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THE PHYSICAL MATRIX OF CASTLE LAKE

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ABSTRACT

The physical framework or matrix in which the biological processes of aquatic ecosystems occur is currently under investigation at the Castle Lake Research Station. Special attention has been given these physical parameters in view of their close interrelationship with important biological properties within the lake (as exemplified by the rate of change of phytoplankton biomass). A series of prognostic submodels is being developed and tested using equations that describe the energy flow, eddy diffusivities, water and elemental cycling, and the heat budget of the lake. The weather station and varied instrumentation that have been established at Castle Lake to measure these parameters are also described.

In discussing and modeling the varied biological processes of lakes, it is important to consider the physical environment that provides the framework, or matrix, for these processes. For example, the rate of change of phytoplankton biomass in Castle Lake is given by the equation (Jassby and Goldman 1972):

$$dB/dt = P_n - (G + F + S + B + D) \quad (1)$$

where P_n = net productivity, G = herbivore grazing rate, F = vertical turbulent diffusion, S = passive sinking due to gravity, B = horizontal transport, and D = death.

The interrelationship between the biological and physical properties of an ecosystem is apparent in equation (1) since:

(1) metabolism, of which P_n is the result, is an increasing function of temperature (according to the Q_{10} rule),

(2) G is temperature-dependent in Castle Lake (unpublished data),

(3) B is dependent upon heat content of the water column and wind, and

(4) P_n (thus the entire ecosystem) is driven by solar energy.

Implicit in equation (1) are measurements of evaporation and inflows needed for calculations of water and nutrient budget.

THE HEAT BUDGET

The basic physical structure of a lake, i.e., stratification, heat content, and turbulence, is related to its heat budget. The first measurements of thermal heating in Castle Lake were made by Bachmann and Goldman (1965).

The heat budget of a lake may be approximated by the balance (Sundaran et al. 1969, Myrup et al. 1971):

$$RN = LE + Q + H + S \quad (2)$$

where RN = net radiation absorbed by the lake, LE = evaporative energy loss, H = sensible heat loss, S = storage of heat in the water column, and Q = net advection into and out of the lake.

The net radiation at Castle Lake may be described by (Sellers 1965):

$$RN = R_{SW}\ (1 - \alpha) + R_{IR}{\downarrow} - R_{IR}{\uparrow} \quad (3)$$
$$= 0.95\ R_{SW} - 7.86 \times 10^{-111}\ [(273 + T_s)^4 + 9.35 \times 10^{-6}\ (273 + T_a)^6]$$

where R_{SW} = incoming shortwave radiation, $R_{IR}{\downarrow}$ = downward flux of long wave radiation, $R_{IR}{\uparrow}$ = upward flux of terrestrial radiation, T_s = water surface temperature, T_a = air temperature, and α = albedo.

The energy loss through evaporation from the lake surface and the sensible heat transfer may be calculated from the bulk aerodynamic equations (Roll 1965):

$$LE = \rho L\ C_P\ U_a\ (Q_s - Q_a) \quad (4)$$
$$H = \rho C_P\ C_D\ U_a\ (T_s - T_a) \quad (5)$$

where ρ = density of water, L = latent heat of evaporation (585 cal g^{-1}), C_P = specific heat capacity (0.24 cal g^{-1} °C^{-1}), U_a = wind speed at screen height (cm/mm), Q_s = specific humidity at surface, Q_a = specific humidity at screen height, T_a = air temperature (°C) at screen height, T_s = air temperature (°C) at surface, and C_D = wind drag coefficient on the water surface. It may be approximated by:

$$C_D = (0.5 + 0.001\ U_a) \times 10^{-3} \quad (6)$$

Net advection is described by:

$$Q = \rho C\ \rho \Delta V \Delta t \quad (7)$$

where ΔV is the difference in volume between incoming and outgoing waters and Δt is the temperature difference of those waters.

The heat storage is given by:

$$S = \rho C_P \int T_z dz \quad (8)$$

where T_z = temperature at a particular depth and z is that depth.

The determination of eddy diffusivities from temperature profiles has been discussed by Hutchinson (1957). The basic problem in those methods not assuming a region of constant vertical eddy diffusivities (which would be unjustified in Castle Lake) is of obtaining an appropriate boundary condition for heat flux. The heat flux at the surface (equation 5) is ideal for this purpose. Given the heat flux at the surface and the changes in the heat content over a period of time in a cube of water between the surface and a depth of 1 m, one can compute the vertical flux at 1 m, leading to an estimate of eddy diffusivity (K_H) (Sundaran et al. 1969):

$$H = -C_P K_H \frac{\partial T}{\partial z} \tag{9}$$

Continuing the process over the water column gives complete vertical estimates of eddy diffusivity. The lack of strong current-producing winds in the protected Castle Lake basin and the negligible flow through of water after June (the turnover rate of lake water is less than 1 percent of the total per day) enables one to ignore net horizontal transport of heat (B in equation 1) after a sufficiently long period, e.g., one month. The eddy diffusivities so obtained are then used directly in the conservation of mass equations for phytoplankton and nutrients.

INSTRUMENTATION

To measure the above parameters a weather station on a raft was established in August 1971 in conjunction with existing facilities and with IBP funding from the Coniferous Forest Biome. Humidity and air temperature (Q_a, Q_s, T_a) measurements were made with a hygrothermograph (Weather Measure Corp., Sacramento, California, model #311), and calibrated with a sling psychrometer. A contract anemometer (WM model W164-A) with an event recorder (WM model 5-A) is used to measure wind speed (U_a); R_{SW} was measured with an Eppley pryheliometer (model 50, Eppley Laboratory, Inc., Newport, R.I.) previously installed. A Whitney TC-5 (Monteporo Corp., San Luis Obispo, Calif.) thermistor was used for water column temperatures. Volume of inflow and outflow streams was monitored beginning in June 1971 by constructing several small weirs (after Bormann and Likens 1967). Precipitation during this period was negligible. Changes in water level were measured by a gage designed by our research team; T_s was measured at intervals with a thermometer and continuous values were estimated by extrapolation. Planned instrumentation for 1972 includes a thermistor attached to a Rustrak recorder to give continuous readings for T_s. A hot-wire anemometer is to be used to provide direct measurement of K_H.

Data from 1971 are currently being reduced and applied to further modeling (Jassby and Goldman 1972; unpublished data). Three papers on biological aspects of the study were presented at the 18th International Limnological Congress in Leningrad, August 1971 (Goldman et al. 1972, Stull et al. 1972, Amezaga et al. 1972).

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