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BASIC HYDROLOGY, WATER RESOURCES AND DAF BOAT PLANT FOR LAKE RESTORATION

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BASIC HYDROLOGY, WATER RESOURCES AND DAF BOAT PLANT FOR LAKE RESTORATION

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ABSTRACT

This chapter introduces the basic hydrology, water resources and a dissolved air flotation (DAF) boat plant for lake water treatment. Specific coverage includes: special features of water and their relationship to life on earth, hydrology, evaporation, transpiration, evapotranspiration, infiltration, percolation, runoff, ground water, impact of pollution on lakes, thermal impacts on the aquatic environment, toxics in water resources, goals of water pollution control, dissolved air flotation boat plant for lake restoration, glossary, and a list of senior author's recent publications.

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NOMENCLATURE

A	=	the tributary drainage area in hectares or acres or mi^2 .
B	=	the ratio of heat loss by conduction to heat loss by evaporation
C	=	the coefficient of runoff, is equal to the ratio of runoff to precipitation for the individual area at a specific time, and usually averages about 0.3. However, if there was a recent antecedent storm that has saturated the ground, the value may approach 0.9, and it may be greater than 1 with melting ice and snow.
c	=	the weir coefficient, which varies between 2.5 and 3.5
C_e	=	a coefficient which varies, being 15 for small shallow lakes
d	=	drawdown in m (ft) in the vicinity of the pumping well in which the observation well is r m (ft) from the pumped well
e	=	the voids ratio, e , is the ratio of the pore volume to the solid volume and equals:
E	=	the evaporation, in/mo
e_a	=	the vapor pressure of the air in millibars
e_s	=	the vapor pressure of the water surface in millibars
F	=	the recurrence interval or frequency in years that a stated intensity is equaled or exceeded.
f	=	a coefficient equal to $T_m \times P_m/100$ and equal to the monthly consumptive use
H	=	the head above the spillway in m (ft)
H_v	=	the latent heat of vaporization which is assumed to be 536 cal/g
i	=	the average intensity of rainfall for the specified period of time and may be expressed as cm/h (in/h).
k	=	the monthly consumptive use coefficient, which equals 0.55 for garden vegetables, melons, and winter grain, 0.65 for grasses, brambles, leaves, peas, potatoes, tomatoes, peppers and small grain, and 0.75 for corn, alfalfa, and orchard with cover.
K	=	10
L	=	the length of flow in feet

L	=	the length (width) of the spillway in m (ft)
L_a	=	leakage and refers to groundwater flow into or out of mercury,
n	=	the number of events and m is the order of magnitude of a particular event;
O	=	the excess rainfall in in/h
p	=	the porosity, which is equal to the ratio of the pore void or interstitial space to the total volume of the rock or soil
P_a	=	the atmospheric pressure
P_m	=	the monthly percent of daytime hours of the year
P_t	=	precipitation
Q	=	the rate of runoff at a given location and time
Q	=	the discharge in m ³ /d (gal/min)
Q	=	the rate of discharge in m ³ /s (cfs)
Q_b	=	the net energy loss by long wave radiation to the atmosphere
Q_r	=	the reflected solar and sky short-wave radiation incident at
Q_s	=	the solar and sky short-wave radiation incident at the water
Q_v	=	the net energy advected to the water which is the difference
Q_θ	=	the increase in energy stored in the water
R_0	=	runoff
s	=	slope in ft/ft
S	=	storage
Sc	=	the coefficient of storage as a decimal
STEM	=	science, technology, engineering and mathematics
t	=	the duration of rainfall in minutes.
T	=	the coefficient of transmissibility in m ³ /d unit gradient (gal/day (ft/ft))
t	=	the time of pumping in days
T_a	=	the temperature of the air in °C

T_m	=	the mean monthly temperature in °F
T_s	=	the temperature of the water surface in °C
U	=	the consumptive use in inches per period (usually a month)
u	=	a tabulated value in the Theis method
V_a	=	the vapor pressure of the air or dew point temperature, in
V_s	=	the vapor pressure of the water surface in inches of
w	=	the wind velocity 30 ft above the surface in mi/h
$W(u)$	=	Theis' well function value
ρ	=	the density of the water

BASIC HYDROLOGY, WATER RESOURCES AND DAF BOAT PLANT FOR LAKE RESTORATION

1. INTRODUCTION

It has been said that pollution is mostly a resource out of place. That is, most natural things are subject to change and recycle, but when they are exposed to a new environment or are present in excessively high concentrations, they interfere with the natural system.

When *Homo sapiens* evolved, knowledge also evolved, with its application, thinking. At first there were only a few humans around, and they did not upset the balance of nature. However, by thinking they developed tools, created housing, and controlled fire. They developed agriculture, and controlled animals. They seemingly overcame nature and were able to survive longer. They learned to control diseases and to ameliorate human imperfections. But their desire was not only health, longevity, and reproduction, but also comfort. In order to provide these comforts, agriculture, mining, manufacturing, transportation, and communications were developed using chemicals that were either harmful to the environment in certain concentrations, or were persistent so that they would not deteriorate. We are now starting to realize the consequences of all human activities. Also, nearly all these activities involve water in some fashion.

Before disease transmission was understood, pollution control was most likely influenced by the presence of foul odors. This could be considered an aesthetic problem or an air pollution concern. Body wastes and other decomposing materials generally have an undesirable odor, thus creating an aversion to them. Thus decomposing matter was usually removed as far as possible from the cave or other housing. Unknowingly, this controlled the spread of many diseases.

However, humans' gregarious nature caused them to congregate into communities, leading to the large cities of today. This has resulted in human wastes where they are not desirable. Inadequate management of human

wastes has been traced to many of the great plagues of the Middle Ages. The commonly accepted first incidence of relating human wastes to disease is attributed to studies of a cholera epidemic in London in 1849 by Dr. John Snow. Through an epidemiological study he traced the incidence of cholera to a well that was contaminated by human wastes in a certain block of housing. Whether or not the story is true that he resolved the problem by removing the handle from the pump, Dr. Snow did show the relationship between human wastes and disease. These findings were independent of the development of the microscope by Pasteur in France only a few years later. This led to the removal of human wastes from homes and the modern concept of water carriage of wastes. This also resulted in gross water pollution problems downstream from the sewage discharge. Thus early pollution control efforts were related to public health.

Most frequently cities were located along bodies of water, which could be used as a source of food supply and as a source of power, and the water itself could be used for drinking, for manufacturing processes, for transportation of raw and manufactured goods, and as a recipient of the wastes from all these sources. It was found that the increased organic load exceeded the reaeration capacity of the stream or lake, creating conditions inhibitory to desirable fish and aquatic organisms. Depending upon the orientation, it could also contaminate the drinking water supply. Significant pollution control activities arose in the early 1900s with disinfection of drinking water by chlorination, coagulation and filtering of drinking water, and treatment of wastes to remove the organic load before discharge. Thus began the era of the sanitary engineer.

Although waste treatment greatly reduced disease transmission, the removal of the organic materials did not reduce the oxygen demand as expected. It was observed that inorganic nutrients, particularly nitrogen and phosphorus, were little reduced in the waste treatment process. These nutrients were available to stimulate aquatic growths, especially photosynthetic algae, which is new organic material. When these algae die, they decompose and exert an oxygen demand on the receiving body of water, not unlike the organic load that was so diligently removed by the treatment system. Although this was not a public health hazard, it did interfere with biological life in the receiving waters, including eliminating certain fish. As more and more inter-relationships between waste treatment and its impact on the receiving water were observed, we had the development of the

so-called environmental engineer.

Despite our concerted efforts to treat wastes to a degree that the effluent will have no deleterious impact on the environment, we are continually developing and finding new substances that are or can be deleterious. These include toxic and hazardous materials frequently used in manufacturing processes, persistent or refractory substances that may have been developed for this very purpose (*viz.* PCBs, various insecticides and herbicides), hormones from bioengineering processes, endocrine disruptors, and antibiotics from constant use and overuse in controlling diseases and infections. In addition to direct discharges of treated wastes, there are indirect discharges such as leaching from landfills, leakage from underground storage tanks, and condensation of volatile substances in the atmosphere during rainfall. Oxides of nitrogen and sulfur from combustion produce acid rain that may be carried great distances from their source, resulting in lakes of acidity high enough to interfere directly with aquatic life, particularly fish, or to dissolve inhibitory minerals from the surrounding rocks, with similar effects. Each problem requires its own solution. Thus it can be seen that as mankind progresses, pollution problems seem to increase.

Whereas we place greatest emphasis on the effects of pollution on humans, it must be realized that other parts of the environment, including both plants and animals, may also be impacted. Frequently, these may also indirectly impact humans. A commonly used example of this is the benefit of DDT in controlling insect borne diseases. After considerable use and study it was found that the DDT created thin shells in the eggs of birds, thereby interfering with their reproduction. Particularly, birds of prey were reduced, resulting in an increased population of rodents and other small animals with the subsequent destruction of many crops. The chain of impact is often diverse.

Although there are sources of pollution from the air and the soil, this chapter will be restricted to the study of water bodies. This is not to lessen the importance of these other sources; however, limits must be placed on the coverage in an individual chapter. This is just one part of humans learning to control their environment without destroying it.

2. SPECIAL FEATURES OF WATER AND THEIR RELATIONSHIP TO LIFE ON EARTH

Water is an unusual substance. It has many physical and chemical properties that do not follow the normally expected trends. Scientists have been able to explain them. However, this does not make them any less special. The observation of the peculiar properties of water dates back at least as far as L. J. Henderson (1), in 1912, in which he describes the properties of water that are most important. First of all was that $\frac{3}{4}$ of the earth's surface is covered by water and that, if it were not for the mountains of land, the entire earth would be covered by 4 kilometers (2.5 miles) deep of water.

Chemically, water is very stable; very few substances react directly with it, although many reactions take place within it. Perhaps its thermal properties are the most anomalous properties of water. The first of these is its specific heat or heat capacity. Water is the standard, having been assigned a value of 1.000 in the range of 0-1°C. This is a relatively high value and enables water to maintain a relatively constant temperature. It is important in the stabilization of biological and chemical reactions in the aquatic environment, and serves to moderate the earth's climate by providing a reservoir of heat in the tropical oceans and a reservoir of cold in the polar ice caps. These effects in turn help aquatic organisms maintain a constant temperature and reduce the amount of heat regulation necessary for mammals.

A second important thermal property is water's latent heat of fusion and vaporization. The latent heat of fusion, 88 cal/g, is quite high. The latent heat of vaporization, 536 cal/g, is the highest known for any substance. The latent heats represent the amount of heat that must be provided to a given weight of water to convert it from either the solid to the liquid or the liquid to the vapor state at the same temperature. This is very important in the evaporation of water and represents a large transfer of energy from the tropical oceans, where energy is available to evaporate the water, and to release this energy elsewhere on the earth in the form of condensation. The latter effect is also very important since it regulates or moderates temperatures throughout the world, preventing the tropics from becoming excessively hot and the poles extremely cold. It is similarly important in physiological heat regulation, in terms of both perspiration in animals and transpiration in plants.

The thermal conductivity of a substance represents the time rate of transfer of heat by conduction through a unit thickness across a unit area for a unit of temperature in a unit of time. The value for water of $0.0125 \text{ cal/s-cm-cm}^2\text{-}^\circ\text{C}$, is quite high compared to other liquids. Ice, however, has a higher thermal conductivity, which results in a lake's more rapid cooling once the first layer of ice has formed.

Probably the most significant thermal anomaly is thermal expansion. Because of orientation of the water molecules, the most compact configuration occurs at 4°C . Thus, the most dense water will be 4°C . This results in deep temperate climate lakes having a fairly constant temperature of 4°C on the bottom. Furthermore, ice, the solid state of water, is less dense than water and therefore floats on the surface. Water is the only substance whose solid state floats on its liquid surface. This is very important in our environment since if this were not the case ice would form at the bottom of all deep lakes and this ice would never thaw. Such a circumstance would severely restrict biological activity in the bottom of the lake and result in a buildup of layers of sediments and ice in the bottom of all lakes.

There are several non-thermal properties of water that are also peculiar to it. The first one to be considered is its solvent power. More elements and compounds dissolve in water than in any other liquid. This is very important in making nutrients available to biological life in the water, whose food must be waterborne. In addition, the materials dissolved in the water help to maintain the osmotic pressure of the aquatic organisms.

Water also has a very high ionizing power as a result of its high dielectric constant, which helps to reduce the force of attraction between atoms or molecules in the liquid. This is important in providing soluble nutrients to aquatic organisms and also affects cell permeability.

Only mercury has a higher surface tension than water. The value for distilled water is $7.5 \times 10^{-6} \text{ N/m}$ (75 dynes/cm), whereas for mercury it is $43.6 \times 10^{-6} \text{ N/m}$. This creates a tough, thin elastic film on the surface of the liquid and results in the formation of drops. It also affects capillarity, which controls the rise of liquid in the

soil. The surface film of a lake actually forms a habitat for certain organisms known as pleuston. Microscopic pleuston are called neuston. Those living on the upper surface of the interface film are called epineuston, and those on the underside are called hyponeuston. The pleuston include the water striders, the mosquito larvae, certain snails, and other organisms. Some organisms that do not live in the surface film nonetheless deposit their eggs there. Thus the surface film of water is a very special habitat to certain organisms.

The viscosity or resistance to flow of water varies with its temperature. This affects lake mixing, particularly during the summer, when the surface of the lake is warm and more readily mixed by the wind. It also affects the flotation of organisms in the euphotic zone (the area through which sunlight penetrates). This is important in maintaining balanced algal growths and in differentiating between the species that may be present at certain times of the year as a function of temperature.

Water is considered a noncompressible fluid, although precise measurements show that it is very slightly compressible. For all intents and purposes it may be considered a noncompressible fluid for either measurement purposes or for the aquatic organisms living therein.

From all these physical and chemical parameters it may be seen that water is very important in sustaining life. It is the author's belief that water is the most important factor in maintaining life on earth and that if scientists want to determine whether or not life could exist on any other planet, they must measure its presence there. In short, all life is dependent upon water and its unique properties.

3. HYDROLOGY

Hydrology is the science of the phenomena of water in all its states; its distribution and occurrence in the earth's atmosphere, on the earth's surface, and in the soil and rock strata; and the relationship of these phenomena to the life and activities of humankind. It is concerned with both the quality and the quantity of water available. Since water is essential to the preservation of life on earth, we need a good understanding of hydrology.

The amount of water present on the earth today is essentially the same as that which was present when the earth was formed. It may be in a different physical state and some minor additions may have occurred through chemical reactions and cosmic particle bombardment, but for the most part, the total quantity of water on the earth has not changed. It does, however, undergo many physical transformations from the vapor phase to the liquid and the solid phases. This is a constant and ongoing cycle, commonly called the hydrologic cycle. Figure 1, from Osborn and Harrison (2), depicts the various phases and locations of water on the earth. It may be seen that water vapor occurs in the atmosphere, condenses, and forms precipitation that falls over the face of the earth, both the land and the water. A portion of the water evaporates in falling; another amount evaporates after striking objects on earth such as trees or buildings. Another portion flows along the ground, forming streams and/or lakes, whereas still another part infiltrates the soil to become ground water. Both surface water and ground water flow toward the lowest level, ultimately reaching the ocean. Here a large amount of the evaporation occurs. Evaporation occurs from all moist ground surfaces and all open waters. In addition, transpiration occurs from all plant life. Usually in evaluating the amount of water vapor formed, evaporation and transpiration are combined as evapotranspiration since it is difficult to differentiate one from the other on the earth's surface.

Tremendous amounts of water pass through the hydrologic cycle. Some idea of this can be gained from Fig. 2 (3). Large amounts of energy are utilized in the evapotranspiration process in converting water to water vapor. Also, the amount of precipitation onto the land and the ocean is similar when one considers that approximately 75% of the earth is covered by the ocean. This does not imply, however, that the distribution of rainfall over the earth's surface is uniform. There are many localized factors that control the distribution of precipitation across the earth's surface.

The main source of energy for evapotranspiration is the sun. Small increases in evaporation may occur as a result of human activities, particularly in the use of heat for power generation. However, this total amount is small compared to the energy of the sun and is significant only in localized areas. When water evaporates, the

vapor is lighter than air; therefore, it rises and expands as the atmosphere rarifies. Expansion causes cooling, which ultimately results in condensation, releasing again the energy that was required to evaporate the water initially. Fortunately, the water vapors do not rise in the atmosphere indefinitely. About 50% of the water condenses before it reaches 1.6 km (1 mi) altitude. About 4% remains at 6 km (4 mi) and essentially none has been observed above 20 km (12 mi). Therefore, the water vapor does not escape the earth's atmosphere.

Precipitation occurs in many forms. Rain, in which droplets of liquid water fall to the earth, is the most common. Drizzle is the descent of very fine droplets of liquid water, usually with a diameter of less than 0.5 mm, which are small enough so that wind currents easily carry them both horizontally and occasionally upward. Snow is the precipitation of solid water, primarily in the form of hexagonal crystals. In North America, sleet is rain that falls through subfreezing air masses that cause the rain to freeze into ice pellets. In Britain, sleet is considered melting snow or a mixture of snow and rain. Freezing rain is caused when liquid rain falls on a subfrozen object coating it with ice. Whereas sleet occurs primarily in winter, hail is a form of frozen rain droplets that are found primarily in summer thunderstorms. In the formation of hail, the water droplets fall through a subfreezing air mass, forming small ice pellets. Depending upon the rising force of the air masses, these ice pellets may be carried upward into the warmer air mass where more condensation occurs, therefore, increasing their size. They fall again through the cold air mass, where the newly condensed water on the surface freezes forming a larger hailstone. Repeated rising, growing, falling, and freezing has been known to create hail stones as large as 5 cm (2 in). Dew forms directly from condensation on the ground, mainly during the night when the ground surface has been cooled by outgoing radiation. In some circumstances, dew can be a significant portion of the total precipitation.

All of precipitation is the result of cooling that causes the condensation of the water vapor. There are three main forms of cooling: dynamic, upward movement of air, and external cooling. Dynamic cooling is caused by the expansion of the air as it rises to a higher altitude. In general the temperature of the air above the earth's surface decreases with altitude. This change in temperature with altitude is called the lapse rate. In the first 3 to 5 km above the earth's surface it is extremely variable. In some cases it is even negative (an increase in temperature

with altitude), which is called an inversion. Generally in the range of 5 to 11 km of altitude, the decrease in temperature averages $0.7^{\circ}\text{C}/100\text{ m}$ altitude ($3^{\circ}\text{F}/1000\text{ ft}$). In the free atmosphere, where there are no other sources of heat or means of removal, the rising air cools at the dry adiabatic lapse rate. In the middle latitudes this decrease in temperature is $1^{\circ}\text{C}/100\text{ m}$ ($5.5^{\circ}\text{F}/1000\text{ ft}$). This decrease in temperature occurs until the dewpoint is reached. It must be pointed out that the dewpoint also decreases at a rate of $0.2^{\circ}\text{C}/100\text{ m}$ ($1.1^{\circ}\text{F}/1000\text{ ft}$). After the dewpoint has been reached, the wet or, as it is sometimes called, retarded adiabatic lapse rate occurs. This results in a decrease in $0.6^{\circ}\text{C}/100\text{ m}$ ($3.2^{\circ}\text{F}/1000\text{ ft}$). The difference between the wet and dry adiabatic lapse rate is caused by the latent heat of condensation, which releases energy as condensation occurs.

Under adiabatic conditions, three scenarios can occur, as shown in Fig. 3. The first scenario represents stable air in which the existing lapse rate is less than both the wet and dry adiabatic lapse rate. Therefore any rising air would be cooled more rapidly than the surrounding air and, since it would be cooler, it would not rise. Under this condition there would be no convective rising. This is depicted in the first diagram in Fig. 3. The second scenario is one of unstable air. If the existing lapse rate is greater than both the wet and dry adiabatic lapse rates, any rising air will be cooled less rapidly than the surrounding air and thus would be relatively warmer than the surrounding air and would continue to rise. This creates the unstable conditions and is shown in the middle diagram in Fig. 3. If the existing lapse rate is less than the dry adiabatic lapse rate, but greater than the wet adiabatic lapse rate, the scenario is one of conditional stability. The condition would be stable only when no moisture is condensing. However, when moisture is condensing, unstable conditions would develop and the water vapor would continue to rise. This condition is useful in artificial rainmaking, which relies upon initiating the precipitation using dry ice, silver iodide, or some other nucleating agent.

Upward movements of air that cause precipitation generally fall under three categories. The first is convective movement, which is typified by tropical rains and thunderstorms. The surface air is heated rapidly by a warm sun during the day. The water vapor rises rapidly, expanding to the point at which it then cools, condenses and precipitates. In tropical areas this is responsible for the routine daily precipitation that falls sometime in early

afternoon. Thunderstorms may occur any time of the day or night, but are most common late in the afternoon as a result of the rapid daytime warming by the sun.

The second upward movement of air is called orographic precipitation. This occurs when horizontal currents of warm air pass over large bodies of water, such as the ocean, where they pick up moisture. When they reach land, the air is forced upward by the coastal mountains where it is cooled and forms precipitation. Since the moisture is removed in the upward motion that produces this cooling, the air mass becomes warmer and hence drier as it proceeds down the other side of the mountain. Thus on the windward side of the mountain, areas of heavy rainfall occur, whereas on the leeward side deserts occur. As a typical example, in the Pacific Northwest, 190 to 300 cm/yr of precipitation occurs (75 to 125 in./yr) producing rain forests on the windward sides of the mountain ranges. On the leeward sides, only about 5% as much precipitation occurs. In some areas this is called the Chinook effect.

The third upward movement of air is caused by cyclonic motion. The air around low pressure areas flows in a counterclockwise direction. On the surface of the earth the air moves from areas of high pressure to areas of low pressure. This creates areas of differential temperature, and where such cooling occurs precipitation also occurs. The third scenario for precipitation is caused by external cooling, usually the presence of cold air masses. When cold air comes down out of the Arctic (from the Antarctic below the Equator), it comes in along the surface of the earth, forcing the warm moist air upward. This creates cooling that results in precipitation.

In addition to the variation of precipitation with location and means of formation, precipitation within a storm also varies with time. As a general rule, the longer the duration of precipitation, the less is the rate of precipitation. Figure 4 depicts the intensity duration curves for New York City. The figure also shows the recurrence interval or the number of years that a given precipitation would not be exceeded. For design parameters, the cumulative worst possible storm is also plotted. It is clearly evident from this figure that the longer the duration of precipitation, the less intense will be the storm.

In addition to the variation of precipitation with time, there is a very definite geographic variation in precipitation, particularly in considering a large area such as a drainage basin. Numerous methods have been presented to determine a representative value for precipitation over a large drainage basin area. The first method for determining a representative value would be to take the arithmetic mean of several precipitation stations within the basin. Values can be based on monthly or annual precipitation, but usually are not based on shorter periods of time. In the arithmetic method, only values from stations that are located within the stated drainage basin area are used. No results from adjacent stations are employed, even where a station may be very close to, but outside of, the drainage basin under study.

This has been corrected significantly by utilization of the Thiessen method (4) for determining precipitation over an area (Fig. 5). In this method stations located close to the basin boundary may be considered, but only a weighted average as a function of the area within the given basin that is represented by that particular station. To put it another way, if a station adjacent to the basin is so close to the basin that the perpendicular bisector of a line between a station immediately outside of the basin and its closest station inside the basin falls within the basin, then the area closer to the outside station, but within the basin is considered representative of the results of the station located outside the basin. In order to depict this, a stylized drainage basin is chosen as shown in Fig. 5. The points indicate the location of precipitation measuring stations within and adjacent to the basin. In order to determine the portion of the total area represented by each station, construction lines (shown as dotted lines in the figure) are drawn between each adjacent station. Then perpendicular bisectors of each of these dotted lines are drawn. The perpendicular bisectors are extended until they meet a similar perpendicular bisector of an adjacent line. With careful construction all lines should meet in points and it can be determined whether or not an area inside the basin is closer to a measuring station outside the basin. The perpendicular bisectors are drawn as solid lines on the figure. Then by means of a planimeter the area represented by each station may be measured. The total precipitation in the basin is then derived from the sum of all of the individual values of precipitation at the representative measuring stations multiplied by the fractions of the area of influence within the basin from that measuring station. A typical example of the calculations involved is shown in Table 1.

A third method for measuring precipitation in a large basin is the isohyetal method. Here the values of

precipitation for each station are indicated on a map showing the location of each station. Smooth lines are drawn through areas of equal precipitation, as shown in Fig. 6. Now the area between each contour line is measured with a planimeter and the average precipitation between the two lines is multiplied by the ratio of that area to the total basin area, the sum of the individual values giving the total precipitation over the drainage basin. An example of the calculation for Fig. 6 is shown in Table 2.

All of these methods have some sources of errors. However, the use of the isohyetal method can also take into account such known conditions as mountains, lakes, and so on. Thus, the method may be improved by some subjective interpretation of the data.

Of importance to the engineer is the frequency of recurrence of a storm of a given intensity or the maximum or minimum rainfall over a given period of time. This normally requires extended periods of record that frequently are not available. In lieu of extended records, information may be obtained from a similar location or a nearby location where long-term data are available. Where sufficient data are available the probability of any event occurring can be determined by plotting the individual values on probability paper. Either an arithmetic normality or a geometric normality may be plotted. This is accomplished by arranging the individual data points in ascending (or descending) order of magnitude. The probability of recurrence of any value then is the order of magnitude of that event divided by the total number of events plus 1. These values can then be plotted on a graph similar to Fig. 7. To determine the probability of any event exceeding (or being less than) a given value, one needs only to refer to the probability curve. The mean value is that which is exceeded every other year as a statistical average and this produces a mean value at the 50% occurrence. For a value that would be exceeded once in 10 yr, one would refer to the 90% level and for once every 100 yr refer to the 99 yr probability, and so on. It must be remembered that these are statistical values. Fig. 7 was plotted from 26 actually measured values. It may be seen that the upper end of the curve does not fit the data points. Furthermore, there is nothing to prevent a 100-yr occurrence from happening 2 years in a row. The information merely provides data upon which the engineer can design a facility or a structure to handle the worst anticipated problem in a given period of time. The value of the structure and the value of the potential property damage must all be taken into account.

For example, a dam should be constructed to handle the worst possible conditions, whereas a small storm drain could be designed to overflow on an average of once every 20 years if there would be no significant damage caused by such flooding. Obviously, social concerns must also be considered, not just the financial aspect.

4. EVAPORATION

Evaporation is the formation of water vapor. Strictly speaking, it is the formation of water vapor from a liquid surface; however, for the sake of this discussion, evaporation here will also include evaporation from the solid state or ice, which technically is called sublimation.

The most important factor causing evaporation is the amount of solar radiation. Indirectly, other factors affecting evaporation are also related to solar energy. The vapor pressure of the air controls the relative humidity; the lower the vapor pressure, the greater the evaporation. The temperature of both the water and the overlying air affects the vapor pressure. The higher the temperature, the greater will be the evaporation. Wind is very important in creating evaporation in that it carries away the saturated monolayer of water vapor immediately above a body of water. This brings in fresh air with a lower vapor pressure, thereby allowing increased evaporation to occur. An increase in the barometric pressure decreases evaporation. Thus, the lower pressure at greater elevations would be expected to result in increased evaporation. However, this effect is generally small and is exceeded by those from the temperature differential and the wind velocity, each of which has a greater effect upon evaporation at higher altitudes. The greater the quantity of dissolved salts in the water, the less evaporation occurs. Thus, slightly less evaporation occurs over oceans than over fresh water bodies. The difference becomes significant only in the evaporation of salt brine. The motion of water also increases the evaporation as a result of the increase in surface area created by waves, and of course by the formation of spray droplets from waterfalls. Also important is the shape of the bottom of the body of water, particularly in lakes. The greater the relative area of shallow water to deep water, the higher will be the rate of evaporation. Several means are available for determining the amount of evaporation from open water surfaces. The simplest is the use of the water budget, following the equation:

$$E = P_t - R_0 \pm S \pm L_a \quad (1)$$

in which

- E = evaporation
- P_t = precipitation
- R_0 = runoff
- S = storage
- L_a = leakage and refers to groundwater flow into or out of the given basin

The precipitation may be fairly readily measured by means of rain gages. The runoff can be determined by a flow-measuring device on the outlet stream of the body of water. Storage merely refers to the change in elevation during the period of reference. It relates to the volume of water involved in any change in elevation. Normally on an annual cycle using the water year beginning October 1, the storage is approximately 0 from year to year. The groundwater inflow or outflow is rather difficult to determine. In actuality, this equation is often used to determine the amount of leakage based upon some measured amounts of evaporation.

Evaporation (E) may also be determined by the use of an energy budget. In this case, the equation may be written as:

$$E = \frac{Q_s - Q_r - Q_b + Q_v - Q_\theta}{\rho H_v (1 + B)} \quad (2)$$

This equation gives E in cm when the energy values of Q_s , Q_r , Q_b , Q_v , and Q_θ are measured in cal/cm².

- Q_s = the solar and sky short-wave radiation incident at the water surface
- Q_r = the reflected solar and sky short-wave radiation incident at the water surface
- Q_b = the net energy loss by long wave radiation to the atmosphere
- Q_v = the net energy advected to the water which is the difference between the energy of the inflow and the outflow of the

given basin

Q_θ = the increase in energy stored in the water

ρ = the density of the water

H_v = the latent heat of vaporization which is assumed to be 536 cal/g

B = the ratio of heat loss by conduction to heat loss by evaporation

and is commonly known as the Bowen ratio. The Bowen ratio (B) may be written

as:

$$B = 0.61 \frac{T_s - T_a}{e_s - e_a} \left(\frac{P_a}{1000} \right) \quad (3)$$

in which

T_a = the temperature of the air in °C

T_s = the temperature of the water surface in °C

e_s = the vapor pressure of the water surface in millibars

e_a = the vapor pressure of the air in millibars

P_a = the atmospheric pressure

There are numerous mass transfer equations that can determine evaporation mathematically. Most of these are empirical and have been designed to fit a specific location. Typical among these is Meyer's equation:

$$E = C_e (V_s - V_a) (1 + w/K) \quad (4)$$

in which

E = the evaporation, in/mo

V_s = the vapor pressure of the water surface in inches of
mercury,

V_a = the vapor pressure of the air or dew point temperature, in
inches of mercury

w = the wind velocity 30 ft above the surface in mi/h

$$K = 10$$

C_e = a coefficient which varies, being 15 for small shallow lakes and ponds and for leaves and grass and 11 for large and deep bodies of water.

Evaporation may also be measured by means of a pan. Here the basic principle is to place water in an appropriate pan and to measure the amount of water evaporated over a given period of time. There are numerous sizes, shapes, and depths of pans. However, they come under three basic types. First is the sunken pan, which is usually placed in an indentation on the shore of the body of water whose evaporation is to be determined. By placing these in the ground there is less heat loss through the sides, and the pans may be somewhat larger; however, they have a higher cost and are not portable. The second type is the floating pan, which is placed directly in the body of water. These most nearly simulate evaporation from that water, since there are no significant heat losses in this system. However, this type presents problems particularly from splashing and wave action, which can change the volume of water inside or outside of the pan. Also, it is difficult to read the water level when the water in the pan may be sloshing back and forth, and they are difficult to maintain in place. The third type of pan is a surface pan and is the most common type used. It is portable and relatively inexpensive. The standard weather bureau class A pan is 4 ft (1.2 m) in diameter and 10 in. (25 cm) deep. It is filled to 8 in. (20 cm) and evaporated to 7 in. (17.5 cm). It is placed above the ground adjacent to the body of water whose evaporation is to be measured. Nomographs and, of course, computer programs can be used to determine the pan coefficient, which relates the evaporation in the pan to the actual evaporation in the body of water.

In addition to evaporation from a water surface, there is evaporation of moisture from soil. This is usually a function of the evaporation of recent precipitation, but where the groundwater level is close to the ground surface, capillary action may maintain moisture at the surface of the ground, where the moisture may evaporate. As a general rule, ground cover reduces the amount of evaporation from the soil surface. Compared to the evaporation from bare ground, areas covered by vegetation may result in only 0.7 to 0.8 as much evaporation,

and a dense forest may result in only 0.2 to 0.4 as much. In general, the same factors that affect evaporation from an open water surface also have similar effects upon evaporation of the soil moisture.

5. TRANSPIRATION

Transpiration is the vaporization of water from the breathing pores of leaves and other plant surfaces. This amount can be significant in forested areas and can be as much as 2 million pounds of water per acre per year (300,000 kg/ha-yr). The amount of transpiration increases significantly with an increase in temperature, and sunlight is necessary for the process to occur. It is relatively difficult to measure transpiration alone, but it can be determined experimentally in special plots, greenhouses, and so on. However, it is difficult to compare these experimental studies with actual field conditions. In general under field conditions, it is almost impossible to separate transpiration from evaporation from the soil surface.

6. EVAPOTRANSPIRATION

Since it is difficult to determine transpiration alone, and since the total amount of vaporization of water is really the important parameter, evaporation and transpiration are usually combined in a term called evapotranspiration.

Evapotranspiration may be estimated by the inflow-outflow method, which is essentially the same as the method for measuring evaporation, where the two are combined and called evapotranspiration.

Considerable attention has been paid to the total of evapotranspiration by soil scientists. Meyer (5) has designed a series of charts that show the estimated amount of evaporation as a function of the rainfall during a month and the potential transpiration over the same period of time. These charts are available for different latitudes, but are basically designed for use in the middle latitudes. From the charts for evaporation and transpiration, the total evapotranspiration for a given area may be estimated.

Another method for determining evapotranspiration is the BlaneyCriddle method (6). This method provides the

potential consumptive use: that is, the amount of evapotranspiration that would occur if sufficient precipitation were available. It can be modified to provide the actual use based on the precipitation and a balance sheet. The basic equation for this method is:

$$U = \Sigma (f \times k) \quad (5)$$

in which

U = the consumptive use in inches per period (usually a month)

f = a coefficient equal to $T_m \times P_m / 100$ and equal to the monthly consumptive use

factor

T_m = the mean monthly temperature in °F

P_m = the monthly percent of daytime hours of the year

k = the monthly consumptive use coefficient, which equals 0.55 for garden vegetables, melons, and winter grain, 0.65 for grasses, brambles, leaves, peas, potatoes, tomatoes, peppers and small grain, and 0.75 for corn, alfalfa, and orchard with cover.

Obviously with this method the operator must know the areas of each crop under production in the area being studied. The time of growth must be known and information must be available about the possibility of a second crop. This is a function of the length of the growing season for the particular area. The method gives more precise data, but obviously considerable calculation is involved in determining the areas of the various crops produced. Since U is merely the potential consumptive use, a balance sheet must be made up over a complete growing season or year, as appropriate. When precipitation exceeds potential evapotranspiration, the excess moisture may be stored. When evapotranspiration exceeds precipitation, the potential consumptive use may be fully utilized if there is sufficient storage from the previous month when there was excess precipitation. This may continue until all of the stored water has been utilized. Beyond this point, evapotranspiration cannot exceed the precipitation. The typical situation for the Northern latitudes is to have excess precipitation during the spring and insufficient precipitation in summer to allow for all of the potential consumptive evapotranspiration. One of the uses of this method is to determine when and how much additional irrigation would be needed to provide the optimum crop growth.

A more detailed method, based upon the potential evapotranspiration, for determining evapotranspiration has been developed by Thornthwaite (7). The formula involves the relationship between temperature, latitude, and potential evaporation, and the actual use also depends upon the climate, soil moisture supply, plant cover, and land management. Since this method also determines potential evapotranspiration, a balance sheet similar to the Blaney-Criddle method must be utilized in order to determine the actual evapotranspiration over a growing season.

7. INFILTRATION AND PERCOLATION

The term infiltration represents the entrance of surface water into the ground at the soil-water or soil-air interface. It is affected by topography, the surface conditions of the ground, the characteristics of the surface material, and the rate of precipitation. It is greatest with plowed fields, with vegetative cover, and on flat ground.

Percolation represents the flow of water within the soil in both the horizontal and vertical directions. There is a fine line of distinction where infiltration ends and percolation begins. Percolation is controlled by gravity and the type of soil through which the water is flowing. Percolation will continue in a downward movement until an impermeable barrier is reached. This may be a very fine material such as clay or an impermeable substance such as rock. From this point the water will flow in more of a horizontal direction, but still down slope along the top of the impermeable barrier. The velocity of flow is a function of the soil material and the amount of water being applied to force the system in a downward direction as a function of gravity. This zone of water above the first confining layer is called the free or unconfined ground water. Since at various locations on the earth there are intermittent layers of porous and nonporous materials, water may enter a lower level and in flowing downward may pass under an impermeable layer and become a confined aquifer. Confined aquifers usually flow under pressure as a function of the connection to the free groundwater surface. Thus there may be numerous aquifers as one proceeds deeper into the earth. However, as a general rule, the deeper the aquifer, the more dissolved solids are present and the poorer the quality of the water. Since the free ground water has the potential to be contaminated from the surface, the most desirable water from the standpoint of domestic use is usually that

found in the first confining aquifer. A more detailed discussion of ground water is given in a separate section on ground water.

8. RUNOFF

Precipitation which does not evapotranspire back into the atmosphere or infiltrate into the soil as groundwater runs across the surface of the earth as runoff, forming streams and lakes. These may be used as a source of water for various uses including navigation, recreation, waterpower both directly and in the generation of electricity, and many industrial uses including production of materials and cooling water. Surface waters serve as a water supply for many people particularly for large metropolitan areas. The animals in the water provide food for many people. When used for irrigation the water may be used for growing crops on land. Runoff represents the earth's freshwater resources. Once the water flows to the ocean, it becomes saline and takes on significantly different characteristics.

There are numerous factors that affect stream flow. These may be listed as follows:

1. Precipitation, particularly the amount of water equivalent, its distribution across a given watershed and the extent and duration of storms.
2. Temperature is important particularly with regard to the accumulation of ice and snow during the winter months in temperate and polar climates.
3. Topography, specifically the slope and character of the ground.
4. Geology with regard to the relative imperviousness of the soil and the bottom of a stream. This represents the difference between surface water runoff and ground water.
5. Ground surface covering, specifically the extent, character, and type of vegetation.
6. The storage of water, whether it be naturally in lakes, ponds, swamps, or marshes, or under artificial storage in dams, reservoirs or within dykes.
7. The watershed itself, particularly the size, the prevailing winds, and the orientation of the watershed in relation to storms and mountains.
8. Wind intensity which will carry precipitation into or out of a basin and which, under

unusual conditions, may even control the outflow of a river.

9. Erosion and silt, which tend to fill the stream bottom causing the channels to change and to increase flooding potential with subsequent storms.

When studying a given watershed, items 3-9 are normally considered to be constant. There can be some allowable changes in the character and type of vegetation, and artificial storage can be provided. Within limits, erosion and silt pollution can be controlled. Also in studying runoff, conditions during the nonfreezing time of the year are usually considered. However, it must be recalled that the worst potential for flooding in a stream occurs when a heavy rainfall coincides with spring snowmelt. This leaves the amount and distribution of precipitation as the most important factor to consider when evaluating storm runoff in a given drainage basin.

In evaluating storm runoff, the greatest concern is normally the peak or maximum rate of discharge. Normally, the peak discharge occurs at the time of concentration, which is the longest time for flow from the farthest point in time in any given drainage basin to reach a specific location downstream. The development of the time of concentration, t_c , is shown in Fig. 8. An idealized drainage basin is depicted with a stream flowing through it. The point of determination of flow is designated as point A. The units of time are designated as the numbers 1 through 5. This indicates that in the first unit of time all of the water falling within line B will reach point A. These lines are not necessarily arcs of a circle, but may be contoured as a function of the slope and the character of the ground. However, for convenience they are shown as relatively smooth lines on the figure. By the end of the second time period, all areas within line C will contribute flow to point A. Continuing this analogy, finally, after somewhat more than 5 time periods, any rainfall that occurs within the given drainage basin area will flow to point A during that given amount of time. The time needed for the rainfall that comes down the farthest distance from point A in the basin to reach that point A is considered t_c . As the area contributing to point A increases, the amount of runoff reaching point A increases significantly. However, it must be recalled from Fig. 5 that as the time of precipitation increases, the intensity of precipitation decreases. Thus, up until the time of concentration there are two factors that affect the rate of runoff: they are the increasing area with time, and the decreasing rate of precipitation with time. However, after t_c , the area contributing is constant and the only factor affecting runoff is the duration of precipitation, which results in a decreasing rate of precipitation within time.

Thus, a curve of runoff vs. time during a storm event is depicted in Fig. 9, which shows that the initial increase in runoff is affected by both the increasing area contributing and the decreasing intensity of precipitation up to t_c and, thereafter the decrease in runoff is caused by the decrease in intensity of the storm. As a general rule, for a given basin, the shorter the t_c , the higher will be the peak runoff rate; or conversely, anything done to increase t_c will reduce the peak flow.

The value of t_c can be determined for a small drainage area, such as that going into a storm sewer or culvert, or for a large area to determine the flow in a stream. The main difference is the time factor, whether this is in minutes or days. An empirical equation to calculate t_c has been given by Homer and Flint (8):

$$t_c = 4.68L^{0.332}O^{-0.675}s^{-0.281} \quad (6)$$

in which

L = the length of flow in feet

O = the excess rainfall in in/h

s = slope in ft/ft

For L in m and O in cm/h, the constant becomes 3.62. Excess rainfall is defined as that which produces runoff. It may be seen that this is also a function of prior wetting or the wetness of the ground surface at the beginning of the storm. The highest runoff occurs when a storm occurs shortly after a previous storm that has saturated the ground with water. Then a greater portion of the new precipitation occurs as runoff instead of infiltration.

There are numerous methods available for estimating storm runoff. The statistical method implies a Type III Pearsonian family curve. This is valid when large amounts of data are available from previous runoff data. Frequently insufficient data are available and other methods must be used to estimate the storm runoff.

The most common method for measuring runoff is the rational method using the equation:

$$Q = CiA \quad (7)$$

Q = the rate of runoff at a given location and time

C = the coefficient of runoff, is equal to the ratio of runoff to precipitation for the individual area at a specific time, and usually averages about 0.3. However, if there was a recent antecedent

storm that has saturated the ground, the value may approach 0.9, and it may be greater than 1 with melting ice and snow.

i = the average intensity of rainfall for the specified period of time and may be expressed as cm/h (in/h). It may also be calculated by the equation:

$$i = \frac{KF^x}{a + t^n}$$

in which $K = 5$ to 50 , $a = 0$ to 30 , $n = 0.5$ to 1.0 , $x = 0.1$ to 0.5 . All of the values K , a , n , and x vary with geographical location. F is the recurrence interval or frequency in years that a stated intensity is equaled or exceeded. Thus, F equals $(n + 1)/m$ where n is the number of events and m is the order of magnitude of a particular event; t is the duration of rainfall in minutes. The values expressed all present i in units of in/h.

A = the tributary drainage area in hectares or acres or mi^2 . For ready conversion factors, there are $640 \text{ ac}/\text{mi}^2$. Also, if English units of area in acres are combined with precipitation in in/h, the value of Q becomes ac-in/h and this is approximately equal to $1 \text{ ft}^3/\text{s}$ (cfs) (actual value, 1.002). If metric units of hectares are used for area, the value Q is given in ha-cm/h, which can be converted since $\text{ha-cm} = 100 \text{ m}^3$. The intensity of the rainfall can also be determined by a precipitation gage and knowing the duration of precipitation. This will provide the average intensity of rainfall during the time of precipitation.

Numerous empirical relationships based upon the rational method have been proposed as shown in Fair et al. (9) and Gray (10). As may be expected, the empirical equations apply most validly to the specific drainage basin being studied by the researchers who published their results.

The rational method is useful for mean storm runoff values over the period of time of a storm. For the maximum flow, the time of precipitation used for the equation should be the time of concentration, t_c . To determine runoff at any particular time during and after a storm occurrence, various values of time would have to be chosen and the total flow integrated over a longer period of time.

In order to avoid the multiple calculations in determining storm flow by the rational method, Sherman (11) has

devised a system called the Unit Hydrograph. The hydrograph applies only to a specific drainage basin and is derived from data pertaining to runoff over a period of one complete storm event. Based on this storm hydrograph, the anticipated flow from other storms in that same drainage basin can be estimated using four basic assumptions. These are:

1.   The effects of all physical effects of a basin are reflected in the shape of the storm runoff hydrograph. That is, all runoff in that specific basin will have the same characteristic shape of curve.
2.   For a given duration of rainfall, the duration of runoff is essentially constant and independent of the magnitude of the rainfall. This indicates that the curve is the same length for the same time of precipitation.
3.   The ratio of added runoff for a certain duration of rainfall is proportional to the total volume of storm runoff. This means that an increased magnitude of precipitation over the same duration of rainfall will increase proportionately all portions of the hydrograph curve.
4.   Precipitation extending over several durations of time, with or without interruption, creates a hydrograph that is a composite of all the hydrographs from Unit Hydrographs starting with the first duration of time of rainfall. The total runoff is a sum of the individual runoffs based upon the unit hydrograph values.

The Unit Hydrograph is the hydrograph of direct runoff from any storm that produces exactly 1.0 inch of net rain (12). The duration of rainfall varies as a function of the size of the basin; for stormwater inlets it may be in the order to 10 min, whereas in large basins it may be in the order of 1 d. Frequently a 6-h duration of precipitation is a convenient value for calculating the unit hydrograph for a river.

In the use of the concept of the Unit Hydrograph, the first process is to determine stream flow as the result of an individual storm event. When possible, the beginning time for this sequence should be long enough after a significant pre-occurring precipitation so that the stream will reach its base flow or relatively constant flow. The onset of precipitation and its total amount are recorded and correlated with the stream flow resulting from this storm. When possible, the flow data are continued until the flow returns to the initial base flow. This is depicted in Fig. 10. After the storm flow is plotted, the base flow is subtracted from the storm flow. Base flow is considered to be the value at the lowest point of the runoff curve immediately prior to the start of the increase in

flow caused by the storm. The point at which the flow returns to base flow is determined by N as in Fig. 10. For large drainage basin area N is usually measured in terms of days. The value of N may be determined by one of several means, most of which are empirical. Two of these are shown in Table 3. Using a determined value of N , which is time from the peak of the runoff until it is considered that the stream has returned to base flow, a line can be drawn representing base flow. Individual values of base flow are then subtracted from the storm hydrograph to provide the unit hydrograph as a function of the specific storm as shown in Fig. 11. There are numerous alternatives for determining base flow, but in general the use of a straight line as indicated in Fig. 10 provides results that are just as valid as any others. Fig. 11 represents a hydrograph for the duration of the storm studied. Also the figure represents the amount of runoff from the measured amount of precipitation. To convert this hydrograph to a Unit Hydrograph of 1.0 in of precipitation (or 1 cm), this may be calculated by multiplying or dividing the individual values in Fig. 11 by the ratio of 1 in to the total inches of storm precipitation. This makes the Unit Hydrograph convenient in calculating the impact of future storms. For example, using a Unit Hydrograph for 1 cm of precipitation, if the actual precipitation were 2 cm, each individual value on the Unit Hydrograph would be multiplied by a factor of 2 to determine the actual storm runoff. If the precipitation continues for longer than the unit of time for which the hydrograph has been drawn, a subsequent curve starting 1 unit of time later can be calculated and a series of curves drawn until the end of the storm. The total runoff then caused by the storm would be the sum of the individual values of each of the unit time hydrographs. It must be kept in mind that, to determine the total stream flow, the value for the base flow must be added to the total flow in the stream.

The information obtained from this method is useful in predicting storm runoff from any intensity and duration of storm. One precaution, however, must be taken when using the unit hydrograph for determining peak flow. This is that the values obtained in the initial storm hydrograph may represent different conditions of groundwater moisture content at the start of the storm. This directly affects the ratio of the precipitation to the runoff. If the ratio of the total precipitation to the runoff is determined for the initial storm hydrograph, proportionate calculations can be made for any other ratio of precipitation to runoff.

The amount of flow and the rate of flow are important in the design of flood control facilities and for the design of dam spillways. The maximum height of a flood or the adequacy of a spillway design can be determined by a method called flood routing, per Creager et al. (13) and Pickels (14). Basically this compares the amount of inflow to a reservoir during any short period of time with the rate of outflow through any control systems such as culverts, penstocks, or the spillway. When the inflow exceeds the outflow, the reservoir elevation will rise. As the reservoir elevation rises, the rate of discharge through the control systems also increases. Thus, by plotting the incremental increases in water level vs. the rate of discharge through the outlet devices, the maximum flood level and the duration and amount of runoff downstream can be calculated. This sequence can be determined utilizing a computer program or by a graphical method, as shown here.

The first step in flood routing is to determine the initial reservoir stage at the start of the design flood. As a general rule, if the volume of the flood runoff is high compared to the storage capacity of the reservoir, it is assumed that the reservoir would be full at the beginning of the design flood. However, if the capacity of the reservoir is large compared to the volume of flood runoff, then the initial reservoir elevation would be that expected at the beginning of the design flood or the elevation obtained by a flood having an average frequency of once every 25 yr. The rate and volume of inflow into the system may be determined utilizing the unit hydrograph and projecting to the worst conceivable storm. The worst conceivable storm can be estimated if sufficient long-term data are available for the watershed in question. The other information needed concerns the nature of the discharge system. This may consist of any combination of regulating outlets, penstocks, consumer demand, and so on. In a small dam, the discharge may be considered through a culvert. To determine the rate of flow through a culvert the equation used is:

$$Q = KA \sqrt{2gh} \quad (8)$$

in which

Q	= the discharge in m ³ /s (cfs)
K	= the coefficient of discharge
g	= gravity, 9.81 m/s ² (32.2 ft/s ²)
h	= the effective head on the center of the orifice in m (ft)

K may be calculated as

$$1/(1 + 2 gL/C_c^2 R_h)$$

in which

C_c = the Chezy coefficient

L = the length of the conduit in m (ft)

R_h = the hydraulic radius which $= A/w_p$ = the area (A) divided by the wetted perimeter (w_p). Once the pipe is full, the value of R_h = pipe diameter/4.

For discharge over a spillway, a sharp crested weir with no approach velocity may be assumed. Here

$$Q = cLH^{3/2} \quad (9)$$

in which

Q = the rate of discharge in m³/s (cfs)

c = the weir coefficient, which varies between 2.5 and 3.5

H = the head above the spillway in m (ft)

L = the length (width) of the spillway in m (ft)

The next information needed to evaluate the flood routing is the volume of storage in the reservoir at any elevation. This may be determined by measuring the area under water at a series of different elevations. The volume then becomes the sum of the calculations of the mean area times the difference in elevation between any two area measurements. The calculations for the storage are shown in Fig. 12. The upper portion of the figure indicates the method for calculating the volume at a given elevation, and this may be applied to the total storage available at any given elevation, as shown in the lower diagram. In this figure, English units of area and volume are indicated because of the simplified relationship between ac-ft and cfs. Obviously, metric units may be used with the appropriate conversion factors. For convenience, the discharge through the control devices may be plotted on the same curve as the storage vs. elevation, with the scale of the discharge in cfs double the scale for storage in ac-ft, as shown in Fig. 13. The reason for this correlation of scales is that 1 cfs is approximately equal to 2 ac-ft/d. However, in working with mean rate of discharge it is desirable to work with half of the mean rate

of discharge at the beginning of the time period, and half of the mean rate of discharge at the end of the time period. That this is equivalent to the mean rate of discharge is shown by the comparison:

$$\frac{Q_1}{2} + \frac{Q_2}{2} = \frac{Q_1 + Q_2}{2} = Q_M \text{ or } \bar{Q} \quad (10)$$

which represents the mean rate of discharge over a given time period. Also, one normally works with only a 12-h period, which is one-half of a day. Thus to determine half of the outflow rate at a particular time with an inflow of 12 h (1/2 d) the calculation would be:

$$\frac{cfs}{2} \times 2 \frac{ac - ft}{d - cfs} \times \frac{12h}{24h/d} = \frac{ac - ft}{2}$$

Thus by setting the scale of discharge (in cfs) in Fig. 12 to 1/2 that of the ac-ft, we have effectively correlated the ac-ft half day and half of the mean discharge over that time period. For a 6-h interval of inflow, which is used over the peak period, we would have to divide the cfs by another factor of 2.

Next, on a curve such as Fig. 13 are plotted the values of the storage plus and minus half of the outflow over a 12-h period and plus and minus half of the storage over a 6-h period (Fig. 14). The storage minus half the outflow in a 12-h period is designated as

$$S - \frac{Q_{12}}{2}$$

or B_{12} indicating the beginning curve for a 12-h period, and the plot

$$S + \frac{Q_{12}}{2}$$

is indicated by the E_{12} curve or the ending line for a 12-h period. The similar lines for a 6-h period are indicated as the B_6 and the E_6 curves. Since the discharge curve in its upper scale is equal to half of the discharge in a 12-h period at any elevation, a compass can be used to draw the B_{12} and E_{12} curves. The value of the spillway discharge Q is, respectively, added to and subtracted from the storage curve in ac-ft. The B_6 and E_6 curves then are the midpoints between the respective B_{12} curve and the storage curve and the E_{12} curve and the storage curve. These lines are indicated in Fig. 14.

The next step is to choose the inflow hydrograph and determine the values of inflow during a 12- or 6-h period. An example of computation for this is shown in Table 4. The first column indicates the corresponding lines that have been drawn in Fig. 14. The first few influent calculations are not indicated as lines because the lines would be too short and would not show in the figure. The values for the first five columns are the values to be used to enter the Fig. 14. It may be seen that 12-h intervals may be chosen for the noncritical portion of the curve; however, a 6-h interval should be chosen over the peak of the curve. This time interval may vary for different drainage basin sizes. The values for column 3 are the instantaneous rates of inflow in cfs determined from the storm hydrograph; and the values for column 4 are merely the mean rate over the time period. Column 5 simply converts these values of cfs to ac-ft during the time interval. As may be seen during the 12-h time interval, these are exactly the same values as for cfs, and for the 6-h period are half these values. Then, choosing the predetermined elevation of the reservoir at the start of the flood (for this example, the reservoir was considered to be empty), the amount of runoff from column 5 is added to the appropriate B (B_{12}) line in Fig. 14. For example, line AB occurring 48 h after the beginning of the flood represents an inflow of 112,700 ac-ft and it is added to the B_{12} line at an elevation of 433.6 ft, which is the elevation at the end of the previous time period. The length of line AB represents the 112,700 ac-ft inflow. Since this line extends beyond the E_{12} or ending curve for a 12-h period, line BC must be drawn in an upward direction in order to meet the E_{12} curve. This establishes a new reservoir elevation at the end of the time period and a new discharge rate that is equivalent to the Q value from the Q curve at the new elevation. From this point, a 6-h time interval was used and line DE therefore is drawn as the volume of flow of 98,600 ac-ft beginning with the B_6 curve and extending to the right. Again, this line extends beyond the E_6 curve, and therefore must be extended as line EF upward to the E_6 curve. In all instances, when working with a 12-h influent one must begin and end with a 12-h curve and correspondingly when working with a 6-h influent one must begin and end with a 6-hr curve. This system is continued until the point where a line designating the influent does not extend beyond the ending curve, then a downward line would have to be drawn to the corresponding ending curve, indicating a drop in elevation of the reservoir and a decrease in the discharge rate. It may be seen from the values of Table 4, column 6, that the maximum reservoir elevation reached was 451.8 ft. at which time the spillway discharge equaled the volume of inflow.

The final results of the calculations in Table 4 are shown in Fig. 15, which plots the inflow vs. the outflow and also shows the stage or elevation at the corresponding time periods. Note that the units for stage are in feet of elevation, whereas the inflow and outflow units are given in terms of flow. It may be seen that the peak of the stage occurs at the point where the inflow and outflow curves cross. Also the peak flow has been reduced by this reservoir. Increasing the time of concentration and reducing the peak flow both combine to reduce the possible flood damage downstream. The calculation will also indicate the maximum stage, and if this exceeds a predetermined elevation it will enable the design engineer to adjust the size of the spillway discharge to decrease the maximum stage. Conversely, the maximum stage can determine the limit of flooding and provide information on restrictions on building in the flood plain.

It should be noted that this type of calculation lends itself to a computer solution, since the rate of outflow at any elevation can be entered and the rate of inflow can be applied. The storage capacity would also have to be entered into the program. Once the storage vs. elevation and the rate of discharge are determined for any particular system, the impact of any potential storm can be readily determined.

In some instances, not the maximum flood, but the maximum dependable supply is desired. This is essential where a dependable supply is required for any purpose such as drinking water supply, navigation, or hydropower. For this purpose a dam may frequently be constructed to create a reservoir for storage of water for periods when the flow is less than normal. The parameters in question include the stream flow, the demand flow, and the storage that can be provided. At any point in time, the demand flow cannot exceed stream flow plus the storage capacity. Storage capacity must be provided prior to the demand's exceeding the stream flow. The limit of demand approaches the mean stream flow over an extended period of time.

The relationship between runoff, demand, and storage may be shown in a mass diagram using the Rippl method (15). In this system, a long-term cumulative plot of runoff vs. time is first made. It is desirable to keep the time integral for runoff to a maximum of a month, because if annual plots were made, a severe drought occurring during 11 months of a year could be missed if all of the annual precipitation occurred during 1 month. From the plot of the long-term data, the period of the most severe drought can be extracted and plotted on an expanded

scale. A typical mass diagram of flow vs. time is shown in Fig. 16. Using this figure, several factors can be determined. If a desired draft is known, the rate of this draft can be plotted on the same scale as the mass diagram. In order to determine the practicality of this rate, a line parallel to the draft is drawn on the mass diagram tangent to the point at which the maximum drought begins. This line is shown as line D on Fig. 16. If this line intersects the mass diagram of the stream flow later in time, then this demand can be satisfied providing that a reservoir is constructed that represents the maximum difference between the stream flow and the desired draft. This is represented as the line S_D in Fig. 16. In order to determine the maximum draft that can be exerted on this stream during this drought, a line tangent to the start of the drought and tangent at the end of the drought could be drawn. This is designated as line M on Fig. 16, representing the maximum draft when the assumption is made that there are no physical limits on the size of the dam or the reservoir. In this case, the maximum storage to be provided is the maximum difference between this draft and the runoff and is depicted as S_M . Any demand that exceeds this rate could not be supplied because it would be impossible to build a storage reservoir large enough to provide this water. Obviously, the maximum draft may also be limited by the maximum size of the dam and/or the storage reservoir. If this is the controlling factor, then the potential available storage should be drawn on the figure and a line tangent at the start of the drought and touching the top of the maximum storage capacity should be drawn. Thus, this simple diagram can be used to determine the maximum allowable draft and the maximum size of the reservoir needed to provide this draft. One other useful bit of information can be derived from this figure. If a line is drawn parallel to the chosen draft, but tangent at the lowest point of the drought and extended backward in time until it again meets the runoff curve, this will indicate the time at which the reservoir would have had to have been built in order for it to have filled prior to the onset of the design drought. Thus it may be seen that this figure represents a simplified balance between stream runoff as it varies, the amount of withdrawal from the stream, and the storage that must be provided prior to the withdrawal exceeding the stream flow. It must be pointed out that the demand curve does not have to be a constant value; however, at no time can the total demand exceed the sum of the inflow and the storage available.

9. GROUND WATER

Ground water represents a significant source of water supply. In the order of 30 billion gal/d (110 million m³/d)

of ground water is used in the United States. It is the prime source of water for drinking in rural areas. Many medium size cities and numerous industries use ground water as their source of supply for drinking, processing, and cooling. One principle advantage of ground water is its relatively cool and constant temperature. Furthermore, the soil acts as a filter, removing particulates including bacteria. Thus, under most circumstances ground water is not subject to contamination as is surface water. Potential sources of contamination include industrial discharges, landfills, and chemical dump sites. These are discussed in more detail in a later section.

Ground water results from the infiltration of precipitation into the soil. The water will proceed downward vertically until it reaches the first confining layer. Above this layer there is a saturated layer of soil containing the ground water. The upper edge of this saturated area is called the groundwater table. This will vary with the amount of precipitation and the time since the last precipitation. There is flow in this saturated area in a downhill gradient. At some point the water in the saturated zone may flow under a confining zone. This now produces a confined aquifer. An aquifer is defined as a geologic formation that contains water and transmits it from one point to another in quantities sufficient to permit economic development. This usually defines a sand or gravel soil. An aquiclude is a formation that contains water, but cannot transmit it rapidly enough to furnish a significant supply. This is usually represented by clay, which holds much moisture but does not transmit it. An aquifuge is a formation such as rock that neither holds nor transmits water. There may be many intermittent levels of aquifers, aquicludes, and aquifuges through the soil. Water may occur at any depth and there are few locations where there is no water whatsoever beneath the soil surface. However, in general, as the depth increases, the total dissolved salts increase, with saline water being found at great depths. Thus, the useable quality of the water decreases with depth.

The volume of water in a saturated formation is a function of the pore space of the soil. The porosity, p , is equal to the ratio of the pore void or interstitial space to the total volume of the rock or soil as:

$$\rho = \frac{\text{void volume}}{\text{total volume}} \quad (11)$$

Concurrently, the voids ratio, e , is the ratio of the pore volume to the solid volume and equals:

$$e = \frac{\rho}{1 - \rho} \quad (12)$$

The safe yield of an aquifer is the rate at which water can be withdrawn from it without depleting the supply to such an extent that further withdrawal at this rate is no longer economically feasible. The safe yield thus is a function of the velocity of flow through the aquifer and the source of recharge of the aquifer. The velocity of flow through an aquifer is a function of the permeability of the soil. According to Darcy's Law $V = ks$, in which s is the slope of the hydraulic grade line in vertical units divided by horizontal units (m/m, or ft/ft), and k is a constant as a function of the type of soil. Some relationships between soils and various parameters are shown in Fig. 17 and Table 5. The quantity of flow through the soil, Q , is a function of $Q = Ps$, in which Q is the flow per unit area and P is the permeability. Standard English units for permeability have been gal/ft²-d at a slope of 1 ft/ft at 60°F; the equivalent metric units would be m³/m²-d at a slope of 1/1 at 15°C. To handle large areas, a standard field coefficient of permeability is sometimes used in which the slope is extended to 1 ft/mi. In metric units this translates to 1 m/km. It must be noted that the permeability P is through a unit area of cross-section. To determine the coefficient of transmissibility, $T = Pt_a$, in which t_a is the thickness of the aquifer. T then has units of volume/day/unit of area of the aquifer for its entire depth. This is useful information in terms of determining the amount of water available.

It is useful to know the direction of flow of groundwater and the slope. This can be determined by the use of three or more observation wells. The water level of each well is measured relative to some reference elevation. Frequently, mean sea level is used, but this is not necessary. The three (or more) observation wells are plotted in plan to scale (see Fig. 18). Choosing three adjacent wells, a line is drawn between the well with the highest water level elevation and the well with the lowest water level elevation. This line is then subdivided into equal increments assuming that for the relatively short distance between these two points the slope is constant. This line will then represent equal increments of slope such as meters or feet. A line is then drawn connecting the intermediate level well to its equivalent elevation on the line drawn between the highest and the lowest water levels. This is then considered a line of equal elevation. Any line perpendicular to this line will indicate the direction of flow from the highest to lowest elevation. Further if this perpendicular line is extended on the

diagram to the location of the well with the highest water level, the distance from the well to this line can be determined. Knowing the change in elevation and the distance, the slope can be determined as the change in elevation with distance. In large areas where more than three wells are located, similar sets of wells are studied and the direction and slope may be determined for each area. In some instances both the slope and direction of the flow may change in a relatively small distance.

It is also useful to know the time of flow so that the velocity between any two points may be established. This can be most readily accomplished by means of various tracers, but the dye Rhodamine WT has been found to be very useful for monitoring groundwater flow (Aulenbach and Clesceri, 1966). The dye or other tracer is placed in the well with the highest water level elevation. Samples are then obtained continuously or periodically (usually daily) until the dye appears in the next downstream well. Depending upon the means and location of the injection of the dye, either the first appearance or the peak concentration of the dye in the observation well is used. Knowing the time until the tracer is observed in the observation well and the actual distance within the soil, the velocity may be determined as the distance divided by time. It may be seen that the slope of the groundwater table is especially essential in this case since the flow in a nonhorizontal direction will increase the distance from one point to another.

Since wells are utilized to obtain water from the ground, it is necessary to determine how much water can be obtained from the soil without exceeding the safe yield. Separate calculations must be made for wells in an unconfined aquifer and those in a confined aquifer. Those in an unconfined aquifer are frequently referred to as gravity or nonpressure wells, whereas those in a confined aquifer are referred to as pressure wells. If water is removed from a well at a constant rate until the conditions within the soil reach equilibrium, measurements can be made to determine the permeability of the soil under a set of operating conditions. Knowing the permeability, the maximum safe yield can be determined. For both nonpressure and pressure wells, at least one observation well is needed within the zone of influence of the pumped well. If measurements of water level can be made in the pumped well, this can serve as the second observation well. If it is not possible to determine the water level in the pumped well, then a second observation well is needed for the determination.

For the nonpressure well in the surface aquifer, the relationship between the flow and the permeability may be determined by the equation:

$$Q = \frac{\pi K_p (h_1^2 - h_w^2)}{\ln \frac{r_1}{r_w}} \quad (13)$$

The terms of h_1 , h_w , r_1 , and r_w for the equation are shown in Fig. 19, in which one observation well and the pumped well are used. K_p is a coefficient. If two observation wells are used (see Fig. 20), then h_1 and r_1 become the observation well farther from the pumped well, and h_2 and r_2 for the second observation well closer to the pumped well may be substituted for h_w and r_w , respectively.

For pressure wells in a confined aquifer, the equivalent equation is:

$$Q = \frac{2\pi K_p t (h_1 - h_w)}{\ln \frac{r_1}{r_w}} \quad (14)$$

The representative parameters for this equation are shown in Fig. 20. It may be seen that, in working with a pressure (artesian) well, the water level in the observation well will rise above the confining layer. This water level represents the piezometric surface or the elevation or pressure head to which the water will rise with no confinement. In this case, however, there is no actual cone of depression surrounding the pumped well in the confined aquifer. There is only a reduction in the piezometric head in the neighborhood of the pumped well.

The previous two equations assume that the zone of influence is circular. Under actual conditions this may not be true, since there is some horizontal flow in the aquifer and, therefore, the cone of depression will be lower on the downstream side of the pumped well. Also, under certain conditions, it may take a long time (up to 10 yr) to establish equilibrium. Thus, other methods for determining the yield of an aquifer are necessary.

One common method is the Theis method (17). This considers the fact that an aquifer is somewhat elastic, so that removing water from it causes a lower pressure in the area of the pumped well that causes more water to enter into the area. The Theis method is based upon four assumptions: (a) the soil of the aquifer is homogeneous, (b) the coefficient of transmissibility, T , is constant, (c) the coefficient of storage, S_c , is constant,

representing the yield of water per unit area of aquifer per unit drop in hydraulic gradient, and (d) the water is released from the aquifer instantaneously. Actually under normal conditions there is a lag in the release of the water from the aquifer. The Theis method makes use of the well function $W(u)$.

$$W(u) = \int_u^{\infty} \frac{e^{-u}}{u} du \quad (15)$$

For metric units

$$d = \frac{QW(u)}{4\pi T} \quad (15a)$$

$$u = \frac{r^2 S_c}{4Tt} \quad (15b)$$

in which Q is in m^3/d .

For English units

$$d = \frac{114.6QW(u)}{T} \quad (15c)$$

$$u = \frac{1.87r^2 S_c}{Tt} \quad (15d)$$

In these equations

- $W(u)$ = Theis' well function value
- d = drawdown in m (ft) in the vicinity of the pumping well in
which the observation well is r m (ft) from the pumped well
- Q = the discharge in m^3/d (gal/min)
- T = the coefficient of transmissibility in m^3/d unit gradient (gal/
day (ft/ft))
- S_c = the coefficient of storage as a decimal
- t = the time of pumping in days

u = a tabulated value in the Theis method

In English units of measurement, the constants convert directly from time of pumping in days to discharge in units of minutes. Theis has prepared a table of values for u and $W(u)$; however, it is much easier to plot these values on a log-log scale, as shown in Fig. 21. This diagram is for English units of measurement and the time t must be in terms of days. To solve this system, a well is pumped at a constant rate and the level of water in an observation well is determined on a daily basis. On log-log paper with the same scale as the type curve (Fig. 21) values of d in ft and r^2/t in ft²/d are plotted. Then, overlaying this plot on the type curve and keeping the ordinates parallel, the one curve is moved over the other until they coincide or produce a curve of best match. Note that the two lines in the type curve (Fig. 21) are really one continuous line merely divided into two different ranges. With the two curves coinciding, any point on the two curves may be chosen and the values for u , $W(u)$, d , and r^2/t can be determined. Using these values, the transmissibility T can be determined as:

$$T = \frac{QW(u)}{4d} \quad (16)$$

and

$$S_c = \frac{4T + u}{r^2} \quad (17)$$

For English units

$$T = 114.6 \frac{QW(u)}{d} \quad (16a)$$

and

$$S_c = \frac{uT}{1.87(r^2/t)} \quad (17a)$$

Jacob modified the Theis method to simplify it. His calculations are

$$T = \frac{264Q \log(t_2 / t_1)}{d_2 - d_1} \quad (18)$$

and

$$S_c = \frac{0.37t_0}{r^2} \quad (19)$$

In Jacob's equations (Fig. 22),

d = the drawdown, ft, in the observation well at time t , in days, from the start of pumping

Q = in gal/min

Values of the $\log t$ are plotted vs. the drawdown, d . This may be done by plotting t on the log scale of semi-log paper. To simplify the calculation, corresponding values of d over one log cycle of t may be taken, as shown in Fig. 22. This simplifies the calculations because t_2/t_1 will always be 10 and the log of 10 = 1. To determine the transmissibility, T , the values of the drawdown at the two times then may be substituted into the equation and T determined. For the calculation of the storage, t_0 must be determined. This is determined by extending a curve of best fit of a straight line intersecting the origin of the drawdown line. This gives a projected value of t at $d = 0$. The equation then may be used for determining the storage of water in the aquifer.

The International Ground Water Modeling Center at Colorado School of Mines, 1500 Illinois Street, Golden, CO 80401, USA; www.mines.edu/Research/Centers/igwmc, has an annotated database of groundwater models from all over the world.

10. IMPACT OF POLLUTION ON LAKES

It has frequently been stated that all lakes are born to die. This implies that over an extended period of time lakes will slowly fill in from erosion, and increase in nutrient content to support ever greater biological life, which will also die and settle to the bottom, increasing the rate of sedimentation and filling in of the bottom. As the lake becomes shallower, rooted aquatic plants can grow in the nutrient-rich sediment, thereby increasing the

production of organic matter and increasing the rate of sedimentation by both the dying plant life and increasing the sedimentation of erosion by slowing the velocity of the flow of water in the area where the rooted aquatic plants occur. Ultimately the lake will fill in and may become a bog in which very little water is found, but high productivity occurs. Ultimately the large rooted terrestrial plants take over in the moist soil and a high-moor or climax bog is produced as the climax of the lake. Whereas all lakes may eventually reach this termination naturally, the rate at which this process proceeds is often influenced by humans, whose activities frequently result in increasing the erosion process that speeds the filling of the lake with sediment. Also, the discharge of sewage effluent and runoff from fertilized land may add to the nutrients in the lake, thereby increasing the rate of biological growth. This also adds to the increasing rate of sedimentation. Whereas little can be done to control the natural cycle of a lake, much can be done to prevent the increased rate of eutrophication that occurs from anthropogenic sources.

In terms of the natural rate of eutrophication in lakes, the morphology of the lake frequently has the greatest controlling influence. The morphology may even limit or restrict the impact of human activities until the morphology has been changed. As a general rule, a deep lake with steep sloping sides will have a much slower rate of eutrophication from all causes than a lake of similar volume that is shallow and has large shallow shoreline areas. Also the larger the total volume of the lake, the slower will be the rate of eutrophication.

Lakes in a temperate climate normally go through a stratification pattern that results in dimictic conditions (equal mixing throughout the lake twice a year). This is primarily caused by the anomalous temperature-density relation of water. It may be recalled that the most dense phase of water is 4°C; thus, water at this temperature will tend to settle on the bottom of the lake, assuming that the external air temperature reaches 4°C or lower sometime during the year. During the winter, ice will form on the surface of the lake, with the temperature of the water immediately below the ice at or near 0°C. However, with a deep lake the temperature at the bottom approaches 4°C. As spring comes and the sun warms the water, the ice melts and then begins to warm the surface of the lake. When all of the lake is warmed to 4°C even a gentle wind will circulate the water from top to bottom of the lake creating the spring overturn. As spring continues and the sun warms the

surface of the lake, the warmer surface waters will tend to float on the colder lower temperature water. If this heating occurs during a period of strong wind there may still be complete mixing of the lake and the entire lake is warmed to the temperature of the surface. However, if warming occurs on a calm day, the surface of the lake will become significantly warmer than the lower level. With several days of warming and little wind, a point is reached at which the wind does not have sufficient energy to mix the upper warmer layers of lower density and lower viscosity water with the colder lower levels of higher density and greater viscosity water. Thus a period of stratification begins. Frequently, in large temperate lakes the level of stratification is established near 10 m depth. In addition to the combination of warming and wind during the establishment of stratification, the shape and orientation of the lake with the wind have a great influence on the depth of the upper mixed zone. During the summer, there is an upper layer that is equally mixed by the wind, then a zone of rapidly decreasing temperature with depth, and then a third layer at the bottom with relatively constant and cold temperatures. The upper layer is called the epilimnion, the zone of great temperature vs. depth change is called the thermocline or metalimnion, and the lower layer is called the hypolimnion.

Once this summer stratification is established, there is little to no mixing in the hypolimnion. This also restricts the reaeration of the hypolimnion from the surface. Thus if large amounts of organic material reach the hypolimnion, the oxygen available will be utilized and the area will become anaerobic. If on the other hand there is little productivity in the lake, or if the lake is so clear that photosynthesis can occur in the hypolimnion, then there will not be oxygen depletion in the hypolimnion and this area will support a fine crop of cold-water fish. Also keeping the hypolimnion aerobic helps to stabilize the nutrients that settle to the bottom and are normally precipitated under aerobic conditions. It can be seen that this is a critical condition, for once the hypolimnion becomes anaerobic the nutrients that are soluble under anaerobic conditions are released to the water column, allowing for the growth of more biological materials that will in turn die, settle to the bottom, and utilize more dissolved oxygen. Thus, in order to maintain the lake in an oligotrophic condition, management efforts should be made to maintain the hypolimnion in an aerobic state.

As fall approaches, the surface of the water is cooled and the cooler water circulates to a depth of equal

temperature and/or density. This tends to lower the thermocline until the lake again becomes uniform in temperature and even a gentle wind will mix the lake from top to bottom. This is called the period of fall turnover. As the air temperature reaches 4°C and becomes colder, the surface of the lake will approach 0°C, but the warmer 4°C water will remain on the bottom. After ice is formed, there is no wind effect on the lake to cause mixing. Thus the bottom of a deep lake never freezes. However, again during ice cover there is no opportunity for reaeration of the lake from the surface, and thus the biological activity in the water must be such that it does not utilize the available oxygen in the lake. Because of the cold temperature, this is usually fairly easy to maintain; however, in certain eutrophic lakes, oxygen depletion may occur under the ice. This period of stratification under the ice is called the winter stratification period. In evaluating a lake it may be seen that it is essential to evaluate it under all conditions of stratification and nonstratification.

A lake contains many biological communities. Within the water column are numerous organisms of microscopic size. These are generally termed plankton, which are microscopic floating organisms. The plankton may be subdivided into two general groups: the phytoplankton are the plant life and include the algae, the fungi, and the pollen that fall into a lake, and the zooplankton, which represent the animal forms. In another category, the plankton may be broken down into the nekton or free swimming organisms, and the benthon, which are the microscopic organisms that exist on the bottom.

A prime concern is the algae, the microscopic green plants floating in the water column. These organisms represent the base of the food chain in that they can convert simple inorganic materials into organic materials with the aid of sunlight. In addition, during the daytime or sunlight hours these plants undergo photosynthesis, which is a process in which oxygen is liberated in the water. It has been estimated that $\frac{3}{4}$ of the world's supply of oxygen is generated by algae in the ocean. In terms of the food chain, the algae are normally consumed by the zooplankton, which are in turn consumed by larger animal forms, which may be consumed by small fish, which may be consumed by large fish, which may be consumed by larger vertebrates, including humans. But it is the small algae that are the base of this food chain.

All biological systems require the presence of the proper balance of nutrients in order to grow and reproduce. For the larger organisms, the smaller organisms provide these nutrients. However, the algae, as the base of the food chain, must gain their nutrients in the inorganic form from the surrounding water. Organisms that rely on inorganic matter for growth are termed autotrophic, whereas those that require organic matter as a source of food are called heterotrophic. Growth is a function of the nutrients available (plus other limiting factors, such as temperature, light, and so on), but these nutrients may vary both with location and time within a lake. Specific organisms may vary in their specific nutrient requirements; however, in general these organisms have a certain demand for the essential elements. Carbon may be obtained from the solution of carbon dioxide. Hydrogen may be formed by hydrolysis of water, or from bicarbonates dissolved in the water. Oxygen may be produced in photosynthesis or may be secured from dissolved atmospheric oxygen. Nitrogen is secured from dissolved nitrogenous materials including both ammonia and nitrates. Phosphorus is usually derived from soil and animal excreta. Sulfur is usually derived from the soil, but is also present in animal excreta. The needed ratio of each individual material varies, but there is a general demand for approximately 60 parts of carbon to 15 parts of nitrogen to 1 part of phosphorus in most cellular material. In addition to these stated growth factors, there may be many other trace elements that are required in order to support adequate growth. Most frequently, the requirements for these elements are so low that there is an adequate amount available. Certain specific organisms may have special requirements. A typical example of this is the diatoms, which require the presence of silicon in order to manufacture their cell case, called a frustule.

Normally organisms such as algae will grow until one of the nutrients becomes limiting. Then growth may be retarded or eliminated entirely. The limits are in the ratio of the requirements; therefore, the limit is different for each element. This is referred to as Liebig's Law of the Minimum, which states that biological systems will grow until they are limited by the nutrient that is present in the limiting concentration. In lakes the most common limiting nutrients are nitrogen and phosphorus; however, in a few instances carbon has also been shown to be limiting. Most frequently, phosphorus is the limiting constituent; however, this is not exclusively so and there are many lakes in which nitrogen is the limiting factor.

Productivity is a measure of the utilization of inorganic material to produce plant growth. Very frequently, productivity in lakes is measured by the amount of fish available in the lake. Since the number of fish is indirectly related to the growth of the other organisms lower in the food chain and, ultimately to the amount of algal growth, it may be seen that the productivity of fish is merely an indirect measure of the amount of algae growth in the first place. Whether or not productivity is desirable, is a function of individual taste. A lake that is low in productivity will be clear and conversely will have a small fish population. On the other hand, a productive lake will be turbid because of the high concentration of plankton, but this will support a large fish population. However, this fish population usually represents different species. A lake low in productivity tends toward the more preferred game fish such as trout and salmon, whereas a lake that is high in productivity is more commonly inhabited by bass, pickerel, and catfish. The term oligotrophic has been used to describe lakes of low productivity and eutrophic for lakes of high productivity. In between is a region called mesotrophic, indicating that there is a gradual transition between oligotrophic and eutrophic. These terms are not intended to imply that all eutrophic lakes are undesirable or that all oligotrophic lakes are desirable. The desirability of a specific level of productivity is a function of the specific use of the lake and a balance of various types is needed. The long-range problem is that as lakes age the nutrients accumulate within the lake. New nutrients are brought into the lake by allocthonous inputs, which are substances entering the lake from outside of the water body. This includes siltation, organic matter from decaying leaves and, of course, anthropogenic sources such as sewage or treated sewage effluent. Autocthonous inputs are those that are generated within the lake. This mostly represents a recycling of the nutrients within the lake since these are relatively constant. Thus, as there is an increase in allocthonous sources, more nutrients are made available to the organisms within the lake, and the productivity increases.

Based on Liebig's Law of the Minimum, it is possible to control excess productivity by eliminating one of the essential nutrients. It is not necessary to eliminate all of them. Since phosphorus is most commonly the limiting nutrient, most efforts have been expended towards controlling phosphorus inputs to lakes in order to control excess productivity. Whereas little can be done to control the natural process of eutrophication, there can be control of the anthropogenic sources of the nutrients that will encourage the unwanted higher productivity. In

some instances, reduction of the anthropogenic sources of nutrients has been shown to reverse the eutrophication trend. In other instances the lowering of anthropogenic inputs merely slows down or delays the rate of eutrophication. What works in one lake may not necessarily work in another seemingly similar lake.

Since phosphorus is most frequently the limiting nutrient in a lake, more efforts have been directed toward finding means of reducing phosphorus inputs to a lake. This may include diversion of all storm runoff from gaining direct access into the lake, treatment of wastewaters for phosphorus removal prior to discharge, and use of land application wastewater techniques that have been shown to reduce phosphorus content significantly. Another reason phosphorus has been chosen as the nutrient to remove is that it may be fairly readily removed by chemical precipitation with iron, aluminum, or calcium. The next most important nutrient for removal would be nitrogen. Removal of nitrogen is somewhat more difficult; however, it can be achieved by producing a nitrified treatment plant effluent and then creating denitrification (anaerobic or anoxic) conditions. This will convert the nitrate nitrogen to atmospheric nitrogen, which will then escape to the atmosphere. However, there are certain organisms, particularly blue-green algae, that are able to utilize or “fix” nitrogen directly from the atmosphere into plant material. Since elementary nitrogen makes up approximately 80% of the air, it can be expected that there will be sufficient nitrogen available in the water body to provide for all of the nitrogen fixation that may be needed in most lakes. Thus phosphorus has received the greatest attention in terms of a method for controlling excessive productivity. It has been shown that controlling phosphorus to concentrations of less than 10 µg/L at the time of spring overturn, and 5 µg/L under summer growing conditions, will result in the control of excess productivity in most lakes (18).

Sakamoto (19) has shown a direct correlation between the phosphorus concentration in a lake at the time of spring turnover and the productivity measured as the amount of chlorophyll-*a* present in the summer (Fig.23). It may be seen that there is a good correlation between the total phosphorus and the chlorophyll-*a* concentration. Greater chlorophyll-*a* content, which indicates the presence of algae, would be expected to increase the turbidity of the water, and therefore lower the clarity of the water as measured by the Secchi disc depth. Whereas there is good correlation between phosphorus content and chlorophyll-*a*, there is poor correlation between chlorophyll-*a* content and the clarity of the water. Other substances in the water, such as zooplankton

that feed on the algae, and particulate matter, such as fine clay or silt, which is carried into the body of water from allocthonous sources, can reduce its clarity. This is especially true near the mouth of a stream after a heavy rain that produces significant runoff. Thus, there is poor correlation between the clarity of the water and the phosphorus or the algae content as measured by chlorophyll-*a*.

Many models have been derived to correlate certain specific parameters with the trophic state of a lake. However, two stand out as being quite reliable and simple. These both relate total phosphorus loading to the trophic state of the lake as a function of the body of water. In the original work of Vollenweider (20), a correlation was shown between the total phosphorus loading and the mean depth of a lake, based on observations from many lakes around the world. In most cases there was a good agreement with the general observations of the trophic state of the lakes and these parameters. Vollenweider worked with Dillon (21) to improve this model by comparing phosphorus loadings with the mean depth and the hydraulic detention time of the lake (Fig. 24). It was conceded that in lakes where phosphorus was not the limiting nutrient this correlation was poor. However, in lakes in which phosphorus is the limiting nutrient, which is the most common occurrence, this correlation has been shown to be extremely satisfactory.

Information such as this is being used to indicate means of controlling productivity in lakes. One of the largest efforts in this direction is the study of controlling nutrients in the Great Lakes of the United States and Canada. Knowing the phosphorus inputs to a lake and the morphology of the lake, it can be determined what amount of phosphorus control would be required to limit the productivity to a certain desired level. This is presently being done by varied means, including the removal of phosphorus from all wastewaters being discharged into the Great Lakes Basin, by controlling urban runoff through the use of holding tanks and subsequent treatment, and by placing buffer zones between farmland and streams into which fertilizers would otherwise be leached. Based on these calculations, the most efficient and/or economical system for control of phosphorus discharges into lakes can be established.

In addition to the overall limitation to biological growth by the major nutrients, special conditions are frequently

controlled by minor nutrients. Two of these are iron and silicon. Iron is essential to photosynthesis, and can be limiting under certain conditions. Silicon is essential to the growth of diatoms that produce a frustule that is composed mainly of silicate.

Diatom growth is important in relation to control of blue-green algae growth. Diatoms and green algae are considered the base of the food chain in that they can convert inorganic matter to cell growth and oxygen in the presence of sunlight. In addition, they are consumed by higher organisms, thereby controlling their population growth. The blue-green algae, although they also produce cell growth and oxygen by photosynthesis, are much less desirable as a food source by higher organisms. Therefore, they can grow uninhibited to massive numbers, or blooms. Then when they die, their organic matter consumes the oxygen available in the water, creating an undesirable condition.

Studies made on Saratoga Lake (22) indicated that when sufficient silicon is available for diatom growth, they can out-compete the blue-green algae for the available nutrients. However, after all the silicon is depleted by a large diatom growth, their growth diminishes, and the blue-green algae can take over. Since the blue-green algae are only slightly consumed, they proliferate until more soluble silicate is made available, after which they decrease in numbers as the diatoms again increase.

Rabalais, *et al.* (23) studied iron and silicon concentrations along with nitrogen and phosphorus in coastal plankton food webs. They particularly related their results with the hypoxic conditions that exist in the Gulf of Mexico. Babbitt (24) reported that as much as 7,000 mi² of the Gulf are presently hypoxic. This has become a concern since this restricts the production of shrimp, a major economic crop of the Gulf. The hypoxic conditions correlate with the proliferation of blue-green algae in the affected area. The depletion of silica in the Gulf correlates with the excess blue-green productivity. Rabalais, *et al.* (23) attributed the low levels of silicon reaching the Gulf to the numerous dams along the Mississippi River that trap the silt and sand which normally contribute to the silicate levels in the Gulf. The lack of this essential silicon for the diatoms has allowed the blue-greens to proliferate resulting in less competition to use the large amounts of nitrogen and phosphorus

contributed from the Mississippi River.

11. THERMAL IMPACTS ON THE AQUATIC ENVIRONMENT

With increasing human activities, and the accompanying increasing demand for energy, more and more waste heat is being produced. Where possible, means are being considered for the utilization of this waste heat. In other instances, the heat is merely wasted to the environment. The two main categories of the environment receiving this waste heat are the atmosphere and the water. Discharge of heat into the atmosphere may even impact lakes or streams by changing precipitation patterns. If dry cooling towers are used, the atmosphere is heated and the relative humidity thereby decreases. On the other hand, if wet cooling towers are used, significant amounts of water vapor are passed into the atmosphere, thereby increasing the relative humidity and increasing the possibility of precipitation downwind. In terms of discharge into bodies of water, this can directly increase the temperature of the body of water, resulting in increased evaporation and loss of water in the surface lakes and streams.

Excess heat in the aquatic environment may be considered to be another form of pollution: a resource out of place. Every human action produces heat in some form or other. It is the main source of energy and energy itself is usually expended in the form of heat: friction produces heat. The problem is compounded by the fact that industries are expanding and concentrating. When there were many small mills spread around the country, there was no serious problem. However, because of the economy of scale, there are now fewer but much larger mills located at a few choice locations. Thus, the same amount of heat may be produced, but it is discharged into a much more limited local area where it has a greater impact. One of the greatest sources of heat is from electrical power generation.. A major problem in a thermal power generation system is the efficiency of utilizing the heat. For fossil fuels, the efficiency is only about 40%, whereas for a nuclear fuel the efficiency is only 33%. Thus, over half of the heat that is generated to produce the electricity must be discharged in some satisfactory manner. Much effort has been expended in finding uses for this waste heat. However, particularly with nuclear power reactors, the heat is frequently produced in a location remote from where it can be readily used. The

losses in transmitting such heat long distances preclude its use at distant locations. Thus large amounts of waste heat frequently reach the aquatic environment.

There are many problems that occur as the temperature of a lake or stream is increased. Some of these are obvious, but some represent problems that are difficult to assess. Probably the simplest problem that can be seen is the reduction in the saturation value of dissolved oxygen in a stream at an elevated temperature. At 20°C, approximately 9.2 mg/L of oxygen is the saturation value. At 30°C this is 7.6 mg/L, at 40°C it is 6.6 mg/L. Thus it may be readily seen that there is less oxygen available for biological respiration at the higher temperature. Another physical impact is the reduction of viscosity at a higher temperature. This is a benefit in waste treatment plants in that it allows a more rapid settling of the particulate matter. However, certain plankton require a specific viscosity of water in order to remain in suspension. At a lower viscosity they will sink and may not be able to remain in the euphotic zone. Obviously, greater evaporation occurs at a higher temperature, thereby removing water from the liquid to the vapor phase. This does result in an increased rate of cooling; however, the net effect is a greater loss of water. Rapid heating of water or pressure reduction, such as in passing through a power turbine, causes supersaturation of the nitrogen in the water, which has been shown to kill fish by the formation of nitrogen bubbles in their blood systems.

In terms of chemical effects, most rates of reaction are increased at a higher temperature. Unfortunately, this reduces the biological tolerance to change. This is similar to the reaction with enzymes or catalysts that normally are more effective at higher temperatures. Tastes and odors are also increased at higher temperatures. The BOD rate, which is both chemical and biological, also increases, thus satisfying the BOD in a shorter period of time. This can benefit an area farther downstream, but can result in serious oxygen depletion in the area immediately below a discharge containing a high BOD. Since there is less oxygen available at the higher temperature, it may be seen that the depletion is considerably more rapid and oxygen deficiency occurs in a shorter period of time.

From the standpoint of the biological system, there are many interrelated factors that result from the impact of

higher temperatures. In general there is an increased rate of reaction at the higher temperature. Photosynthesis is somewhat increased at the higher temperature. However, the rate of BOD satisfaction, which is a function of respiration, may exceed the increase in oxygen production from photosynthesis. The combined impact of photosynthesis and respiration is shown in Fig. 25. The actual ordinates of the graph will vary for each individual organism or species, but the concept is valid. It may be seen that at a lower range of temperature, the increase in photosynthesis may exceed the increase in respiration; however, at higher temperatures, the respiration exceeds the increase of photosynthesis. The respiration increases to a maximum rate at the optimum temperature, and at an only slightly higher temperature reaches a critical or fatal temperature at which the organism is destroyed. Since individuals and different species have different optimum and critical temperatures, it may be seen that a change in temperature may seriously change the character of the biological systems present at different temperatures. As a rule of thumb, in the growth range, respiration doubles for each 10°C rise. The increase in the rate of respiration is correlated with the increased rate of metabolism. Also, the rate of reproduction is increased. This normally is recorded as a shortening of the time for the reproduction cycle to be completed. Thus, more organisms are produced that respire and metabolize at a higher rate, thereby utilizing the diminished oxygen reservoir in a stream at a higher rate. This, of course, will reduce the BOD rapidly, but with a commensurate reduction in DO. As all these factors increase, the total activity may be limited by the availability of food.

Some organisms have a temperature sensitivity in which they prefer warm or cold water. In general in cold streams, fish swim toward warm water, whereas in warm streams, fish swim toward cold water. However, there are also some fish that are quite temperature insensitive. This can result in an accumulation of fish and other swimming aquatic organisms at either a warm spot or cold spot in a stream. Here they may utilize all the food available, ultimately resulting in their demise.

The increase in temperature also adds to the synergistic effects of other harmful substances, such as toxicity, disease and so on. In general, organisms have a lower tolerance to these impacts at a higher temperature. In some instances, for example, disease may be controlled by a lower temperature. Thus, the

higher temperature merely adds to other antagonisms. Another important factor is the rate of change of temperature. Many aquatic organisms can tolerate a slow change in temperature, but not a rapid one. If there is a discharge of hot water into a stream, there can be a narrow zone of mixing resulting in a rapid change in temperature within a short distance.

Another problem regarding a rapid change in temperature is that power plants must shut down at certain times for maintenance and/or accidents. If the thermal discharge from a power plant has been keeping a stream warm through the winter, a sudden stoppage of the power generation would allow the stream to cool very rapidly. This would impact a significant thermal shock on the aquatic organisms. Therefore, most regulations call for prohibiting routine shutdowns during the winter months. Obviously, accidental shutdowns may still occur. Thus there are two main concerns: (a) the impact of the higher temperature and (b) the impact of sudden changes of temperatures because of operation of the thermal generating system.

There are many combinations of impacts related to increasing aquatic temperature. For example, certain organisms will reproduce only at or above a certain temperature. If the body of water is maintained above this temperature they will reproduce for a longer period of time or constantly. However, their development is dependent upon the food available to them. If the food on which they rely is not available because of other temperature impacts, then they cannot survive. If they cannot survive, their predators may in turn disappear, because they are not available at the proper time for use by their predators. Thus, it may be seen that a change in temperature at one location can impact the entire food chain throughout a stream or ecosystem. Blue-green algae are more tolerant of higher temperatures. Some have been shown to be present at up to 77°C in hot springs such as at Yellowstone. Most of the colors in the hot springs are produced by different species of blue-green algae. The blue-green algae, however, are less desirable as food for other organisms. Therefore, they will consume the nutrients available and produce organic matter that is not readily used by higher organisms in the food chain. This obviously distorts the entire system.

The impact of a thermal discharge in a body of water will become dissipated with time and the water body will

reach equilibrium after sufficient time. In a stream this implies sufficient flow time from even a constant discharge of heat. However, in a lake, since there is no flow time, the only time would be that from the batch discharge of a slug of heat. The temperature relationship in a stream during summer and winter is depicted in Fig. 26.

Although there is no space here for detailed description of control methods, some basic concepts should be mentioned. The first is the use of cooling ponds in which the water is recirculated through the cooling pond and reused for cooling. Crescent-shaped ponds have been shown to be quite economical. The heated water is discharged into one end and as evaporation causes cooling, the cooler water is taken from the opposite end. Various forms of cooling towers are also used for dissipating heat. There are various combinations of wet and dry towers using natural or forced draft. Detailed descriptions of these may be found elsewhere. Reference section of this chapter has the authors' suggested reading (25-44).

Regulations on thermal discharges are the responsibility of the various states. It is impossible to cite regulations common to all states; however, some of the criteria for evaluation should be useful.

The first criterion is the definition of a thermal discharge, usually as one that is at a temperature above a set value such as 70°F (21°C) or if it causes a natural body of water to rise above a recommended limit, such as 3-5°F (1.5-3°C). It should be defined separately in terms of lakes, streams, and tidal waters. There is usually a definition for trout and nont trout streams in which the requirements are more stringent for trout streams. There may be greater temperature tolerances during the summer. Summer and winter may be defined as periods when the temperatures reach certain limits. Many criteria involve the degree of mixing in a stream with a description such as at least 50% of the cross-sectional area and/or volume of the stream, including a minimum of ½ of the surface, shall not be raised above a certain minimum temperature. This is to allow fish to pass a heated section of the stream. In a lake, frequently the regulations are to prevent a certain temperature rise in a circle or a plume from the point of discharge into the lake. Here it is recommended that a surface area be specified rather than a radius of a circle, which is frequently specified. This will compensate for any distortions in the shape of the plume other than circular. In a summer stratified lake, there should be no discharge of heated effluent into the

hypolimnion. Withdrawal of water for cooling may be from the hypolimnion or the epilimnion, depending upon regulations. Discharging the heat to the epilimnion will help maintain the cool water in the bottom and maintain the thermocline relatively constant. These are just some of the generalities to be observed in regulations on thermal discharges.

It is most useful to find alternate uses for this excess heat. When homes or factories may be located close to a source of heat, it may be used for heating or industrial processes. However, during the summer there is less need for this heat unless it can be converted to operating air-cooling systems. The heat has been used for agricultural purposes. Here, again, this has benefit only during certain times of the year. Some aquaculture systems have been put into operation in which the waste heat is placed in ponds, lagoons, or bays to encourage the growth of fish or shellfish. This has been shown to be very beneficial in reducing the reproduction time and the time to reach maturity. However, again this has limited use and will not solve all the problems of the utilization of excess heat. As energy becomes more and more expensive, it is certain that more systems will be devised to utilize this excess heat.

12. TOXICS IN WATER RESOURCES

The concern for toxic materials in water supplies has created one of the greatest controversies of recent time. The US Environmental Protection Agency issued a list of 129 priority pollutants that are of concern and should be eliminated from water supplies. However, there is uncertainty about what concentrations of these substances represent hazardous levels. One problem is that individuals and different age groups may have varying tolerances to these substances; the other problem is our present analytical methods. In some cases we do not have sufficient precision to measure concentration in ranges low enough to detect their presence, whereas in other cases we are improving our techniques by finding even lower concentrations that may or may not prove to be harmful. To add to this dilemma are the present requirements that in some instances tend to add to the problem of toxic materials. A typical example is the requirement for chlorination of wastewaters before discharge and of drinking waters prior to treatment. Chlorination of certain organic materials produces the trihalomethanes, which are on the list of priority pollutants. If chlorination of wastewater is not practiced there

will be fewer trihalomethanes produced. However, the downstream area will have a higher disease potential because the pathogenic organisms have not been reduced sufficiently. Similarly, in the water intake, where poor quality water is used as the drinking water supply, prechlorination has been practiced to reduce the number of pathogenic organisms. This can result in an increase in the trihalomethane content. In order to reduce trihalomethane production, it is recommended that prechlorination not be applied, but that secondary chlorination, after the removal of the organics, be the only point for chlorination. This of course will reduce the production of the trihalomethanes, but may increase the potential for the carryover of pathogenic organisms in the water supply system. Similarly, several heavy metals are on the list of priority pollutants. Some of these metals have been shown to be essential growth factors in very low concentrations. However, at only slightly higher concentrations, they have been found to be detrimental. Thus, very close tolerance limits must be set, and it is difficult to establish safe levels and still prevent the occurrence of unsafe levels.

Another problem comes in the determination of the priority pollutants. The regulations call for the banning of any substance suspected of being carcinogenic or mutagenic. This usually is based upon feeding massive doses to a susceptible species of mice or rats. If any carcinogenic or mutagenic effects are found, that substance is placed on the priority pollutant list. There is, however, no guarantee that what is harmful to rats and mice will also be harmful to humans. Also it is difficult to extrapolate to humans the concentration limits that were harmful to the animals.

A regulatory agency must of necessity be extremely conservative. Therefore, any substance even suspected of being harmful must be included on this list. Environmental conditions are to be maintained so that even the most susceptible individual is protected from any harm. Thus, the most conservative values and the lowest levels are considered in listing the priority pollutants and their concentration limits.

One of the major problems in the evaluation of priority pollutants is the impact of long-term use of any substance. There may be no immediate symptoms, but symptoms may occur after long periods of time, in another generation, or in a very indirect manner. For example, the use of certain drugs (Thalidomide) for

increased fertility has been shown to have an impact on the offspring of the second generation of persons who used these drugs. Findings such as these take 20-25 yr to evaluate. Another is the use of DDT, which has not been shown to be harmful to humans, but indirectly has particularly affected the eggs of certain fish and birds. In society's total concern for the environment, these impacts are also valid concerns. The problem then arises about how one evaluates a new substance that appears to have no deleterious impact at the moment, but may in the future. We certainly cannot ban every new substance. The answer probably lies in continued evaluation and monitoring of any new substances, particularly those that are or are suspected of being related to other substances that have been shown to be deleterious. However, there must also be provision to remove a substance from the priority pollutant list if it has been proven over a long period of time not to be harmful to humans or the environment.

Another condition that has not been evaluated is the risk: benefit ratio. As an example, DDT has been shown to have saved on the order of 500 million lives, particularly in preventing malaria. It is now on the priority pollutant list primarily because of its impact on organisms other than humans. There must be some means of evaluating a substance to determine whether its adverse effects may be more than offset by its benefits.

Of some concern must also be cost; however, cost related to human health must be the final evaluation. Costs for analysis of trace quantities of certain toxics may represent a significant cost to a small water supply system. A question may arise about the need for such a complete analysis for every water supply system. Obviously some evaluation must be made of the potential harm or pollution of water supply systems. A water supply not subject to contamination may not need a complete analysis; however, where potentially toxic chemicals are in the area or in the ground, it is advisable to monitor water supply systems to assure that such contaminants do not reach the public through the water supply system.

There is no simple solution to the concern for toxic materials in the aquatic environment. What is essential is continued monitoring for the presence of toxic materials and a rational evaluation of the impact of these potentially toxic materials upon humans.

13. GOALS OF WATER POLLUTION CONTROL

Goals should not be the conclusion of any discussion of water pollution control. They should be the reason for establishing some procedure for pollution control. Once proper goals are established, one can make some reasonable decisions in terms of what is necessary and how they may be accomplished. However, some goals have already been established, and it is assumed that the previous information will aid in reaching the prescribed goals.

The goals of water pollution control have been summarized briefly: to provide fishable, swimmable, and drinkable water. Public Law 92-500 passed by the US Congress and commonly known as the Amendments to the Federal Water Pollution Control Act, starts off with a “declaration of goals and policy.” A summary of this section is in order. The main objective of this Act is stated to be “to restore and maintain the chemical, physical and biological integrity of the Nation’s waters.” In order to achieve this, stated goals include: (a) discharge of pollutants into the navigable waters should be eliminated by 1995, (b) an interim goal of water quality providing for the protection and propagation of fish, shellfish, and wildlife and providing for recreation should be achieved by July 1, 1983, (c) the discharge of toxic pollutants in toxic amounts should be prohibited, (d) there should be Federal financial assistance to construct publicly owned treatment works (POTW), (e) to assure adequate pollution control areawide, waste treatment management processes should be developed and implemented, and (f) there should be major research and development to develop the technology necessary to eliminate the discharge of pollutants.

The successor to the above law was Public Law 95-217, commonly known as the Clean Water Act. Its main goals were similar to the previous legislation with some minor modifications in the timetable. Greater emphasis was placed on innovative and alternative technology, individual wastewater treatment systems, sludge disposal, and energy conservation.

These basic laws have been renewed, frequently postponing deadlines in recognition of the difficulty in

obtaining the information needed to carry them out or the difficulty in enforcing them. Litigation has ensued in both directions: those who want immediate action and those who want to delay enforcement.

Some additional laws have been passed which impact the aquatic environment. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund, was designed to control cleanup of hazardous waste sites, many of which created water pollution problems primarily through leachate. The Endangered Species Act indirectly affects water resources by protecting listed species, some of which require both adequate water supplies and high quality water. The Federal Insecticide, Fungicide and Rodenticide Act controls the discharge of these materials that enter water bodies primarily from agricultural runoff. The Oil Pollution Act of 1990 is designed to prevent discharge, either as a waste or from an accident, of oils to the aquatic environment. The Resource Conservation and Recovery Act (RCRA), supports both waste reduction and waste elimination. The Safe Drinking Water Act (SDWA) regulates the quality of drinking water. Details on these and other environmentally related regulations may be obtained from the US Environmental Protection Agency (USEPA) at www.epa.gov/epahome/laws.htm.

All of the laws and regulations that have been passed and promulgated by the USEPA and various other agencies have as their goal the protection of the quality of the water within the US. To this end, much money and time have been expended. Some improvement has been seen; however, there are some glaring cases where the efforts have not been successful. Some of these most likely will be taken care of in a matter of time; in other specific cases, there may be other problems that will have to be resolved.

Over the years the approach to pollution control enforcement has changed, although both approaches were included in the first act. These approaches were (a) effluent discharge limits and (b) stream quality limits. Initially discharge limits were set for each industry and permits issued to control the amount of a pollutant that may be discharged over a given period of time. This simplified enforcement, and evened out treatment costs within an industry. It also lessened the moving of an industry from a state where standards were high to a state with lower standards, since standards were similar throughout the United States. Recently the total maximum

daily load (TMDL) concept has gained popularity in which each stream or watershed is evaluated for its ability to absorb a given amount of a pollutant while remaining within its desired stream quality standards. Whereas this is more equitable from the standpoint of the stream, it does require considerable more information, both to set the standards and to enforce them. In addition, standards may have to be set for any potential pollutant that may be discharged into a specific stream. This is more difficult than previous standards based on only BOD loading or dissolved oxygen levels in the stream. Also, it may encourage an industry to move to a less polluted river, thereby allowing it to utilize a larger share of the allowable load, while simultaneously decreasing the quality of the river. Both approaches have their valid points.

One of the major concerns in any effort or program, whether it be that of the Federal or local government or of any other organization, is who is to be the beneficiary of the energy expended. There are two major directions to which pollution control efforts can be directed. One is to improve the quality of the environment for the sake of the environment and the other is to improve the quality of the environment for the sake of society. There is no clear-cut distinction between the two because in general what benefits the environment also benefits humankind. However, there are specific instances where benefits to the environment may not have any obvious benefit to humans; thus, certain individuals may question the expenditure of public monies that will not directly benefit the public.

It is the author's belief that there is room for both points of view. There are cases in which the environment is and should be the sole direct beneficiary of any control practice. For example, there are areas of the Adirondack Park in New York that are to be preserved as "forever wild." Even airplanes are not allowed into these areas to land on the lakes to provide for hiking, hunting, or fishing. Large areas of Alaska have been set aside as wilderness area in which humans are viewed as unwanted interlopers. Many areas of Africa are presently wildlife areas that will have to be preserved if we hope to salvage some of the rarer animals. In some instances it has been questioned whether we really need certain of these rare animals. They may have no direct benefit to humans and in some cases, aside from hunting expeditions that benefit only a very small number of individuals, they could probably be allowed to become extinct without any serious impact upon the environment. On the

other hand, we must consider that humankind is also a part of the environment and not the only factor within that environment. Other species have just as much right to exist on this earth as do humans. Another concept that must be considered is the fact that the earth has maintained a balance of biological systems that house various species including humans. As the latter increase excessively in number, they crowd out the other species. This may result in a biological imbalance in which humans may ultimately destroy themselves by overpopulation. It may be necessary to control population so that the earth can continue to support a limited number of human beings. This concept of course rankles many people. Each person feels that he or she has a right to propagate as much as seems desirable and to fill the earth with his or her progeny. Certainly we do not want to have a dictator or government body dictating who may have how many children, when, and where. On the other hand, human beings must take responsible positions and realize that in the total environment, population control is essential. To accomplish this will take a considerable amount of education. It is made more difficult by the fact that traditions and religious beliefs have fostered the concept that humankind is the center of the universe. Thus, we can do whatever we want and everything was made for us. Even though everything may indeed have been made for us, if we utilize everything made for us there will be no more left and of course we will decline. It would be far better for us to control our own numbers than to have these numbers controlled by a large famine, pestilence, or other noxious factor.

In terms of the concept that the environment should be controlled for the benefit of society, there arises the concept that complete pollution elimination may not be a desirable situation. For example, an oligotrophic lake is very unproductive, particularly in terms of producing the large amounts of fish that could provide food for many. Just as adding fertilizer to the land increases the productivity of the terrestrial crop, adding nutrients to a lake will increase the total productivity of that lake. This will result in increased plant growth and ultimately increased animal (fish and shellfish) production. Obviously, limits of productivity are controlled in the aquatic environment by the amount of dissolved oxygen that is available. Here again, in terms of benefits to humans, we could install aerators in all lakes and use them to their maximum productivity. This may even be necessary one day if the population continues to increase as it has. Thus, a different set of goals would have to be established if all of the environment were to serve humankind directly.

There is probably some middle ground that offers the best solution. It is certainly desirable to maintain some wilderness areas undisturbed. It is desirable to have some bodies of water that are highly oligotrophic. The problem seems to be that, if these are preserved in their pristine purity, how will humans get to appreciate them. Possibly here limited access will have to be provided to some oligotrophic lakes. Other lakes however may be maintained at higher productivity levels. This will provide greater production of fish and similar related business and recreational activities. Thus, there could be a balanced, diverse environment that would satisfy both phases of the pollution control concept. A problem that arises here, of course, is how does one establish whether a particular area or lake or stream is to be preserved for the benefit of the environment and which other area is to be maintained for the benefit of society?

These are not simple questions to answer. Each individual has a personal concept that has some validity. This will require a considerable amount of discussion and cooperation among individuals and obviously will result in various pressure groups trying to get a little more for themselves or a special cause. However, we must look at the total picture, not just at what affects a few individuals here and now. Considerations must be made for the future so that humankind can coexist with the environment on earth for many years to come. With an educated society, logical thinking, and good information, human beings can make good decisions about what efforts must be expended both now and in the future in order to improve and preserve the environment for the best use of all for now and for time to come.

14. DISSOLVED AIR FLOTATION BOAT PLANT FOR LAKE RESTORATION

One of the primary causes of the death of a lake is excessive biological growth, called eutrophication. Biological growth is limited primarily by the availability of the nutrients necessary for growth. It has been shown that phosphorus is most frequently the limiting nutrient to control biological growth in a lake, but nitrogen is also commonly limiting. Phosphorus may be permanently removed from a lake by various processes, whereas nitrogen is difficult to remove permanently due to the fact that certain blue-green algae can fix

atmospheric nitrogen as a nitrogen source. Thus, emphasis has been placed on the removal of phosphorus. There are various methods for the treatment of wastewaters to remove the nutrients before being discharged to a body of water. Once in a lake, phosphorus removal is most frequently achieved by producing an insoluble aluminum salt of the phosphorus, but iron salts are effective under aerobic conditions. Calcium salts are effective in removing phosphorus, but they generally adversely increase the pH of the lake. Precipitated aluminum phosphate salts may be allowed to settle to the bottom of the lake, or they may be removed from the water column. A study showed that removing the phosphate-rich hypolimnetic waters from a summer stratified temperate climate lake, precipitating the phosphorus as either aluminum or iron salts, separating the precipitate by dissolved air flotation (DAF), and returning the phosphate reduced water to the lake were very effective in controlling the phosphorus nutrient content in Devils Lake, WI, USA.

Figure 27 shows a dissolved air flotation boat plant designed by Dr. Lawrence K. Wang of the Lenox Institute of Water Technology (LIWT) and Dr. Milos Krofta of Krofta Engineering Corporation (KEC) (44). The readers are referred to the authors' another article (30) for the detailed technical information of lake restoration using dissolved air flotation process.

15. GLOSSARY (37-44)

Dissolved air flotation (DAF): One of dissolved gas flotation (DGF) processes when air is used for generation of gas bubbles. A typical example is Krofta Engineering Corporation's Supracell clarifier; See dissolved gas flotation (DGF).

Dissolved gas flotation (DGF): It is a process involving pressurization of gas at 25 to 95 psig for dissolving gas into water, and subsequent release of pressure (to one atm) under laminar flow hydraulic conditions for generating extremely fine gas bubbles (20-80 microns) which become attached to the impurities to be removed and rise to the water surface together. The impurities or pollutants to be removed are on the water surface are called float or scum which scooped off by sludge collection means. The clarified water is discharged from the flotation clarifier's bottom. The gas flow rate is about one percent of influent liquid flow rate. The attachment of gas bubbles to the impurities can be a result of physical entrapment, electrochemical attraction, surface adsorption, and/or gas stripping. The specific gravity of the bubble-impurity agglomerate is less than one, resulting in buoyancy or non-selective flotation (i.e. Save-All).

Eutrophication: Over-enrichment of a water body with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration.

Groundwater: The supply of fresh water found beneath the earth's surface (usually in aquifers) which is often accessed through wells and springs.

Hydrologic cycle: The cycle that water through its natural process of evaporation and precipitation: from the sea, through the atmosphere, to the land and back to the sea.

Lake: An inland body of water, fresh or salt, of considerable size usually greater than 50 acres (200,000 square meters) and occupying a basin or hollow on the Earth's surface.

pH: An expression of both acidity and alkalinity on a scale of zero to 14, with seven representing neutrality; numbers less than seven indicate increasing acidity and numbers greater than seven indicate increasing alkalinity. Acid rain can increase the pH level of the water in a lake, thereby killing all life.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen from carbon dioxide and water in the presence of chlorophyll, using sunlight as an energy source. Plants thereby absorb carbon from the atmosphere with the process, and store it in their forms.

Phytoplankton: Usually microscopic aquatic plants, sometimes consisting of only one cell.

Plankton: Those organisms that are unable to maintain their position or distribution independent of the movement of water or air masses.

Pollution: The contamination of a natural ecosystem, especially with reference to the activity of humans.

Precipitation: Any and all forms of water, whether liquid or solid, that fall from the atmosphere and reach the Earth's surface. A day with measurable precipitation is a day when the water equivalent of the precipitation is equal to or greater than 0.2 mm.

Urban runoff: Storm water from city streets and adjacent domestic or commercial properties that may carry pollutants of various kinds into the sewer systems and from there to rivers, lakes or oceans.

Water Resources: Water in various forms, such as rain, snow, ice, clouds, surface water, groundwater, reclaimed water, or reused water – that is potentially useful for domestic, industrial, commercial, or recreational applications.

ACKNOWLEDGMENT AND DEDICATION

1. From Three Co-authors, Professors Lawrence K. Wang, Mu-Hao Sung Wang, and Nazih K. Shammass of the Lenox Institute of Water Technology (LIWT), Newtonville, NY, USA.

This STEM (Science, Technology, Engineering and Mathematics) technical paper is published in memory of our senior author, Dr. Donald B. Aulenbach, who worked closely with Professors Lawrence K. Wang, Mu-Hao Sung Wang, Nazih K. Shammass, William A. Selke, Milos Krofta and Daniel Guss from 1981 to 2019 for developing a humanitarian engineering program at the Lenox Institute of Water Technology (LIWT; formerly Lenox Institute for Research, Lenox, MA, USA), teaching/researching there as an Adjunct Professor for almost two decades (42-43), and publishing many research papers and textbooks (26-35) for academic contribution to the humanity. We salute and will forever remember Don. LK Wang and MHS Wang always treasure their good old days at Rensselaer Polytechnic Institute (RPI), Troy, NY, USA, with both Don and his dear wife, Marie Aulenbach, therefore, they modified an old poem of *Thousand Winds* (original author is unknown) for celebration of Don's entire life :

Do not stand at my grave and weep
In Memory of Don B. Aulenbach,

An Environmentalist, A Family Man, A Teacher and A Musician

(Thousand Winds, a modified poem by Lawrence K. Wang and Mu-Hao Sung Wang)

Do not stand at my grave and weep
I am not there, I do not sleep
I am in a thousand winds that blow
I am the fresh air up there
I am the fertile soil on land
I am the swimming fish in water

I am in the morning hush
I am in the graceful rush
Of beautiful birds in circling flight
I am the servant on duty
I am in the homes with love
I am in the classrooms
I am the birds that sing

I am in each lovely thing

Do not stand at my grave and cry
I am not there, I do not die

The following is a photo of Dr. Donald Bruce Aulenbach, our dear colleague and lifelong friend.

2. From Dr. Donald B. Aulenbach's Daughter, Louise Trakimas

My Dad, Donald B Aulenbach was passionate about his work, family, music, and his church community. His energy was boundless. It was often hard to keep up with him.

Born in Pennsylvania, his father was a minister, and his older brother became a minister. My Dad, however, decided to pursue a career in Science. He graduated from Franklin and Marshall College and then earned his PhD in Environmental Engineering from Rutgers University. His first position was as a bacteriologist/chemist for the Delaware Water Pollution Commission. In 1960 we moved to New York State where my Dad began a 30 year career as a Professor of Environmental Engineering at Rensselaer

Polytechnic Institute (RPI) in Troy, NY , and an Adjunct Professor at the Lenox Institute of Water Technology (LIWT) in Lenox, MA. (42-43)

I remember going into his lab as a child and he would show me how the chemicals turned different colors and what he did to make this work. He always encouraged my siblings and me to learn and be involved-not only in academics but in projects around the house. He was also an excellent handyman.

Dad taught summer courses at Lake George at RPI's Freshwater Institute and/or at LIWT. The students loved his classes as they were hands-on and he was so active and engaging.

Dad loved to travel. We had many family vacations across the country. Even as adults, he made sure all 4 children and our families would get together each year. His biggest trip was to China for two months where he was a consultant for the country's waste- water disposal facilities.

Dad spent hours each year preparing for the New York State Mathcounts competition as regional coordinator-and often went to Washington DC with the students who qualified for the finals.

Music was another love of his. I remember him spending Saturdays listening to classical music or playing his violin. He played his bass violin in a band well into his 80's. He loved to sing-and sang every Sunday in our church choir. You could be sure to hear his voice among the others-as he loved to perform. Dad was a member of many professional societies, authored numerous articles on environmental engineering, was involved in the church, but always had time for his family. I aspire to be like him. He is sorely missed.

Respectfully yours,

Louise Trakimas, Daughter of Donald Aulenbach

3. From Professor Henry Bungay III of Rensselaer Polytechnic Institute, Troy, NY, USA

I treasure my warm friendship with Donald Aulenbach that started in 1976 and lasted until his recent death. We were together when the university administration at RPI experimented with merging environmental engineering and chemical engineering. I continued to teach environmental engineering courses for almost two decades after Don and the other environmental professors went to civil engineering as I opted for chemical engineering. His unique perspectives were inspirational, and he was outstanding for research in the field while training students at Lake George and Dyken's Pond. After retirement we often sat together at events such as monthly luncheon gatherings. I pray for his soul. (45)

4. A Warm Tribute to Our Dear Friend and Colleague, Professor Emeritus Donald Bruce Aulenbach (Aulie) from Professor Emerita Lenore S. Clesceri and Professor Emeritus Nicholas L. Clesceri of Rensselaer Polytechnic Institute, Troy, NY, USA.

When we returned from our post-docs in Switzerland in 1965, to begin teaching at Rensselaer, Don was among the first friends we developed. His help and friendship will always be highly valued. His good humor is legendary.

He was very involved in the research at Lake George and the development of the Lake George Water Research Center (LGWRC) with Nick.

Reflecting on the early days, Don and Nick made quite a few trips to Gull Bay in Putnam County on the eastern shore of Lake George, specifically, to Smith Bay. It seemed that each time we ventured forth, we encountered snow, which we could have anticipated at that time of the year. But, Nick and Don never faltered! Lots of Fun...

As things started to take shape, President Richard Folsom and Provost Clayton Dohrenwend encouraged us to see what might occur. Nick and Don had many meetings with them, keeping them “in the loop”. Then, Professor Steve Wiberley (and later, Provost) was tasked by Provost Dohrenwend to work with us on developing the LGWRC. As fate would have it, Steve viewed the Gull Bay area for suitability for a fledgling LGWRC with Nick and Don...In a SNOW STORM!

Through President Folsom, we made connections with RPI Board of Trustee Member, Mr. Harold Strang, retired GE VP, who lived in summers at Smith Bay. In addition, Mr. Strang owned an adjacent former camp for youngsters. Mr. Strang offered his camp as a location to initiate LGWRC research. As was standard, and expected, at that stage, Nick and Don were the principle salesmen.

BUT, this historical sojourn would take many more pages to describe; however, a few things alert the brain cells, namely, “around-the-clock” lake water sampling, “through-the-ice” water sampling and stream sampling, to name just a few things that Don did so well.

Bringing things to the present, this ultimately led to RPI’s Darrin Fresh Water Institute., located in Bolton Landing, NY on the western shore of Lake George.

Don’s research was far-ranging, from Radiological Health, to Public Health to his forward-thinking work with his students on the Village of Lake George Wastewater Treatment Facility. He literally probed the subsurface as he studied the sand infiltration beds, which functioned as tertiary treatment for this system. This research placed Don in a small cadre of fellow researchers from around the world who were seeking understanding of sand infiltration capability for tertiary treatment. He collaborated with them and presented at specialty conferences.

Lastly, Don’s contributions in the Department’s educational endeavors were manifold. He was a key figure in the Department gaining the first-in-country ABET accredited degrees in Environmental Engineering. Nick and Don team-taught a number of courses, which was always constructive for the Department’s reputation.

Don also taught a Limnology course at the Lake George facility, which Lenore inherited.

On a personal note from Nick, in addition to the brief notes above, Don was a Father, Family man, Educator, Patriot and God-Fearing human being. He faithfully served his Church in Clifton Park, NY for decades. How full a life is that!!

I consider him a BROTHER.

Aulie, Rest In Peace, dear friend.

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TABLE 1
Calculations for Thiessen Method

(1)	(2)	(3)	(4)	(5)	or (5a) omit (4)
Location	Ppt'n cm	Area km ²	Fraction (or %) of total area ^a	Weighted ppt'n, cm (2) X (4)	Ppt'n X Area (2) X (3)
A	1.65	7	0.01	0.0165	11.55
B	3.71	120	0.90	0.7049	445.20
C	4.88	109	0.18	0.8784	531.92
D	3.91	20	0.03	0.1173	78.20
E	6.83	120	0.19	1.2977	819.60
F	7.16	0	--	--	--
G	7.57	92	0.15	1.1355	696.44
H	11.43	76	0.12	1.3716	868.88
I	12.70	82	0.13	1.6510	1041.40
J	4.44	0	--	--	--
K	4.95	0	--	--	--
Σ		626	1.00	7.17	$\frac{4492.90}{626} = 7.18$

^a(4) = $A/\Sigma A = (3)/\Sigma(3)$ (x 100 if using %)

TABLE 2
Calculations for Isohyetal Method

(1)	(2)	(3)	(4)	(5)
Isohyet, cm	Area (A), km ²	Fraction (or %) of total area $A/\Sigma A = (2)/\Sigma(2)$	Avg. ppt'n, cm	Weighted ppt'n, cm (3) X (4)
12	13	0.021	12.2	0.2562
10-12	77	0.123	11.0	1.3530
8-10	116	0.185	9.0	1.6650
6-8	145	0.232	7.0	1.6240
4-6	150	0.239	5.0	1.1950
2-4	105	0.168	3.0	0.5040
2	20	0.032	1.8	0.0576
Σ	626	1.000		6.6500

Alternative for column (5): $\Sigma (2) \times (4) / \Sigma(2) = (5)$

TABLE 3
Values of N as a Function of
Drainage Basin Size

Area, mi ²	N	$N = A^{0.2}$
100	2	2.5
500	3	3.5
2,000	4	4.5
5,000	5	5.5
10,000	6	6.3

Table 4
Sample Flood-Routing Computations

Line on Fig. 14	Time From start of flood, h (1)	Length of time interval t, h (2)	Instan- taneous inflow rate I , cfs (3)	Mean inflow rate during interval $(I_1+I_2)/2$ cfs (4)	Vol. of inflow during interval $(4)X(2)X$ $t/24$ ac-ft (5)	Reser- voir elev. at end of interval, ft (6)	Spillway discharge rate at end of interval, cfs (7)
AB DE GI KJ	0	12	2,000	--	--	430.0	0
	12	12	3,800	2,900	2,900	430.3	500
	24	12	10,400	7,100	7,100	431.0	2,000
	36	12	52,400	31,400	31,400	433.6	12,000
	48	12	173,100	112,700	112,700	440.5	64,000
	54	6	221,400	197,200	98,600	444.6	106,000
	60	6	245,800	233,600	116,800	448.2	147,000
	66	6	237,500	241,600	120,800	450.6	178,000
	72	6	211,800	224,600	112,300	451.8	193,000
	78	6	180,000	195,800	97,900	451.8	193,000
	84	6	148,600	164,200	82,100	451.1	184,000
	96	12	92,800	120,700	120,700	448.1	146,000
	108	12	54,100	73,400	73,400	444.5	105,000
	120	12	29,700	41,900	41,900	441.0	69,000
	132	12	16,500	23,100	23,100	438.2	44,000
	144	12	8,800	12,600	12,600	436.1	28,000
	156	12	4,000	6,400	6,400	434.5	17,000
	168	12	2,500	3,250	3,250	433.4	11,000
	180	12	2,500	2,250	2,250	432.6	8,000
	192	12	2,000	2,000	2,000	432.0	5,000

TABLE 5
Characteristics of Soils

Type	Size		Porosity %	Permeability gal/ft ² -d	Velocity
	in	mm			
Quartzite, granite				0.1	
Limestone and shale			5	1	
Sandstone			15	700	
Gravel	>0.08	1.5 – 8	25	100,000	1,000 mi/yr
Very coarse sand	0.04 – 0.08	0.8 – 0.3	30	65,000	600 mi/yr
Coarse sand	0.02 – 0.04	0.5 – 2	35	8,500	80 mi/yr
Medium sand	0.01 – 0.02	0.25 – 0.5	40	2,000	20 mi/yr
Fine sand	0.005 – 0.01	0.05 – 0.25	45	80	1 mi/yr
Very fine Sand	0.003 – 0.005	0.005 – 0.05	50	2	100 ft/yr
Silt	<0.003	0.005 – 0.05	58	1	50 ft/yr
Clay		0.005 – 0.05	70	0.002	1 ft/10yr
Colloidal clay		10Å – 0.01	90	2 X 10 ⁻⁵	1 ft/1,000 yr

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The diagram illustrates a well system in an unconfined aquifer. Key components and labels include:

- Ground Surface:** The top boundary of the aquifer system.
- Piezometric Surface Before Pumping:** A horizontal line representing the initial water table level.
- Piezometric Head During Pumping:** A curved line showing the water table depression around the well.
- Well:** Consists of a vertical pipe with a **Well Screen** at the bottom, located within the **Aquifer**.
- Aquiclude:** A layer above the aquifer that does not allow water to pass through.
- Impervious:** The bottom boundary of the aquifer system.
- Bottom of Well:** The lowest point of the well casing.
- Observation Well:** Two vertical pipes (labeled 1 and 2) used to measure the water table at different radii.
- Radius Labels:**
  - R : Radius of the observation well.
  - r_1 : Radius at observation point 1.
  - r_2 : Radius at observation point 2.
  - r_w : Radius of the well.
- Head Labels:**
  - H : Total head at the static water table.
  - h_1 : Head at observation point 1.
  - h_2 : Head at observation point 2.
  - h_w : Head at the well screen.

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