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PROFILE

An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation

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ABSTRACT / While external factors (drivers) determine the net heat energy and water delivered to a stream, the internal structure of a stream determines how heat and water will be distributed within and exchanged among a stream's components (channel, alluvial aquifer, and riparian zone/floodplain). Therefore, the interaction between external drivers of stream temperature and the internal structure of integrated stream systems ultimately determines channel water temperature. This paper presents a synoptic, ecologically based discussion of the external drivers of stream temperature, the internal structures and processes that insulate and buffer stream temperatures, and the mechanisms of human influence on stream temperature. It provides a holistic perspective on the diversity of natural dynamics and human activities that influence stream temperature, including discussions of the role of the hyporheic zone. Key management implications include: (1) Protecting or reestablishing in-stream flow is critical for restoring desirable thermal regimes in streams. (2) Modified riparian vegetation, groundwater dynamics, and channel morphology are all important pathways of human influence on channel-water temperature and each pathway should be addressed in management plans. (3) Stream temperature research and monitoring programs will be jeopardized by an inaccurate or incomplete conceptual understanding of complex temporal and spatial stream temperature response patterns to anthropogenic influences. (4) Analyses of land-use history and the historical vs contemporary structure of the stream channel, riparian zone, and alluvial aquifer are important prerequisites for applying mechanistic temperature models to develop management prescriptions to meet in-channel temperature goals.

Stream temperature directly influences the metabolic rates, physiology, and life-history traits of aquatic species and helps to determine rates of important community processes such as nutrient cycling and productivity (Allen 1995). Fluctuations in water temperature induce behavioral and physiological responses in aquatic organisms and permanent shifts in stream temperature regimes can render formerly suitable habitat unusable for native species (Holtby 1988, Quigley and Arbelbide 1997, Wissmar and others 1994b). Because of the ecological importance of stream temperature, preventing or mitigating anthropogenic thermal degradation is a common concern for resource managers (Coutant 1999).

KEY WORDS: Stream temperature management; Shade; Hyporheic zone; Groundwater; Channel morphology; Riparian vegetation; Anthropogenic influences

Perhaps because of the widespread use of quantitative models (and associated simplifying assumptions), management actions seldom consider the multitude of interacting environmental processes that determine stream temperature regimes or the wide variety of pathways by which humans may affect stream temperature. In this paper, we attempt to succinctly describe a number of these important processes and pathways. Our most detailed discussions focus on heat energy exchange and transport within stream systems because, in our opinion, these processes provide great promise for successful stream temperature management, yet are most often overlooked during the development of management plans. Although the discussion and examples in this paper focus on the Pacific Northwest, USA, the ecological principles and processes discussed are applicable to lotic systems in general.

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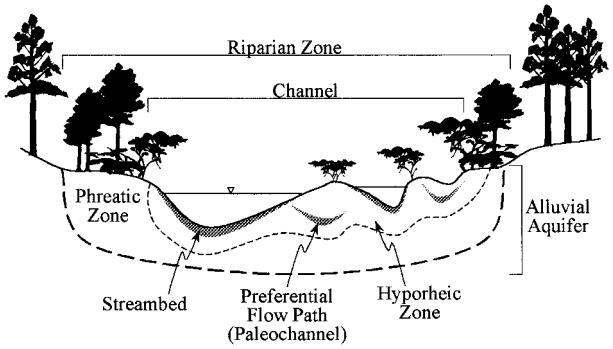

Figure 1. Structural components of a stream system (not all features exist in all streams.)

Fluvial System Structure

At least three integrated and interdependent components determine stream structure: the channel, riparian zone, and alluvial aquifer (Findlay 1995, Gibert and others 1994, Stanford and Ward 1988, 1993, Ward 1989, 1998a,b). Thus, the edge of a river is not its channel margin, but the edge of the riparian zone (Gregory and others 1991). Similarly, the bottom of a river is not the streambed, but the bottom of the alluvial aquifer (Ward 1998b) (Figure 1). Interactions between external drivers of stream temperature and the internal structure of the integrated stream system ultimately determine channel water temperature. The relative importance of various drivers and structures varies spatially. Together, drivers and structures interact to produce heterogeneity in stream temperature at a variety of spatial and temporal scales.

Although other factors also affect stream temperature, the primary determinants of stream temperature are climatic drivers (such as solar radiation, air temperature, and windspeed), stream morphology, groundwater influences, and riparian canopy condition (Sullivan and Adams 1991). Therefore, this paper focuses on the importance of stream morphology, groundwater influences, and riparian canopy conditions as factors that markedly influence stream temperature and that are substantially altered by various human activities.

The stream channel is the portion of a stream system that transports water across the earth's surface. The channel boundary is approximately the typical annual high water level on each streambank. Stream channels may be discontinuous in cross section and comprised of the main channel, side channels, and channels that are active seasonally during high flow. On floodplains, the locations of channels change over time (Leopold and others 1964, Naiman and others 1992). Changes occur gradually over decades (as in meandering systems) or suddenly as streams cut new channels or recapture previously abandoned channels during floods (as in anastomosed systems) (Nanson and Knighton 1996). Dynamic channels create and maintain floodplain complexity and habitat diversity, thus directly influencing important in-stream dynamics (e.g., nutrient and carbon cycles, natural floodwater storage, and water temperature buffers) and enhancing biological diversity (Abbe and Montgomery 1996, Creuzé des Châtelliers and others 1994, Harvey and Bencala 1993, Sedell and Froggatt 1984).

The riparian zone is the land area influenced by stream-derived moisture. For small streams, it extends a short distance (from meters to tens of meters) laterally from the channel margin. However, for large streams, the riparian zone extends further (from tens to thousands of meters), at least to the edge of the active floodplain (Gregory and others 1991). For rivers like the Mississippi and Amazon, the riparian zone may extend even further (from kilometers to hundreds of kilometers) (Salo and others 1986). Periodic flooding of the riparian zone encourages the exchange of water, nutrients, sediments, and energy between the stream channel and riparian zone, creating unique habitats, enhancing natural productivity, and driving biological processes that contribute to the ecological integrity of streams (Ward 1998a).

A stream's alluvium (sediments that have been deposited by the stream) along with the groundwater contained therein form the alluvial aquifer (Creuzé des Châtelliers and others 1994) The alluvial aquifer underlies both the stream channel and the riparian zone (or floodplain). In streams flowing across bedrock, the alluvial aquifer may consist of pockets of sediment trapped in bedrock depressions. In most large rivers, however, the upper substrate of the floodplain is built entirely from alluvial deposits that can be meters thick. Stream channels and their alluvial aquifers may rapidly and frequently exchange substantial amounts of water and in both directions (Gibert and others 1994). Hyporheic groundwater is water that enters the alluvial aquifer from the stream, travels along localized subsurface flow pathways for relatively short periods of time (perhaps from minutes to months), and reemerges into the stream channel downstream without leaving the alluvial aquifer. The portion of the alluvial aquifer that contains at least some hyporheic groundwater (White 1993) is referred to as the hyporheic zone (Brunke and Gonser 1997, Jones and Holmes 1996, Stanford and Ward 1988). Therefore, two types of groundwater influence streams: hyporheic groundwater and phreatic groundwater (water derived from the catchment aquifer). Phreatic groundwater feeding a river enters the

bottom of the alluvial aquifer and, as it moves towards the stream, mixes with hyporheic groundwater. Depending on localized subsurface flow dynamics, groundwater entering the stream channel may be predominantly phreatic, predominantly hyporheic, or a mixture of both. The hyporheic zone can exert an extremely strong influence on the biological, chemical, and physical processes that occur in a river (Brunke and Gonser 1997, Findlay 1995, Stanford and Ward 1993).

Water Temperature in Stream Channels

Water temperature is not a simple measure of the amount of heat energy in water. Instead, temperature is proportional to heat energy divided by the volume of water:

$$\textit{Water temperature} \propto \textit{heat energy/water volume}$$

Conceptually, water temperature is a measure of the concentration of heat energy in a stream. All water contains heat energy; warmer water simply contains a higher concentration of heat energy than does cooler water.

The heat load is a measure of heat energy added to a stream; any increase or reduction in heat load will affect stream temperature by altering the amount of heat energy in the system. Discharge is a measure of the volume of water flowing in a stream channel. Substituting heat load and discharge into the above equation results in:

$$\textit{Water temperature} \propto \textit{heat load/discharge}$$

Therefore, stream temperature is dependent on both heat load and stream discharge; any process that influences heat load to the channel or discharge in the channel will influence channel water temperature and can be considered a driver of stream temperature.

A stream channel gains heat energy any time water is added and loses heat energy any time water is removed. When cool water enters a stream, the temperature falls not because heat energy is lost, but because the concentration of heat energy in the stream is diluted. Although heat energy is lost when water leaves a stream, the loss of energy does not affect temperature because the concentration of heat energy in the stream remains the same. (Note that evaporation is an exception to this rule. Water absorbs additional heat energy as it evaporates thus altering the stream's heat-energy to water-volume ratio.)

Streams also gain or lose heat energy without adding or removing water. Heat flows between the stream and atmosphere in ways that do not require water movement (Naiman and others 1992). Heat energy is transferred from the sun to the stream via radiation. Atmospheric heat reaches the stream surface via convection, conduction, and advection and then enters the stream channel via conduction. When heat enters or leaves a stream channel without altering stream discharge, only the heat load changes. An increased heat load applied to the same stream discharge will increase stream temperature. By extension, the same heat load applied to a lesser discharge will also increase water temperatures. This illustrates the importance of discharge in determining the stream temperature response to a given heat load.

Table 1. Examples of natural drivers of channel water temperature

Topographic shade
Upland vegetation
Precipitation
Air temperature
Wind speed
Solar angle
Cloud cover
Relative humidity
Phreatic groundwater temperature and discharge
Tributary temperature and flow

Drivers of Stream Temperature

Stream temperature drivers are external to the stream system and help form the stream's physical setting. Drivers control the rate of heat and water delivery to the stream system and therefore have the ability to raise or lower stream temperature. Some examples are listed in Table 1. While all stream discharge derives from precipitation, precipitation enters the stream via a number of pathways: directly, via surface flow, and via groundwater discharge after infiltrating the catchment aquifer. Climatic drivers interact with the geographic drivers (i.e., topography, lithology, and upland vegetation) to determine how water enters the stream.

Although some streams in arid climates carry only surface runoff, many streams derive the majority of their discharge from groundwater. Therefore, the temperature of the phreatic aquifer is generally the baseline temperature from which stream temperature deviates (although streams fed by snowfields and glaciers are exceptions to this rule). Often, channel water temperature trends away from baseline temperature and toward atmospheric temperatures in a downstream direction (Sullivan and others 1990). As soon as groundwater enters the stream channel and is exposed to the atmosphere, heat exchange begins and the water tem-

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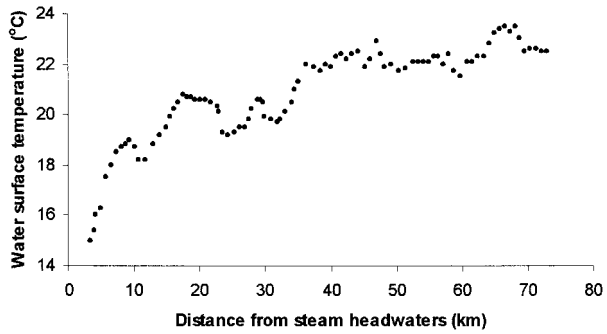

Figure 2. Downstream profile of water surface temperature in the North Fork John Day River. Data are from Torgersen and others (1999).

perature may begin to change. In the absence of insulating and buffering influences, streams will rapidly trend away from groundwater temperature and toward atmospheric temperatures. However, where insulating and buffering influences are strong, downstream temperature trends are reduced or eliminated. Regardless of the magnitude of temperature trends, downstream temperature profiles are punctuated typically by trend reversals due to changes in local structural characteristics along the stream (e.g., Figure 2). These reversals contribute to spatial and temporal heterogeneity often important to native biota.

Groundwater from the phreatic aquifer influences channel water temperature when it enters the stream channel; if the water in the channel has warmed or cooled while flowing downstream, phreatic groundwater inputs tend to moderate channel water temperature year-round (Holmes 2000), although geothermal waters typically moderate winter temperatures but increase summertime maximum temperatures. Temperatures of lateral surface water inputs to the stream network reflect the seasonal climate and are much less consistent over a year than that of groundwater inputs. Similar to groundwater inputs, however, lateral inputs from tributaries and surface runoff affect water temperature by pulling the channel temperature toward that of the incoming water.

Temperature Dynamics within Fluvial Systems

Unlike external stream temperature drivers, the stream's physical structure (channel and floodplain morphology, riparian vegetation structure, and the alluvial aquifer stratigraphy) exerts internal control over water temperature. While drivers determine heat and water delivery to the stream, stream structure determines stream channel resistance to warming or cooling. Additionally, stream structure determines the means and rates of heat and water entry into, flow through, storage within, and release from the stream system and its components. The physical dynamics occurring within a stream and the interaction between a stream and its catchment strongly influence stream structure. (Beschta and Platts 1986, D'Angelo and others 1997, Hawkins and others 1997, Vannote and others 1980).

A wide variety of stream characteristics (i.e., descriptions or measures of stream structures) affect channel water temperature response to external temperature drivers (Table 2). Some characteristics influence insulating processes by controlling the rate of heat flux into or out of the channel. Other characteristics influence buffering processes by removing heat/water from the channel when temperature/discharge is high and releasing heat/water to the channel when temperature/discharge is low.

Insulating Processes

Stream characteristics that influence the rate of heat flux into and out of a stream insulate the stream. These characteristics include the channel width and the riparian vegetation height, density, and proximity to the channel. Riparian vegetation blocks solar radiation from reaching the channel and reduces the stream's heat load (Davies and Nelson 1994, Hostetler 1991, Li and others 1994, Naiman and others 1992). Vegetation also reduces near-stream windspeed and traps air against the water surface. This action reduces heat exchange with the atmosphere by decreasing convection and advection of heat energy to the water surface (Naiman and others 1992). Channel width influences channel surface area across which heat is exchanged; a greater surface area allows for more rapid heat conduction and radiation. Under the same climatic conditions, narrower, deeper channels will not absorb as much heat as shallow, wide channels. Similarly, riparian vegetation more effectively shades a narrower channel.

Buffering Processes

Buffering processes may either heat or cool a stream channel, but buffers differ from drivers in several ways. First, buffers operate by storing heat already in the stream system rather than by adding or removing heat. For instance, buffers may transfer water and heat between the components of the stream (i.e., from the alluvial aquifer to the stream channel), but water and heat are not added to nor withdrawn from the system. Secondly, buffers operate by integrating variation in discharge and temperature over time. If water and heat flow regimes in a stream are constant, buffers can have no effect on channel water temperature.

The two-way water exchange between the alluvial

Table 2. Stream structures that influence insulating and buffering characteristics

Component and characteristic	Determined by	Ecological influence over
Channel		
Slope	catchment topography	flow rate
Substrate	flow regime, sediment sources, stream power	resistance to groundwater flux; channel roughness and therefore flow rate and thermal stratification
Width	flow regime, sediment sources, stream power, bank stability	surface area for convective heat exchange
Streambed topography	flow regime, sediment sources, stream power, bank stability, large roughness elements (e.g., large woody debris)	gradients that drive hyporheic flux
Pattern	flow regime, sediment sources, stream power, bank stability, large roughness elements, valley shape	gradients that drive hyporheic flux; potential shade from riparian vegetation
Riparian zone		
Vegetation	flow regime, vegetation height, density, growth form, rooting pattern	shade to reduce solar radiation; windspeed, advective heat transfer, conductive heat transfer; bank stability
Width	(same as channel pattern)	potential for hyporheic flux; potential for shade
Alluvial aquifer		
Sediment particle size	(same as channel substrate)	potential for hyporheic flux
Sediment particle sorting	(same as channel substrate)	diversity of subsurface temperature patterns by determining stratigraphy; extent of hyporheic flux
Aquifer depth	(same as channel pattern)	extent of hyporheic flux

aquifer and stream channel (hyporheic flow) is perhaps the most important stream temperature buffer. The stream channel pattern, streambed heterogeneity, alluvial aquifer structure, and streamflow variability determine the magnitude of hyporheic flow in a stream (Creuzé des Châtelliers and others 1994, Evans and others 1995, Evans and Petts 1997, Hendricks and White 1999, Henry and others 1994, Morrice and others 1997, Poole 2000, White and others 1987, Wondzell and Swanson 1996).

Hyporheic flow occurs at different spatial and temporal scales. At the finest scale (streambed scale), hyporheic flow is driven by alternating pool/riffle sequences in the stream channel (Vaux 1968, White and others 1987). Water enters the streambed (i.e., the alluvial aquifer) at the downstream end of pools, flows through the streambed sediments, and reemerges at a downstream riffle (Figure 3). Channels with complex streambed topography have higher rates of streambed hyporheic flow (Harvey and Bencala 1993). Streams with relatively little streambed complexity may lack the pool/riffle sequences that drive streambed hyporheic flow. Streambed scale hyporheic flow pathways may be anywhere from minutes to days in duration.

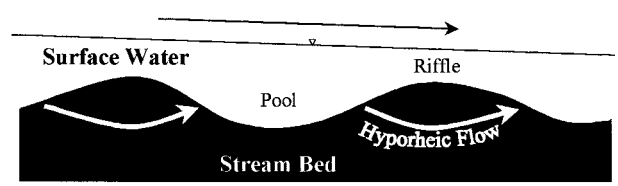

Figure 3. Downstream vertical profile of a stream showing by hyporheic flow within the streambed.

At an intermediate spatial scale (meander-bend scale) hyporheic flow is driven by the development of mid-channel bars and meander bends (Wroblicky and others 1994) and by the presence of side channels, backwaters, and abandoned channels (Stanford and others 1994, Poole 2000). Water enters the upstream end of a gravel or sand bar, flows through the underlying alluvium, and reemerges into the stream at the downstream end. Similarly, hyporheic water follows preferential flow pathways underneath abandoned channels or flood channels and reemerges in backwaters and side channels or as springbrooks on the floodplain (Stanford and Ward 1992). Stream sinuosity and the presence of geomorphic features such as side chan-

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Table 3. Relative influence of stream characteristics on temperature in small, medium, and large streams

Stream Order	Stream characteristics: Riparian shade	Stream discharge	Tributaries	Phreatic groundwater	Hyporheic groundwater
1–2	High	Low	Moderate	High	Low–Mod
	Riparian shade and lateral phreatic groundwater inputs provide thermal stability. Lateral tributaries can frequently affect overall stream temperature. Large wood stores sediments and creates streambed complexity, driving hyporheic flow. (However, hyporheic influence is high and shade moderate in alpine meadow systems.)				
3–4	Moderate	Moderate	High	Moderate	Mod–High
	Temperature of lateral tributaries has strong influence on stream temperature. Effects of riparian shade modest. Thermal inertia due to larger flows becomes more important. Where floodplains form, channels patterns become more complex, and alluvial aquifers are well developed, hyporheic influence can be high. Large wood creates habitat complexity and forms channel-spanning jams that may provide significant shade to the stream.				
5+	Low	High	Low–Mod	Low–Mod	Mod–High
	Complex floodplain morphology creates a diversity of surface and subsurface flow pathways with differential downstream flow rates allowing for stratification, storage, insulation, and remixing of waters with differential temperatures. The resulting mosaic of surface and subsurface water temperatures continually remix to buffer channel temperature and create thermal diversity. The thermal inertia of large water volumes allows the stream to resist changes in temperature. Where side channels exist, shade from vegetation can be important.				

nels, flood channels, and backwaters are critical influences on the magnitude of hyporheic flow at the meander-bend scale. Hyporheic flowpath duration at this scale may be anywhere from days to hundreds of days in duration.

At the coarsest scale (floodplain scale) water tends to enter the alluvial aquifer at the upstream end of floodplains, flow laterally through the alluvial aquifer, and reemerge at the lower end of the floodplain (Stanford and Ward 1993). Valley morphology and sediment characteristics are the primary drivers of hyporheic flow at this scale. Where river morphology alternates between reaches confined by bedrock and those with well-developed floodplains, floodplain-scale hyporheic flow is apt to be common. Hyporheic flow duration at the floodplain scale may be on the order of hundreds to thousands of days. At this scale, however, the distinction between hyporheic flow and catchment aquifer recharge from the stream is blurred. Floodplain scale hyporheic flow arguably might be better conceptualized as "classic" phreatic aquifer recharge/discharge dynamics depending on the duration and magnitude of the flow dynamics.

Thermal diversity in the alluvial aquifer is determined by alluvial aquifer structure, stream channel morphology (Evans and others 1995, Evans and Petts 1997, Stanford and others 1994, White and others 1987), and seasonal variations in stream discharge that drive floodwater storage and release in the alluvial aquifer (Creuzé des Châtelliers and others 1994, Hendricks and White 1995, Martí and others 2000, Morrice and others 1997, Wroblicky and others 1998). In streams where flood spates occur during winter and spring months, the highest aquifer recharge period occurs while the stream channel is coldest. In these systems, hyporheic exchange and floodplain storage of floodwaters may be an especially effective buffer against stream channel warming because the aquifer is recharged predominantly with cold water. This cold water is discharged to the stream during baseflow periods when the highest stream temperatures are apt to occur. Where hyporheic flow pathways are of short duration (perhaps ~100 days or less) and spatially distinct from the phreatic groundwater flow network, hyporheic water temperatures can retain much of their original thermal signature before reemerging into the stream. In these instances, the alluvial aquifer integrates daily and annual changes in channel water temperature, rendering hyporheic flow as an effective stream temperature buffer (Pringle and Triska 2000). Where hyporheic flow pathways are long in duration or integrated with phreatic flow networks, hyporheic flow may be better viewed as a cooling effect like phreatic groundwater. In either case, however, hyporheic exchange results in a horizontal and vertical mosaic of groundwater temperature across the alluvial aquifer that can ameliorate extremes in water temperature.

Pathways of Human Influence

The physical structure of stream channels, riparian zones, and alluvial aquifers changes along the contin-

uum from headwaters to river mouth (Creuzé des Châtelliers and others 1994, Naiman and others 1992, Vannote and others 1980). As stream structure changes, the processes that drive and mediate stream temperature vary in their relative importance (Table 3). Generally speaking, as streams become larger, insulating processes become less effective and buffering processes (which are driven by stream morphology) become more important.

Over time, humans have substantively altered the structure of stream systems and the physical context through which streams flow. It is sometimes difficult to imagine the complex historical structure of streams based on an examination of their current state (Sedell and Froggatt 1984, Triska 1984). A conceptual understanding of the processes and structures that influence stream temperature in unaltered systems can provide a framework from which to understand the breadth of human activities that may influence stream temperature. Several key conclusions can be drawn by understanding how drivers, physical stream characteristics, and resulting insulating and buffering processes influence channel temperature:

1. Human activities that alter the ecological drivers of stream temperature can affect water temperature in stream channels by changing the timing or magnitude of the amount of heat energy delivered to the channel (heat load) or the amount of water delivered to the channel (flow regime).
2. The dominant mechanism controlling water temperature differs among stream systems with different structural characteristics (e.g., low- vs mid- vs high-order; constrained vs unconstrained; forested vs nonforested). Therefore, streams with different structural characteristics will differ in their sensitivity to specific human activities that alter ecological drivers and/or stream system structure.
3. The physical structure of streams influences how water temperature in a stream channel will respond to a given heat load and flow regime. Changing the physical structure of a stream system has the potential to influence both the heat load to the channel and the stream's ability to withstand a given heat load without substantive increase in channel water temperature (i.e., the stream's assimilative capacity for heat).

Dams, water withdrawals, channel engineering (e.g., straightening, bank hardening, diking, etc.), and the removal of vegetation (upland or riparian) alter the drivers of stream temperature, the structure of stream systems, or both. Therefore, they are all potential mechanisms by which human activities can influence stream temperature. Table 4 provides a summary of many of these impacts along with their operative mechanisms; Figure 4 is a schematic representation of the web of pathways by which temperature may be increased during warm periods of the year.

Dams

Dams directly affect downstream temperature depending upon their specific mechanism of water release (top or bottom release). When considering stream temperature alone, dams can be operated to provide desirable stream temperature regimes directly downstream (e.g., through selective withdrawal of water from varying reservoir depths) (Stanford and Hauer 1992). However, from a broader perspective, other ecologically deleterious impacts from flow regulation (Ward and Stanford 1995), including effects on temperature insulating and buffering processes, may not be so easily addressed.

Especially in the western United States, dams often store spring and summer flows for use in irrigation, recreation, and to generate hydropower during periods of peak electrical demand. In basins where water rights are overallocated, there is a tendency for dams to be operated such that summertime flows below dams are severely restricted. Large reductions in flow (sometimes to the point of river stagnation) affect water temperature by reducing or virtually eliminating the stream's assimilative capacity for heat.

Flow regulation also reduces the magnitude of hyporheic flow. For hyporheic flow to act as a temperature buffer, differential storage of heat and water over time must occur. Differential heat and water storage are driven by variation in stream temperature and flow. Since flow regulation dampens variation in both flow and temperature, the potential for hyporheic exchange to act as a temperature buffer is reduced by flow regulation (Ward and Stanford 1995). Dams also affect hyporheic flow by altering the downstream morphology of the channel and geomorphology of the alluvial aquifer. The downstream flux of sediment along the river continuum is disrupted, resulting in downcutting, bed armoring, and, when combined with reduced peak flows, channel stabilization. (Church 1995, Simons 1979). The lack of channel migration and avulsion disrupts fluvial processes critical to creating and maintaining heterogeneous channel patterns (Stanford and others 1996, Ward and Stanford 1995) and alluvial aquifer structure (Creuzé des Chatelliers and others 1994) that drive hyporheic flow at the streambed and meander-bend scales.

Finally, dams are often built at constrictions in rivers

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Table 4. Mechanism and influences of human influence on channel water temperature

Process/implication	Influence and mechanism
Reduced phreatic groundwater discharge results in reduced assimilative capacity	Removal of upland vegetation decreases infiltration of groundwater on hillslopes and reduces baseflow in streams. Pumping wells for irrigation or municipal water sources can reduce baseflow in nearby streams and rivers.
Reduced stream and tributary flow during low-flow periods reduces assimilative capacity	Water withdrawals reduce baseflow and draw down the watertable in the alluvial aquifer. Dams alter the flow regime of a river. Removal of upland vegetation results in flashy stream flow. Dikes and levies confine flows that would otherwise interact with the floodplain and recharge the alluvial aquifer.
Simplified alluvial system structure reduces assimilative capacity by reducing hyporheic flow.	Dams reduce peak flows, preventing rejuvenation of alluvial aquifer structure. Removal of upland vegetation increases fine sediment load which clogs gravels and reduces hyporheic exchange. Dikes and levies confine peak flows which eliminates floodplain inundation and rejuvenation of alluvial aquifer structure; channelization severs subsurface flow pathways. Riparian management may remove large woody debris (and its sources) that contributes to streambed complexity.
Simplified channel morphology reduces hyporheic flow thereby reducing assimilative capacity; wider, consolidated channels are less easily shaded and have greater surface area leading to increased heat load	Removal of upland vegetation increases peak stream power and/or increases sediment volumes altering the interaction between water and sediment regimes and changing channel morphology. Dams remove peak flows that maintain channel morphology. Dikes and levies confine flood flows that maintain channel morphology and decrease subsurface floodwater storage and, therefore, reduce groundwater discharge during baseflow periods. Riparian management may remove large woody debris (and its sources) that contributed to streambed complexity.
Reduced riparian vegetation reduces shade and increases heat load.	Riparian management may reduce shade to the channel and may reduce the amount of air trapped by the vegetation, increasing convective and advective heat transfer from the atmosphere to the riparian zone and stream surface.

just below large alluvial floodplains to maximize the reservoir storage capacity while minimizing the physical size of the dam. Therefore, dams tend to inundate alluvial river segments where hyporheic buffering is most prevalent, thereby reducing the stream's assimilative capacity for heat (Coutant 1999).

Water Withdrawals

Water withdrawals reduce in-stream flow and therefore also reduce the assimilative capacity of streams. Although some of this water is eventually returned to the stream, the fraction is typically low. Solley and others (1993) estimated that only approximately one third of the water withdrawn in the Pacific Northwest was returned to lakes and streams (as cited in National Research Council 1996). Additionally, water returned to the river after withdrawal is often at a markedly different temperature than it was when withdrawn, thereby affecting the heat load to the stream. The water withdrawals are typically used for industry, municipal water supplies, and agriculture. Regulations may sometimes require that the temperature of industrial and municipal effluent be restored before discharging to the stream, but the fate of water withdrawn for agriculture is less certain. Water from agricultural withdrawals that is not transpired or evaporated will eventually return to the stream. After application, this water sometimes percolates into the phreatic flow network and returns to the stream as groundwater discharge. Although there is the theoretical potential for irrigation to moderate stream temperature by increasing phreatic groundwater inputs to the stream, in practice the impact of the initial reduction in stream flow is not likely to be overcome by returning a small fraction of that water through phreatic flow pathways.

Drain tiles are commonly installed in agricultural

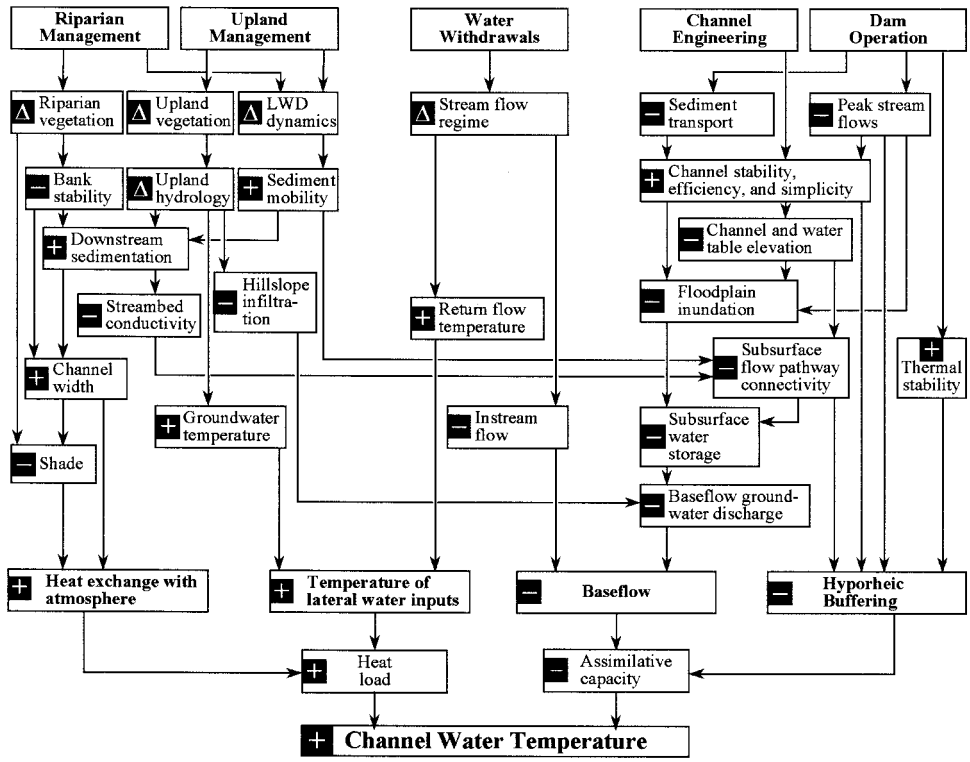

Figure 4. Potential pathways of human-caused warming of stream channels. (+): indicates processes apt to increase. (−): indicates processes apt to decrease. (Δ): indicates a process where a charge is likely but the direction of change varies.

fields to remove excess water from the soil after irrigation. Water flowing out of these drain tiles usually enters a network of artificial ditches, which deliver the water back to the stream. The temperature of these returns can differ substantially from stream temperatures, further exacerbating the temperature affects of agricultural withdrawals (National Research Council 1996).

Major withdrawals from wells penetrating the phreatic groundwater network feeding a stream may reduce flows in a stream channel (Bouwer and Maddock 1997, Glennon 1995, Pringle and Triska 2000, Wilber and others 1996). Additionally, withdrawals via wells can draw hyporheic water away from the stream and into the phreatic groundwater system (Hibbs and Sharp 1992). Therefore, a substantial influence on water temperature may precede marked reductions in surface flows due to changes in the groundwater flow within the alluvial aquifer and changes in net water exchange between the hyporheic zone and phreatic groundwater system (Long and Nestler 1996). In this case, the buffering capacity of the hyporheic flow network may be substantially reduced because hyporheic water would not be returned to the stream channel to moderate channel-water temperature.

Channel Engineering

Straightening, diking, dredging, snagging (removal of large wood), and rip-rapping of channels are all undertaken in an effort to prevent lateral movement of stream channels and increase channel efficiency. These activities focus the erosive energy of streams toward the middle of the channel, encouraging downcutting (National Research Council 1996), and ultimately decreasing the interaction of stream channels with their floodplain in all but extreme flood events. This loss of ecological connectivity between the channel and floodplain can occur through many mechanisms. First, since engineered channels carry water more efficiently, both the amount of time floodwaters spend on the floodplain and the surface area inundated is reduced during average annual high-flow events. This action reduces the opportunity for floodwaters to penetrate the alluvial aquifer (Steiger and others 1998) and, in turn, decreases baseflow by reducing groundwater discharge during the low-flow season. Second, engineered channels typically lack heterogeneity in channel pattern and streambed topography (Jurajda 1995), thereby reducing hyporheic flow. This loss of hyporheic potential can result, in part, from the removal of large wood from the channel, eliminating major structural elements responsible for creating channel heterogeneity (Abbe and

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Montgomery 1996, Piegay and Gurnell 1997, Sedell and Froggatt 1984). Third, when downcutting occurs, the streambed is lowered; stream water no longer reaches the floodplain surface, and existing subsurface preferential flow pathways can be disconnected from the stream channel (Wyzga 1993). In a manner similar to flow regulation below dams, channel modifications sever linkages between the channel and floodplain thereby reducing groundwater buffering of stream flow and temperature (Ward 1998a) and may reduce the efficacy of streamside shade by concentrating flow in one large channel rather than a series of smaller parallel channels.

Upland Vegetation

Whether the catchment of a stream is urban, forested, rangeland, or agricultural, disturbance of upland vegetation associated with human activities has the tendency to increase sediment delivery, warm lateral water inputs, alter the relative amount of surface runoff (and therefore, peak flows), and alter upland water infiltration and groundwater recharge (Naiman and others 1992, National Research Council 1996). When considering stream channel temperature, perhaps the most pervasive and best studied effect of upland land use is the change in channel morphology (usually widening and shallowing of channels) in response to increased sediment load (Dose and Roper 1994, Knapp and Matthews 1996, Richards and others 1996, Sidle and Sharma 1996). Wider channels have greater surface area and are not as easily shaded by riparian vegetation, thereby facilitating the exchange of heat with the atmosphere. Increasing sediment load can also clog coarse streambed gravels with fine sediments (Megahan and others 1992), thereby decreasing streambed conductivity and reducing the exchange of groundwater and surface water across the streambed (Schälchli 1992). Depending on basin characteristics and the nature of the land use, upland land use may augment (Harr and others 1982, Ziemer and Keppeler 1990) or reduce (Burt and Swank 1992, Harr 1980) baseflows, thereby altering the assimilative capacity and erosive power of the stream. When stream power is altered, the historical channel morphology is likely to be disrupted, altering the physical structure of the stream and therefore the dynamics of heating, cooling, and temperature buffering. Where shallow phreatic groundwater systems are important sources of stream water, removal of vegetation in the catchment can alter upland groundwater temperatures, increasing the temperature of water delivered to the stream (Hewlett and Fortson 1982).

Riparian Vegetation

Removal or alteration of riparian vegetation can have important implications for stream temperature (Beschta and Taylor 1988, Hostetler 1991, Naiman 1992, National Research Council 1996). The primary mechanism by which riparian vegetation controls temperature is through insulation (i.e., shading the stream and trapping air next to the stream surface). However, riparian vegetation removal can also destabilize streambanks, thereby facilitating erosion, increasing sediment loads, and ultimately changing the physical structure of the stream (Li and others 1994). These actions may alter the rate of heat exchange with the atmosphere and restrict hyporheic flow by reducing streambed permeability. Loss of riparian vegetation may have major consequences for in-channel processes for forested streams since riparian vegetation is the primary source of large wood to the channel. The size of large wood (Hauer and others 1999, Ralph and others 1994) and rate of large wood recruitment determine its influence on the channel; therefore current land-use practices such as the selective removal of standing riparian vegetation may have important ramifications for channel morphology (and therefore channel temperature) over time.

Documenting Thermal Degradation

Without an understanding of expected patterns of response, we are more apt to attempt to study and monitor stream temperatures in the wrong way, at the wrong location, or at the wrong time. Given a more comprehensive understanding of stream temperature dynamics, we can begin to describe the expected response of stream temperatures to anthropogenic influence. Clearly, it is possible for anthropogenic actions to change the average daily temperature of a stream at any particular sampling location. However, different measures (for instance, spatial or temporal variation in temperature) may be more sensitive to anthropogenic influences and therefore may occur long before a measurable change in average stream temperature. Here we discuss three expected patterns of stream temperature change that may be ecologically significant, but could easily fail to be captured by monitoring experiments not designed specifically to detect them: (1) increased amplitude in diel temperature swings; (2) loss of spatial temperature variability at the habitat-unit and stream-segment scales (as defined by Frissell and others 1986); and (3) variable response in stream temperature along the downstream profile.

As is the case with almost any buffer, a reduction in

buffer efficiency results in larger swings in cyclical response patterns within the buffered system. Temperature is no exception. Anthropogenic reductions in the efficiency of stream temperature buffers will likely result in higher maximum and lower minimum daily and seasonal temperatures in the stream. Monitoring methods that provide a means of capturing daily maxima and minima (such as continuous data recording across days and/or seasons) are necessary to document this expected change.

Spatial variability in temperature within stream reaches may provide localized refugia against stream temperature extremes for fishes and other organisms (Berman and Quinn 1991, Gibson 1966, Kaya and others 1977). Localized temperature variation is driven by habitat heterogeneity (Cavallo 1997, Hawkins and others 1997) and the associated changes in the relative influence of stream temperature drivers across small (meters to hundreds of meters) spatial scales. Simplification of localized habitat structure (dredging, diking, bank hardening, etc.) will reduce localized habitat and therefore temperature variability. Loss of small-scale refugia will affect an organism's ability to avoid undesirable temperatures associated with diel temperature fluctuations, potentially changing good habitat to marginal, and marginal habitat to unusable. Similarly, changes in variability along the downstream temperature profile are likely to affect the spatial variability and distribution of organisms along the stream (Roper and others 1994, Theurer and others 1985, Torgersen and others 1999). If interruption of buffering processes results in a reduction in thermal stability in stream segments that act as refugia, habitat quality is apt to be reduced. Monitoring programs that do not first document and then monitor existing thermal variability at multiple scales will not be able to document changes in spatial temperature patterns over time. Given our growing understanding of the importance of thermal heterogeneity across multiple spatial scales, it seems clear that monitoring programs may be inadequate if they cannot capture expected changes in the spatial thermal variability of streams.

Stream temperatures may respond differently to anthropogenic impacts in different parts of the stream. For instance, where stream temperatures naturally trend upward along their downstream profile (Sullivan and Adams 1991), stream temperatures may be dominated by groundwater (or snow melt) temperature in the stream's headwaters and by equilibrium temperature near the stream's mouth (Figure 5A). Therefore, alteration of processes determining heat transfer rates may not drastically affect stream temperatures at the top or perhaps even the bottom of the stream. Rather,

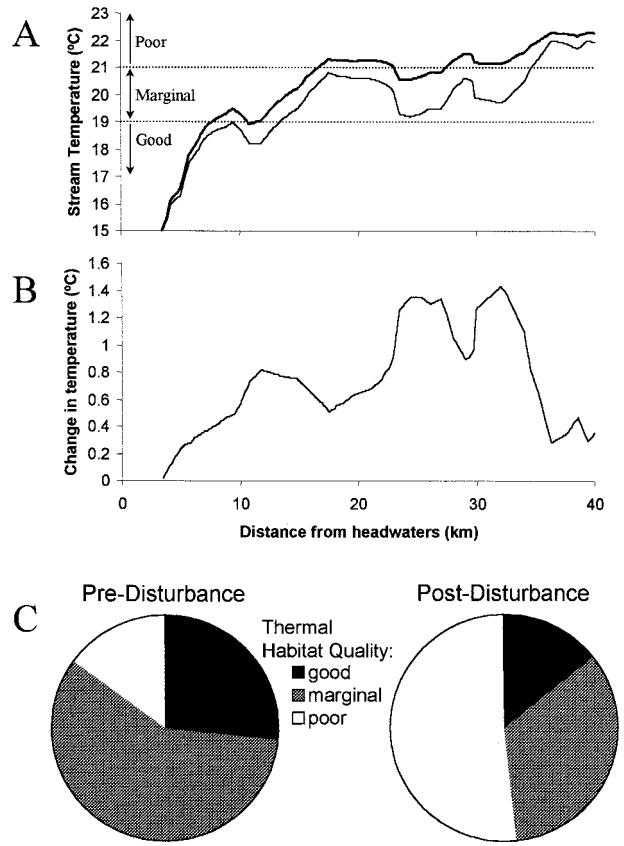

Figure 5. Quantitative depiction of results from a conceptual model of stream warming. (A) Thinner predisturbance line derived from data presented by Torgersen and others (1999); thicker postdisturbance line represents the effects of a hypothetical change in stream structure that results in a cumulative 2.5% increase per stream kilometer in the rate at which water approaches an assumed equilibrium temperature of 22.5°C. Zones demarcated by dashed lines show associated habitat quality of a hypothetical species of concern. (B) Change in stream temperature resulting from the hypothetical structural change. (C) Change in thermal quality of habitat after the hypothetical structural change.

the most dramatic (and perhaps most measurable) change may occur in the middle reaches where the stream's temperature regime transitions from being dominated by groundwater temperature to being dominated by atmospheric conditions (Figure 5B). This could drastically reduce the length of stream that contains usable habitat if the temperature change occurs in a critical range for stream biota (Figure 5C), even though the change in temperature at the mouth of the stream is minimal. In essence, loss of insulating and buffering processes can reduce the distance that groundwater temperature dominance extends downstream. Similarly, stream temperature drivers may have

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different relative influences in different stream segments (Table 3). Anthropogenic influences that affect a particular driver or stream structure cannot be expected to influence stream temperature where the driver or structure is not influencing stream temperature. Results from experiments designed to test for stream temperature response to anthropogenic influence will provide conflicting results if investigators do not account for expected variable response to anthropogenic influence. [See Long and Nestler (1996) for a similar discussion relative to detecting changes in stream flow]. Further, monitoring programs that do not take measurements in areas prone to temperature change will not detect ongoing degradation as soon as might otherwise be documented.

Management of Stream Water Temperature

Not all of the pathways illustrated in Figure 4 are likely to be important in any given catchment. Determining which natural drivers, stream structures, and human activities have been or may be most influential on water temperature is important for designing an effective management strategy. To accomplish this, watershed analysis is a powerful assessment tool (Montgomery and others 1995). The analysis should include an assessment of historical stream structures and processes, thereby providing a reference condition for assessing the present-day influences on stream temperature (Kondolf and Larson 1995). It should also attempt to document, in a spatially explicit manner, the historical channel morphology, riparian structure, and extent of the alluvial aquifer along the stream network. An assessment of management history and ongoing activities within the basin (Wissmar and others 1994a) is useful for interpreting changes in stream structure and for making strong inferences regarding causal linkages between management activities and degradation of water temperature. Additionally, an analysis of the present day channel morphology, riparian structure, and extent of alluvial aquifer is helpful in prioritizing stream segments for restoration.

Since a plethora of different water temperature models have been developed (e.g., Bartholow 2000, Brown and Barnwell 1987, Chen and others 1998, Sinokrot and Stefan 1993), watershed assessment can be useful also for determining the utility of a specific model for use on a stream. For instance, if the results of a watershed assessment were similar to the generalizations shown in Table 3, a temperature model that is not capable of simulating hyporheic flux may be appropriate in headwater streams but could provide erroneous predictions for larger systems. Beyond simple miscalculations of expected water temperature, poor management decisions can result from applying a model that is ill-suited to the critical determinants of a given stream's temperature regime. In fact, if a model is not well-matched to the processes that determine (or historically determined) the stream's temperature regime, the scope of management alternatives can be constrained more by the limitations and assumptions of the model than by the stream's condition and characteristics. For example, managers often simulate several alternative scenarios to compare various proposed management actions. If the chosen model is incapable of simulating the thermal influence of simplified channel patterns and streambed heterogeneity on hyporheic flow, no model scenario can test the efficacy of restoring floodplain geomorphology to enhance hyporheic exchange. Instead, the model scenarios will identify restoration actions targeted at temperature drivers or system structures to which the model results are sensitive. A plan to plant trees along the dikes of a large river may result from analysis of a shade-based stream temperature model's predictions. However, the dikes themselves may be a primary source of thermal degradation because they limit seasonal floodwater exchange with the alluvial aquifer, reduce thermal diversity, and reduce hyporheic flux. Although the best remediation may be to identify portions of the floodplain where dikes could be removed and floodplain connectivity reestablished, planting large shade trees on the dikes would only further harden and add permanence to the dikes. A thorough watershed assessment based on the concepts presented in this paper would identify dikes as a possible contributor to thermal degradation. Ideally, this would encourage development of more comprehensive suites of potential remedial actions and help inform the model selection process before using model results to choose between remedial management plans.

Conclusions

Since stream temperature is a measure of the amount of heat energy per unit volume of water, changing either the amount of heat energy entering the stream or the amount of water flowing in the channel has the potential to alter stream temperature. Further, since a diversity of physical processes in the stream channel, riparian zone, and alluvial aquifer influence the temperature of water in stream systems, degradation of stream temperature can result from modification of external drivers as well as modification of the internal structure of the integrated stream system.

A holistic understanding of the pathways of human influence on water temperature in stream chan-

nels underscores the need for an integrated approach to managing and restoring channel water temperature. To be effective, management programs designed to prevent degradation of water temperature or restore previously degraded systems should consider the breadth of practices occurring in the basin to determine those that are most influential on water temperature. Restoration of geomorphic channel structures, channel-forming processes, sediment dynamics, and flow regimes (Poff and others 1997, Stanford and others 1996) may be critical to the reestablishment of historical temperature regimes in streams. Restoration of streambank vegetation likely will not be sufficient to meet stream temperature goals in streams where degraded channel morphology is the largest cause of undesirable stream temperatures.

To be successful, monitoring and research programs need to account for the functional dynamics of stream temperature. Recovery and protection of stream temperature dynamics should start with identification of the dominant historical external drivers and internal structural modifiers of stream temperature in a spatially and temporally explicit manner across a basin. This information should be combined with an analysis of human activities likely to affect stream temperature and used to develop spatially explicit management prescriptions relevant to the identified human activites. Poorly designed research and monitoring programs that do not account for spatial and temporal patterns of stream temperature, the relative influence of various drivers and/or structures, and the expected response of stream temperature to anthropogenic influences will ultimately not provide reliable answers to relevant scientific or management questions. In short, if we are to improve management and protection of valuable aquatic resources from thermal degradation, scientific questions and management issues must be set in the context of a more holistic understanding of the functional ecological basis for the expression of stream temperature regimes across space and time.

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