Summary: Interaction between Reservoirs and the Atmosphere and Its Hydrometeorological Elements

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The atmosphere and its meteorological and hydrometeorological factors represent one of the most important physical components of the environment of all water surfaces and bodies. They have an interaction with the water body, be it freshwater or ocean, and influence not only the physical and in particular the hydrologic behavior of the body and its other environmental components but also its biological and ecological systems. It is therefore most difficult to examine in a relatively short paper all the aspects of this interaction, on parts of which books have been written [*Timofeev*, 1963]. Further, it should be noted that the most important intention of this volume is that the problem be considered as a broadly interdisciplinary one, and the paper is not therefore intended for meteorologists or hydrologists but for a broader audience of specialists from all fields concerned with man-made lakes and lakes in general.

It will certainly be appreciated that the paramount interaction between a reservoir and the atmosphere is the process of evaporation. It has in itself warranted many symposiums, and both scientific and operational aspects of this problem attract the attention not only of individual specialists and national agencies but also of international nongovernmental and governmental organizations, particularly the *World Meteorological Organization* [1966; *Hounam*, 1971].

The interaction of a lake and the atmosphere occurs mainly through exchange of mass, heat, and momentum [*Bruce*, 1963]. The evaporation process and some others cut across at least two such exchanges. In addition, environmental changes resulting from man-made lakes necessarily invite a different approach from the one used for natural lakes. In many cases the concrete problems of interaction of a man-made lake with the atmospheric environment must be solved or at least envisaged before the lake exists, and thus the necessary initial data for an empirical solution are completely lacking. A theoretical analysis imposes itself in such cases, and it is often based on data collected on natural lakes under similar environmental conditions.

Thus the first and most important task for further improvement of scientific and operational knowledge of the man-made lakes interaction with the atmosphere will be a systematic collection of data. We will examine this task first, and a detailed example is offered in this direction by the *USSR Hydrometeorological Service* [1957]. The second point, which is examined in some detail, is the theoretical aspect of the problems of the turbulent exchange and vertical distribution of meteorological elements in the air-water interface and the profile above and near the reservoir. Since heat balance is at the base of the meteorological regime above water bodies, elements of this balance are examined.

Practical conclusions from and influence of the interaction of man-made lakes with the atmosphere depend on the size of the water body. A classification of such man-made water bodies from the point of view of practical implication on atmospheric processes, be they in meteorological macroscale, mesoscale, or microscale, is therefore useful.

The interaction may further be considered either as the influence of the water body on the meteorological factors or vice versa. Depending on the size of the body, this problem will be equally examined, and a summary of detailed studies presented in other papers in this section are quoted for this purpose. Furthermore, work undertaken on the North American Great Lakes by United States and Canadian scientists yields significant results in this direction. The instrumentation used for collection of data and in particular for research on the air-water interaction is constantly improving. In addition to routine observations, specially equipped boats, aircraft, radar, radioisotopic tracers, and satellite imagers are used to improve the insight into the processes in space and time.

Because of these instrumental developments, progress in research acquires a rapid pace. It is, however, important that the main direction of future research be oriented toward acute problems of the environment and the urgent necessity of its protection. Some ideas in this direction will be forwarded.

The breakdown of the subject will therefore be as follows: data collection systems, theoretical substance of the problems, influence of the air-water interaction in reservoirs and its practical implications, instrumentation developments for research purposes, and conclusions and future research trends.

DATA COLLECTION SYSTEMS

Although this paper is mainly concerned with the interaction of meteorological and hydrometeorological factors with water bodies, the data collection systems indicated below tend to integrate all observations to be made on such bodies. Indeed, not only for reasons of financial economy but also for the sake of an interdisciplinary consideration of a man-made water body, the integration of all operations should be the rationale behind data collection systems installed at all reservoirs. Thus meteorological, hydrologic, geologic, biological, and all other data should be gathered within one integrated system whenever possible. Examples from the USSR, United States, and Canada demonstrate the usefulness of such an approach.

Although meteorological and hydrologic observations are made in accordance with the principles of such observations at any observing station, special instructions and methods are required and exist for lakes and man-made reservoirs in addition to general principles, which have been put forth on an international level by the *World Meteorological Organization* [1968*a*, *b*, 1970].

An inventory of lakes and reservoirs on a national level is a prerequisite for the installation of comprehensive observational networks. Such an inventory, as initiated, for example, in the USSR [*USSR Hydrometeorological Service*, 1957], is based on the following data for individual lakes: (1) name, (2) type of water body (man-made reservoir, lake, and so on), (3) short description of the hydraulic work (for man-made reservoir), (4) geographical coordinates, (5) area of the catchment, (6) morphometric data (area, widths, lengths, depth, normal levels, and so on), (7) description of the shoreline and of the depression forming the bottom, (8) basic elements of the hydrologic regime, (9) degree of data collection progress (including research campaigns), and (10) use of the reservoir (power production, navigation, and so on).

An inventory of all lakes comprising the above elementary data allows the possibility of rapidly ascertaining the amount of data available not only for any particular reservoir but also for a generalized research program. In addition to the inventory of reservoirs, all permanent observational stations on reservoirs should be listed in a published inventory. (In the USSR, such an inventory is published every fifth year, e.g., 1960, 1965, 1970, and so on.)

Routine basic meteorological observations that should be made on every reservoir are air temperature, absolute values of air moisture, precipitation, cloudiness, wind speed, and frequency of wind speed in different directions of the wind rose. Hydrologic observations involving meteorological elements include records of water levels (particularly during wind setups and seiches), temperatures of the water surface, and the water profile in depth. In addition, the ice and snow conditions; chemical composition (basic components are Ca, Mg, Na+, K, HCO_3, SO_4, and Cl); and height, period, amplitude (length), and velocity of propagation of waves should also be measured and indicated. The wave regime description should include frequency evaluation. In research stations the meteorological elements in the profile above the lake should be indicated. The direction and velocity of currents should also be observed on lakes that are large enough to warrant such observations.

The manual of the *USSR Hydrometeorological Service* [1957], in addition to instructions for all the above observations and their processing, indicates the computation of the water balance of each reservoir or lake. It is, however, considered by the author that methods for the computation of such a balance are rather difficult to standardize and that the instructions included in the manual may serve only as a useful example. Within the USSR Hydrometeorological Service [*Vikulina and Seljuk*, 1966] a specialized observational network on man-made reservoirs has been organized and is operating at present 13 hydrometeorological observatories and 30 lake stations as well as >250 hydrometeorological stations, which provide basic data for man-made reservoir study.

THEORETICAL SUBSTANCE OF THE PROBLEMS

Although macroscale, mesoscale, and microscale processes present different facets of practical implications [*Bruce et al.*, 1968], the theoretical approach may be integrated with the examination of differential equations governing mass and energy transfer between the water body and the atmosphere on one side and the mass and energy transfer between the land (shores) and the atmosphere on the other side. Depending on the boundary conditions, the practical conclusions vary for small and large reservoirs in space and time over the water surface and its land environment.

The basic elements of the heat balance equation must be considered for the air-water interface (the water surface) and for the active air layer above it, which, depending on the size of the water body, may vary considerably. The basic heat balance equation for the active boundary layer of the air on the air-water interface may be written in the following form [*Budyko*, 1956]: $R = LE + P + B$, where R is the difference between the heat energy received in radiation form and that returned to the atmosphere, LE is the loss of heat due to condensation or evaporation, P is the heat exchange between the water surface and the adjacent atmosphere, and B is the heat exchange between the active air layer and adjacent layers.

It is to be noted that in the solution of this equation (and in particular for the estimation of evaporation) an important ratio of two of the above elements has been introduced, namely, the Bowen ratio P/LE, which may be expressed through the values of the saturation deficit and the temperature of the water surface corresponding to the boundary conditions of the active layer of the air. Thus the measurements of air temperature and moisture in the profile above the water surface and the temperature of the latter acquire particular importance among the meteorological and hydrologic elements to be measured on reservoirs and lakes. The above equation and the variations of its elements govern the meteorological regime above the water and the surrounding environment.

The equation of mass transfer (in this case, of water evaporation by diffusion and turbulence) and that of energy transfer are most sensitive to the vertical profile of the wind turbulence and thus to the values of the drag coefficient and surface stress. The logarithmic wind profile approach is probably the most widely known method for estimating these parameters, although other methods are also used [*Bruce et al.*, 1968] for the lower layer of air over the water body. *Timofeev* [1963] indicates the value of the roughness length (coefficient) Z_0 as 10^{-4} meters, which is 2 orders of magnitude less than the value over the land. This difference in order of magnitude applies equally for the coefficient of turbulence of air motion over water and land. Whereas the logarithmic profile applies approximately to conditions of equilibrium (neutral atmospheric stability) in nonequilibrium situations, the vertical profile of meteorological elements (wind, temperature, and humidity) may be expressed by the exponential equations. Such equations have been derived for spring inversion situations and convection by *Laichtman* [1961], *Budyko* [1956], *Monin and Obukhov* [1954], and *Timofeev* [1963]. Direct measurement of the drag coefficients has been undertaken and reported recently by many authors, and results are briefly reported by *Bruce et al.* [1968].

Once the question of exact determination of the drag coefficient either indirectly or by direct measurement (in this latter case the type of instrumentation used represents a problem that requires much further research and study) is satisfactorily terminated, it will help to solve many practical problems of the air-water boundary layer.

On the basis of the analysis of the equations of energy and mass exchange the following classification of reservoirs has been proposed [*Timofeev*, 1963] with respect to the interaction with the atmosphere: (1) large (or unlimited) reservoirs where the dimension along the wind direction axis L is $>10^6$ meters, (2) limited reservoirs where 10^3 meters $< L < 5.10^5$–10^6 meters, and (3) small reservoirs where $L < 10^3$ meters. However, it is to be noted that, for the purpose of evaporation estimates, this classification is insufficient since the depth of the reservoir is of paramount importance for this process.

The diurnal, seasonal, and annual variations of temperature, moisture, and wind values of the atmosphere over the reservoirs, over their environment, and in the active layer of the water depend largely on the dimensions and classification given above and will be described briefly from observational and experimental results, some of which are reported in this volume. As has already been mentioned, this paper will not discuss the specific problems, either from a theoretical or from a practical aspect, of different methods of evaporation assessment from the free water surface (be it for small and shallow or large and deep man-made reservoirs or natural lakes), since sufficient attention is devoted to such methods in the references indicated, e.g., in the above-mentioned World Meteorological Organization publications.

INFLUENCE OF THE AIR-WATER INTERACTION IN RESERVOIRS AND ITS PRACTICAL IMPLICATIONS

Man-made reservoirs that have an influence in macroscale and mesoscale meteorological processes are rather few, and observations on them are even fewer. The only reported observations are those from reservoirs in the USSR and the United Arab Republic, namely, the Kuybischev Reservoir [*Borushko,* 1965] and Lake Nasser [*National Center for Atmospheric Research*, 1966]. Borushko, investigating the distribution of temperature and absolute humidity of the atmosphere from the meteorological stations at varying distances from the shore, came to the conclusion that the influence of reservoirs on variation of mean monthly temperature and absolute humidity is inversely proportional to the logarithm of the distance of the shoreline. The creation of the Kuybischev Reservoir did not alter the temperature in winter, but its cooling effect appears to be rather substantial in the spring. The possible atmospheric manifestations of the Lake Nasser (area of 4500 km^2) are the subject of rather controversial opinions. It is not, however, anticipated that the moisture entering the atmosphere from the reservoir will, in the absence of uplift to adequately low temperatures, produce even clouds much less precipitation; nor will the lake influence the occurrence or intensity of thunderstorms. Opinion differs on the extent of the influence, if any, of the reservoir on the low-pressure trough trending northeasterly over Lake Nasser to the north of the intertropical convergence.

The macroscale and mesoscale meteorological and hydrometeorological effects of large natural lakes, particularly according to research on the North American Great Lakes, seem to be rather more significant than those observed or predicted on man-made reservoirs. In a complex study of the climate of southern Ontario the influence of Lake Huron, Lake Erie, and Lake Ontario is discussed [*Brown et al.*, 1968]. The effect of differences of temperature over the lakes and the land is most noticeable in the coastal areas immediately to the lee of the lakes but also results in alternating breezes that cause, in these areas, diurnal and temperature regimes that are allied to the lake temperature regime. A very apparent lake effect is the heavy snowfall that occurs in the lee of the Great Lakes on very cold winter days. There is also evidence that the lakes tend to suppress thunderstorm activity in the early summer and that their influence on winds is a factor to be considered in planning the control of air pollution.

Similar studies on Lake Michigan [*Changnon,* 1966] report various effects on mesoscale atmospheric convective systems. Lake influences were found to affect thunderstorm activity in all four seasons, the greatest changes occurring in the summer and fall. The influence both in the increasing and decreasing sense depends on the wind direction and time of day and reaches values of 40–60%. The lake effect also reduces hail frequency throughout lower Michigan. Similar effects are reported for Lake Erie [*Lavoie et al.*, 1970]. The influence of lakes on precipitation have, in general, the main practical implications, as is shown in many studies on the North American Great Lakes [*Changnon*, 1966, 1968; *McVehil and Peace*, 1965; *Lyons*, 1966; *Strong*, 1968] and on Lake Baikal [*Kornienko*, 1969; *Verbolov et al.*, 1965]. As a result of the lake's influence on thunderstorms, hailstorms, and snowfall, the amount of precipitation over Lake Michigan is 6% less than that over the land portion of the basin, which represents 1.85×10^6 fewer cubic meters of water per year in the lake. On the other hand the investigations on Lake Baikal indicate that the evaporation from the lake in periods of low air humidity in the catchment (November and December) increases the precipitation on the southeastern shore of the lake by 10–16%.

It is therefore more difficult to form a general conclusion and in particular to forecast the future influence on precipitation of a man-made reservoir without a most detailed study of mesoscale and macroscale meteorological conditions in the area. Indeed, a statistical study of mesoscale meteorological processes over Lake Balaton in Hungary, which represents a man-controlled natural lake [*Kovacs*, 1965], indicates that this lake is not exerting any significant influence on the temperature and humidity of the air masses passing over the lake.

This conclusion would again not be valid for Lake Victoria, Lake Kyoga, and Lake Albert in Africa. A detailed study of meteorology, hydrometeorology, hydrology, and of other elements influencing the lake's regime is under way [*Krishnamurthy and Ibrahim*, this volume]. The final objective of the project is to establish as exactly as possible the water balance of the lakes and their catchments. The preliminary results already indicate that the water balance equation is highly sensitive to the values of direct rainfall over and evaporation from the lake and to the differential between the two parameters. There is no doubt that it is only at the end of this project that research will be possible on the effects of Lake Victoria on these meteorological parameters, although some of the mesoscale meteorological elements have been studied by aerological methods [*Fraedrich*, 1968]. Although precipitation is the most important element to be considered, other elements such as cloudiness, air temperature, and air moisture [*Davidson*, 1967; *Timofeev and Kirillova*, 1966] are considerably influenced by large water bodies, and *Timofeev* [1963] proposes a theoretical method to forecast the changes of these elements resulting from establishing large man-made reservoirs.

The macroscale and mesoscale effects being the privilege of large lakes and reservoirs, microscale meteorological interaction between water bodies and atmosphere is the subject of many studies in several countries. Local temperature and humidity contrasts around small reservoirs and lakes cause several microclimatic changes and effects, of which the most important is fog formation. A short survey of such studies [*Gregory and Smith*, 1967] and a study of Selset Reservoir (man-made) reveal that here again a generalization may prove dangerous. A study [*Holmes*, this volume] on the effect on the atmospheric boundary layer of three small man-made prairie lakes in Alberta and the downwind consequences indicates that surface radiation temperature differences between dry and moist areas were large and that temperature differences of air cooled by passage over the water were measurable, i.e., amounting up to 3°C. Surface temperature of the surrounding land varied greatly and occasionally was 28°C warmer than the temperature of the lake surface. The cooling of air persisted for 3–4 km at 40 meters after the air passed the shoreline of two of the small reservoirs. In addition to influence on temperature and humidity a larger number of smaller reservoirs in the same region may have some influence on the frequency of summer thunderstorms. Such effects have been reported on the natural Mazury lakes in Poland [*Stopa*, 1967; *Okolowicz*, 1967; *Kossowska*, 1967; *Breier*, 1966].

Although a variety of opposite effects are reported in this respect depending on the actual meteorological situation, a definitely increasing occurrence of fog is reported by a number of studies on smaller lakes [*Pelko*, 1967]. Investigations of the Swedish Meteorological and Hydrological Institute [*Rodhe*, 1968] indicate an increased frequency of fog mainly in winter for this country. Although, in general, the formation of fog may result from cold advection (passage of cold air over warmer surface of the water) or warm advection (passage of warm air over colder water surface), the first case presents a most important point of interest for man-made reservoirs (cooling ponds) of industrial complexes. The paper by *Tsai and De Harpporte* [this volume] on a method for predicting fog produced by cooling ponds proposes a mathematical model for the numerical solution of the heat and moisture diffusion equations for the turbulent atmospheric surface layer over such ponds. Buoyancy considerations are included so that the effect of inversions on the fog may be calculated. The authors indicate good corroboration by observations of predictions made by the model and present an example of its use.

Although the prediction of the fog over cooling ponds represents an important aspect of 'thermal pollution,' the substance of fog is of ever more increasing concern to environmental scientists and authorities. Indeed the thermal pollution of man-made and natural lakes in some cases may create undesirable climatic effects through the modification of near-shore sensible heat exchange [*Bruce et al.*, 1968].

The last but not the least important aspect of the air-water interchange is the qualitative aspect of precipitation washouts polluting man-made and natural lakes. This aspect has been recently indicated by a study concerning the Great Lakes

(W. C. Ackermann, personal communication) in which even limited analyses of precipitation chemistry ascertained a large presence of nitrogen compounds but in which analyses yielded no phosphates. The danger of eutrophication of lakes being as great as it is all over the world, a more detailed chemical analysis of precipitation water is no doubt needed. Furthermore, a washout of heavy metal fallout is a cause of concern. Although most metal concentrations are under the permissible level, cadmium concentration was found in one instance to be almost double the permissible level. A most interesting study of meteorological influence on ecosystems in man-made reservoirs, in particular on the floristic composition of plant communities on the shores of dam reservoirs, is reported by ecologists from Czechoslovakia [*Seda*, 1966].

INSTRUMENTATION DEVELOPMENTS FOR RESEARCH PURPOSES

The air above the water bodies no doubt represents an important environment not only as a subject of observations but also as the carrier of observational instruments, which have a high spatial mobility. Thus the use of specially equipped aircraft is reported by *Holmes* [this volume]. The 'oasis effect' of the small man-made lakes was studied with the help of an airborne system capable of measuring the flux of heat and vapor. Similar arrangements were used on Lake Erie [*Lavoie et al.*, 1970]. Automated combined meteorological and hydrologic lake stations and research ships are reported from several countries [*Bellaire et al.*, 1967; *Okolowicz and Stopa*, 1964; *Richards*, 1967; *Zaitsev and Serova*, 1965; *Bruce et al.*, 1968], and modern methods of isotopic tracing [*Fontes*, 1970] permit estimation of the climatic zone of influence of the lake in the atmosphere, as demonstrated in the example of the Lake Leman (Geneva) in Switzerland. The use of weather radar has become most important for the observation of mesoscale effects of large reservoirs. Probably one of the most important instrumental developments for air-water interface observation is the airborne radiation thermometer technique (ART), which permits complete aerial surveys of water surface temperatures of reservoirs of any magnitude [*Richards*, 1967].

The development of remote sensing space technology via earth satellites is also applied to the instrumental developments for reservoir and lake observations. Already, the Tiros satellite pictures have been used for corroboration of the macroscale influence of great lakes on atmospheric systems [*Lyons*, 1966].

A paper by *Ackermann and Rabchevsky* [this volume] indicates the applications of Nimbus satellite imagery to the monitoring of man-made lakes. Information on gross shoreline configuration, areal extent, and meteorological changes surrounding large man-made lakes provided by Nimbus satellite imagery is specially emphasized for Lake Nasser, Volta Lake, Okavango basin, and Fort Peck Reservoir. It is estimated that further applications might be possible with more sophisticated satellite instrumentation and that a new limnological classification might also develop from such information. In this connection the hydrometeorological and hydrologic applications of the World Weather Watch system developed under the auspices of the World Meteorological Organization must be mentioned, since they include a systematic measurement of the atmospheric moisture flux for hydrologic purposes, including that of water balance of large reservoirs [*Bruce and Nemec*, 1967].

CONCLUSIONS AND FUTURE RESEARCH TRENDS

The general assessment of studies of interaction of man-made lakes with the atmospheric environment indicates that, although research conducted on natural lakes may be extremely helpful, it can be no substitute for theoretical and experimental work designed to clarify and permit forecasts of the effects of man-made reservoirs in their planning and design stage. Thus the installation of an observational network on sites of planned reservoirs that is expanded and completed after reservoir construction is the first prerequisite for successful research in this direction.

The aims of research may be summarized as follows: (1) modification of climate by large and small water bodies; (2) prediction of movement of water including circulation, diffusion, waves, and ice phenomena; (3) assessment of techniques for measuring evaporation and its reduction; (4) water balance of reservoirs; (5) meteorological and hydrometeorological factors affecting the chemical, biological, and thermic composition of water.

It will be noted, for example, that the joint research program of the Canadian and United States scientists, the International Field Year for the Great Lakes [*Richards*, 1967], well expresses such aims, although this program is not concerned with man-made lakes. Thus a rigid line may not and should not be drawn between research on natural and man-made lakes.

Immediate and urgent needs call for studies of evaporation and its suppression, standardization of all observations, development of instruments, and methods for evaluation of drag and stress coefficients in the establishment of wind profiles above water surface. More and more apparent is the need for the control of precipitation washout of pollutants, be they phosphates, nitrates, or toxic metals and gaseous exchanges at the air-lake interface; this control is important for the biological productivity of lakes. There is a need to follow closely the thermal pollution of reservoirs and its possible influence on meteorological and limnological conditions.

First attempts have been made to establish mathematical models of atmospheric circulation over large and small lakes (including man-made lakes as reported in this volume). The refinement of such models [*Strong*, 1968; *Timofeev*, 1963] may represent the most valuable tools of prediction of the interaction of man-made reservoirs and the atmosphere, which for the time being depends largely on observations of existing reservoirs and even more so on observations of natural lakes.

At the University of Pennsylvania a single-layer model simulating the mesoscale lake disturbance and including evaporation from and precipitation to the lake was developed. A vertical cross-section model complemented the single-layer model to eliminate its simplifications. This cross-section model generated a realistic lake storm disturbance [*Lavoie et al.*, 1970].

The World Meteorological Organization through its programs of the World Weather Watch, its efforts within the Global Atmospheric Research and Man and His Environment, its operational hydrology programs, and in particular its commissions for hydrology, climatology, and atmospheric sciences is ready to contribute to research in all the above-mentioned directions as it has in the past. There is no doubt that research on air-lake interaction in general and on man-made reservoirs in particular is gaining momentum.

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