Steam Cooling by Heat Transfer to Partially-Submerged Rocks

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ABSTRACT

This study tested the hypothesis that partially submerged rocks in small streams contribute significantly to the heat loss from the stream during icing episodes. The experiment took place in a small stream on the eastern border of the Sierra Nevada mountains in California. Thermistors were placed in granite and quartz monzonite rocks, and the rocks were placed along transects across the stream. Rock, stream and air temperatures were measured along with other meteorologic variables during freezing events. The components of the energy balance over the stream and heat transfer rates between the rocks and the stream were estimated. Exposed rocks in a pool reached temperatures below stream temperatures during icing events, particularly when the stream temperature dropped to the melting point of ice. The energy loss rates from the stream to some of the rocks were the same magnitude for short periods as the energy losses from the surface of the stream. On the other hand, rock temperatures closely tracked the stream temperatures during daily warming. Analysis of one of the freezing episodes is presented here.

INTRODUCTION

Interannual variability of winter stream flow and modification by man results in a variety of flow regimes, sometimes exposing or submerging objects such as rocks. Exposed rocks in a stream appear to be preferential sites for ice formation and growth, in turn which potentially affect trout habitat and spawning sites. This observation raises the possibility that partially submerged rocks may act as "cooling fins", significantly reducing water temperatures, which leads to the basic hypothesis of this investigation:

> Partially submerged rocks in small streams can transfer significant heat from the stream during freezing.

As a step toward identifying factors influencing the thermal regime of freezing streams, this investigation evaluated the winter energy exchange between rocks and the stream flow during an icing episode. Further, this study compared the magnitudes and timing of heat exchange between the rocks and the water with estimates of the heat exchanges occurring at the water-atmosphere surface.

Little is known regarding the formation of different types of stream ice and their effects on trout. Johnson et al. (1982) reported on estimates of the relative exclusion of salmonid habitat by ice formation in small streams in Wyoming. They used multiple linear regression to show that the relative amount of habitat excluded by ice formation is related to the number of days since winter solstice, degree days of frost, mean water velocity, and mean effective water depth. This simple parameterization of the problem of stream icing is site dependent and does not add to the basic physical understanding of stream freezing. On the other hand, Ashton (1990) presented the physically-based calculations necessary to estimate the effects of ice on hydraulics and fish habitat. While this work provides the necessary physics behind river ice formation, the methods can probably only be applied to larger rivers, where the scale yields more uniform ice formations.

Many studies of seasonal heating and cooling of streams and rivers have concentrated on the temperature change in small streams following timber harvesting of adjacent terrain, and the freeze up and thaw of large rivers and lakes. Most investigated stream warming in watersheds subject to logging (e.g. Beschta and Taylor 1988; Rishel et al. 1982; Brown et al. 1971; Swift and Messer 1970; Meehan 1970; Brown and Krygier 1970; Brown 1969 1970). Methods to calculate the energy budgets of rivers and lakes have been described by Pivovarov (1973), Ashton (1980), Shen et al. (1984), Gosink et al. (1986), and Shen and Wasantha Lal (1986). These techniques can be used to forecast freeze up and thaw of bodies of water with relatively large depths and volumes. However, small streams are more thermally sensitive to temporal and spatial changes in energy balance variables because they have lower volumes of flow than large rivers.

Much work has qualitatively documented ice formation and its prevalence in streams (e.g. Dean 1986; Bredhauer and Schoch 1986; Osterkamp and Gosink 1983), but little has been written concerning the prediction of small stream freezing using physically based models. This is probably because the sensitivity of the stream along its course to local micrometeorological conditions makes the problem much more complex. The dynamics of ice formation as influenced by local heat sources and sinks and the associated heat advection along small streams are unclear. If the heat exchange rates could be estimated and the depths and velocities could be calculated during periods of ice cover, the results could be used for input into simulations of the physical habitat, for example the system reported by Milhous et al. (1984).

BACKGROUND

Surface Energy Exchange

Variations in stream temperature are primarily caused by exchange of heat at the water surface (e.g. Pivovarov 1973; Gosink et al. 1986). The heat transfer at the surface of the water includes the same processes that warm and cool nearby earth surfaces, radiation, turbulent exchange and advection from precipitation. The amount of heat gain or loss is directly proportional to the area of water exposed to the atmosphere. Small streams have lower volumes of flow and much higher surface area/volume ratios than large rivers and are thus more sensitive to temporal and spatial changes in energy balance variables. Minor sources of heat in most streams include heat from sediments stored over the warmer part of the year, geothermal heat sources, and heat owing to friction produced by flow. Generally, the heat produced by these sources amount to the order of 1–4 $W m^{-2}$, and the frictional source dominates above water velocities of about 0.6 $m s^{-1}$ (e.g. Pivovarov 1973). A major potential contributor to stream heat is influent groundwater.

For unshaded and partially shaded streams, insolation is the dominant heating component of the energy budget for clear skies when the air temperature is near to the stream temperature. The reflectance of solar radiation a water surface depends on the illumination angle, becoming greater with increasing solar zenith. It typically varies between 0.015 and 0.15 for deep water, but can be strongly influenced by bed material in shallow streams. Thus shading patterns along a stream can be of significant importance in determining the overall heat budget along a stream reach. Reflection from ice is similar to water, but the amount of energy absorbed is a strong function the number of enclosed air bubbles. Typically the spectrally integrated reflectance from snow varies from about 0.60 to 0.98. The reflectance of granite by comparison varies from 0.17 to 0.30.

The thermal or longwave radiation is absorbed and emitted without appreciable scattering at the surface of most earth materials. The radiation emitted from a water surface at 0° C is about 311 $W m^{-2}$, whereas the clear sky longwave radiation in the eastern Sierra varies between 100–150 $W m^{-2}$, and the cloudy-sky incoming longwave radiation can be as high as 300 $W m^{-2}$, depending on atmospheric conditions (Marks et al. 1992). Thus for open reaches the longwave radiation generally represents a cooling effect.

As long as the air is not saturated with respect to ice there will be evaporation from the water, ice or snow. Latent heat loss will also occur from partially submerged stream rocks if they are wet or ice-covered. For streams the evaporated water vapor is readily carried away by buoyant and turbulent diffusion since water vapor is lighter than air and the stream causes air motion near the surface. Hence the evaporation rate is strongly controlled by the wind. If the air is colder than the stream or rocks there will also heat loss by sensible exchange.

The heat flux owing to precipitation promotes cooling when snow falls on open water, or when rain falls in warmer water. For example a snowfall of intensity of 1 $mm hr^{-1}$ of snow water equivalent with the snow and the stream near the melt point removes an average heat of -90 $W m^{-2}$. At the same snowfall intensity and air/snow temperatures of −20° C, the heat flux is about -105 $W m^{-2}$.

Stream Ice Formation

Small streams have a well-mixed water column even though most of the heat exchange takes place at the surface (Gosink et al. 1986). The temperature of the water controls its density, which is at a maximum of 1 $Kg\,L^{-1}$ at a temperature of 4° C. When the water temperature approaches 4° C, turbulent mixing prevents thermal stratification, and the stream can be considered well mixed at roughly constant temperature. Streams continue to flow once the temperature has reduced to 0° C because the latent heat of fusion for water is high relative to its heat capacity. Continued energy loss results in supercooling, which is usually limited to a few tenths of a degree below 0° C (Ettema et al. 1984), and is accompanied by either frazil ice formation, or an ice cover forming from the borders of the flow.

The rate of frazil ice formation is proportional to the intensity of the turbulence of the water in which it is forming, up to some threshold, and the degree of supercooling when the water is seeded (Ettema et al. 1984). Ice crystals such as snow, frozen fog, or ice fragments are required to initiate the formation of frazil ice; chilled, non-aqueous particles of objects do not cause frazil ice to develop until the water is several degrees below the melting point. As the crystals of frazil ice form, they are entrained by the flow and transported downstream. Frazil ice is in an active state in supercooled water and adheres to other ice crystals, obstructions in the flow path, and the stream bed. Anchor ice forms when the frazil crystals adhere to the stream bed. Frazil crystals grow dramatically once they have adhered to stationary objects (Osterkamp 1978).

Anchor ice formations on the riffles can cause a phenomenon termed "staging", where the accumulation raises the water level, slows the velocity, and promotes surface ice formation, which also slows the velocity. Surface ice may form from floating frazil ice or by rejection of latent heat to the supercooled water (Osterkamp 1978). Surface ice, or shelf ice, tends to grow from colder surfaces such as the stream banks, vegetation, and partially submerged rocks out into the flow (Johnson et al. 1982). Shelf ice may also grow slightly above the mean water surface by splash onto colder objects (T. Jenkins, Sierra Nevada Aquatic Research Laboratory).

The sequence of ice formation in streams with a pool-riffle configuration consists of anchor ice accumulation on the riffles, then staging with accompanying shelf ice formation in the pools. Once the stream is iced over for large reaches, pressure can build in the flow, sometimes breaking through to the surface of thc icc and refreezing; this is called aufeis. Flooding because of aufeis commonly extends beyond the stream banks, and can build to large thicknesses over many cycles (Dean 1986). Schohl and Ettema (1990) present a model for the two-dimensional spreading and thickening of aufeis.

METHODS

Components of stream-rock and stream-atmosphere heat transfer were estimated during freezing and thawing events in Convict Creek, on the east side of the Sierra Nevada near Mammoth Lakes, California. Granite rocks with internal temperature sensors were placed in a riffle and a pool at selected locations and depths along transects across the stream. Stream, rock and air temperatures were sampled for periods up to several days. The results from the pool site at the Sierra Nevada Aquatic Research Laboratory (SNARL) are reported here because of the close proximity to a weather station. Meteorological variables were measured at a station about 200 m from the stream transect, which allowed estimation of the components of the surface energy balance over the stream.

Study Site

Several stream transects were tested in this study, but either because of problems with winter logistics or significant heat sources from influent ground water, most were abandoned. Data analyzed in this paper were collected at one of the successfully operated transects. The Convict Creek site had a relatively open canopy of willow, and the transect was about 4 m wide, across relatively slow moving water. This transect was located on Channel 1 of the experimental stream reaches at SNARL and had a controlled discharge of about 0.04 $m^3 s^{-1}$. The reach of stream in this area loses water to the ground water table so that there was no contribution of heat from influent ground water and the ground heat flow was probably negligible as well.

Instrumentation and Measurements

Rock, stream, and air temperatures were measured with teflon-covered thermistors, which were individually calibrated to ± 0.2° C. Granite and quartz monzonite rocks were selected for this study from local stream beds. Nearly spherical rocks were chosen so that the calculation of submerged and exposed areas was straightforward. The rocks ranged in size from an average diameter of about 0.10 m to an average diameter of about 0.35 m, and a weight of about 2 kg to about 47 kg. Holes were drilled to the center of each rock, and the thermistors were cemented in place using an epoxy with high thermal conductivity. Thc holes were then backfilled with a mixture of granite dust and silicon sealant. The rocks were divided into four size classes. A randomly selected rock from each of the four classes was placed in the stream and the exposed height was recorded for each experimental run.

The stream temperature sensors consisted of 10 cm of iron bar stock, 1 cm in diameter, with a thermistor installed in the center along an axial hole. Two stream sensors were placed on the stream bed at the transect where they were in the shade throughout most of the day. The air temperature sensor was a thermistor encased in a copper jacket, and shielded from the sun by a passively aspirated plate-type shield. The air temperature sensor was placed 1 m above the stream. The wire leads from the rock thermistors, stream sensors, and air temperature sensor were connected to a data logger nearby on the stream bank. The temperatures were sampled every minute and the averages were recorded at half hour intervals. The surface temperatures of the rocks in the stream were measured occasionally with a narrow-view radiant thermometer. The stage height of the stream was also recorded at half hour intervals.

The meteorological station recorded incoming solar radiation, wind speed, relative humidity and precipitation. The station is located in an open field away from the riparian vegetation along Convict Creek. Wind speed and relative humidity were not measured along the stream over the transect. The canopy over the transect was measured with a forest densiometer to estimate the percentage of the sky hemisphere over the stream obscured by the vegetation or the nearby terrain.

The spectral reflectances of the stream and the rocks were measured from a vertical view using a narrow-view spectral radiometer, with 256 channels ranging from the ultraviolet to the near-infrared wavelengths. The reflectances were integrated over the wavelength band of the instrument, and values from the literature were used to estimate the reflectance in the near-infrared spectrum.

Data Analysis

The components of energy balance consist of net radiation R_n, sensible heat transfer H, latent heat transfer LE, conduction G with objects in contact with the flow and advection from precipitation Q_p

$$R_n + H + LE + G + Q_p = 0 \qquad (1)$$

adopting the convention that terms bringing heat to the surface are positive and those taking heat from the surface are negative. Because there was no precipitation during the study period the term Q_p is not discussed in detail.

The net all-wave radiation at a point is the incident spectral irradiance minus spectral exitance integrated over all wavelengths. The irradiance term includes direct and diffuse solar radiation and longwave radiation emitted from the atmosphere, the adjacent terrain and the overhead vegetation canopy. Exitance includes both reflected and emitted radiation from the surface.

Unobstructed incoming solar radiation S_{in} was measured directly with a hemispheric cosine collector. The percentage canopy was used to adjust the measured incoming solar radiation and the estimated incoming thermal radiation. The relationship between incoming solar radiation and the estimated incoming thermal radiation was complex and depended on sky conditions and solar geometry. Therefore a constant correction was made by averaging the difference between the solar radiation at the meteorological station and spot measurements made at the transect for several clear days. At this site the correction was 0.84 of the measured incoming solar radiation.

The incoming thermal radiation was estimated for the clear-sky conditions using (Brutseart 1975)

$$I_{thsk} = (1.24 \left[e_a / T_a \right]^{1/7}) \; \sigma T_a^4 \qquad (2)$$

where T_a and e_a are the air temperature and vapor pressure respectively, and $\sigma = 5.6697\times10^{-8}$ $\mathrm{W\,m^{-2}}K^{-1}$ is the Stephan-Boltzmann constant. The incoming thermal radiation at the transect was calculated from the percentage of the overhead canopy, the air temperature and the estimated incoming thermal radiation from the sky

$$I_{in} = I_{thsk}\,(1 - p_c) + I_{tree}\, p_c \qquad (3)$$

where I_{in} is the thermal radiation incident at the stream and p_c is the percentage of vegetation canopy. The thermal radiation contributed from the trees I_{tree} was calculated according to a similar relation used to calculate the radiation emitted from the stream surface, assuming the branches were at the ambient air temperature. The radiant emission from the stream I_{th} (or I_{tree}) was calculated with

$$I_{th} = \varepsilon_s \, \sigma T_s^4 \qquad (4)$$

where ε is the surface emissivity (≈ 0.99 for water), and T is temperature of the surface (K).

The eddy diffusivities of water vapor and air molecules were assumed equal and the Bowen ratio

R_B was used

$$H + LE = LE\ (1 + R_B) \tag{5}$$

where the mixing terms controlled by the wind speed and eddy diffusivities cancel. The Bowen ratio

$$R = c\ \frac{P_a}{1000}\ \frac{T_w - T_z}{(e_s - e_z)} \tag{6}$$

where P_a is the atmospheric pressure and $c = 0.60$ is a constant. Two other methods to estimate LE were compared before one was selected because some studies have shown that the eddy diffusivities differ when the air temperature is much lower then the water temperature.

The calculation of evaporation and sensible heat exchange for a stream sheltered by steep banks, overhanging vegetation, or steep topography is hindered by the difficulty in selecting a suitable exchange coefficient. An empirical equation applicable to winter field conditions for open streams is (Rimsha and Donchenko, 1957)

$$LE = (6.04 + 0.26\ (T_w - T_z) + 2.95\ V_z) \times (e_s - e_z) \tag{7}$$

where T_w and T_z are the water and air temperatures respectively. In a situation where the stream is protected from the wind by vegetation or surrounding terrain, free convection may play a role in the latent heat flux (Ryan et al., 1974)

$$LE = (3.20\,V_z + 2.70\,(\Delta\theta)^{1/3})(e_s - e_z) \tag{8}$$

where $\Delta\theta$ is the potential temperature difference (in K) between the water surface and the air

$$\Delta\theta = \left[T(1 + 0.378e_s/p_a\right] - \left[T_z(1 + 0.378e_z/p_a\right] \tag{9}$$

where p_a is the atmospheric pressure (mb).

While it was recognized that the heat flow within the rocks would best be represented as a three-dimensional heat transfer problem, the position was adopted that a simple analysis would be sufficient to test the hypothesis. The magnitude of the heat flow is calculated as the product of the thermal conductivity of the rock and the temperature gradient between the center of the rock and the wetted rock surface. The conduction equation

$$G = \mathrm{K}\left[\frac{\Delta T}{\Delta z}\right] \tag{10}$$

was used where K is the thermal conductivity (granite $\approx 2.9\ \mathrm{W\,m^{-1}C^{-1}}$), and z is the distance between the temperature measurements, expressed in m. This approach makes a variety of assumptions: 1) the heat flow between the water and the rock represented a steady state, 2) the temperature gradient was linear and radial between the water and the rock, 3) the proportion of rock exposed and submerged remained the same, 4) the conduction between the rock and the stream bed was negligible, and 5) the stream was thermally well mixed. The heat conduction was calculated at each time step of the input data.

By approximating the shape of the rocks as spheres, the amounts of exposed and immersed area of each rocks were obtained from the height of the rock above the water surface. The effective radii r of the rocks was taken as half the mean diameter determined with calipers. If the maximum height of the rock surface above the water level is h, the exposed area A_{ex} is

$$A_{ex} = 2\,\pi\,r\,h \tag{11}$$

The wetted area of the rock is

$$A_{wt} = 4\,\pi\,r^2 - A_{ex} \tag{12}$$

and the area of the circle of intersection between the stream surface and the rock is

$$A_{eff} = \pi\,\sqrt{4h\,(2r - h)} \tag{13}$$

RESULTS

Many of the early experimental runs in Convict Creek ended when the instrumented rocks rolled downstream from their placements, or when they were completely encased in stream ice. Almost half of the test rocks were eliminated from further use this way and most of the winter was spent trying to get continuous measurements. A complete and continuous data set was obtained from February 6 to May 5, 1989. The stream was frozen with a continuous ice cover until the first week of February, after which it began to thaw and break up. The test transect was free of ice by February 23, and the stream and air temperaure record is show in Figure 1 for the period February 23 to March 15, 1989. A freezing episode took place March 2 and 3 (days 7 and 8 in Figure 1) during which air temperatures dropped to near record lows. This episode was the subject for this analysis.

Temperature Measurements

During the freezing episode in March, temperatures from three rocks were recorded. Rock 2 had an effective radius of 0.07 m and a mass of 3.5 kg, rock 8 had an effective radius of 0.09 m and a mass of 10.2 kg and rock 9 had an effective radius of 0.10 m and a mass of 10.5 kg. All three rocks were situated in the stream with half of their area submerged (i.e. $h = r$) at the start of the run. The three rocks cooled more quickly than the stream and the cooling was more pronounced for the larger rocks, 8 and 9. This is demonstrated in Figure 2a, which shows stream temperature and the temperatures for the three rocks during the freezing episode. The rocks also reached 0° C earlier than the stream water and reached colder temperatures.

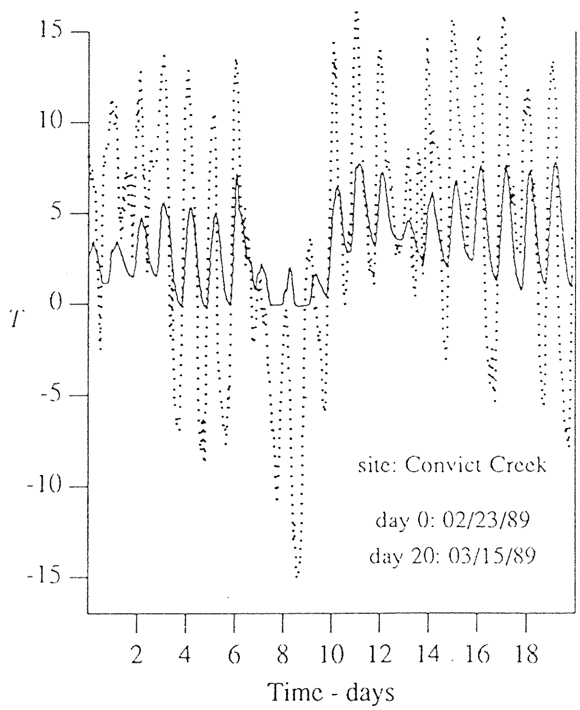

Figure 1. Air (dotted) and stream (solid) temperatures from Convict Creek, Mono County, California. Freezing episode (days 6-9) shows near-record low air temperatures for March.

The temperatures of the rocks were also influenced by the height of the stream water level. Figure 2b shows the record of stream stage height for the same period. On the first night of freezing (7.5 d) a slight rise in water level submerged the smaller rock so that its temperature did not become much depressed below the stream temperature. On the second night the stream staged later, relative to the drop in air temperature (Figure 1). This allowed the smaller rock to develop a slight temperature gradient before being submerged and warming to the water temperature. On the second night the larger rocks developed substantial temperature gradients before they were submerged by the water.

The instantaneous heat transfer rate for rock 9 (Figure 2a) in the stream during the coldest period between logger day 8 and 9 was estimated using the average temperature gradient between the rock and the water. For a period of 3 hours this heat transfer index averaged approximately 60 W.

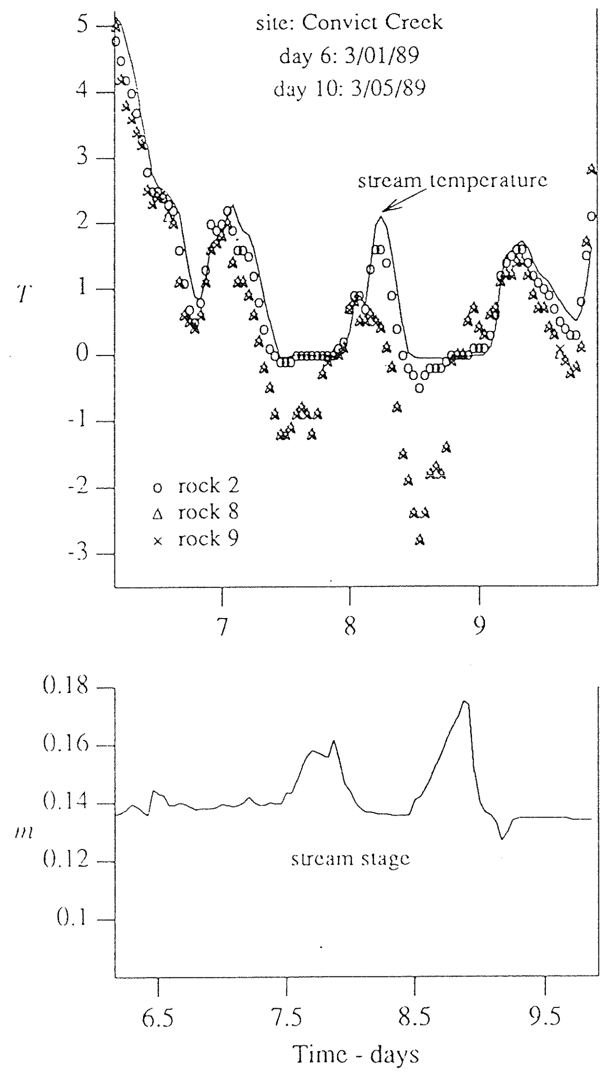

Figure 2: Upper graph (2a) shows rock and stream temperatures during freezing episode in Convict Creek, while lower graph (2b) shows stream height for same 4-day period in March 1989.

Energy Balance Evaluation

The net solar radiation was calculated from measured incoming solar radiation at SNARL, the canopy coefficient, and the integration of the spectral reflectance of the stream. The measurements and calculations of the radiation balance over the stream are shown in Figures 3 and 4. The measured spectral reflectances in in the visible and near-infrared spectral regions are shown in Figure 3 and were integrated to calculate the net solar radiation. The estimated components of the radiation budget at the stream are shown in Figure 4 for the period in early March, 1989.

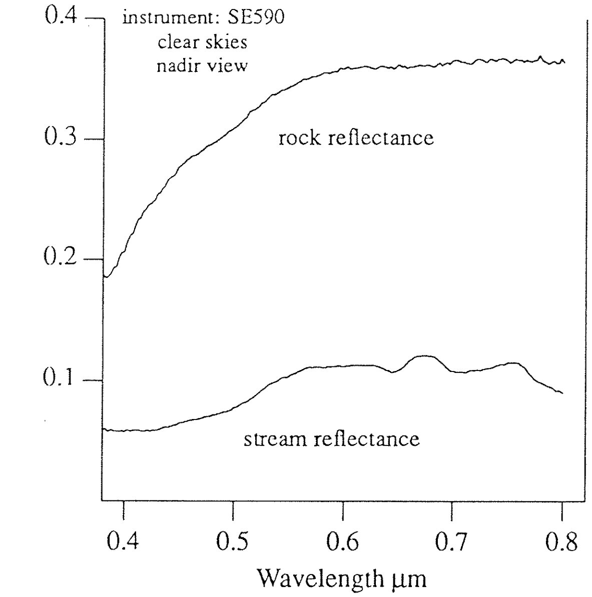

Figure 3. Spectral reflectance of rocks and stream, plotted for wavelengths covering the visible and part of the near-infrared spectral region.

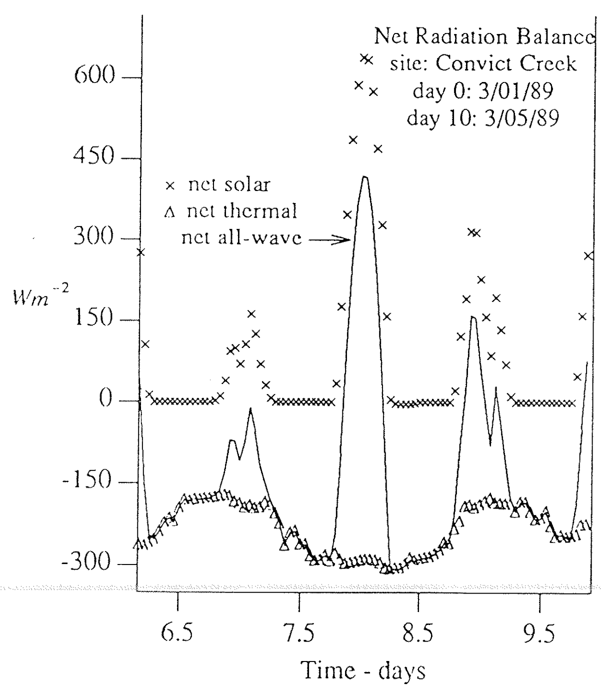

Figure 4. Estimated components of the net radiation budget over Convict Creek during 4-day freezing episode in March, 1989

The net solar radiation (×) shows the expected diurnal pattern, peaking around midday and zero at night. The net thermal radiation (Δ) shows a fluctuating, but relatively consistent trend averaging about -200 Wm^{-2}. The net global radiation, or sum of the two, is shown as a solid line. Figure 4 shows that over the experimental period the net radiation was negative, with the exception of a few hours on each of the second and third days.

The latent heat loss (evaporation) and the sensible heat exchange were calculated from the stream and air temperatures, measured at the transects, and the relative humidity and wind speed, measured at SNARL. The latent heat exchange estimated by the Bowen ratio (equations 5 and 6) and by equation 7, Rimsha and Donchenko (1957), were almost the same. but some differences were apparent between those and the results from equations 8 and 9, Ryan et al. (1974). Figure 5 shows the latent heat exchange calculated by the two methods, Rimsha and Donchenko and Ryan et al.. Based on the obvious artifact late in day 8, the method of Rimsha and Donchenko, which agreed with the Bowen ratio, was selected for further discussion.

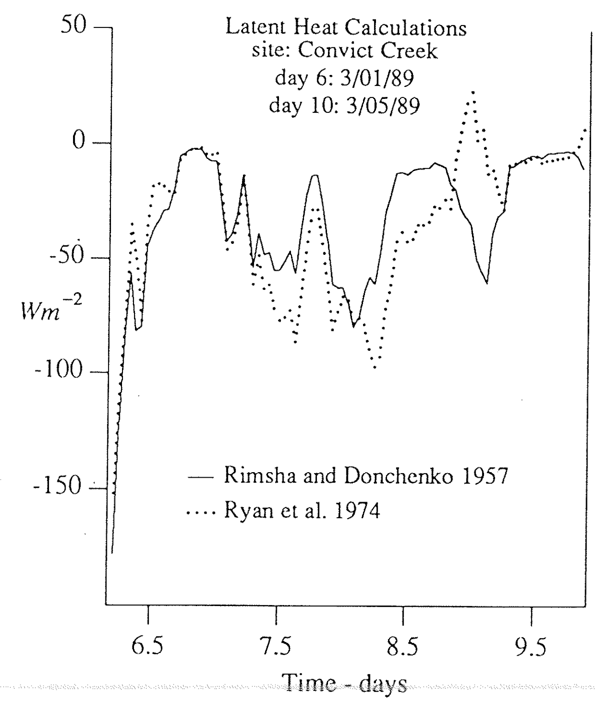

Figure 5. Latent heat transfer over Convict Creek during freezing episode, estimated by two methods.

The estimates of the sensible and latent heat fluxes are shown in Figure 6. As expected over freely evaporating surfaces, the two energy transfer components show opposite diurnal trends. For the experimental period the average turbulent exchange amounted to about –50 Wm^{-2}.

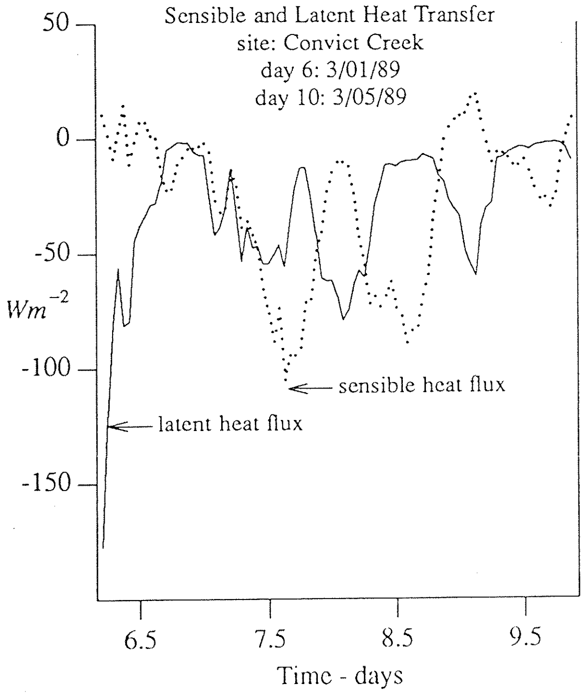

Figure 6. Estimated latent and sensible heat fluxes over Convict Creek.

DISCUSSION

During the freezing episode all rocks cooled more quickly than the stream as long as they were exposed to the air. The reason for this can been seen by comparing Figures 2a and 6. Once the dew point of the air over the stream dropped below the surface temperature of the water, the latent heat from condensation offset the cooling by other energy balance components. This did not occur over the rock surfaces because they were not wet, so the cooling rate was more rapid. Relative differences between the changes of heat content of the rocks and the stream are not evident from the temperature record, while the water is at 0° C, because the heat content of the water is better represented by the relative fractions of liquid water and ice.

It is unclear how to directly compare the stream-rock heat flow estimates with the other surface energy balance terms. For example, if the 60 W estimate is divided by any of the areas described by equations 11-13, then the result (Wm^{-2}) compares closely with the maximum energy loss by thermal radiation. With the uncertainties involved this means that the heat loss was about the same as if the rocks were not there, being replaced by water. The rocks also seemed to have little effect on the stream thermal budget during the heating part of the cycle. Figure 2 shows that the rocks and the stream warmed at about the same rate, and the rock temperatures rarely exceeded the stream temperature. This was the case for nearly all of the experimental runs. The reasons for this are that the stream had a low volume of flow, so that it was sensitive to solar heating, and the rocks had a much higher reflectivity than the stream, at all wavelengths in the solar spectrum (Figure 3). Furthermore, the stream was absorbing radiation throughout the water column and at the bed, while the rocks are opaque and absorbed only at the surface.

While the rocks are unlikely to have been sites of frazil nucleation because the temperature depression in the rocks did not exceed a few degrees, they appeared to be preferential sites of shelf ice formation, and spot measurements with a radiant thermometer showed that their surface temperatures were well below the ice melting point during the periods just before the stream staged. After the morning breakup of the anchor ice dams on the riffles, the rocks were left with caps of shelf ice until further melting took place.

CONCLUSIONS

Partially submerged rocks cooled more quickly than the stream water during the freezing episode. Temperature gradients from the stream to the rocks were maintained until the stream staged and the rocks were submerged. Simple heat transfer analysis suggested that stream-rock heat flow approached the same order of magnitude as thermal radiant cooling, which was the dominant mechanism of cooling, only for short periods when the rocks were the coldest. The partially submerged rocks had little effect on the stream heat transfer during the heating cycle. Therefore in this experiment, the cooling effect of partially submerged rocks in a stream was small despite rather strong surface-air temperature gradients.

ACKNOWLEDGEMENTS

This work was partially funded by the California Department of Fish and Game Stream Requirements Program under contract FG7613. Other support was provided by the Army Corps of Engineers Project 4A762784AT42. NASA Goddard Space Flight Center loaned the spectral camera for the reflectance measurements. Dan Dawson of the University of California Sierra Nevada Aquatic Research Laboratory provided meteorological parameters and field support. Tom Jenkins provided valuable insight and comments on stream icing early draft manuscripts. George Ashton also provided valuable review comments.

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