Lakes, reservoirs and ponds, vol. 4(2): 81-108, 2010

THE INFLUENCE OF MONK EQUIPPED PONDS ON THE QUALITY OF BASIN HEAD STREAMS, THE EXAMPLE OF WATER TEMPERATURE IN LIMOUSIN AND BERRY (FRANCE)

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Abstract

In the centre-west regions of France, the deep water outlet system known as a "monk" is used in 13% of bodies of water. The authorities are strongly encouraging this to increase, arguing that this system would reduce pond induced warming of the hydrographical network. We have measured the water temperature in four monk equipped ponds for 13 years to such an extent that this paper draws on an analysis of 142,200 original measurements. Compared to a surface outflow, a monk is a system which shifts the warming of the emissary water course to the end of summer and the autumn which reduces average annual warming by about 1°C. This reduces the heating of diurnal maxima but increases warming of the minima. A monk equipped pond warms the river with deep water which has acquired its heat by mechanical convection generated by the wind, as opposed to a weir equipped pond which provides surface water warmed by insolation. In winter the monk equipped pond does not damage the thermal living conditions for Fario trout embryos and larvae under the gravel. In summer, the monk prevents night time cooling of the emissary and increases the temperature of the minima excessively for sensitive species.
Keywords: pond, stream, basin-head, water temperature, convection, monk, valve, Fario trout

Introduction

Water temperature is the major physical property which governs the health and quality of hydrographic networks (Williams, 1968). It directly influences the life of aquatic organisms (Brett, 1956, Burrows, 1967, Brown, 1969, Brooker, 1981, Verneaux, 1973, Dajoz, 1985, Calow and Petts, 1992, Amoros and Wade, 1993, Harper, 1995, Crisp, 1996, Angelier, 2000) and indirectly affects them by affecting oxygen saturation (Truesdale *et al*., 1955) and gas solubility (Labroue *et al.*, 1995). Less studied than the effect of ponds created by dams on large rivers, the thermal effects of bodies of water on streams requires in depth research. This has become crucial since the implementation of the 2000 European Framework Directive which requires the quality of the water in river basin heads to be preserved. Does the effect of water bodies on the water quality of the basin-head small hydrographic network depend on the water outlet equipment installed in the banks of those bodies of water? If yes, how can the effect of ponds on the temperature of emissary streams be minimised? In France, the authorities are strongly recommending replacing surface weirs with a more costly device: the monk[1]. Is this deep or mid-depth water outflow system truly effective and suitable for all situations? This study in the Centre-West region of France, focused on Limousin and Berry, may provide some answers to this. These crystalline regions have a very large number of bodies of water of various sizes, about 20,000 of them, a significant number of which are very deep. Because of these deep ponds, thermal analysis of the depth from which water is drawn out at the pond embankment can be carried out over a particularly wide range.

1. Principle of Operation of the Monk and the Study Site

1.1 How the monk operates and the layer of water extracted at the bottom of the pond

The monk is a pond water evacuation system located in front of the dike and drain pipe which is used to draw water at different depths and to control the outgoing flowrate (Huet, 1970, Bachasson, 1997, Arrignon, 1998, Breton, 2001, Schlumberger, 2002, Boch, 2004). It is comprised of masonry built sections, the base slab and the cage, and removable components which form one or more screens and sets of boards.

The permanent parts which were formerly made of different materials including brick are nowadays made of concrete. This forms a foundation slab supporting a cage. This is traditionally made up of three vertical walls – one parallel to the dike and often attached to it, sometimes a few meters in front of it and the other two perpendicular to it. The cage is open in the direction of the pond (Photo 1). In Limousin and southern Berry however a fourth wall is frequently added so that the structure takes the form of a closed chamber from all sides (Photo 2). In recent

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[1] “Withdrawal of bottom water with a suitable system delivers cooler water downstream than using surface water but this water may be de-oxygenated” (Géonat, 2008, p. 13). “A monk is used to control the water level, but can cause “shocks” ” (*ibid*., p. 19). “Monk […] advantages: (i) ease of controlling the water level (ii) allows for partial emptying (iii) enables pond bottom water to be drawn off” (*ibid*., p. 51). “The thermal impact […] of built in devices such as the monk, enables ponds to be emptied by removing the coldest water from the bottom and therefore to limit this type of impact” (Trintignac et Kerléo, 2004, p. 34). “The system means that deep water can be drawn off, i.e. cold water, which is advantageous for pisciculture during the summer” (Denardou, 1987, p. 5).

monks the cube is even replaced by a cylinder. The dimensions of a monk are such that the distance between the last row of boards and the drain pipe must be equal to at least twice its diameter (Schlumberger, 2002).

The interior of the cage is grooved for the removable components to slide within. The most complete monk has three or four slideways, in front or behind which a screen can slide and two or three sets of boards. It is then called a Herrguth monk (Schlumberger, 2002, Boch, 2004). As indicated beforehand, the moveable screen facing the pond is now replaced fairly often with a fixed solid wall. Through this there is only a deep outlet pipe protected by a small mesh.

The two or three internal slideways are the most important part of the monk: each of them holds a set of boards, traditionally made of oak and fitted with hooks so they can be raised and lowered. The upstream set does not reach the bottom and the basal space at the bottom can be widened by removing boards; the downstream sets do not reach the top and the space at the top can also be increased by removing boards. The first set is used to control the thickness of the bottom water layer drawn out by the system and the second and third rows control the flowrate between the surface of the water, which is the same in the monk and the pond, and the top of the highest board.

The advantages gained by being able to control the position of all the sets of boards on the other hand requires monitoring and maintenance which can be considered as being fastidious. This is why the monk is often made less flexible with a certain number of modifications. The most common and oldest method is to fill the space between the second and third row of boards with clay so that the internal barrier which controls the flowrate is leaktight (Photo 3). As for the first set, it is often concreted completely or at the bottom with a pipe through it at the bottom. In this situation the thickness of the water layer drawn out can no longer be varied (Photo 4 and Photo 5).

1.2. Geographical distribution of monk equipped ponds

Across the Limousin, a region where an inventory of bodies of water has been completed (Bartout, 2010), it is possible to demonstrate the numerical and spatial importance of bodies of water equipped with a monk. Out of the 18,187 bodies of water which can be considered as being ponds[1], the water outflow system has been identified for 10,858. Only 1,453 ponds have a monk or 13% of the total studied.

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[1] We consider here as bodies of water, so-called “étangs” (ponds), “lacs” (ponds) and “mares à système de vidange” (ponds with an emptying system) as defined by P. Bartout (2010).

Photo 1: Monk cage with three walls at Ribières Pond (commune of Monteil-au-Vicomte) seen from inside the body of water while dry (photo L. Touchart, 2006)

Photo 2: Monk cage in the form of an enclosure at Chaume Pond (commune of Azérables) seen from the dike (photo L. Touchart, 2008)

Photo 4: Concreting of the bottom boards of the monk at Ribières Pond with a pipe through it (photo L. Touchart, 2006)

Photo 3: Space between two internal rows of boards in the monk at Ribières Pond filled with clay (photo L. Touchart, 2006)

Photo 5: Outlet from the bottom conduit for the monk at Pouge Pond (commune of Saint-Auvent) seen from the emissary (photo L. Touchart, 1998)

This relatively low percentage is well below that desired by the national authorities and shows the amount of work that remains to be done to raise awareness and see this system become the preferred device in pond embankments, if that was ever desirable. However since there is no equivalent data on any other regional scale it is difficult to know if the Limousin is over or under supplied in monk equipped bodies of water compared to weirs.

Although it is not possible to make a spatial comparison with any other region the reference base of ponds in the Limousin can be used to analyse the characteristics of monk equipped ponds. Geographically speaking, no region in particular comes out as having a high number of monk equipped ponds, which reinforces the idea that this device reflects individual rather than collective initiative (Fig. 1). However, at another scale, that of the catchment area, the characteristics of monk equipped ponds comes more to the fore. Using the Strahler method for ordering water courses, we see the predisposition of ponds in the Limousin towards basin heads (order 0, 1 and 2). Monk equipped ponds are slightly differentiated overall by favoring order 1 and 2 as against order 0 water courses (Table 1).

Table 1: Distribution of ponds fitted with an emptying system in Limousin ranked on the Strahler scale (original data: P. Bartout).

Order on the Strahler scale	*Number of ponds per order*	*Percentage of ponds in the order*	*Number of monk ponds per order*	*Percentage of monk ponds in the order*
Order 0	4313	39.7 %	386	26.6 %
Order 1	3665	33.8 %	577	39.7 %
Order 2	1921	17.7 %	336	23.1 %
Order 3	703	6.5 %	123	8.5 %
Order 4	222	2.0 %	23	1.6 %
Order 5	34	0.3 %	8	0.6 %

How can this significant difference be explained? Is it a problem of raising awareness with owners of ponds in order 0? A need for a permanent water supply because the monk creates outlet losses which have to be compensated for? Or the effect of legislation, given the presence of the pond on a fluvial continuum, to protect aquatic life directly downstream?

All of these theories are correct but in the absence of a more detailed study it is impossible to really know how significant each one is.

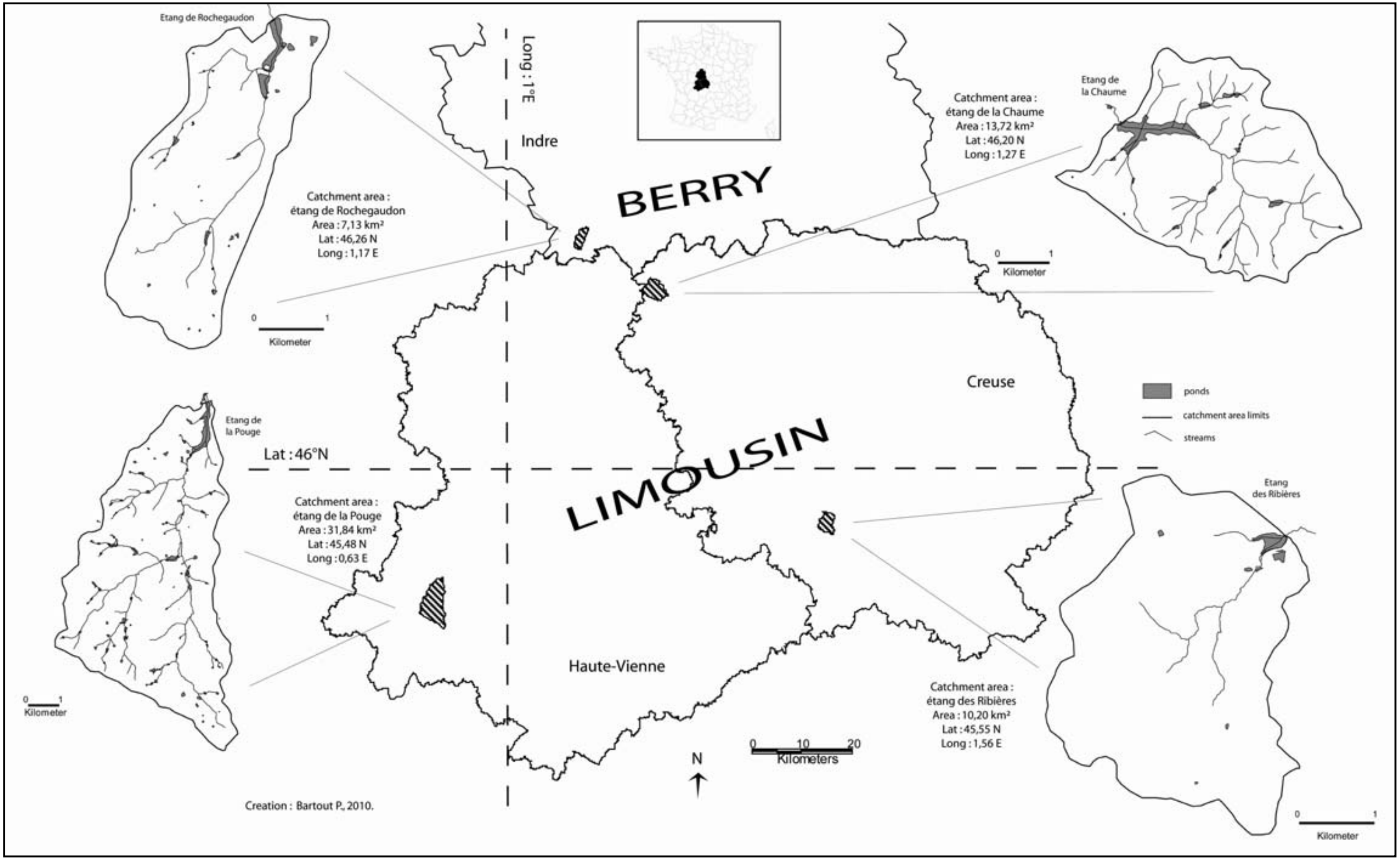

Fig. 1. Map showing the location of the four ponds studied and their catchment basin in Limousin and Berry

However, since the Decree of 1999 abolishing the declaration system and the Water Law of 2006, enforcement against owners of undeclared or “badly equipped” ponds has become more and more pressing, particularly in areas upstream of catchment basins. The issue is that water quality in these basin heads could be affected by the ponds. The response by the authorities which is strongly influenced by the ecological and fishing sectors is a clear choice: either the pond is simply removed or it is fitted with a monk and diversion channel. However this does not take into account the particular features of ponds equipped with a monk compared to those fitted with other drainage systems.

In terms of depth, the mean for monk ponds is slightly higher than for all ponds with all drainage systems taken together (2.44 m as against 2.11 m). The difference is increased if the median values are compared (2.20 m against 1.80 m).

Similarly in terms of surface area the mean difference between monk ponds and all ponds with all types of drainage system taken together is even greater, since they are more than twice as large: 1.26 ha against 0.60 ha. The median backs this up with 0.52 ha against 0.24 ha.

The particular features of monk equipped ponds must be stressed: they are significantly larger (more than 30% of them cover more than 5 ha compared to 11.5% for all types together). They also appear to be slightly deeper than the mean: most of them are between 2 m and 6 m deep while the 0.8 – 2 m and 2 – 6 m classes are very close to each other for all ponds together (Table 2).

Table 2. Comparison of surface area and depth of monk equipped ponds with all types of ponds together (original data: P. Bartout).

Pond surface area	*Percentage of total ponds*	*Percentage of monk ponds*	*Pond depth*	*Percentage of total ponds*	*Percentage of monk ponds*
… < 0,1 ha	20.5 %	8.9 %	… < 0.8 m	6.9 %	5.9 %
0.1 ≥ … <1 ha	67.8 %	61.0 %	0.8 ≥ … < 2 m	46.4 %	36.8 %
1 ≥ … < 5 ha	10.3 %	26.0 %	2 ≥ … < 6 m	45.9 %	54.9 %
… ≥ 5ha	1.4 %	4.1 %	… ≥ 6m	0.8 %	2.4 %

In summary, monk ponds are less frequently present at a source head, cover a surface area significantly above the mean and are slightly deeper than the norm in the Limousin region. Even so, their relative mean depth is much less than the pond mean (10.84 against 17.56 per thousand) which implies a particular morphology with much less pronounced internal slopes than many nearby ponds. In this must be seen the influence of their preferential categorisation in order 1 and 2 of the Strahler scale in the lower concave parts of topographical slopes.

Additionally monk ponds are often part of a chain of water bodies (54% compared to 37.6% for all ponds together) and are rarely at the most upstream end of the chain. In nearly one out of two cases the emissary water has therefore already had its physical properties modified before entering a pond equipped with a monk (mean distance from the closest upstream pond is 70 m compared to 110 m for all ponds taken together).

Finally monk ponds are slightly older than the others: 18.5% pre-date 1945 compared to a mean of 14.9%. Perhaps this indicates fewer initial creations compared to restoring old ponds whose bathymetry enables the system to be made viable.

These facts all prove that it is not as simple to deal with the problem of ponds as the authorities would like one to believe and therefore it is a matter of adjusting the operation of a monk equipped pond in relation to its weir equipped neighbours. To do that we will use four test basins: Pouge Pond in Haute-Vienne, the Ribières and Chaume Ponds in Creuse and Rochegaudon Pond in Indre.

1.3. Monitoring the four monk equipped ponds

Since the majority of water bodies in the region only have a surface weir, this is the type of system which was prioritised in our research and which has been covered in other reports (Touchart, 1999, 2001, 2007). However, given the importance of the issues and the pressure from the authorities to provide bodies of water with a permanent deep water outlet system, we also included four monk equipped water bodies in our sample which are the subject of this paper. They all belong to the Loire basin and the Vienne sub-basin.

The two measuring sites are at Pouge Pond (45°47' North – 0°56' East, in the commune of Saint-Auvent) and Chaume Pond (46°20' North – 1°27' East, in the commune of Azérables). Each water body is of comparable dimension and bars a water course of order 4 on the Strahler scale. These are the Gorret River (Gorre basin) and the Chaume stream (Creuse basin). We recall that order 4 water courses have the highest diurnal thermal amplitude according to Vannote (1980). This order can be taken as that in which all short timescale variations are the greatest. The monk in each of these two selected water bodies takes water from the bottom so that in theory they have a maximum cooling effect on the water course. Each year their high water spillway operates for a few weeks during the highest spring water levels; at this time of year the emissary water therefore becomes a mixture. Pouge Pond covers 32 hectares and is 5.6 m deep. Its volume is 631,000 cubic meters on the mean dimension (Carlini, 2006). Chaume Pond covers 35 hectares and is 4.3 m deep. Its volume is estimated at 700,000 cubic meters.

Two observation sites were added where measurements were not performed as such to quantify the effect of the monk alone. These are complex chains of ponds where not only are there successive bodies of water but also several water outlet systems such as weirs, bypass channels and monks. The Ribières chain (45°55’ North – 1°57’ East, in the commune of Monteil-au-Vicomte) belongs to the Thaurion basin; the Rochegaudon and Moulin chain (46°26’ North – 1°17’ East, in the commune of Chaillac) belongs to the Creuse basin. In the latter case upstream from the water bodies the Allemette is a Strahler order 0 water course which dries up all summer so that a comparison between the input and output from the Rochegaudon chain can only be performed during the cooler months.

2. Methods of recording the hourly water temperature

Knowing that apart from a few exceptions (Webb & Walling, 1996, 1997), the majority of studies on river water temperatures and how it is affected by water bodies only cover a few continuous months duration (Smithm 1972), the main methodology innovations in this research are the length of time the continuous data series covers and how representative it is spatially.

The water temperature is measured by submerged recording thermometers. These are *Tinytag Data Loggers*, with an internal sensor that has a response time of a minute and a half. This is protected by an IP68 shock resistant enclosure, waterproof down to a depth of 15 m. The thermometers are programmed to take a reading every hour. The only disadvantage of these instruments is their fairly low thermal precision since they use a piezoelectric sensor. 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 Pt100 sensor. The long class A platinum sensor in a 300 mm long and 4 mm diameter protective stainless steel tube uses the most precise technology, i.e. a 4 wire system, to measure the voltage. This is proportional to the resistance since the device uses constant DC current. The resistance of the wire increases with temperature, increasing from 100 Ohms at 0 ºC to about 138.5 Ohms at 100 ºC. However the exact resistance to temperature transfer function is specific to each device. Te general precision given by the manufacturer for this type of instrument is a hundredth of a degree at 0 °C and two hundredths of a degree between –40 °C and +200 °C. The thermometer used in this study has serial number 033.0805.0202.4.2.1.20. Its precision is guaranteed each year with a certificate issued by Avantec’s metrology department for temperatures of 0 °C and 30 °C. The calibration results between the *Lufft C100*, which was taken as the benchmark and the *Tinytag Data Loggers*, which we are currently using in the field vary depending on the age of the data loggers. New instruments had the best precision and achieved a tenth of a degree. As they age, the piezoelectric sensor recording thermometers lose precision.

Out of ten thermometers eight years old, our calibration gave a average precision of 0.37 °C (Fig. 2).

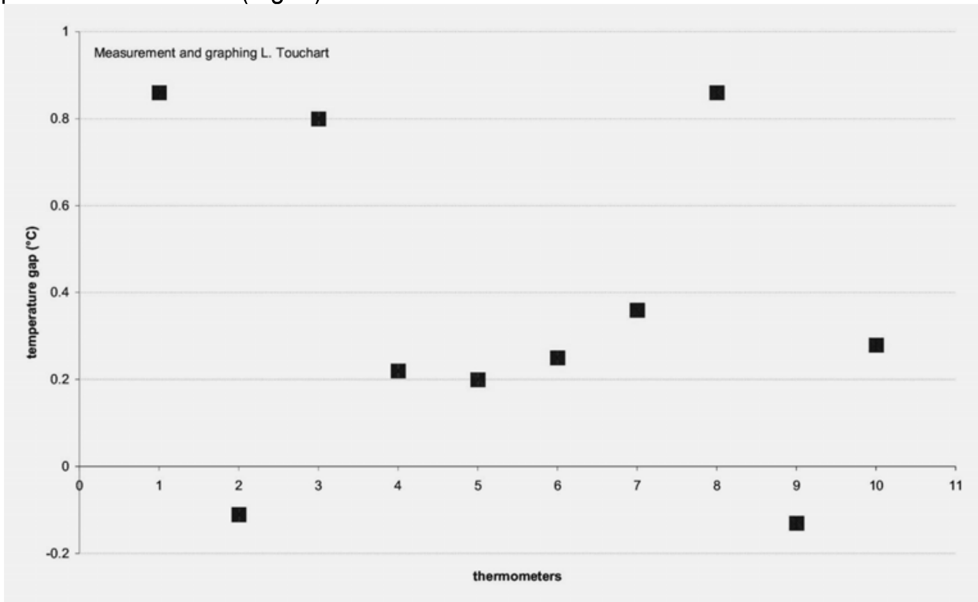

Fig. 2. Temperature variation between ten piezoelectric thermometers and a 4 wire platinum thermometer at 23.35 °C

From 1997 to 2010 we directly set up, maintained and took measurements in the field from forty underwater recording thermometers distributed over 30 sites in Limousin and Berry. Taking into account malfunctions, losses and other problems we collected in total about one million seven hundred thousand original water temperature readings over a 12 year period (data L. Touchart). Within this total most of the data relates to water bodies with a surface weir and secondly, small dam ponds with a bottom valve. Measurements on monk equipped water bodies are only in third place and represent about 140,000 temperature readings or 8% of our total database. The Pouge water body provided 104,700 readings from December 1997 to September 2002 and at Chaume 24,100 readings from July to November 2007. Water body chains, where monks are used to some extent, provide some additional data. These amount to 2,700 temperature readings in the Ribières chain at Monteil-au-Vicomte in July and August 2006 and 10,700 readings from the Rochegaudon chain at Chaillac from June 2009 to February 2010.

We placed thermometers in three types of location. First, each tributary into the water body was instrumented several tens or hundreds of meters upstream from the water body. Then each fluvial emissary was instrumented over several hundred meters or kilometres downstream to determine the length of the effect of the water body and how long it took to re-establish the initial fluvial properties. Finally each water body was instrumented with thermometers in a chain buoyed every 25 cm down to 2 m depth and then every meter down to the bottom. This point is essential. The water body is not considered as being a black box but as an engine for transforming a water course from upstream to downstream. If the way it operates can be analysed then the influence of the monk can be understood and the most suitable work proposed to intelligently manage the environment.

3. Results: moderate but permanent warming of the hydrographic network

3.1. The difference between the inlet and outlet from the pond: warming of the water course but reduction in diurnal variations

Over the long term the annual effect measured by comparing the inlet and outlet from Pouge Pond where the continuous data series is the longest can be considered as being a warming slightly in excess of 1 °C. The annual mean of 8,760 hourly measurements during 1998 in the Gorret River is 11.2 °C at the inlet and 12.4 °C at the outlet, or a temperature increase of 1.2 °C due to the monk equipped pond. The mean annual temperature increase is exactly the same in 1999 for an inlet temperature of 11.6 °C and an outlet of 12.8 °C. The annual median warming due to the water body, in other words where 50% of the hourly readings are above and below this value is 1.1 °C over both years together.

The seasonal cycle analysed using the monthly means shows practically no influence by the pond on the water course during the cold half of the year shifted onto spring, from December to May and a net temperature increase during the warm half of the year shifted onto autumn, from June to November. Warming of the Gorret by Pouge Pond ends in August and September (Table 3). This complete seasonal cycle for the Pouge is corroborated by the incomplete upstream and downstream measurements for the Chaume body of water. The importance of warming in the autumn, which remains strong in October, clearly appears in the data for the second monk equipped pond.

Table 3. Mean monthly temperature difference of the Gorret River between the inlet and outlet from Pouge Pond equipped with a monk (Monthly means calculated from hourly readings over two complete years (1998 and 1999, original data L. Touchart)

Month	J	F	M	A	M	J	J	A	S	O	N	D
Inlet-outlet difference	0.0 °C	-0.4 °C	+0.3 °C	0.3 °C	-0.3 °C	+1.5 °C	+2.3 °C	3.7 °C	+3.6 °C	2.0 °C	1.6 °C	-0.4 °C

Over the thirty three complete months available form January 1998 to July 2000 for Pouge and in August and October 2007 for Chaume Pond the mean monthly warming of the water course by the monk equipped pond exceeded 4 °C for two months (Pouge in August 1998 and September 1999), was between 3 °C and 4 °C for three months (Pouge in September 1998 and August 1999, Chaume in August 2007), was between 2 °C and 3 °C for four months (Pouge en July 1998, July 1999 and October 1999, Chaume in October 2007), was between 1 °C and 2 °C for five months (Pouge in October 1998, November 1998, June 1999, November 1999 and July 2000). The complex case of the Moulin and Rochegaudon chain at Chaillac can be added to this effect of an isolated monk equipped pond, where the first monk equipped pond has a bypass channel which is dry during the warm season and the second water body has a monk which is fixed to operate as a weir. Between the upstream and downstream of the chain the mean warming for the last three weeks before the tributary dried up in July 2009 was 6.5 °C. During winter when the bypass channel for the first monk equipped pond is full of water the chain cooled the water course by a complete monthly mean of 0.4 °C in December 2009 and 0.1 °C in January 2010. The same chain warmed the water course with an incomplete monthly mean of 1.2 °C during the last two weeks of November 2009.

If we take the raw hourly data without converting it into monthly means, the annual study shows that the monk equipped body of water warms the water course for two thirds of the year in a range where the class going from 2 to 4 °C takes on a remarkable significance. For the 17,520 hours from 01:00H on 1st January 1998 to 23:00H on 31 December 1999, the Gorret River was warmed by Pouge Pond for 11,587 hours or 66% of the time. The temperature was exactly the same (to a tenth of a degree Celsius) between the pond inlet and outlet for 1,116 hours or 6% of the time. The river was cooled by the monk for 4,817 hours or 27% of the time. Of the 11,587 hours where the monk generated heating, 6,040 hours or 34% of the total time over the two years and 52% of the heating time generated values greater than or equal to 2 °C; 1,878 hours (11% of the total time and 16% of the heating time) generated values equal to or greater than 4 °C; 398 hours (2% of the total time and 3.4% of the heating time) generated values greater than or equal to 6 °C and 24 hours (0.1% of the total time and 0.2% of the heating time) values greater than or equal to 8 °C. The highest instantaneous variation was recorded on the 1st September 1999 at 08:00H when the outlet temperature from Pouge was 8.5 °C higher than the inlet. Upstream and downstream from Chaume Pond the highest instantaneous variation was 7.1 °C on the 5 August 2007 at 08:00H. Upstream and downstream from the chain of two monk equipped water bodies of Moulin and Rochegaudon where the bypass channel for the first was dry and the second operated as a weir, the highest instantaneous difference was 9.5 °C on 29 June 2009 at 15:00H. Our readings show therefore that the warming generated by a monk is significant while the existing literature leads one to believe that a surface weir is the only system which causes such levels of warming.

On a short timescale, the diurnal minima and maxima, the diurnal amplitudes and the daily average deviations in a water course are changed to a large degree by a monk equipped body of water.

The maxima are the least changed. The absolute maximum out of 8,760 hourly temperature readings is practically unchanged by the monk. In 1998 the instantaneous maximum temperature of the Gorret was 22.7 °C upstream and 23.0 °C downstream. If we look at the absolute maximum for each month, the monk equipped pond reduces the warmest peak values of the river in winter, spring and at the beginning of summer but increases them at the end of summer and in the autumn. Therefore for eight months of the year the pond reduces the absolute monthly maximum hourly temperature. The warmest instantaneous eight monthly average river temperature for 1998 was cooled by 1.4 °C by the monk. But the opposite occurs from August to November. The absolute maximum October 1998 hourly temperature reading was 13.8 °C upstream from Pouge and 17.7 °C downstream, i.e. +3.6 °C. The increase due to the monk was +1.8 °C in September, +0.4 °C in November and +0.3 °C in August. These values were confirmed at another pond, the Chaume. The absolute maximum hourly temperature at the end of July and the end of August 2007 was 22.2 °C upstream and 23.3 °C downstream, i.e. +1.1 °C due to the monk.

As against the river thermal maxima which are only slightly changed by the monk equipped pond the minima are warmed strongly. Upstream and downstream from Pouge Pond the absolute minimum for all 12 months of 1998 was increased by the monk. This warming ended in August since the temperature never went below 10.6 °C upstream and 18.8 °C downstream or an increase of 8.2 °C due to the monk. The temperature increase in the lowest river values continued significantly in September (+ 4.0 °C) and October (+4.7 °C). Chaume Pond confirmed this strong increase in the absolute minimum of the hourly data during the end of summer and autumn months since, in August 2007, the temperature never fell below 12.0 °C upstream and 16.8 °C downstream, i.e. an increase of 4.8 °C due to the monk. In October 2007 the minimum instantaneous warming in the stream going through the Chaume was 4.4 °C.

The maxima were little changed but the minima were strongly warmed. The evident consequence of this is that the monk reduces the temperature difference between night and day. The diurnal amplitude of the river is strongly reduced by the pond at all times during the year. On average, the monk reduces the diurnal amplitude by more than a degree and a half and it is four times lower at the pond outlet than at the inlet (Table 4).

Table 4: Reduction in diurnal thermal amplitude in the Gorret water course due to Pouge Pond equipped with a monk (Values calculated from 1998 and 1999 hourly readings, original data L. Touchart)

Month	Mean diurnal amplitude upstream	Mean diurnal amplitude downstream	Difference between upstream and downstream
January 98	1.2 °C	0.3 °C	-0.9 °C
February 98	2.4 °C	0.4 °C	-2.0 °C
March 98	2.7 °C	0.5 °C	-2.2 °C
April 98	1.9 °C	0.6 °C	-1.3 °C
May 98	2.8 °C	0.6 °C	-2.2 °C
June 98	2.6 °C	0.4 °C	-2.2 °C
July 98	2.4 °C	0.7 °C	-1.7 °C
August 98	3.4 °C	0.5 °C	-2.9 °C
September 98	2.0 °C	0.4 °C	-1.6 °C
October 98	1.3 °C	0.5 °C	-0.8 °C
November 98	1.4 °C	0.4 °C	-1.0 °C
December 98	1.2 °C	0.3 °C	-0.9 °C
1998 Year	2.1 °C	0.5 °C	-1.6 °C

A final criterion can be used to understand the effect of the monk on short timescale river temperature variations. This is the difference between the maximum and minimum daily mean for each month which will be called the interdiurnal variation. For ten months of 1998 this value was greatly reduced by Pouge Pond. Summer is particularly affected since the highest reduction was measured in June, July and August. For example in June 1998 the interdiurnal variation was 5.8 °C upstream and only 1.3 °C downstream. Only in May and September was this variable not changed by the monk.

In total, the monk equipped pond warms the water course the most at the end of summer, particularly in August and September, both in terms of the monthly mean and the instantaneous maximum. However it is during these hottest months that the monk equipped pond stabilises short term river temperature variations the best, from hour to hour and from day to day.

3.2. The length of emissary affected: a question of diurnal minima

The longest linear fluvial length downstream from a pond with a monk for which we have data is along the stream of the Chaume, instrumented with five thermometer recorders positioned over more than ten kilometres downstream from the dike down to where it joins the Benaize. A sixth thermometer was positioned upstream from the pond (code name “combe”) to give the unaffected fluvial reference temperature. Complete thermal data from 29 July to 23 August 2007 will be commented upon here as a monthly summary.

In August the mean monthly difference between the inlet and outlet to the monk equipped pond was +3.6 °C. The difference between the emissary and the inlet was still +1.4 °C at a point 4.2 km downstream from the dike and +0.7 °C at 10,425 m. The entire linear fluvial of the emissary is therefore influenced by the warming down its confluence with the large river in the region, the Benaize. On average however the emissary is cooled by 3 °C over ten kilometres and greatly reduced the thermal anomaly generated by the pond (Fig. 3).

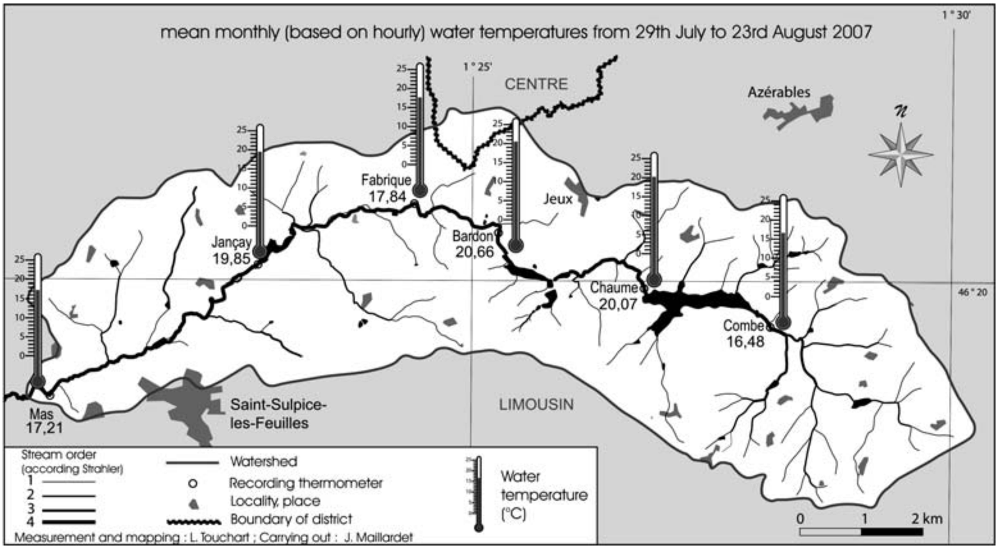

Fig. 3. The linear fluvial influenced by a chain of ponds, the first of which has a monk: the Chaume streamlet as an example

Within this monthly mean, the diurnal maxima are little changed from upstream to downstream and the values are practically the same between the pond inlet and the point located ten kilometres downstream. The small amount of warming caused by the monk was compensated for by cooling along the length of the emissary. On the other hand the diurnal minima, which are strongly warmed by the monk pond, are propagated far downstream. For example the largest instantaneous variation between the thermometer 10,425 m downstream and the one upstream from the pond, which was 2.92 °C, was measured on the 1st August at 07:00H. The second, which reached +2.90 °C occurred on the 14th August at 06:00H. All these values corresponded to very pronounced upstream diurnal minima while the monk was supplying fairly warm and stable water without variation from one hour to the next.

By having little effect on maxima while warming the minima, the monk equipped pond reduces the diurnal amplitude and this lower deviation is also propagated several kilometres down the outlet emissary (Fig. 4).

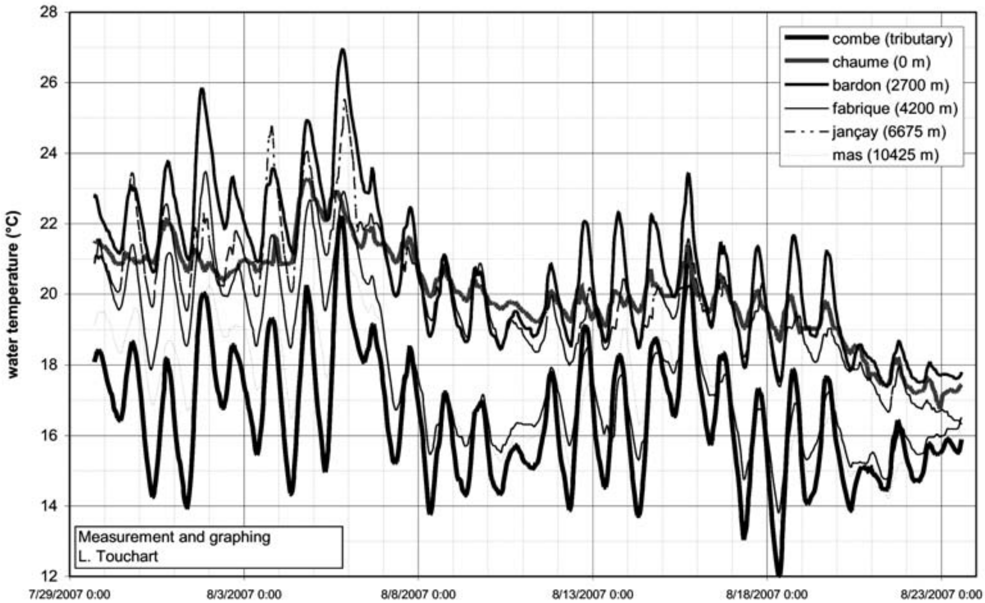

Fig. 4: Instantaneous temperatures in the stream of the Chaume over an 11 km linear stretch upstream and downstream from monk equipped Chaume Pond.

4. Discussion: how does deep pond water propagated down a fluvial emissary degrade the biogeographic quality of a water course?

4.1. Limnological Discussion: a thermal effect governed by forced mixing.

Even taking account of the fact that the monk is used in Limousin more as a fixed valve at the bottom rather than a mixing system which could provide some flexibility, the emissary water at the pond outlet is despite everything not exactly the same as at the bottom of the pond. It is more a mixture of deep waters. The monk removes a layer of water of a certain thickness and also disturbs the stratification at the embankment. For example, at Pouge the monk takes the water to the bottom, then it passes through a valve which sends it out. When the 251.80 m level is reached, the water goes over the central board of the monk and the emissary flow rate increases. The first passage is 80 cm wide so that the water covers it from the bottom to a depth of 4.80 m, less during low water. At 3.65 m depth (normal level of 251.80 m) a 15 x 15 cm valve is used to control the flowrate.

Therefore it is useful to compare the temperatures taken just outside the monk outlet and those at the bottom of the pond further upstream where there is no risk of the stratification being disturbed by the monk. At Pouge Pond we located the vertical buoyed chain 175 m upstream from the dike where the depth was still 5 m. At Chaume the thermometer chain recorded data in the geometric centre of the pond which is only 120 cm deep at this point, 450 m upstream from the dike (Table 5).

Table 5: Temperature difference between pond bottom and emissary fed by the monk
(Monthly means calculated from hourly readings, data L. Touchart. Year 2000: Pouge Pond, temperature at 500 cm depth; Year 2007: Chaume Pond, temperature at 120 cm depth. April: from 13/04 at 16:00 to 30/04 at 23:00. August: from 01/08 at 00:00 to 08/08 at 16:00. May, June, July: complete months. October: from 15/10 at 19:00 to 27/10 at 16:00)

Month	Pond bottom temperature	Monk temperature	Difference
April 2000	11.28 °C	11.76 °C	+0.48 °C
May 2000	12.99 °C	14.45 °C	+1.46 °C
June 2000	16.52 °C	18.16 °C	+1.64 °C
July 2000	18.41 °C	19.01 °C	+0.60 °C
August 2000	18.0 °C	19.7 °C	+0.7 °C
October 2007	11.0 °C	11.5 °C	+0.5 °C

In spring, summer and autumn the water which leaves via the monk is systematically warmer than that at the bottom of the pond. This difference can be interpreted by artificial mixing of deep layers occurring in the water outlet system. This difference reaches a maximum during the period of pond thermal stratification when the monk artificially mixes different types of water, adding other warmer layers which were above it to the bottom layer. The temperature of the water drained out through the emissary is then significantly higher than that at the bottom of the pond. On the other hand, the difference falls when the pond is itself naturally mixed which usually occurs in April and October during a thermal reversal or, exceptionally, as in July 2000, marked by a very large number of atmospheric disturbances.

Thus it is the temperature of the deep layers in the pond drained out by the monk which determines the temperature of the fluvial emissary. The amount of heat in the pond depths depends on two conditions experienced by the pond during the warm season: stratification and mixing. Most of the time the ponds in Limousin and Berry are stratified at a depth below 1.50 m. During brief and fairly rare intervals the water layer is mixed, down to three to four meters over about a 10 day interval and for four to five weeks beyond that down to five to six metres (Touchart, 2002).

During the most long lasting summertime condition, that of thermal stratification, the pond heats the emissary to a moderate degree. The tributary is fairly warm upstream while insolation on the pond isolates a deep layer called the hypostagnion for several weeks under the thermocline (Touchart, 2007), which has no contact with the surface layers. In general the hypostagnion is certainly a bit warmer than the incoming water course but the difference is small so that the emissary is only slightly warmed by the pond. This is the situation in June. At the end of long hot spells which have warmed the stream upstream while isolating a cold hypostagnion, the monk equipped body of water can even cool the water course.

This stratification condition explains how the monk reduces short timescale variations, i.e. diurnal amplitudes or interdiurnal variations. Since there is no exchange with the pond surface the hypostagnion holds water for several weeks at a temperature that does not vary from day to day or between day and night as long as the stratification is not disturbed.

Finally this stability in the deep layer of the pond explains why the temperature variation between the water course upstream and downstream from the monk equipped body of water depends almost entirely on upstream variations. Without any change in the outlet water temperature, periods of upstream cooling cause the widest thermal variations with the downstream and periods of upstream heating reduce the temperature difference with the downstream, by creating a situation where the downstream is permanently warmer than the upstream. In concrete terms, during periods of stability, this phenomenon causes diurnal warming maxima generated by the pond on the water course early in the morning when the tributary is coldest.

As opposed to the condition of thermal stratification, the deep pond water in Limousin or in the extreme south of Berry experienced several periods of mixing during the warm half of the year. The thermocline broke down, the wind mixed the previously overlying layers and the heat energy in the surface was distributed throughout the body of water down to the bottom. Then the monk drew out water which had been warmed by mixing with the surface. On all timescales, the periods during which the water course is the most warmed by the monk equipped pond correspond to periods when the thermal stratification breaks down. On a long timescale, this explains sustained warming of the emissary which is revealed in the end of summer and autumn monthly means, particularly with elevated values in September. On a short timescale, this explains the strong warming caused by the pond over a few hours when mixing occurs after a period of high insolation during the summer when there is an atmospheric disturbance or a storm. This also explains why the absolute minimum water course temperature during each summer month is the variable the monk equipped pond warms the most from upstream to downstream the body of water. However the situation for the minima is complex and it requires more detailed analysis.

During the warm half of the year, the minima for the water course entering the pond have two sources. The first accompanies atmospheric disturbances and the second is caused by night time radiation during a period of anti-cyclonic stability.

The coldest minima in the water courses occur, upstream, when a depression from the west reaches the region and delivers summertime precipitation. Accompanied by the wind, the disturbance causes forced mixing in the pond. Mechanical convection takes the heat which has previously built up in the surface layer down to the bottom. The monk then draws out warmer water from the pond and supplies it to the emissary. Therefore the difference is very high between the inlet water course temperature, which is at its summer minimum and the outlet water course, which is not far from its maximum. Significant absolute warming of the stream is generated by the monk.

Another family of tributary water course minima is that from the fairly cold temperatures which occur during periods of calm anti-cyclonic weather in the early hours of the morning, from clear night radiation. It is true that this heat loss also reaches the surface of the pond and causes free convection which makes the thermocline go deeper and weakens it. But, except in thin layered ponds, the phenomenon does not break down the stratification layering. The hypostagnion reduces in thickness but the temperature at the bottom of the pond remains unchanged. This strong nocturnal cooling in the upstream water course which is not felt at the outlet from the monk equipped pond generates a high difference between the inlet and downstream. The monk equipped pond then causes relative warming of the water course, in that upstream cooling occurs while a deep layer in the pond remains unchanged that generates the large temperature difference.

During the cold season other processes occur. The most pronounced minima in the upstream water course give the water a temperature close to 0 °C. During these periods the pond is frozen or, at least, experiences fairly stable inverse stratification. The monk then draws out water close to the maximum density temperature, causing the water course to warm which can approach 4 °C over a few days, raising the minima. At the monthly mean scale however the periods of winter mixing dominate in the temperate hyper-oceanic regions of Centre-West France, so that the monk equipped pond slightly cools the water from December to February.

4.2. Hydrographic Discussion: diurnal minima propagated by the inability of the emissary to cool night time water during the day

From the pond's point of maximum influence, corresponding to the water outlet system, the emissary water course tends to progressively regain its initial condition over a distance which depends on climatic conditions, the relationship with groundwater levels and other water inflows. In the case of the catchment area for the Chaume, the fairly homogeneous crystalline lithology dominated by the Saint Sulpice two-mica granite causes small groundwater layers to form in the alterites which have a fast response time and tend to dry out by the end of the summer. Their effect on the emissary falls to practically zero from August to October. The same applies to surface streams which enter the emissary from Chaume Pond over the eleven kilometres which separate it from its confluence with the Benaize. These are temporary inflows of order 0 in the natural state, some of which have become permanent flows due to the presence of small pools.

This is why it is probable that the emissary from Chaume Pond would readjust its temperature depending on climatic conditions, in similar ways to those we had studied previously for a pond on the Millevaches plateau (Touchart, 2007). The distance over which the fluvial properties would be re-established would be about 12 kilometres.

The Chaume stream has five bodies of water along it. Two of them, Bardon and Jançay are of large size and bar the main course of the emissary. The other smaller ones are on inflowing streams. Some of these also have a monk but most of them only have a surface weir. Monk equipped Chaume Pond is in fact only the first in a succession of water bodies along the water course and this chain of ponds explains the fact that nowhere does the fluvial water have enough distance to re-establish its upstream qualities, since it enters a new pond before having significantly lost its heat gain. Nevertheless, near the confluence with the Benaize, more than 10 km downstream from the monk, the mean warming of 0.7 °C is no higher than that described by us on a linear flow without a chain of bodies of water beyond the first one.

Notwithstanding the succession of multiple bodies of water after Chaume Pond, the characteristics of the monk in the largest of all these ponds, which is also the first one in the chain, would appear to play a role in the fact that it is the raised minima which are propagated the furthest in such a distinct manner. Anti-cyclonic night time cooling which rapidly affects the stream above the pond does not significantly reduce the river temperature several kilometres downstream from the pond dike. The monk equipped pond had an effect in between the two. However during these calm sunny periods in summer, the pond becomes permanently stratified so that the monk supplies water at a stable temperature which is hardly any cooler at the end of the night than at the end of the day. This relatively warm morning water does not cool down in the emissary since it flows down during daytime hours; we postulate here that the main reason for this is the time shift, creating a maximum difference between the pond inlet and outlet in the early morning, which is a major feature of the operation of a monk compared to other water outlet systems such as a weir. In addition, the phenomenon is perhaps accentuated by the inertia of a river swelled downstream by other inflows.

4.3. Biogeographic Discussion: negative effect of the monk in summer, positive in winter

Since it is written by geographers this is not a biological article and the authors make no pretensions in this field. However, it seemed relevant to follow the hydrological discussion with a biogeographical summary, based on rare and sensitive species. Fario trout can be considered as being symbolic for these. For reasons of clarity, the discussion covers two distinct parts. First, the connection between temperature and young and adult life in the water, which is a summertime risk and secondly, the relationship between temperature and sub-gravel life, from egg-laying to emersion, where the risk occurs during the winter.

The most widely used indicator, since the biotypology developed by J. Verneaux (1973) was perfected, which enables the link between temperature and water course biology to be quantified in a simple way, is based on the mean temperature of the thirty warmest days during the year. In the case of the Gorret River, classification in descending order of the 365 diurnal means for 1998 showed the significance of Pouge Pond. Upstream from the body of water, the mean of the thirty highest diurnal means was 18.9 °C, while downstream from the monk it was 21.2 °C, i.e. warming by 2.3 °C. However the difference between upstream and downstream increases as the mean diurnal temperature decreases (Fig. 5), confirming that the monk, as opposed to other water outlet systems, warms the lowest summer water course temperatures more than the highest. Due to this the J. Verneaux indicator minimises the influence of the monk or rather shows that the system has a moderate effect on the warmest temperatures which would be detrimental to the most important species.

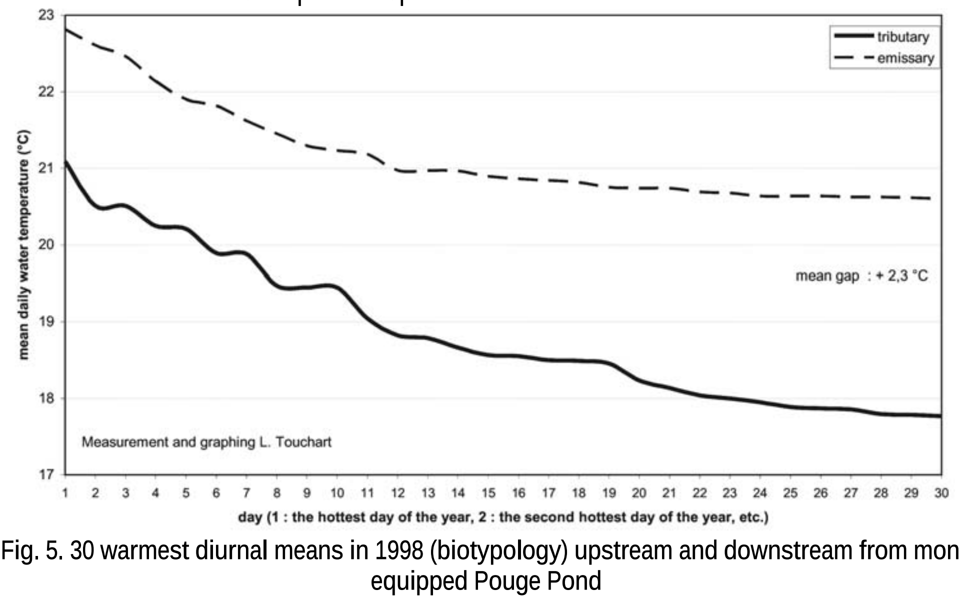

Fig. 5. 30 warmest diurnal means in 1998 (biotypology) upstream and downstream from monk equipped Pouge Pond

Two other simple criteria give significant indications if we study not the diurnal means but the hourly data. These are the mortality threshold and the preferendum threshold. The first can be set at 25 °C and the second at 19 °C. If these limits are exceeded it can be quantified in terms of the total number of hours, the number of sequences, the number of consecutive hours in the longest sequence and the highest sequence.

The lethal threshold has never been observed to be exceeded at our sites. Of the 17,520 hours from 00:00H on 1st January 1998 to 23:00H on 31 December 1999 no readings ever reached 25 °C, either upstream or downstream from monk equipped Pouge Pond. Similarly, for the 669 hours from 18:00H on 26 July 2007 to 14:00H on 23 August 2007, no temperature readings were ever recorded over 25 °C, either upstream or downstream from monk equipped Chaume Pond.

Studying the sequences enables the analysis to be fine tuned. We performed this on Pouge Pond for all of 1998. Upstream, the 377 hours where the 19 °C limit was exceeded are distributed over 33 sequences with the longest being 61 hours (16% of the total). This is not the sequence containing the instantaneous maximum of 22.7 °C which occurred during a 45 hour sequence. Downstream, the 1,616 hours where the threshold was exceeded are distributed over 9 sequences, the longest being 1,331 hours (82% of the total) and that sequence also recorded the instantaneous maximum (23 °C). Of the 33 upstream sequences, 21 coincide with downstream sequences where the limit was exceeded. During these sequences it can be considered that the monk does not change the thermal properties of the water course.

What is significant are the distortions in both directions. During the 12 short sequences, the threshold is exceeded in the water course upstream but not downstream, from the pond. Then the monk can be viewed as a positive factor which prevents the river leaving the preferendum. These short sequences are all concentrated in spring and at the very beginning of summer since they occur between 14 May (a six hour sequence) and 24 June (a seven hour sequence).

On the other hand, the threshold is exceeded downstream from the pond during the 8 long sequences while the river stays within the preferendum upstream. Most of these sequences are shifted towards the end of summer with the longest occurring uninterrupted from 5 July to 29 August and the last one in the season occurring from 2 to 11 September. Then the monk can be considered as being a system which degrades river water quality. By preventing the water course from cooling during the night and significantly increasing diurnal minima, from July to September the monk permanently sets up water conditions that are too warm for sensitive species even though the water course only experiences fairly short excess thermal spikes upstream from the pond.

In winter the thermal hazard no longer really concerns adult life in the water itself but sub-gravel life, between egg-laying and emersion. If we look at the work by

D.T. Crisp (1996) and Jungwirth & Winkler (1984), optimal development of trout eggs and embryos occurs at daily temperatures between 1 °C and 12 °C. The date of egg-laying, which occurs from November to February, reaches a maximum in December, knowing that the number of hours of daylight during the shortest days is very important for release of the spawn. Following on from A. Caudron *et al.* (2008), we will arbitrarily select here 15 December.

On the River Gorret upstream from the pond, if the point of departure is taken as 15 December 1997, the 420 degree-days between egg-laying and hatching are reached on 24 February 1998 without any diurnal means exceeding the 12 °C threshold. The following 310 degree-days between hatching and emersion are reached on 1 April 1998 at the point when two days, 29 March and 1 April, have just exceeded the 12 °C diurnal mean by 0.2 °C. Downstream from the monk at Pouge Pond the 420 degree-days between egg-laying and hatching are reached on exactly the same day, 24 February 1998, under the same favourable conditions, with no diurnal means exceeding the 12 °C threshold. The following 310 degree-days between hatching and emersion are reached a day earlier on 31 March 1998 under better conditions than upstream with no diurnal mean exceeding 12 °C over this period. The following winter confirms the effect of the monk. Upstream from 15 December 1998, the 420 degree-days between egg-laying and hatching are reached on 2 March 1999 without any diurnal means exceeding the 12 °C threshold. The following 310 degree-days between hatching and emersion are reached on 4 April 1999, with the limit exceeded over the last four days, reaching a degree above the 12 °C threshold. Downstream from the monk at Pouge Pond the 420 degree-days are reached on the 7 March under the same favourable conditions, with no diurnal means exceeding the 12 °C threshold. The following 310 degree-days are reached on 7 April under better conditions than upstream with the threshold exceeded by only 0.1 °C on the 6th April and by 0.3 °C on the 7th April.

Therefore it can be considered that both upstream and downstream from the pond the thermal conditions for the sub-gravel existence of Fario Trout embryos and larvae are met. According to this biogeographic criterion the monk does not degrade the thermal properties of the river in any way and even has a tendency to improve it slightly.

Conclusions and comparison of the thermal effect of the monk and other pond flow control systems

The monk is a system used in a very small number of ponds in crystalline Limousin and Berry but which is being strongly recommended to owners by the authorities to replace surface weirs. The purpose of this study is to analyse the operation of the monk and the effect on the hydrographical network of ponds which use one compared to other bodies of water. The study is based on original measurements and the actual situation of ponds equipped with a monk which are managed in a complex way. The monk is not a simple device for drawing out deep water. First of all, in Limousin and southern Berry, it is most often used as a fixed bottom valve rather than as a flexible control system. Secondly, it is often used along with other devices: our study on the Moulin and Rochegaudon chain of ponds shows two successive bodies of water with a monk but the first also has a bypass channel which is dry during the four or five warm months and the monk in the second is practically frozen in place to operate as a surface weir.

The relevance of our scientific study for regional planning, as a response to a socio-economic demand, requires us to draw conclusions not only about the effect of the monk on water courses but to compare the effect of monk equipped ponds and those which use other devices, i.e. a surface weir or a bypass channel.

(i) From a descriptive point of view the monk warms up the annual mean temperature of the emissary by about 1 °C, compared to 2 °C for a weir. The highest warming season occurs in August and September downstream from the monk while this occurs in June and July downstream from a weir. The summer maxima are practically unchanged by a monk while they are strongly raised by a weir. On the other hand, the summer minima are very significantly warmed by a monk while they are practically unchanged by a weir. In summer the monk and weir each generate very strong warming for the same length of time as each other (Table 6). But the minima are raised to a high degree by the monk while it is the maxima which are strongly warmed downstream from a weir. The monk and weir operate in such a way that downstream warming is very distinct in both cases and only slightly moderated by the monk. In fact, a bypass is the only system which is really different and works effectively against warming.

Table 6. The proportion of time the water course is warmed in summer by the pond as a function of the water outlet device (Percentages calculated in proportion to the total bimonthly time from hourly readings taken by L. Touchart. The monk ponds are Chaume in July and August 2007 (first figure) and Pouge in July and August 1998 (second figure). The surface weir pond is Oussines in July and August 2005. The bypass pond is Ribières in July and August 2006. The water course is order 4 at Chaume, Pouge and Oussines and order 2 at Ribières)

	Monk	Weir	Bypass
Warming greater than 5 °C	17 % ; 24 %	19 %	0 %
Warming greater than 4 °C	41 % ; 38 %	59 %	0 %
Warming greater than 3 °C	64 % ; 56 %	88 %	0 %
Warming greater than 2 °C	85 % ; 71 %	99 %	2 %
Warming greater than 1 °C	97 % ; 83 %	100 %	35 %

The monk equipped pond reduces the diurnal amplitude of the emissary by three quarters while the pond with a surface weir reduces it by a quarter. But the major difference with the weir pond is that the monk lowers day to day temperature variations, flattening the diurnal means, while the weir increases them.

The monk equipped pond can warm emissary water as far as twelve kilometres below the embankment but, over such distances, this warming is particularly visible on the minima, on morning temperatures. While the distances affected are more or less the same downstream from a weir, on the other hand the very warm afternoon temperatures are propagated the furthest.

(ii) The above differences are explained by the fact that the monk equipped pond warms the river with deep water which acquired its heat from forced mixing of the pond. This mechanical convection, caused by the wind, occurs after heat has built up in the pond surface by insolation. This explains the time shift in warming of the emissary to the end of summer and autumn, the reduction in total mean warming, the reduction in warming of the maxima and the increase in warming of the minima. This means that the temperature of the air and the emissary, which is supplied by deep pond water from the monk, are not correlated. On the contrary, the temperature of the air and an emissary downstream from a surface weir are correlated because the heat in pond surface water depends on insolation. To simplify things, when stream water upstream from a weir pond is warm it is very warm downstream while stream water above and below a monk equipped pond experiences much less simple and predictable variations. This is because it largely depends on the occurrence of atmospheric disturbances and windy periods which disturb the pond's thermal stratification.

(iii) The consequences of these thermal effects on the biogeography of the hydrographic network are sufficiently different for the different devices to be compared.

In winter neither monk nor weir ponds degrade water course thermal quality. More precisely, both upstream and downstream of the pond the thermal conditions for the sub-gravel existence of Fario Trout embryos and larvae are met. According to this biogeographic criterion not only does the monk not degrade the thermal properties of the river but it even has a tendency to improve it slightly.

There is a larger contrast during the warm season. In summer, the monk tends to prevent the emissary from cooling at night and strongly increases minima temperatures. It thus creates conditions which are continuously too warm for sensitive species while the weir leaves night time downstream cooling windows which are good for the thermal preferendum. On the other hand, the lethal temperature limit is never reached below a monk, while very strong warming peaks exceeding the lethal temperature for the most sensitive species do occur downstream from a weir.

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