

3. THE NEW WATER BODY

When the reservoir begins to fill, the physical structure of a new ecosystem begins to take form, and there begins a new complex of relations between the lake and the adjoining area. A stage is set for biological and social transformations. This sequence has happened many thousands of times, and man-made lakes now regulate to some degree about one-tenth of the global land runoff (Lvovich, 1969). The physical impact of reservoirs is not only confined to the area they cover, but of course extends far downstream, creating major changes in hydrologic regimes. It is not within the scope of this discussion to describe this whole pattern of downstream change, but where major effects substantially contribute to the judgment of feasibility of a reservoir scheme, they are discussed.

Inasmuch as the essential function of the reservoir is to store water, the basic questions in the feasibility stage (I, Fig. 1.4) of a man-made lake are whether there are better ways of impounding water and whether there are alternative ways of meeting social needs without water storage. In the planning stage (II), the possible effects of the dam on sediment storage, earth stresses and microclimate require exploration. The most crucial aspects of the new water body, however, are the patterns of water quality, density and flow which develop in response to the local conditions and in relation to river inflow and outflow as regulated by man. These may be predicted with considerable accuracy during stages I and II, evolve in the filling stage (III), and are the subject of continued study and manipulation thereafter. Even if the physical relationships were clear and stable, the manipulation of the new physical system is certain to change as the human values affecting demand for water shift in emphasis.

Water Management Alternatives

From the hydrological and water management points of view, man-made lakes are storage elements of a local or regional water resource system built to control the flow regime of the system according to requirements of different water uses to be served. Water regulation by the reservoir operation is one physical means of advancing specific social aims as defined by the government. If it is concluded that some type of water management is required there are several alternative solutions to water resource development (National Academy of Sciences, 1968) which may serve partly or entirely as substitutes for man-made lakes in favorable circumstances. These options may include: a) extension of groundwater exploitation; b) artificial recharge of groundwaters; c) increase of streamflow by watershed management; d) long-distance water transport; e) decreasing of demands for water by economic measures such as pricing or by technological changes (e.g., recycling of waste water); f) desalination; and g) cloud seeding.

Some of the above options (like e or f) may have little or no environmental implication, but others (like c or g) may have equal or even greater impact on the physical and biological environment than a man-made lake. It is a mistake to assume that any alternative may be an effective substitute for another in a given

situation. But it is also an error to assume that water storage necessarily is socially the most desirable action.

Man-made lakes represent creation of *additional* storage capacity in the hydrological system. Always present is the natural storage capacity of the river basin itself which transforms the precipitation regime into the streamflow regime of the river. This basin storage and its streamflow regulating effect usually surpass con-

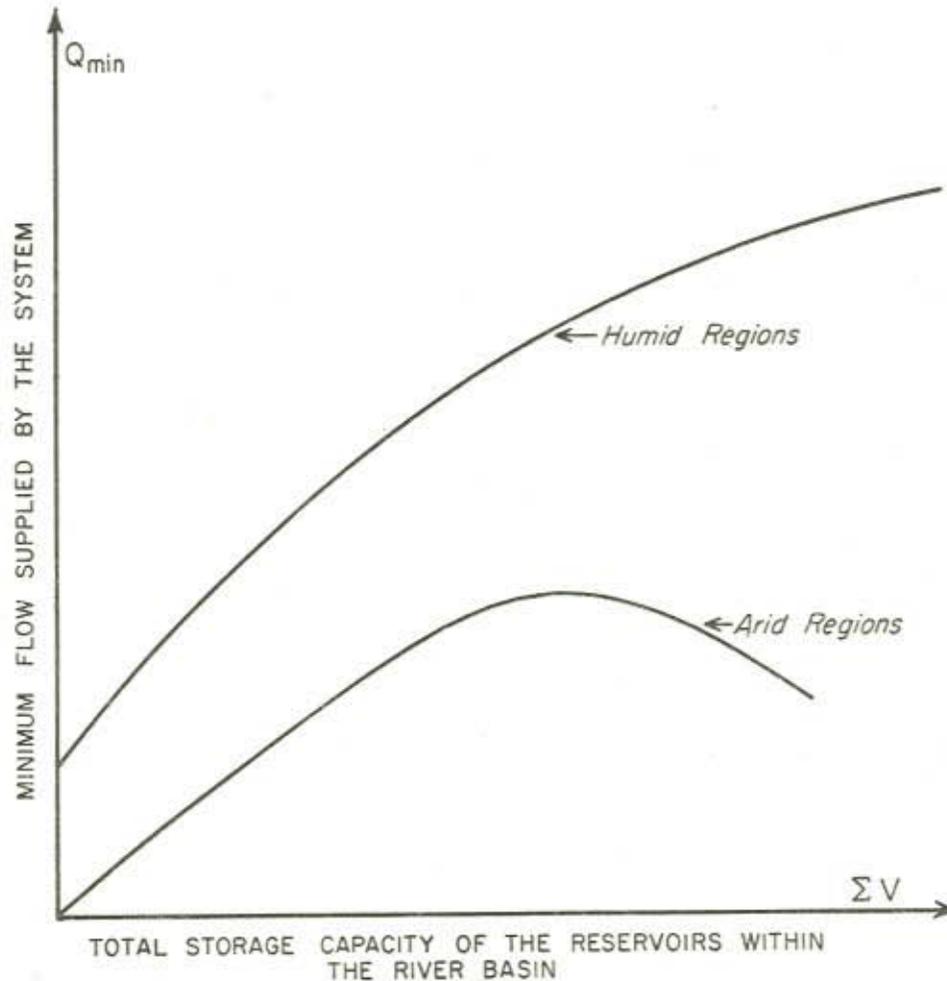


FIG. 3.1 - Effect of Storage Development on Minimum Flow

siderably that of the storage reservoirs. On a global scale the total amount of the annual streamflow regulated by the natural basins — storage to produce baseflow in dry weather — is estimated to be on the order of 12,000 cu. km., i. e., about one-third of the total runoff from land areas (Lvovich, 1969; Szesztay, 1970). Changes in land use or in soil cultivation practices may result in increased basin-regulated flow and may serve in some instances as a partial or alternative solution to constructing

storage reservoirs. In other instances they may decrease basin-regulation and increase or create problems of floods and erosion.

Natural or artificial changes in storage capacities of a river basin generally alter not only the streamflow regime, but also the water balance. These effects may be of particular significance in arid and semi-arid regions (see Figure 3.1). Comparative studies have shown that the construction of several small and medium size storage reservoirs (with a total capacity of about 200×10^6 cu. m.) have reduced the annual flow by 10 percent in average years and by 25 percent during dry years in a 2,000 sq. km, semi-arid river basin of northeast Brazil (Dubreuil and Girard, AGU, in press).

This hydrological side-effect should not be overlooked in planning storage reservoirs and comparing them with other alternative solutions of water supply. In arid and semi-arid basins such as the Colorado, increased storage reservoir development may reach a point beyond which the reduction of water yield by evaporation losses surpasses the possibilities of increasing low flow discharges from reservoir storage (Langbein, 1959).

Storage of Sediment

While designed to store water, a new man-made lake immediately begins to store sediment carried by the stream. Storage reservoirs may lose a considerable part of their storage capacity due to silting, particularly in arid and semi-arid regions. Erosion processes within the drainage area and the inflowing rivers are the principal sources of silting, but shoreline erosion in the lake itself, precipitation of a part of the dissolved materials of the inflowing waters due to changed chemical balances in the lake, non-reducible remainders of biological processes and wind-drifted materials may also contribute to the silting process. The range in observed rates is tremendous: in 1,105 small reservoirs in the United States (with storage capacity less than 100 acre feet or 0.14 million m^3) there was a loss of 54 percent of their storage capacity in 20 years under average conditions (Dendy, Champion, Wilson, AGU, in press). The corresponding value for big reservoirs (over 1,400 million m^3 or 1 million acre feet storage capacity) is 3 percent. Although many attempts have been made to develop theoretical schemes and regional empirical formulas for estimating sediment transport and rate of silting of rivers on the basis of basin characteristics, great uncertainties remain. The effects downstream on channel cutting and filling and on nutrition of estuaries and coastal beaches are of course linked to the volumes of silt remaining in the reservoir.

Earth Stresses

The filling of a lake imposes new stresses on the earth's crust which in turn generate seismic movements and in some cases earthquakes of a severity (Richter scale of 6) causing human losses. These may vary in magnitude and time in accordance with a number of factors. Water height of 100 meters or more in a reservoir constitutes a factor which may be of major seismic importance in combination with geological formation and structure. Generally, the seismic movements build

up slowly to a peak several years after the reservoir begins to fill, and then gradually decline (Rothé, AGU, 1971). Moreover, the saturation of sedimentary formations by seepage from the reservoir may not only cause major losses of water but additional seismic movements.

Unless account is taken of these stresses by prior study and observations, both the dam and nearby areas may be subjected to unexpected damage. Anticipation of such effects becomes an essential part of feasibility investigations. Preliminary studies should include detailed examination of geological and geomorphological conditions of the reservoir and neighboring areas. Potentially active geologic structures should be explored, and seismic activity assessed by a network of at least three permanent seismograph stations, plus temporary observations. These studies are needed in Stage I, Fig. 1.4.

Microclimates

Relatively little is known about the precise influence of new reservoirs upon weather and climate. At the microclimatic level, most of the evidence comes from comparison with natural lakes and their influence on precipitation, direction and frequency of wind, thunderstorms, hail, snow, and other phenomena. Further research will depend in large part upon refinement of models of micro-scale atmospheric calculation (Timofeev, 1963). The impact of the new lake on temperature, precipitation, and water balance in adjoining areas is related to both local conditions and meso-scale meteorological elements.

Transformation of Water Quality

The physical, chemical, biological, and radiological properties of the water leaving a lake may differ significantly from the waters entering the lake. A large number of factors affect this quality-transformation process, and the water balance conditions of the lake are of basic importance in understanding, predicting, or influencing these changes. Four indices of the water balance regime play significant roles in setting the quality regime in a reservoir: 1) The renewal (exchange) process of the water stored in the lake, which depends upon the ratio of fluxes to the « participating » storage capacity; storage capacity participating in the renewal process in the lake is affected to a great extent by stratification conditions and internal flow regime, 2) The ratio of the amount of precipitation on the surface of the lake to the total amount of inflow, 3) The ratio of the groundwater inflow (including direct inflow and baseflow of the entering rivers) to the total inflow, 4) The ratio of the evaporation and evapotranspiration from the lake water to the total outflow fluxes.

When these indices are known it becomes possible to anticipate gross changes in water quality, but the precise mix that will take place in the reservoir and thereby in the outflow is subject to other conditions as well. These are the conditions that in conjunction with the climate govern density stratification and flow patterns within the water body.

Density and Flow Patterns

The possibility of a density stratification is the first question to be clarified if the flow regime of a reservoir is to be predicted. Seasonal temperature fluctuations governed by the energy regime are the most common causes of a density

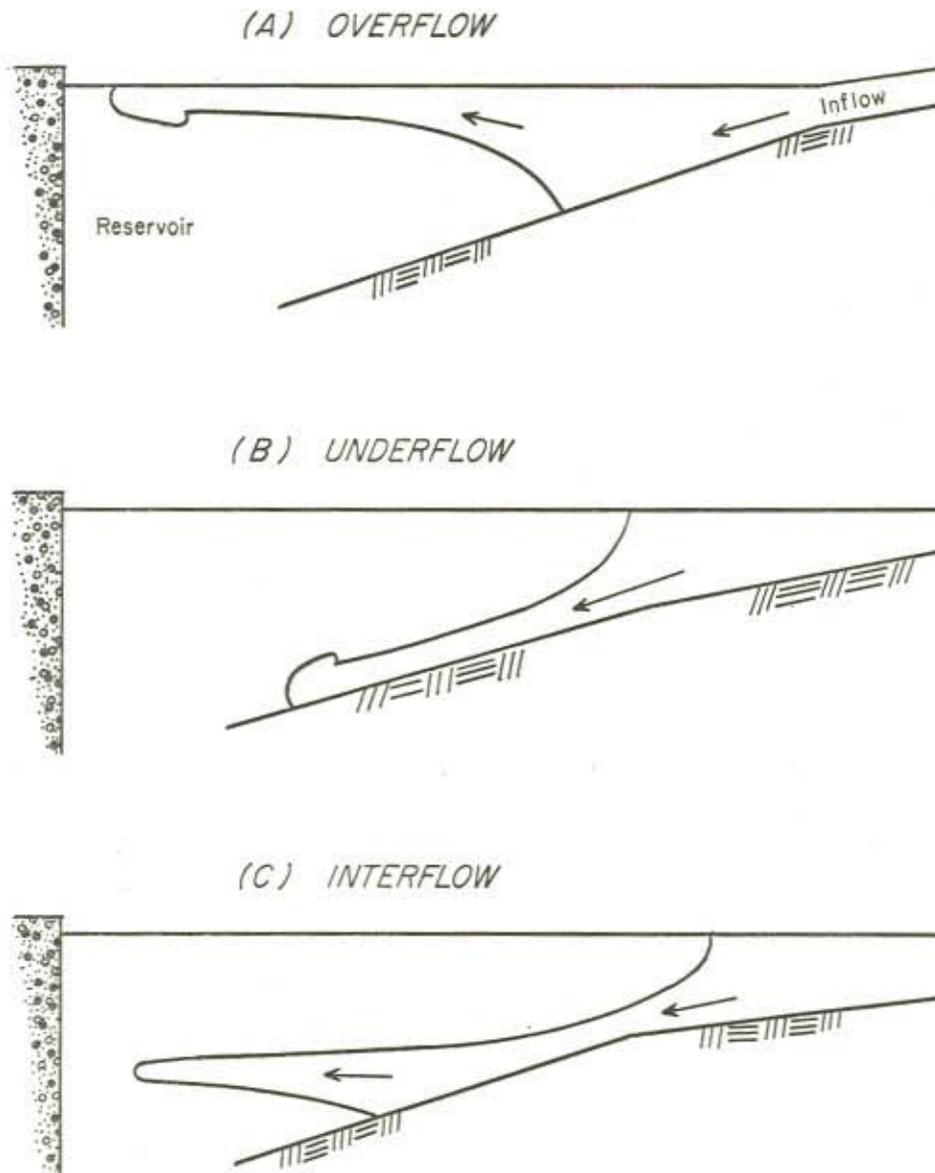


FIG. 3.2 - Principal Inflow Patterns of Man-made Lakes

stratification, but other agents such as dissolved or suspended solids can also be influential. Beyond differences in densities (temperature) at different depths, the

rate of flow through a given cross-section is the principal factor determining the possibility of the formation of a stagnant layer or distinct water masses in the reservoir. A critical value of the densimetric Froude number (comparing the rate of flow to density gradient) has been derived theoretically for specifying conditions for the formation of a stagnant layer. However, laboratory and field data indicate that differences in morphometrics and flow characteristics cause significant deviations from this theoretical value (Elder and Wunderlich, AGU, in press). In the Temperate Zone, stratification in reservoirs having little inflow and outflow may be observed even where they are shallow (10 to 12 meters). In contrast, strongly flushed reservoirs may be homogeneous down to several times those depths.

Where density stratification occurs, the inflow waters may move and be stored at the surface (overflow), at the bottom (underflow), or at an intermediate depth (interflow), according to how the conditions of their temperature (density) fit into the temperature profile of the reservoir (see Figure 3.2). For similar reasons, flows caused by natural outflows or withdrawals develop also in specific layers of limited thickness. As a result, several distinct and independent internal currents may simultaneously exist within a density-stratified reservoir.

Wind drift is a major factor of the flow regime in shallow waters and in the surface layers of deep lakes (Filatova and Alejarv, AGU, in press). Geometry of the shoreline and the lake basin play important roles in the formation and development of the flow pattern corresponding to a wind of given direction, velocity and duration. Due to changes in wind regime and to the secondary flows generated by wind which cause changes in the water surface, the actual flow pattern reflects the residual effect of several preceding winds.

It thus becomes practicable to predict certain of the gross parameters of depth, area, water volume, sediment volume, and water quality in the new water body if there are data or estimates of the factors noted. Where these are missing the characteristics are much more conjectural. This doubt is increased by man's potential to manipulate inflow and outflow, and, thereby, some aspects of temperature distribution in the reservoir. The totality of currents in a reservoir, whatever the causes for their generation, comprise a dynamic system for which relatively sophisticated model study is necessary as a basis for anticipating the consequences of altered schedules of manipulation.

Waste Discharges into the Lake

In many reservoirs the human discharge of waste has a significant effect upon water quality, often as a result of measures not taken into account when the reservoir was planned. Thermal discharges may be highly significant, and flows of domestic and industrial effluents, of farm waste, and of excess fertilizers and pesticides may drastically modify the quality of stored water. In Western Europe there are numerous reservoirs and some natural lakes that have experienced major changes in quality over recent decades as a result of such wastes.

Heated waters are frequently released into man-made lakes by thermoelectric generating plants. Comprehensive evaluations of the applicability of the results of theoretical investigations lead to a few conclusions as to physical effects (Parker, Polk, Benedict, Motz, Krenkel, and Edinger, AGU, in press). In conditions of strati-

fied flows the wedge lengths of the heated waters may be predicted with considerable accuracy on the basis of theoretical solutions. Where there is no heat loss, which obtains close to the discharge point, the surface area within a specified temperature rise and the distance to complete mixing can be computed with reasonable accuracy on the basis of several diffusion models. Surface cooling usually has little effect in the initial regions, but it may become a significant factor if the influenced area increases in extent.

For maintaining the required water quality conditions it is important that waste discharges into the transient flows of man-made lakes be released in a prescribed proportion to the instantaneous flow passing the point of release. Thus, a continuous forecasting service of the inflow and transient flow rates is a prerequisite for the effective solution of such problems (Cranju, Garrison, and Price, AGU, in press). It can be very important in evaluating the effects of thermal discharges on biological production.

Predictive Capacity

A great part of the present knowledge on hydrology and hydraulics of reservoirs is based on the data of regular hydrological observations and special field measurements. In addition, hydraulic models and laboratory tests are widely used tools in studying basic and applied problems of stratification conditions, flow regime, erosion, and sedimentation.

The development of a hydrological model applicable to simulate the water balance and the related hydrological events of a lake and its incorporating system is certainly the most promising basis for designing man-made lakes and evaluating their environmental aspects. For studying nutrient budget and aging processes of Lake Minnetonka, U.S.A., a three sub-unit model was recently developed to simulate the water budget and lake level fluctuations on a monthly time scale (Barr and Gebhard, AGU, in press).

A comprehensive model for lake-studies is under development at the University of Texas for simulating *long-term water quality* changes (Clay and Fruh, AGU, in press). At its present phase the model is composed of four principal components: 1) inflow thermal and chemical routing; 2) atmospheric and radiation sources and sinks of heat; 3) vertical diffusion of heat and chemical concentrations; and 4) outflow routing (selective withdrawal). In the course of further development it is intended to include additional components, such as chemical-biological changes of non-conservative chemicals within the impoundment, and accounting for continuous changes in the water, heat, and chemical budgets.

Present investigations focus on heat balance and temperature regime. In the computations concerning stratification conditions and flow regime the Koh and the Bohan-Cracee solutions have been tested and the latter has been applied. Heat balance components related to the water surface and those determined by the inflow and outflow were assessed separately, but combined in later phases of the procedure. Investigations involving temperature profiles, total heat content and outflow temperatures as criteria for comparing computed and observed values are under way in several areas, including France, Rumania, and the United States.

Theory and techniques of modelling and simulating large complex systems consisting of a hierarchy of models or sub-models are developing rapidly, and it may be expected that evaluation of alternatives for man-made lakes will be assisted by this method with due regard to fairly wide ranges of their hydrological, environmental economic, and social aspects (McLeod, 1971). By way of caution it should be noted that present predictive models for temperature regimes of reservoirs are still in the experimental stage, due mainly to lack of precise input over time as well as to differences among reservoirs in morphological, hydrological, and atmospheric conditions. However, this involves modelling biological systems as well. If and when they can be brought to the point of practical use, then other water quality parameters such as dissolved oxygen may be introduced. Both density and chemical stratification are intimately related to fish production and harvest.

The Process of Creating a New Water Body

With regard to hydrological and engineering activities the process of creating a new water body has four major phases which only slightly differ from those specified earlier (see Fig. 1.4) from the broad ecological point of view.

- 1) Within the *feasibility studies* the water management options need to be specified with due regard to a tentative evaluation of all possible reservoir sites within the given region. These studies are principally based on available maps and data banks.
- 2) *Engineering design* may provide details of one or more of the accepted options and is usually based on extensive field surveys and observations. This is the phase when social and environmental impacts should be identified and evaluated before final decisions are made as to design.
- 3) The phase of *completing the project* includes the construction of the dam and other engineering works (sluices, spillways, channel improvements) and the filling of the reservoir which is usually the responsibility of the constructors and may overlap with the construction period.
- 4) The *operation and maintenance* phase requires short-term and long-term forecasts on the hydrological regime, as well as regular control of processes predicted or assumed in the design (rate of silting, temperature and ice regime, filtration under and across the dam, subsidence of the structures, etc.).

Regulation of Lake Level Fluctuations

Short-term and long-term fluctuations in the lake levels reflect the non-equilibrium character of the water balance as governed by the meteorological events (primarily by the precipitation and temperature regimes).

Such fluctuations usually do not correspond, either singly or simultaneously, to the requirements for fish production, navigation, recreation, power production, or other water uses under natural conditions. In the tropics and warm-temperate zone, mats of vegetation also greatly affect the water balance, and may hinder navigation, fisheries, and other uses. The construction of sluices to control the rate of outflow from the lake is the simplest and most widely applied way of intervening

in the natural water balance and influencing the lake level fluctuations. Many attempts are made to reduce evaporation rates by monomolecular layers or surface covers on small reservoirs of the arid regions, but a complete control of lake level fluctuations usually requires diversions from neighboring river systems.

Such diversions of course impose changes upon distant ecosystems. In mountainous regions, diversion by tunnel through a large vertical height, with only modest lake storage, may be attractive for power generation. The drawdown may thus be largely below natural lake levels, with exposure of lake bottom. These kinds of reservoir projects pose many problems which are variations on the usual themes of reservoir impact. For example, natural river flows may be reduced in the drainage that was naturally receiving the diverted water, creating problems of passage for anadromous fish (the Nechako diversion in British Columbia is a good example).

Effects of Withdrawal

Any withdrawal of water by the lake from its inflowing rivers influences the water balance and stage regime. The result is a shift in the long-term equilibrium of the water balance and mean lake level. The direction and extent of the shift are determined by differences between long-term average precipitation and water surface evaporation. If evaporation exceeds precipitation the result is a decrease in lake level and surface area, as in Lake Valencia, Venezuela. Quantitative estimates of the effects of withdrawals can be made on the basis of generalized water balance equations or diagrams specifying the long-term averages of the water balance components in relation to changes in the mean water level or surface area of the lake (Figure 3.3).

Hydrological Forecasting Services

Safety and efficiency of riparian developments and water uses served by the lake may benefit from regular information about water levels and flows to be expected during operating periods. Short-term forecasts of flood flows of inflowing waters based on water stage and rainfall data at selected stations of the lake basin are essential to proper manipulation of spillways and sluices to avoid or decrease flood damages along the shoreline or at the dam site. Monthly and seasonal predictions of expected minimum and mean inflow may have great economic significance by making possible advance measures and regulations for water use. Predictions on water temperatures and ice regime are based on short-term and long-term meteorological forecasts and are facilitated by the great thermal inertia of the water body of the lake. The significance of such predictions of transient flow with regard to waste disposal already has been noted.

Hydrological Observations on Man-made Lakes

Regular and occasional hydrological observations and field surveys are required for the following principal purposes:

- 1) to supply basic data for hydrological information and forecasting services needed

LAKE FERTÖ

$P = 710 \text{ mm}; E = 900 \text{ mm}; r = 0.085; A_{\text{lake}} + A_{\text{drainage area}} = 1300 \text{ sq. km}$

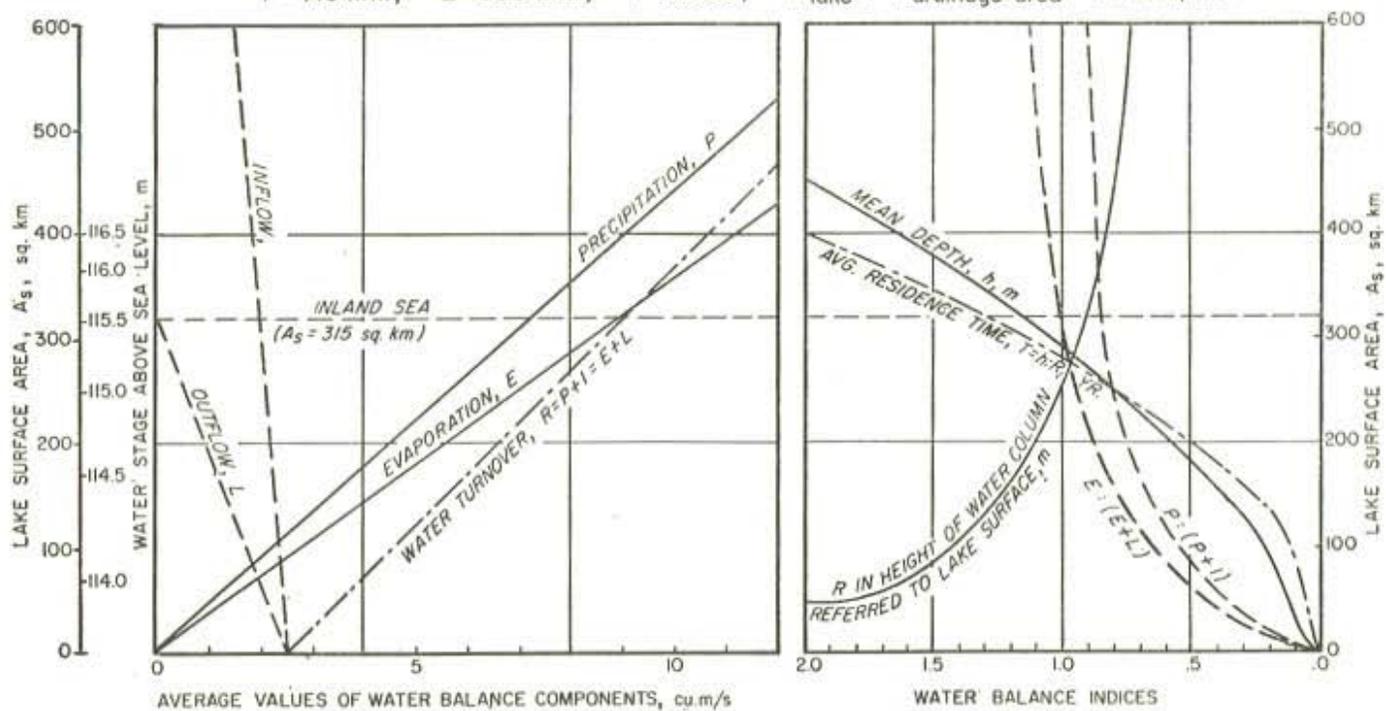


FIG. 3.3 - Interrelations Between Long-term Values of the Water Balance and Mean Elevation of Lake Level for Lake Fertő

- for operation of the reservoir and the riparian water uses (possibly by telemetering systems in case of short-term warnings and forecasting);
- 2) to check the development of long-term hydrological processes which may influence the safety and efficiency of reservoir operation (rate of silting, filtration below or across the dam, shoreline formation, effects on groundwater, etc.); and
 - 3) to supply data for further research on the processes involved.

National Inventories of Man-made Lakes

With regard to both hydrologic observations and national inventories of characteristics of existing lakes, the opportunities for data collection are enormous, and national agencies must judge how much information is essential to wise operating decisions. National or state registers may serve as a basis for selecting a few representative lakes and reservoirs for regular observation and detailed studies.

A register summarizing a few basic data (surface area, average and maximum depth, purposes and extent of utilization) would include all lakes, reservoirs, ponds and dead river arms surpassing a reasonable lower limit. As an example illustrating the significance of small size lakes and reservoirs, in Hungary the total number of lakes and reservoirs surpassing 100 hectares is only 34 but this number increases to 300 and 1200 if 10 hectares or 0.5 hectare are selected as lower limits of the register. Aerial photographs may supply most of the data required for this kind of national register, and, with appropriate dating, provide a basis for evaluating seasonal and year by year changes.

Changing Uses and Values

Although it is true that most dams are built to endure over centuries, it is a grave mistake, often not accepted by the designer, that their uses likewise will remain unchanged. The record of the past four decades shows that the specific uses made of the water body may evolve rapidly after construction. However precise may be the allocation of water among expected uses, new technologies and new social values may alter the desired mix. Flood control storage may be claimed for low-water waste disposal as on the Ohio River. Recent experience in the Ruhr sector of the Rhine basin illustrates how increasing demands for recreation may inhibit fluctuations in water level first designed solely to serve navigation or electric power production. Such modifications in operating schedules in turn alter the hydrologic characteristics of the lake. The fourth stage (IV) is never completely uniform. And the accompanying biological transformations never are final, even though they may be more stable than during the filling stage.

The likely course of physical and chemical events in a man-made lake is more nearly predictable than are the socio-cultural events, but the two are interlocked, for man continues to manipulate the basic inputs and outputs of water and chemicals. Thus, the stage that is set for biological transformations is bound to remain unsteady.