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IMPACT OF A THERMOCLINE ON WATER DYNAMICS IN RESERVOIRS – DOBCZYCE RESERVOIR CASE

While modeling water dynamics in dam reservoirs, it is usually assumed that the flow involves the whole water body. It is true for shallow reservoirs (up to several meters of depth) but may be false for deeper ones. The possible presence of a thermocline creates an inactive bottom layer that does not move, causing all the discharge to be carried by the upper strata. This study compares the results of hydrodydynamic simulations performed for the whole reservoir to the ones carried out for the upper strata only. The validity of a non-stratified flow approximation is then discussed.

1. Introduction

1.1. Thermal stratification in reservoirs

If a reservoir is deep enough, thermal stratification may occur within it during the summer time. It usually leads to forming of three layers. The upper one is called the epilimnion. There the water is relatively warm and it is sensitive to the changes of external factors (like mixing by the wind). The water of the lowest layer – the hypolimnion – is colder (about 10–14°C) [1] and it does not move for the most time of the year (spring – autumn). The middle layer – the thermocline (metalimnion) – is the area of rapid temperature decrease and it constitutes the border between layers sensitive and insensitive to the changes of external parameters [2]. During the summer time, the vertical mixing between the layers occurs rarely (opposite to spring and autumn times). According to [2] (p. 60), in summer only the water contained in the two upper layers participate in collective movement. In that case, the horizontal velocity pattern is flatten. Approximate depth distribution of the

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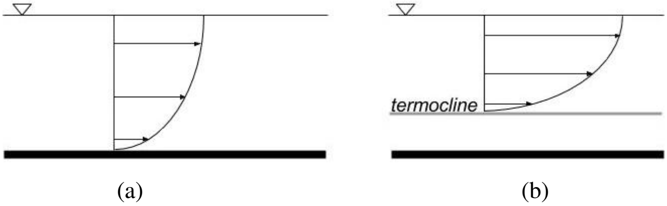
horizontal component of water velocity is shown in Fig. 1 for absence (a) and presence (b) of a stable (not susceptible to horizontal movement in the upper layer) thermocline, respectively.



(a) (b)

Fig. 1. Approximate, stable distribution of velocity (horizontal component) in a reservoir without (a) and with (b) thermocline; no vertical mixing assumed

1.2. Thermocline in 2D simulations

Numerical simulations of water velocity field in reservoirs are often made using a two dimensional depth averaged approach [3–5]. Within this scheme it is assumed that vertical movement of water can be neglected and only horizontal movement is considered. The 2D depth averaged method proved to be useful in the cases where the whole water body can be treated as one body: the average horizontal velocity of a water column is calculated and its vertical distribution is assumed to follow a tachoida (velocity curve), as shown in Fig. 1a. This approach is justified when no stratification is present. This approach is obviously inappropriate when stratification forms (or declines) or vertical mixing occurs. The question is then: can a 2D depth averaged calculations be reliably used when a stable stratification exists within the reservoir?

The presence of a stagnant bottom water stratum (hypolimnion) effectively reduces the reservoir depth for the moving water. In the regions it is present for a given discharge rate, the average velocity is higher (Fig. 1b). So, the first approximation of the 2D flow dynamics with a thermocline present may be that the planar distribution of the unitary discharge (discharge per perpendicular cross-section unit, or velocity times depth, [m^2/s]) is still the same, only the average velocity should be modified as follows:

$$v'_{av} = \frac{h_B}{h_T} v_{av} \quad \text{if} \quad h_B > h_T, \tag{1}$$

where: v'_{av} – two-dimensional average velocity with a thermocline present [m/s], h_B – total depth in the given location [m], h_T – depth of the thermocline layer [m], v_{av} – calculated two-dimensional average velocity (without a thermocline) [m/s].

In this rough approximation if the primary thing of interest is water exchange between certain parts (basins) of the reservoir, and unitary discharges are more important for the user than velocities, then no thermocline-related corrections are necessary.

Investigating the problem further, one should notice that the effective change of the reservoir bed shape and roughness may alter not only the water velocity value but also its direction. In fact, the whole pattern of the flow (currents, stagnant areas, whirls) may appear in different locations than in the uniform thermal distribution case. Intuitively, these changes should not be dramatic, as the impact of the bed shape and roughness on the flow decreases with the depth [6] and the metalimnion tends to appear relatively deep [1, 2].

2. Object, tools and methods

2.1. Dobczyce Reservoir

The area of research is the Dobczyce Reservoir located on the south of Poland in the Lesser Poland voivodship. The location and the area shape of the reservoir with the key objects is presented in Fig. 2. The reservoir was created by constructing a dam on the 60th km of the Raba River, which is one of the Vistula River tributaries. The surface of the catchment area is 768 km^2. The main function of the Dobczyce Reservoir is supplying water for the nearby city of Krakow. The reservoir of Dobczyce is the one of the deepest dam reservoirs in Poland. The maximum depth is over 30 m.

Fig. 2. Overview of the Dobczyce storage reservoir

Normal conditions (low inflows) favor the appearance of a seasonal thermal stratification. Stable stratification occurs in the central and eastern regions reservoir in the summer time (May – September) provided no very high flow occurs (Fig 3). Because the reservoir is deep enough there, the thermocline layer is not sensitive to daily or longer-term changes of water surface elevation [1]. Such changes affect

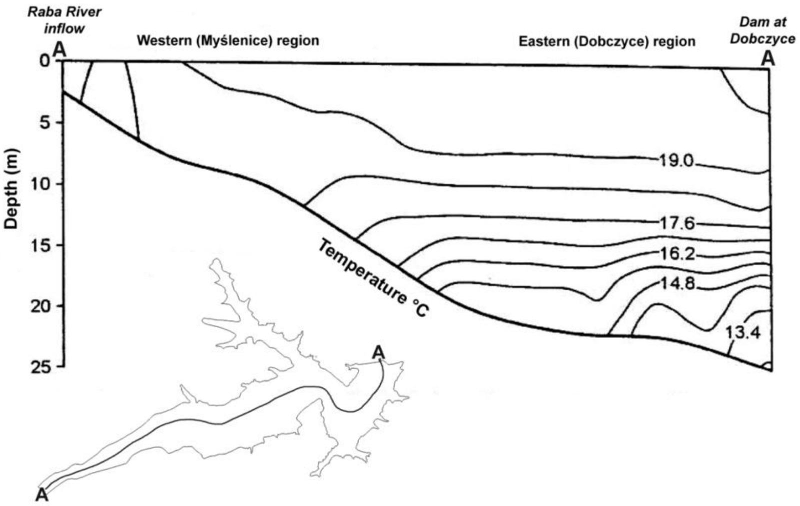


Fig. 3. Vertical temperature distribution along the Dobczyce Reservoir in summer time [2]

the epilimnion only. Within the reservoir, the metalimnion can be found between 8 m and 12 m of depth [2]. It should be noted that the shallow western regions remains roughly uniform with respect to their temperature.

2.2. AdH model

The AdH (Adaptative Hydraulics model) [7] has been created by The US Corps of Engineers and it is available in the SMS (Surface Water Solution) package [8]. The model belongs to the group of two-dimensional depth averaged finite element method modeling tools. Other models belonging to the SMS package have been successfully used for calculations related to water velocity field in storage reservoirs and water quality issues there (see [3–6, 9–12] and references therein). Being more versatile and more stable than older models [7, 13] AdH is their natural successor.

Finite elements in AdH are triangles with discretisation nodes located in their vertices. The AdH model adapts the computational mesh in the regions where it is necessary to obtain convergence (this is why it is called "Adaptative Hydraulics model" after all). This is done by refining (i.e. splitting) the elements into smaller triangles. Such a procedure generates additional vertices that are used in the given time step. The basic input data for this model include: bed shape (bathymetry); bed friction parameters; initial water surface level; water parameters (density, viscosity); inflows and outflows (constant, time dependent or surface level dependent). For the calculations described below, the listed model parameters were set as follows: bed shape according to the digital map of the reservoir, bed friction as manning $n = 0.025$, initial WSE = 262.6m a.s.l, water density and viscosity left as model defaults, constant (steady-state) inflows and outflows as described in chapter 3. The upper boundary condition was a constant discharge, whereas the lower one was a constant water surface level. This may be extended by other case-specific conditions including wind conditions, atmospheric pressure changes, Coriolis effect, fixed ceilings (e.g. bridges), and parameters of the ice layer.

The main result of the model run is a two-dimensional planar field of the average horizontal velocity of water. This field may be static or time-dependent according to the conditions imposed upon the domain. Some additional features of AdH include drying and wetting of bed regions, particle tracking, and basic sediment transport. AdH model solves numerically conservation equations of mass (continuity equation) and momentum. The continuity equations use the cross-section area and the discharge in any given cross-section as the variables of interest:

$$A = \int_B H \, \mathrm{d}B, \tag{2}$$

$$Q = \int_B U \cdot H \, \mathrm{d}B, \tag{3}$$

where: A – cross-section area [m^2], Q – discharge [m^3/s], U – vertically averaged velocity of the flow [m/s], H – local water depth [m], B – section width [m].

The mass conservation equation for any given planar element is:

$$\frac{\partial H}{\partial t} + \frac{\partial (H v_x)}{\partial x} + \frac{\partial (H v_y)}{\partial y} = 0, \tag{4}$$

where: v_x, v_y – velocity components in x and y directions, respectively [m/s].

The AdH model solves numerically two-dimensional momentum conservation equations – in both x and y directions. These equations fare as follows:

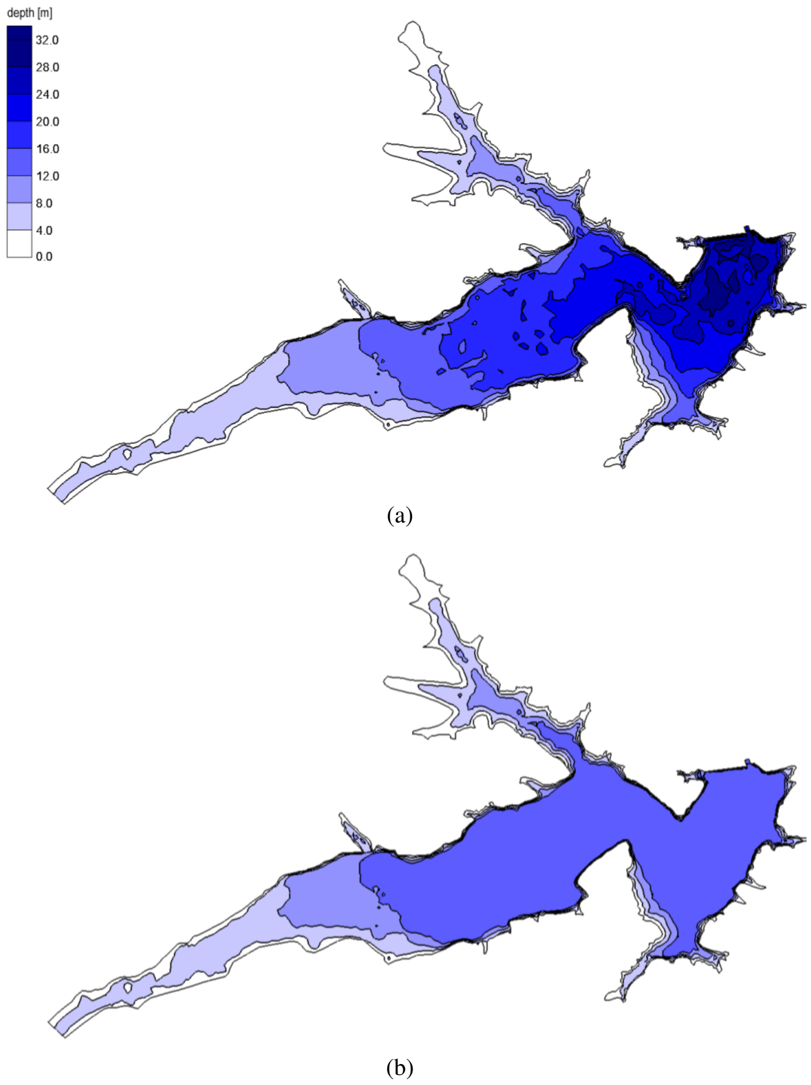
$$\begin{gathered} \frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} - c_f v_y + g \frac{\partial \zeta}{\partial x} + g v_x \frac{\sqrt{v_x^2 + v_y^2}}{C^2 H} - v_x \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} \right) + \frac{1}{\rho} \frac{\partial p}{\partial x} = F_x \\ \frac{\partial v_y}{\partial t} + v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} - c_f v_x + g \frac{\partial \zeta}{\partial y} + g v_y \frac{\sqrt{v_x^2 + v_y^2}}{C^2 H} - v_y \left(\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} \right) + \frac{1}{\rho} \frac{\partial p}{\partial y} = F_y \end{gathered} \tag{5}$$

where: F_x – unitary force in the x direction [m/s^2], F_y – unitary force in the y direction [m/s^2], c_f – Coriolis factor [1/s], g – gravitational acceleration [m/s^2], ζ – bed level [m], C – Chezy roughness coefficient [m$^{1/2}$/s], p – external pressure [Pa], ρ – water density [kg/m^3].

If necessary, the equations may be simplified or supplemented with additional terms. For standard calculations of water flow in retention reservoirs, the external pressure (the atmospheric pressure) is considered to be constant over the reservoir's water surface The Coriolis effect is small for water reservoirs and hence the "Coriolis terms" are neglected in equations (5). This allows omitting appropriate terms and simplifying the equation. Other forces caused by ice or wind may be added to this equation if desired.

2.3. Applying the thermocline

In order to simulate water velocity field in the reservoir with the thermocline present, the authors started from the bathymetric data of the reservoir bed successfully used before [3, 5, 9] (Fig. 4a). A computational mesh for the AdH model was then generated for that data. The shape of the mesh is shown on Fig. 5, along with the basic data about the mesh. Then, another mesh was derived from the above: for each node with elevation lower than 260.6 m a.s.l. the elevation was modified



(a)

(b)

Fig. 4. Reservoir bathymetric map as used for calculations: without (a) and with (b) the thermocline applied

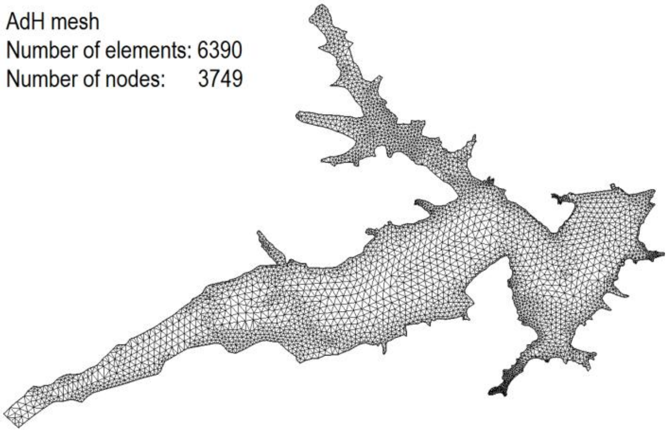


Fig. 5. The computational mesh

to be exactly 260.6 m a.s.l. As the result, two meshes were obtained with the same properties except for the bathymetric data. The bathymetry applied on the second mesh is shown in Fig. 4b. The resulting depth does not exceed 12 m there, which is roughly equal to the depth of the transition zone between the metalimnion and the hypolimnion. As a result, in the model calculations only water contained in the epilimnion and the metalimnion could move; everything below the specified depth was cut-off by an artificial bottom.

The AdH model parameters – the bed roughness is interpreted as the Manning roughness factor n. Its default value is 0.025, which has proved to give reasonable results in previous analyses of water velocity field in storage reservoirs (e.g. [10, 11]). As the artificial bottom introduced in the model is actually a water-water boundary, it is very smooth. So, for the region where the bottom is the thermocline and not the reservoir bed, the roughness has been set to a lower value. To keep the numerical solution to equations (5) stable, this value has been set to 0.001. It has been shown that solution does not change significantly along with the changes of this parameter. (As a general remark: for all the 2D depth averaged models contained in the SMS environment dependence of the results on bed roughness is significant only in shallow regions of the modeled reservoirs, see e.g. [6, 13]).

3. Results

The simulations has been carried out for 4 values of the total discharge:

- 2.03 m^3/s – the most probable flow in the reservoir happening during moderately dry seasons. The pattern of currents, stagnant areas and whirls observed on the reservoir in such conditions is chaotic and highly susceptible to external conditions such as wind [1].

- 10.6 m^3/s – the yearly average discharge. It happens during moderately wet periods. The flow pattern observed on the reservoir is still chaotic but more stable than that above.
- 50 m^3/s – a moderately high discharge that appear after rains. The main observed current is strong enough to be visible throughout the reservoir.
- 200 m^3/s – a discharge with 50% probability of appearance each year after heavier rainfall in the catchment. According to [1], if a high discharge happens in a given year, it is strong enough to destroy the stratification within the reservoir. Thus, the authors assumed 200 m^3/s as the order of magnitude of the highest discharge that still can flow through the reservoir without disturbing the thermocline.

The inflow to the reservoir has been split – 99% of the recharge for the Raba River in the western part of the reservoir and 1% from the Wolnica creek trough the northern bay. The outflow was handled by a single outlet located at the dam. For each discharge value, simulations with and without a thermocline were executed. Resulting horizontal velocity maps are shown in Fig 6. Sub-figures 6a to 6d present the velocity field calculated for different discharge values without taking the thermocline into account (i.e. with bathymetric data shown in Fig. 4a). Sub-figures 6e to 6h are their counterparts calculated for appropriate discharge values with the thermocline present (i.e. with bathymetric data shown in Fig. 4b). Note the logarithmic scale along the z (velocity) axis.

It can be seen that the overall character of water dynamics in the reservoir depends on the discharge value rather than the fact whether any stratification is present or not. It changes from low velocity and chaotic for low discharges to high velocity with stable current for high discharges. The average velocities are higher when the thermocline is present as with limited depth the discharge must fit within smaller cross-sections.

It is noteworthy that for the lowest discharge rate (Fig. 6a, 6e), the changes in the pattern of currents and whirls are present even in the regions far from the actual changes in the bed bathymetry. This is the result of the chaotic nature on the flow in these circumstances – even small changes of external conditions can produce a different (but still visually similar) result. The velocities of currents and whirls are still small, and the local flow character still depends primarily on volatile out-of-control conditions. Concluding, the general character of simulated flow does not change for the lowest discharge rate with introducing of the thermocline.

For the yearly average flow (Fig. 6b, 6f), in the shallow regions of the reservoir a distinct current appears, while in the deeper parts the velocities are not high enough to maintain it and a chaotic pattern occurs again. Introducing a thermocline does not change the picture much: the current on the shallows is shifted slightly to the north, the chaotic regions remain so and the transition zone between those remains in place.

For high discharge values (Fig. 6c, 6g and Fig. 6d, 6h) no differences appear in the flow pattern in shallow regions. The water velocities within the reservoir dominate the image details. At the depths, where the thermocline may be present or not, there are differences in fine details but no apparent changes of velocity field are visible: the currents and stagnant areas occupy very similar areas and the whirls rotate in the same direction.

When considering water dynamics as one of the factors influencing processes important for water quality, it is not enough to look just at the velocities but rather at unitary discharges as the measure of water exchange rate between regions (or "basins") of the reservoir. When stratification is present in the summertime, the hypolimnion (the bottom stratum) can be considered as a stagnant zone. Then, water flow through higher strata of the reservoir: the epilimnion and the metalimnion. The question is: does the existence of stratification significantly modifies the rate of water exchange between the basins? For water exchange issues it is not enough to look at the velocities, unitary flow (velocity times depth) should be used instead. As the measure of water exchange rate differences, the normalized unitary differential flow field was introduced as follows:

$$\overrightarrow{q_n} = \frac{H|\overrightarrow{v_1} - \overrightarrow{v_2}|}{Q}, \tag{6}$$

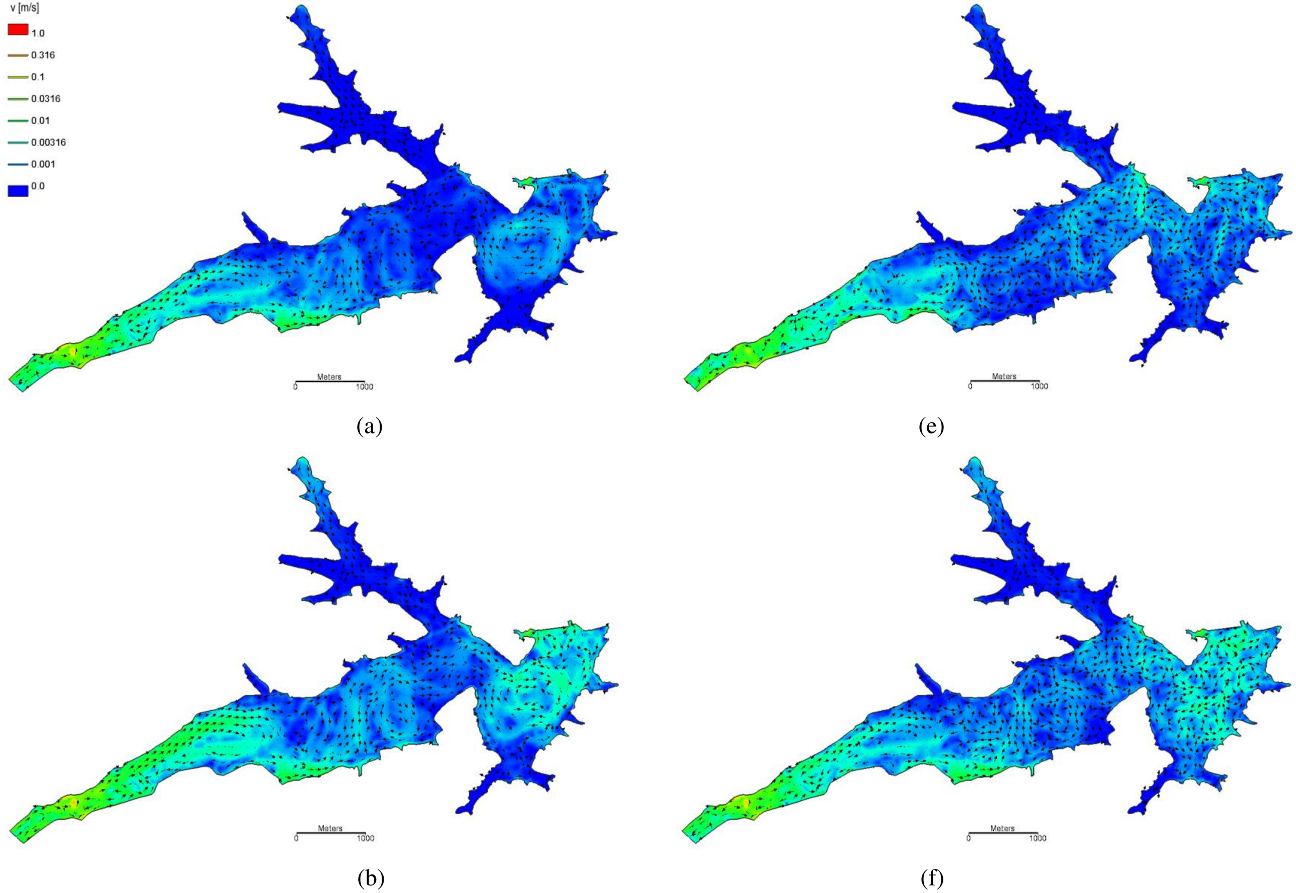
where: q_n – unitary differential flow [1/m], $\overrightarrow{v_1}$, $\overrightarrow{v_2}$ – horizontal velocities at any given point belonging to the compared velocity fields [m/s], Q – total discharge [m^3/s].

The meaning of q_n is the relative difference between two discharges per meter of any given cross section (relative means: what fraction of the total discharge is it).

Maps of q_n for all four total discharges are shown in Fig. 7a to 7d accordingly.

It is evident that the impact of the thermocline decreases with the total discharge (or with increasing stability of the flow). For both high discharge values, 50 and 200 m^3/s, the changes are negligible in the whole domain except regions closest to the dam. On the contrary, for the small discharge value of 2.03 m^3/s the impact on the velocity field is clearly visible in the whole domain. But in the latter case the presence of stratification in the reservoir is just one of many factors that influence the chaotic velocity field of the water body. Presence or absence of a moderate wind can have an impact on velocity field greater by an order of magnitude in such a case [1]. Thus, for both high and low discharge regimes it is a valid approach to treat the thermocline as a factor altering only the velocity field within the upper layers of water but not changing the water exchange representation in any significant manner.

The most interesting case is shown in Fig. 7b. There slight changes are visible in two regions: the deep basin close to the dam and the shallow part at the west, close to the mouth of the Raba River. The latter can be interpreted as shifting the main current northwards. So, within the moderate discharge range, the presence of stratification or its absence may have some impact on the water exchange between reservoir basins and it should be considered.



(a) (e)

(b) (f)

Fig. 6. Horizontal velocity maps for *lower* discharges: 2.03 m^3/s without (a) and with (e) thermocline, and 10.6 m^3/s without (b) and with (f) thermocline

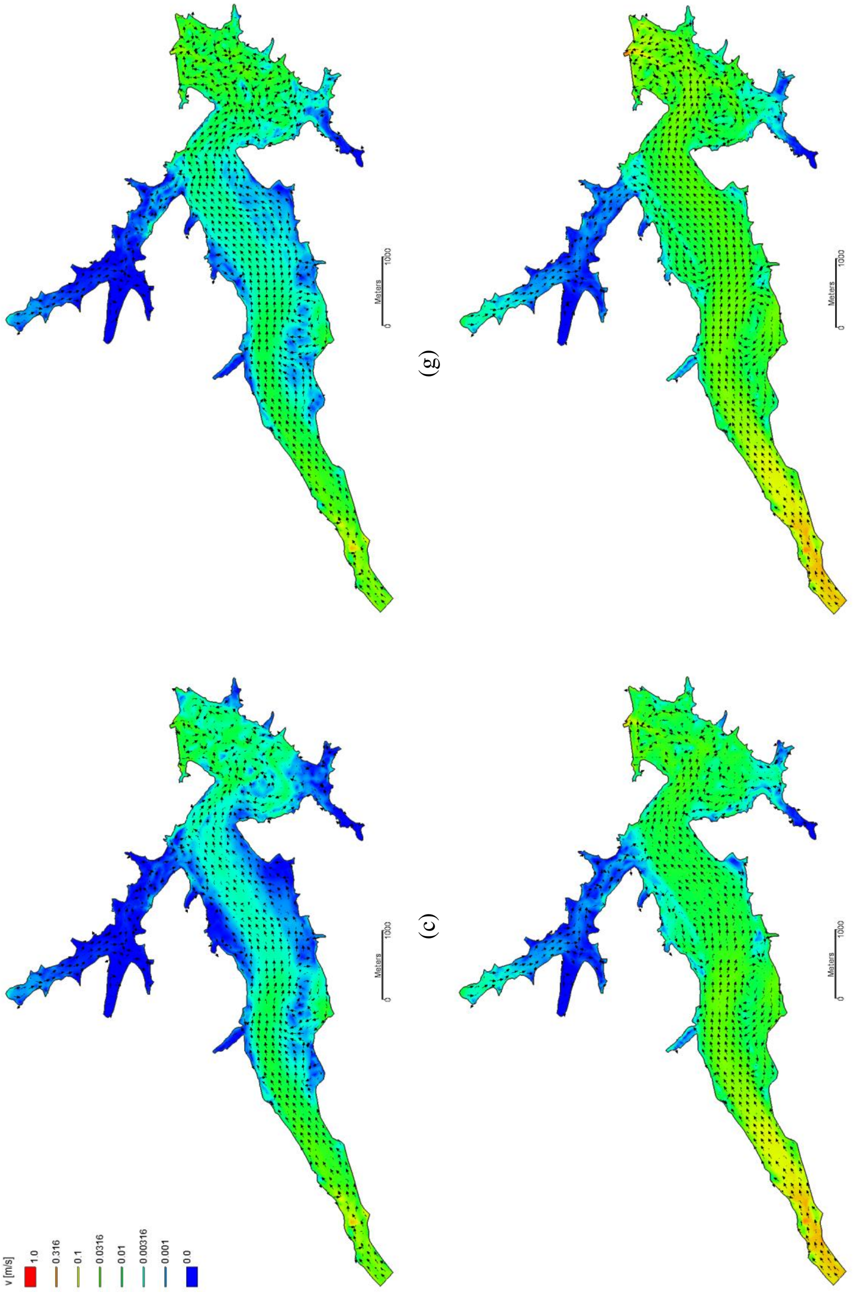
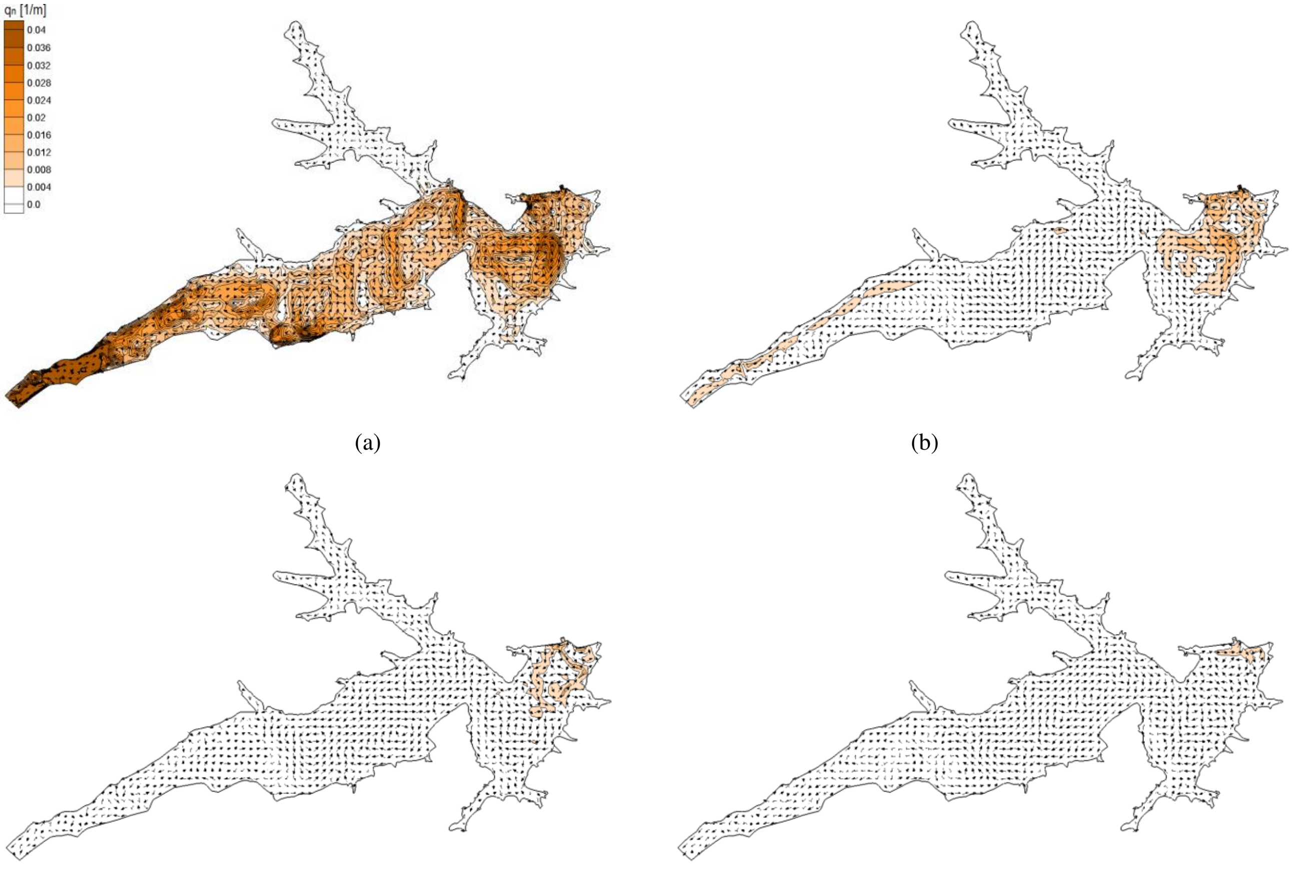


Fig. 6. Horizontal velocity maps for *higher* discharges: 50 m^3/s without (c) and with (g) thermocline, and 200 m^3/s without (d) and with (h) thermocline



(a) (b)

(c) (d)

Fig. 7. Maps of unitary differential flow for the total discharge of 2.03 (a), 10.6 (b), 50 (c) and 200 (d) m^3/s

4. Remarks on model sensitivity

In order to validate the result, sensitivity analysis was performed. The depth the thermocline was being changed by up to one meter up and down and the value of the roughness coefficient was also treated as a variable. The response of the model was stable with slight changes of the velocity field following the changes of the input variables. The same applied to the gradual changes of the inflow discharge value. The model reached the 4th order Runge-Kutta convergence within 0.001 for each calculation node with the output variables changing steadily. (That is, the maximum residual norm for calculated velocity was less than 1 mm/s and for calculated water surface elevation less than 1 mm.) Minor changes of mesh element shapes have no visible impact on the computed velocity field, either. In all those cases, there were no rapid output change that would lead to different interpretations than the ones presented in the chapter 3.

A special remark should be made for the outcome insensibility with respect to the roughness factor imposed on the thermocline surface. Fig. 8 is a counterpart of Fig. 7b but with the roughness coefficient is equal to 0.01, so it is 10 times greater than before. The differences in the calculated flow are negligible. This is important as the thermocline surface may have a significant "roughness" due to turbulent mixing [14].

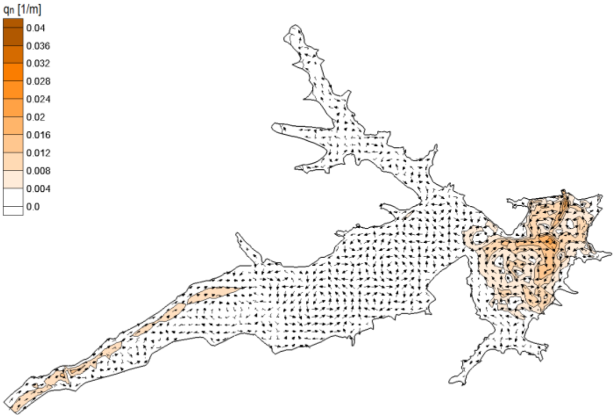


Fig. 8. Map of unitary differential flow for the total discharge 10.6 m^3/s and for the roughness parameter 10× greater than in Fig. 7b

The output may be also dependant on the water eddy viscosity coefficient that in principle may be variable with temperature. For the analysis presented in this article, it was kept at its default value for the whole domain, as recommended by the authors of the AdH model, which brought to mind some doubts in the past. Cutting out the cold bottom layer and obtaining results consistent with previous ones can be treated as a kind of justification for that approach.

5. Conclusions

The research leads to the conclusion that the impact of reservoir stratification on the 2D horizontal water velocity field is not very strong. It varies with the total discharge:

- For very low discharge values, the hydrodynamic models are generally not very reliable [3, 4, 6, 12] due to the fact that the primary factor that shapes the pattern of the currents is wind, not gravity [1]. With the changes of the wind, the currents and stagnant areas change their shape and location, seemingly randomly. While this analysis does not include any wind impact, it shows that the relative discharge changes caused by the presence of the thermocline may be significant. Much care should be taken while interpreting any results in that case.
- For moderate discharge values, the impact of the thermocline on the flow pattern is visible. The velocities are higher, but the water exchange (represented by the unitary differential flow) is not affected much. Taking into account that the accuracy of the modeling method is by itself limited, excluding the thermocline from the model and taking the reservoir as one body seems to be acceptable.
- For higher discharges, the impact of the stratification on the horizontal velocity field is negligible.

It should be noted again that the thermocline appears in the Dobczyce reservoir only for a few months in a year, depending on the weather. A very high flow may destroy it prematurely. Model calculations performed for the whole water body give reliable results when there is no stratification. From the computer experiments made with the use of AdH modle it can be concluded that this approach may be used also when a thermocline is present in the reservoir. Stratification does not change the general properties of the 2D horizontal velocity field. Some corrections may be needed for the medium range of total discharge depending on the accuracy required, especially for the obtained velocities (important for transition time issues). Unitary discharge field (important for water exchange concerns) is affected to lesser extent.

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Sources of photographs:
http://www.mpwik.krakow.pl/

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