click on "Identify Location" tab above image
- Cross reference stream location within county using Montana Atlas/Gazetteer
- Record any applicable weather stations (with station ID, station name, lat/long, elevation, etc.) within the county and surrounding counties containaing each reference stream
- Determine which weather station(s) seem to be most representative of the reference stream site climatic conditions (according to similarity in elevation and proximity with stream site)

Air temperature data request and manipulation methods

Once a weather station was chosen for each stream, air temperature data from each was requested electronically from the National Climatic Data Center's NNDC Climate Data Online database.

- Go to website [http://www.ncdc.noaa.gov/oa/ncdc.html]
- Under "Data & Products", click on "Data Access tools"; click Climate and Weather; then click Global Surface Data; then click on Station Name under "Search Options" (or go to [http://www7.ncdc.noaa.gov/CDO/cdo], click on "Station Name" under "Search Options")
- Type in Station Name of desired weather station (found using method described above); press Enter
- Find desired station in list; next to option "DS3505 – Surface Data, Hourly Global", ensure that the record includes the desired date range (1998-2008); click "DS3505 – Surface Data, Hourly Global"
- Under "Select Date Restrictions", select "Use Date Range" and enter range of dates from January 1998 to December 2008; click Continue.
- Under "Hourly Obs Available", click on "View Inventory"; ensure that necessary data is available for each month within each desired year.
- If the inventory indicates that the record is sufficiently complete, check the box that says "Inventory Review" assuring that you've reviewed the inventory prior to placing a data request; to request data, enter valid email address *Note: this data was accessed from a university computer and so was free; typically there is a substantial cost per weather station record requested

- After receiving notification via email indicating that the data is available, follow the link provided in the email to access each weather station's data; save each station's data as a text file (opened using Microsoft Notepad).
- Import each station's text file into a Microsoft Excel spreadsheet, using tab and space delimited commands, label each file with the station's name, and save.
- Remove all columns from the spreadsheet except the date (YR—MODAHRMN) and air temperature (TEMP) columns.

Appendix C – Basic ‘Proc Mixed’ code for random coefficient regression model presented here

With Ecoregion, DAAT2, and DAAT3 variables:

```
Proc Mixed covtest data=work.wat;

class ER S;

model DAWT= DAAT DAAT1 DAAT2 DAAT3/ solution ddfm=satterth outp=pres;

random int DAAT  DAAT1 DAAT2 DAAT3/ solution sub=ER;

random int DAAT  DAAT1 DAAT2 DAAT3/ solution sub=S(ER);

repeated / type= ar(1) sub=S(ER);

run;
```

Without Ecoregion*, DAAT2, and DAAT3 variables:

```
proc mixed covtest data=work.wat;

class ER S;

model DAWT= DAAT DAAT1/ solution ddfm=satterth outp=pres;

random int DAAT  DAAT1/ solution sub=S(ER);

repeated / type= ar(1) sub=S(ER);

run;
```

*****Note: one level of “randomness” (ecoregion) has been removed