THE STABILITY OF THE WATER COLUMN IN FRENCH PONDS (LIMOUSIN REGION) BY THE CALCULATION OF THE WEDDERBURN NUMBER

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ABSTRACT. The stability of the water column in French ponds (Limousin Region) by the calculation of the Wedderburn number. Oxygenation and biological life in lakes, reservoirs and ponds depend on the stability of the water column and on the rhythms of stratification and mixing periods. Slight thermal stratification in ponds often is regarded as the same as instability in shallow lakes. Nevertheless fetch in ponds is very short, what reduces the mixing. Wedderburn number (quotient of the buoyancy by the mixing) is used to quantify the stability in shallow water bodies. We calculate it for some ponds in French region Limousin, due to original hourly water temperature measurements in all depths and wind data of Météofrance stations. First results show that very high values (above 10) are frequent in summer and spring period (during 41% of the total time of 2 336 hours from May to July in three ponds). That is why we may consider Limousin ponds as stable stratified bodies of water despite their shallowness. Continuous measurements allow to calculate the diurnal cycle and other time scales of the Wedderburn number, with periods of weakening, when air temperatures and surface water temperatures decrease, wind speed increases and when the wind blows in the same direction with the length of the pond. The most complex variable is the depth of the thermocline; a light increase of the breeze thickens the upper warm layer and strengthens the stability, but an important increase of the wind tends to destroy the stratification.

Keywords: pond, water temperature, buoyancy, mixed layer.

1. INTRODUCTION AND STUDY SITE: THE IMPORTANCE OF THE STABILITY OF PONDS FOR THE LAND MANAGEMENT

The concept of “thermal resistance to mixture” in a lake was at first brought up by E. Birge (1910, p. 989). Then Wilhelm Schmidt (1915, 1928) defined the stability of a lake as the quantity of work (in the sense of mechanical energy) necessary to mix the entire water column of a lake and to homogenize the temperature profile, still keeping the same heat. The Austrian scientist gave the first mathematical equations for calculating the stability of a freshwater lake in ergs (ten millions Joules) per unit area. The calculation has been complicated by O.

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Eckel (1950). W.H. Munk and E.R. Anderson (1948) suggested transforming potential in effective stability, which would be later the way to the creation of the Richardson number. They separated the mixed layer of a lake, due to the process of free convection, and the wind stirred layer, due to the process of forced convection.

But some limnologists noted that there is an original stability within the epilimnetic layer of a lake, i.e. above the parent-thermocline (Horne & Goldman, 1994). The epilimnion consists in a succession of small mixed layers, wind-stirred layers, diurnal thermoclines and temporary thermoclines. The Wedderburn number (W) has been established by R.O. Thompson and J. Imberger (1980) and used in order to quantify the stability within the epilimnion and to enter simplified numerical data in one-dimensional thermal and density computer models (Patterson *et al*., 1984, Imberger, 1985). Several authors used W to predict internal waves too (Boegman *et al*., 2005). Some geographers affirm that a pond is a truncated lake, with a water column reduced to the epilimnion and a surface reduced to the littoral zone (Loup, 1974). The authors of the present paper do not agree with this hypothesis (Touchart, 2007), because the bottom of a pond is not equivalent to a parent-thermocline and because the fetch is very short compared to a lake. Moreover E. Gorham and F.M. Boyce (1989) showed that the depth of the parent-thermocline increases with the area of the lake. That is why it is interesting to test W in small and shallow bodies of water (Gorbunov, 2007), especially for checking the specificity of ponds (Touchart, 2002).

Deep layer oxygenation, mineralization in bottom mud, density currents and water movements, plankton oscillations depend on the stability modifications in the water column of the ponds. In headwater regions where the hydrographic network is dammed by thousands ponds, such as Limousin, the estimation of mixing rhythms and stratification stability should be of outstanding importance for regional land management and for chossing water evacuation systems, monks, spillways, weirs, deep sluice gates, derivation channels and other arrangements in the dam of ponds.

In France, where the average size of the 251.289 ponds is 1.05 ha (data 2007, P. Bartout, first published in Touchart *et al*., 2012), and still more in region Limousin, where the average size of the 16 971 ponds is 0.6 ha (Bartout, 2010, 2012), ponds usually are very small. But we intentionally selected large ponds, where fetch and mixing will develop maximum values, so that W will be at the minimum. Then the stability may be regarded as a bottom-value for ponds in general. Cieux’ area is about 40 ha, Pouge’s 30 ha, Oussines’ 15 ha and their respective depth is 3.7 m, 5.6 m and 2.4 m.

2. METHODS: CONTINUOUS MEASUREMENTS OF WATER TEMPERATURE AND CALCULATION OF WEDDERBURN NUMBER

According to R.O. Thompson and J. Imberger (1980), W is the ratio of the buoyancy (product of the reduced gravitational acceleration due to the density across the thermocline with the squared thickness of the mixed layer) by the mixing (product of the fetch with the squared surface friction velocity). We use the Markofsky and Harleman's formula (1971) for calculating the density of the freshwater ponds from the water temperature. We assimilate the temperature of the mixed layer above thermocline to thus of the thermometer located at a depth of 25 cm, and the temperature of the deep layer to thus of the deepest thermometer. For estimating the thickness of the mixed layer, we calculate the temperature gradient between each thermometer and we select the highest value of all the segments, except if this number is located above 75 cm because we consider in such a case that it corresponds to a temporary surface thermocline. For calculating the characteristic shear velocity we multiply the wind velocity (at 10 meters high) by a coefficient of $1.3\ 10^{-3}$ (Salençon & Thébault, 1997). We assimilate the fetch to the length from the buoy to the shoreline from where blows the hourly wind.

Based data are water temperature one (data L. Touchart) and meteorological one (data Météofrance). The water temperature is measured by recording thermometers with an internal piezoelectric sensor. The precision is within 0.2 °C. L. Touchart directly calibrates (by the means a resistance thermometer with a 4 wire platinum 100 sensor), sets up, maintains and takes measurements. All thermometers are padlocked on a galvanised chain buoyed every 20 or 25 cm down to 2 m depth and then every meter down to the bottom. Our hourly water temperatures within ponds represent about 300 000 data. Only a selection of 2 336 data is used here.

3. RESULTS: A VERY HIGH STABILITY DURING 40% OF THE SUMMER TIME

3.1. At long-time scale

Taking one year with another the stratification of Limousin ponds is about six months long, from the end of April to October (Touchart, 2002). Some monthly examples may illustrate the duration of the stability.

In the pond Pouge, the water temperatures are registered above the central plain, 90 m south of the dam, in a water column of about 5.0 m depth. Meteorological data are Limoges-Bellegarde's airport ones. According to the narrow extension of the pond, the maximum fetch (more than 1900m) happens when the wind blows from the south, but values sharply fall when the wind deviates from this direction. From the 1st to the 31st of July 2000, during the heart of the warm season, the average value of W is equal to 38.7. W is above 10 (very high stability) during 59.1% of the 744 hours, between 3 and 10 (rather high stability) during 27.6%, between 1 and 3 (slight stability) during 11.0%. It means that the deepest pond of our sample during the warmest month is not stable only during 9.5% of the time (W below 1).

In the Great Pond Cieux, the buoyed chain registers the temperatures above the central deep area, 300 m north-east of the dam, in a water column of about 3.0 m depth. Meteorological data are Limoges-Bellegarde's airport ones. According to the multilobate shape of the pond, the maximum fetch happens if the wind blows from the north-east, but many other directions make great lengths (1 000 m NE, 860 m NNE, 430 m ENE, 330 m WSW, etc.). From the 1st to the 17th of June 2002, i.e. during 398 hours, the average value of W is equal to 11.7. W is above 10 during 29.1% of the total time, between 3 and 10 during 22.9%, between 1 and 3 during 20.8%. It means that the pond is not stable during 27.1% of the time (W below 1).

Pond Oussines, representative of Limousin Highlands' water bodies, is located at an altitude of 836 m. Our buoyed chain registers the temperatures above the central deep area, 120 m north-east of the dam, in a water column of 1.8 m depth. Meteorological data are Ussel-les-Plaines' station ones, at an altitude of 670 m, where high winds often blow. According to the extension of the pond and its knee shape, the maximum fetch (more than 600 m) happens for a south-east wind. From the 1st to the 31st of May 2002, during the beginning of the warm season, the average value of W is equal to 9.8. W is above 10 during 28.6% of the 744 hours, between 3 and 10 during 22.4%, between 1 and 3 during 14.8%. From the 1st to the 19th of June 2002, during 450 hours, the average value of W is equal to 33.0. W is above 10 during 52.9% of the total time, between 3 and 10 during 18.4%, between 1 and 3 during 14.0%. It means that the shallowest pond on the highest and windiest highland is not stable (W below 1) during 34.1% of the time in May and only 14.2% in June. The comparison between Cieux and Oussines seems to show that the pond area is a more important criterion than the altitude. The smallest is the pond, the greatest is W.

If we add the 2336 hours from May to July in the three ponds, W is above 10 during 40.9% the total time, between 3 and 10 during 23.4%, between 1 and 3 during 14.6%, below 1 during 21.1%.

3.2. At short-time scale

A focus on a representative example (Great Pond Cieux, 6-7th June 2002) allows to compare the evolution of temperature profiles, density gap, buoyancy, mixing and Wedderburn number during a diurnal cycle.

At 19 h (17 h UTC), the temperature profile is significant of the evening during a sunny day of the end of the spring. Water is warm near the surface and cold near the bottom, so that the stratification is sharp, with a gradient of 1.8°C.m^{-1} in the mid-layer. A rather high wind during several hours in the afternoon has homogenized an epistagnion of about 80 cm thick, and the profile is convexo-concave. The density gap between epi- and hypostagnion is sharp, but buoyancy remains rather low, since thermocline is not deep. This situation continues to 23 h, with a very moderate evolution: the profile grows colder parallel to itself due to thermal convection, from which a decrease of the buoyancy. The rather high wind of the afternoon (until to 19 h) causes a rather strong mixing and a low W.

At 0 h (22 h UTC), free convection goes on decreasing surface and subsurface temperatures, while a slight forced convection makes the profile convex, from which a sudden increase of the buoyancy. But due to a rather high wind, mixing is strong and the Wedderburn number, although it increases, does not reach 5.

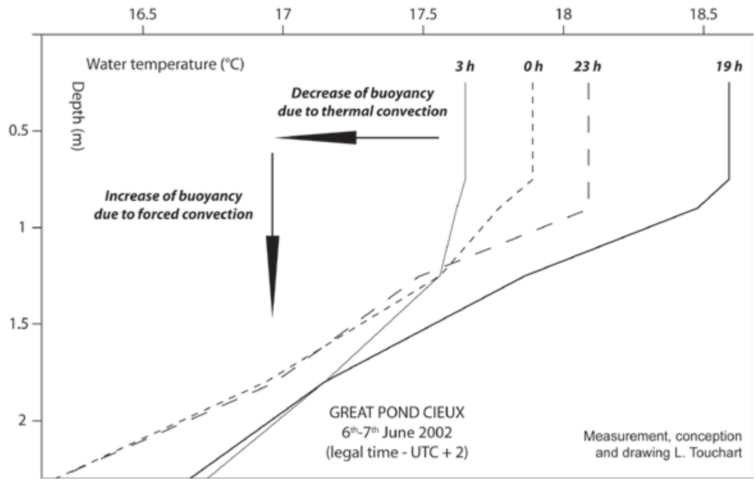

Fig. 1. Temperature profiles during night cooling in Great pond Cieux (6-7th June 2002)

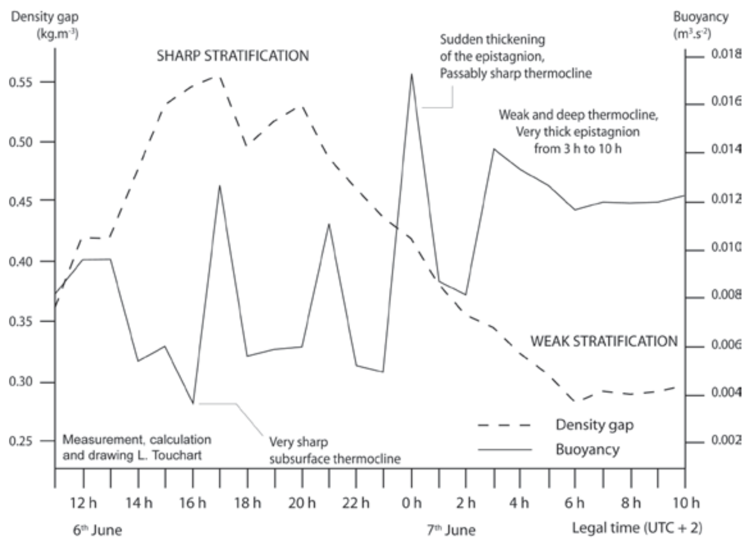

Fig. 2. Hourly evolution of density gap and buoyancy in Great pond Cieux (6-7th June 2002)

At 3 h (1 h UTC), after the wind has dropped, thermal convection becomes the exclusive process and weakens the temperature gradient. But thermocline remains in deep layers, so that buoyancy, though decreasing, keeps high values. Since the weather is still, mixing is almost absent and W goes beyond 11, the maximum value during this diurnal cycle. This situation continues just as it is during the rest of the night and in the early morning.

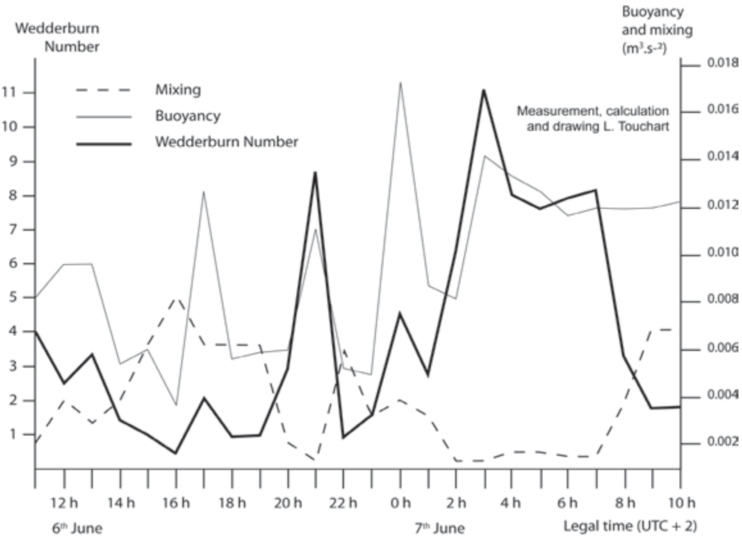

Fig. 3. Hourly evolution of buoyancy, mixing and Wedderburn number in Great pond Cieux (6-7th June 2002)

4. DISCUSSION AND CONCLUSIONS: A DURABLE STABILITY IN PONDS DEEPER THAN 2 METERS

Our research shows that the stability of ponds deeper than 1.8 m, quantified by W, is more durable than it is usually said in the bibliography about stratification in Limousin ponds (Combrouze, 2000, according manual punctual measurements) or in shallow reservoirs and ponds in other countries (Krambeck *et al.*, 1994, long-term stratification only above 4 m depth deeper for Israeli reservoirs). Our study even lowers the minimum-depth of 2 m for stability of small water bodies with area less than 100 ha, measured and calculated by M. Gorbunov (2007) in Russian ponds. In studied Limousin ponds deeper than 1.8 m, the Wedderburn number is above 1 during 79% of the total time of the warm season (spring and summer). During 41% of the time, thermocline may be assimilated to a horizontal plan and simple density models may be used to predict how operate ponds. Small area added to relatively great depth and, in some cases, by narrow extension along a dammed embanked valley is in favour of high stability of Limousin ponds. The ponds with such a size (0.1-100 ha; 1-6 m) should be regarded as specific water bodies for land management.

Our hourly study shows that a moderate wind increases W, but a high one decreases W. It confirms the fact according which a breeze makes the thermocline deeper, but a stiff wind destroys it. Horne and Goldman (1994) had noted this process in lake epilimnion.

But we shall admit that interpretation of W is difficult and not always fit for a geographical way. The calculation is initially made to put mathematical models reducing the epilimnion thermocline to a plan and lake to a rectangular basin (Shintani *et al*., 2010). If it is used in another aim, some biases may appear. For example the transformation of a convexo-concave to a convex profile causes a high increase of buoyancy, even if the profile has not changed by forced convection, but only by free convection within the margin of error of the thermometer and of the extrapolation curve between two instruments. The profile of 7th of June 2002 at 22 h UTC in the Pond Cieux may be regarded as such a case.

However that may be, the stability in French Midwest's ponds is high and thermal stratification is very more durable than a daily subsurface thermocline in the epilimnion of a lake or a deep reservoir, although it is obviously less durable than a seasonal parent-thermocline. That is why we suggested in previous publications (Touchart, 2002) to name "epistagnion" such an upper pond mixed layer, which the foot is limited by a discontinuity layer including a mid-stable thermocline during several days or weeks.

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