Thermal and hydraulic characteristics of a geothermally influenced trout stream : the Firehole River of Yellowstone National Park
by Dalton Earl Burkhalter

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Zoology
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Abstract:
The Firehole River in Yellowstone National Park, Wyoming, is thermally enriched by the effluents of three geyser basins and numerous other geothermal features. During summer months temperatures in the lower reaches frequently exceed levels considered lethal for trout, however, self-propagating populations of brown and rainbow trout exist there year-round. Hydraulic and thermal characteristics of this stream were measured from July, 1974, to September, 1977, as part of a broader study of the thermal environment and biology of these resident trout populations. The river discharge averaged 2.1 and 7.5 m^3/s, respectively, at stations separated by 18.5 km above and below the bulk of the thermal inflow. About 1.5-2.5 m^3/s was estimated to enter the Firehole from geothermal features in the study reach, representing approximately 20-40% of total discharge during non-runoff periods.

The upper (unheated) station mean temperature ranged from 2.0 to 14.5 C, while the lower (heated) station mean ranged from 12.0 to 26.0 C. The lower station averaged about 11 C higher than the upper station. The highest temperature recorded at the lower station was 29.5 C and although this exceeds the upper lethal limit for trout, no fish kills were observed.

The power added to the river between the upper and lower stations by geothermal features was estimated as 425 MW. Average monthly solar insolation on a horizontal surface from sun and sky during critical summer months ranged from 5.2 to 7.2 kW-h/m^2-day averaging about 78% of possible clear-sky insolation. The thermal loading from solar insolation on the river surface between upper and lower stations was estimated in the annual range 26-108 MW.

Thermal infrared (IR) imagery was utilized to thermally map the river throughout the reaches where thermal inflows occur. The IR imagery identified five areas in the river where significant thermal gradients occur, some of which very probably influence fish movements.

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ABSTRACT

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INTRODUCTION

Thermal enrichment of natural waters and its effects on resident organisms have received extensive attention in the literature (Krenkel and Parker 1969; Parker and Krenkel 1970; McKee and Wolf 1963). The U.S. Environmental Protection Agency has published recommendations for temperature regimes for some freshwater fishes (National Academy of Sciences and National Academy of Engineering 1972). Numerous articles deal with heat budgets and with modeling of thermal inflows to lakes and streams (Jackman and Yotsukura 1977; Jobson 1973; Bauer and Mackenroth 1974; Morse 1970; Brown 1969, 1972; Raphael 1962; Wright and Horrall 1967).

Sources of thermal enrichment have historically included geothermal features (relatively few locations), impoundments, municipalities, industries, and electric power generating facilities. The demand for electric power is approximately doubling every ten years in the U.S. Fossil-fueled and nuclear-fission plants will provide the major share of the increase in power production in this century. Hydroelectric power is, for all practical purposes, fixed at present capacity and alternate energy sources (solar, wind, etc.) and nuclear fusion are too far away to assume a significant share of the load (Krenz 1976).

Fossil-fueled steam electric plants have reached a practical limit of about 40% efficiency and fission plants are somewhat lower in efficiency due to materials and safety considerations (Krenz 1976;

Parker and Krenkel 1970). Nuclear power plants transfer essentially all waste heat to cooling water; fossil-fueled plants transfer about two-thirds to cooling water and the remainder occurs as stack loss (Parker and Krenkel 1970). Electric power generation through conversion of magnetohydrodynamic energy may yield efficiencies up to 80% (Rosa 1968) but this process is confined to the experimental stage at this time.

Although cooling towers are utilized in many instances in transferring waste heat to the atmosphere, many present and future installations use, and will use, once-through cooling with a natural body of water receiving the final heat load. As the population increases and demand for manufactured goods and electric power continues to rise, ever increasing demands will be placed on our natural waters for cooling. As a result, the pronounced changes in biological communities which accompany thermal enrichment will continue to be more widespread.

Heat assimilated from exogenous sources (i.e. geothermal, industrial, or power generation) manifests itself as "excess temperature" in a flowing stream. Excess temperature is defined as any increase over the natural stream temperature which would exist in the absence of any exogenous source. Excess temperature decays through dissipation of heat to the surrounding environment, primarily to the atmosphere. Conduction to the stream bottom is generally considered insignificant and is usually ignored. An exception is claimed by Brown (1969, 1972) in which conduction into the stream bed amounted to 20-25% of total energy transfer for shallow streams with a bedrock bottom.

Four mechanisms of heat exchange at a water surface are recognized. They are shortwave and longwave radiation, evaporation (or condensation) and conduction (Jackman and Yotsukura 1977). Shortwave radiation (contained in solar radiation) contributes the greatest individual component of natural heat flux. Positive values (heat flux into the water is positive) in excess of 1 kW/m^2 are common during summer months. Longwave radiation contributes a lesser amount to solar insolation. A percentage of solar insolation is reflected off the water surface. Reflected radiation expressed as a percent of total incoming radiation is known as the albedo of the surface. The albedo of water is typically about five.

Longwave radiation is essentially the only constituent of back radiation from the water surface. Back radiation is temperature dependent and can amount to a negative 300-450 W/m^2 for water in the range 0-30 C. Back radiation, H_r, follows the Stefan-Boltzmann equation,

$$H_r = \varepsilon \sigma T^4$$

where ε is emissivity (0.97 for water), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2-K^4), and T is absolute temperature in K.

Evaporative heat flux is dependent on wind speed and relative humidity and can amount to negative values of 400 W/m^2 for a dry atmosphere and moderate wind speeds. Positive values can occur when conditions result in condensation on the water surface. Evaporative heat flux, H_e, is given by Jackman and Yotsukura (1977) as,

$$H_e = \lambda N \upsilon \Delta p$$

where λ is latent heat of vaporization (2,495 J/kg), N is a mass transfer coefficient (typical value, 2.42×10^{-8} kg/m-N), υ is wind speed (m/s), and Δp is the difference between the saturation vapor pressure at the temperature of the surface and the partial pressure of water vapor in the surrounding air (N/m^2).

Conductive heat flux is dependent on evaporative heat flux and the ambient air temperature. Typical values can amount to a positive or negative 200 W/m^2. Conductive heat flux, H_c, is given by Bowen (1926) as,

$$H_c = BH_e$$

where H_e is evaporative heat flux and B is the Bowen ratio,

$$B = 6.1 \times 10^{-4} P \Delta T / \Delta p$$

where ΔT is the temperature difference between air and water (positive for air temperature > water temperature), P is atmospheric pressure in N/m^2, and Δp is the difference in pressure as defined for H_e, above.

Although the decay of excess temperature is complex and nonlinear, linearized approximations exist which work well for excess temperatures within about 10 C of natural temperatures (Bauer and Mackenroth 1974; Jackman and Yotsukura 1977). Use of a model of this type allows prediction of decay of excess temperature with downstream flow. Dissipation of excess heat is a gradual process and can extend over long distances. Jackman and Yotsukura (1977) cite five of seven studies in which the remaining excess heat amounted to more than 50% of the initial excess at points 30 km downstream.

An integral part of the assessment of impacts of thermal enrichment on biological systems is the description and quantitation of thermal loading. With increasingly greater heat loads to be assimilated and more numerous sources to monitor, analysis of assimilative capacity and excess temperature becomes exceedingly complex. The biologist or engineer is faced with greater demands upon time and equipment to accomplish the task of quantifying biological impacts, temperature changes, and dissipation of excess heat to the atmosphere from the water surface. The present work was done, in part, to develop and apply some rather novel methods and techniques for describing the physical aspects of the more complex occurrences of thermal enrichment in streams. The balance of the work was done using standard procedures to describe the hydraulic parameters of a stream in conjunction with an overall assessment of the impacts of thermal enrichment on resident trout populations (Kaya 1977, 1978a; Kaeding and Kaya 1978; Kaya et al. 1977).

The stream studied was the Firehole River in Yellowstone National Park, Wyoming. This stream receives effluent from three major geyser basins of Yellowstone Park as well as numerous other geothermal features. The distribution of thermal features along the river is complex and is such that recovery can not occur from one inflow to the next. Mid-summer water temperatures in the warmest part of the river frequently exceed values considered as ultimate upper incipient lethal temperatures for trout (National Academy of Sciences and National Academy of Engineering 1972; Hokanson et al. 1977). In spite of these temperature regimes, viable trout populations exist and have been self-propagating since cessation of stocking in 1955 (Jones et al. 1978).

A comprehensive and accurate description of these complex temperature distributions and the obtaining of routine hydraulic and meteorologic data formed an important part of the overall study.

DESCRIPTION OF STUDY AREA

The Firehole River is wholly contained within Yellowstone National Park (Fig. 1). Its sources originate just under the east side of the continental divide at elevations approaching 2,560 m. From Madison Lake (el. 2,506 m) near the headwaters, it is a small cold stream flowing about 14.5 km to Kepler Cascades, which forms a natural barrier to upstream fish movement. Station A (2,317 m) was located about 0.5 km above Kepler Cascades for measurement of discharge and temperature. The stream is essentially uninfluenced by geothermal inflow above Kepler Cascades.

About 3 km below this point the Old Faithful Geyser area (2,246 m) is encountered. This is part of the Upper Geyser Basin and the first significant thermal contributions occur here. The stream flows 4 km from here to its confluence with Iron Spring Creek (2,210 m). The Little Firehole River joins Iron Spring Creek just above its junction with the main Firehole. The Little Firehole River is a small cold stream while Iron Spring Creek is warmed by numerous thermal inflows. Above the confluence of the Little Firehole River, Iron Spring Creek averages somewhat higher in temperature than the main Firehole.

From Kepler Cascades to the Old Faithful Area, the river flows through a deep narrow canyon with a gradient of about 1.5%. The substrate is a mixture of bedrock, boulders, sand, and gravel. The bedrock is rhyolite lava which occurs throughout the Firehole drainage

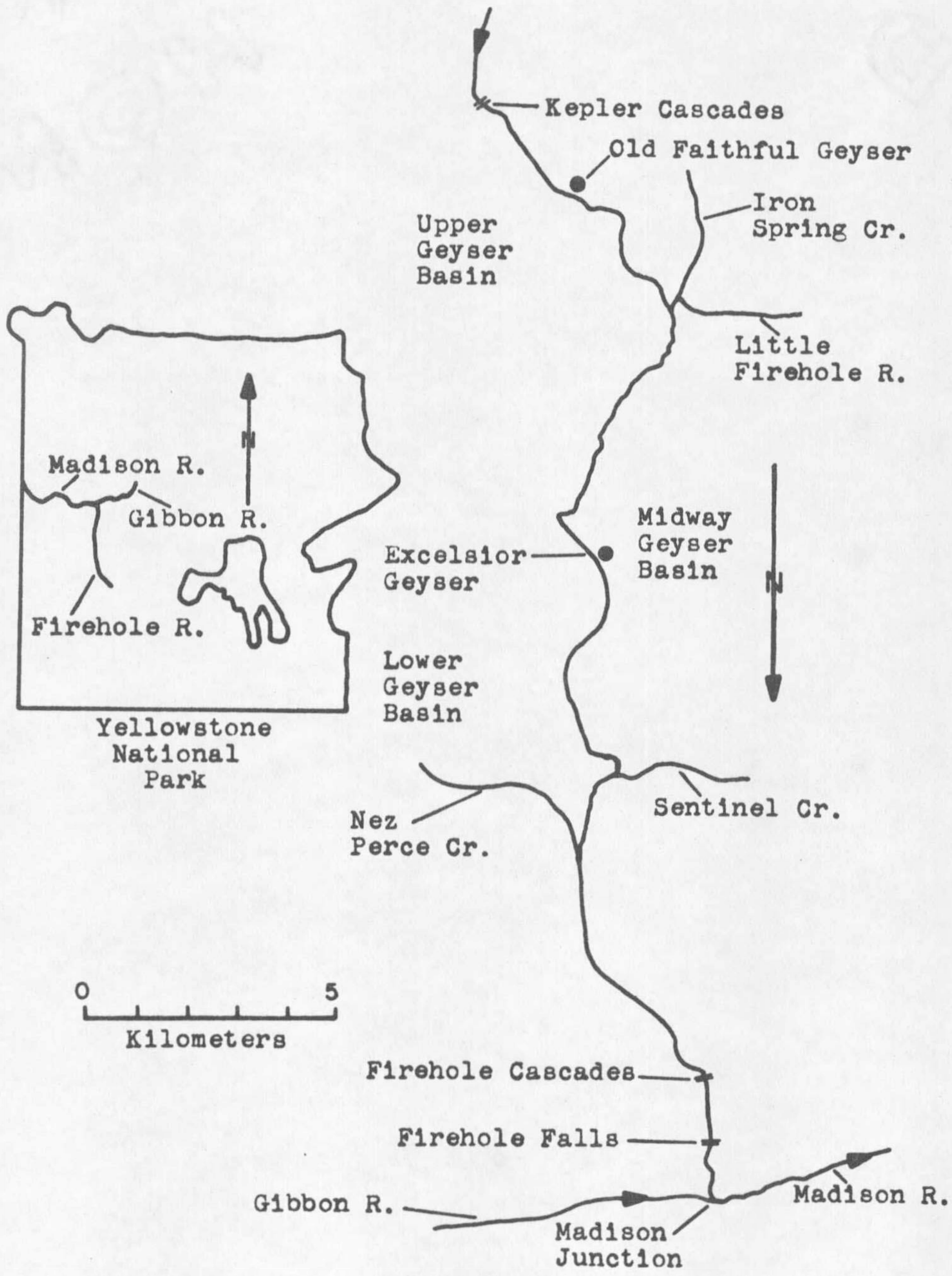

Figure 1. Map of lower 28 km of Firehole River and its location in Yellowstone National Park. Note north arrow on inset differs in direction from principal map.

basin (Alt and Hyndman 1972). From Old Faithful to Iron Spring Creek the river flows through a wide valley and is largely unshaded and shallow. The gradient is about 0.60%. The substrate is bedrock with limited areas of sand and gravel.

Below the confluence of Iron Spring Creek the river flows 7 km (gradient 0.25%) through alternate meadow and forest to Midway Geyser Basin (2,201 m) where a second concentration of geothermal features discharges into it. The most notable of these is the presently steady flow (0.17 m^3/s, Allen and Day 1935) from the dormant Excelsior Geyser. Prior to its cessation of activity in 1888 this was a giant geyser erupting to 91.5 m and causing the Firehole River to rise appreciably (Haines 1977). From Iron Spring Creek to Midway, the substrate is bedrock mixed with boulders and gravel.

From Midway the river deepens in a 4 km reach to a point about 1 km upstream from Sentinel Creek. Station B (2,189 m) was established here for measurement of discharge and temperature. The stream from Midway to Station B is largely unshaded and flows alternately over bedrock, gravel, and mud. Station B was in the Lower Geyser Basin and below the bulk of the thermal inflows.

About 1 km below Station B, Sentinel Creek (small and cold, 2,186 m) joins the Firehole. Nez Perce Creek (2,181 m) joins the Firehole 2 km below Sentinel Creek. Virtually all thermal inflows of the Firehole have occurred above this point. From Station B to Nez

Perce Creek the river is unshaded and flows over bedrock, gravel, and mud. From Midway to Nez Perce Creek the gradient is about 0.25%. From Nez Perce Creek the river flows 6.5 km (gradient 0.25%) to Firehole Falls (an upstream barrier to fish movement) and thence 1.5 km to its confluence with the Gibbon River at Madison Junction (2,073 m). The combined flows become the Madison River at this point. The Firehole flows largely through forest below Nez Perce Creek and is in a deep canyon from Firehole Cascades to Madison Junction. Below Nez Perce Creek the substrate is bedrock, large boulders, and gravel.

The reach between Stations A and B is about 18.5 km and contains an elevation difference of 128 m.

Geothermal features contribute significant amounts of Na^+, HCO_3^-, Cl^-, and SiO_2 to the river which becomes progressively richer in these substances as it flows through the succeeding geyser basins (Wright and Mills 1967; Allen and Day 1935).

Above Firehole Falls the river has populations of brown trout (*Salmo trutta*), rainbow trout (*Salmo gairdneri*), and brook trout (*Salvelinus fontinalis*) in various patterns of distribution. These are the only fish species present in this stream reach which was historically barren of fish. Trout were artificially planted in the Firehole beginning in 1889. They have been self-sustaining since the cessation of stocking in 1955.

METHODS

Water temperature was measured with a standard mercury-in-glass thermometer or a hydrographic thermometer (Whitney Corporation). Continuous temperature recordings were made with Ryon submersible 30-day thermographs. Air temperature was recorded by the National Park Service at the Old Faithful Ranger Station by a mercury-in-glass minimum-maximum thermometer. Mean daily temperature was defined as the simple average of the daily minimum and maximum. Temperatures from air and water were entered into a computer program written by the author to calculate monthly means, minima, maxima, 5-day means, etc.

Discharge was determined with a Price, type AA, current meter (the Gurley Co.). Procedures used in measurements and calculations followed those of the U.S. Bureau of Reclamation (1967). Stage-discharge relationships were established at Stations A and B to verify accuracy of the measurements. These relationships were analyzed with the aid of a polynomial regression program; r-values of 0.99 ($P<.01$) were achieved. Discharge volumes were obtained by integration of hydrographs.

Solar insolation was measured with a radiometer (Fowlkes Engineering, Bozeman, Montana) utilizing a silicon photovoltaic cell. This type of radiometer is much less expensive than the standard thermopile-type and provides accuracy to ± 5% (Selçuk and Yellot 1962). This instrument was calibrated against a Kipp and Zonen pyronometer. Total radiation (power) from sun and sky incident on a horizontal surface was recorded on strip chart (Fig. 2) by a Rustrak battery-operated continuous recorder. Power-time curves were integrated with a compensating polar planimeter. Monthly means, maxima, minima, and 5-day averages were calculated by computer.

Infrared (IR) imagery from Station A to below Nez Perce Creek was obtained by an overflight conducted by the U.S. Forest Service, Boise Fire Laboratory, Boise, Idaho. The equipment was developed for use in forest fire detection (Wilson et al. 1971) but is used to advantage to map water surface temperatures (Boettcher et al. 1976; Skinner and Ruff 1973). The IR imagery was calibrated with mercury thermometer data obtained by observers stationed along the river during the overflight (ground-truth data).

IR imagery may be used to determine stream surface temperature because of back radiation from the water surface which obeys the Stefan-Boltzmann law (see introduction). The detector and associated equipment sense the radiative power from the desired target. The signal is converted to a voltage whose magnitude is proportional to absolute temperature.

Radiative power at a given temperature does not all occur at the same frequency but instead follows a wavelength distribution curve known as Planck's law. The peak radiative power occurs at a unique wavelength for any given temperature and this wavelength is found from