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Coarse and Fine Particulate Organic Matter Transport by a Fourth-Order Mountain Stream to Lake Bourget (France)

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Abstract: Transport of coarse particulate organic matter (CPOM) derived from forest litterfall has been hardly studied in rivers, unlike fine particulate organic matter (FPOM) or dissolved organic matter (DOM). Yet, many rivers are dammed or run into lakes, and there is growing evidence that CPOM accumulation in river delta participates substantially in ecological processes such as greenhouse gas emissions of lakes and reservoirs. We investigated the transport of CPOM and FPOM by the Leysse River (discharge from 0.2 to 106 $m^3\ s^{-1}$) to Lake Bourget (France) in relation to aerial litter deposition, river network length, and discharge. Over a 19-month study period, the volume-weighted mean CPOM and FPOM concentrations were 1.3 and 7.7 g $m^{-3,}$ respectively. Most CPOM and FPOM transport occurred during major flood events, and there were power relationships between maximum discharge and particulate organic matter (POM) transport during these events. The annual export of CPOM (190 t AFDM) was 85% of the litter accumulation in autumn on permanent sections of the riverbed (224 t AFDM), which suggests that export is a major process compared to breakdown. Export of CPOM was 1.25 t $yr^{-1}\ km^{-2}$ of the forested catchment area. This study highlights the need to account for long-range CPOM transport to describe the fate of litter inputs to streams and to quantify the organic matter input and processing in lakes and reservoirs.

Keywords: forest litterfall; CPOM; FPOM; river; transport; lake

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1. Introduction

«One of two things can happen to allochthonous material once it enters a stream: it can be broken down, or it can be transported downstream» [1]. In headwater forest streams, plant litter tends to be transported over relatively short distances (up to several hundred meters [1–5]) before being retained by obstacles [6] and breakdown. This process, which combines leaching, physical abrasion, microbial decomposition, and shredding by invertebrates [7–9], finally releases fine particulate organic matter (FPOM, between 0.45 and 1 mm in diameter) and dissolved organic matter (DOM), which are more easily carried downstream [10].

Ample information has been compiled by stream ecologists on litter breakdown, using mass loss from litter bags attached to the stream floor [11–13]. The basic concept supporting these measurements is that in-stream litter breakdown, which supplies energy to the stream food web, is a major process compared to export. Accordingly, carbon loads in the forms of DOM and FPOM contained in total suspended solids (TSS) have been monitored and quantified in rivers worldwide [14–17]. Additionally, the transport of large wood pieces [18], which break down very slowly, has been quantified. However, there has been little effort (however, see attempts by the authors of [19]) to quantify the transport of coarse particulate organic matter (CPOM) by rivers. This is probably due to unsuitable monitoring protocols (CPOM does not enter automated river sampling systems) and methodological challenges at stormflow [20–22]. Yet, this information is needed because

(1) many rivers flow into lakes and reservoirs, and litter breakdown may not be achieved before litter fragments enter water bodies, and (2) there is growing evidence that the accumulation of CPOM in the delta of lakes and reservoirs fuels primary production [23], and methane emissions [24–27]. Moreover, as forest litterfall is the source of CPOM, and forest cover has strongly changed in the last centuries [28], CPOM loads to lakes and reservoirs may have drastically changed, and this evolution should be taken into account when relating the carbon budgets of water bodies to global change [29].

This study aimed at measuring the transport of CPOM by the Leysse River, a fourth-order mountain stream, to Lake Bourget (France), in comparison to FPOM transport. Our hypothesis was that the transport of litter during river floods was a major process compared to litter breakdown and a significant component of catchment yield to the lake.

Our objectives were to (1) monitor CPOM and FPOM loads in a fourth-order stream in relation to discharge; (2) relate the export of CPOM to litter aerial deposition on the river network and to total OM export; (3) discuss the ecological significance of these loads in relation to global change.

2. Materials and Methods

2.1. The Leysse River and Catchment

The Leysse River, located in the French Alps, is the main tributary to the Bourget Lake. The Leysse River is composed of 4 sub-catchments (Figure 1). The Albanne, Hyères, and Upper Leysse Rivers are high gradient third-order streams. These rivers meet in Chambéry and form the Lower Leysse River, which is channelized from Chambéry to the lake [30].

The total watershed surface area is 281 km^2. Altitude ranges from 1845 to 235 m above sea level (m.a.s.l.). The landscape is mainly structured by hard limestone terrains forming high-altitude plateaus, cliffs, and upper slopes. Gentle slopes and valleys are developed on shales, sandstones, and marlstones, as well as glacial deposits. These bedrocks are poor in petrogenic carbon. Mixed deciduous forest, crops and meadows, and artificial surfaces cover 54%, 32%, and 14% of the catchment's area, respectively (Figure 1). Above 800 m.a.s.l., mixed beech forest with fir, spruce, and birch dominate. Below 800 m.a.s.l. the forest is a mixed oak forest with boxwood on south-exposed sites and hornbeam, cherry, ash, maple, and hazelnut on north-exposed sites. Along the streams, willow, alder, hazelnut, ash, and poplar are more frequent. Over about 1 km across Chambery City center, the river is channeled underground. Riverbanks (about 3 m high) of the Lower Leysse River are planted by riparian hedgerows (5–20 m wide, 5–20 m high) of alder, willow, ash, maple, hazelnut, and oak trees. From its source to the lake, the river mostly flows on pebbles (D_{50} = 10 cm), which do not support the growth of macrophytes. Mean annual air temperature in Chambéry (altitude: 250 m.a.s.l.) is 11.6 °C, and mean annual precipitation is 1250 mm, and reaches 1600 mm at 1000 m.a.s.l. The mean annual discharge (Q) of the Leysse River is 6.2 m^3 s^{-1}. Exceptional discharges above 100 m^3 s^{-1} and 130 m^3 s^{-1} occur every 2 and 5 years, respectively. River water is transparent at low flow ($Q < 5$ m^3 s^{-1}) (Figure 2A,B) but gets opaque when $Q > 15$ m^3 s^{-1} and brown over 30 m^3 s^{-1} (Figure 2C). Home and industrial sewage inputs are treated before being exported to the Rhône River and do not enter the Leysse River and Lake Bourget, except at very high flow ($Q > 80$ m^3 s^{-1}) [31].

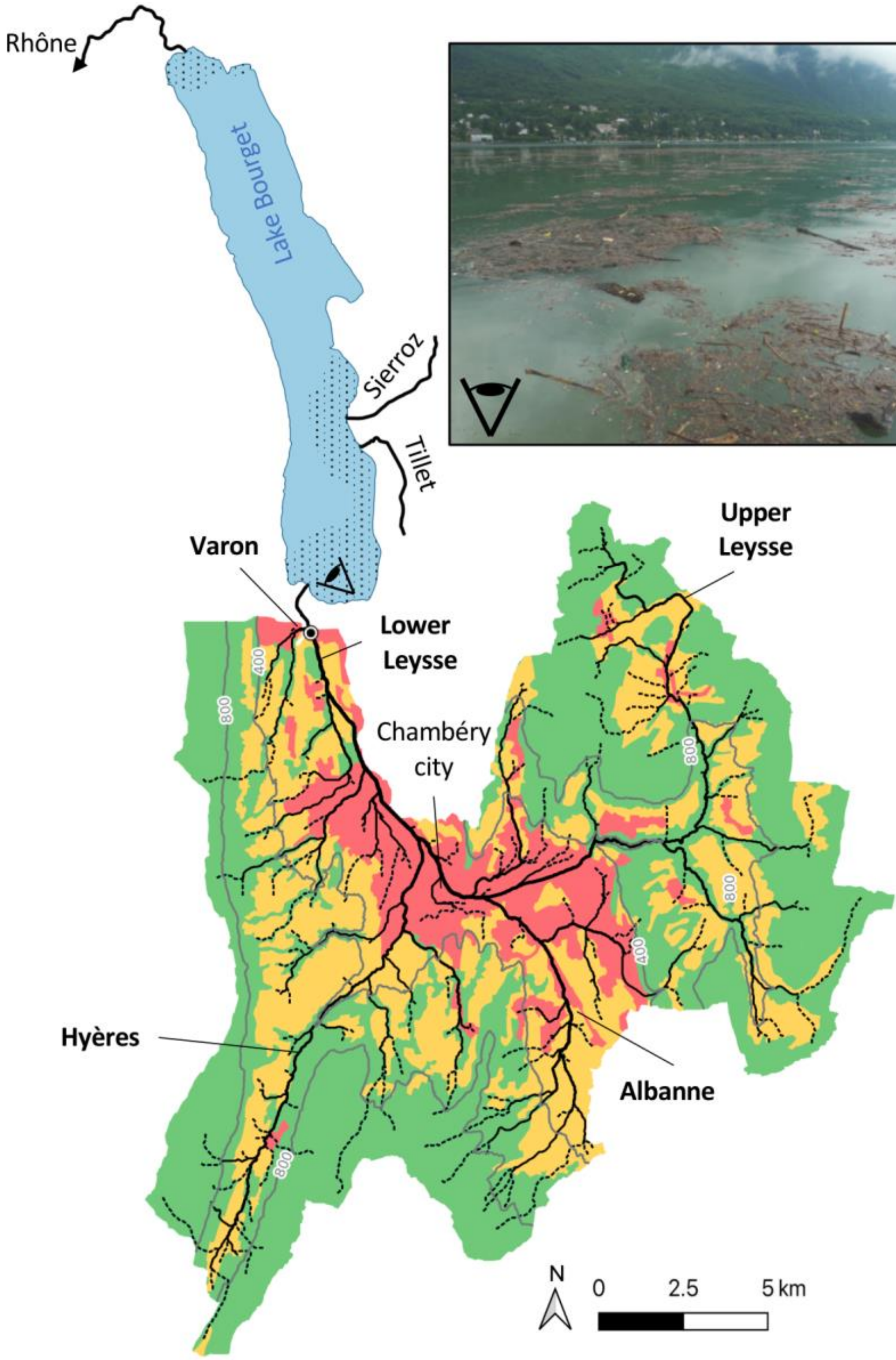

Figure 1. Map of the Leysse River catchment. Land uses are shown following Corine Land Cover (green: forest; yellow: agriculture; red: urban). The elevation contour lines 400 m and 800 m are shown in gray. Rivers are indicated in black, intermittent creeks being in dotted lines. The black dot indicates the university bridge where CPOM measurements were made. The dotted area in Lake Bourget indicates the presence of gas bubbles in the sediment [32]. The photograph showing floating litter on the lake was taken after a large flood.

Figure 2. Pictures of the Lower Leysse River at the university bridge. (**A**): riverbed at low flow with litter accumulations upstream of boulders (13 November 2018, Q: 1 $m^3 s^{-1}$, water depth: 20 cm, width: 14 m); (**B**): river bank on 19 March 2019, after a high flow event. The white dotted line indicates the highest level reached by the stream. (**C**): Brown turbid water during a rising limb at very high flow (Q: 170 $m^3 s^{-1}$, water depth: 3.4 m, width: 20 m) with floating logs and branches in the middle of the river; (**D**): sample collection using the hanging net technique during a falling limb (Q: 9.4 $m^3 s^{-1}$, water depth: 0.8 m): note the water transparency.

2.2. Definition of High Flow Events

The discharge in the Leysse River was monitored hourly 1.8 km upstream of the university bridge. The beginning of a high flow event was arbitrarily defined by a discharge gradient higher than 0.3 $m^3 s^{-1} h^{-1}$, lasting more than 3 h. The end of a high flow event was defined as the time discharge decreased below 25% of peak discharge (Qpeak). Periods in between were considered as baseflow periods. Major floods were defined when Qpeak > 30 $m^3 s^{-1}$. From May 2018 to March 2020, 45% and 55% of the total discharge occurred during high flow events (15 major and 35 minor floods) and baseflow periods, respectively.

2.3. River Length, Width, and Forest Percentage along Stream Banks

River length (m) in relation to stream order and the percentage of forested banks were estimated using the digital elevation model and images of the Institut Géographique National. Continuous hedgerows formed by trees along the river banks were considered forest. When only one side of the stream was forested, the percentage of forest considered for this segment was 50%. Bankfull channel width as well as the intermittency of streams was estimated using the SYRAH-CE databank [33] and controlled by pedestrian prospection of the stream network.

2.4. Direct Litter Deposition in Streams

The litter accumulated on dry gravel banks along a 2 km-long segment of the Varon stream, a second-order affluent (width: 2–5 m) of the Lower Leysse River (see Figure 1), was collected in late fall (26 November 2020) at 30 forested sites. All the litter was collected within a 0.15 m^2 frame, dried at 30 °C, and weighted. Water content (110 °C) and ash-free dry mass (AFDM) were measured after calcination at 550 °C. This organic matter accumulation was considered as the reference input (g AFDM m^{-2}) in autumn, which might be transported by forthcoming floods. The relationship between the litterfall deposition and stream width was computed from a literature review of inputs from forested banks to rivers [34–37] and lakes [38–41]. In closed-canopy streams, up to 5 m widths, litterfall deposition (g m^{-2}) is constant and equal to the reference deposition in the forest [37]. For wider streams or lakes, litterfall deposition decreases linearly or exponentially in relation to the distance to the stream bank (or lake ridge) up to between 7 and 12 m. As a result, considering the two banks, direct litter deposition was obtained by multiplying the reference input (g m^{-2}) to the bankfull width (m) of the stream, up to the width of 9 m [42].

The sampling site was located below the university campus bridge, 1.6 km upstream from the lake (Figures 1 and 2D). Water depth was measured as well as the water velocity using an electronic current meter (OTT C2–Z400). To collect CPOM, two meters-long plastic nets, with a 1 × 2 mm mesh size, attached to metal frames were used.

When the water depth was below 0.7 m (Q < 8 m^3 s^{-1}) (Figure 2A), a metallic frame (width: 1.05 m, height: 0.83 m) was used. The frame was hand-held vertically for 3 min in the middle of the stream (collecting floating and submerged debris) by two operators.

For higher flow, the net was attached to a metallic ring (diameter: 0.47 m) fixed to a 5-m-long metallic handle (Figure 2D). To stand the flow current, the ring was held by two ropes, the first attached to a shore-side tree, about 10 m upstream and the other passing into a return pulley hanging below the bridge and attached by a slip knot to a post driven on the shore bank where the operator stands. This type of setting allowed to place the net into the flow and to remove it in 2 s. The ring was kept facing the flow, 0.1–0.2 m below the water surface for 1 to 3 min, depending on flow. Measurements were always triplicated.

Debris were then collected in nylon nets (mesh size 0.1 mm) and stored for a week in front of a ventilation fan. Collected debris were then dried at 40 °C for 48 h, hand-sorted into three categories (leaves and soft organic debris, woods and hard organic debris, and man-made debris), and weighed. Water content and AFDM were measured on a subset of 17 samples (one per sampled month). In total, from May 2018 to March 2020, 226 triplicated collections (n = 678) were made (see Figure 3). A total of 9 major floods out of a total of 15 (72 triplicated collections) and 8 minor floods out of a total of 35 (58 triplicated collections) were intensively monitored, while 17 triplicated collections were made at baseflow. Other collections (79) were made during flood events that were not intensively monitored.

CPOM loads (g m^{-3}) were computed from the AFDM concentration of coarse particles (g), the area of collection (m^2), the water velocity (m s^{-1}), and the duration of the measurement (s).

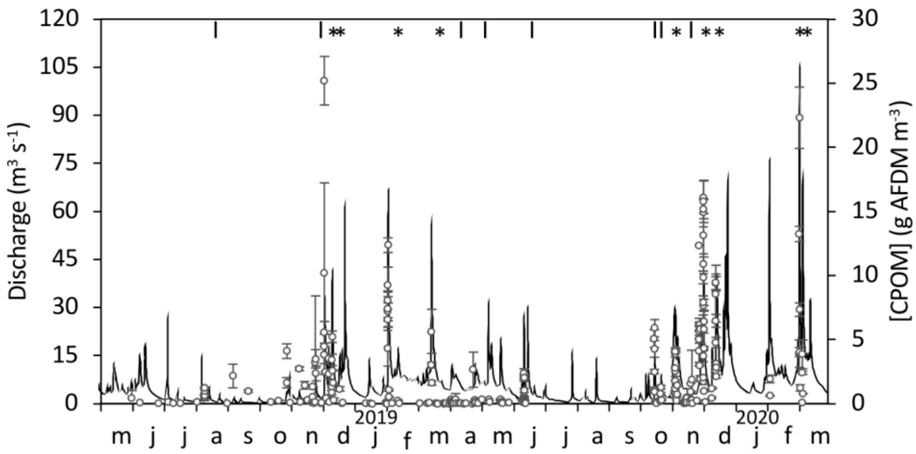

Figure 3. Variations of mean ± SD CPOM concentration (g AFDM m^{-3}, gray open dots) and discharge ($m^3\ s^{-1}$) (black line) during the study period. Vertical dashes indicate monitored minor flow events. Asterisk indicate monitored major flow event (Q > 30 $m^3\ s^{-1}$).

2.5. TSS and FPOM Measurements

One grab sample (0.5 L) of surface water (depth 0.2 m) was manually taken about 1 m from the riverside at the same site and time as CPOM measurements. In total, 141 samples were taken, but only five major high flow events monitored for CPOM were sampled. TSS was measured after filtration on glass microfiber filters (GF/F porosity 0.7 µm) calcinated at 550 °C. The filters were weighted after drying 24 h at 110 °C in order to measure TSS and weighed again after calcination 4.5 h at 550 °C to measure FPOM concentration.

2.6. Tentative Calculation of CPOM, FPOM, and TSS Annual Fluxes

For each monitored high flow event, missing hourly CPOM, FPOM, and TSS concentration values were extrapolated using linear relationships between concentrations and discharge for rising and falling limbs independently (see result section). Loads were then computed by adding hourly fluxes (concentration × discharge) from the beginning of the rising limb to the end of the event.

For non-monitored high flow events, loads were estimated using the relationship between CPOM and FPOM loads at the flood event scale for the monitored events (see the previous paragraph) and peak discharge [43–45]. A detailed description of the relationships used is available in the result section.

Because of the very low concentrations at baseflow (see results), fluxes during baseflow periods were computed from monthly (CPOM) or yearly (FPOM) average concentrations at baseflow, multiplied by the corresponding discharge.

The volume-weighted mean annual concentrations were obtained by dividing the annual fluxes by the average discharge.

3. Results

3.1. Litter Input to the Stream in Relation to the Physiography of the Leysse River

The mass of litter accumulated along the Varon River bed in late autumn, before winter floods, was 350 ± 92 g m^{-2} DM or 301 ± 79 g m^{-2} AFDM. Applied to the bankfull area of the streams, it represents a total litterfall mass of 255 t OM on the Leysse River network (Table 1). Although half of the Leysse River length is formed by narrow intermittent streams (Strahler order 0 [46]), litter deposition on these sections was only 12% of total litter deposition because their surface area is small and only 65% of their banks are forested (Table 1). The largest and most forested sections of the stream (Strahler orders 2 and 3, relative length: 24%, relative area 54%) received 63% of the litter input.

Table 1. Stream characteristics, litter accumulation on river banks in autumn (t AFDM) in relation to stream order and cumulated input. Intermittent streams are named as Strahler order 0. Cumulated litterfall inputs are computed from upstream.

	Strahler Order				
	0	**1**	**2**	**3**	**4**
Stream length (km)					
Upper Leysse	44.9	21.4	20.6	5.7	
Albanne	33.6	19.6	6.5	6.6	
Hyeres	40.4	19.6	16.6	3.3	
Lower Leysse	37.2	22.0	11.8	7.9	11.2
Leysse River (total)	156.2	82.6	55.4	23.6	11.2
River mean slope (%)	12	10.5	7	2	0.2
Forested bank (%)	65	69	78	80	64
Bankfull width (m)	1.0	2.6	8.6	9.0	18.5
Length ∗ width (ha)	16	21	47	21	21
Litter accumulation (t AFDM)	31	44	110	51	19
Cumulated input (t AFDM)	31	75	185	236	255

3.2. Composition of CPOM Sampled in the Leysse River

The OM content of the collected material was 86.6% ± 3.7% (n = 17) (water content of 12.8% ± 1.2%). On average, organic material collected by the net was composed of small woody debris (6%) and leaf material (94%), except during small floods in late summer when a significant contribution of algae was noted, but not separately measured. Woody debris were composed mainly of small branch fragments. Leaf debris composition differed with the season. In autumn, the proportion of fresh leaf debris for which origin could be recognized was much higher than in winter. Especially, unaltered plane tree litter, derived from riparian trees within Chambéry City, and oak litter, were frequently identified. During high flow events, the proportion of easily recognizable beech litter fragments was always high even though this species was rare below the altitude of 800 m and infrequent above the stream bed. In spring, the collected material was quite fragmented and could not be attributed to a known tree species, but the proportion of flowers and buds increased.

3.3. Relationships between CPOM, FPOM, TSS, and Discharge at the Whole Study Scale

CPOM concentration varied strongly with river discharge (see Figure S1 in Supplementary Materials). The volume-weighted average CPOM concentration was 0.2 g m^{-3} at baseflow, while it was 1.9 and 7.0 g m^{-3} during high flow events with Qpeak below and above 30 m^{-3} $s^{-1,}$ respectively. Over the study period, the volume-weighted average CPOM was 1.3 g m^{-3}. TSS and FPOM also experienced high variations with the discharge (see Figure S1). Their volume-weighted average concentrations were 86.4 g m^{-3} and 7.7 g m^{-3}, respectively. Relationships between CPOM or FPOM concentrations and discharge were poor (see Figure S1 in Supplementary Materials). Relationships between CPOM or FPOM concentrations with TSS concentrations were stronger (Figure 4).

3.4. Variation of CPOM and FPOM Loads at the Flood Scale

Variations of CPOM and FPOM loads in rising, and falling limbs depended strongly on the event (Figure 5). Within isolated high flow events resulting from one main rainfall event (as in Figure 5B), the changes in CPOM and FPOM loads with discharge could be almost symmetrical in rising and falling limbs. However, when the discharge peak was very high and narrow, as on 2 March (Figure 5C), the drop in CPOM and FPOM loads was faster and sooner than the drop in discharge.

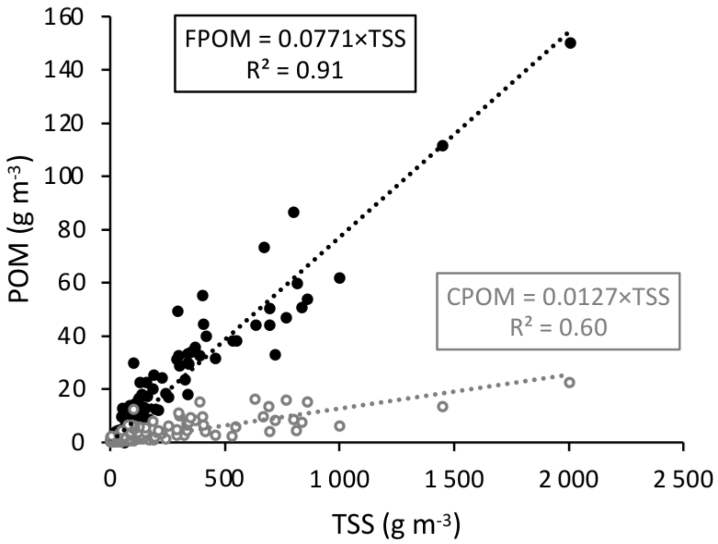

Figure 4. Instantaneous transport of CPOM (grey open dots) and FPOM (black dots) (g m^{-3}) in relation to TSS (g m^{-3}).

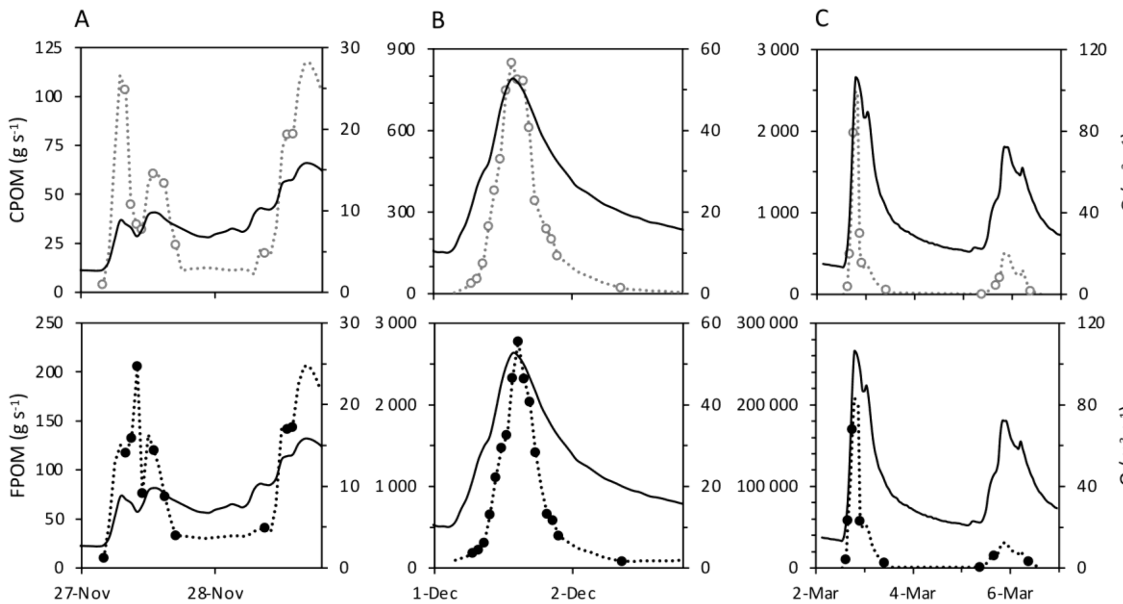

Figure 5. Time variation of discharge (m^3 s^{-1}) and transport load (g s^{-1}) of CPOM (gray open dots) and FPOM (black dots) during three selected high flow events. (**A**) 1–2 December 2019; (**B**) 27–29 November 2019; (**C**) 2–7 March 2020. Dots indicate measurements, and dotted lines indicate interpolated values.

During complex high flow events, resulting from sequences of precipitation events, a plateau or a small decrease in discharge, as on the 28/11 (Figure 5A), induced a strong decrease in CPOM and FPOM loads. Moreover, for a given discharge, POM transport reached a first high flow peak was higher than in the second peak, as illustrated in Figure 5C.

3.5. Transport Fluxes in the Leysse River

During the 21-month long study period, the nine major flood events monitored for CPOM transported 210 t of CPOM (Table S1). The five major events monitored for CPOM, FPOM, and TSS transported 137, 759, and 9827 t, respectively. In comparison, during the same study period, the eight minor flood events monitored transported only 14 t of CPOM (Table S1).

There were power relationships between POM loads and peak discharge during flood events (Figure 6). However, for CPOM, this relationship strongly depended on the season (Figure 6). From December 2018 to March 2020, similar CPOM loads (40.0 t; 42.5 t; 47.0 t) were observed for maximum discharges of 34, 68, and 107 m^3 $s^{-1,}$ respectively. This seasonal variation was not observed in FPOM.

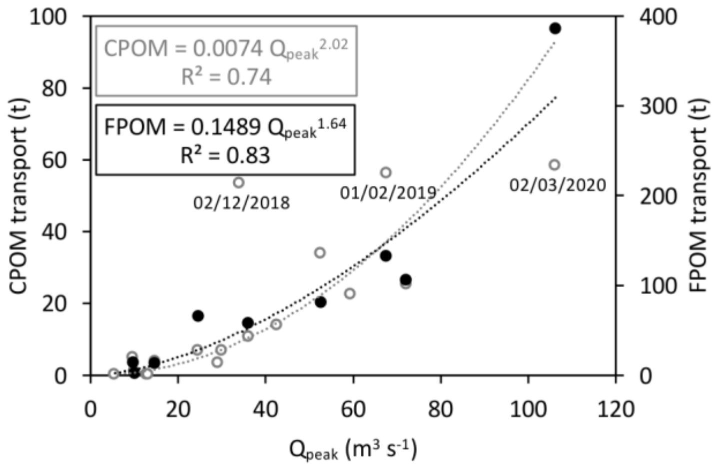

Figure 6. CPOM (grey open dots) and FPOM (black dots) transport (t) during high flow events in relation to maximum discharge (Qpeak).

3.6. Budget

Annually, the contributions of CPOM and FPOM to the transport of OM to Lake Bourget were 190 and 1054 t, respectively (Table 2). Export of CPOM by the Leysse River was 75% of the OM accumulated in litter over the whole of the river network (255 t), or 85% of this load (224 t) accumulated on permanent sections of the riverbed. Major winter floods represented 80% of the annual CPOM load, while baseflow contributed only to 8% (Table 2). On a surface area basis, transport of CPOM was 1.2 t km^{-2} of the forested catchment area or 2.3 t km^{-2} of the forested permanent river area.

Table 2. CPOM and FPOM mean volume-weighted measured concentrations (g m^{-3}) and annual loads (t yr^{-1}) and variation in relation to discharge; catchment yield (t km^{-2}).

		CPOM	FPOM
Mean volume-weighted measured concentration (g m^{-3})		1.3	7.7
	Base flow	0.2	1.8
	High flow-Q_{peak} < 30 m^3 s^{-1}	1.9	20.6
	High flow-Q_{peak} > 30 m^3 s^{-1}	7.0	41.3
Annual loads (t yr^{-1})		190	1054
(%)	Base flow	8	14
(%)	High flow-Q_{peak} < 30 m^3 s^{-1}	12	18
(%)	High flow-Q_{peak} > 30 m^3 s^{-1}	80	69
Catchment yield (t km^{-2})		1.25	6.95

4. Discussion

4.1. Limitations and Uncertainties

The main limitation regarding CPOM sampling is that we were unable to sample the whole water column, especially during high flood events. We assumed that the high turbulence during these events tended to homogenize vertically and laterally CPOM and FPOM concentrations [47]. Moreover, samples were not taken in the middle of the river at high flow, where floating debris concentrate, but at an intermediate distance between the shore and the middle.

As most CPOM and FPOM transport occur during major flood events, the accuracy of our estimation was mainly related to the density of measurements during high flow events and to the seasonal distribution of sampled floods. This is a common pattern and the main difficulty when trying to estimate annual fluxes of TSS [48]. That is why a special effort has been made to sample these events with a high temporal resolution. Given the seasonal variation of concentrations, we estimate that the confidence interval of our estimate may be about ±20%. For FPOM, it may be worse because less high flow events were monitored, but the seasonal variation of concentration may be smaller.

4.2. Litter Deposition

The litter standing on riverbanks (301 ± 79 g m^{-2} AFDM) in late autumn was readily available to the stream before the rise in discharge in winter. This amount was close to the annual litterfall deposition (373 g DM m^{-2} or 354 g AFDM m^{-2}) measured in deciduous plots of the French forest monitoring network RENECOFOR [49], assuming 95% of the dry mass is organic matter [50]. Yet, this amount was expected to be lower, as floods have carried out previous winter litterfall, and the litter deposited in spring, summer, and early autumn should already have lost weight. This similarity may be related to the higher productivity of riparian forest [51,52].

4.3. The Intermittent Downstream Transfer of CPOM

Low-order streams contain many obstacles such as logs, branches, and rocks, which are very effective at trapping leaf litter and limit the travel distance of CPOM [1,53] and thus the flux at the sampling station close to the lake. Walking along the small creeks (Strahler order 0 and 1) in the upper part of the Leysse catchment, even after high flow events, we observed that the river bed was full of branches and fallen trees, with packs of leaf litter retained by these obstacles as well as by roots and plants along banks. Higher-order streams are expected to transport leaves over longer distances, especially during high discharge periods [6]. Transport is enhanced by managers of the Leysse River who remove logs and large branches from the streambed to avoid riverside flooding and bridge damage. In addition, the Lower Leysse River (Strahler order 4) is channelized so that litter retention is reduced. Transport is triggered during rising limbs because leaves temporarily trapped in eddies or along the river shore are released by the rising flow and turbulence of the stream. Hence, the litter that accumulated in the riverbed between high flow events moves downstream during the rising limbs and sediments during falling limbs.

The time duration of rising limbs in high flow events varied between about 7 and 24 h (mean: 13 h). The average water velocity during these rising limbs was about 1.3 m s^{-1}. If we assume that CPOM is transported at the same velocity as water during rising limbs, the distance traveled by CPOM per hour would be 4.7 km h^{-1}, which means that CPOM would take about 3 h to travel from Chambéry City to Lake Bourget. In 13 h (mean rising limb duration), it is very likely that the CPOM standing in active streambeds of upstream segments belonging to Strahler order 2 to 4 were also flushed. This mechanism, and the recalcitrant nature of beech litter, explained why we collected large amounts of beech litter originating from upstream reaches during high flow events.

In rising limbs, the flow mobilized the litter standing within the riverbed, up to the maximum level reached by the river (as in Figure 2B). While during falling limbs, litter progressively settled along the banks. Hence, within a time sequence of two high flow events, the transport rate at peak discharge in the second event depended on the level reached by the water during the first event and the litter amount accumulated in the river bed in between. As most litterfall occurs in autumn, litter loads carried by floods decreased from December to March (see Figure 6), as the litter reservoir in the riverbed was progressively depleted.

4.4. Relationship between Litter Deposition, Decomposition, and Export

The fact that the annual export of CPOM (190 t AFDM) was 75% of the litter accumulation in autumn on the riverbed (255 t AFDM) suggests that CPOM export is a major process compared to breakdown.

This proportion is supported by breakdown rates. In fact, the first major floods occurred in December and the last in March, while most litterfall began in mid-October and ended in December. Hence, litter spent on the average 2 months either in the river or on the banks, before being washed down by floods. Leaf litter from beech (*Fagus sylvatica* L.) and alder (*Alnus glutinosa* (L) Gaertn.) contributed to a large extent to litter inputs to the streams in our study. These species display contrasting litter degradability, with beech and alder leaf litter being among the most recalcitrant and labile organic matter sources to decomposers, respectively [54]. In their global analysis of in-stream litter decomposition, Follstad et al. [55] computed the mean decay rates of leaf litter from *Fagus* (0.007 d^{-1}) and *Alnus* (0.023 d^{-1}) trees at 10 °C. Hence, within the 2 months, on average, about 35% of the litter deposited in streams may be broken down and transformed in FPOM and DOM before experiencing long-distance transport. However, these rates should be decreased to about 25% [56] because the average temperature of the Leysse River in winter is 5.3 °C. Given all uncertainties, this proportion is remarkably consistent with the proportion of litter deposited on the streambed area and transported as CPOM. Hence we suggest that litter transport by rivers is a major process compared to breakdown.

This conclusion might be extended to mountain streams in temperate climates, where major floods shortly follow autumn litterfall and winter temperatures limit litter breakdown. In fact, expressed in units of the forested catchment area, the transport rate of CPOM in the Leysse River (1.25 t yr^{-1} km^{-2} of forested catchment area) compares well with that (1.0 t yr^{-1} km^{-2}) obtained by Bilby and Likens [57] in 0.1 km^2 catchments of the Hubbard Brook Forest (USA). In addition, CPOM yield was 2.4 times higher when debris dams were removed from this stream [57]. For two mountain streams draining 10 km^2 coniferous catchments, Bunte et al. [46] computed a ten-year average export of 2.1 t yr^{-1} km^{-2} of the forested catchment. By contrast, Iroumé et al. [58] computed a smaller export (0.68 t yr^{-1} km^{-2}) from a third-order mountain stream draining a 5 km^2 evergreen broadleaf forest, where litter falls all year round and breakdown is favored by a mild climate.

4.5. Ecological Significance in Relation to Global Change

Dissolved organic carbon (DOC) concentrations and fluxes had been monitored between 2004 and 2016 in the Leysse River [59]. After conversion to DOM using a ratio of 2 [60], an average annual export of 605 t DOM has been estimated. Hence, CPOM represents only 10% of total (CPOM + FPOM + DOM) organic matter transport by the Leysse River to the lake. This apparently small proportion may have significant importance in terms of energy input and greenhouse gas emission in the lake delta. In fact, the river supplies DOM to the whole lake, whereas POM sedimentation mainly feeds the delta. Moreover, studies comparing POM and DOM processing in inland waters suggest that POM microbial degradation is much faster [61]. Comparing the mineralization rate of different size classes of POM, Yoshimura et al. [62] showed that the microbial mineralization of the FPOM derived from CPOM processing by invertebrates is 2–3-fold lower than that of the original CPOM. Moreover, if CPOM transport is 75% of the OM input in the litter, it means that litter-derived FPOM supply only 6% of the annual FPOM load, and the rest is derived from riverside soils. Yet, soil-derived FPOM is often bound to mineral components such as clays or carbonate particles, which protect OM from mineralization [63–65]. Hence CPOM might be a significant energy input delivered to the lake delta, fueling the high GHG emissions of these areas [27,66].

CPOM loads transported by the Leysse River may have drastically changed during the XXth century as the forest area strongly increased (×1.6) in the upper catchment [67], as elsewhere in Europe. Although the historical document used to draw the extension of ancient forests is very precise (Sarde cadastre dating from 1732, scale: 1/2400, French cadaster dating from 1840, same scale), it does not describe the state of riverbanks. The few old photographs from the Leysse landscape [68] suggest that riverbanks in the farmed landscape of the XIX century were most often naked. The dramatic consequences of landscape deforestation and farming since the Middle Ages on soil erosion and sediment accumulation in Lake La Thuile (upper Leysse catchment) has been studied by Bajard et al. [69], while the corresponding increase in sedimentation rate following regional deforestation has been recorded in the sediments of Lake Bourget [70]. In both studies, sedimentation rates decreased from the middle of the XXth century, following landscape afforestation. These studies could be extended to investigate the input and fate of forest litter in lake sediments during deforestation and afforestation periods.

5. Conclusions

This study highlights the need to measure CPOM transport by rivers in various landscapes to address the total OM supply to the delta of lakes and reservoirs. In temperate mountain landscapes, where winter floods shortly follow litterfall, we suggest that the export of CPOM is about 75% of the litter mass deposited on the permanent river network in autumn. This extends to rivers the synthesis statement of Webster [1] about headwater streams at Coweeta: «Thus, an organic particle on the stream bottom is more likely to be transported than broken down by biological processes». Hence, a global description of the fate of litter inputs to streams should include the storage and processing of CPOM in the river delta.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13192783/s1, Figure S1: Variations of CPOM and FPOM concentrations (g m^{-3}) in relation to discharge (m^3 s^{-1}), Table S1: Discharge, total and rising limb time lengths, and water, CPOM, TSS, and FPOM fluxes measured during 17 flood events. *: major flood events (Qpeak > 30 m^3 s^{-1}, n = 9). |: minor floor event (Qpeak < 30 m^3 s^{-1}, n = 8).

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