ABSTRACT

The paper describes specific changes in the quality of the Danube river water under the conditions of backwater effects in the Hydropower Plant Djerdap I storage. The results of long-term tests in five profiles of the investigated section, at various discharges give a global view of the intensity of changes in the composition of water mass. The analysis included changes in the contents of: organic matter, oxygen regime, reduction of turbidity and changes in the composition and abundance of plankton.

The specific changes in the domain of physico-chemical and biochemical processes and changes in the biological status of the watercourse (composition and structure of plankton) at varying retention times complete the picture of short-term changes in the investigated system. Presentation of some settling effects and processes in the sediment of the storage provides an idea of some long-term changes in the conditions of backwater effects of the Danube in the investigated section.

INTRODUCTION

Changes in the composition of the water mass in a river are a result of a large number of physico-chemical and biological processes occurring in certain conditions: climate (temperature, insolation etc.), geometrical and hydraulic characteristics of the watercourse and water composition in the inflow section. The greatest attention was paid to the processes related to mineralization of organic matter and restoration of oxygen consumption in the water mass (Streeter-Phelps) etc. A number of mathematical models were made in order to describe the natural processes, with more or less success, depending on the changes of conditions and the extent to which the relevant processes were included in the analysis.

In natural lakes and reservoirs with longer retention times, due to their specific features, the problem of organic matter generation is in the foreground, together with the related processes (formation of reduction zones, elution of products of anaerobic processes etc.). Particularly detailed analysis was carried out of the processes of nutrient recirculation (macro and micro elements) in the system, limiting factors of the production etc. (Goldman, G.R., Horne, A.J.) [2].

Reservoirs in watercourses, particularly those exposed to a higher degree and variety of pollution, have a number of specific features compared to a river and a natural lake system. The changes in flow rate induce changes in the conditions: retention time, flow rates in the accumulation basin, settling, elution of deposited material etc. The analysed section of the Danube is a typical system of an open reservoir, where the occurring processes are characteristic of this type of lake with variable retention times.
METHODS AND RESULTS

The analysed section of the Danube covers the backwater influenced part of the Djerdap I reservoir from Smederevo to Kladovo (Fig. 1). Changes in the composition of the water mass in this section were analysed in five profiles. Investigations of the water content were made at three sampling points in the profile (at the left bank, central flow and the right bank) at characteristic discharges (spring high water, summer and autumn low water). Sampling of water was done at 0.5 m from the water surface. All analyses of physico-chemical characteristics of water were by standard analytical methods (Standard Methods) [4]. For biological analyses, composite samples of 40 l were taken from the left and right bank and central flow and filtered through a plankton net No. 20. The analysis of phyto and zooplankton (qualitative and quantitative composition) was made with regard to species, while the estimate of the water quality was made according to Knopp and Pantle–Buck. Investigation of the changes in water composition along the section under study, at various discharges, was done with regard to the transport time from profile to profile.

FIG. 1. INVESTIGATED SECTION OF THE DANUBE

The range of changes of the basic water composition parameters: suspended particles, BOD₃, dissolved oxygen content and quantitative composition of plankton for characteristic conditions in the watercourse (change of flow rate from 1 850 to 11 900 m³/sec) is shown in diagrams Fig. 2 to Fig. 5. Changes in the content of some parameters of water composition, relevant to the production in the system, are shown in Table 1.

Table 1 – Detected changes of some indicators of the river Danube water content in the Smederevo–Tekija section

<table>
<thead>
<tr>
<th>Profile</th>
<th>Secchi disc, m</th>
<th>pH</th>
<th>HCO₃⁻</th>
<th>CO₂⁺</th>
<th>NH₄⁺</th>
<th>NO₂⁻</th>
<th>NO₃⁻</th>
<th>Total P</th>
<th>Ortho. P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min.</td>
<td>max.</td>
<td>min.</td>
<td>max.</td>
<td>min.</td>
<td>max.</td>
<td>min.</td>
<td>max.</td>
<td>min.</td>
</tr>
<tr>
<td>Smederevo (1116)</td>
<td>0.20</td>
<td>7.60</td>
<td>3.15</td>
<td>0.00</td>
<td>0.09</td>
<td>0.004</td>
<td>1.85</td>
<td>0.180</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>8.50</td>
<td>3.55</td>
<td>0.40</td>
<td>0.44</td>
<td>0.036</td>
<td>3.96</td>
<td>0.585</td>
<td>0.255</td>
</tr>
<tr>
<td>V. Gradište (1059)</td>
<td>0.25</td>
<td>7.60</td>
<td>3.20</td>
<td>0.00</td>
<td>0.15</td>
<td>0.021</td>
<td>1.80</td>
<td>0.147</td>
<td>0.106</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>8.45</td>
<td>4.25</td>
<td>0.15</td>
<td>0.52</td>
<td>0.092</td>
<td>2.78</td>
<td>0.270</td>
<td>0.213</td>
</tr>
<tr>
<td>D. Milanovac (990)</td>
<td>0.35</td>
<td>7.70</td>
<td>3.05</td>
<td>0.00</td>
<td>0.11</td>
<td>0.026</td>
<td>1.82</td>
<td>0.170</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>8.40</td>
<td>4.25</td>
<td>0.05</td>
<td>0.42</td>
<td>0.110</td>
<td>2.97</td>
<td>0.298</td>
<td>0.200</td>
</tr>
<tr>
<td>Tekija (955)</td>
<td>0.50</td>
<td>7.70</td>
<td>3.00</td>
<td>0.00</td>
<td>0.06</td>
<td>0.031</td>
<td>1.75</td>
<td>0.140</td>
<td>0.070</td>
</tr>
<tr>
<td></td>
<td>1.95</td>
<td>7.95</td>
<td>4.70</td>
<td>0.00</td>
<td>0.51</td>
<td>0.070</td>
<td>2.85</td>
<td>0.245</td>
<td>0.196</td>
</tr>
<tr>
<td>Kladovo (943)</td>
<td>0.50</td>
<td>7.70</td>
<td>3.05</td>
<td>0.00</td>
<td>0.115</td>
<td>0.032</td>
<td>1.90</td>
<td>0.180</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>1.80</td>
<td>7.90</td>
<td>4.75</td>
<td>0.00</td>
<td>0.49</td>
<td>0.062</td>
<td>2.67</td>
<td>0.254</td>
<td>0.157</td>
</tr>
</tbody>
</table>
DISCUSSION

For the presentation of dominant processes in the studied section characteristic for hydropower reservoirs, this work analyses elements of the systems presented in Tabl. 1, 2. Changes in the flow conditions: rate, geometrical characteristics (changed ratio of water surface to the total volume) lead to the changes in the conditions of depositing suspended material, reaeration characteristics, conditions for plankton development and a number of other processes relevant to the water quality. Particularly important are the changes in water composition at varying flow regimes through the storage, which have the greatest impact on the intensity of dominant processes and their effects.

Transportation processes relevant to: sedimentation, reaeration, intensity of exchange on the contact layer water/sludge changed considerably, depending on the discharge. Some basic data related to the transport processes in the storage are shown in Table 2.

The data presented in Table 2 and criteria for the evaluation of the stratification based on the value of Froude’s number (Water Resources Engineers) [3],

\[ F_d = 10^{-s} \frac{L}{z \tau} \]  

where: \( L \) – storage length (m), \( z \) – mean depth (m), \( \tau \) – retention time (yrs), enable us to evaluate the potentials of this process. In keeping with this principle, for the values of \( F_d > 0.32 \), the reservoir is thermally homogeneous, which is the case with the analyzed section of the river Danube.

Sedimentation Processes and their Effects

One of the basic features of the backwater influenced reservoirs is a high level of reduction of the entered suspended material. The effects of this process are manifold and are reflected in the deposition of organic dissolved and undissolved materials, of a large number of materials and specific organic micropollutants.

The results of measurements (mean values in the profile) of the suspension composition in the inflow and outflow profile, shown in diagram Fig. 2, point to a considerable degree of correlation between the suspension content and discharge. The increase of water transparency in the conditions of low water is considerable: from the value of about 0.5 m in the inflow profile to that of about 2.0 m in the profile of Tekija. The increase of the photic zone up to the value of about 8 m in the outflow part should result in an increased production. However, this does not happen to the extent which, in view of this fact and the content of macro and micro elements (Table 1), could be expected.
Degradation of Organic Oxidizable Material and Oxygen Regime in the Reservoir

The presented results (Tab. 2) indicate the considerable effects of the removal of organic oxidizable material in the section influenced by backwater. Bearing in mind the fact that the share of 'old' organic pollution is quite large (a major part of degradation occurs in the phase of nitrogen oxidation), the effects of BOD removal are extremely large, particularly in the conditions of minimum discharge in watercourse. The diagram in Fig. 3 clearly shows a major decrease in organic load in the inflow profile along with the increase of discharge. As opposed to this, higher discharges in the outflow profile result in an increase of BOD. Accordingly, the effects of BOD content reduction in the studied section range from 25 to over 75%. The constants of the total reduction of BOD (Kr) for certain subsections are derived from the expression:

\[ L = L_0 e^{-Kr} \]  

(2)

where \( L_0 \) and \( L \) are inflow and outflow BOD loads for the studied sections. The values of Kr presented in Table 2 for individual subsections at similar temperature conditions differ by an order of magnitude.

![Image of Fig. 3](https://iwaponline.com/wst/article-pdf/131598/181.pdf)

**FIG. 3. CHANGES OF BOD\(_3\) IN THE INFLOW AND OUTFLOW PROFILE, AS A FUNCTION OF DISCHARGE**

![Image of Fig. 4](https://iwaponline.com/wst/article-pdf/131598/181.pdf)

**FIG. 4. CHANGES OF THE CONTENT OF DISSOLVED O\(_2\) IN THE INFLOW AND OUTFLOW PROFILE AS A FUNCTION OF DISCHARGE**

\[ y = 6.4720 - 2.6223e^{-4x} \quad R^2 = 0.475 \]

\[ y = 0.96518 + 7.6731 e^{-5x} \quad R^2 = 0.238 \]

\[ y = 7.0293 + 2.2996e^{-4x} \quad R^2 = 0.765 \]

\[ y = 2.7430 + 6.0468e^{-4x} \quad R^2 = 0.741 \]
For the determination of the constants of reaeration in the analysis of critical conditions in this section (minimum flowrate), Perišić M. et al. [5], a number of models have been analyzed: O'Connor-Dobbins [11], Churchill-Elmore-Buckingham [6], Paden-Gloyna [7]. It was concluded that the relations O'Connor-Dobbins and Padden-Gloyna agree to a considerable extent with the experimental data acquired in the studied section. Table 2 shows values of the constant K2, calculated with the correction for temperature effects.

For the characteristic conditions of the discharges presented in Table 2 under similar temperature conditions in the watercourse (about 15°C), certain important facts have been determined, related to the conditions of changes in water composition in the studied section.

<table>
<thead>
<tr>
<th>Table 2 – Biochemical degradation and reaeration in the studied section (characteristic discharges, water temperature about 15°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Smederevo to</td>
</tr>
<tr>
<td>V. Gradište</td>
</tr>
<tr>
<td>D. Milanovac</td>
</tr>
<tr>
<td>11 900</td>
</tr>
<tr>
<td>V. Gradište to</td>
</tr>
<tr>
<td>D. Milanovac</td>
</tr>
<tr>
<td>9 500</td>
</tr>
<tr>
<td>11 900</td>
</tr>
<tr>
<td>D. Milanovac to</td>
</tr>
<tr>
<td>Tekija</td>
</tr>
<tr>
<td>9 500</td>
</tr>
<tr>
<td>11 900</td>
</tr>
</tbody>
</table>

The first subsection is characterized by extremely high values of the constant Kr, which rise along with the increased discharge. In the downstream subsections the values of Kr are stable.

Reaeration constants in all subsections increase considerably when the mean velocity in the section increases.

Although the values of the constants Kr and K2 lead to the conclusion that the biodegradation process and reaeration are balanced, and should bring about increased content of dissolved oxygen at higher rates, the results of measurements in all hydrological conditions provide data on the constant increase in the deficit in the whole studied section, except for that of oxygen deficit at the discharge of 11 900 m³/sec.

The balance of dissolved oxygen compensation does not include effects of wind, which in some periods of investigation considerably increases the reaeration effects. Similarly, the consumption of dissolved oxygen in the process of sediment mineralization may be quite important for oxygen balance. The organic matter content in the storage sediment is 15–120 mg O₂/g of the dry mass of mud, depending on the place of sampling. In the main course, the organic matter content is minimum and increases in the parts of the reservoir with lower velocities. Mineralization in the deposit occurs in the transitory field of Redox potential: oxidation processes take place in unconsolidated mud layers and anaerobic ones occur in the homogeneous deposit.

The coefficient of mass transport on the liquid/soil border line is determined by the following expression: (Levich) [9].

\[ K = \frac{D}{Li} \]  

where: \( D \) – molecular diffusion of \( O_2 \) or BOD in the liquid and \( Li \) – thickness of diffusion layer determined by kinematic viscosity (\( \nu \)) and dissipation energy (\( \epsilon \)):

\[ Li = \left( \frac{\epsilon}{\nu^3} \right)^{-1/4} \]

The increase of mean velocity in the reservoir increases the effects of mass transfer on the liquid/solid border line and, in such conditions, the total oxygen consumption too. This is certainly one of the reasons for the increased oxygen deficit in the conditions of major effects of reaeration.
PRODUCTION AND CHANGES IN THE BALANCE OF INORGANIC CARBON

The production of organic matter consumes inorganic carbon from the carbonate system. The total content of available carbon in water is:

\[ C = \text{CO}_2(aq) + \text{H}_2\text{CO}_3 + \text{HCO}_3 + \text{CO}_3 \]  

(5)

where: 
- \( C \) – total dissolved inorganic carbon
- \( \text{CO}_2(aq) \) – concentration of dissolved \( \text{CO}_2 \)
- \( \text{HCO}_3 \) – concentration of bicarbonate ions
- \( \text{CO}_3 \) – concentration of carbonate ions

The buffer capacity of water is realized as presented in the following reactions:

\[ 2\text{HCO}_3^- \rightarrow \text{CO}_3^- + \text{H}_2\text{O} + \text{CO}_2 \]  

(6)

\[ \text{HCO}_3^- \rightarrow \text{CO}_2 + \text{OH}^- \]  

(7)

\[ \text{CO}_3^- + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 2\text{OH}^- \]  

(8)

Consumption of \( \text{CO}_2 \) in the process of production shifts the balance shown by relations (6–8) to the right. The beginning of this process, i.e. lower levels of production, is characterized by the relation 6, where pH of the water shifts to the alkaline range, over 8.4, to be followed by the release of \( \text{OH}^- \) ions and greater alkalinity of the solution.

The appearance of \( p- \)alkalininity, i.e. presence of measurable concentrations of carbonate ions, was observed only in the most upstream part of the studied section and only in the conditions of autumn low waters and higher plankton contents. The observed value of \( p- \)alkalininity is about 0.4 meq/l in the Smederevo profile, in the subsection to V. Gradište it decreases down to about 0.2 meq/l, and at D. Milanovac to only 0.1 meq/l. In the downstream subsection (Tekija), \( p- \)alkalininity was not detected.

Concurrently with the consumption of \( \text{CO}_2 \) in the process of organic matter production, recarbonization occurs through the process of: respiration, sorption from the air and biochemical degradation in the water and sediment.

The effect of compensation for \( \text{CO}_2 \), from the air, in the process of sorption determined by Henry’s law, depends on the temperature and balance in the carbonate system. According to experimental measurements [10], at pH values recorded in all profiles and alkalinity of about 3.5 meq/l, recarbonization is equivalent to decarbonization.

Microbiological degradation in the mud deposits is a major source of \( \text{CO}_2 \). Tests in laboratory conditions resulted in the values of 12–45 mg C/m²/h depending on the transport in the water/mud contact layer.

The most important source of \( \text{CO}_2 \) is the process of microbiological degradation of BOD where, in the actual conditions, about 50 mgC/m²/h is released in the most upstream section. Since all the other phenomena of recarbonization are connected to the surface, they can be neglected for balance purposes.

The concentration of carbonate ions detected in the first three profiles is low, which is one more indicator of the small production in this system. The absence of carbonate ions in the downstream profiles proves that plankton reduction as well as production do take place, and it has been proven in all studied seasons.

Changes in Plankton Composition along the Section

Throughout the years, plankton has had similar characteristics. Differences occurred in abundance, although even then similar relationships remained among certain groups and similar compositions in certain subsections of the watercourse.

In phytoplankton, almost in all profiles, Bacilliariophyta dominate both in quality and quantity. They vary most in the two upstream profiles and gradually less after that, while a small number of species (Asterionella formosa and Synedra) were observed throughout the watercourse. Chlorophyta are usually better developed in summer than in autumn. The most frequent species are Scenedesmus and Pediastrum. Of the other algae groups, Heteroconta are present everywhere, while Euglenophyta and Cyanophyta were found in a small number of species and low abundance, mostly in the initial profiles under study.

Zooplankton has been, as a rule, less numerous than phytoplankton. Rotatoria almost always dominate both in quality and quantity. The most frequently observed are various species of Brachionus and Keratella genera. Brachionus species dominate in the upstream and Keratella in the downstream part of the studied section. The subdominant ones are:
Protozoa; in the first profile in autumn, there are various species of Ciliata and in the downstream - Testacea (Tintinidium and Diflugia). Cladocera and Copepoda appeared in small numbers of species and small abundance. The variety, and even more abundance, of phytoplankton decrease from the upstream to the downstream part of the studied section.

Fig. 5. Zooplankton is usually the most developed in the Ram profile, and decreases downstream both in the number of species and abundance. All the results, in accordance with the criteria for the evaluation of water quality, lead to the conclusion that the studied water is of the second class. However, the values of saprobic index below 2 are more frequently recorded in downstream profiles, which points to the effects of improved water quality of this section of the Danube. The recorded effects of plankton reduction, both with regard to quality and quantity in the studied backwater influenced section of the Danube, are one of the interesting phenomena in the changes of water communities, in specific flow conditions encountered in open reservoirs.

![Fig. 5. Changes in plankton composition along the section](image)

CONCLUSIONS

Major effects of sedimentation processes in the backwater influenced conditions in an open reservoir result in a high level of reduction of suspension and organic degradable matter contents.

The released organic load is broken down in the reservoir with effects which are better the longer the retention time and the lower the flow rate.

Compensation for the oxygen dissolved in water and consumed in the process of biochemical degradation in the open reservoir is mostly made in the process of reaeration. The efficiency of this process does not produce a favourable oxygen balance, resulting in an increased deficit throughout the watercourse. The only exception to this are maximum water discharges when oxygen deficit in the downstream profile decreases. The deposit in the reservoir accounts for a major share in the consumption of dissolved oxygen, particularly in the periods of higher mean velocities.

The decrease in plankton diversity and abundance along the studied section brings about decreased production in the lower part of the reservoir. Although the content of macro and micro nutrients is on a level which facilitates a high level of production, the sedimentation processes and, above all, mixing effects with changed geometrical characteristics (surface to depth ratio), are limiting factors for production in the reservoir, requiring clarification of these phenomena in further investigations.
REFERENCES