BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LX (LXIV), Fasc. 1, 2014
Secţia
CONSTRUCŢII. ARHITECTURĂ

HYDRODYNAMICS AND WATER QUALITY ASPECTS OF GOLEŞTI RESERVOIR IN ROMANIA

BY

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Received: November 4, 2013
Accepted for publication: December 20, 2013

Abstract. Many aquatic ecosystems have become more eutrophic at the present. In this context, several models have been already developed for simulate the behavior of eutrophic ecosystems which involve hydrodynamics, food chain and nutrient cycles. Most of the reservoirs have a complex use allowing the flood attenuation, generation of hydroelectricity, household and industrial water supply, and irrigation. Stratification and water movement in those reservoirs is affected by variability in heat fluxes through the lake surface, in addition to chemical and biological processes. The resulting internal hydrodynamics is important in understanding the lake’s physical, chemical, and biological structure.

This paper presents a hydrodynamic model which reproduces water movement in lakes caused by solar radiation and wind kinetic energy. Also, the lake stratification and thermocline variation (temperature gradient and depth) will be studied, correlated with exploitation conditions. The model was calibrated with data from 2008...2011 in the Goleşti Lake, which has a 55 million m^3 volume and a maximum depth of 32 m. The developed model is a global one, based on regional climatology and lake morphology. Another aspect of this study is to identify the benefits of durable exploitation of lake on diminishing eutrophication phenomenon which is currently affecting Goleşti Lake.

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Key words: reservoirs; thermocline; stratification; eutrophication.

1. Introduction

Reservoir water quality is a complex function, depending on its morphometry and watershed characteristics including climate, hydrology, geology, morphology, and land uses. Ecologically, it is very important to be able to say if the meteorological conditions are capable to cause the surface layer to mix or stratify at a certain moment in time. This is particularly useful due to the influences of the near surface structure on phytoplankton production and species composition. The annual cycle of temperature fluctuations in a lake or reservoir may be quite complex and prediction of these changes is necessary if proper control of water quality must be achieved. Many lakes/reservoirs exhibit horizontal homogeneity and thus a time-dependent one-dimensional model which describes temperature variation in the vertical direction is adequate (Spigel *et al*., 1986).

Water quality models allow the integration of water circulation processes, based on lake morphometry and definition of advective transport and density gradients. Using simulation tools for studying a reservoir is particularly important because these impoundments may be more complex than natural lakes (Tufford & McKellar, 1999). In the case of studying a reservoir with multiple uses, this approach is particularly useful and desirable (Garcia Iturbe, 2005).

The hydrodynamics of lakes is connected with the motion of a stratified fluid affected by external forcing, the instability of these motions, and the dynamics of turbulence in a stratified environment. Most lakes become stratified, as solar energy is input at the surface. Through the expansion of the water, this thermal energy is converted to a mechanical stability, which arrests vertical motion in the lake. Wind, stream inflow, and withdrawal of water modify the stratification (Imberger & Hamblin, 1982). For lake/reservoir ecosystems the temperature distribution in time and depth is influenced by heat exchanges between water mass and atmosphere. These heat exchanges along with the kinetic energy of wind action, are the dominant factors which control the thermal regime, namely the dynamic of the analysed ecosystems.

Because the circulation and mixing in lakes/reservoirs are driven primarily by momentum and energy exchanges with the atmosphere, inflowing rivers and offtake discharges, in this study we focused on turbulent mixing that result from meteorological exchanges. This paper proposes a complex model to calculate the solar radiation and the depth of the thermocline. Also, the possibilities of thermocline disruption or lake destratification as a result of water withdraw by energetic intake will be investigated.

2. Study Area

Goleşti Lake is an artificial reservoir, located near Piteşti town. It has 55 million m³ volume and 32 m maximum depth. Its use is complex, allowing flood control, hydropower generation; household and industrial water supply, and irrigation. Thus, it prevents downstream flooding of an 50 × 10^6 m^2 area, provides a flow of 156 m^3/day for Bucharest (domestic and industrial) and 9 m^3/s for irrigation of an 100 × 10^6 m^2 area, it is secondary source for industrial water supply of Pitesti City up to 6 m^3/s flow and it is used also for electricity generation having an installed power of 8 MW for a discharge of 90 m^3/s. It is a heavily modified water body, its physical characteristics being substantially changed due to human activities (Dumitran *et al.*, 2012). In order to achieve good surface water status it is necessary to change its hydromorphological characteristics which would have a significant adverse impact on the water environment (Ordre no. *161*/2006).

Goleşti arrangement includes the dam, spillways and bottom discharge structures, hydropower plant and a pumping station. The energetic intake is placed at 7.5 m above the thalweg, and can transit up to 90 m^3/s.

For Goleşti reservoir, values of inflow and outflow from 2008, January (day1) to October, 2009 (day645) were available (Fig. 1).

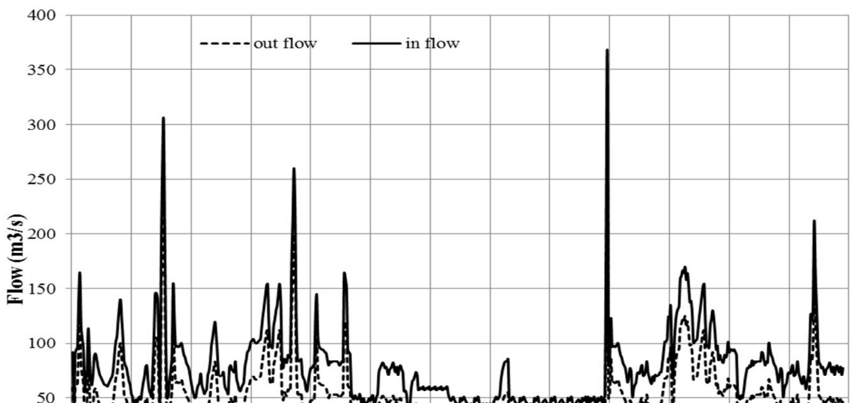

Fig. 1– Inflow and outflow values for Goleşti reservoir (2008…2009).

Goleşti reservoir exhibits several annual limnological cycles. Each year, as the lake surface warms through the springtime, a thermocline develops in the lake by early summer. This thermal gradient isolates cold and dense water within the reservoir's lower layer. As the summer progresses, the dissolved oxygen (DO) in this lower layer of water (hypolimnion) are consumed, leading to anoxia (no oxygen) by late September. The mean water temperature is between 2°C and 23°C and the values of DO are between 6.91 and 13.3 mg/L. During the last few years, high concentrations of nutrients (phosphorus, nitrogen) and algal biomass have been occasionally recorded, amplifying the deterioration of water quality and generating an eutrophication tendency of the lake. The trophic status index (TSI > 50) obtained for Goleşti reservoir shows the lake was in eutrophic status throughout 2008...2009. There were also some exceptions: phosphorus values in early summer 2008 placed the lake in the hypertrophic category and the nitrogen and chlorophyll content for a short period in 2009 placed it into the mesotrophic category (Dumitran *et al*., 2012).

In Goleşti reservoir, summer circulation is characterized by thermal stratification. Thermal stratification usually occurs in late March or early April and lasts until the end of October. During stratification, the lake is characterized by an upper layer of more or less uniformly warm, circulating and sometimes turbulent water called the *epilimnion*. The thermocline separates the upper warm waters from the colder and denser bottom layer of the lake, the hypolimnion, and is the plane of maximum rate of decrease of temperature with respect to depth (Wetzel, 2001). Usually, the thermocline layer during the summer stratification establish at 6...7 m depth (Fig. 2). If it is a windy spring, the thermocline will setup lower and gradually rise as further heating occurs. If there are light winds at the time of thermocline onset, stratification will setup

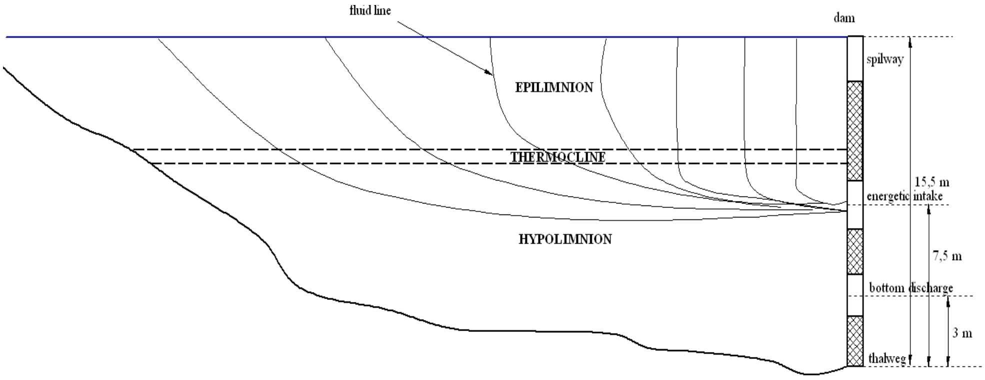

Fig. 2 – Schematic representation of lake stratification applied to Golesti reservoir.

higher and progressively descend as wind-induced mixing establishes the epilimnion. After setup, the depth of the thermocline will deepen as the upper layer gains small amounts of heat throughout the period of stratification (Wetzel, 2001). During the summer, when the daily heat input exceeds the nighttime loss, the thermocline will strengthen and deepen. In the fall, nighttime cooling exceeds daytime heating and the stratification is eroded. At the onset of stratification, a thermal bar occurs. There is an inclined thermocline separating warmer water in the nearshore band from the still barotropic cooler waters in the middle of the lake. As time progresses, the volume of warm water increases and the thermocline becomes stronger and moves further out from shore (Imberger & Hamblin, 1982) and eventually establishes thermal stratification throughout the entire lake.

3. Methodology

The greatest source of heat for lakes is solar radiation. The direct absorption of solar radiation accounts for only about 10% of the observed distribution of heat. Most of the heat distribution profile results from circulation caused by wind stress. Significant motion is restricted to the warmer layers above the thermocline (Csanady, 1972). The transport of heat by turbulence decreases as the stability of stratification increases throughout the summer months and the heat flux in the hypolimnion varies minimally with increasing depth (Wetzel, 2001). Mixing will occur when the action of the wind will be able to overcome the action of thermal stratification. Wind stress imparts momentum to the surface of the water, causing formation of surface waves due to the friction between the air molecules and the surface water.

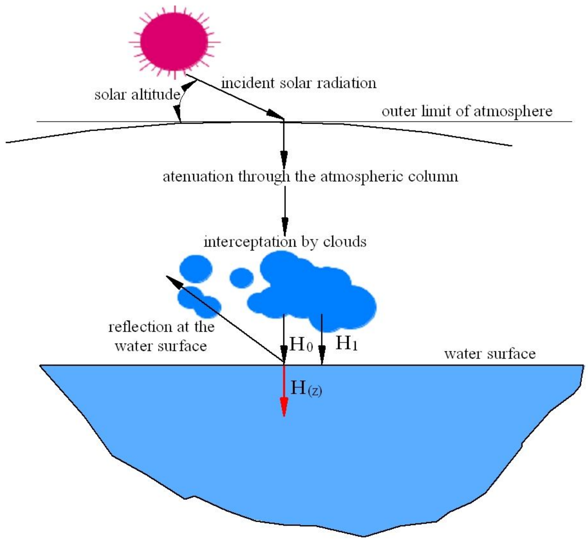

Fig. 3 – Components of water surface heat exchange.

For aquatic ecosystem the net heat flux into the water surface depends on both the internal hydromechanical behavior of the water body and the physics of its interaction with the overlying air mass (Fischer *et al*., 1979; Charuchittipan & Wilson, 2009). The total solar radiation is reduced by attenuation through the atmospheric column (absorption and scattering in the atmosphere) and by clouds interception (Fig. 3). The residual radiation which reach the water surface is called *net solar radiation* (Oswald & Rouse, 2004).

The rate at which solar energy imparts radiative energy to the surface of the water column is a function of the net solar shortwave radiation, H_0, and the remaining heat fluxes at the surface of the lake, H_1, (cumulative effect of longwave, latent and sensible heat transfer), both coming in the water surface. The short-wave radiation in a water column decays exponentially with depth, *z*, and is given by the Beer's Law. The remaining heat flux is done by simultaneous processes of radiation, evaporation and conduction, thus it can be calculated as follows:

$$H_1 = H_{an} - \left(H_b \pm H_c \pm H_e\right), \tag{1}$$

where: H_{an} is net atmospheric long-wave radiation into the water surface, H_b – long-wave back radiation from the water surface, H_c – conductive heat flux from the water surface, and H_e – evaporative heat flux from the water surface.

The meteorological elements that significantly affect lake thermal regimes and heat storage include air temperature, wind and net radiation. Unfortunately, in practice there are many situation when these data are not available. In this paper is investigated the consistency of a model which simulates the radiation fluxes variation on a lake surface and the influences on lake's water temperature. The total heat flux variation on lake surface varies less on seasonal scale than on dayly scale. The total thermal minimum flux coincides with the minimum of solar radiation, while the thermal maximum flux is reached much sooner than maximum of solar radiation. The one-dimensional unsteady heat transfer eq. use in numerical simulation models for water temperature profiles in lakes and reservoirs is (Dumitran & Vuță, 2012):

$$\frac{\partial T_w}{\partial t} = \frac{1}{A} \cdot \frac{\partial}{\partial z}\left(k_z A \frac{\partial T_w}{\partial z}\right) + \frac{H_{(z)}}{\rho C_p}, \tag{2}$$

where: T_w is the water temperature, [ºC], *t* – the time, [day], *A* – the horizontal area, [m^2], as a function of depth *z*, [m], k_z – the vertical turbulent heat diffusion coefficient, [m^2/day], C_p – heat capacity of water, [J/m^3.ºC], ρ – the density of water and $H_{(z)}$ – the heat source or sink strength per unit volume, [J/m^3.day].

4. Results and Discussion

The developed model allows to estimate the energetic budget due to solar radiation on aquatic ecosystem, based on its geographical position only. Thus, the daily extraterrestrial radiation is determined and the component radiation of the total flux at the level of the studied aquatic ecosystem is computed (Fig. 4). Throughout the spring and summer the sensible heat flux, H_c, is often directed towards the lake surface. Once cooling begins, H_c is consistently positive due to unstable atmospheric conditions. Since the total thermal flux, H_w, is the result of interactions between the atmosphere and the lake, it directly influences the water temperature. Thus, for positive values of H_w , the water temperature will increase.

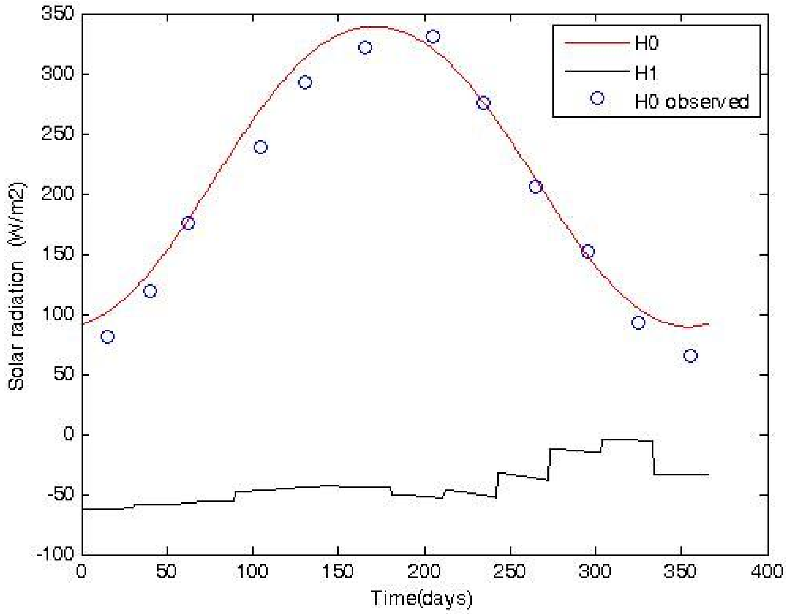

Fig. 4 – The simulated and measured value for net solar shortwave radiation, H_0, and the simulated remaining heat fluxes at the surface of the Goleşti lake, $H_{1.}$

Secondly, the water column temperature variation over the year is computed. The behavior of the water column temperature is shown in Fig. 5. Goleşti reservoir is dimictic and undergo spring and autumn vertical overturning and summer thermal stratiphication. The lake surface temperature increased in March when the net energy flux is positive. The thermocline is very well established in June when heat is received at a higher rate than the rate of transfer to deeper layers and the thermocline depth increased rapidly.

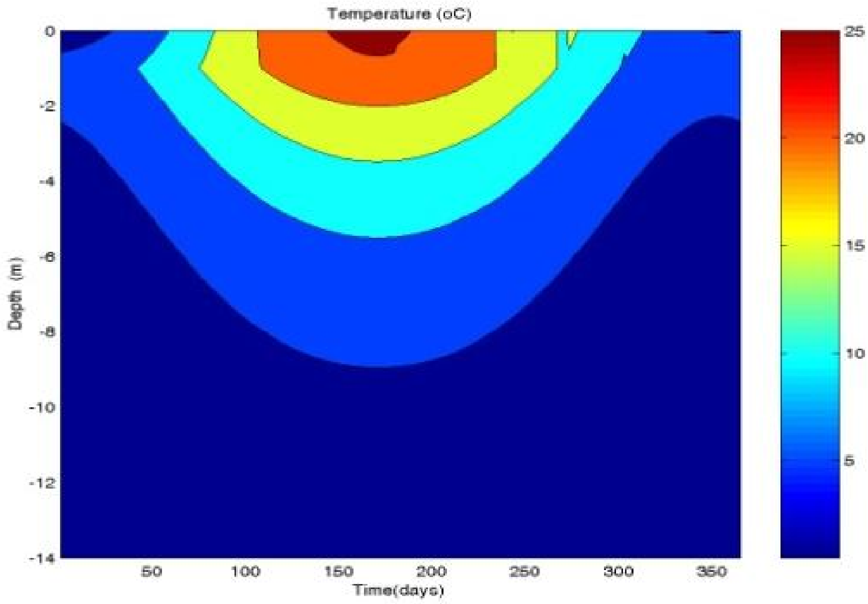

Fig. 5 – Temperature variation over the year in Goleşti reservoir (2008).

In this study, the transit of flow from lake to downstream of the dam is investigated. This transit is expected to have positive effects on lake water's quality, resulting in thermocline disruption or lake destratification. Thus, the depth of disturbed water layer due to the flow by energetic intake is analysed. Also the possibilities of thermocline erosion have been assessed.

Considering a constant daily discharge and knowing the variation of lake's water temperature/density in depth, the withdrawal layer structure was investigated. First, the Brunt-Vaisala frequency is computed by:

$$N_0 = \sqrt{\frac{\mathrm{g}}{\rho_0}\left(\frac{\mathrm{d}\rho}{\mathrm{d}z}\right)}, \tag{3}$$

Where: g is the *gravitational acceleration*, ρ_0 – the water density at the surface, [kg/m^3], and dρ/dz – the vertical density gradient. The withdrawal layer structure is determinate by the value of internal Froude and Grashof numbers, which are given by:

$$Fr_i = \frac{Q_w}{N_0 L^2}\ ,\ Gr = \frac{N_0^2 L^4}{\varepsilon_v^2}, \tag{4}$$

where: Q_w is the *discharge per unit width*, [m^2/s], L – the reservoir length, [m], and ε_v – the average vertical eddy diffusivity, [m^2/s]. Thus, the thickness of perturbed water is computed (Fig. 6).

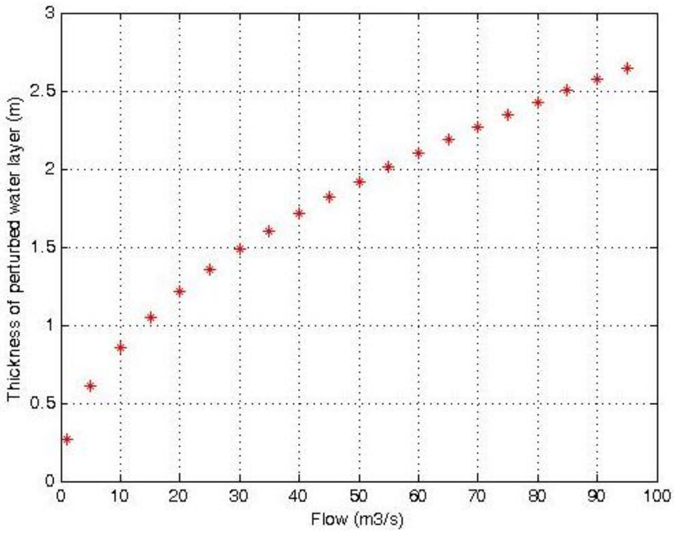

Fig. 6 – The dependence between thickness of perturbed water layer and energetic intake outflow for Goleşti reservoir.

5. Conclusion

A numerical model for a seasonal mixed layer is presented, based on the one-dimensional eqs. for conservation of thermal energy. The model was tested over one year using field data from Goleşti reservoir – Romania. The simulated isotherms demonstrate the strong degree of temperature stratiphication induced by solar radiation. The Goleşti lake was a least partially stratified for nine mounths of year. The case study presented in this research provided a good opportunity for testing the model. All the results of the simulation have a good fit with the observed data.

Because the lake destratification is one of the restauration techniques with benefic effects onto eutrophic ecosystems, this study analysed the erosion of the thermocline by the outflow dynamics in Goleşti reservoir. Destratification was appointed as technique in lakes management in 1950 and over the years has been the most used method to improve water quality in lake and reservoir ecosystems (Dumitran & Vuță, 2011). The main effect of this technique is the increase in dissolved oxygen content in the water over time. Destratification therefore has benefic effects on water quality by oxygenation and chemicals oxidation throughout the water column leading to improvement of aerobic organism's habitat. Complete movement can reduce phosphorus growth and algal biomass by increasing the mixing depth, thus reducing light and subjecting the algae to rapidly changing hydrostatic pressure. In Goleşti reservoir case, lowering or destroying the thermocline will result in a better oxygenation of deepest water layers, leading to an improvement of water quality.

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HIDRODINAMICA ŞI CALITATEA APEI
Aspecte privind rezervorul de la Goleşti în România

(Rezumat)

Se prezintă un model hidrodinamic care reproduce mişcarea apei în lacuri cauzate de radiația solară şi energia cinetică a vântului. De asemenea, stratificarea lacului şi variația climei (gradient de temperatură şi adâncime) vor fi studiate, corelate cu condiții de exploatare. Modelul a fost calibrat cu datele din 2008...2011, din lacul Goleşti, care are 55 de milioane de m³ în volum şi o adancime maxima de 32 m. Modelul dezvoltat este unul global, bazat pe climatologia regională şi morfologia lacului. Un alt aspect al acestui studiu este cel de a identifica beneficiile de exploatare durabilă a lacului urmărind diminuarea fenomenului de eutrofizare, care în prezent afectează lacul Goleşti.