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THERMOCLINES IN PONDS: A NEW TYPOLOGY BY THE STUDY OF CONTINUOUS WATER TEMPERATURE MEASUREMENTS

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Abstract

The management of ponds and the choice of equipments aimed to reduce the impact on the rivers depend on pond water evacuation systems. The depth at which the pond water is drawn off determines temperature, oxygen saturation and chemical composition of the emissary. The study of stratification within ponds is necessary to understand the efficiency of monks and deep sluice gates. The discontinuity layer in four ponds and two reservoirs of Limousin region (France) has been followed up by means of recording thermometers. According to Brönsted and Wesenberg-Lund, we regard thermocline as the point of maximum temperature gradient. But we modernize the definition by calculating the most negative value of the directional derivative of the temperature profile. Depth and duration of summer thermoclines allow to describe three types. (i) The surface thermocline is several hours long. The temperature profile of this discontinuity layer is concave, so that the thermocline is located at a depth of 0 m. (ii) The thermocline located at a depth of about 0.8 m is several weeks long. It goes down during the night and the temperature gradient lowers at the same time. The profile of this discontinuity layer is convexo-concave and the thermocline forms the change of direction of it. (iii) The thermocline located at a depth of about 5 m remains stable during four or five months, without modifying temperature gradient according diurnal cycle. The temperature profile of this discontinuity layer is convex, so that the thermocline is located on the bottom of the pond. Meteorological data and calculations on pond stability by Wedderburn Number are used to make assumptions about thermoclines development and running. (i) The surface thermocline takes the exact profile of the penetration of the solar radiation through pond water during the hottest hours of a calm and sunny day. It disappears by nocturnal convection. (ii) The intermediate thermocline weakens but resists during the night, when it becomes deeper because of the thickening of the mixed layer. It is destroyed only when atmospheric disturbances with cold front or thunderstorms cause strong winds and temperature drop. Most of ponds, which are 1.5 to 4 m deep, are entirely mixed and stirred during these homothermies by a combination of convection mixing and wind-induced turbulent stirring. (iii) The deepest ponds present a parent-thermocline. They encroach on lake metalimnion, as it is proved by our measurements within two neighbouring reservoirs.

Keywords: pond, water temperature, thermocline, discontinuity layer, metalimnion, mixing.

1 INTRODUCTION

The contrast of periods with thermal stratifications and periods of mixing is important for the life within ponds. Then, heavy phytoplanktonic species such as diatoms sink toward the bottom of the pond, if the stratification is several days long. Well, the ponds located in the French Central Massif, composed of crystalline and metamorphic rocks, are supplied by tributaries whose water is rich in silica and propitious to development of diatoms (Touchart & Bouny, 2008). The study of rhythms of stratifications and mixing is also necessary to forecast the effect of ponds on water quality of the fluvial emissaries and to reduce their impact. In fact, building, management and efficiency of water evacuation systems located on the dam, such as spillways, weirs, deep sluice gates or monks, depend on the durations and the oscillations of the thermoclines.

2 STUDY SITE: A PANNEL OF FIVE PONDS AND TWO RESERVOIRS

The research is conducted in seven bodies of water situated in the north-western part of the French Central Massif, more specifically in Limousin region and the surrounding areas. Five ponds present the heart of the study, but we added two reservoirs for comparison to slightly deeper bodies of water. Basic morphometric characteristics of ponds and reservoirs and given in table 1.

**Table 1. Main features of studied ponds and reservoirs (with seasonal variations if known)
(unpublished data P. Bartout, D. Brunaud, C. Carlini, V. Maleval, B. Savy, L. Touchart)**

Name	Area	Maximal depth	Volume	Latitude	Longitude
Pond Oussines	15 ha	2.4 m	157,000 m ³	45°38' N	2°04' E
Pond Chaume	35 ha	4.3 m	≈ 700,000 m ³	46°20' N	1°27' E
Pond Pouge	From 29 to 34 ha	5.6 m	From 534,000 to 746,000 m ³	45°47' N	0°56' E
Pond Cieux	From 32 to 46 ha	3.7 m	From 486,000 to 807,000 m ³	45°59' N	1°03' E
Pond Landes	From 89 to 102 ha	2.2 m	836,000 m ³ for 89 ha	46°11' N	2°19' E
Mas Chaban reservoir	193 ha	19.0 m	14,200,000 m ³	45°48' N	0°39' E
Saint-Pardoux reservoir	324 ha	16.7 m	22,000,000 m ³	46°02' N	1°17' E

The table 2 shows that the studied ponds are part of the largest and deepest ponds of the region Limousin. We purposefully chose large ponds to consider long fetches. Then the calculations about stability will be regarded as minimal values.

**Table 2. Depths and areas of all Limousin ponds
(after Bartout, 2010, and unpublished data P. Bartout)**

Maximal depth	Area	Number of ponds	Percent	Ponds examples
Less than 0.7 meter	Less than 0.1 ha	4 350	19.08 %	
	Between 0.1 and 1 ha	811	3.56 %	
	Between 1 and 10 ha	11	0.05 %	
	More than 10 ha	0	0 %	
0.7 to 2 meters	Less than 0.1 ha	2 615	11.47 %	
	Between 0.1 and 1 ha	5 729	25.13 %	
	Between 1 and 10 ha	431	1.89 %	
	Between 10 and 100 ha	7	0.03 %	
	More than 100 ha	0	0 %	
2 to 5 meters	Less than 0.1 ha	489	2.15 %	
	Between 0.1 and 1 ha	6 177	27.10 %	
	Between 1 and 10 ha	1 465	6.43 %	
	Between 10 and 100 ha	56	0.25 %	Pond Oussines Pond Chaume Pond Cieux
	More than 100 ha	1	0.01 %	Pond Landes
More than 5 meters	Less than 0.1 ha	6	0.03 %	
	Between 0.1 and 1 ha	379	1.66 %	
	Between 1 and 10 ha	213	0.93 %	
	Between 10 and 100 ha	42	0.18 %	Pond Pouge
	More than 100 ha	11	0.05 %	Mas Chaban reservoir Saint-Pardoux reservoir

3 METHODS: CONTINUOUS TEMPERATURE MEASUREMENTS AND CALCULATION OF DIRECTIONAL DERIVATIVE IN THERMAL PROFILES

The water temperature is measured by submerged recording thermometers. These are *Tinytag Data Loggers* with an internal piezoelectric sensor. This is protected by an IP68 enclosure, waterproof down to a depth of 15 m, which is sufficient for all ponds and most parts of reservoirs. Nevertheless, for the deepest parts of man-made lakes, it is necessary to use manual thermometers. The recording thermometers are programmed to take a reading every hour. According to the manufacturer, they are precise to within 0.2 of a

degree. However we calibrated the recording thermometers ourselves with a very high precision manual thermometer. This was a *Lufft C100* resistance thermometer with a 4 wire platinum 100 sensor. From 1997 to 2010, L. Touchart directly set up, maintained and took measurements in the field from the five ponds. For the two reservoirs, he was helped by N. Ishiguro and B. Savy. Finally each water body, except the deepest part of the two reservoirs situated in the front of the dam, was instrumented with recording thermometers in a chain buoyed every 20 or 25 cm down to 2 m depth and then every meter down to the bottom. Only the pond Chaume in 2007 was instrumented every 10 cm. Because of the waterline of the buoy, the first thermometer is padlocked on the galvanised chain at a depth of 20 or 25 cm, except when, for example in the Pond Cieux in 1999, we add a rope with a small float at a depth of 0 cm.

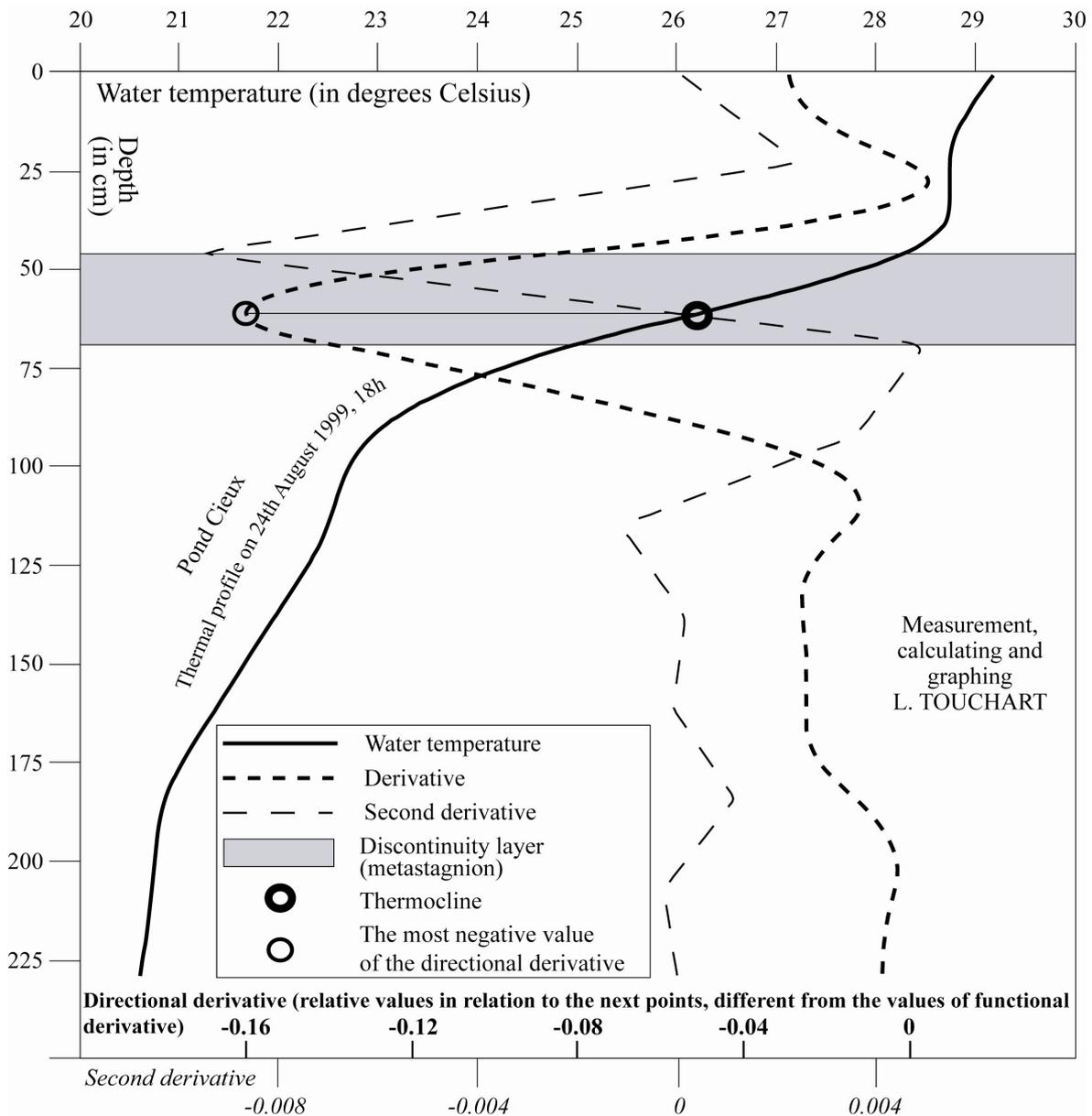


Figure 1. Methodology for determining thermocline by directional derivative calculation

According to Brönsted & Wesenberg-Lund (1911) and other more recent authors (Boulton & Brock, 2001), we regard thermocline as the point of maximum temperature gradient. But we modernize the definition by calculating the most negative value of the directional derivative of each temperature profile and by using several thousands of profiles (Touchart, 2002). The difficulty lies in the simultaneous need of interpolation between water temperatures and depths and of independence between the horary profiles. We used the software *Surfer* for resolution of the problems. To determine the point of maximal curvature of the profile, we used the second derivative. It is important to localize the upper and lower limits of the

discontinuity layer on both sides of the thermocline (here discontinuity layer means the German Sprungschicht or the French couche de saut).

The Wedderburn Number is a ratio, first defined by Thompson & Imberger (1980) for expressing the stability within the epilimnetic layer of a lake. Its dimensionless number is the quotient of the buoyancy by the mixing. We decided to use it in ponds, because it explains short-term mixing patterns (Horne & Goldman, 1994), although the water column here does not exactly work as a lacustrine epilimnion above a parent thermocline (Touchart, 2002). Buoyancy is determined by the product of the reduced gravitational acceleration due to the density across the thermocline (Patterson & collab., 1984) with the squared depth of the mixed layer. Mixing is expressed by the product of the fetch with the squared characteristic shear velocity.

4 RESULTS: SURFACE, MID-DEEP AND BOTTOM THERMOCLINES

It is possible to distinguish two types of thermoclines in shallow ponds and three in the deepest ones, according to their depths and durations. Each thermocline is located within a layer of strong temperature gradient (discontinuity layer).

The surface thermocline is several hours long. It usually appears in the early afternoon and is broken in the late evening. The temperature profile of the discontinuity layer is concave, so that the thermocline is located at a depth of 0 m.

The intermediate thermocline is several days, or even weeks, long. It is usually located at a depth of about 0.8 m, sometimes 1 m or 1.2 m. It goes down during the night and the temperature gradient lowers at the same time. The profile of this discontinuity layer is convexo-concave and the thermocline forms the inflection point of the curve, the change of direction of it. The upper limit of the layer is often located at a depth of 0.6 m and the lower limit at 0.9 m; the thickness of the layer usually is 25 to 40 cm and the mean location of the thermocline is slightly closer to the lower limit of the layer. Between the upper and lower limits, the temperature gradient may reach 8 to 10 °C in the afternoon, but 2 or 3 in the early morning.

The thermocline located at a depth of about 5 m remains stable during four or five months, without modifying temperature gradient according diurnal cycle. The temperature profile of this discontinuity layer is convex, so that the thermocline is located on the bottom of the pond. Only the deepest ponds of our sample present such a profile: a seasonal duration is clearly expressed in the pond Pougé.

5 DISCUSSIONS: STABILITY, CONVECTION MIXING AND TURBULENT MIXING IN PONDS

The surface thermocline takes the exact profile of the penetration of the solar radiation through pond water during the hottest hours of a calm and sunny day. It disappears by nocturnal convection. Its duration is similar to the temporary thermocline within an epilimnion, in the sense of Horne & Goldman (1994), but its situation, almost always located at the surface, is simpler and more regular than in a lacustrine epilimnetic layer. But some thermal profiles in ponds present more complex situations, with series of small segments in steps. Small thermoclines, which formed a few hours earlier, are separated by mixing layers of some decimetres inherited from breeze-induced stirring.

The intermediate thermocline weakens but resists during the night, when it becomes deeper because of the thickening of the mixed layer. It is destroyed only when atmospheric disturbances with cold front or thunderstorms cause strong winds and temperature drop. Most of ponds, which are 1.5 to 4 m deep, are entirely mixed and stirred during these homothermies by a combination of convection mixing and wind-induced turbulent stirring. We exploit the Wedderburn Number in an unusual way, by considering the characteristic shear velocity as the variable and the Wedderburn Number as a fixed number with a value equal to one. Our calculations for the great pond Cieux, with a potential fetch of 800 m, and the wind meteorological data in the MétéoFrance station of the Limoges-Bellegarde airport, show that the thermal stratification seldom may be destroyed. During the strong afternoon stratification, the speed of the wind of South-Western direction necessary to the mixing only happens during 1.4 % of the total time of the summer. During the weak morning stratification, such a wind happens once every ten days. For other deeper ponds, the stability is higher.

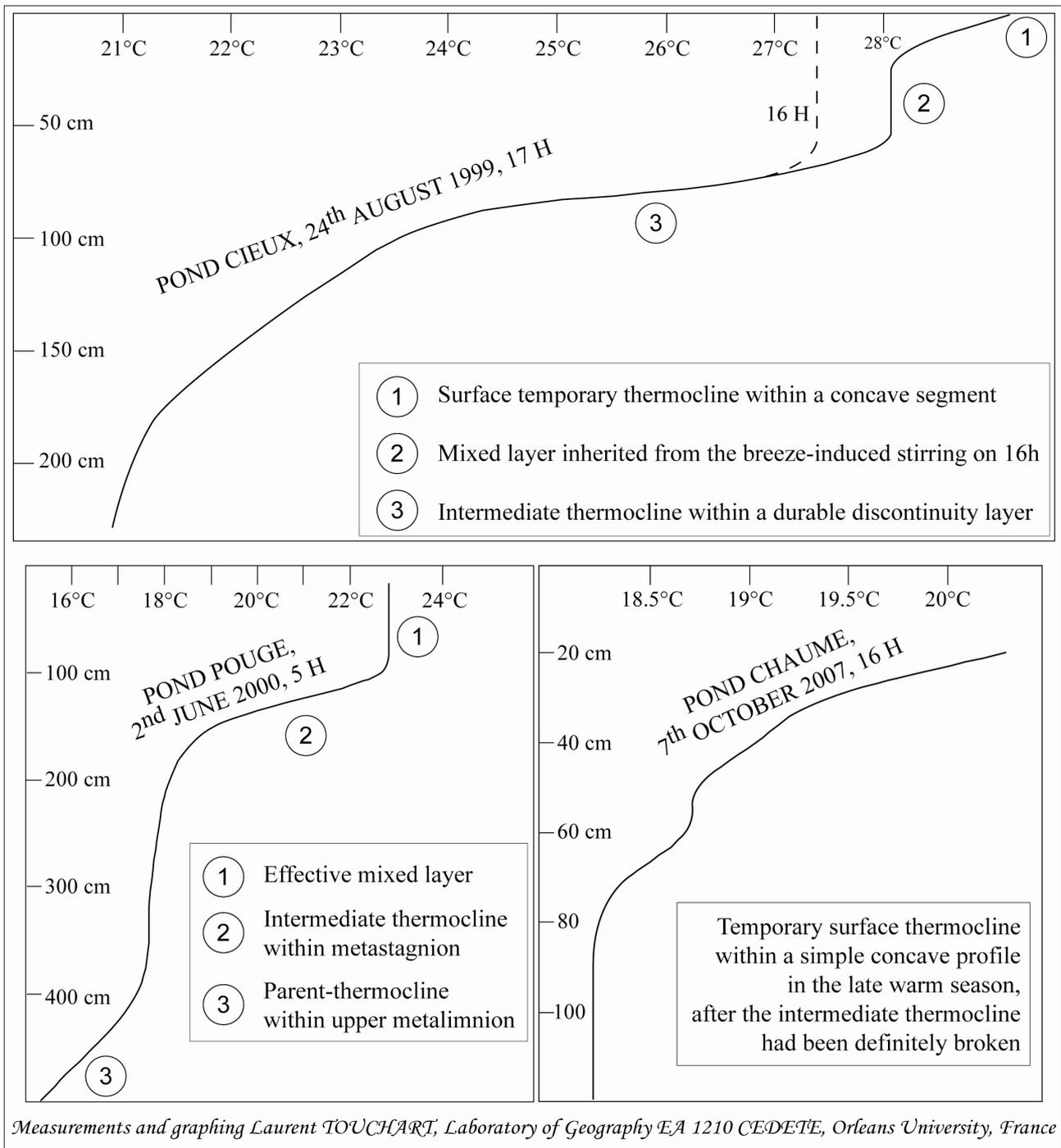


Figure 2. Thermal profiles in three ponds with three types of thermoclines

The deepest ponds present a parent-thermocline. The pond Pougé, the deepest of our sample, offers a bottom seasonal thermocline from the end of April to the beginning of September. The discontinuity layer shows its upper part from 4 m to the bottom at 5.6 m, but the pond is not deep enough to have the lower part. The deep layers of the pond encroach on lake metalimnion, as it is proved by our measurements within two neighbouring reservoirs.

6 CONCLUSIONS

Most of ponds in Limousin and Central France do not exactly work as lacustrine epilimnions. The mid-deep intermediate thermocline, located at a depth of 0.6 to 1 m, presents a middle stability. It is more durable than an epilimnetic temporary thermocline, but less durable than a parent thermocline. The main reason is the great depth of the Limousin ponds relative to their small area. The short fetch do not allow

wind-induced stirring during sometimes six or seven weeks. A subordinate reason is the climate of this region, where summers offer hot anticyclonic periods broken by Atlantic depressions. We suggested to name “metastagnion” (“stagnion” for pond, as “limnion” for lake) this intermediate discontinuity layer, which does not include nor a daily nor a seasonal thermocline. Because of the metastagnion, an evacuation system of bottom water, such as a deep sluice gate, is efficient only if the pond is deeper than 1.2 m. The evacuation system named “monk”, which draws a mixing of bottom and mid-deep waters, is not very efficient in shallow ponds with a depth less than 2 m.

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