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Analysis of seasonal changes of thermal stratification in reservoir for drinking water supply (Slovakia, Turček reservoir)

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Water reservoirs are important source in supplying inhabitants with drinking water of high–quality. In total, there are 8 reservoirs in Slovakia for drinking water supply purpose. The youngest of them is the Turček reservoir located in the middle of Slovakia, which is also the object of this study. In the article, we deal with the thermal stratification in it during 3 seasons (spring, summer, autumn). Based on the analysis of data provided by the operator of the reservoir from its operation start, it came out that the thermal stratification in the reservoir occurs significantly during the summer. In the given hydro–climatic conditions, it starts at the end of April and ends in October. We also analyzed the existence of the thermocline layer, which occurs mainly in the summer, but also in spring and in autumn, but not so significantly and regularly. Thermal stratification can be classified also by Thermocline Strength Index (TSI) that indicates the steepness of the thermocline or the average gradient of the thermocline layer, so the part of the study was focused also to this indicator.

KEY WORDS: water reservoir, water temperature, stratification, thermocline

Introduction

Thermal stratification is a phenomenon in water bodies such as lakes and reservoirs where the epilimnion and hypolimnion are separated by strong vertical density gradients (metalimnion or thermocline) as a result of seasonal temperature variations (Boehrer and Schultze, 2008; James et al., 2017). Stratification plays a vital role in reservoir water quality management, as it can significantly influence the hydrodynamics and water quality regimes (Lee et al., 2013), eutrophication and sediment transport processes (Scheu et al., 2015; Zhang et al., 2020) and nutrient and phytoplankton dynamics (Liu et al., 2009).

Thermal stratification is one of the primary physical processes in lakes and reservoirs, resulting from the thermal expansion of water by solar heating (Woolway and Merchant, 2019). This stratification is crucial for water quality and ecological processes assessment in deep lakes and reservoirs and can be substantially affected by meteorological and hydrological processes in the catchment (Liu et al., 2020).

The degree of stratification depends on climatic factors, as well as on morphology, and in the case of reservoirs flow rates. In temperate zones, a lake is isothermal with typical temperatures at about 4°C in early spring. As the season progresses, lakes begin to warm and differential absorption of heat induces stratification forming the so-called epilimnion and hypolimnion. Later during cooling periods, when the temperature of the water at the surface begins to decrease, convective mixing occurs through the unequal density of the water. Strong circulation and mixing of water can eventually destroy thermal stratification. Water turnovers are especially pronounced when surface waters reach 4°C, i.e. maximum water density. Wind mixing also contributes to water temperatures distribution (Meyer et al., 1994).

Impacts of global climate changes may cause modifications of stratification regimes. The impact of rainfalls on the thermal stratification and dissolved oxygen in riverine zone was more impressive than that in transitional and lacustrine zones of reservoirs (Liu et al., 2020). According to the hydro–meteorological data from the Turček reservoir, there are no frequent occurrences of storms or heavy rains there – storms occur 2–3 times per year – so a strong influence on stratification at the given site is unlikely.

Anyway, many studies have highlighted that increasing air temperature has led to the rapidly warming of water (Bajtek et al., 2022; Vyshnevskyi and Shevchuk, 2022) and stronger thermal stratification (Kraemer Benjamin et al., 2015; Onderka, 2004; O' Reilly et al., 2015; Piccolroaz et al., 2018; Valerio et al., 2015; Woolway

and Merchant, 2019). On the other side, decreasing wind speed coupled with increasing air temperature led to increased thermal stability and reduced water column mixing in Lake Tanganyika (O' Reilly et al., 2003). So, there are still many questions without clear answers to them.
Aim of this study is the analysis of seasonal changes of thermal stratification in the Turček reservoir, which was started to build as a reservoir for drinking water supply in 1993 and put in the full operation in 1998. This study aims to gain a good understanding of the thermal regime changes of a reservoir on the base of data analysis from the reservoir operation start and on that base (outcome information) it will be able to predict trends in different future conditions.

Layers of stratification

Stratification is defined as the act of sorting data, people or objects into distinct groups or layers. In case of the thermal stratification in reservoirs it means the dividing of water volume of reservoir in general to three layers.
The upper layer, epilimnion is constantly mixed by wind and a wave generated with it, and is warmed by sun. The epilimnion thickness is not constant over the stratification period. In spring, a thin layer is formed, which throughout the summer gradually gains thickness because of wind action. It is not until autumn, that colder water from the water body surface can erode the stratification to the hypolimnion at a larger rate. During this later period of thermal stratification, substances dissolved in hypolimnetic waters, such as nutrients, become available in the epilimnion again. If surface temperature falls enough, epilimnion and hypolimnion can be mixed, and the entire water body is homogenized (circulation period) to one layer, the so-called mixolimnion. (Boehrer and Schultze, 2008)
The next layer, metalimnion, is described by a steep temperature gradient in a body of water (Liu et al., 2020). This layer is the middle layer between the mentioned epilimnion and the deepest layer, hypolimnion (see Fig. 1). As it was mentioned above, water temperature in the metalimnion changes steeply with water depth. Some authors define this middle part, where the water temperature changes by the steepest way, as the thermocline. Thermocline is a relatively thin part of the metalimnion layer in which temperature decreases rapidly with depth increase. The thermocline has been defined for partial unification, but on a strictly arbitraty basis, as a layer of water in which the temperature decrease 1° or more along 1 meter of the depth. A decrease in temperature is accompanied by an increase in density and a corresponding increase in resistance to mixing. (Kittrell, 1965)
The bottom layer of the reservoir is the hypolimnion. Water in this layer is excluded from the atmosphere influence by the overlying metalimnion and epilimnion. Only few light and heat from the sun penetrates these depths, and there is very little temperature rise once the stratification is formed. Most of the increase takes place in the upper part of the hypolimnion, which produces a slight temperature gradient from top to bottom. (Kittrell, 1965)

Description of locality

The Turček Water Reservoir was built from 1993 to 1996. The main task of the Turček Water Reservoir is the accumulation and supply of raw water for later drinking water treatment process. Its secondary mission is flood protection of the downstream part of the Turiec brook basin, to ensure ecologically stable flow throughout the year, and to produce electricity in small hydroelectric power plants. The reservoir is located at the confluence of the Turiec and Ružový brook streams above the Turček village. The dam profile is placed below the confluence of both streams. The width of the valley is approximately 120 m and the elevation in the dam profile is 719 asl. The total volume of the reservoir is 10.8 million m^3, while its storage volume is 9.1 million m^3 and the constant volume is 0.3 million m^3 of water. The strength of the dam is ensured by its retaining wall, which has a height of 59 m

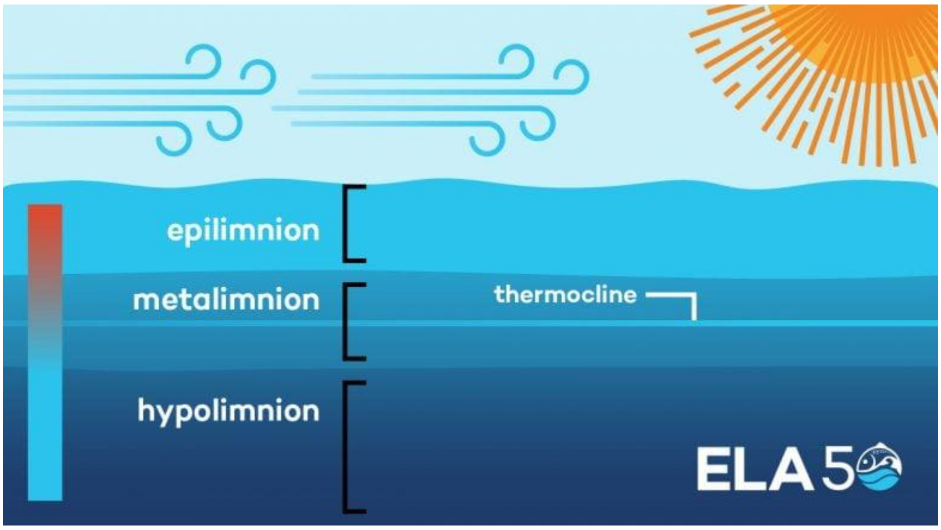


Fig. 1. Layers of water stratification (Source: Fafard, 2018).

and a crown length of 287.6 m. The total area of the basin is 29.85 km^2. The amount of water supplied to the water treatment plant is 15.8 million m^3 per year. The Turček water reservoir was put into operation on May 15, 1996. (Chmelár, 1998) Mean annual precipitation is 960 mm with maximal values in June and July, mean air temperature is 6.4°C with maximal values in July and August (Rules of manipulation, 2019). Current bathymetry of the reservoir from own measurements is shown in Fig. 2.

Method

Data on air temperature and water quality were provided to us by the water reservoir operator, the Slovak Water Management Enterprise, from its archives for period 1997–2022. Data was in the paper form, so for the next use and analysis, it was necessary to digitize them.

Water quality is monitored at 4–5 monitoring localities/points inside the reservoir in vertical direction at several horizons (Fig. 3, Table 1), with taking samples in each 5 m depth and by in situ measurements (pH, dissolved oxygen, water conductivity, water temperature) which was performed directly on the water surface from a boat equipped with a motor for maintaining the position and the GPS device for locating points. This kind of measurement was made in each meter of depth. A selected range of physiochemical, microbiological and hydrobiological indicators was monitored in the reservoir 3 times per year (spring, summer, autumn) (Mikula, 2022).

Monitoring dates were as follows: spring sampling was carried out from the end of April (because of ice cover) to mid-May, summer sampling was carried out during July, and autumn sampling was carried out from mid-October to the beginning of November.

Vertical water temperature profiles were evaluated analytically and also graphically for each measurement campaign, based on this evaluation, the distribution of epilimnion, metalimnion and hypolimnion layers was determined for each case where thermal stratification was formed. At the same time, based on the definition of the thermocline, it was determined where the thermocline layer was located in individual years during the monitored period.

Thermal stratification can be classified also by the Thermocline Strength Index (TSI) (Yu et al., 2010). This indicator can be computed using the equation:

$$TSI = \frac{\Delta T}{\Delta h} \qquad (1)$$

where

ΔT – is the difference of water temperature [°C],

Δh – is and the difference of water depth [m].

TSI simply indicates the steepness of the thermocline or the average gradient of the thermocline layer (Liu et al., 2019).

Existence of a thermocline is recognized if TSI > 1 [°C m^{-1}] and the stratification becomes more pronounced with a higher TSI value (Horne and Goldman 1994).

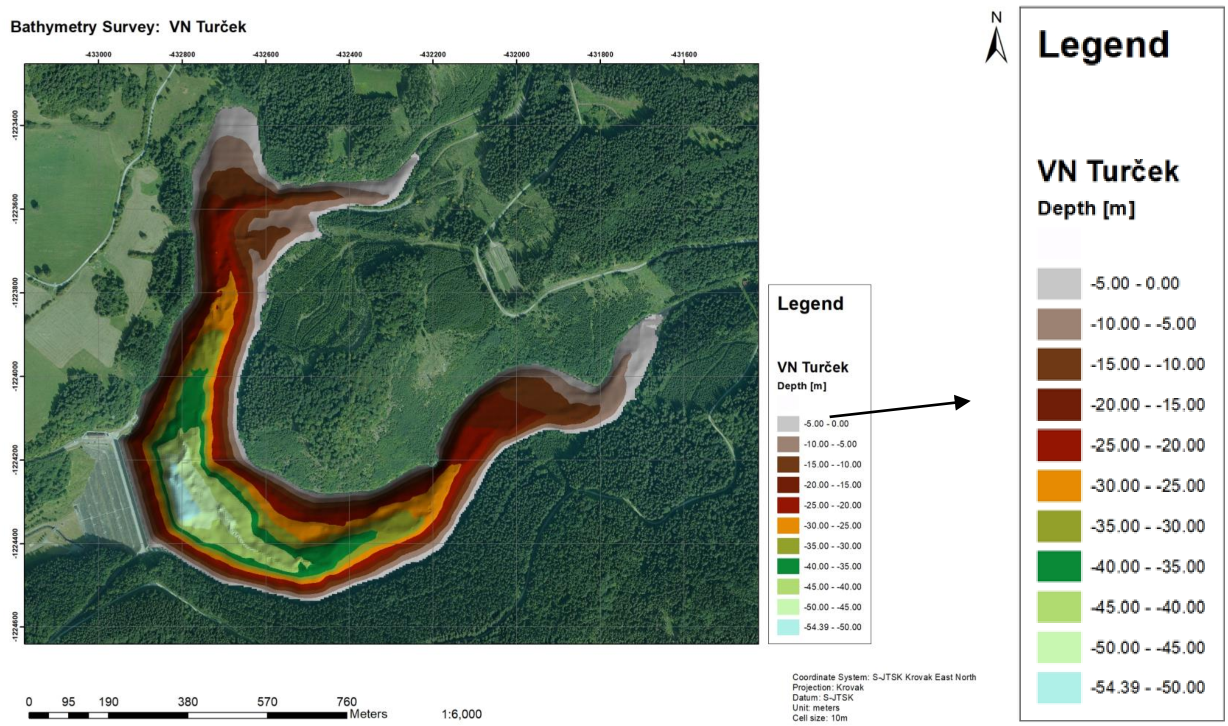


Fig. 2. Map of the Turček reservoir bathymetry.

Table 1. Coordinates and depths of 5 monitoring sites

Monitoring site	Coordinates (N / E)	Max depth
1	48.763159 / 18.939620	47 m
2	48.763666 / 18.945901	27 m
3	48.765962 / 18.949415	13 m
4	48.764264 / 18.937379	40 m
5	48.768097 / 18.938869	24 m

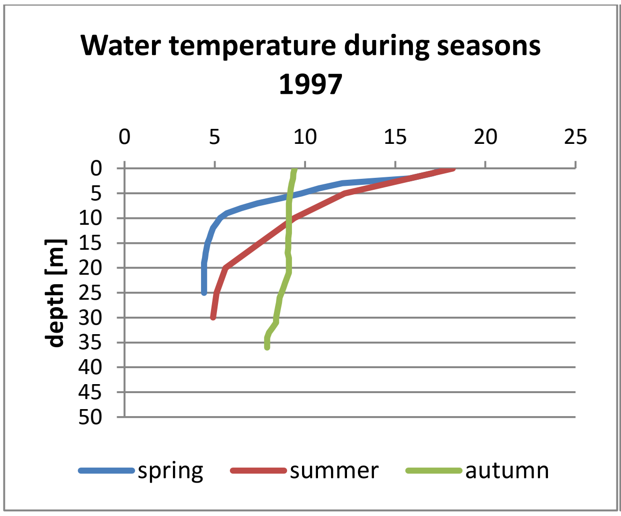
Fig. 3. Monitoring sites for measuring water quality parameters.

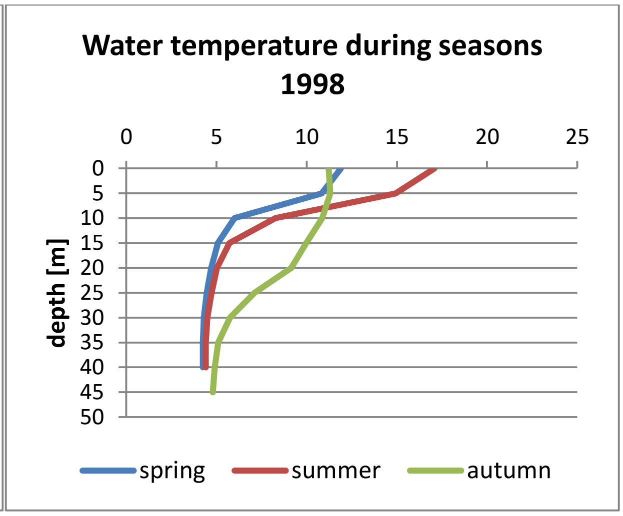
Results and discussion

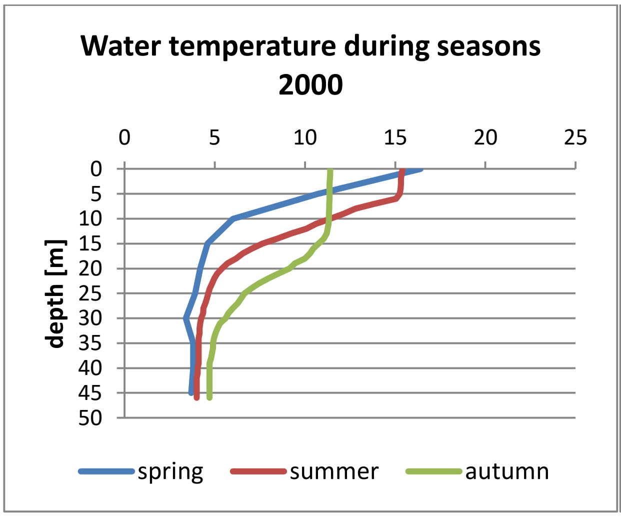
In general, three vertical thermal profiles averaging temperature from 5 monitoring points could be determined for each year in evaluated period 1997–2022, one for each season. Anyway, in the years 2015, 2017 and 2020, data from some seasons were missing. In the study, we do not report all vertical water temperature profile graphically, but only mention some peculiarities, anomalies that occurred during the monitored period (Fig. 4). An example of an atypical distribution of temperatures is the year 1997. It is logical, because this year was the year of gradual filling of the reservoir, so there was no possibility of creating classic thermal stratification. On the other hand, the thermal stratification was fully created in the next years. Atypical water temperature profile was obtained in the autumn 2010, when de facto the water temperature distribution along the water column was constant. This case should be analyzed in connection with time series of hydro–meteorological data (air temperature, wind) in the locality and evaluate the reality of this phenomenon or whether it is a measurement error. A somewhat similar situation arose also in the years 2002 and 2021, but not so pronounced. Spring season has also some case when the thermal stratification has not even begun to form, for example in 2006, 2008, 2018, 2021 and 2022, It could be caused by later beginning of spring and ice cover melting. Anyway, again it should be analyzed in connection with hydro-meteorological data analysis.

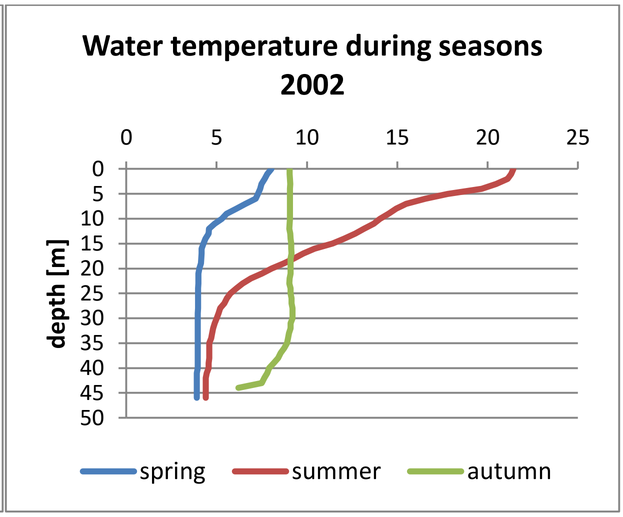
Next task of this study was the determination of the thermocline in case of thermal stratification creation. This stratification was always created in summer season. As we can partially see in Fig. 4, the water temperature was stratified even in 1998–2000, but we do not know exactly at what depth the thermocline was formed during summer, as the data from these years were measured in the depth interval of 5 m. Anyway, we determined the depth of the thermocline in partial measured points for each season separately in all years when it was possible. and the thermal stratification was formed. Results are shown in Fig. 5. For each year, it was determined also the thermocline depth by averaging measuring points during the season to see what inaccuracy we would incur in using such a value given the results from specific points. From Fig. 4 and mainly Fig. 5, we can see that during the spring season the thermocline occurs mainly in the range of 2–7 meters of depth.

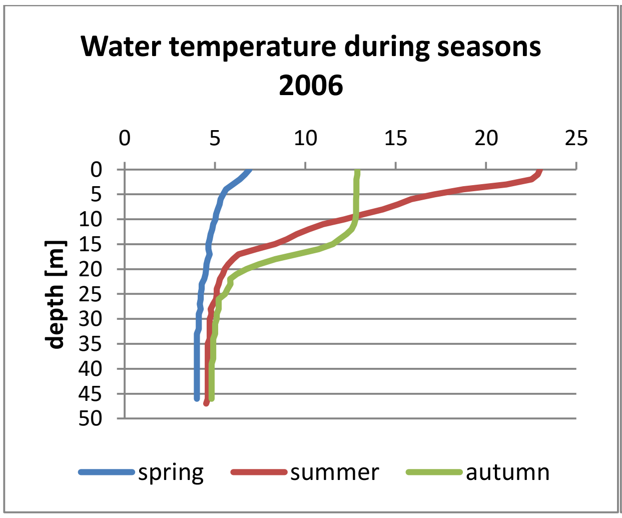
In the middle part of Fig. 5 – graphic summary of depths

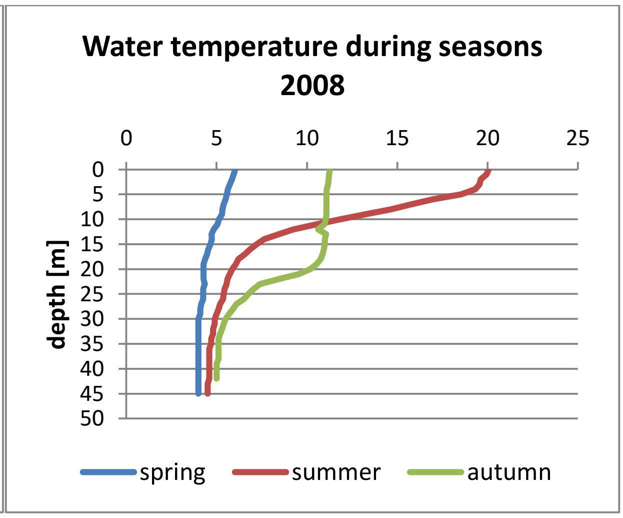












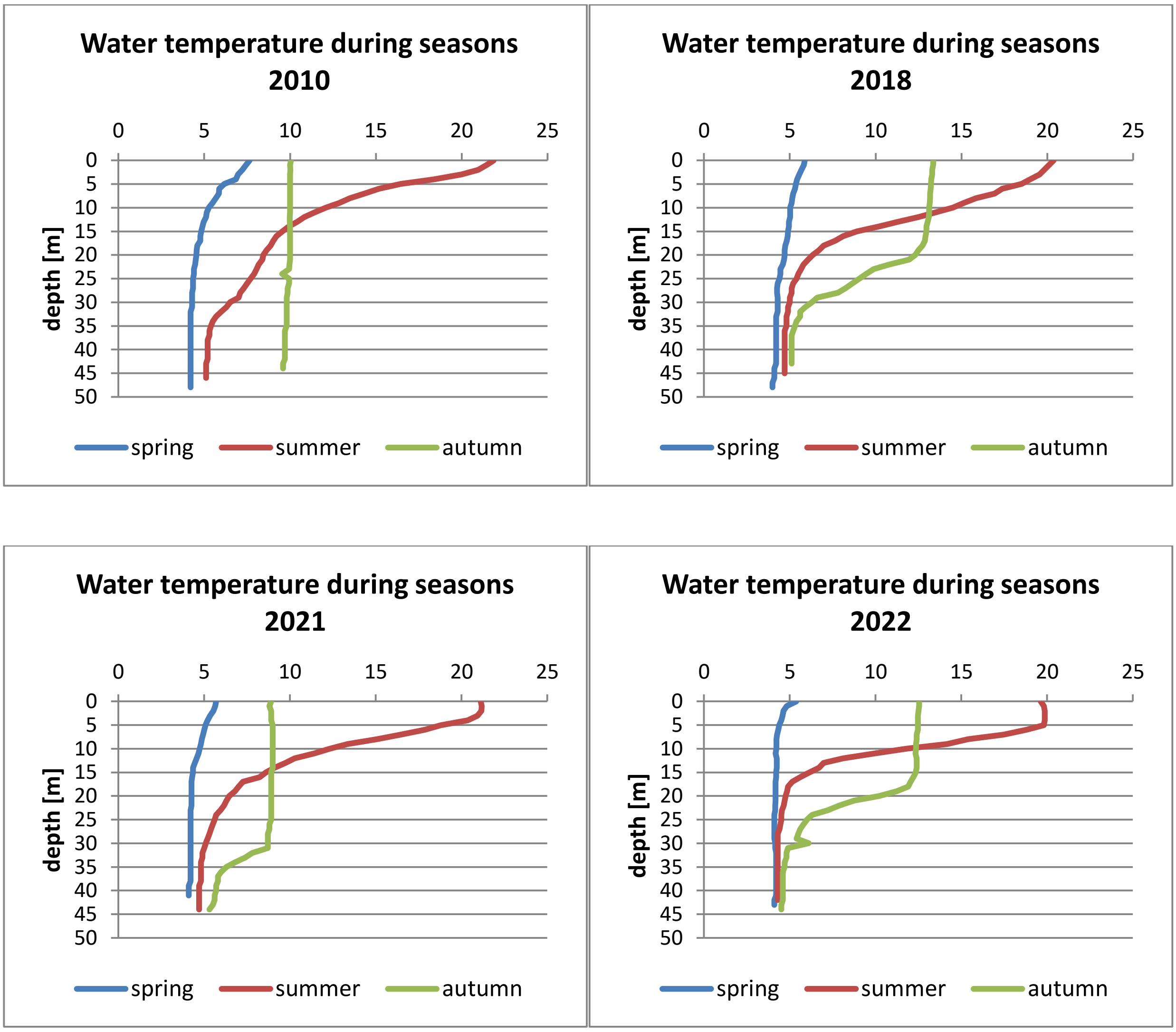


Fig. 4. Vertical water temperature profiles [°C].

of thermocline for the summer season, the course of the thermocline layer with its upper and lower edges is drawn. It was intended for the summer season, because spring and autumn are periods when temperature stratification of water does not form for many years. Based on this course, we can conclude that the thermocline in the initial years of monitoring occurred mainly in the depth range of 5–10 meters in the summer seasons. However, in recent years (approximately since 2013), the depth of the thermocline has been increasing, and in some years, the extent of this thermal stratification layer has been expanding. The least amount of data on water temperature was from the autumn seasons; so the course of the thermocline depths from this season is only slightly informative and illustrative. However, it is evident that the thermocline is deeper in this season from 17 m to 33 m.

In more details, if we take into account that the thermocline is a layer in which the temperature drops by 1°C or more per 1 meter of the depth, then during the spring seasons in case of 11 years, the thermocline was not formed in the early measurement period in April. In the years when the thermocline layer was formed, it occurred on average at depths of 4–6 m. During the summer season, when the water in the reservoir is stratified in each year, this layer occurred on average from 5–8 m, with its average value at the depth of 6m. If we look at the autumn season, a temperature drop of 1°C or more was recorded only in 10 years out of the entire 25-year period. Compared to the summer season, we can see a decrease in the thermocline, with an average depth of 23–24 m, and only in points 1, 2, 4 and 5, as point 3 is located in the shallow area of the reservoir. In 2006, the depth of the thermocline was the smallest one and appeared at the deepest measured points 1, 2 and 5, at depths of 15–19 m. The greatest depth of the thermocline was recorded in 2013, in the depth range of 32–33 m, but only at point 1, which is located on the sampling tower in the deepest part of the reservoir.

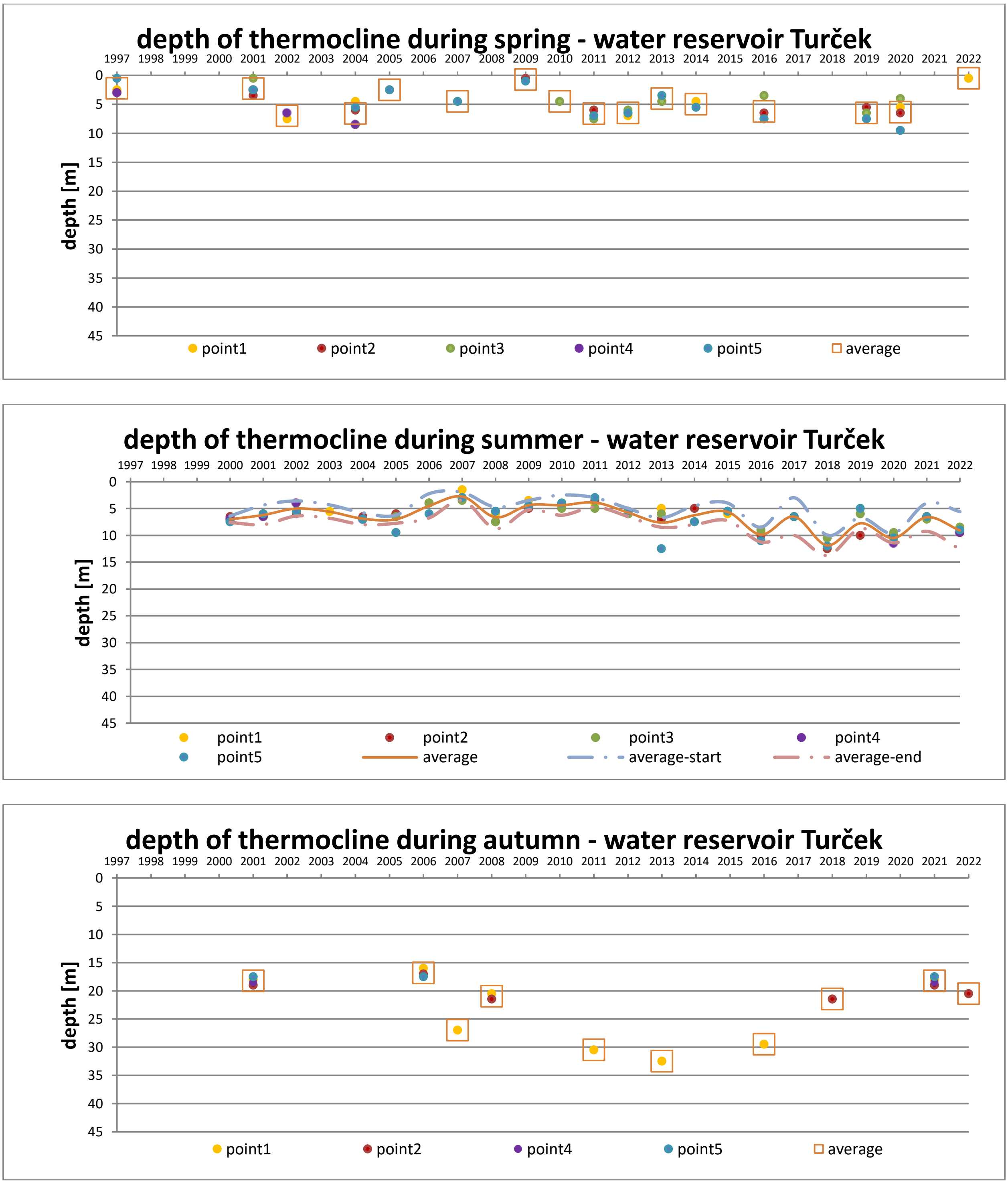
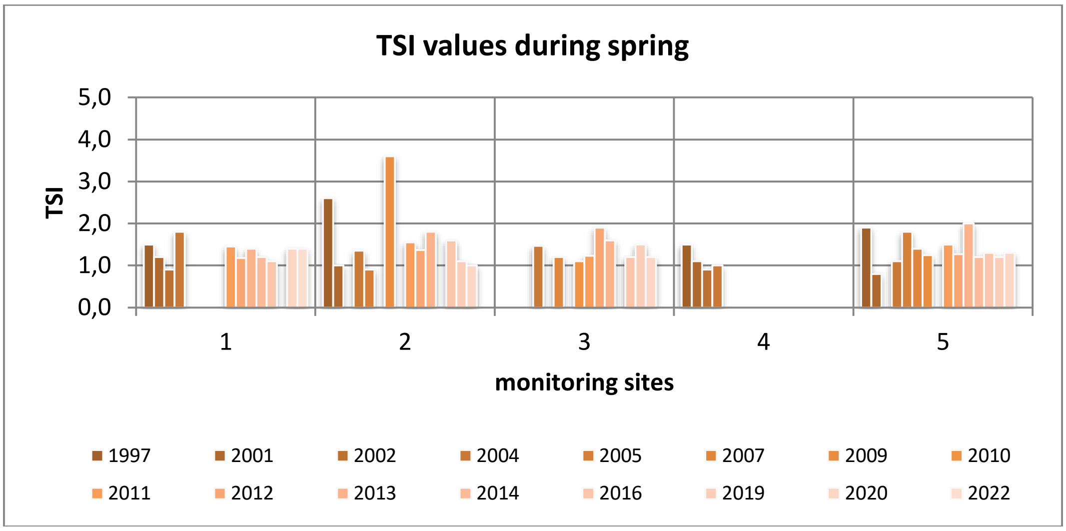
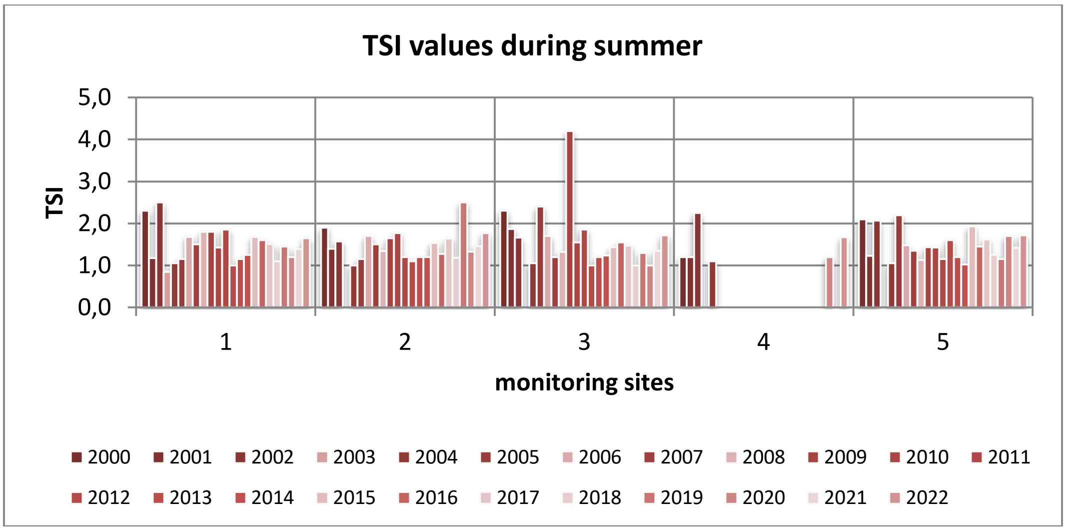


Fig. 5. Depth of the thermocline in partial measured points and average value from 5 measuring points during 3 seasons – spring, summer, autumn – in the period 1997–2022.

As a next indicator of the thermal stratification we evaluated values of TSI. This indicator was determined for each season separately and summary of results are shown in Fig. 6. Overall, the fewest observations are in point 4, which were omitted from monitoring in some years for operational reasons. Value of this index was in majority not higher than 2 – in the autumn seasons it never exceeded this value, but as we said above, this season is not covered enough by measured data. The most and the highest exceeding of this value was observed in the summer season, in the spring season there was only twice. Higher TSI values were observed in the part of the reservoir where the Turiec stream (left tributary) flows into it.





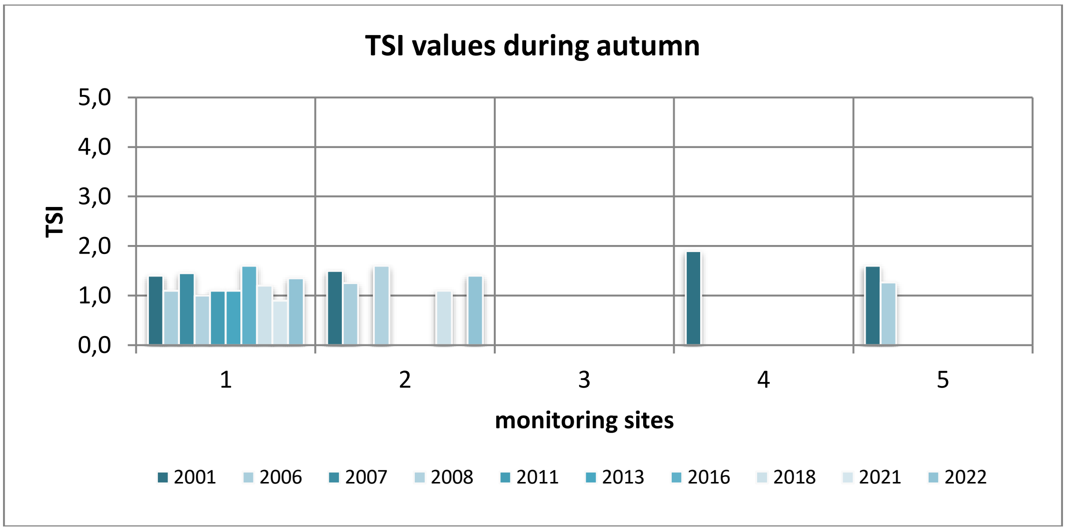


Fig. 6. Thermocline strength index during seasons for 5 monitoring sites during 1997–2022.

Conclusion

This study deals with analysis of seasonal changes of thermal stratification in the Turček reservoir. This reservoir was built primarily for drinking water supply, but also for flood protection of downstream part of the basin and for ensuring ecological discharges, as well. Thermal stratification has an important impact on the cycling of reservoir water quality. Uneven vertical distribution of water quality factors, such as dissolved oxygen and nutrients, occurs during seasonal stratification, which creates chemical stratification. Typically, thermocline and chemocline characteristics vary across different reservoirs, so it is important to study them in valid natural conditions of each reservoir separately.

Results of this study are based on analysis of water temperature values monitored during the whole operating time of the Turček reservoir. The most pronounced thermal stratification was formed in summer, in the given hydro–climatic conditions it starts at the end of April and ends in October. We also analyzed the existence of the thermocline layer, which occurs mainly in the summer, but also in spring and also in autumn, but not so significantly and regularly. The value of TSI, as an indicator of steepness of the thermal stratification, was in majority not higher than 2.

The results presented here are not applicable to reservoirs in general in terms of thermocline structure and variability. However, for objective characterization purposes and monitoring the thermocline as a boundary influencer of biological and chemical processes in this reservoir, these results are useful and helpful for further analysis focused on the development of chemistry in this reservoir, mainly in connection with its purpose to supply the population in the region with drinking water.

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