The Washington Water RESOURCE

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Message from the Director

The late arrival of the *Newsletter* reflects the long-felt desire to display the results of our four-year regional stream temperature study, coupled with the unanticipated challenges in analyzing and presenting over 2500 individual temperature records collected across four counties by more than 200 different people in a four-year period. The work is still not entirely finished, but enough has been processed that this quarter's issue is given over entirely to the preliminary report of that study. The combined, rechecked, comprehensive data set from that four-year study is now posted as an Excel workbook on the RESEARCH page of the Center's web site, depts.washington.edu/cuwrm/, and you are welcome to download it for whatever additional analyses or location-specific investigations might prove useful. Questions, comments, or interesting results? Please email us here at cuwrm@u.washington.edu.

The other, immediate activity here has been our continued progress on the merging of CUWRM with the Center for Streamside Studies (CSS). We held our second annual joint presentation of centers' research on February 6 to an audience of more than 450. Formal administrative approval has worked its way up the organizational ladder of the University, and the date for formal joint operations is anticipated for the last quarter of this year. This combined, broadened set of interests and expertise promises to be a very positive development both for our student and faculty University colleagues, and for our external contacts and collaborators in public agencies, tribal government, and private firms. Look for more information in the next issue.

Regional, Synchronous Field Determination of Summertime Stream Temperatures in Western Washington

Cold-water fisheries can be strongly affected by elevated summertime stream temperatures. Several decades of study have investigated the causes, and the consequences, of warmed water in rivers and streams. The Pacific Northwest is one area where such conditions are pronounced—undisturbed watersheds are characterized by extensive forest cover, relatively cool summertime air temperatures, and a hydrologic regime where groundwater supplies most of the flow during the hottest times of year. Human disturbance of these watersheds has produced a variety of changes that may alter those conditions, particularly through the clearing of riparian vegetation and altered hydrologic processes that result from upland soil compaction and, in the case of urban development, construction of impervious surfaces.

Although the causes of elevated stream temperatures are relatively well understood

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in principle, their quantification in any given watershed is confounded by the vagaries of groundwater and surface-water inflows, and the complex interplay of stream orientation and sun angle, canopy cover, and air temperature. Individual temperature measurements can characterize the state of a particular stream, but they do not provide any context to evaluate "unusual" temperature conditions, whether natural or human-induced.

Even where a reliable temperature record exists, or where the consequences of potential land-management activities can be predicted, biological consequences are more difficult to evaluate. As a simplified problem in space and time, criteria for "optimal," "marginal," and "lethal" temperature ranges can be established through laboratory studies and fortuitous observations in natural rivers. So, for example, the species of greatest concern in Pacific Northwest rivers and streams, members of the *Salmonid* family, display the following tolerances at various stages of their life cycle:

National Marine Fisheries (1996) temperature criteria for salmonids:

"Properly Functioning"	10-14 °C
"At Risk"	14-16 °C (spawning)
	14-18 °C (migration and rearing)
"Not Properly Functioning"	>16 °C (spawning)
	>18 °C (rearing)

Temperatures for biological functions of salmonids
(from EPA-R-01-007, August 2001):

Common summer habitat use:	10-17 °C
Lethal 1-week exposure temperature	>21-22 °C (adults)
	>23-24 °C (juveniles)
Spawning initiated	7-14 °C
Optimal growth	13-19 °C (unlimited food)
	10-16 °C (limited food)

Yet the utility of such determinations are unclear in natural stream networks. Salmon are both adaptable and mobile; temperatures that would be truly intolerable are uncommon in either natural or disturbed streams. They are transitory in time, insofar as the diurnal cycle rarely holds temperature at problematic levels for more than a few hours, at most, per day. They are also localized in space—microhabitats can hold water 5-10 degrees colder than the surrounding stream, and the distribution of temperatures across a channel network can be highly variable as a consequence of riparian cover, topographic aspect, and groundwater inputs. Thus simple point determinations of temperature without temporal and spatial contexts have little meaning.

Historically, stream temperatures have been investigated via either of two approaches. The first is simple empiricism, aided greatly over the last decade by the development of simple and inexpensive continuous-recording temperature gages. Extensive records of stream and river temperatures are available from thousands of sites, some spanning many years and others installed for only a season or two. These records provide detailed, local records that can suggest the degree to which temperatures may be biologically significant and provide the basis for calibration of the second major approach, that of energy-balance modeling.

The energy balance of a stream displays the variety of ways in which heat is added, lost, and stored in a stream. Its general form is:

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$$H = N + T + B + S + E$$

where H is the change in stored heat per unit surface area of the water,

N is the long- and short-wave radiation,

T is the heat added by surface-water and groundwater inputs,

B is the heat conduction between the water and the bed of the stream,

S is the heat conduction between the water and the air, and

E is the heat exchanged between the water and the air by evaporation or condensation.

Changes in stream temperature are the expression of changes in the stored heat per unit surface area and the volume of water passing through that surface area: that is, stream temperature depends on both the rate of heat energy input and the water discharge.

Decades of measurements and models demonstrate that the most important term is the net radiation (N), which in turn is determined by the sun angle, stream aspect, and degree of canopy cover. Conversely, the least important terms are generally those of conduction and evaporation (S and E), which are small in absolute magnitude and also move in opposite directions with changing conditions—increasing wind, for example, that might increase the turbulent transfer of heat from warm air to cool water will also increase the rate of evaporative cooling. Of the remaining terms, the input of sensible heat from runoff warmed on the land surface ($T_{surface}$) is generally nonexistent during periods of potentially high stream temperature in the Pacific Northwest. In contrast, the analogous (but generally cooling) influence from groundwater input (T_{ground}) is potentially significant but also quite variable across a channel network, depending on both local and regional variations in subsurface geology, soil thickness and permeability, and upland land cover.

Existing studies, both empirical and modeling, suggest the likely magnitude of water-temperature changes resulting from human activity. Most have been conducted in regions with higher typical summertime temperatures than the Pacific Northwest, but they can still suggest the likely scale of observed influences from human activity. During air temperatures typical of Pacific Northwest summers, Hewlett and Fortson (1982) report maximum water-temperature increases in the southeastern Piedmont of about 3 °C (± 3 °C) from riparian clearing. A pre- and post-clearcutting investigation of a small headwater stream in Pennsylvania (Rishel and others, 1982) showed the average monthly maximum stream-temperature increase to be 4.4 °C. Pluhowske (1970) reported urban-induced increases in summertime stream temperatures on Long Island by as much as 5-8 °C. Klein (1979) noted the importance of riparian vegetation in moderating diurnal temperature variation, and he noted one measured stream in suburban Maryland with an 11-degree difference between shaded and unshaded reaches. LeBlanc and others (1997) investigated various human-induced changes via a calibrated temperature model for a temperate mid-latitude site, finding typical temperature increases from vegetation removal to be about 2 °C, from increased channel width (from urban-increased discharges) of up to 1.7 °C, and over 2 °C for various scenarios of baseflow reduction.

These studies leave several important questions unanswered. How reliably can we predict the temperature of a site where both natural and anthropogenic factors may be influencing temperature? How does the spatial pattern of temperature across a channel network moderate, or amplify, the biological effects of locally hot (or cool) water? Finally, how can we interpret a single measurement, or even a series of measurements, at a single site? Is "hot" too hot? Is it "unnaturally" hot? In short, what are the channel-network and regional *contexts* for a measurement, or set of measurements, from which we might evaluate the biological significance of the resulting temperature data? The purpose of this study is to explore one method of providing that context, and to investigate some of the apparent consequences of human activity on the summertime temperatures of Puget Lowland streams.

METHODS

Establishing the regional context for measured stream temperatures requires broad spatial coverage. A model could nominally accomplish this goal, but the need for calibration data (or, in the absence of calibration, the consequently high magnitude of uncertainty) makes this approach infeasible. The alternative, at first blush, also appears daunting—collect enough spatially separated measurements under "equivalent" conditions to define the pattern of stream temperatures across a region. The challenge is not in taking a temperature measurement itself, but in taking *many* such measurements without influence of the diurnal temperature cycle, whose magnitude at any one site is similar to the spatial patterns of interest over the region as a whole; and to take those measurements with identical protocols that provide good (or at least known) precision and accuracy. The first objective of this study, therefore, was to take a very large number of simultaneous (or near-simultaneous) temperature measurements, using identical protocols, at broadly distributed locations that span a variety of topographic, geologic, and human influences.

To provide this context of regional stream temperature, over 100 individuals, representing approximately 20 different agencies and community groups, collected over 500 temperature measurements across the south-central Puget Lowland in a two-hour period on each of four years, from 3:00 to 5:00 PM, on August 19th 1998, August 3rd 1999, August 2nd 2000, and August 1st 2001. Sites were arrayed to provide coverage of both scattered individual sites and whole stream systems on a watershed-wide basis, with drainage areas ranging from over 200 km^2 down to somewhat less than 1 km^2, approximately the lower limit of perennial flow in this region (Konrad, 2000). Reflecting an overriding interest in quantifying human influences,

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watersheds with primarily urban and suburban land uses were targeted but some rural and forested basins were included as controls.

Generating a truly "regional" data set presented several scientific and logistical problems. The changeability, and unpredictability, of western Washington weather required a set of same-day measurements; the magnitude of diurnal stream-temperature variations (typically 3-5 °C or more, based on data from existing continuous gages) further narrowed the time interval available to collect truly "equivalent" data. Yet no agency or institution could install a sufficient number of recording temperature gages, nor field a sufficient number of staff or volunteers, to provide anything approaching the magnitude of near-instantaneous spatial coverage envisioned.

An acceptable period of near-maximum and relatively unchanging stream temperatures was determined from existing records. Seasonal patterns showed that early August had the greatest likelihood of yielding annual maximum water temperatures (Figure 1), consistent with other studies in temperate latitudes in the northern hemisphere. Within any particular day in the summertime, the late afternoon had the dual advantage of having temperatures that included the daily temperature peak and also varied most slowly with time. Thus non-instantaneous measurements might be collected with minimum influence from the diurnal cycle, a hypothesis that could be tested with the data once collected. The final choice was for a two-hour interval of data collection, chosen to balance the desire to collect truly instantaneous data unaffected by diurnal changes with the intent to collect the largest amount of data, over the broadest area, with sufficient spatial resolution to discern patterns and trends within individual channel networks.

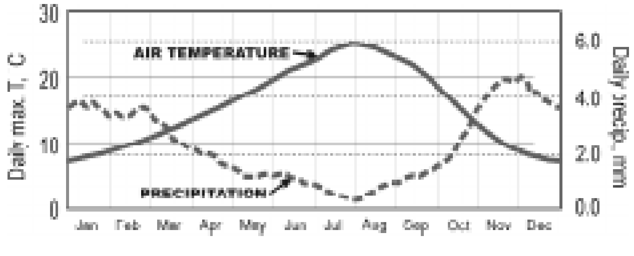

Figure 1.
30-year daily average of air temperature and precipitation at SeaTac airport (Western Regional Climate Center; http://www.wrcc.dri.edu)

Even with a predefined window during which near-equivalent data might be collected, the task of identifying a sufficient number of data-collecting personnel was daunting. Resolution came primarily from the willingness of agencies and tribes to offer their staff, and to share and coordinate their citizen volunteers, on behalf of this effort. These included:

- King County
- Snohomish County
- Pierce County
- Kitsap County
- Tulalip Tribe
- Stillaguamish Tribe
- Puyallup Tribe
- Muckelshoot Tribe
- Washington Department of Fish and Wildlife
- City of Bellevue
- City of Seattle
- City of Renton
- City of Tukwila
- Washington Trout
- Adopt-a-Stream
- Thornton Creek Alliance
- Ravenna Creek Alliance

In total, about 100 teams of one or two people each dispersed throughout the region on predetermined routes during the same two-hour interval. The logistics of such a number of teams required that the date for the effort be selected far in advance of any useable weather forecast. Work schedules suggested a weekday (Wednesday was chosen for all four years); the region's legendary traffic and general courtesy to the volunteers required a termination of data collecting by 5 p.m.

The sample locations, and the routes, of each team were planned well in advance of the sampling date. The sites all lie on lowland streams with nearly all drainage areas under about 100 km^2; although temperature conditions on the region's larger rivers is also of concern to fisheries managers, the differing scales would have imposed irreconcilable differences in the choice of date and time of day for maximum temperatures. Furthermore, the smaller systems that were our focus have been affected most directly, and severely, by urban development of their watersheds, which in some cases has resulted in 100 percent urban development in their contributing area. Logistics and sampling efficiency required that all sites lie on or very close to road crossings; given this requirement and the feasible number of sites, locations were generally spaced 1-3 km apart on the streams that were covered for this survey.

Routes were designed to minimize driving time and to allow individual teams to see the patterns of temperature in a particular stream system emerge from their own data, as much as feasible. Many routes circled back on themselves, requiring teams to make an independent measurement late in the two-hour period at the same site that they had visited earlier in the day. Nearly one-quarter of the routes also sampled a site that had been (or would be) sampled by *another* team in the course of the afternoon, unbeknownst to either group (except where the two groups accidentally met). These two types of semi- and wholly independent measurements have provided a critical measure of

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the accuracy and precision of the collected data, and they enabled us to characterize the limits of the data's utility.

Field data collection was designed to be rapid. The requested measurements and observations were specified on a one-page "site form" that could be filled out in less than five minutes:

Basic information to specify the site and to evaluate the route logistics:

- Site number
- Time of day
- Any detailed driving or walking directions to the sampling point

The basic data needed for the study:

- Air temperature
- Water temperature

Local flow conditions by choosing one of the following terms:

- Free-flowing
- Sluggish
- Stagnant
- Dry

Conditions of the nearby riparian canopy by choosing one of the following terms:

- Fully shaded
- Partially shaded, predominantly trees
- Partly shaded, predominantly shrubs
- Full sun

Information on the detailed location of the water-temperature measurement, included on form mainly to encourage data collection at the best location:

- Location of the temperature measurement, specified as one of the following:
  - -Center of the channel
  - -Near the edge of the channel
- Estimated depth of flow at the measurement point

To minimize variability in the results, standardized forms and pre-determined routes were mailed to all volunteers (or their agency coordinators). Every volunteer was first asked to calibrate their thermometer in an ice-water bath, and to note the temperature registered by their thermometer after 10 minutes to the nearest degree (°F) or half-degree (°C). Between 55 and 60 percent of the volunteers reported a "true" temperature, within the limits of this precision (i.e. ice-water reading less than ±0.5 °C); only a few percent in each year had a correction greater than 1 °C. The reported calibration value was used to adjust all reported temperatures. The volunteers were also asked to comment on the quality of their thermometers (e.g., "lab grade," "cheap"). Interestingly, 0° calibrations were by no means the exclusive domain of the most expensive instruments.

Each route was planned in accord with the principles of regional coverage, channel-network density, and transportation efficiency. In the first year (1998), routes were assembled from local knowledge and promising road crossings of streams suggested by topographic maps. In subsequent years, reports back from volunteers improved routes by eliminating mis-mapped channels and sites for which private property or heavy brush made access infeasible. For all years, the desired sites were plotted on a road map and sent to the volunteers along with a thermometer-calibration form and individual site forms. Limited time, changing land use, erroneous plotting, and creative volunteers continue to produce final data sets that differ from the planned set; but over the four years of this effort the "yield" of readily located, well-distributed sampling points has been over 90 percent of those assigned.

DATA ENTRY AND ANALYSIS

Data forms were generally returned by mail over the two weeks following the date of measurement. The field forms were reviewed for any ambiguities in location or obvious errors in recording (e.g., water temperature reported for a dry channel). Routes were also evaluated for their duration and successful access; any changes were noted to improve the following year's effort. All information was then entered into a spreadsheet, maintaining a record of which volunteer collected which data and applying any calibration adjustment to the measured temperatures.

The data were analyzed through both regression relationships and spatial analysis. Various potential dependencies of water temperature on other measured variables, particularly air temperature and canopy, were displayed graphically and characterized algebraically, if warranted. Spatial analysis was conducted in ArcView 3.2 by first plotting every point of the 1999 survey (our most voluminous) on digital raster graphics (DRG's) of 7.5-minute topographic maps, available through the U. S. Geological Survey (USGS). Scripts in ArcView were then executed to determine the UTM coordinates of each plotted point and to define the watershed area draining to each point, using a 10-m digital elevation model (DEM), also available for this region from the USGS. These watersheds were used in ArcInfo 8.0 to "clip" regional coverages of land cover and geology. The contributing watershed area was also tabulated for each point.

The source of land-cover data was a classified GIS layer produced from Landsat imagery (Hill and others, 2000). The classification scheme followed a multi-step process of:

1. Combination and manipulation of the raw satellite images;
2. Selection of training sites, where different land-cover categories could be defined;

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3. Extraction of the "typical" Landsat signatures for each coverage;
4. Classification of the entire image, following the characteristics defined for each class; and
5. Defining the average land-cover characteristics of each classification by checking actual field conditions at selected locations.

To accomplish these steps, a Landsat image from 1998, with a resolution of 30 meters, was obtained for northwestern Washington State. The raw Landsat image was imported into the ERDAS Imagine software package and geocorrected to the UTM projection (zone 10N, spheroid Clarke 1866, datum NAD27). The raw Landsat images contain seven superimposed sets of reflectance values received by the satellite sensors in various wavelength bands. Three of these bands (corresponding to the visible blue, near infrared, and mid-range infrared portions of the EM spectrum) were extracted from the raw image and processed using Imagine's Model Maker module into a single composite image. Nine 1-km^2 "training sites" of relatively uniform land cover were selected from around the region to determine characteristic reflectance for different types of vegetative and urban ground cover. The Signature Editor module in ERDAS's Imagine software was then used to extract spectral "signatures" for each training site, which in turn were used to classify the entire Landsat image. Randomly selected pixels from the classified image were then compared with low-elevation orthophotos to determine the actual land cover that corresponds to each category in the classified image, and thus to determine the impervious-area percentages associated with each category.

Geologic data was compiled from those published maps currently available in a digital format (Ralph Haugerud, USGS, pers. comm., 2000). In the northeastern and east-central part of the study area, this coverage reflects the most recent geologic work, generally published since 1980 at an original scale of 1:24,000. Elsewhere, the geologic data is more generalized but is likely to define the relative coverage of the primary geologic materials with errors of mis-assignment of only about 10 or 20 percent.

RESULTS

Conditions of Rainfall and Temperature

Conditions in our four sampling years differed only modestly. The summer of 1998 was somewhat drier than usual (July rainfall was 10 mm compared to an average of 19 mm). Our sample date (August 19) was exactly the average for the month of August (24 °C), and our sample period (3-5 PM) was within 1°C of the maximum water temperature of that day, as recorded on various continuous recording gauges around the region. This day was too late in the summer for what turned out to have been the hottest interval of 1998, and so the results are representative of "normal" but not "extreme" conditions. In contrast, 1999 was a wetter summer than average (July rainfall was 30 mm), and 5.3 mm of rain were recorded for the morning of the sampling day at SeaTac Airport, the regional station with the longest record. The day's maximum air temperature was almost identical to that in 1998; the maximum recorded temperatures for the year (both air and water) came several weeks later. In 2000, monthly precipitation (6 mm in July) and the air temperature on August 2nd (25.5 °C) were both drier and warmer than long-term seasonal normals; no measurable rain fell for the 11 days preceding the year-2000 measurement. 2001 was our coolest day, with a maximum SeaTac temperature of 21.1 °C. July rainfall was 26 mm, with the last precipitation occurring four days before our sampling.

Date	Max. SeaTac Air T	July rainfall	Antecedent dry period
August 19, 1998	23.9	10	2 days
August 3, 1999	23.3	30	< 1 day
August 2, 2000	25.6	6	11 days
August 1, 2001	21.1	26	4 days

Data Acquisition

Data quantity was voluminous in each year of this four-year effort. Because of logistics and community interest, the number of sites increased dramatically between the first year and the second; a desire to better focus our efforts on systems with particular agency concerns or of regional biological significance led to systematic, targeted reductions the two years following:

	1998	1999	2000	2001
Volunteer teams	88	101	91	71
Data points	555	792	671	508
Number and percent of replicates	42 sites (7.6%)	122 (15.4%)	97 (14.4%)	73 (14.4%)
Number and percent of dry sites	29 dry sites (5.2%)	54 (6.8%)	51 (7.6%)	30 (5.9%)

In all four years, the data-collection logistics were comparable in both areal coverage and level of effort. Statistics for the size distribution and land-cover distribution of contributing watersheds, therefore, are very similar for all years and can be adequately represented by the year with the greatest number of points and the most complete land-cover analysis (1999).

Contributing watershed areas ranged from less than 1 to 261 km^2; the median size was about 9 km^2(Figure 2). Total impervious area in these watersheds, estimated from the 1998 classified Landsat image of Hill et al. (2000), displayed a broad range from nearly undeveloped to almost fully urbanized (Figure 3).

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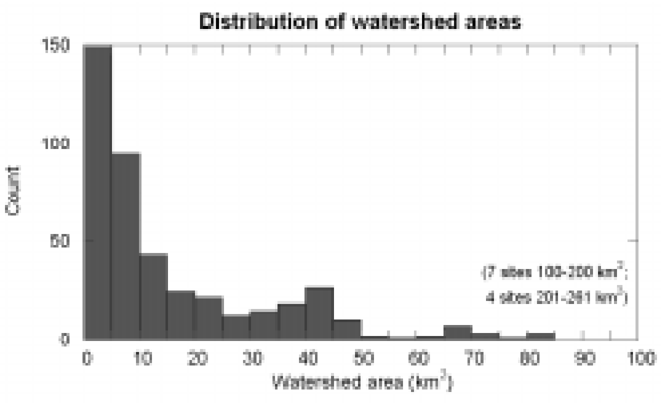

Figure 2.
Range of watershed areas draining to temperature sites (based on 1999 survey population).

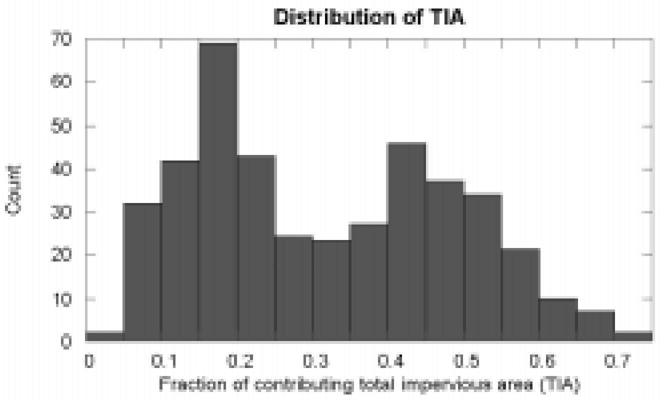

Figure 3.
Proportion of total impervious area in the contributing watersheds (based on 1999 survey population; land cover analysis by Hill et al. 2000).

Data Quality

A major focus of this study was the evaluation of data quality, not only to determine whether the study results carried any useful information about stream temperature patterns but also to evaluate the general utility of volunteer efforts in otherwise impossibly large data-collection efforts. Three approaches were used in this evaluation: (1) review of any systematic temperature trends, (2) repeated sites (same observer, different times), and (3) replicate sites (different observers, different times). The first approach evaluated whether our measurement window was so long as to violate the assumption of "uniform" conditions; the second investigated the influence of random fluctuations in temperature and in thermometer reliability. The third was most critical, because it showed us not only the variability in data we should expect from multiple observers but also the minimum recorded temperature difference that would be meaningful in any subsequent analyses.

The results of all three approaches are best described graphically. The plot of temperature as a function of time (Figure 4) shows no obvious pattern; the least-squares regression line has a slope of less than 0.1 °C per hour during the two-hour period. The relationship between multiple temperature measurements at the same site is not independent of whether the same person or different people take the two readings (Figure 5), but in both cases the majority of measurements lie within 0.5 °C of one another. Statistically, over 95 percent of the readings (i.e. 2 sigma) lie within 1 °C of each other, which determines the useful precision of the data—about one order of magnitude less than the range of measured water temperatures (8.9-25.0 °C in 1998, 8.9-27.5 °C in 1999, 9.7-28.5 °C in 2000, and 9.0-24.0 °C in 2001).

Year	1998	1999	2000	2001	TOTAL
Number of T pairs	42	122	97	73	334
Standard deviation (°C)	0.17	0.53	0.53	0.27	0.47

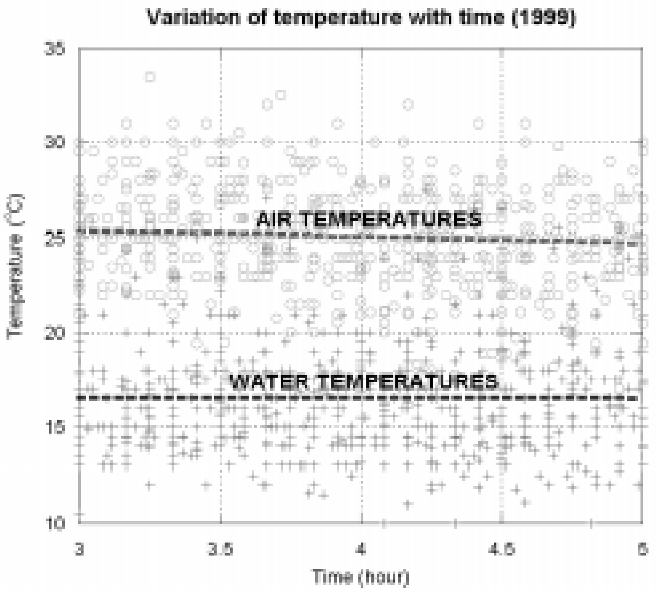

Figure 4.
Variation in air and water temperatures over the 2-hour measurement period (1999 data). Air temperatures decline by about 1 °C; water temperatures show no systematic variation at all.

Flow and canopy conditions were also recorded at both repeated and replicated sites, but here the results differ even more strongly between the different types of replication. Generally (but not invariably), the same person described the same site in the same way; only 5 of 251 repeated measurements, for example, had any differences in the characterizations of either flow or canopy:

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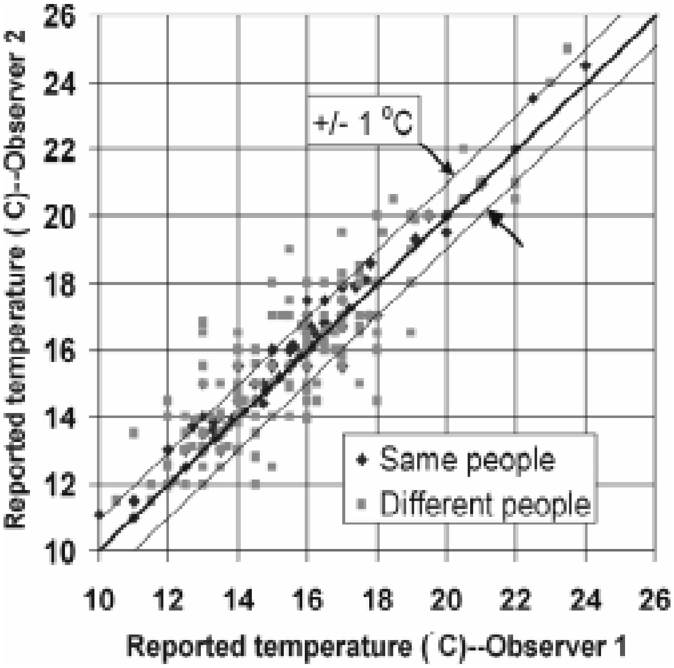

Figure 5.

Replicate measurements by the same observer at different times or by different observers (all years of data combined; n = 334). Many sites, particularly those of the same observer, overlap precisely on the graph and so are not evident in this display. ±1 °C represents approximately two standard deviations off of the mean.

SAME PERSON

	Free-flowing	Sluggish Flow	Stagnant Pools	No Water
Free-flowing	112			
Sluggish Flow	1	16		
Stagnant Pools	0	0	2	
No Water	0	0	0	1

	Full Shade	Partial Shade (trees)	Partial Shade (shrubs)	Open Sun
Full Shade	25			
Partial Shade (trees)	2	49		
Partial Shade (shrubs)	1	2	35	
Open Sun	1	0	0	14

Different observers, however, were not so agreeable:

DIFFERENT PEOPLE

	Free-flowing	Sluggish Flow	Stagnant Pools	No Water
Free-flowing	152			
Sluggish Flow	36	33		
Stagnant Pools	1	1	3	
No Water	0	2	5	12

	Full Shade	Partial Shade (trees)	Partial Shade (shrubs)	Open Sun
Full Shade	23			
Partial Shade (trees)	41	37		
Partial Shade (shrubs)	13	39	36	
Open Sun	5	6	8	22

From these comparisons, certain observations are clearly unreliable. Although the same person will presumably always return to the same location, and presumably see the same conditions with (nearly) the same set of implicit criteria (>98 percent agreement for flow and 96 percent agreement for canopy), neither of these assumptions can be held with confidence when multiple observers are involved. Flow categories were identically categorized in 82 percent of paired observations by two different people, but only 51 percent of the canopy observations were identical. More than 80-percent agreement in canopy is achieved only by lumping all "shaded" categories together, suggesting that single-site evaluation of shade conditions by multiple observers is little better than "open sun" vs. "not open sun," where criteria are descriptive and locations are not rigidly controlled. In contrast, flow conditions are much more persistent along a reach of channel, and so minor differences in location will produce only modest disagreements.

Upstream Limits of Perennial Flow

Perennial flow is defined by the year-round presence of running water. In the Pacific Northwest, the normal pattern of prolonged summer drought allows persistent streamflow only as a result of shallow or deep groundwater discharge. Because land-use changes have been implicated in documented reductions in baseflow (e.g., Seabold, 1969), our data set can be evaluated for the potential influences of land cover and watershed area. Antecedent precipitation varied between the four years, and so only the data with the most complete catalog of "dry" channels, 1999, was evaluated. Konrad's (2000) review of these same data noted no clear "threshold" of minimum drainage area for perennial flow: dry channels were observed in channels draining watersheds up to 14 km^2, and flowing streams from watersheds smaller than 0.5 km^2 (Figure 6). At drainage areas of less than about 3 km^2, chances are about 50 percent of encountering free flow (as opposed to sluggish, stagnant, or dry conditions).

These trends suggest that watershed-scale land cover is a poor predictor of baseflow conditions, either because geologic conditions are of overriding importance, or because increased runoff from developed areas is roughly balanced by imported water that either is used for landscaping or is added to the groundwater system through septic systems.

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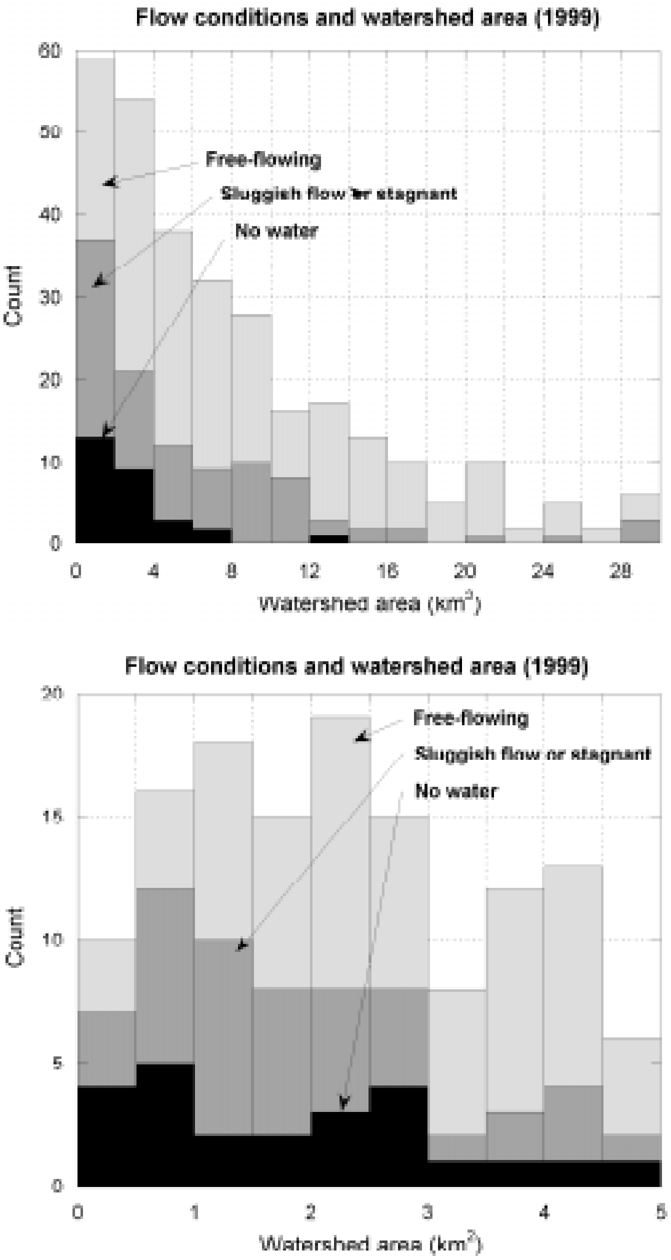

Figure 6.

Tally of flow conditions, grouped by watershed area (1999 data only). Figure 6A shows the general decline in "dry" sites as watershed area increases, particularly above about 8 km^2; Figure 6B provides greater detail in the distribution of flow conditions for the smallest watersheds in the study.

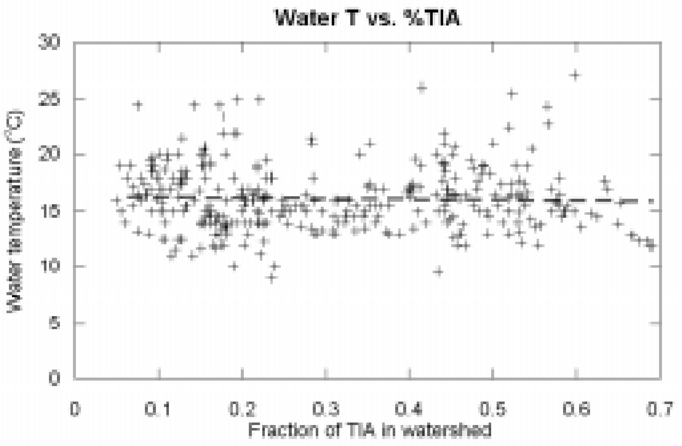

Figure 7.

Insensitivity of measured stream temperature to fraction of total impervious area in the contributing watershed (1999 data). Within the precision of our measurements, the distribution is completely uniform.

Broad Determinants of Water Temperature

This data set provides a unique opportunity to investigate the causes of summertime stream temperatures. At a site, diurnal variations recorded by continuous gauges demonstrate the importance of air temperature and insolation (Figure 8), but no correlation shows at all between measured air temperature and measured water temperature across the sites (Figure 9). Thus any correlation between these two parameters, if developed on a "representative" set of streams, is unlikely to provide accurate results if applied elsewhere.

Konrad (2000) found no obvious land-use influence on summertime water temperature, using road density as a proxy for development intensity. With the current analysis we can now use a more direct measure of land cover (watershed fraction of total impervious area, or TIA), but there still is no apparent influence (Figure 7).

Between-Year Variability

Although the maximum daily air temperature ranged by 4 degrees between the four years of data collection, water temperatures varied by significantly less. The best data for this evaluation are those from the 177 sites that were visited in all four years:

		Water Temperature (site visits in every year)		
Date	SeaTac Daily Max. Air T	Average of all sites	Max. reported	Min. reported
August 19, 1998	23.9	15.2	23.0	8.9
August 3, 1999	23.3	16.1	26.5	8.9
August 2, 2000	25.6	16.2	26.4	9.7
August 1, 2001	21.1	14.2	24.0	10.5

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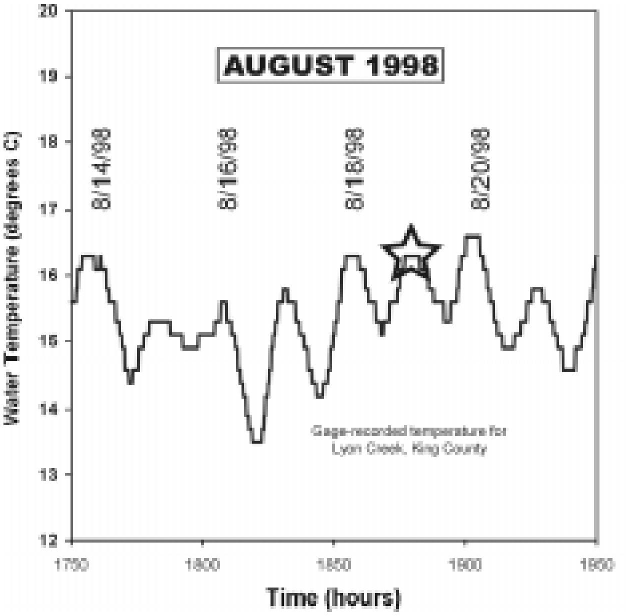

Figure 8.
Diurnal variation in stream temperature, displayed by continuous recorded data in Lyons Creek (northern King County; data courtesy of King County Water and Land Resources Division). The star indicates the period of the 1998 survey.

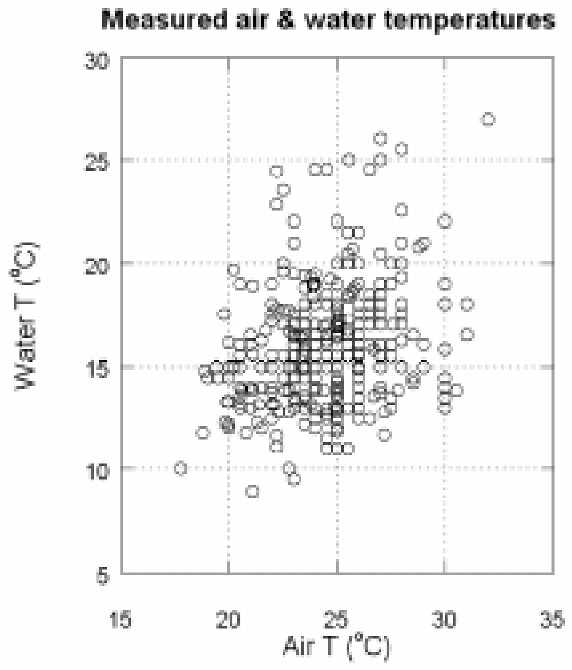

Figure 9.
Simultaneous, paired air-water temperatures (all years' data). No correlation is evident.

Riparian Canopy

Riparian canopy, long recognized as a significant factor in stream temperature, is influential in our data set as well. For each of the four observer-described local canopy conditions (full shade, partial shade trees, partial shade shrubs, open sun), the median and the range of measured temperatures generally climb upward (Figure 10). Differences between adjacent categories are not all statistically significant, however; in particular, the two "partial" categories scarcely differ at all. The strongest relationship is between the category "open sun" and the three shaded categories, a result that is mirrored by the reliability of different-observer reports of the same four categories (see above).

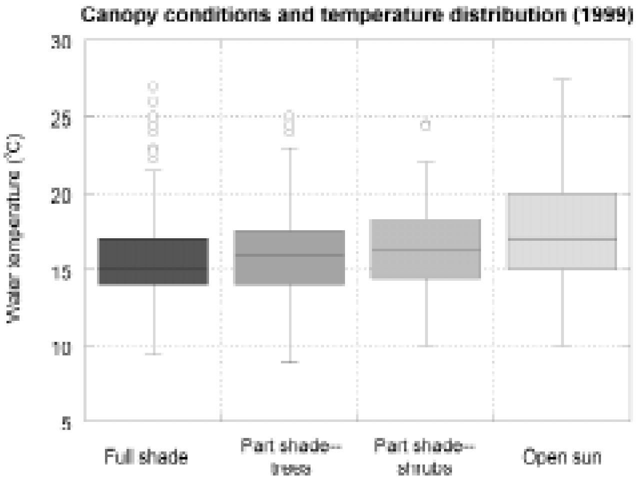

Figure 10.
Box plot of all reported temperatures in 1999, grouped by reported canopy conditions (n = 738). Boxes include 25th through 75th percentile of data; whiskers span 10th through 90th percentile.

Lakes

Although not evaluated systematically, inspection of data after the first year's collection suggested that lakes have a discernable influence on downstream temperature. In this region, most lakes are shallow and unshaded; as a result, incident sunlight might be expected to warm the downstream water. This relationship was evaluated crudely, by defining a "lake" as any body of water so represented on 1:24,000-scale (1'=2000') USGS topographic maps, and then by measuring the downstream distance from the outlet to a sampling point. Sites more than about 3 km downstream were ignored, generally because the accumulation of non-lake-influenced tributary areas reduced the "lake-influenced" water to significantly less than half of the total. There was no effort to quantify this relationship more precisely, however, and so results here are provisional.

Nonetheless, the measured data suggest that the "lake-influenced" water is commonly about 2 °C warmer than the body of data would otherwise suggest (Figure 11). In contrast, comparison of air temperatures collected at the same sites with the full-data average for each year show less than 1 degree's difference.

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Displaying these lake-influenced water temperatures against their distance downstream from a lake displays a noisy, but suggestive, trend (Figure 12). Parenthetically, these results suggest that the regional strategy of constructing permanent open-water ponds for water-quality improvement (e.g., Comings and others, 2000) may simply be trading one pollution problem for another.

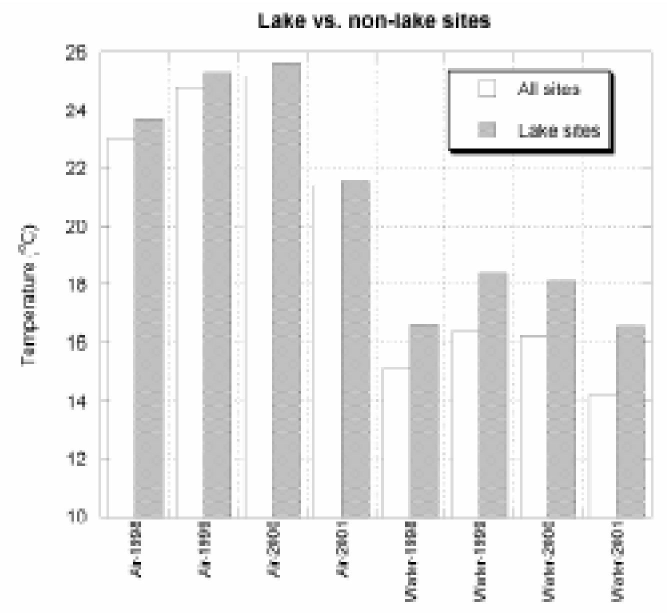

Figure 11.

Air and water temperatures compared for lake-influenced and all sites, grouped by year. Air temperatures show no appreciable difference, suggesting that the lake sites are generally "representative" of the year as a whole; water temperatures, however, are generally about 2 °C warmer.

Urban Development

Although a variety of factors have been suggested for the influence of urbanization on stream temperatures, our data show that using the fraction of impervious area in the upstream watershed does not provide any predictive value (Figure 7). This relationship was evaluated using only one year of data (1999) for several reasons. Most importantly, this approach eliminated the problems of confusing between-year temperature variability with between-site land-use variability. Fortunately, the data from 1999 was well-suited to this task, being the year with the largest number of temperature sites having digitally compiled land-use data, the year of near-warmest average water temperatures and broadest water-temperature range, and a year whose land use would have differed little from that of the Landsat image that characterized land cover.

The reason(s) for this lack of observed correlation is(are) evident, in part. Water temperatures in August are almost entirely determined by groundwater inflows (plus lakewater contributions, if any). Watershed-scale landcover will influence these inputs only indirectly. Greater non-forested areas in paved urban settings permit greater solar heating of the ground surface and increasingly effective shading of underlying aquifers occurs where buildings are present. Groundwater recharge volumes will be less where stormwater is routed efficiently over the watershed surface by constructed ditches and pipes, but they will be greater during the summer in areas with septic systems (rural and suburban areas) or lawn irrigation (all urban areas). We make no attempt to quantify these various factors here but simply note that their influences in small streams under summertime baseflow conditions, which coincide with the periods of highest water temperature, are either individually so trivial or collectively so well balanced that they produce no net effect at the resolution of these data.

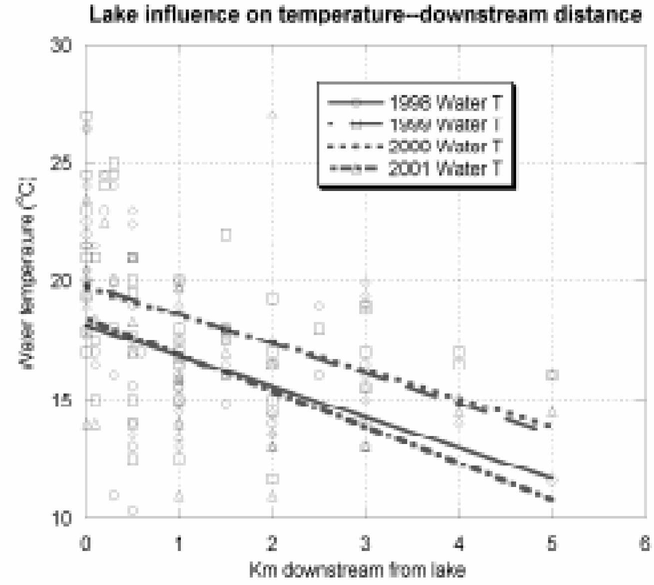

Figure 12.

Crude trend in water cooling downstream of a lake outlet. Consistent with the two-degree difference displayed in Figure 11, that magnitude of change is seen in the yearly best-fit linear curves at a downstream distance of about 2-3 km.

These results do not contradict the measured influence of riparian canopy (above), however. Clearing of riparian vegetation is a common expression of human disturbance but does not require "urban development" in order to be present; some of our most consistently cleared systems are in agricultural settings with very little imperviousness in their watershed. More generally, the land cover adjacent to any particular site along a stream is only weakly correlated to the land cover of the watershed as a whole (Morley, 2000) and so the importance of the former variable does not guarantee its expression by the latter.

Geology

Like the weak or absent influence of watershed-scale land cover on water temperature, any contribution of watershed-scale geology to summer baseflow temperature is not immedi-

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ately evident. These analyses are not yet complete, and so this evaluation is currently restricted to examples from around the Puget Lowland where the channel networks in question are known to flow predominantly over deep, permeable gravel and sand deposits. Such settings would be anticipated to contribute the highest proportion of deep groundwater to surface-water streams, minimizing the relative contribution of shallow water sources perched within the upper meter or so of soil above the other (and most common) geologic deposit of the Lowland, glacial till. If solar heating of near-surface groundwater is a factor in stream temperatures, independent of whether or not those settings are correlated with watershed land use, then channels with a relatively greater proportion of their baseflow fed by deep groundwater sources might display systematically cooler temperatures.

The available data, however, do not support this model. The distribution of reported 1999 temperatures from those stream systems that flow predominantly over broad outwash plains, as displayed by geologic maps of the region, were plotted against the distribution of all 1999 temperatures (Figure 13). The "outwash-dominated" stream systems so identified were lower Woods Creek (Snohomish County); lower Jenkins, Covington, and Rock creeks (King County); and Spanaway, Chambers (including Leach, Flett, and Clover), Fennel, Murray, and Muck creeks (Pierce County). Although the actual percentages of contributed groundwater (or even of outwash soils) have not been calculated, this group of streams should have the greatest hydrologic influence from this source, and so the absence of a discernible systemic trend suggests that additional detail would not change this result.

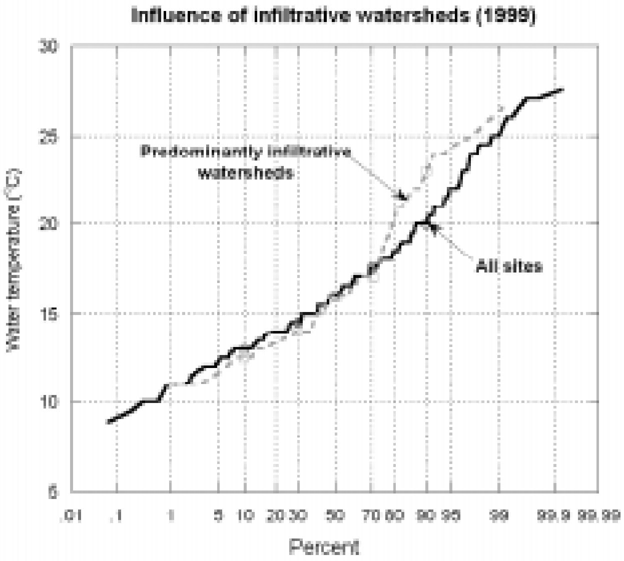

Figure 13.
Cumulative probability graph of stream temperatures comparing outwash-dominated watersheds, reflecting presumably high inputs from deep groundwater. There is no significant difference between these two populations.

Yet individual systems do show the local importance of this factor. Soos Creek, a major tributary to the Green River in the east-central part of our study area, provides one such case study. The watershed, about 150 km^2 in area, drains across two distinctly different geologic settings. The northern part, which encompasses the upper Soos Creek drainage and the headwaters of one of its two major tributaries, Jenkins Creek, is a rolling till-mantled upland surface with shallow perched groundwater, small headwater channels that dry rapidly (and respond to rainfall quickly), and abundant wetlands that reflect the shallow perched water table. Stream temperatures are generally moderate in the trunk channels of this area, with the highest reported temperatures in the highest headwater reaches. The southern part is a broad plain of outwash, punctuated by till and bedrock hills around which the main stream channels of Jenkins and Covington creeks flow on their way to their confluences with Soos Creek. Streams, associated wetlands, and lakes are

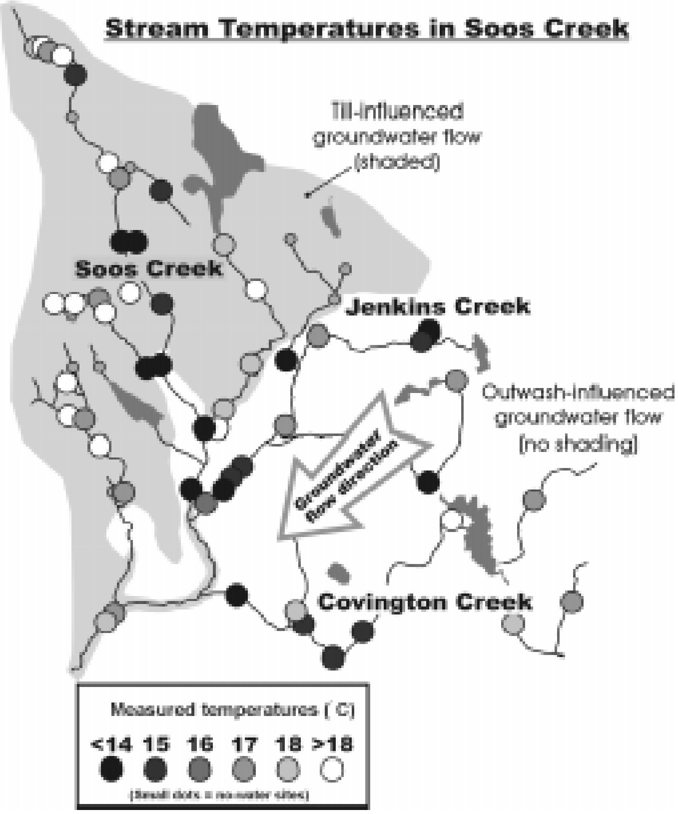

Figure 14.
Stream temperatures in the Soos Creek basin (1999 data), displayed spatially with respect to dominant geologic deposits and inferred groundwater flow. Shallow subsurface flow perched over glacial till (shaded region) correlates with relatively warm temperatures; deep groundwater flow through glacial outwash sands and gravels correlates with a marked cooling of water, whether contributed from the northern till uplands or from sun-warmed lakes. Cool temperatures are also found in the main channel of Soos Creek, which flows through a broad, outwash-filled valley not well-represented at map scale.

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all expressions of the regional water table, which fluctuates only slowly throughout the year and produces both steady discharges in the summertime and slow response to rainfall throughout the year. Stream temperatures here are predictably high downstream of lakes, but otherwise they show a strong moderating thermal influence of deep groundwater, particularly along the axis of the upper Soos Creek watershed and in the lower parts of both Jenkins and Covington creeks (Figure 14).

DISCUSSION AND CONCLUSIONS

Stream temperature is a complex integration of various physical conditions. The theory for predicting stream temperature is well developed, but its real-world application to a particular channel, and in particular the confounding (but rarely known) influences of groundwater influx and local riparian shading, impose an irreducible error in any calculated values. Our alternative, massive measurements under identical conditions of weather and insolation, imposes a different set of inaccuracies. These errors, however, can be quantified and are substantially less than the range of the phenomena being investigated.

The results confirm many theoretical expectations and past empirical studies. Human influence is a noteworthy determinant of stream temperature, particularly through the clearing of riparian vegetation. Watershed-scale changes in land cover are much less influential, however, at least under conditions of summertime low flow. This is because the most dramatic effects of paved surfaces, the interception of precipitation and resulting conversion of subsurface to surface runoff, is not active at this time. Thus heated runoff, as reported in other studies from other climates, is not a factor here. Reductions in groundwater recharge during the rainy seasons, which if translated into lower summertime flow might tend to yield higher summertime water temperatures, is either inconsequential or is roughly balanced by landscape watering or septic systems.

Given the importance of groundwater flow to summertime temperatures during non-storm conditions, an influence of regional geology is anticipated but not broadly evident in our data set. Only with a system-specific analysis can such an influence be displayed. In aggregate our regional data apparently combines so many different effects that only the most consistently influential, here the effects of riparian vegetation and the warming from of upstream lakes, display any systematic trends. Geologic conditions apparently do not approach this degree of systematic effect.

These data also offer both encouragement and caveats on the use of volunteer data. Replicability is good but by no means perfect. Inconsistencies render certain types of information nearly useless and place irreducible limits on the precision of others. Yet such efforts can generate information obtainable in no other way, and we believe that the results can well justify the effort involved and the limitations imposed.

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