Summary: Hydrology and Man-Made Lakes

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From a hydrologic point of view, lakes are storage elements of a local or regional hydrologic system. They alter the quantity and quality regime of the water flowing through this system. The evaluation of the actual or potential effects of a man-made lake on its physical and biological environment should usually start with the identification of the changes in the hydrologic regime as a first step and basis for further studies.

The basic role of hydrologic considerations in the topics of this volume is well reflected by the great number of papers devoted to these questions. The papers on the hydrologic aspects of the subject are discussed in this summary and then are presented as separate papers.

The title of the volume implies two criteria with regard to waters belonging to the subject: they should be 'man-made,' and they should be 'lakes.' Both terms may raise some concern if precise definitions are to be made.

Beyond the really man-made lakes (for which nature supplies only the principal element, water), there are a great number of lakes created by natural processes but altered and controlled more or less by man (artificial decrease or increase of the average water level and surface area, regulation of the shoreline, control of the inflow and outflow, introduction of heat and chemicals by waste disposals, and so on). The identification and agreed application of some indices expressing the relative significance of human influences would probably be of help if distinctions are to be made between natural and man-made lakes. It also seems to be rather difficult to specify accurate dimensions beyond which water bodies are large enough to be called lakes.

Most of the papers belonging to this subject area interpreted the above criteria in a broad sense and discussed generally the problems of storage reservoirs with some emphasis on larger ones. Many of their considerations and findings may be equally applied to problems of natural lakes.

MAN-MADE LAKES AS ELEMENTS OF WATER RESOURCE SYSTEMS

Each natural or artificial water resource system includes two kinds of components: fluxes (inflows and outflows) and storages. The greater the total capacity represented by the storage elements, the more the supply from the system can follow time variations of the water uses served by the system. Man-made lakes are important tools for increasing the total storage capacity of the water resource systems. Estimations on a global scale indicate that the total amount of water supplied for various purposes from the world's storage reservoirs is on the order of 4000 km^3/yr, and it is expected that this value will be roundly tripled until the year 2000 [*Lvovich*, 1969].

To build or not to build man-made lakes in the future is certainly not the right formulation of the question. A more proper formulation, perhaps, is where, when and how to build, and what supplementary studies and actions to undertake to achieve the intended benefits without unwanted damage.

River basins as storage reservoirs. Man-made lakes represent additional storage capacity of hydrologic systems. There always exists an initial (natural) storage capacity of the river basin itself that transforms the rainfall and snowmelt regime into the streamflow regime of the river. The streamflow-regulating effect of this basin storage usually considerably surpasses that of the storage reservoirs. On a global scale the total amount of the streamflow regulated by the natural subsurface storages into base flow (dry weather flow) is estimated to be on the order of 12,000 km^3, 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 cases as a partial or alternative solution for constructing storage reservoirs. In other cases, these changes may decrease basin regulation and may raise or increase problems of floods and erosion.

Man-made lakes and water balance of the river basins. 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 semiarid regions. Comparative studies have shown that the construction of several small-size and medium-size storage reservoirs (with a total capacity of about 200×10^6 m^3) has reduced the annual flow by 10% in average years and by 25% during dry years in a 2000 km^2 semiarid river basin of northeast Brazil [*Dubreuil and Girard,* this volume].

This 'hydrologic side effect' should not be overlooked in planning storage reservoirs and comparing them with other alternative solutions of water supply. In arid and semiarid regions, by increased storage reservoir development, a point may be reached beyond which the reduction of total water yield by increased evaporation losses surpasses the possibilities of increasing low flow discharges from reservoir storage [*Langbein,* 1959].

Alternatives in planning of man-made lakes. The basic reason for constructing reservoirs and man-made lakes is usually the increased need for domestic, agricultural, or industrial water supply. When water demands of the region are specified, a careful study of all possible alternatives should follow, perhaps including the following principal types of solutions: (1) construction of storage reservoirs, (2) artificial recharge of groundwaters, (3) extension of groundwater explorations, (4) diversion of water from neighboring regions, (5) increase of the streamflow by watershed management, and (6) decrease of the specific water requirements by technological changes.

Within each type of solution, usually several alternatives may be found. In case 1, for example, the same increase in water supply may be assured by one big reservoir or several small reservoirs or by combining this solution with any of the others. Some of the alternatives or combinations may be sorted out rather easily, but others may require intensive studies before a selection can be made [*National Academy of Sciences*, 1968].

One of the important issues concerns the involvement of studies of environmental effects of man-made lakes into the very beginning phase of formulating and evaluating alternatives. Theory and techniques of modeling and simulating large complex systems consisting of a hierarchy of models or submodels are rapidly developing, and it may be expected that alternative problems of man-made lakes will soon be studied by this method with due regard to all their hydrologic, environmental, economic, and social aspects.

Classification of lakes: a tool for integrating experiences. Positive and negative experiences of existing reservoirs and man-made lakes are important sources of improved planning and management in the future. For example, the valuable documentation and studies of the *Food and Agriculture Organization* [1970; *Lagler,* 1969] can be mentioned. One of the difficulties in evaluating and interpreting experiences is the large variety of problems and reasonable methods of solution according to local conditions. A problem-oriented classification of lakes and reservoirs based on the primary hydrologic and environmental factors predetermining or influencing their physical, chemical, biological, and radiological regime could be one of the tools for overcoming or decreasing this difficulty.

With regard to the selection of the basic factors of the classification, a reasonable compromise should be found between requirements of completeness and representativeness on the one side and those of an easy interpretation and availability in the planning stage on the other. As a very tentative list the following groups of factors may serve as a basis for further consideration: (1) size and geometry of the lake or reservoir, (2) water balance conditions, (3) climate, (4) soil and vegetation at the site of the reservoir before its construction, (5) soil, vegetation, and morphology of the drainage area, (6) age of the lake or reservoir, and (7) influence of men on the natural conditions.

Within each of the above groups a few parameters should be specified. In the case of group 2, for example, the following three indices may identify the principal features of the water balance conditions [*Szesztay,* 1967]:

1. The first is the average volume of water in the lake related to the average annual flux. The latter is the sum of input (precipitation + inflow) or output (evaporation + outflow) components of the water balance. This ratio characterizes the renewal process of water in the lake.

2. The second is the ratio of average annual precipitation on the lake surface to the average annual flux.

3. The third is the ratio of average annual evaporation to the average annual flux.

After having specified each of the appropriate classification indices for a sufficiently large number of existing lakes and reservoirs in different parts of the world, we can make a statistical evaluation. The aim of this evaluation is to derive correlation relationships between classification indices and the principal parameters characterizing the physical, chemical, biological, and radiological conditions of the lakes and their environmental effects. These relationships and the classified data bank are of great help in estimating expectable conditions or selecting analog cases for detailed studies during the first phases of the planning process.

FLOW REGIME AND STRATIFICATION IN MAN-MADE LAKES

Water is certainly the medium for which man-made lakes are created. But not all kinds of water may satisfy human needs. Its quality has to correspond to certain criteria depending on the purposes for which the water in the lake or supplied from the lake is used. The planning of a man-made lake requires predictions not only on quantities of water filling the bed of the lake and causing fluctuations of its level, but also on the quality regime of the water that will be stored in or supplied from the lake.

The physical, chemical, biological, and radiological properties of the water in the lake or leaving the lake can considerably differ from the properties of the waters entering the lake. It is not possible to understand, predict, or control this change without knowing the flow regime and the stratification processes within the lake.

Basic considerations. First, the existence or the possibility of a density stratification is the first question to be clarified if the flow regime of a lake or reservoir is to be investigated. Seasonal temperature fluctuations are the most common causes of a density stratification, but other agents such as dissolved or suspended solids could also be factors. Beyond differences in densities (temperature) in different depths the rate of flow through the given cross section is the principal factor determining the possibility of the formation of a stagnant layer. A critical value of the densimetric Froude number (comparing the rate of flow to the density gradient) has been derived theoretically for specifying conditions of the formation of a stagnant layer, but laboratory and field data indicate that differences in geometries and flow characteristics can cause significant deviations from this theoretical value [*Elder and Wunderlich*, this volume]. In the temperate zone reservoirs with little inflow and outflow, expressed stratification may be observed even in cases of small depth (10–12 meters), whereas strongly flushed reservoirs may be homogeneous down to several times those depths.

Second, in case of density stratification 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 [*Slotta*, this volume]. For similar reasons, flows caused by natural outflows or withdrawals are also developing in specific layers of limited thickness. As a result, several distinct and independent currents may simultaneously exist within a lake or reservoir with density stratification.

Third, wind drift is a major factor of the flow regime in shallow waters and in the surface layers of deep lakes [*Filatova and Kalejarv*, this volume]. The geometry of the shoreline and the lake basin plays an important role in the formation and development of the flow pattern corresponding to a wind of given direction, velocity, and duration. Because of the changes in wind regime and the secondary flows generated by wind that cause changes in the water surface, the actual flow pattern reflects the residual effect of several preceding winds.

Methodology of investigations. Hydromechanical analysis of the basic processes, field surveys, and physical or conceptual models are equally important and mutually interrelated tools in investigating flow regime of lakes and reservoirs. The determination of the thickness of the withdrawal flow layers in the case of selective withdrawals is a good example for the combined application of hydromechanical analysis and field research [*Wunderlich and Elder*, this volume]. As a result, two formulas have been derived for such problems: one for the cases of surface and bottom withdrawals and another for intermediate withdrawals.

Hydraulic models and laboratory tests are widely used tools in studying basic and applied problems of flow regime and stratification. Transient flow problems (including dilution of waste waters and identification of the effect of the geometric configurations on flow patterns) can be analyzed with satisfactory results also by models with geometric distortion on the basis of specifically adopted conditions of kinematic similarity. In the case of wind-caused currents, quantitative results can be expected only by models having the same horizontal and vertical scales.

Hydraulic models have been successfully applied also to studies concerning the influence of entering streamflow on currents of density stratified reservoirs [*Slotta,* this volume]. Laboratory results were compared also with data of an interesting field measurement traced by dye concentrations at one of the Tennessee Valley Authority (TVA) reservoirs.

Applications. The identification of stratification and flow regime is the basis of the solution to many practical problems concerning movement of heat and dissolved or suspended materials in lakes or reservoirs. In the man-made lakes of the TVA system, the power-peaking operations of the hydropower plants are the dominating factors determining flow regime [*Granju et al.,* this volume]. For maintaining the required water quality conditions, it is important that waste discharges to the system be released in a prescribed proportion to the instantaneous flow passing the point of release. A good example of the applicable methods for solving such problems is reported by *Granju et al.* [this volume] for Kentucky Lake. The flow regime of this reservoir is determined by the intermittent operations of the upstream and downstream hydropower plants as well as by an uncontrolled navigation canal connecting Kentucky Lake with the upstream reservoir. The solution was based on a mathematical routing model and supplied predicted flows and stages for 21 cross sections at 1-hour intervals for a 42-hour forecast period in < 1 min of computer time on an IBM 360/50 system. The forecasts are based on the expected power production of the two plants that is revised day by day.

Heated waters are frequently released into the lakes and reservoirs by steam electricity generating plants. A comprehensive evaluation of the applicability of the results of theoretical investigations under the conditions of the TVA reservoirs led to the following principal conclusions [*Benedict et al.,* this volume]:

1. For the conditions of stratified flows the observed wedge lengths of the heated waters agreed closely with those computed on the basis of the theoretical solution proposed by G. L. Bata.
2. For the case of no heat loss, which prevails 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 proposed diffusion models.
3. Surface cooling usually has little effect in the initial regions, but it may become a significant factor if the influenced area increases.

A comprehensive model is under development at the University of Texas for simulating long-term water quality changes [*Fruh and Clay,* this volume]. In its present phase the model is composed of four principal components: inflow thermal and chemical routing, atmospheric and radiation sources and sinks of heat, vertical diffusion of heat and chemical concentrations, and outflow routing (selective withdrawal). In the course of further development it is intended to include components such as chemical-biological changes of nonconservative chemicals within the impoundment and accounting for continuous changes in the water, heat, and chemical budgets of the impoundment.

Present investigations are focused on heat balance and temperature regime. In the computations concerning stratification conditions and flow regime, the Koh and the Bohan-Grace 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 were combined in later phases of the procedure. Temperature profiles, total heat content, and outflow temperatures have been selected as criteria in comparing computed and observed values of Lake Travis (south central Texas) for a 2-year period.

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