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THERMAL STRATIFICATION IN RESERVOIRS

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ABSTRACT

A lake's vertical thermal regime has dual significance to the water quality modeler. Temperature has direct importance as it influences the rates of chemical and bio chemical reactions. However, it has additional significance as a tracer of mass transport in the water column. Infact, heat balances are a primary tool for estimating mixing rates in the vertical dimension. Temperate lakes are those with surface temperature above $4^{o}C$ in winter, thermal gradients large, two circulation periods in spring and autumn. Although other lake types can be severely polluted, discussion generally focuses on temperate lakes because many of the world's developed areas are in temperate climate and consequently many lakes in these climates are subject to pollution. The study reviews the vertical temperature variation in lakes and the mathematical models available for temperature stratification in lakes have been understood for application. Various models like Water Resources Engineers, Tennessee Valley Authority, MIT and Cornell have been reviewed.

1.0 INTRODUCTION

Any water resources development plan should have water quality as a major consideration, and out of the many-many parameters responsible for water quality, the temperature is a key factor in determining quality. The effect of temperature on aquatic organisms have always been of great interest to biologists and much research in this area has been carried out in the nineteenth century. A huge bibliography on the subject can be found in literature (Brett, 1956; Guntur, 1957; Mackenthum, 1967; De Silva, 1969; Trembly, 1960; Raney and Menzel, 1967). This underlines the importance of temperature variation in water bodies. As physical and chemical properties of water are greatly influence by its temperature, a reasonable prediction of the temporal and spatial variation of thermal structure within the reservoir is necessary for successful management.

In advanced countries thermal water quality standards have specifically included in the water quality standards. With the exponential growth of the size of power production units and plants and the trend of nuclear power, the prediction of thermal structure in receiving water is even more so as necessary. Here it would not be out of turn to distinguish between deep reservoir or tank and shallow, run of the river reservoir is the maintenance of horizontal isotherms and a strong stratification during summer. Also deep reservoir usually have a low annual through flow to volume ratio.

In any storage reservoir, inhomogeneous distribution is the main cause for development of density stratification and a particular type of flow. Density stratification and associated flow phenomena play an important role in the water quality development of impounded water and in the annual water quality regime of releases from impoundments. It has been observed that for Tennessee Valley Authority(TVA) reservoirs, for example, outflow temperature, influences the quality of rivers and reservoirs downstream over a distance of about 300 km.

Thermal stratification occurs in almost all reservoirs. In shallow 'run of rivers' reservoirs the stratification may be relatively weak and in certain cases the temperature distribution becomes a function of distance, as indicated by isotherms tilted in the downstream direction. In deep reservoirs with a storage volume of the same order as or greater than the annual inflow the temperature structure is independent of distance and the isotherms are horizontal during most of the year.

With the increase in the size of power production units and plants and the trend to nuclear power, the prediction of thermal structure is receiving waters is even so necessary. Consequently, a large number of mathematical models have been developed but most have had only very limited field verification. Though there are many mathematical models available today for calculation of temperature rises in reservoirs, few of them have been so thoroughly explicated that they can be used easily except by a specialist.

As the application of the use of mathematical models for prediction of temperature stratification for Indian reservoirs (deep) or lakes has not been attempted in any appreciable degree, it was considered worthwhile to review features of various available models, understand them, know their limitations and to suitably implement one of the comprehensive models. This is the primary objective of this report. In this report, a brief description of deep reservoir models, mathematics involved, effect of temperature on water quality, effect of temperature on aquatic life and details input required and output generated by some models have been incorporated. One of the most capable computer programme given by water resources Management Methods Staff for use of Tennessee Valley Authority has been implemented at the VAX-11/780 system of the National Institute of Hydrology and input data requirement has been spelt out. It is proposed to collect necessary data for Indian reservoirs so that the ready made computer program could be used for predicting temperature stratification. The computer programme is a very comprehensive package and is fairly large (about 2800 statements).

In India and other temperate zones of the world, heating during spring time tends to warm up the water closest to the surface. This heating may primarily be because of absorption of solar and atmospheric radiation. However, surface cooling, due to back radiation, evaporation and conduction, and well induced turbulence cause mixing whenever the density gradient is too shallow to maintain a stable conditions. During this period the temperature distribution is only weakly stratified. The heat is surface layers is slowly transported down to the deep water primarily by advection. As solar heating continues, the temperature of the upper region, epilimnion, increases, while the lower region, hypolimnion, remains cool and relatively undisturbed. A zone in between the two regions in which the temperature gradient is the largest is called thermocline. This steep density gradient tends to inhibit the transfer of heat and momentum between the warm upper layer, and the underlying cooler waters. The schematic description of the epilimnion, hypolimnion, and thermocline has been given in another chapter, where the effects of stratification on water quality have been discussed. The thermal stratification has many-fold effects, some of these could be:

i) Extent of dilution

ii) Mixing of inflow water,

iii) Quality of water specially dissolved oxygen(DO concentration.

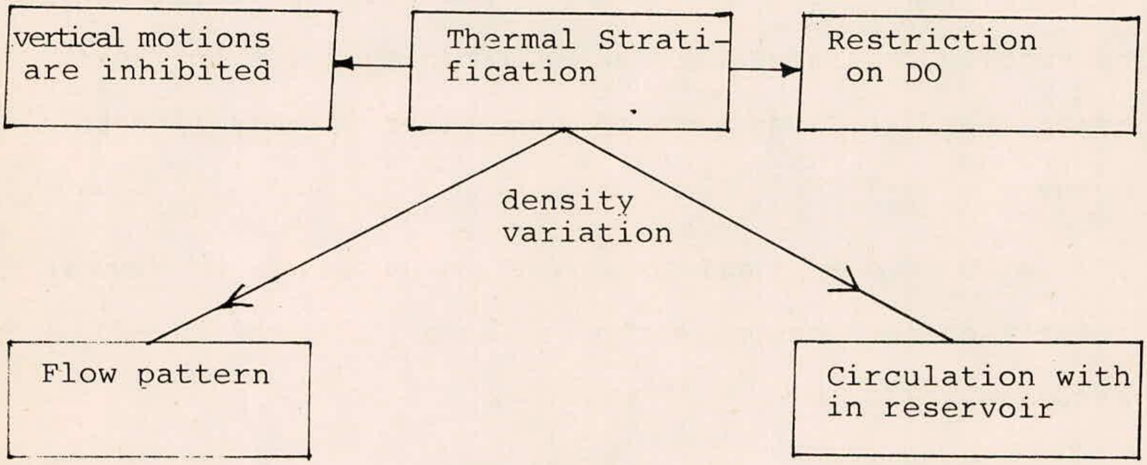
The deficit of DO usually follows the establishment of thermal stratification. After its formation the thermocline moves downward as the stratification increases. When the surface water attains its maximum temperature and then begins to cool, the epilimnon tends to become more dense and unstable with respect to the lower, less dense waters. The thermocline sinks rapidly as the epilimion cools further until the whole reservoir mixes or overturns and is isothermal.

The phenomena of stratification is highly complicated. This is controlled by meteorologic, hydraulic and hydrodynamic factors. The thermal and density properties of water are also very important.

As mentioned earlier, the water quality of reservoirs and lakes is governed both by the biological and bio-chemical reactions taking place within the water body and the hydro-dynamical advective and convective transport of the reactive material. The hydrodynamic transport is in turn, influenced by thermal stratifiction through which convective transport between epiliminion and hypolimnion is restricted. This may lead to poor water quality in hypolimnion.

A very good and schematic presentation of thermal stratification phenomena can be found in Markofsky and Harleman (1971).

In the springtime the reservoir is fully mised of constant temperature (isothermal). Since a stream warms faster than a large body of water, the stream temperature in spring and summer is warmer than large body of water, the stream temperature in spring and summer is warmer than a large body of water, the stream temperature in spring and summer is warmer than the main body of water and the incoming water enters at the surface water level. In addition, the reservoir temperature increases due to warming through the reservoir surface. In the fall and winter the opposite occurs. The stream cools faster than the reservoir, and as the incoming temperature is lower than the reservoir temperature, the stream enters the reservoir at some intermediate depth corresponding to its temperature. Cooling of water surface, associated with decreasing air temperature, solar radiation, etc. in the fall and winter, additionally results in density instabilities which lead to the mixing of the reservoir. Hence, throughout the year the temperature structure in the vicinity of outlet may result in seoective withdrawal causing water to be withdrawn from a layer of restricted depth. The figure below shows the effects of thermal stratification.



Due to changing temperature field, any pollutant or water quality parameter contained into the inflowing water will enter the reservoir at different elevations through out the year, depending on the temperature of the inflowing water and the terthermal structure of the reservoir at that time. The elevation at which water enters, coupled with the changing thermal structure within the reservoir, will determine the detention time of that water in the reservoir. The longer the detention time, the greater the possibility that poor water quantity will result.

2.0 EFFECTS OF HEATED DISCHARGES ON WATER QUALITY

The increase in temperature of surface waters resulting from the discharge of heated water affects water quality in two ways: directly and indirectly. The direct effect of the raised temperature may be detrimental to man's interests if, for example, it is to be used for further cooling processes, or if required as a potable water supply. In some cases, the raised temperatures may be benefitial-for recreational bathing. The indirect or secondary effects induced by increased temperature involving ecological changes in the biology and chemistry, may also be of applied significance.

2.1 Stratification in Impounded Waters

When discussing the effects of heat on water quality management, it is necessary to review the phenomenon of stratification in an impounded water. The stratification process in reservoirs and lakes is well known but the resulting changes in water quality are not. These changes are becoming increasingly important because of the growth of complex water resources systems developed as a result of expanding water conservation requirements.

At the end of a winter season, the impounded water is usually of a fairly uniform quality and has a relatively low temperature. At the onset of higher atmospheric temperatures, the surface water and the incoming water temperatures are raised and this lighter water tends to "float" on the colder and denser water already in the lake.

Three definite strata may be formed, the surface stratum or epilimnion, the lower stratum or hypolimnion, and a transition zone called the thermocline, where the maximum rate of change of temperature with depth occurs. In the southeast the thermocline persists from about April to November and is approximately 10 to 20 feet in thickness. In a deep reservoir the epilimnion may be approximately 30 to 50 feet in thickness and the hypolimnion will usually extend to the reservoir bottom.

These conditions may exist untill autumn, when the lake begins to lose heat more quickly than it is absorbed. As the water becomes cooler and more dense, the thermocline sinks, unstable conditions occur and the reservoir mixes or overturns. In climates where the water temperature goes below $4^{\circ}C$, two turnovers may occur per year.

Many impounded waters circulate completely but some circulate only partially, these lakes being called meromictic by limnologists. This stable, lower layer can be caused by either an accumulation of dissolved or suspended solids in the water and may render this lower portion of the lake unsuitable for a watersupply.

A typical reservoir profile (Kittrell, 1959) as described above is shown in figure 1.

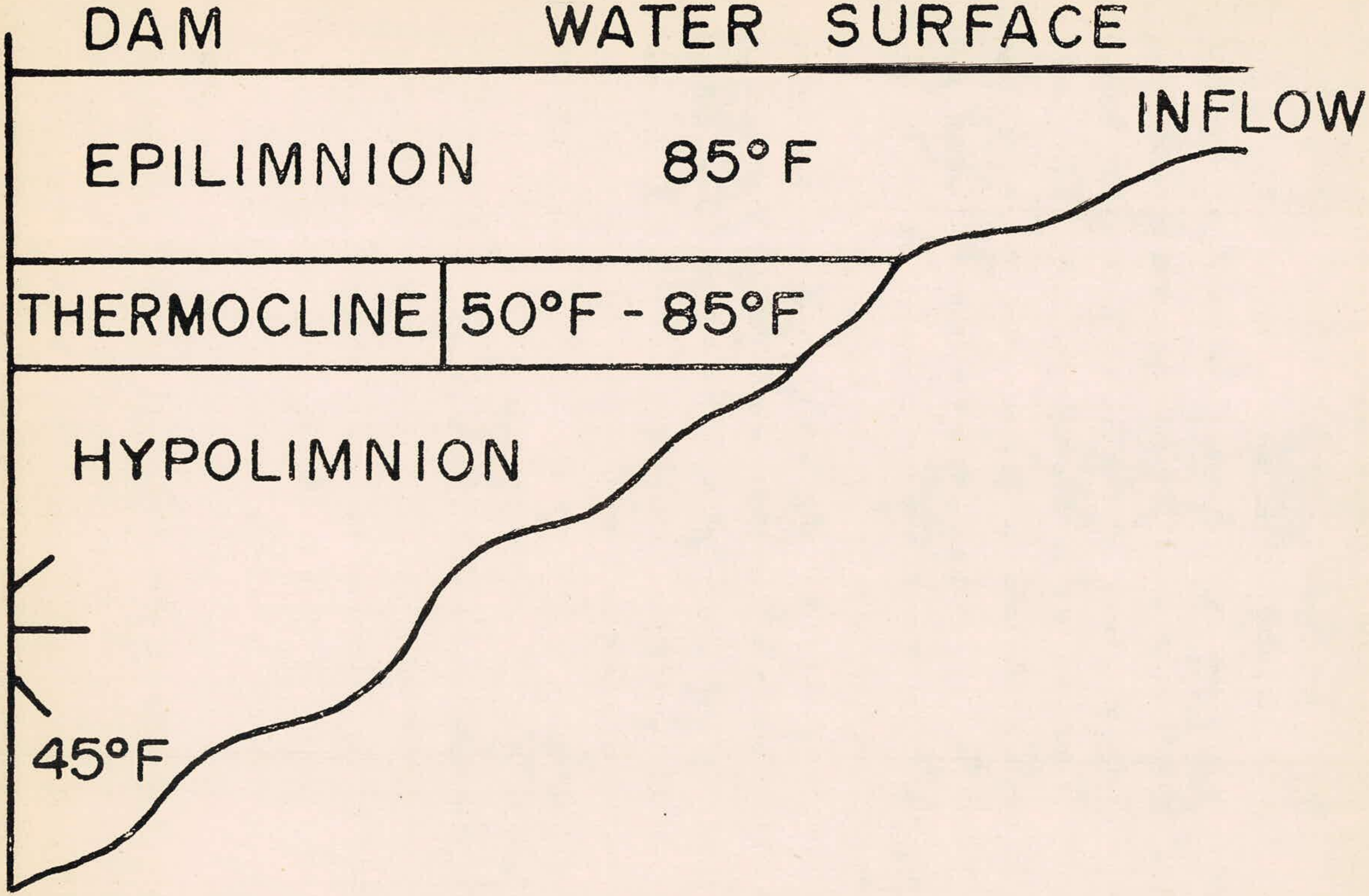


FIGURE 1 TYPICAL STRATIFIED RESERVOIR PROFILE
(FROM KITTRELL, 1959)

2.2 Discharges of Differing Density

Density currents, density flows, under-flows, overflows and interflow are all synonomous with stratified flow. As defined by the National Bureau of Standards (Anon, 1938), "A density current is the movement, without loss of identity by turbulent mixing at the bounding surfaces, of a stream of fluid under, through, or over a body of fluid, with which it is mixible and the density of which varies from that of the current, the density difference being a function of the differences in temperature, salt content, and/or silt content of the two fluids".

The various forms of a density current, the overflow, the interflow, and the underflow are shown in figure 2. Each of these currents may affect water quality in an adverse manner. The most important form of density current to the thermal pollution is the overflow because of its occurrence in the discharge of cooling waters.

Stratified flow had been observed when $\Delta \rho\rho \geqslant 0.005$, where ρ is the fluid density and $\Delta\rho$ is the density differential between the fluid layers (American Society of Civil Engineers Committee on Sedimentation, 1963). It is interesting to note that this condition is satisfied with water temperatures of 31^{0}C and 32.5^{0} C.

In order to illustrate these various forms of density currents, the following examples, each with a possible effects on water quality are presented.

2.3 The underflow

Underflows can be caused by the discharge of colder, more dense water from an upstream stratified reservoir

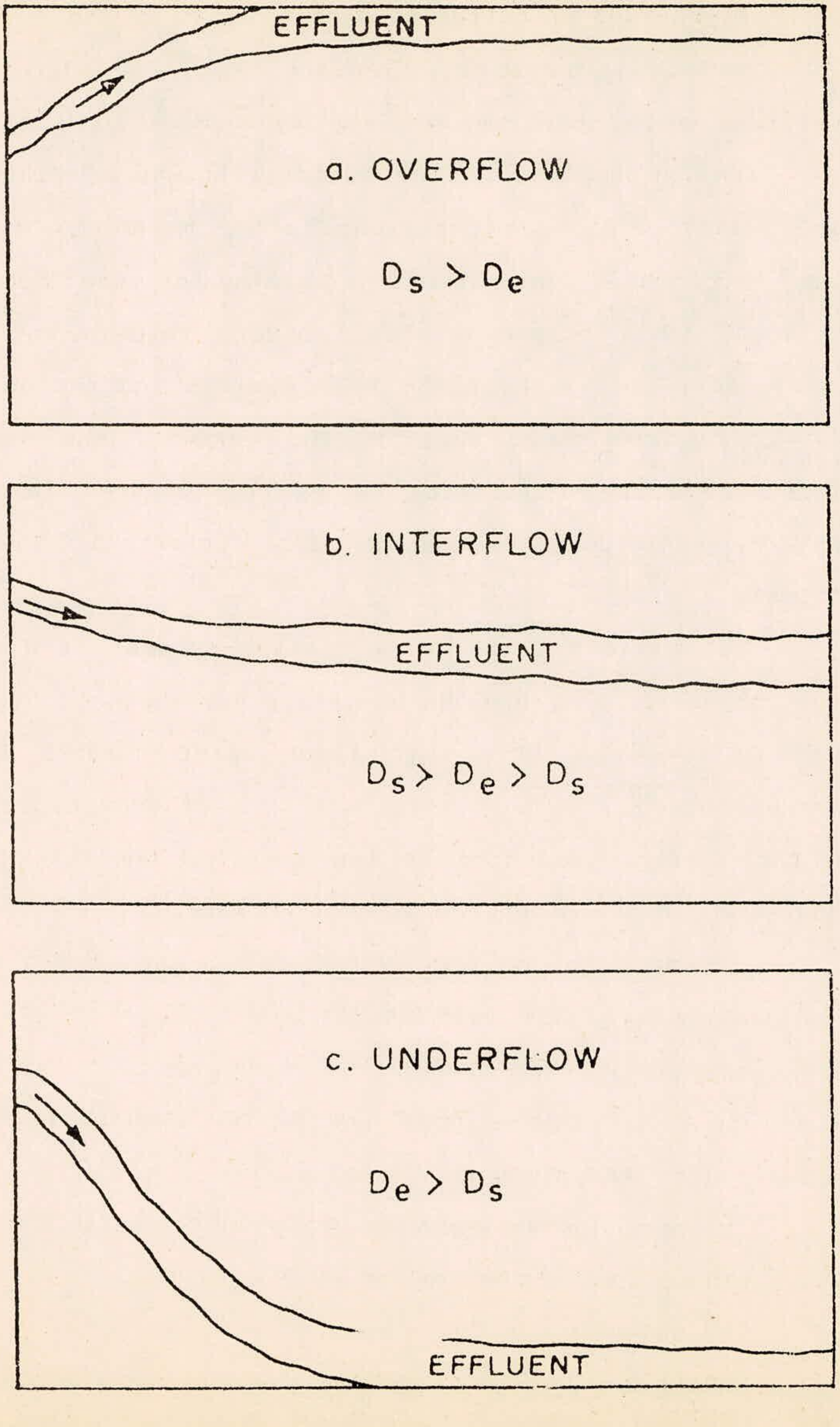


FIGURE 2 DIFFERENT FORMS OF DENSITY INTERFLOW
(FROM KRENKEL AND PARKAR, 1969)

or by water containing excessive suspended or dissolved solids. Underflows caused by highly turbid waters were first noted on Lake Mead while the underflow caused by the upstream release of hypolimnetic water frequently occurs in TVA reservoirs. Fish kills have been reported to have occurred downstream from Fort Loudon Dam purportedly caused by the low dissolved oxygen content resulting from the release of cold hypolimnion water (Jones, 1964). Figure 3 shows a schematic diagram depicting the flow regime cause by an underflow as presented by Elder (1964). Two different flow regimes are noted, the lower strata, bounded by the channel bottom and the interface with the velocity profile approximating that of distorted pipe flow, and the upper layer, bounded by the interface and the atmosphere and behaving like free surface flow.

2.4 The interflow

The interflow results from the discharge of a fluid of an intermediate density into a stratified flow regime. One example of an interflow is the process of selective withdrawal as shown in figure 4. Under stratified conditions, one would withdraw water from all levels of the reservoir, however, under stratified flow conditions, withdrawal is from a pre-selected layer, depending on the level of the water intake.

2.5 The overflow

The overflow is caused by the discharge of lighter

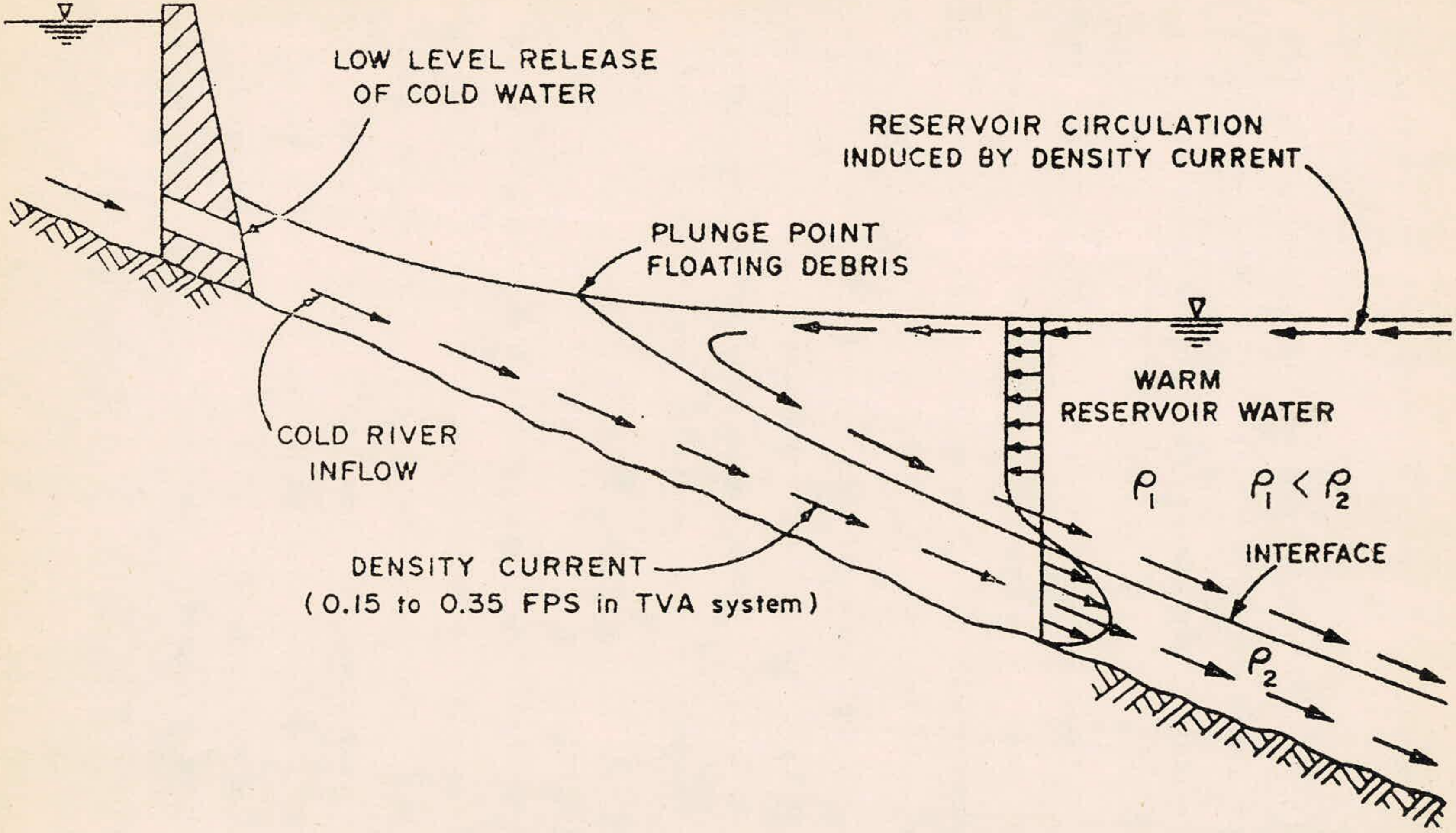
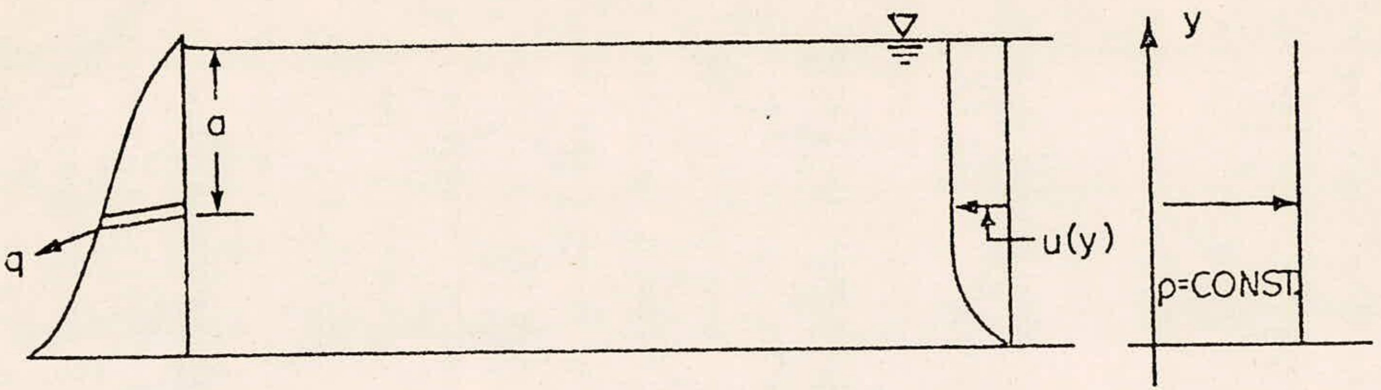
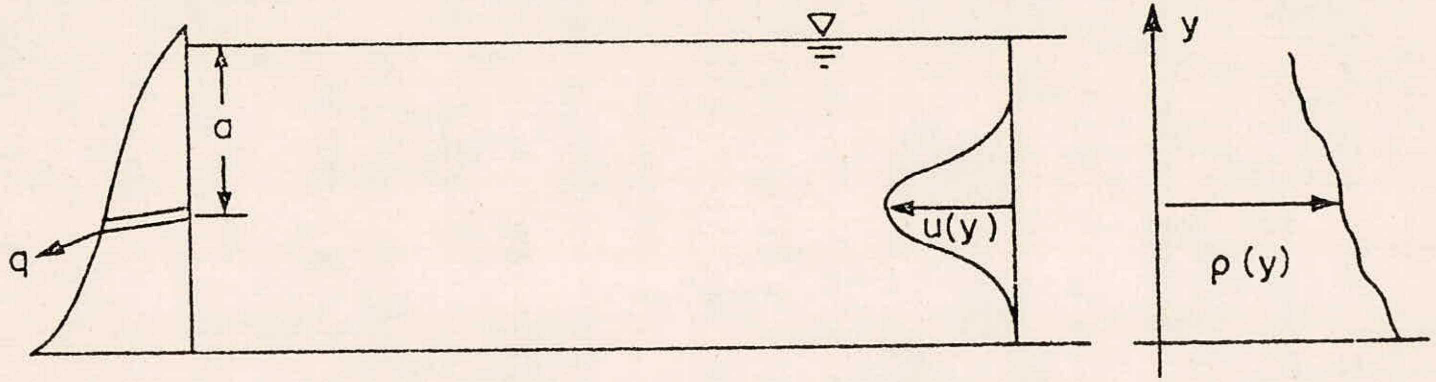


FIGURE 3 . RESERVOIR WITH DENSITY UNDERFLOW
(FROM ELDER, 1964)



(A) Withdrawal from full depth in a homogeneous fluid.



(B) Selective withdrawal in a stratified field.

FIGURE 4 SELECTIVE WITHDRAWAL AS AN INTERFLOW (FROM ELDER, 1964) density water and is most commonly observed when cooling waters are discharged into a receiving water at its surface. While the heat is obviously dissipated more rapidly with this means of discharge than if the cooling water were completely mixed with the receiving water, the higher temperature of the resulting stratified flow may be totally unacceptable from the water quality standpoint.

2.6 Effects of Stratified Flow on Water Quality

2.6.1 Dissolved oxygen

Water containing organic material entering a stratified reservoir will deplete the oxygen resources of the reservoir due to biological respiration. In the epilimnion, mixing by wind currents, photosynthesis and sedimentation may render the epilimnetic water satisfactory. However, in the hypolimnion, oxygen removed by biological action is not replaced, algae cannot grow, essentially no vertical mixing takes place and the products of sedimentation from the epilimnion may add additional organic load. The net result is a depletion of the dissolved oxygen resources, thus making septic conditions possible.

If this hypolimnetic water with its low oxygen content is discharged from the dam, fish life may not be supported for several miles downstream, a lower waste assimilation capacity may exist and in effect, the dam may be considered as being equivalent to a large BOD concentration.

2.6.2 Iron and Manganese

If there is low oxidation-reduction potential at the mud water interface, conditions amenable to the dissolution of iron and manganese into the hypolimnetic waters will occur. The mechanism is not clear, however, if the oxides of these metals are present in the bottom muds, troublesome concentrations may appear in the water under reduced environmental conditions.

2.6.3 Temperature

The temperature differential in stratified lakes can be quite significant. Since a major water use is for coding purposes, it is obvious that this cooler water is highly desirable for condenser cooling for steam-electrical generation purposes. The use of this colder water by construction of an under water dam at the TVA Kingston Steam Plant was reported to have saved TVA $ 155,000 in operating costs for the year 1956 alone, which was one third the cost of the dam (Elder and Daugherty, 1956).

2.6 .4 Waste Aassimilative Capacity

If the discharge from a power plant is in the form of an overflow, mixing between the upper and lower layers is inhibited, thus minimizing oxygen replacement and self purification in the lower layer. Due to lack of mixing, organic wastes discharged into the lower layer do not have access to the oxygen in that portion of the stream flowing in upper layer. Thus there is less dissolved oxygen, less dilution water and a more concentrated organic load in the lower layer leading to an acceleration of the dissolved oxygen depletion. The net result may be considerable reduction in the waste assimilative capacity of the receiving water.

If the heated discharge is completely mixed with the receiving water, some of the above mentioned effects are eliminated however, the rise in temperature still causes a decrease in the ability of water to hold dissolved oxygen, an increase in the metabolic activity of organisms, an increased rate of Biochemical oxygen Demand exertion and a possible reduction in waste assimilative capacity.

The effects of temperature on the stream self purification process is demonstrated in figure 5 which shows the variation of the rate of constants k_1(de-oxygenation) and K_2 (reaeration) with respect to temperature. Examination of this relationship demonstrates that an increase in temperature causes a considerable increase in k_1. While k_2 also increases with increasing temperature, it is negated by the combination of a lesser dissolved oxygen content and a greater rate of change of k_1 with temperature.

The overall effects of the impoundment on the rate of Oxygen recovery is demonstrated by the lower curve, which depicts the reaeration rate constant under existing, impounded conditions.

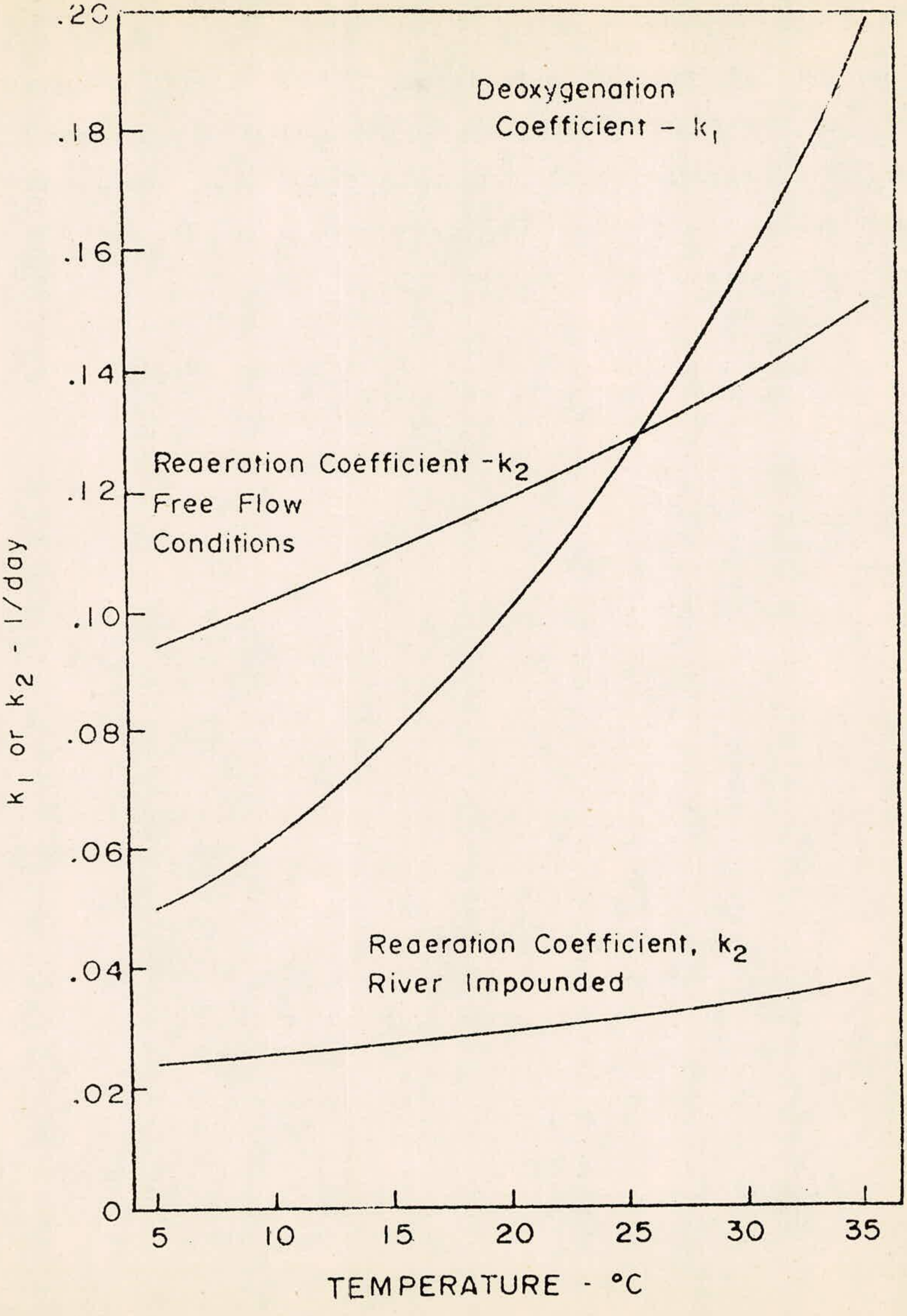


FIGURE 5 SELF PURIFICATION AS A FUNCTION OF TEMPERATURE (FROM KRENKEL AND PARKAR, 1969)

It may be concluded from the above discussion that the addition of heated water to a receiving water can be considered equivalent to the addition of sewage or other organic waste material, since both pollutants may cause a reduction in the oxygen resources of the receiving water.

3.0 ANALYSIS OF DEEP LAKES AND RESERVOIRS

The basic equation (WMO, 1966), relating all the energy inputs to a body of water can be solved for reservoirs, rivers and estuaries and coastal regions.

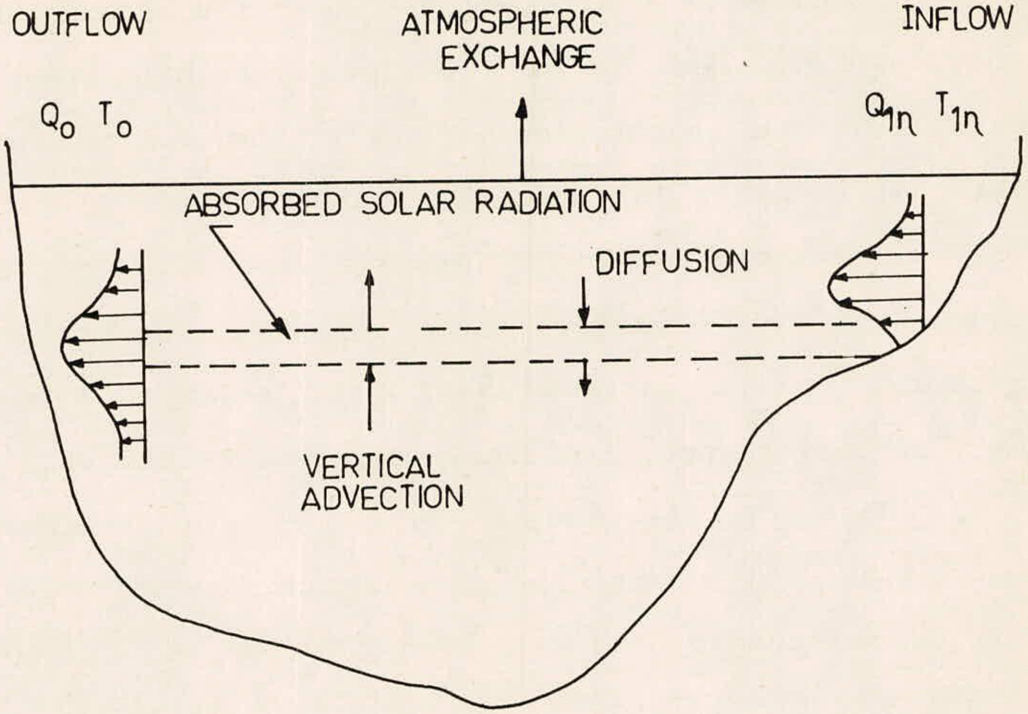
$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e + Q_h - Q_w = Q \qquad (1)$$

where:

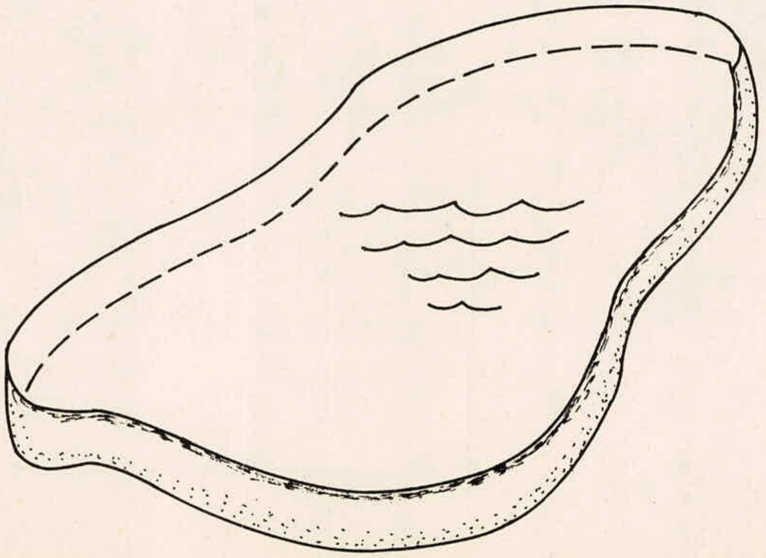
Q_s = shortwave radiation incident to the water surface;
Q_r = reflected shortwave radiation;
Q_a = incoming longwave radiation from the atmosphere;
Q_{ar} = reflected longwave radiation;
Q_{bs} = longwave radiation emitted by the body of water;
Q_v = net energy brought into the water of water in inflow, including precipitation, and accounting for outflow;
Q_e = energy utilized by evaporation;
Q_h = energy conducted from the body of water as sensibile heat;
Q_w = energy carried away by the evaporated water;
Q = increase in energy stored in the body of water.

A three-dimensional analysis is so complicated that it is uaually not justified by the increased accuracy of the results. In most practical problems, one or two dimensional analyses will describe adequately all the principal factors. The existence of horizontal isotherms, although sometimes tilted slightly by the wind action and/or the effect of lag time of inflow, and the much faster dispersion in the horizontal direction than in the vertical direction, ensure that the assumption of horizontal homogeniety of physical properties in the model is compatible with the prototype. Most mathematical models are based on the one-dimensional vertical motion assumption and can predict the thermal structure of reservoirs that are in good agreement with the measured values.

In a stratified reservoir, the body of water must be segmented into a series of discrete horizontal elements to compute the vertical variation of temperature. Therefore, heat flux due to vertical advection, and diffusion between elements is added to Eq.1 and applied to each element. A schematic of the reservoir model considered is shown in Figure 6. For simplicity, the elements except for the top and bottom are usually of equal thickness. The basic heat transport equation and the continuity equation are written for an element. At the beginning of the calculation, the surface elevation is determined either from a measured elevation or calculated from measured inflow and outflow rates. The inflow and outflow distribution in each layer is evaluated according to certain formula or criteria. Applying the continuity equation to each control volume, beginning with the bottom element, the vertical advection across the bounding surfaces can easily be found.



SCHEMATIC OF RESERVOIR PROBLEM



TYPICAL HORIZONTAL SLICE FROM RESERVOIR

FIG. 6-RESERVOIR REPRESENTATION

For a chosen period of time, t, the net change of heat content, or the rate of heat change, in the control volume is evaluated. The heat fluxes considered include that from inflow, outflow, vertical advection, diffusion, and adsorption of radiation energy for an internal element. In addition to these, surface absorbed energy and surface heat losses, due to evaporation, conduction, and longwave back radiation must also be included in the surface layer heat balance. From the rate of heat change, the final temperatures are obtained.

Each of the models developed for temperature simulation is essentially an accounting procedure of the energy budget over a period of time. The procedure iterates until balance is achieved and stability criteria are satisfied, and proceeds to the next time step.

4.0 REVIEW OF SOME PROMINENT MODELS

Here it is attempted to review some of the most useful thermal stratification models. The main features, assumptions, difference etc. are described.

4.1 Water Resources Engineers' Model

The WRE model has been developed by Water Resources Engineers, Inc., through a series of studies for various agencies (W R E, 1967 and 1969). It was the first comprehensive model proposed for predicting the thermal structure in reservoirs. Although this model has many versions and is widely used, most users indicate that an intensive effort is needed to have this model run properly. This is partially due to the difficulty of acquiring full documentation and partially to some computer coding problems. Several errors were detected during past. The most serious one is the concept of 'effective' diffusion, based on the numerical evaluation of the body conductivity coefficient from the measured temperature profile in a reservoir. The density of water, ρ , appears to have been omitted from the diffusion term. Since the MKS system is used, the actual diffusion is approximately one thousandth(1/1000) of the 'effective' diffusion, as defined by WRE. After correction of this error, the magnitude of the 'effective' diffusion coefficient is then of the same order of magnitude as the molecular diffusion coefficient.

Other difficulties is using the WRE model relate to the numerical scheme for evaluation of the heat flow term at the top layer.

4.1.1 Principal assumptions

(a) There is horizontal homogeneity, i.e., stratification is in the vertical direction only.

(b) Effective diffusion accounts for the heat transfer due to wind mixing turbulent motion and reservoir instability.

(c) There is differential absorption of incoming solar radiation.

(d) There is no flux, of volume or heat, through the reservoir bottom or sides except that due to inflow and outflow.

4.1.2 Direct absorption of solar radiation

$$\Phi(z) = \Phi_o (1-\beta)\, e^{-\eta (z_s - 0.3 - z)} \qquad (2)$$

where

Φ_o = net short wave radiation at water surface

$\Phi(z)$ = short wave radiation at elevation z

z_s = elevation of water surface

β = fraction of solar radiation absorbed at the water surface ($\beta = 0.4$ is assumed)

η = radiation extinction coefficient, m^{-1}

4.1.3 Selective withdrawal

(i) Upto five outlets are allowed

(ii) Based on Debler's experimental results. the critical Froude number, F_c - is 0.24, therefore;

$$0.24 = \frac{q}{d^2}\left[\frac{\rho_o}{-g\,\frac{\partial\rho}{\partial z}}\right] \qquad (3)$$

The withdrawal depth in meters, then is:

$$d = 2.0\left[\frac{q^2}{\frac{-g}{\rho_o}\frac{\partial\rho}{\partial z}}\right]^{1/4} = 2.0\,\frac{q^{1/2}}{(g\,\xi)^{1/4}} \qquad (4)$$

where $q = \frac{1}{2}Q/W$, one half of the discharge per unit width, and w is the reservoir width

$\xi = \frac{-1}{\rho o}\frac{\partial\rho}{\partial z}$, normalized density gradient.

(iii) The velocity is uniform within the withdrawal zone

(iv) The principle of superposition is applied for the regions in which withdrawal layers overlap.

(v) Withdrawal layers never extend through the thermoclie or physical boundaries.

(vi) At the onset of fall cooling, when the epilimetic region is well-mixed and isothermal Debler's criteria do not hold for withdrawals from the epilimnion and Craya's approach is used. The flow is withdrawn from epilimnion until the discharge is larger than Craya's critical flow given by:

$q_c = 1.52\ \sqrt{gh^3\frac{\Delta\rho}{\rho}}$ $\quad$ $2h < d_t$ for submerged

and $\quad$ outlets (5)

$q_c = 0.75\ \sqrt{gd_t^3\frac{\Delta\rho}{\rho}}$ $\quad$ for surface outlets (6)

where d_t = depth to bottom of thermocline

h = thickness of thermocline

ρ = density above thermocline

$\rho + \Delta\rho$ = density below thermocline

At greater discharges water will begin to be withdrawn from the hypolimnion.

4.1.4 Depth and velocity distribution of inflow

(i) The inflow is centered at the equivalent water density of the reservoir.

(ii) The inflow layer thickness is determined from measured inflow data by using Debler's criterion.

(iii) The distribution of inflow is proportional to the volume of each horizontal layer within the inflow zone.

(iv) The inflow, Q_i, is calculated from the continuity equation:

$$Q_i = \frac{dV}{dt} + Q_o$$

where V = volume of reservoir

Q_o = outflow rate

(v) The distribution of inflow in each layer is then modified by multiplying the ratio of calculated inflow rate to the measured inflow rate.

4.1.5 Internal mixing

(i) Free convection occurs if stratification is unstable.

(ii) The heat transport, H due to diffusion can be written as:

$$H = \rho\ c.\ D(z,t)\ .\frac{\partial\ T(z,t)}{\partial\ z} \qquad \ldots(8)$$

The general properties of diffusion coefficient D are as follows:

(a) It is usually greatest near the surface but declines rapidly with depth and attains the minimum at thermocline.

(b) In the hypolimnion, it increases with depth in an erratic manner, reaching a maximum at about mid-depth, thereafter decreases as the bottom is approached.

(iii) The form of the diffusion coefficient used is:

$$D = A_1(\text{ constant}),\ E \quad E_C \qquad \ldots(9)$$

$$D = A2E^{A3}, \qquad E \geqslant E_c \tag{10}$$

where E = stability of the water column

$$E = -\frac{1}{\rho}\ \frac{\rho p}{\Delta z} \tag{11}$$

E_c = critical stability parameter

The following values are suggested:

$A_1 = 2.5 \times 10^{-4} m^2/sec$

$A_2 = 1.5 \times 10^{-8}\ m^{1.3}/sec$

$A_3 = -0.7$

$E_c = 1.0 \times 10^{-6}\ m^{-1}$

4.1.6 Governing equation

The time rate of change of thermal energy H in a conttrol volume of thickness z, is:

$$\frac{\partial H_j}{\partial t} = (h_I - h_o)_j + (h_{sw})_j + (h_v)_j - (h_v)_{j+1} + (h_d)_j - (h_d)_{j+1} \quad \ldots(12)$$

where subscript j indicates the increment of depth;

j = 1 at bottom surface

H = The heat energy stored in the control volume (kcal)
h_I = Heat flow associated with inflowing water(kcal/sec)
h_o = Heat flow associated with outflowing water (kcal/sec)

h_v = Heat flow by advection (kcal/sec)

h_d = Heat flow by diffusion (kcal/sec)

h_{sw}= Heat flow by sjprt wave sp;ar radoatopm (kcal/sec)

In terms of temperature T, E_{qn}.12 can be written as:

$$\bar{\rho}_j\ c\bar{A}_j\ \Delta z \frac{\partial T_{j+1/2}}{\partial t} = \bar{\rho}_j c (T_I)_j\ (q_I)_j - \bar{p}_j c (T_o)_j (q_o)_j$$

$$+ hj\ \bar{A}_j + p_j\, c V_j A_j T_j - p_{j+1} c v_{j+1} A_{j+1} + P_j c d_j A_j \frac{\partial T_j}{\partial z}$$

$$- P_{j+1} c D_{j+1} A_{j+1} \frac{\partial T_{j+1}}{\partial z} \tag{13}$$

or

$$P_jC\ {}_jT_{j+\bar{1}/2} = \bar{P}_jc(T_I)_j(q_I)_j\overset{-}{-}p_jc(T_o)_j\,(q_o)_j +$$

$$h_j\bar{A}_j + p_jcv_jA_jT_j - P_{j+1}CV_{j+1}A_{j+1}T_{j+1} - p_jCD_jA_j$$

$$\frac{T_{j+1/2}-T_{j-1/2}}{z} + p_{j+1}\ CD_{j+1}\ A_{j+1}\quad \frac{T_{j+3/2}-T_{j+1/2}}{z} \qquad (14)$$

$$= p_j + Q_j + p_j\ c\frac{D_jA_j}{z}\ T_{j-1/2} - (p_jc\ \frac{D_jA_j}{z} + p_{j+1}C$$

$$\frac{D_{j+1}A_{j+1}}{z}\ )\ T_{j+1/2} + p_{j+1}\ C\ \frac{D_{j+1}A_{j+1}}{-z}\ T_{j+3/2}$$

$$(15)$$

where

$$p_j = p_jc(T_I)_j(q_I)_j - p_jc(T_o)_j(q_o)_j + h_jA_j \qquad (16)$$

$$Q_j = p_jcv_jA_jT_j - P_{j+1}CV_{j+1}A_{j+1} \qquad (17)$$

T = water temperature ($^{\circ}$c)

T_I = inflow temperature ($^{\circ}$c)

q_I = inflow rate (m/sec) into control volume

T_o = outflow temperature ($^{\circ}$c)

q_o = outflow rate (m/sec) from control volume

h' = net insolation heat flux per unit area (kcal/ m^2-sec)

D = diffusion coefficient (m^2/sec)

V = vertical advection velocity (M/sec)

z = thickness of control volume (m)

P = average density of water (kg/m^3)

$j = A_j.z$ volume of jth control volume (m^3)

Z = vertical axis, positive upward (m)

A_j = cross-section area at depth step $j(m^2)$

$$A_j = (A_j + A_{j+1})/2 \quad (18)$$

T = mean water temperature of jth control volume (^oc)

c = specific heat of water(=1 kcal/kg-^oc) since

$$T_{j-1/2} = \bar{T}_{j-1} \quad (19)$$

$$T_{j+1/2} = \bar{T}_j \quad (20)$$

$$T_{j+3/2} = \bar{T}_{j+1} \quad (21)$$

Equation 15 becomes:

$$\bar{p}_j c\ v_j \bar{T}_j + K_{j,1}\bar{T}_{j-1} + K_{j,2}\bar{T}_j + K_{j,3}\bar{T}_{j+1} = p_j + Q_j \quad (22)$$

where

$$K_{j,1} = -p_m c \frac{D_{j+1}A_{j+1}}{z} \quad (23)$$

$$K_{j,2} = p_j c \frac{D_j A_j}{z} + p_{j+1} c \frac{D_{j+1}A_{j+1}}{z} = -(J_{j,1} + K_{j,3}) \quad (24)$$

$$K_j\ 3 = -p_{j+1} c \frac{D_{j+1}A_{j+1}}{z} \quad (25)$$

Taylor series of 2nd order

$$T(t+\Delta t) = T(t) + T(t)\Delta t + T''(t)\frac{\Delta t^2}{2}$$

and by definition of derivative

$$T''(t) = \lim_{\Delta t \quad 0} \frac{T(t+\Delta t) - T(t)}{\Delta t} \quad (27)$$

for small t

$$T(t+\Delta t) = T(t) + T(t)\frac{\Delta t}{2} + T(t+\Delta t)\frac{\Delta t}{2} \quad (28)$$

or use superscript k to indicate time step

$$T^{(k+1)} = T^{(k)} + T^{(k)}\frac{t}{2} + T^{(k+1)}\frac{\Delta t}{2} = Q^{(k)} + T^{(k+1)}\frac{t}{2} \quad (29)$$

where $Q^{(k)} = T^{(k)} + T^{(k)} \frac{\Delta t}{2}$ (30)

By Equations 22 and 29

$$k_{j,1} \frac{\Delta t}{2} T_{kj-1}^{(k+1)} + (\bar{p}_j c \Delta v_j + k_{j,2} \frac{t}{2}) T_j (k+1) + k_{j,3}$$

$$\frac{\Delta t}{2} T_{j+1}(k+1) = p_j(k+1) + Q_j(k+1) - a_{j-1}^{(k)} k_{j,1} + a_j^{(k)}$$

$$k_{j,2} + a_{j+1}^{(k)} k_{k,3} \quad (31)$$

Let

$$S_{j,1} = k_{j,1} \frac{\Delta t}{2} \quad (32)$$

$$S_{j,2} = p_m c v_j + k_{j,2} \frac{t}{2} \quad (33)$$

$$S_{j,3} = k_{j,3} \frac{\Delta t}{2} \quad (34)$$

$$f_j = p_j^{(k+1)} + Q_j^{(k+1)} + a_{j-1} k_{j,1} + a_j k_{k,2} +$$

$$a_{j+1} k_{j,3}^{(k)} \quad (35)$$

Then Equation 31 becomes

$$S_{j,1} T_{j-1}^{(k+1)} + S_{j,2} T'_j(k+1) + s_{j,2} {T''}_{j+1}^{(k+1)}$$

$$= F_j, \ j = 1, 2 \ldots\ldots\ldots N \quad (36)$$

The system is a set of implicit equations and can be solved by the Thomas algorithm and transforms into an upper bidiagonal form. The coefficients of this new system designated by $S_{j,1} S_{j,2}$

$s_{j,3}$ and F_j are as follows:

$$S_{j,1} = o, \quad j=2,3,\cdots\cdots N \qquad (37)$$

$$S_{j,2} = 1, \quad j=1,2,3\ldots\ldots N \qquad (38)$$

$$S_{j,3} = S_{1,3}/S_{1,2}; \quad F_1 = F_1/s_{1,2} \qquad (39)$$

$$S_{j+1,3} = \frac{S_{j=1,3}}{S_{j+1,2} - S_{j+1,1} \cdot S_{j,3}} \qquad (40)$$

$$F_{j+1} = \frac{F_{j+1} - S_{j+1,1} F_j}{S_{j+1,2} - S_{j+1,1} \cdot S_{j,3}} \qquad (41)$$

then $T_N = F_N$ (42)

and

$$T_l = F_l' - S'_{l,3} \quad T_{l+1}, \; l = N-1, N-2, \ldots\ldots 2,1 \qquad (43)$$

$$\bar{T}_j(k+1) = a_j(k) + T_j\,(k+1)\,\frac{\Delta t}{2}, \quad j=1,2\ldots N \qquad (44)$$

This is an implicit method of combining an explicit finite difference and an implicit finite difference scheme. It has advantage of unconditional stability at the cost of complexity of computation and longer computation time. The model has been widely tested (EPA, 1975).

4.2 MIT MODEL

The details of the development and testing of the thermal stratification model are shown in Huber and Harleman (1968). The current version has some modifications in the numerical scheme, selective withdrawal, etc. Most of the assumptions, factors considered in analysis and input data are similar to WRE's. The major differences between these two models are in the numerical scheme and the handling of inflows and outflows. The computer program is clear and easily followed.

4.2.1 Principal Assumptions

(a) Thermal gradients exist in the vertical direction only, i.e., horizontal isotherms.

(b) The diffusion coefficient (molecular) is constant at all depths and at all times; mixing due to unstable density profile accounts for convection in the epilimnion.

(c) Solar radiation is transmitted in the vertical direction only and there is differential absorption of the incoming solar radiation below the water surface.

(e) The sides and bottom of the reservoir are insulated.

(e) The density and specific heat of water are constant.

4.2.2 Factors considered and basic equations

(a) Variable area with depth

(b) Direct absorption

Transmission of radiation at elevation, y, is given by

$$\Phi (y) = \Phi_0(1- \beta)e^{-\eta} (y_s -y) \qquad (45)$$

where

Φ_o = net incident solar radiation

β= fraction of $_o$ absorbed at the surface

η = light extinction coefficient

y_s = water surface elevation

(c) Inflow

(i) Inflow enters at the level at which its temperature, or the mixed inflow temperature if entrance mixing is allowed, matches the temperature in the reservoir.

(ii) An option to account for the travel or lag time of inflows within the reservoir is provided.

(iii) Entrance mixing could be included by providing an entrance mixing ratio; 100% is recommended for Fontana (USA).

(iv) Inflow velocity profile is approximated by a Gaussian distribution, at elevation y

$$-\frac{((y-y_{in}(t)))^2}{2\sigma_i^2} \qquad (46)$$

$U_i(y) = U_{i_{max}}(t)^e$

where:

$U_{imax}(t)$ = maximum value of the inflow velocity at time t,

is determined from:

$$Q_i\ (t) = \int_{Y_b}^{Y_s} B(y)\ U_i(y)\ dy \qquad (47)$$

where

$Q_i(t)$ = total inflow

y_s = surface elevation

y_b = bottom elevation

B(uy) = width of the reservoir at elevation y

$Y_{in}(t)$ = elevation of inflow

σi = inflow standard deviation

(d) Outflow

(i) multiple outlets

(ii) outflows are centered at the outlet with a Gaussian velocity distribution:

$$U_o(y) = U_{o_{max}}\ (t) e^{\frac{-(y-y_{out})^2}{2\ \sigma_0^2}} \qquad (48)$$

where

$U_{o_{max}}$ = maximum velocity or velocity at $y-y_{out}$

Y_{out} = elevation of centerline of outlet

σ_o = the outflow standard deviation calculated on the basis that 95% of the outflow comes from the calculated withdrawal layer or:

$$\sigma_0 = \frac{/2}{1.96}$$

with $U_{o_{max}}$ evaluated from (49)

$$Q_o\ (t) = \int_{y_b}^{y_s} B(y)\ U_o(y)dy \qquad (50)$$

where

$Q_o(t)$ is total outflow at the specified outlet

(iii) Withdrawal thickness calculated from modified Kao's (1965) if the temperature gradient, $\frac{\partial T}{\partial y}$, at the outlet is greater than or equal to $0.01^{o}/cm$

$$\delta \partial = 4.8\ \left(\frac{q^2}{g\,\xi}\right)^{1/4} \qquad (51)$$

where:

δ = thickness of withdrawal layer

q= outflow rate per unit width

ξ = normalized density gradient = $\frac{-1}{\rho} \frac{\partial \rho}{\partial y}$ (52)

g = gravitational acceleration

If the temperature gradient at the outlet is smaller than the value specified above, the withdrawal layer is restricted by the thermocline. The bilt in cut-off gradient is set at $0.55^{o}c/m$.

(iv) the velocities from each outlet are superimposed on one another.

(e) Variable water surface elevation

The surface level is calculated from the initial surface level and the cumulative inflow and outflow. The measured elevations are used as reference only. The reservoir is schematized into a series of horizontal elements with constant thickness, Δ y, except the bottom element, which is half as thick, and the surface element, which varies between 0.25 Δ y and 1.25 Δ y to account for the variation in the surface elevation.

(f) Governing Equations

The heat transport equation applied to each horizontal layer has the following form:

$$\frac{\partial T(y)}{\partial t} = \frac{DC}{A(y)} \frac{\partial}{\partial y} (A(y) \frac{\partial T(y)}{\partial y} = \frac{1}{\rho CA(y)} \frac{\partial}{\partial y} (A(y)$$

$$\Phi(y)) - \qquad (56)$$

$$\frac{1}{A(y)} \frac{\partial}{\partial y} (V(y)A(y)T(y) + \frac{1}{A(y)} (U_i(y)B(y)T_i - U_o(y)$$

$$B(y)\ T(y))$$

where

T(y) = temperature at elevation y

V(y) = vertical velocity at elevation y

$U_i(y)$ = inflow velocity at elevation y

$U_o(y)$ = outflow velocity at elevation y

T_i = inflow temperature

A(y)= area at elevation y

t = time

α = molecular diffusivity

$\Phi(y)$ = transmission of radiation at elevation y

and the continuity equation can be written as

$$\frac{\partial}{\partial y} (V(y)A(y)) = B(y) \qquad (U_i(y) - U_o(y)) \qquad (53)$$

The isothermal profile at the beginning of the Spring provided the initial condition and the two boundary conditions are given by the no heat flux through the reservoir bottom and the balance of heat input at the water surface.

The mathematical model used is an explicit finite difference scheme. The selection of layer thickness, Δy, is restricted by the stability criteria:

$$D\frac{\Delta t}{(\Delta y)^2} \leqslant 1/2 \tag{54}$$

$$V\frac{\Delta t}{\Delta t} \leqslant 1 \tag{55}$$

where:

D = diffusion coefficient

Δt= time increment

V = vertical advection velocity

y = depth increment

A routine check on the second criterion was built into the program to subdivide the time interval if the vertical velocity should become too large.

4.3 CORNELL MODEL

The model was developed through an extension of a study on the physical effects of thermal discharge into Cayuga Lake (Sunderam et.al.1969). It is a one-dimensional model designed for deep stratified lakes. The surface elevation of the lake is assumed to be constant throughout the simulation period and the reservoir is divided into a number of horizontal layers of equal thickness. The geometry of the reservoir is not considered.

Heat flow from inflow, outflow, and vertical advection through each horizontal layer are not considered, nor is the differential adsorption of incoming solar radiation. Eddy diffusivity, which is related to wind induced turbulence and the buoyancy gradient is the primary factor of heat transfer within the reservoir.

4.3.1 Assumptions

(a) Horizontal homogeneity and constant cross-section area.

(b) Lake is deep and isothermal during the springtime.

(c) The lake is turbid and the incoming solar radiation is absorbed within a small layer near the surface.

(d) Eddy diffusivity accounts for all heat transfer within the lake except for the heat added by the power plant and pumping.

(e) The annual equilibrium temperature and wind speed over the lake can be expressed in a sinusoidal form.

4.3.2 Basic Equations

(a) Governing equations

The change in temperature with depth when the plant discharge surfaces is:

$$\frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z} \left(K_H \frac{T(z,t)}{\partial z} + w_p \frac{\partial T(z,t)}{\partial z} S(z) \quad \text{for } z_d \leq z \leq z_i \right. \tag{56}$$

$$\frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z} \left(K_H \frac{\partial T(z,t)}{\partial z} + S(z) \quad 0 \leq z < z_d \text{ or } z_i \leq z < z_m \right. \tag{57}$$

where:

T = temperature ($^{\circ}C$)

t = time (day)

z = depth below the water surface(ft)

K_H = thermal diffusivity (ft^2/day)

w_p = the specified pumping velocity (ft/day)

z_i, z_d=the specified intake and discharge depth(ft)

z_m = the depth of the lake (ft)

$S(z)$ = the explicit thermal discharge or heat input term ($^{\circ}C$/day)

$$S_z = \frac{2w_p[T(z_i) + \Delta T_p - T_s]}{a\sqrt{\pi}} \quad e^{\frac{-(z-z_d)^2}{a^2}} \tag{58}$$

ΔT_p = temperature rise across condenser

T_s = surface temperature

w_p = pumping velocity

z = length scale

When the discharge temperature is less than the surface temperature, the effluent will remain submerged and (s(z) is zero. The pumping speed is related to q_{pp}, the heat per unit area per unit time added by the power plant by the equation:

$$w_p = q_{pp} / \rho \cdot C_p \cdot \Delta T_p \tag{59}$$

where:

ρC_p = heat capacity per cubic foot of water (112.32 BTU/$^{\circ}C$-ft^3)

ΔT_p = temperature difference produced by power plant

$$T_p = T(z_d) - T(z_i) \; (^{\circ}C) \qquad (60)$$

The thermal eddy diffusivity, K_H, has the form given by Rossy and Montgomery (15):

$$K_H = K_{Ho} \, (1 + \sigma R_i)^{-1} \qquad (61)$$

where:

$K_{Ho} = (C_1 + C_2 z) \, w^* =$ the eddy diffusivity of neutral stratification (ft^2/day)

σ = a dimensionless constant (=0.1 for preliminary study)

$$w^* = \frac{\tau s}{\rho} = B_1 + B_2 \sin\left(\frac{2\pi}{365} t + \Phi\right), \text{ friction velocity} \qquad (62)$$

The empirical relation of Munk and Anderson is suggested for determining wind speeds over lakes.

$$R_i = -\left(\frac{qz}{w^* z}\right)^{N-1} \alpha \, v^{z} \, \frac{\partial T}{\partial z}, \text{ Richardson Number} \qquad (63)$$

$\alpha_v = A_1 + A_2 \, (T-4^{\circ}) + A_3 \, (T-4)^2$, Coefficient of volumetric expansion for water

where:

N = a dimensionless constant (N=2)

τ_s = wind shear stress

$A_1, A_2, A_3, B_1, B_2, C_1, C_2$ = constants

(b) Initial condition

$$T(z, t_o) = T_o \qquad (65)$$

(c) Boundary conditions

$$\left(\frac{\partial T}{\partial z}\right) z = z_m = 0 \qquad (66)?$$

$$-\left(\rho C_p \, K_H \, \frac{\partial T}{\partial z}\right)_z = 0 = K(T_E - T_s) \qquad (67)$$

$T_E = \overline{T}_e + \delta T_e \sin\left(\frac{2\pi}{365} t + \Phi\right)$, the equilibrium temperture.

where:

T_s = temperature at water surface

t = time

Φ = phase angle

T_e = average value of equilibrium temperature over one annual cycle

δT_e = one half the annual variation

K = the heat transfer coefficient at the lake surface (BTU/ft^3-day-^oC)

An explicit finite difference scheme is used for numerical evaluation. At each time , t , step, the thermal diffusivity is evaluated from the known temperature profile and its value is restricted to the range between the input maximum and minimum thermal diffusivities. The variable time increment, t, is then determined from the maximum value of the thermal diffusivity at this step by the following equation:

$$\Delta t_{k+1} = C_t\left(\frac{\Delta z)^2}{(K_H)_{max}}\right. \qquad (69)$$

where:

C_t = a nondimensional constant, $0 < C_t < 0.5$

ΔZ = spatial mesh size

The major assumptions made in the models are shown in Table 1. The input parameters are shown in Table 2, whereas Table 3 gives the factors involved in analysis and Table-4 gives the construction features of the models. These tables were drawn by testing the three models on various American reservoirs by Parker et.al(1975).

Table 1 Assumptions

Assumptions	Cornell Model	MIT Model	Water Resources Engineering Model
Horizontal homogeity	Yes-one dimensional stratification in vertical direction only	Yes-one dimensional stratification in vertical direction only	Yes-one dimensional stratification in vertical direction only
Primary mechanism for the formation of thermocline	Nonlinear interaction between in wind induced turbulence and buoyancy gradient[2]	Differential absorption of incoming solar radiation	Differential absorption of incoming solar radiation
surface boundary conditions	one of the three is specified in a sinusoidal form[3] i) Water surface temperature T_s ii) heat flux at surface q_s iii) equilibrium temperature T_E usually T_E is specified	Meteorologic Input Water surface temperature calculated	Meteorologic Water surface temperature calculated
Bottom boundary condition(no flux)	Yes	Yes	Yes
Water budget (water losses due to evaporation and gains to rainfall)	No	No(the reservoir surface elevation is calculated as a function of initial surface level and the cumulative inflow and outflow; the input measured pool elevations has never been used)	Not directly; however the measured daily surface elevation are used a pool level for each simulation day. The water budget implies evaporation, rainfall and possible leakage

Advective heat (add or subtracted)	No	Yes	Yes

1. The reservoir can be represented by more than one segment, with thermal simulation carried downstream segment by segment, to achieve a quasi two dimensional solution from a series of one dimensional solutions.

2. The assumption that the bulk of incoming solar radiation is absorbed within a small layer near the surface is implicit in the governing equations.

3. $A + B \sin \left(\frac{2\pi}{365} t + \phi\right)$
   where A - mean value
   B - amplitude
   t - time in day, t = 0 corresponding to the time when reservoir temperature profile is isothermal
   ϕ - phase angle

Table 2 . INPUT PARAMETERS

Input Parameters	Cornell Model	MIT Model	Water Resources Engineering Model
Unit	Input data in specified units only	Input data in specified units only	can be in any units user supplies conversion factors, standard units as indicated
Short wave solar	No^{3}	Yes(net flux) kcal/m^2-day	^{1,2,4,8} yes(gross flux i.e. no reflection kcal/m^2 -sec)
Net long-wave atmosphere radiation	No	Yes^{1,2,7} kcal/m^2-day	No (calculated)
Wind speed	No^{3,10}	Yes m/sec	Yes^{8} m/sec
Air temperature	No^{3}	Yes ^{o}C	Yes^{8} ^{o}C
Cloud cover	No^{3}	Yes^{2,6} decimal	Yes^{8} decimal
Atmospheric pressure	No^{3}	No	Yes^{1,2,8} mb
Relative humidity	No^{3}	Yes decimal	Yes^{2,5,8} decimal
Wet Bulb Temperature	No	No	Yes^{,2,5,8} ^{o}C
Dew Point Temperature	No	No	Yes^{2,5,8} ^{o}C
Equilbrium Temperature	Yes^{12} (in terms of mean, value, amplitude & phase angle in a sinusoidal form)^{o}C	No	No

Evaporation	No	No(input constant for built-in formula to calculate heat loss	No(input evaporation coefficient to calculate heat loss)
Precipitation	No	No	No
Outlet elevation	Yes(depth of intake for power plant)ft	Yes m	Yes m
Inflow rate	No[9]	Yes m^3/day	Yes(daily avg.) m^3/day
Inflow temperature	No[9]	Yes °C	Yes(daily avg.) °C
Initial Reservoir	(i) Yes (isothermal)	(i) Yes(isothermal only)	(i) Yes (either isothermal or variable
(i) Temperature	°C	°C	°C
ii)Rate of temperature change	ii)(isothermal)	(ii) (isothermal)	(ii) Yes(by default use 1 x 10^{-9} c/sec)
Reservoir surface elevation	Yes (constant reservoir depth)ft	Yes(used for comparison only, the actual value is evaluated from continuity)m	Yes(daily avg) m
Reservoir Geometry (i) Length v.s. elevation (ii) Horizontal cross section area v.s. elev.	(i) No (ii) No[11]	(i) Yes m m (ii) yes m^2 m	(i) No (ii) Yes m^2 m
Fraction of solar radiation absorbed at the water surface	No	Yes (0.4 - 0.5 recommended)	No (Assume equal to 0.4 internally for the top 0.3 m layer)

Outflow rate	No[9]	Yes m^3/day	Yes(daily avg.)m^3/sec
Friction velocity	Yes(in terms of mean, amplitude and phase angle in a sinusoidal form[13])ft/sec.	No	No
Short wave radiation extinction coefficient	No	Yes 1/m	Yes in terms of extinction depth (m) coefficient=6.908/ extinction depth
Diffusion coefficient	Yes(in terms of $(C_1+C_2\ Z)\ w^*$) (upper and lower bound of the coefficient are also inputed) ft^2/day)	Yes m^2/day	Yes, empirical determined constants, A_1, A_2 and A_3 (i) $D_c = A_1$ for $E < E_c$ (ii) $D_c = A_2 E$ for $E \geq E_c$ $E = \frac{1}{\rho} \frac{\Delta \rho}{\Delta z}$ stability of the water column m^2/sec
Heat exchange coefficient	Yes Btu/ft^2-day-^oC	No	No

---

1. May be calculated internally by programm

2. May or may not have to be inputed

3. Wind speed, air temperature, vapor pressure, humidity, short wave solar radiation and cloud cover are necessary data for external calculation of the equilibrium temperature.

4. Calculated internally both with and without reflection. If data are in input, the net flux = input flux × $\frac{\text{cal.flux(with reflection)}}{\text{cal.flux(no reflection)}}$ if not in input, the next flux=cal. flux (with reflection)

5. Only one of the three parameters is used. If more than one are presented the last read in has the priority. But at least one of them should be presented in input data.

6. To be read in only when atmospheric radiation is to be calculated internally by program

7. If calculated by program cloud cover should be known

8. Meteorologic data provide at least one observation per day, constant values such as average monthly meteorologic conditions should be avoided.

9. Taking account of the power plant cooling water only and in terms of heat, q_p per unit area per unit time added by power plant.

10. Also used for friction velocity calculation externally.

11. A constant surface area is needed for calculating q_p (sec 9)

12. Either surface temperature (^{o}c) or heat flux at surface Btu/ft^2-day) can be used to replace equilibrium temperature

13. $A + B \sin \left(\frac{2\pi}{365} t + \phi\right)$

Table 3 . FACTORS INVOLVED IN ANALYSIS

Factors	Cornell Model	MIT Model	Water Resources Engineering Model
1. Diffusivity	Eddy diffusivity Eddy diffusivity $\gg$ molecular diffusivity	Molecular diffusion(constant) neglects turbulent diffusion	So called"effective diffusion" accounts for turbulent diffusion and convective mixing calculated from temperature profile $D_c = A_1$ for $E < E_c$ $D_c = A_2 E^{A_3}$ for $E > E_c$ where $E = \frac{-1}{\rho} \frac{\Delta\rho}{\Delta z}$ stability of the water column, E_c = some critical value of stability.
2. Stability mixing process	Free convection if stratification is unstable	Convective mixing if negative temperature gradient occurs $\frac{\partial T}{\partial y} < 0$ (T-temperature, y-elevation, positive upward)	Convective mixing if negative temperature gradient occurs $\frac{\partial T}{\partial y} < 0$ (T - temperature, Y - elevation, positive upward)
3. Heat transfer in coantrol volume layer)			
1. Direct absorption	1. No	1. Yes	1. Yes
2. Diffusion	2. Yes	2. Yes	2. Yes

3. Vertical advection	3. No	3. Yes	3. Yes.
4. Horizontal advection	4. No	4. Yes	4. Yes
. Heat transfer across water surface 1. short wave solar radiation 2. Net long-wave radiation 3. Evaporation 4. Conductions	In terms of heat flux $q_s = K(T_E - T_s)$ where K-heat exchange coefficient T_E -equilibrium temperature T_s-water surface temperature	1. Yes 2. Yes 3. Yes 4. Yes	1. Yes 2. Yes 3. Yes 4. Yes
5. Inflow consideration 1. enter at the level of equal temperature 2. distribution in vertical direction	1. Yes 2. No (spread instantaneously into a thin horizontal sheet)	1. Yes 2. Gaussian velocity distribution either with or without entrance mixing	1. Yes 2. Uniform velocity distribution over the interflow thickness determined by Debler's criteria
6. Withdrawal consideration 1. Level 2. distribution in vertical direction	1. single level outlet 2. No (uniformly distributed at the level of withdrawal)	1. selective withdrawal 2. withdrawal layer thickness & Gaussian velocity distribution in withdrawal layer.	1. Selective withdrawal 2. withdrawal layer thickness and uniform velocity distribution over withdrawal layer determined by Debler's criteria.

3

3. Limit on withdraw zone	3. No	3. Yes (withdrawal layer never extended over the region with temperature gradient equal or greater than cut-off gradient) of $\frac{\Delta T}{\Delta y} = 0.05$	3. Yes withdrawal zone always on top or underneath the thermocline

TABLE 4 : MODEL CONSTRUCTION

Parameters	Cornell Model	MIT Model	Water Resources Engineering Model
Mathematical scheme	Explicit finite difference scheme	Explicit finite difference scheme	Implicit finite difference schemes
stability criteria for use		$D \frac{\Delta t}{(\Delta y)^2} \leqslant 1/2$ --(1) $V \frac{\Delta t}{\Delta y} \leq 1$ ---(2)	$R_a = \frac{Q(\text{element}).\Delta t}{V(\text{element})} < .5$
Applicability criteria	deep, stratified turbid lake	stratified[2] $F_D < \frac{1}{\pi} = 0.32$	strongly stratified[2] $F_D \ll 0.1$
Time step (t)	Variable $\Delta t_{k+1} = C_t \frac{(y)^2}{(K_H)_{max}}$ $0 < C_t < .5$ K_H-diffusivity	Constant (i) Determine t max. from E_q(1) (ii) guided by time step of input data (iii) must satisfy stability criteria[3]	Constant (i) 1 hr $< \Delta t <$ 1 day (ii) guided by time step of input data
Depth interval (y)	Constant (i) maximum 100 intervals	Constant (i) 50 intervals or less is recommended (ii) min. 20 interals	Constant (i) 1 meter recommended (ii) max. number of steps is 200
Running[1] time for test case	(400 days) 13 min for y = 5 ft	(300 days) 1.4 min for Δy = 2.0 m t = 1 day 2.0 min for y = 1.0 m, Δt = 1 day	(300 days) 2.6 min. for Δy=2.0 m, Δt = 1 day 3.1 min for Δy = 1.0m Δt = a day

1. the program compiling time is not include

2. the densimetric Fronde number in defined as

$$F_o = \frac{LQ}{DV}\sqrt{\frac{\rho_o}{gB}}$$

where L - reservoir length

Q - volumetric discharge through the reservoir

D - mean reservoir depth

V - reservoir volume

ρ_o = reference density

β = average density gradient = $-d\rho/dy$

g - gravitational acceleration

3. Check by stability criteria, Equation (2), internally and the input t is subdivided if necessary in that particular time step.

5.0 CONCLUSIONS

A reservoir's or lake's thermal regime has dual significance to water quality modeler. Firstly because the temperature directly influences the rates of chemical and bio-chemical reactions and secondly it influences as a tracer of mass transport in the water column. In fact, heat balances are a primary tool for estimating mixing rates in the vertical dimension.

The thermal regime of temperate lakes or reservoirs in temperate zones is primarily the result of the interplay of two processes:

i) Heat and momentum transfer across the surface; and

(ii) The force of gravity acting on density differences within the lakes.

Depending upon the season of the year, heat transfer tends to either raise or lower the temperature at the lake's surface as a consequence of number of factors, including the magnitude of solar radiation, air temperature, relative humidity, wind speed and cloud cover, wind blowing over the open area tend to mix the surface waters and transfer heat and momentum down through the water column. The extent of mixing, is in turn, inhibited by buoyancy (and sometimes rotational) effects. These relate to the fact that the density of water varies over the range of temperatures encountered in lakes. Therefore denser waters accumulate at the lake's bottom and are overlaid with lighter waters.

A brief review of some of the available models shows that remarkable progress has been achieved in limnology by numerical modelling of circulation in lakes. The models, in principle, enable us to understand the complex casual dependencies of the atmospheric inputs and hydrodynamical thermodynamical responses of the system under the influence of a given topography and even to forecast them to a certain extent. For further research, three dimensional multi-layer models and properly parameterized two dimensional vertical models seem to be equally useful, both incorporating baroclinic forces.

In our country, at present, the main task is to use these models for actual situations. This means, in the first place, the availability of reliable field data, which are sufficiently representative to be compared with numerical results. This also includes, furthermore, the definition of a fairly objective verification strategy, which gives a quantitative measure of the quality of a model. The next step to verification of these models would be sensitivity analysis, which means what the parameter's influence is and where the possibility of verification is exhausted.

The past studies have also shown that out of the three models reviewed in the report i.e. the WRE model, MIT Model and Cornell model, the most thoroughly verified model is the MIT model. It would be very interesting and informative to use MIT model for an Indian reservoir for the temperature distribution over a period of years to determine the proper coefficients to be used in the model, which are suitable for Indian conditions.

The MIT Model has been modified by Water Resources Management Methods Staff through Tennessee Valley Authority in 1976. The modifications were made to the original formulations for surface heat transfer, inflow and withdrawal velocities, surface cooling and output data presentation. The modified computer programme has been implemented on the NIH computer system, VAX11/780 system. It is a detailed, comprehensive programme of about 3000 statements. The programme consists of one main program and a sub routines. The program has a detailed input requirement and computes the daily temperature in the reservoir, with depth. As a future work, it is proposed to use the models for Indian situations.

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