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# The Winter Environmental Continuum of Two Watersheds

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Academic Editor: Kevin B. Strychar
Received: 16 December 2016; Accepted: 26 April 2017; Published: 9 May 2017

**Abstract:** This paper examines the winter ecosystemic behavior of two distinct watersheds. In cold-temperate regions, the hydrological signal and environmental parameters can fluctuate dramatically over short periods of time, causing major impacts to aquatic habitats. This paper presents the results of the 2011–2012 winter field campaign in streams and rivers near Quebec City, QC, Canada. The objective was to quantify water quantity and quality parameters and their environmental connectivity from headwater creeks above to the larger rivers below over the entire freeze-up, mid-winter and breakup periods with a view toward exploring the watershed continuum. The paper presents how aquatic pulses (water level, discharge, temperature, conductivity, dissolved oxygen and turbidity, measured at seven sites on an hourly basis along channels of different sizes and orders) evolve through the aquatic environment. Ice conditions and the areal ice coverage were also evaluated (on a daily time step along each instrumented channel). Some findings of the investigation revealed that water temperatures remained well above 0 °C during winter in headwater channels, that dissolved oxygen levels during winter were relatively high, but with severe depletions prior to and during breakup in specific settings, that high conductivity spikes occurred during runoff events, that annual turbidity extremes were measured in the presence of ice and that dynamic ice cover breakup events have the potential to generate direct or indirect mortality among aquatic species and to dislodge the largest rocks in the channel. The authors believe that the environmental impact of a number of winter fluvial processes needs to be further investigated, and the relative significance of the winter period in the annual environmental cycle should be given additional attention.

**Keywords:** river ice; water quality; watershed; aquatic environment; winter fluvial processes

## 1. Introduction

The term "aquatic ecosystem" is commonly used, but what is really known about how a watershed works as a system, especially during the cold season? Life subsists under the ice cover of cold regions' river systems. The stress, physical restrictions and environmental conditions endured by aquatic species, directly or indirectly caused by cold air temperatures and consequent freshwater ice processes, have been studied, and key publications on the topic have been completed, e.g., [1–3]. However, so far, continuous aquatic environment monitoring in the presence of ice has seldom been done; the potentially dynamic river ice breakup period generates aquatic habitat constraints that have not been accurately investigated despite the relative importance in the annual hydrological cycle; and the ecological impact of common and less common river ice processes is often only superficially described.

In winter, multiple parameters can vary with greater amplitude and more quickly than during any other season, sending pulses downstream that can either attenuate, amplify or transform.

From a spatial point of view and although scientists and engineers have sampled multiple sites simultaneously, the headwater-to-large-channel dynamics of ice-affected river systems has not been sufficiently documented. This is defendable from a biological point of view since project managers are often emphasizing specific aquatic habitats and channel morphologies. However, the authors believe that measuring the water quality along multiple channel orders is relevant since (1) they are equally important from an aquatic habitat cumulative area or volume; (2) confluences often represent heterogeneous water quality habitats and (3) the water quality at any point in the watershed is substantially influenced by the water flowing from all upstream tributaries.

This paper present continuous environmental data monitored along channels of increasing orders [4] and evolving morphologies in two, geographically-contrasting, watersheds of the Quebec City region, QC, Canada. The data, measured or estimated during the entire 2011–2012 winter season, includes air temperature, channel discharge, ice coverage and ice types, water temperature, specific conductivity, dissolved oxygen and turbidity. The authors propose that this spatiotemporal dataset represents the "winter environmental continuum" of the two watersheds. Here, the continuum can be defined as the multiple, physical links between various parameters at evolving time and space scales. This concept has been presented previously [5,6], but it only included a limited number of monitored parameters in a single watershed.

The objectives of this paper are (1) to demonstrate the relevance of the concept of a winter environmental continuum applied to two independent watersheds and (2) to highlight the local-to-system-scale environmental impact of specific hydrothermal events and ice processes that affect cold regions' watersheds. From an aquatic habitat point of view, the consequences of these events and processes at different channel orders are described or hypothesized, and evident research needs are proposed. The different sections of the paper present a similar structure built on each monitored environmental parameter.

## 2. Background

### 2.1. Channel Discharge

The channel discharge (Q), although only indirectly meaningful to ecosystems, represents an important stream parameter because it directly and indirectly affects multiple aquatic characteristics. In sub-arctic and arctic regions, Q is expected to decline uninterruptedly throughout winter because of the absence of runoff from rain or snowmelt, whereas in more temperate settings (i.e., winters characterized by less than approximately 1800 cumulated degree-days of frost), rain-on-snow events commonly interrupt this natural decline. The path followed by rain drops to reach headwater channels during winter depends on multiple factors including snowpack characteristics (snow water equivalent, temperature distribution, density distribution, etc.), vegetation characteristics (conifer, hardwood, grass, crops, etc.), and ground parameters (temperature distribution, porosity, layer thicknesses, etc.). After a runoff event and as cold air temperatures resume, Q is expected to follow a recession trend that can be exacerbated by ice production-induced flow depressions (or abstraction) of varying intensity and duration, e.g., [6–8].

The succession of cold and mild air temperature spells during winter, the latter potentially accompanied by rain that can generate river ice breakup events, produces hydrological pulses that can significantly impact aquatic parameters at varying time and space scales. The most significant pulse of the cold season is undoubtedly the spring melt hydrograph that triggers breakup. The parameters and thresholds that dictate river ice breakup chronology and intensity are multiple and very site (and sometimes winter) specific. Variations in Q caused by ice processes are usually significantly more sudden than those associated with open water conditions, especially when an ice jam (accumulation of ice blocs and floes that create a hydraulic restriction) releases, and this can impact aquatic species and increases mortality, e.g., [9]. The hydrological impacts of dynamic river ice formation and breakup events are synthesized in [7,10].

### 2.2. Ice Cover and Hydraulic Conditions

At the beginning of winter, the formation of a stationary ice cover necessarily generates an increase in water levels (Y). This rise, which can be estimated by different means, e.g., [11], is generally welcomed because it initially prevents shallow aquatic habitats from freezing. In turn, specific processes such as the production and transport of frazil (ice particles that form in the water column in turbulent flows), the accumulation of anchor ice (ice composed of frazil particles adhering to (and ice crystals that grow on) submerged surfaces; [12]), the formation of ice dams (composed of anchor ice and thermal ice [13]), the thickening of surface ice [14] and the formation of Aufeis (ice that freezes by layers as a result of a pressurized flow conditions [15]), combined with the Q recession, can be detrimental to aquatic species (e.g., freezing, suffocation, skin abrasion; [16]), even those sheltered in the substrate [17]. The type of ice cover and the potential occurrence of specific ice processes, in small to large channels and in steep to low-gradient reaches [18], significantly affect environmental parameters and the quality of aquatic habitats.

At freeze-up, the ice coverage ($I_c$) usually progresses gradually under moderately cold and stable air temperatures (by border ice lateral progression and by ice floes' juxtaposition), but under largely varying meteorological conditions, it can advance or regress quite dynamically. During winter, while $I_c$ remains stable (in the absence of runoff), hydraulic conditions evolve relatively smoothly, and the presence of an ice cover prevents the occurrence of most daily environmental parameter variations.

At breakup, ice and hydrological conditions can change rather suddenly, and $I_c$ may retreat significantly in a matter of minutes. Dynamic breakup events, and more specifically ice jams and ice runs (massive amounts of ice pieces flowing with the water at breakup), can cause direct (moving ice, rocks and woody debris, crushing individuals) and indirect (through hydraulic conditions alteration) impacts on aquatic habitats. Some species are known to prepare for breakup by finding shelters, e.g., [3], but this may not be enough and may certainly not be the case of all aquatic species, especially those of limited mobility.

### 2.3. Water Temperature

The water temperature ($T_w$) and its variations affect the metabolism, behavior and survival rates of multiple aquatic species [2,3,17]. Ice can only form in the water column if $T_w$ cools down to 0.0 °C, and this occurs in most cold regions' fluvial environments during winter. In addition, the occurrence of supercooling events (characterized by a $T_w$ slightly depressed under 0.0 °C), mostly taking place during freeze-up along turbulent streams, e.g., [19], as well as in lakes [20], is generally associated with the production of frazil and anchor ice that can be fatal to fish, at least at their young development stages [17].

During winter, $T_w$ mostly remains at 0.0 °C in the presence of an ice cover, and it cannot rise significantly unless the ice has been melted or flushed downstream. Nonetheless, specific spatiotemporal conditions can create favorable thermal environments for aquatic species' survival and even wealth. The formation of suspended ice covers along steep channels, e.g., [6], and the evolution of a floating ice cover into a free-spanning ice cover supported by the banks as Q decreases along narrow channels enable $T_w$ to rise above 0.0 °C for two reasons: the ice cover is no longer in contact with the flowing water, and groundwater heat cannot escape into the atmosphere. Similarly, $T_w$ may remain well above 0.0 °C in headwater channels, close to groundwater sources or at the confluence of small order channels, and this represents winter thermal refugees for mobile aquatic species, e.g., [16].

At breakup, the heat gained in open water leads can travel under an ice cover over great distances, which generates melting and additional heat absorption, e.g., [11]. At the end of winter, it is not surprising to measure abrupt changes in $T_w$, e.g., [21], and the aquatic environment can warm to 10 °C downstream of long open water sections and upstream of an ice jam [22].

### 2.4. Conductivity

Water conductivity (or the specific conductivity, Sp.C, corrected for $T_w$ variations) is a parameter that is often used to determine the contribution of groundwater during runoff events, e.g., [23]: usually, as Q increases, surface runoff generates a drop in Sp.C, and in turn, as Q declines, groundwater contribution dominates, and Sp.C increases. This explains why snowmelt events in the spring are normally associated with a decline in conductivity (or ionic concentration [24]). The presence and concentration of ions and contaminants has also been associated with Sp.C measurements in lake inlets, e.g., [25]. However, this parameter has not been widely measured under ice conditions in a freshwater environment.

### *2.5. Dissolved Oxygen*

In the late 1990s, the exact link between an ice cover, biological activity and winter DO variations had been investigated, e.g., [26,27], but was still unclear. It was suggested [28] that a thick ice layer, covered with snow, would prevent most photosynthesis activity, which would explain why no variation in day-time and night-time DO could occur. Prowse [2] mentioned that the nature and rate of the winter DO depression depend on many factors, including "the quality and origin of source water comprising the flow, and various biochemical processes, such as decomposition and respiration, operating within the water column and channel bed". In the end, it appears that the first winter DO decline can be attributed to a drastic oxygen production decay combined with a sudden contact reduction between the water and the atmosphere, whereas the mid-winter DO decline would be due to the increasing dominance of poorly-oxygenated groundwater inflow. In turn, the sudden late-winter or spring rise in DO would be mostly associated with reaeration caused by river ice breakup and increasing turbulence. Note that the spring runoff can also generate a pronounced DO decline due to the resuspension of organic material [3,29].

In a temperate setting characterized by ice coverage variations in time and space, DO levels can behave differently from what has been reported for sub-arctic channels, and a winter DO depression may not occur or, at least, it could be less severe [2,26]. In fact, the low $T_w$ promotes high absolute DO levels throughout winter (compared with summer DO levels), especially in organic-rich channels [2]. Nonetheless, a severe winter DO depression was measured in two tributaries of the St. John River, NB, Canada [30].

Above and beyond the harshness of winter and the downstream distance, it seems that a number of parameters affecting DO in streams and rivers has not been specifically investigated, including channel gradient, watershed land use, ice cover type and channel order. The actual technology enables the deployment of autonomous sensors that can measure DO levels on a continuous basis, which greatly facilitate environmental surveys in an aquatic environment and the quantification of spatiotemporal variations on a short time step.

### *2.6. Turbidity and Sediment Transport*

The biotope of aquatic habitats is made of sediment and organic material that can be mobilized by natural forces, and sediment transport represents an important environmental fluvial process. The presence of stationary or fast-moving ice logically impacts the sediment transport capacity of a channel, e.g., [1,7,31–33], and it is not surprising that a number of studies has reported erosion and a redistribution of sediment in the presence of different forms of river ice, e.g., [34–36]. This winter process can either improve aquatic habitats, e.g., [37], or be detrimental to a number of species, including fish and their eggs, e.g., [17]. Some studies have also reported very low turbidity (Turb) measurements (or suspended load) during low winter flow conditions, e.g., [38]. The rate of sediment transport does not only depend on the transport capacity, but also on the supply of sediment, which can become very low during the cold season. Indeed, during winter and as Q declines, tributaries do not carry as much sediment; ice protects the banks and the bed (at grounded ice locations) from erosion; and the emerging portion of unstable banks is usually frozen and/or snow-covered, e.g., [3,39,40].

In turn, at breakup, the combined actions of the rising Q and ice abrasion are known to generate very high sediment transport rates, e.g., [41–43]. It is difficult to distinguish the sediment transport contribution of breakup from that of the spring freshet (spring snowmelt hydrograph) for multiple reasons: (1) they usually overlap, at least initially; (2) automated instruments can be damaged in the presence of moving ice; (3) water sampling is difficult and dangerous to perform in the presence of a deteriorating ice cover or during ice runs; (4) bedload measurements are virtually impossible to perform in the same conditions; and (5) the combined action of ground thawing and ice abrasion may increase sediment supply, e.g., [44], in such a way that sediment transport rates reach values that are well above those estimated from open water sediment transport rating curves, e.g., [3].

Dynamic processes such as ice jams and ice runs are known to generate sediment transport pulses, cause sediment accumulation on high banks, create pools and longitudinal scares in the channel and on the banks, damage the riparian vegetation and alter the surface armor of gravel bed channels, e.g., [3,35,45,46]. As a consequence, frequent and/or intense ice jamming and release events can destabilize channels, affect their morphology, e.g., [47], and therefore, disturb aquatic habitats, e.g., [3].

Techniques normally used to evaluate sediment transport in open water conditions (water samples, turbidity measurements, bedload traps) may underestimate sediment transport rates during winter because ice also represents a direct sediment transport vehicle. Anchor ice released from the bed and grounded ice floes lifted by the rising water level are referred to as "sediment rafts" that can transport significant amounts of material [48–50], including large rocks, e.g., [36,51,52]. The deposition of rafted sediments mostly depends on ice melting rates, and as a consequence, rafted sediment settling locations are often independent of prevalent hydraulic conditions. This means that these particles can disturb aquatic habitats and, in most cases, that they become available for subsequent, hydraulically-driven transport.

Sediment transport in cold region channels has been synthesized in review papers and reports [35,40,53].

## 3. Research Sites and Methodology

Both research watersheds, geographically presented in Figure 1, were selected for their comparable sizes, for their land use and morphology contrasts (Table 1), as well as for their proximity to Quebec City. The Montmorency (M) watershed is oriented north to south, and historically, its winter minimal Q has been two to three times less than its minimal summer Q. The Etchemin (E) watershed is inversely oriented, and historically, its winter and summer minimal Q have been comparable.

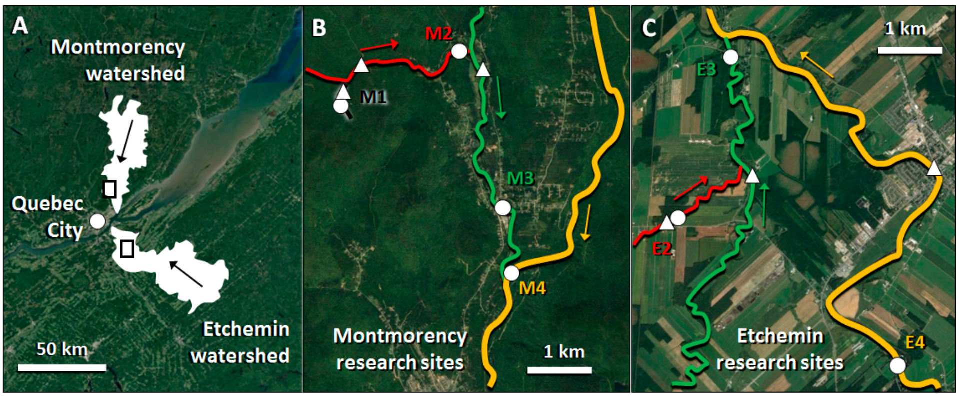


**Figure 1.** (**A**) Geographic location of the Montmorency (M) and Etchemin (E) watersheds located on both sides of the St. Lawrence River in Quebec City; (**B**) Research channels in the M watershed with instrumented sites identified by white circles; (**C**) Research channels in the E watershed with instrumented sites identified by white circles. Channel colors are representative of their approximate Strahler order. White triangles represent discharge estimation sites, and white circles indicate environmental parameter monitoring sites.

**Table 1.** Research channels with their respective Strahler order, code, watershed sizes and land use, as well as geographic and ice characteristics.

| Channel. Name | Channel. Order | Channel. Code | Watershed Size ($km^2$) | Land Use (F: Forest; C: Crops) | Gradient (%) | Width (m) | Morphology | Ice Cover |
|---|---|---|---|---|---|---|---|---|
| Vallée Creek | 1 | M1 | 0.5 | 100% F | 12 | 1 | Cascades | Ice shells |
| Lépine Creek | 2 | M2 | 7 | 95% F | 7 | 3 | Step-pools | Suspended |
| De l'Île Stream | 3 | M3 | 90 | 95% F | 1 | 20 | Rapids | Suspended |
| Montmornecy River | 4 | #M4 | 1100 | 95% F | 1 | 60 | Rapids | Suspended |
| Bélair-Sud Creek | 2 | E2 | 6 | 80% C/20% F | 0.4 | 3 | Artificially-confined ditch | Free-spanning snow |
| Le Bras Stream | 3 | E3 | 200 | 70% C/30% F | 0.2 | 20 | Meandering with few riffles | Confined surface ice |
| Etchemin River | 4 | E4 | 1100 | 35% C/65% F | 0.3 | 60 | Meandering with few rapids | Floating surface ice |

It was initially believed that breakup events would be more severe on the northward flowing E River, as could be expected from what has been mentioned several times in the river ice literature. However, the authors experience over the years suggest that, at this scale (watersheds of about 1000 $km^2$ or less), the north to south $T_{air}$ contrast is compensated by altitude, and that beyond watersheds orientation, their average gradient has a dominant influence on the river ice breakup scenario. This explains why both rivers have been affected by severe mechanical events on a regular basis, but with more frequent mid-winter breakup events on the E watershed. Table 1 also indicates that the ice cover along research channels depends on the local gradient or, more simply, on the morphology [18].

Table 2 presents the parameters that were measured on an hourly basis for 12 months (June 2011–June 2012), this paper focusing on winter results (November 2011–April 2012). The discharge (Q) was estimated using instruments and strategies adapted for each channel (white triangles in Figure 1 indicate Q estimation sites). Along the M1, M2 and M3 channels, specific hydraulic controls were only affected by ephemeral ice development because of a local, groundwater sources (see details about Q measurement in [6]). In this case, autonomous pressure sensors (HOBO U20 anchored to the bed using steel bars and weights) were deployed, and a Sontek Flow Tracker was sporadically used to confirm the stability of the local rating curve. Along the E2 and E3 channels, constant velocity and depth measurements (ISCO 2150 anchor to the channel bed using a PVC-covered steel weight) were performed to evaluate Q, and the Flow Tracker was used a few times (e.g., through holes in the ice cover) to facilitate the interpretation of the reach winter hydrological behavior. Finally, along the M4 and E4 channels, Q were estimated by the Quebec Provincial Government on a 15-min basis and converted into hourly-averaged data.

**Table 2.** Parameters measured or estimated during winter and instruments deployed into or along the different channels.

| Parameter | Code | Units | Instrument | Acquisition Rate |
|---|---|---|---|---|
| Air temperature | $T_{air}$ | °C | Onset HOBO U22-001 | 60 min |
| Discharge | Q | $m^3/s$ | ● Onset HOBO U20 0–4 m<br>● YSI 6600 V2<br>● ISCO 2150<br>● Provincial Government<br>● Flow Tracker | 60 min<br>60 min<br>60 min<br>15 min into 60 min<br>Punctual |
| Ice coverage | $I_c$ | % | Automated Canon 20D | 60 min into 24 h |
| Water temperature | $T_w$ | °C | YSI 6600 V2/YSI 6560 | 60 min |
| Specific conductivity | Sp.C | µs/cm | YSI 6600 V2/YSI 6560 | 60 min |
| Dissolved oxygen | DO | mg/L | YSI 6600 V2/YSI 6050 ROX | 60 min |
| Turbidity | Turb | Nephelometric Turbidity Units (NTU) | YSI 6600 V2/YSI 6036 TRUB | 60 min |

The ice coverage $I_c$ (converted into 24-h averaged data) was estimated by automated camera (Figure 2A) photographs' interpretation along reaches of several channel widths equivalent in length (at least 50). In addition to automated cameras (one per channel), about 30 field trips were completed from freeze-up to breakup in each watershed, and photographs were analyzed as objectively as possible. The same strategy was used to identify reach-specific ice processes that would affect environmental parameters.

Specific water quality monitoring sites (white circle in Figure 1) along each channel were first identified based on the position of nearby tributaries. Indeed, in order to attain the research objectives, instruments were anchored far downstream or some distance upstream of tributaries in order to minimize local water quality interferences that would not be representative of the reach characteristics. The instrument position was also selected based on accessibility and shelter from adverse phenomena. At each site (seven in total), a YSI 6600 V2 probe was placed in PVC tubes anchored to the riverbed

(Figure 2B) where inspections, calibration and battery changes would remain possible throughout winter (sometimes after tremendous amounts of the authors' calories spent breaking the ice cover; Figure 2C). At one site (E3), the channel depth and ice thickness imposed a more robust anchoring installation on a bridge pier (Figure 2D). Environmental parameters were also manually measured using a portable YSI Pro 2030 ($T_W$, Sp.C, DO) and a Lamotte 1979-EPA (Turb) several times during winter in order to confirm that YSI 6600 V2 sensors were not malfunctioning. In minor cases, data points were removed because of suspicious data of known (e.g., anchor ice) or unknown (e.g., possible fish or larvae using the sensor as a habitat or winter shelter; Figure 3) origin.

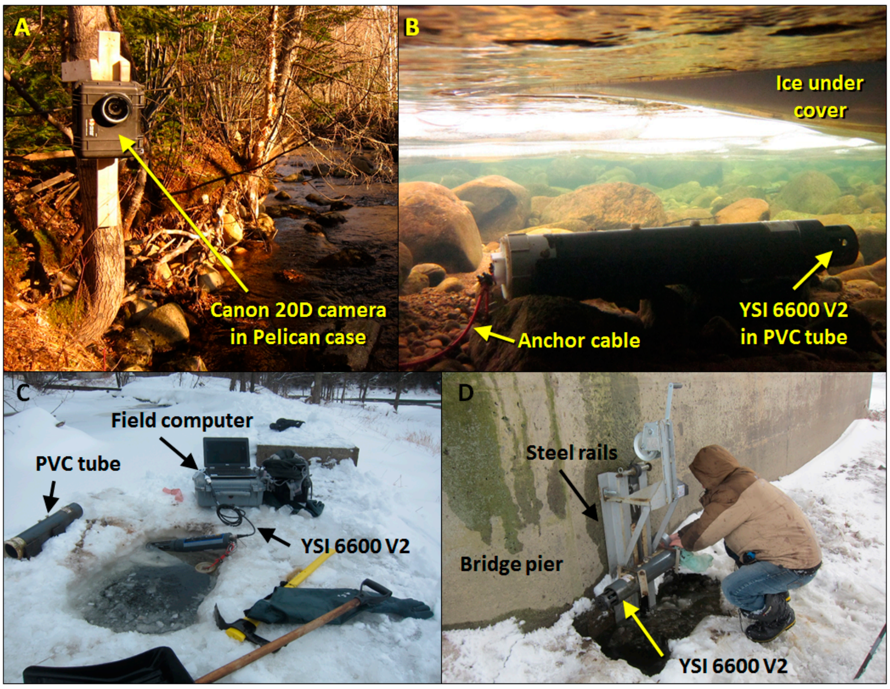


**Figure 2.** (**A**) Automated Canon 20D digital camera in adapted pelican case at Site M2; (**B**) aquatic view of the YSI 6600 V2 in its PVC tube at Site M3; (**C**) retrieving and downloading the YSI 6600 V2 at Site E4 in February 2012; and (**D**) retrieving and downloading the YSI 6600 V2 prior to breakup at Site E3.

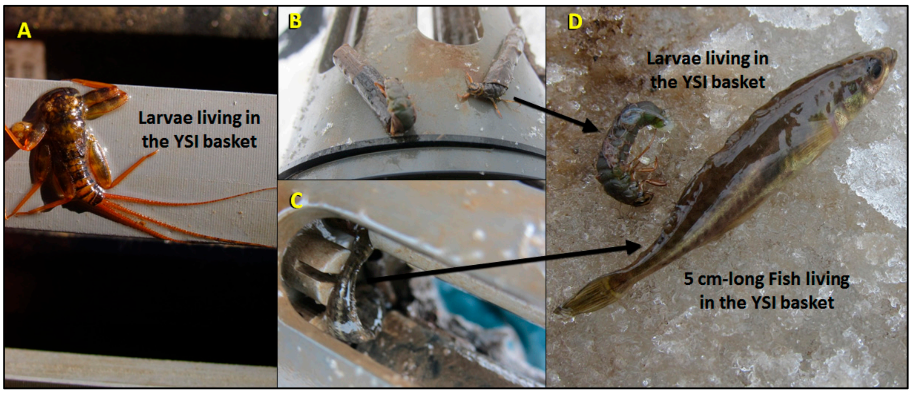


**Figure 3.** Larvae and fish adopting the YSI 6600 V2 basket as a wintering habitat at Site E2.

## 4. Results

### 4.1. Montmorency Watershed

This section presents the results of the 2011–2012 field campaign in the Montmorency (M) watershed. Overall results for each parameter and at each channel order are presented in Figure 4, and key observations, which were either surprising and/or relevant, are highlighted in the different subsections. Straight forward analyses are also presented, leaving more thoughtful interpretations and questioning for the discussion Section 5.

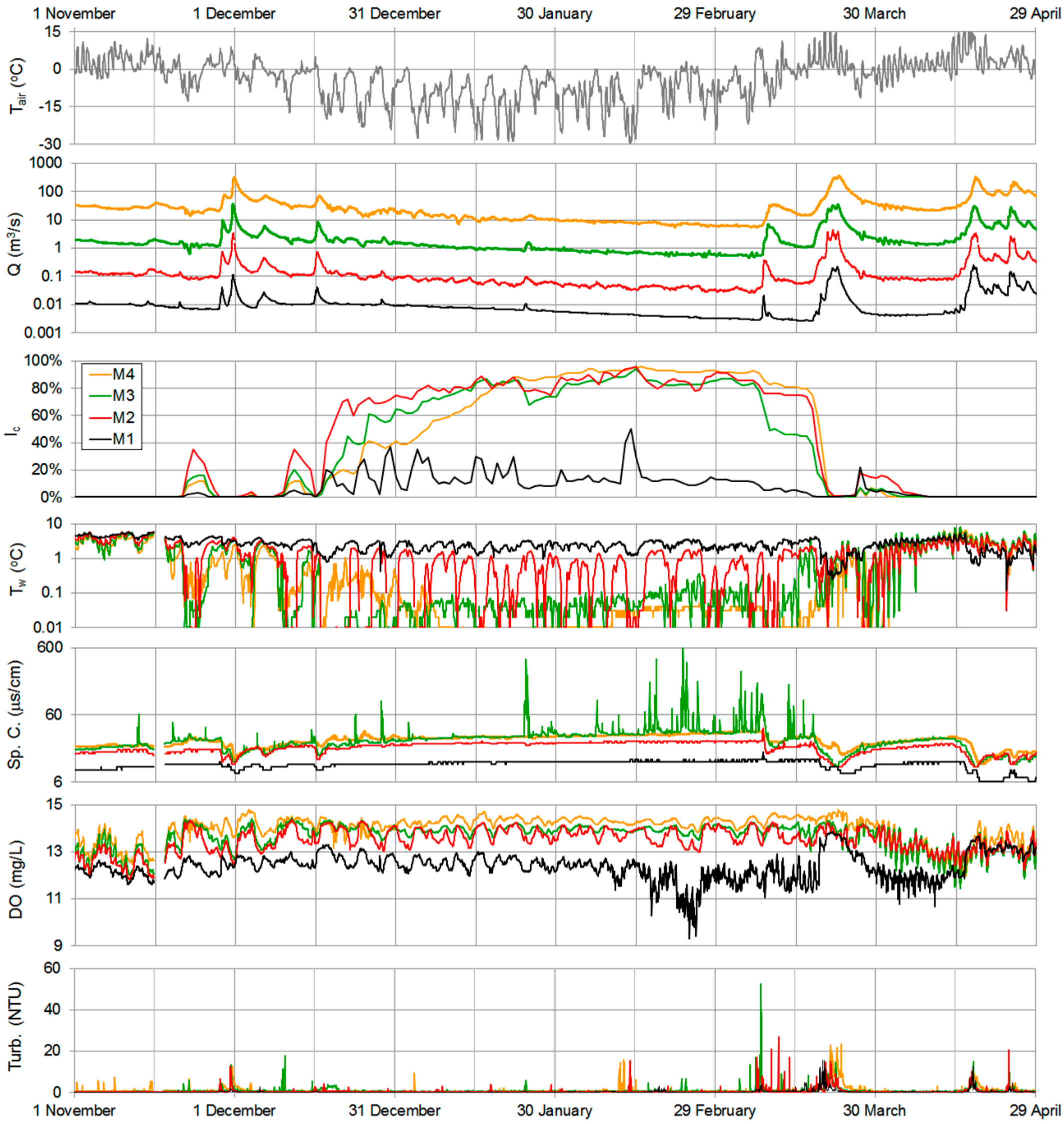


**Figure 4.** Hourly data (air temperature ($T_{air}$), discharge (Q), ice coverage (Ic), water temperature ($T_W$), specific conductivity (Sp.C), dissolved oxygen (DO) and turbidity (Turb)) from 1 November 2011 to 29 April 2012 at Sites M1, M2, M3 and M4.

### 4.1.1. Discharge

After the runoff event of 16 December (accompanied by a Q depressions documented in [6]), winter Q conditions were relatively stable with minor rain-on-snow events on 28 December and 24 January. Hydrological instabilities at Sites M2 (throughout winter), M3 (early winter) and M4 (first half of winter) most often represent Q depressions associated with ice production in upstream reaches and tributaries. A pre-freshet rain-on-snow event occurred on 8 March, and a very early and yet relatively thermal, multi-peak, snowmelt-dominated breakup scenario took place from 18 March–22 March.

The data revealed that, under open water conditions, the maximum Q of each runoff event was usually delayed by about 10 h between Sites M1 and M4, whereas, in the presence of snow on the ground and ice in the channels, runoff maxima were respectively delayed by 21 and 28 h on 24 January and 8 March. This winter alteration of the hydrological continuum is probably caused by the slow percolation of rain drops into the snow cover and by the slower runoff transit in the drainage system, partly associated with the presence of perforated ice dams, e.g., [13], that control the released Q until they cede or become overtopped.

#### 4.1.2. Ice Coverage

Similarly to the 2010–2011 winter [5], the ice cover started forming first in the second order (M2) channel on 16 December by massive anchor ice formation and ice dam development [13]. Anchor ice and ice dams also formed about six days later (22 December) along Channel M3 and about 20 days later in the Montmorency River (M4; 6 January). The reason for this spatial pattern is due to local heat budget differences, but its exact origin still needs to be quantified. In the first order, groundwater dominated, channel (M1), the only ice observed were ice shells [18] that formed and melted in synchronicity with $T_{air}$ variations. Openings in the suspended ice cover at Sites M2–M4 remained visible throughout winter, often downstream of low order tributaries.

The partial ice cover at Site M3 was mobilized during the pre-breakup runoff event of 8 March, mostly likely because ice dams were small (less than 0.3 m on average compared to about 0.6–1.5 m at Sites M2 and M4) and fragile along that specific reach. The exceptionally warm $T_{air}$ from 18 March to 22 March (daily variations between 1 °C and 18 °C) caused an accelerated thermal breakup at Sites M2 and M4, and the only ice jam observed was located some 10 km downstream of Site M4.

#### 4.1.3. Water Temperature

Figure 4 shows that the water temperature dropped, on average, with an increasing channel order. The groundwater heat explains the relatively high winter $T_w$ at Site M1. The annual (July 2011–June 2012) average $T_w$ at that site was 5.51 °C, which compares with the local annual $T_{air}$ average of 4.6 °C. The coldest annual $T_w$ (0.12 °C) at that site occurred during breakup in the presence of massive snowmelt runoff, but $T_w$ barely dropped below 1 °C during the coldest winter nights.

At Site M2, anchor ice and ice dam development events were often initiated by slightly supercooled $T_w$ associated with early-winter, mid-winter and even post-breakup cold spells. These short events were detected 12 times, and the minimum measured $T_w$ was −0.04 °C (these data are not presented on the logarithmic axis in Figure 4 because the YSI 6600 V2 is not meant to measure $T_w$ with such accuracy). As $I_c$ progressed (increasing the channel insulation), freezing $T_w$ at that site became less frequent and shorter in duration. As a consequence, relatively warm $T_w$ (1 °C to 2 °C) transited to the third order channel during most of the mid-winter period.

The winter $T_w$ behavior at Site M3 was comparable to that of Site M2, but winter absolute values were lower (about 0.08 °C) and freezing conditions more frequent and longer in duration. This is explained by the presence of floating ice cover sections (in contact with the flowing water) within the suspended ice cover-dominated reach and by the longer residence time in the drainage system, allowing for additional groundwater heat loss.

Finally, the surprisingly high $T_w$ at Site M4 was probably caused by a local groundwater source that had not been identified before winter (the YSI 6600 V2 was sheltered in small pool along the bank [6]). At that site, measured $T_w$ = 0.00 °C started with the massive formation of anchor ice and ice dams (6 January) and ended when the breaching of ice dams was over (9 February), leaving the ice cover suspended above the flowing water.

#### 4.1.4. Conductivity

The Sp.C in the M watershed is normally close to that of pure water with a slight increase in the downstream direction, and this behavior persisted in the presence of ice. Sp.C values at Sites M1 and M2 were very low for 12 months (respective annual averages of 10 and 18 µs/cm), exhibiting an expected behavior of quick drops and gradual rises respectively taking place during and between runoff events. This indicates that the groundwater in the M2 sub-watershed is almost mineral-free.

Two unexpected results were observed on the Sp.C data at Sites M3 and M4. Along the third order channel, multiple Sp.C spikes were measured during winter. These spikes, reaching a maximum of 600 µs/cm compared with a mid-winter average of 30 µs/cm, either corresponded to the first cold $T_{air}$ of winter or to snow melting conditions, especially after 6 February. They are probably respectively caused by the spreading of de-icing salt, e.g., [25], when $T_{air}$ dropped below 0 °C and to the melting of salty snowbanks under the sun, during the second half of winter. Indeed, Site M3 was located a few meters downstream of a road bridge where sand and salt are used to improve tire adherence and to prevent ice formation on the road, and such Sp.C instabilities only occurred during the winter period.

At Site M4, intriguing Sp.C rises were measured between 16 December and 1 January. A publication by Turcotte et al. (Figure 8 in [6]) shows that these variations occur in synchronism with $T_w$ variations, as well as with Q (and Y) depressions and were therefore associated with local groundwater flux pulses during the ice formation period. However, a similar 24-h rise in Sp.C at site M4 occurred at breakup (21–22 March) during high flow conditions, and the authors have not yet found a reasonable explanation for it.

#### 4.1.5. Dissolved Oxygen

DO levels in the M watershed were usually high and increasing in the downstream direction during the entire monitoring period. Diurnal, open water DO fluctuations were detected at all sites before 10 November and after 30 March and are associated with $T_w$ oscillations, as well as with aquatic biological activity. On the other hand, $T_w$ variations after 10 November and before 30 March mostly concurred with cold and mild $T_{air}$ spells that are normally longer than 24 h, and this explains, in part, why DO variations were so distinctive in the presence of ice and cold water.

At Site M1, DO levels were fairly high at the beginning of winter, but the dominance of poorly-oxygenated water (and potentially snow bridging across the channel) undoubtedly (e.g., [2]) caused these levels to drop prior to breakup. In turn, DO levels remained fairly high throughout winter between Sites M2 and M4 and were generally increasing with the channel order. This is due to $I_c$ remaining lower than 100% (Figure 4), to the highly turbulent hydraulic conditions (steep morphologies; Table 1) and to the increasing cumulative duration of water contact with the atmosphere in the drainage system. Transient, lower-than-expected DO values at Site M4 after 16 December were measured at the same time as higher-than-normal Sp.C values, which reinforces the hypothesis that the monitored water at that site was momentarily affected by high groundwater concentrations.

#### 4.1.6. Turbidity and Sediment Transport

Overall, very low turbidity (Turb) levels were measured at all sites during winter with average values oscillating between 0.1 Nephelometric Turbidity Units (NTU; Sites M1 and M2) to 0.5 NTU (Site M4). Isolated Turb spikes were associated with organic debris, ice pieces or aquatic animals transiting in front of optic sensors (a small fish was seen during winter in the instrumented small side pool at Site M4), whereas consistent, longer-lasting rises in Turb during runoff events were associated with an increase in suspended sediment transport. At Site M3, on 10 December and from 16 December to 20 December, high Turb measurements (respectively, 12 and 4 NTU) were probably caused by frazil transport interference during low $T_w$ events (as observed). At breakup, often the most turbulent period of the year, steady values of 20 NTU were measured at Site M4, while remaining slightly lower at other sites (e.g., 15 NTU at Site M1). These values represent annual Turb maxima associated with the most prolonged suspended sediment transport event of the year. At breakup, Turb rises associated with runoff events generally peaked a few or many hours before Y (or Q; Figure 5). At Site M4 on 9 March and 23 March, a Turb peak seemed to occur when a "jave" (for ice jam release wave [10]) passed by, but this dynamic process (e.g., [45]) is difficult to confirm at an hourly data acquisition rate in a relatively small watershed.

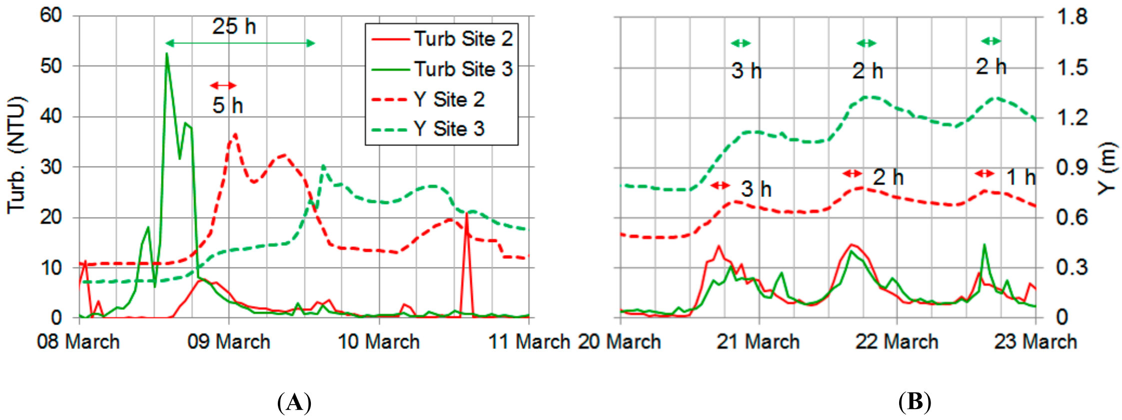


**Figure 5.** Hourly turbidity (Turb) and water depth (Y) data from Sites M2 and M3 (**A**) from 8 March to 11 March and (**B**) from 20 March to 23 March. The delay between turbidity and local Q peaks vary between 1 and 25 h.

It is important to note that sediment transport in steep gravel bed channels is dominated by bedload, a process that can hardly be measured with optic sensors. During winter 2011–2012, apart from anecdotal gravel and rock accumulations at Sites M1–M4 (that complicated the retrieval of aquatic sensors after the freshet period) bedload was not measured, nor estimated. This topic is addressed in the discussion.

### *4.2. Etchemin Watershed*

This section presents the results of the 2011–2012 field campaign in the Etchemin (E) watershed. Overall results for each parameter and at every channel order are presented in Figure 6.

#### 4.2.1. Discharge

The ice period officially started after the runoff event of 16 December. Mid-winter runoff (rain and/or thaw) events took place on 28 December, 2 January, 24 January, 17 February and 4 March. During the event of 24 January, Q was multiplied by two (E4) to five (E3) and seemed to replenish the phreatic storage for several subsequent weeks. The pre-breakup runoff event of 8 March was associated with a three- (E4) to 10-fold (E2) increase in Q, leading to the onset of breakup. Comparably to what occurred in the M watershed, an early, snowmelt-driven, breakup event took place in the E watershed from 18 March to 22 March, but, in this case, the resulting scenario was more mechanical.

Estimating Q at Sites E2 and E3 was challenging for different reasons, and despite the presence of multiple pressure sensors installed at different hydraulic controls, a certain degree of uncertainty remained. This is in part caused by the behavior of the ice cover during runoff events. An earlier research work [54] had revealed that the ice cover at Site E3 is often flooded during runoff events, and that the thickness of the ice cover and surface slush (i.e., the measured water level (Y)) increases as Q rises, but remains high despite Q declining afterward. Subsequent cold spells turn the surface slush into white ice with very limited impact on Y and on the prevalent backwater effect. It is also possible that pressurized flow conditions occurred at Sites E2 and E3, which made difficult the interpretation of the measured water velocity to estimate Q. Finally, the hydrological data later revealed that high water levels (corresponding to an open water Q of about 120 $m^3/s$) along the fourth order Etchemin River affected the rating curve at site E3, which complicated the post-winter estimation of high Q and breakup hydrological conditions.

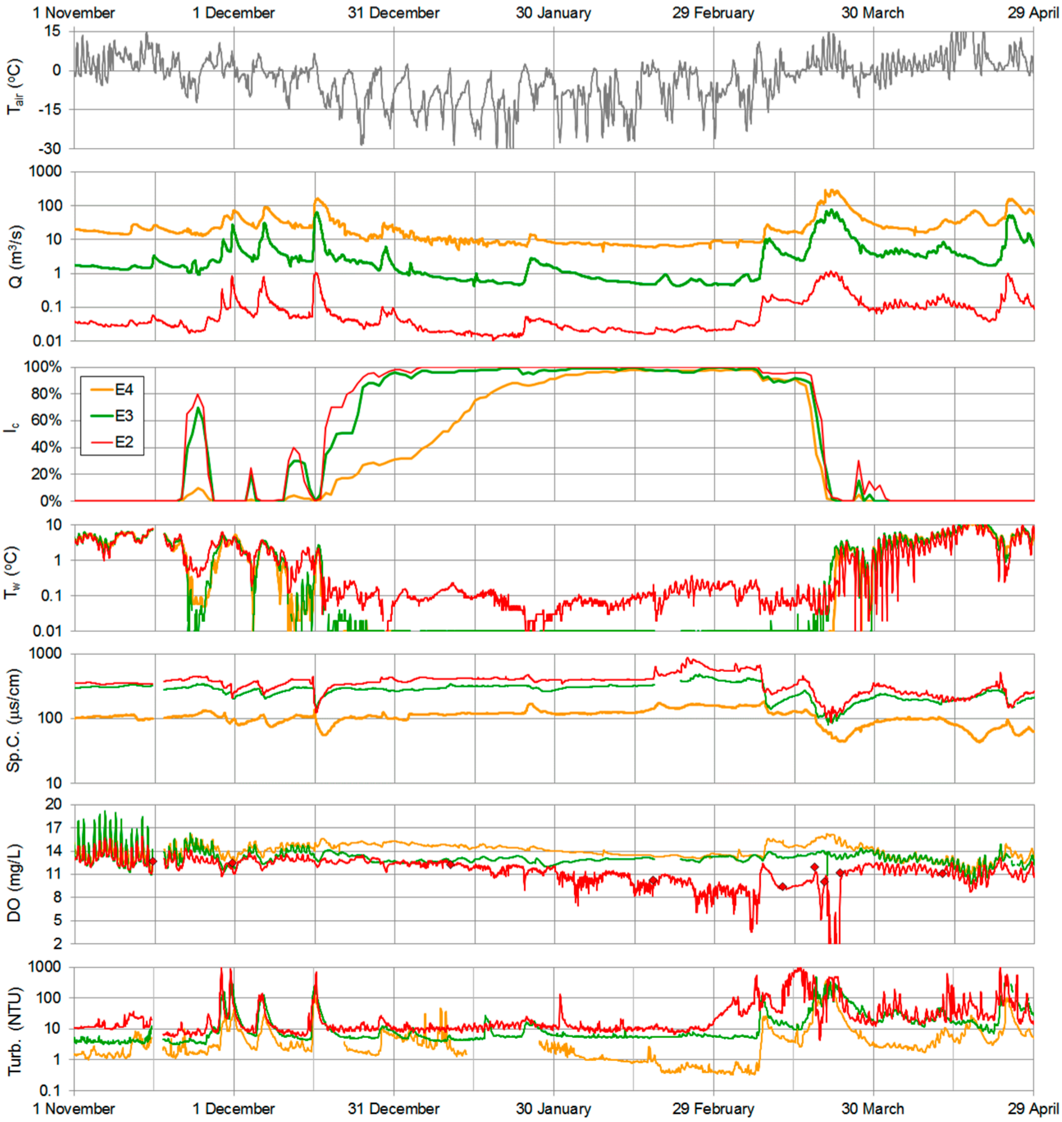


**Figure 6.** Hourly data (air temperature ($T_{air}$), discharge (Q), ice coverage ($I_c$), water temperature ($T_W$), specific conductivity (Sp.C), dissolved oxygen (DO) and turbidity (Turb)) from 1 November 2011 to 29 April 2012 at Sites E2, E3 and E4. The red diamonds in the DO graph represent punctual measurements at Site E2 with a portable instrument.

### 4.2.2. Ice Coverage

As presented in Table 1, the cryologic cover that insulates E2 and E3 channels is particular. Wind-blown snow across open fields is probably the main process that contributed to covering most instrumented and observation sites along Channel E2. This cover, dominated by free-spanning snow in narrow sections with thin (about 5 cm) surface cover made of snow ice at wider locations, extended along almost 100% of the channel in less than 15 days (after 16 December 2011). In Channel E3, the ice cover also formed swiftly, but this process was driven by frazil or snow slush bridging in meanders followed by surface interception and frontal progression in longitudinal segments [54]. As the ice cover thickened, bank and channel characteristics generated confinement, and when Q increased in mid-winter, the ice cover could not float freely at most observation sites. In turn, Channel E4 formed a more conventional, floating, surface ice cover quite gradually (over six weeks). This behavior was not associated with groundwater heat, as observed in the Montmorency watershed, but mostly with the presence of a dam (E4 instrumented site), by which the reservoir intercepted the frazil produced upstream. The downstream (observation) reaches were characterized by meanders with short riffles and bedrock-dominated rapids that were progressively covered by border ice migration, including ice-induced braided patterns (see Figure 9 in Turcotte and Morse [18]).

The snow and ice covers along the E channels were relatively intact on 17 March, before a massive amount of snowmelt water entered the drainage system. In five days, the average $I_c$ dropped from 90% down to 10%, and ice jams formed at a few locations. The most significant observed jam was located upstream of Site E3 (Figure 1), precisely in the reach where Q was estimated (Figure 7A,B). The 1.0-m backwater effect caused by the intact ice cover (compared with the open water rating curve) on 17 March remained the same during the following days until the jam formed on 21 March at midnight. The backwater effect initially rose to about 1.8 m, but the jam started to melt in place. It released at 3 p.m. on the same day while Q was increasing.


**Figure 7.** (**A**) Measured water depth (Y) and estimated discharge (Q) at breakup on the third order channel E3 showing the signature of an ice jam; (**B**) ice jam (photograph taken on 21 March 2012) and (**C**) new gravel bar formed where the jam toe had been momentarily located (photograph taken on 1 August 2012).

4.2.3. Water Temperature

Globally, the water temperature ($T_w$) was lower and more stable during the ice season at all channel orders compared with the open water season. In the second order Channel E2, $T_w$ remained at approximately 0.1 °C throughout winter, a condition explained by the dominance of groundwater heat combined with the free-spanning, insulating nature of the snow cover. Daily, small amplitude $T_w$ variations were registered during the second portion of winter despite an $I_c$ of 100%. These fluctuations began after the runoff event of 24 January and intensified after the event of 17 February. This indicates that each runoff event contributed to melting the underside of the free-spanning snow/ice cover (e.g., [54]), thus reducing the contact between the flowing water and cold surfaces. As a result, daily $T_{air}$ variations could influence the air chamber temperature below the snow cover, thus affecting $T_w$.

In turn, $T_w$ at both Sites E3 and E4 behaved as expected, dropping to 0.0 °C prior to freeze-up and maintaining this conditions until breakup. Supercooling events (not presented in Figure 6) were detected six times at Site E3 during freeze-up and once after breakup (−0.01 °C–−0.03 °C, keeping in mind the limited resolution of the YSI 6600V2). At Site E4, a similar degree of supercooling was measured only once during freeze-up (17 December) and once after breakup (27 March).

4.2.4. Conductivity

The Specific conductivity (Sp.C) in the E watershed (Figure 6) was one order of magnitude higher than that of the M watershed during winter 2011–2012 (Figure 4), a result that also extended to the open water period. The fact that Sp.C decreased with the channel order is probably due to the dominance of agricultural fields in the smaller watershed (Table 1). Indeed, the current agricultural practice involves the use of multiple organic and inorganic substances that modify soil properties, and the geology can also affect the groundwater and drainage system Sp.C.

As previously stated, the Sp.C signal is generally the mirror of Q. This logic was respected at all E sites prior to freeze-up (until 16 December), but mid-winter runoff events (e.g., 28 December, 24 January and 17 February) generated Sp.C rises rather than drops at Sites E2 and E4. This suggests that surface runoff during these events contained a higher concentration of ions and/or minerals than the standard groundwater. A this point, the authors could not identify the exact origin of these consistent high Sp.C levels, and further investigation should confirm if the agricultural practice, the decomposition of crops residues, the use of de-icing salt or another cause can be pointed out. A similar reasoning could also clarify why an important rise in Sp.C was measured at all sites during the second half of February, especially at Site E2, with values reaching 880 µs/cm (twice the value of Sp.C for a comparable Q during the summer of 2011).

#### 4.2.5. Dissolved Oxygen

Aquatic measurements during the winter period indicate that the presence of a complete surface ice cover, a reduced biological activity and a stable $T_w$ at 0.0 °C at Sites E3 and E4 erased diurnal dissolved oxygen (DO) variations. At site E4, DO gradually decreased during the winter period, as should be expected considering the reduced contact between the water and the atmosphere, the longer water residence time, as well as the dominance of poorly-oxygenated groundwater. At Site E3, a comparable decline was not detected, and DO remained fairly stable between 12 and 13 mg/L. It is possible that air pockets under the surface ice cover laying on the banks (confirmed during Q measurements) enabled gaseous exchanges between the atmosphere and the water, thus maintaining reasonably high winter DO levels.

The most relevant observation was made at Site E2 where a winter DO depletion was measured, reaching critically low values at the end of February. The representativeness of automated DO measurements was initially uncertain, but punctual DO measurements (see red diamonds in the DO graph, Figure 6) did not reveal any sign of continuous measurement errors. A number of publications have mentioned that low DO levels could be expected downstream of bogs [55] or industrial sources, e.g., [28,56]. It seems that agricultural practices could also temporarily deplete DO in small channels prior to and during breakup (e.g., [3]). The oxidation of highly concentrated solids and the presence of what appeared to be white, filamentary algae at Site E2 during the second half of winter would explain, at least in part, temporarily lethal DO levels.

#### 4.2.6. Turbidity and Sediment Transport

Turbidity (Turb) values were generally low in the E watershed during winter, but high concentration events were monitored. At Sites E2 and E3, the winter Turb was less responsive to Q variations than what had been measured during open water conditions (Figure 8, based on averaged Turb values for determined relative Q increments), and values at very low Q were somewhat higher than what would have been expected based on open water conditions.

The Turb base value at Site E2 during winter was about 10 NTU, and intriguing daily variations (from 8 to 16 NTU) were detected during the entire cold period. About six days before breakup, while Q was relatively constant, very high daily bursts of Turb were measured. Unfortunately, the maximum YSI 6036 optical sensor range was 1000 NTU, not enough to fully monitor maximum levels. In turn, during the first days of massive snowmelt runoff, relatively low Turb levels were measured as if the sediment available for transport had been depleted (or was not available yet). Weeks after breakup, daily variations of significant magnitudes (50–400%) were again detected and concurred with Q variations (20–50%) and therefore with the sediment transport capacity unlimited by sediment supply. During breakup at Site E3, Turb variations occurred more frequently than Q variations, which suggests that dynamic ice processes generated Turb pulses (e.g., [45]). However, at a data acquisition rate of 1 h, no specific link could be made between detected ice jam release events (e.g., Figure 7) and Turb data.

Turb measurements at Site E4 revealed low winter levels, especially after mid-February and prior to the runoff event of 8 March (Figure 6). In turn, Turb values were higher than what would have been expected from the open water Turb-Q relationship (Figure 8), which is counter intuitive from the sediment supply and sediment transport capacity points of view, but not impossible considering the complexity of hydraulic conditions under an ice cover. The optical data between 16 December and 21 December were affected by anchor ice and were therefore removed from the dataset. A similar decision was made about the data between 13 January and 27 January because of thermal ice formation on the upstream face of the dam where the sensor was installed. At breakup (combined with the freshet), Turb levels reached values of 350 NTU, which is comparable to what had been measured in September 2011 for a Q that was 25% lower.

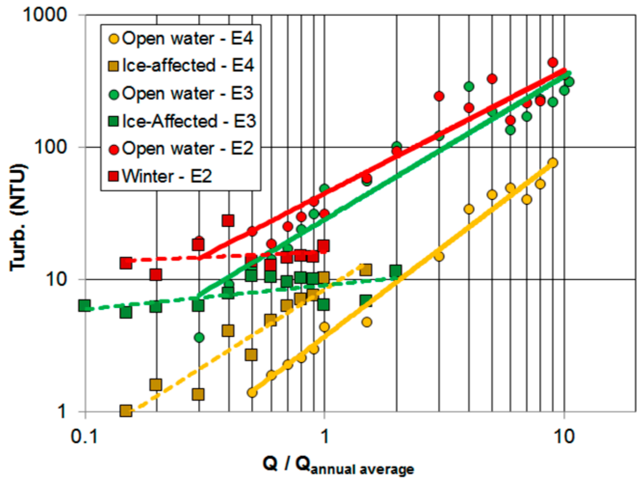


**Figure 8.** Data and power function interpolations between open water and ice-affected turbidity-Q relationships at Sites E4, E3 and E2. Q is made dimensionless by using the annual average Q at all sites.

The ratio of suspended vs. bedload transport in the E watershed is unknown, but it is most probably significantly higher than in the M watershed dominated by gravel-bed channels. In 2013, an attempt was made to link Turb with suspended sediment concentration (mg/L). Figure 9 presents the relationship at both Sites E3 and E4 (the maximum value of 1000 NTU had been reached too often at site E2 during the 12 months of environmental monitoring to perform this analysis). Keeping in mind that these relationships are approximate (e.g., they do not consider seasonal variations or the concentration of fine sediment in the ice), results suggest that respectively 0.2% (260 tons) and 0.5% (72 tons) of the annual suspended load transited through Sites E4 and E3 between 17 December and 7 March (21% of the year). In turn, between 8 March and 24 March (breakup and snowmelt runoff, 4% of the year), 22% of the annual suspended load transited through both sites (respectively 28,600 tons and 3400 tons).

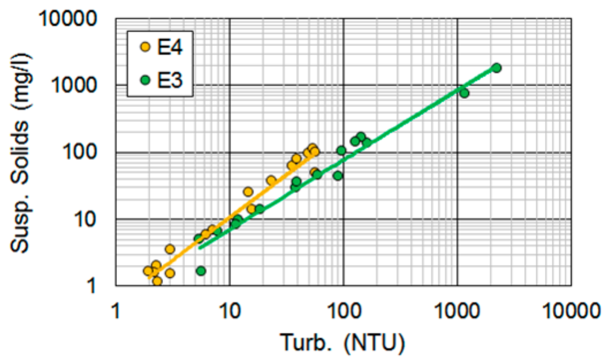


**Figure 9.** 2013 field data and interpolated relationship between suspended solids (mg/L) and turbidity (NTU) at Sites E3 and E4.

## 5. Discussion

### *5.1. Discharge*

Discharge (Q) variations during winter 2011–2012 (Figures 4 and 6) did not directly generate extreme conditions from an environmental standpoint (e.g., there was no significant Q depression, only moderately low late-winter Q and no confirmed dynamic ice-induced Q instabilities associated with ice jam events). In turn, as expected, Q variations did affect other parameters. For example, when Q rose, $I_c$ was reduced at most sites; $T_w$ was reduced at sites where no floating ice cover was present (but the dominance of groundwater heat at site M1 was maintained despite 10-fold increases in Q); and Sp.C often rose unexpectedly (at sites E2 and M3) before dropping.

From a watershed hydrological continuum point of view, the ratio of Q per $km^2$ of the watershed generally remained fairly constant from M1 to M4, including during runoff events, which was apprehended because of the watershed topographical characteristics. On the other hand, this behavior was not observed in the flatter E watershed. It seems that Q could only be estimated with a limited level of confidence at E sites, a winter reality that applies to most cold regions' channels. Because Q directly affects most hydraulic, thermal, cryologic and water quality parameters (i.e., the entire environmental continuum), it appears that estimating Q in the presence of ice, despite being very challenging, is a necessary task that government agencies have often struggled to accomplish for several reasons, including resource and knowledge limitations. The velocity index method, e.g., [57,58], represents one avenue to address this issue. Other empirical approaches could be developed on the basis of site-specific knowledge that involves field data acquisition in a relatively dangerous environment [59].

### *5.2. Ice Processes*

The data from Figures 4 and 6 indicate strong upstream to downstream ice cover formation chronologies in both E and M watersheds, the largest channel being the latest to become ice covered (despite generally lower gradients). At breakup, a combination of heat, Q variation and ice cover fragility usually dictated the spatial chronology of the $I_c$ reduction. Therefore, understanding and monitoring the upstream to downstream ice dynamics (i.e., the cryologic continuum) appear crucial to identify the origin of specific environmental parameter fluctuations, such as $T_w$ and DO.

A number of ice formation processes that were observed during winter 2011–2012 can negatively impact aquatic life. In low gradient channels, the formation of an ice cover at shallow locations (or when Q is low) and the downward migration of thermal ice in the substrate could both cause mortality by freezing. In steeper reaches, the formation of frazil and anchor ice, observed at many sites, could also directly (e.g., abrasion, isolation, freezing) and indirectly (e.g., suffocation, imposed migration to other sites and energy consumption) affect aquatic species (e.g., [2,3,17]). On the other hand, during the studied winter season, the presence of an ice or snow cover positively stabilized a number of environmental parameters, and no mid-winter breakup event was observed (although these processes are common in the region). The spring breakup scenario in the M watershed was relatively thermal, with limited dynamic impact on aquatic habitats; the moderately mechanical breakup in the E watershed generated ice jams that mostly melted in place; and no sign of major ice runs (only small shear walls) was observed.

During the following winters, the authors monitored four dynamic ice phenomena that were observed or assumed to affect aquatic life:

- In the spring of 2014 in the M watershed, a two kilometer-long ice jam was lifted and mobilized by an important jave [60]. Ice movements in secondary channels wiped large zones of riparian vegetation. After the event, fish were found swimming within isolated, shallow pools in the forest (formed by ice jam-induced high water levels), and various dead crayfish parts (probably crushed by moving rocks, woody debris and ice floes) were observed on newly-formed sandy bars (Figure 10A).
- In January 2015, under very low $T_{air}$ (−25 °C), a jave was detected (water level acquisition rate of 5 min) in the Montmorency River at several sites along a 5 km-long reach. This "cold breakup",

an event that has rarely been documented, was probably caused by the release of an unstable ice dam that triggered a cascade effect. The jave celerity was not very high (5 km/h), and the wave amplitude was not significant (0.6 m), but it occurred under supercooling conditions, when species are the most vulnerable (e.g., less mobile). Although no mortality could be observed among the aquatic community, this result appears very likely.

- Mid-winter breakup events can be detrimental to aquatic life, especially when the rain is immediately followed by an intense cold spell. In January 2016, in the Ste. Anne River (fourth order gravel bed channel located near Quebec City, QC, Canada), a runoff event caused multiple ice runs and ice jams concurrently with massive frazil production and high frazil transport rates ($T_{air}$ rapidly fell below −10 °C after the rainfall). This scenario and its outcome is probably comparable to the "cold breakup" described above, although its origin and suddenness are distinct.
- In December 2015, a snow storm generated a snow slush flow that travelled along a few kilometers of the Ste. Anne River. This dynamic event, comparable to a dynamic breakup, was probably caused by the release of a snow slush bridge under its own backwater pressure. Although the wave was not very high (about 1 m), it is still the most likely explanation for the observed mortality in the fish community (Figure 10B). A question arises regarding the ability of aquatic species to instinctively apprehend this type of snowfall-driven freeze-up consolidation event that our advanced society can hardly predict (e.g., [7,10]).

Overall, the grounded nature of moderate and intense ice runs (the water depth is comparable to the size of tumbling ice floes) in steep gravel bed channels such as the Montmorency and Ste. Anne Rivers represents a serious threat to aquatic species lying on or within the substrate. These ice runs can travel a significant distance downstream, rubbing the banks and bed with nowhere to hide.

(**A**) (**B**)

**Figure 10.** (**A**) Dead crayfish (8 cm in length) on a sandy bar along a secondary channel of the Montmorency River after the 15 April 2014 breakup and (**B**) dead fish (5–10 cm in length) found on a gravel bar of the Ste. Anne River after a snow slush consolidation event on 21 December 2012.

### 5.3. Water Temperature

Figures 4 and 6 revealed that $T_w$ can remain above 0 °C in headwater and/or steep channels, even during very cold spells, mostly because of a combination of groundwater heat and suspended ice (or free-spanning snow) cover insulation. Low order streams and confluences can represent a winter refuge for aquatic species including fish, e.g., [16], but questions arise regarding the impact of (1) relatively warm (and unstable) $T_w$ and (2) the possible absence of ice cover on fish behavior, metabolism and predation, thus affecting survival rates, e.g., [17]. Furthermore, under relatively common circumstances, these channels are affected by transient supercooling events, as well as by massive anchor ice formation periods, and some reaches are not accessible to all species and individuals, partially because of the presence of ice, cascades and anthropic hydraulic structures that impede migration. Figure 11 presents a $T_w$ dataset measured with a high resolution sensor (RBR Solo T) deployed in the Ste. Anne River during winter 2014–2015, substantiating that supercooling is very common in small rivers of the Quebec City region at freeze-up, as well as prior to and after breakup.

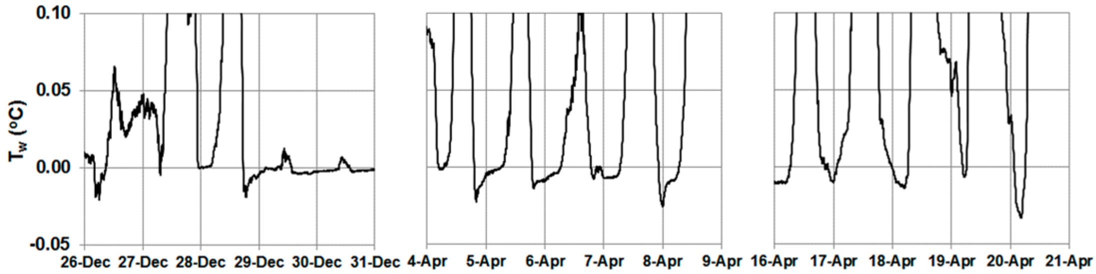


**Figure 11.** Supercooling events measured during freeze-up (**left**), prior to breakup (**middle**) and after breakup (**right**) in the Ste. Anne River watershed located northwest of Quebec City, QC, Canada, during winter 2014–2015.

In higher order and low-gradient channels located downstream, $T_w$ most often remained close to 0.0 °C throughout winter, and most aquatic species are usually adapted to this environment, although they can suffer from long, cold winters, e.g., [17]. Prior to breakup, the rise in Q combined with a $T_w$ of 0.0 °C could represent a limitation to overwintering aquatic species in preparation for a potentially dynamic breakup.

### 5.4. Conductivity

Results presented in Figures 4 and 6 suggest that the winter upstream-to-downstream Sp.C relationship in both M and E watersheds compares with what is normally monitored during the open water season (including the early November and late April periods). However, a number of site-specific signals that either faded or were not detected downstream suggest that humans can substantially modify the winter water quality, as interpreted through the specific conductance (Sp.C).

A publication [25] suggests that the use of de-icing salt on a highway in the Quebec City region was the main cause of the St. Augustin Lake's eutrophication. Transient salty spikes in streams (e.g., Figure 4 at Site M3) probably generated less ecological impacts, and dilution rather than accumulation can occurs downstream; but this should be confirmed by further investigation in a comparably pristine environment.

Furthermore, there are reasons to believe that the current agricultural practice in the E watershed can significantly modify the ion balance at all channel orders and therefore affect the Sp.C (e.g., [61]). The very high Sp.C values measured prior to breakup (e.g., Figure 6 at Site E2) are particularly intriguing. Further research should attempt measuring which ions (e.g., nitrates) or contaminants (e.g., fertilizer residues, de-icing salt) are responsible for this result, if the observed winter growth of algae can be linked to this parameter and if this can be directly or indirectly lethal to aquatic species. In this case also, the downstream site (E3) only registered a moderate late-winter rise in Sp.C, which confirms that contaminant dilution takes place downstream of confluences.

### 5.5. Dissolved Oxygen

Overall, the data presented in Figure 4 suggests that dissolved oxygen (DO) in steep (turbulent and partially ice-covered) channels located in forested settings is not a factor influencing the survival rate of aquatic species. In turn, aquatic species may have to choose between a relatively warm headwater channel with potentially low late-winter water depths and DO levels or a colder, deeper, higher order channel with a consistently DO-rich environment.

In a low-gradient setting (E watershed), the data in Figure 6 show that DO levels can remain surprisingly high during the entire winter season, despite the presence of a DO impermeable ice cover (e.g., [2]). At the opposite, in snow-covered headwater agricultural channels, lethal DO levels can be reached prior to and during breakup (e.g., Figure 6 at Site E2), which could be due to a high concentration of organic material [3]. Further research should confirm the origin, potential intensity and impacts of a multi-day "reduced DO wave" travelling downstream on aquatic life and if this phenomenon could impact higher order channels (which was not the case in the present study).

*5.6. Turbidity and Sediment Transport*

In the M watershed, turbidity (Turb, Figure 4) remained low (under 1 NTU) during the winter period, with measurable, but limited rises during runoff events, a behavior that compares with what was monitored during the open water period. In turn, at breakup and during the freshet event, Turb levels were multiplied by 10–50 for several days. Undoubtedly, a large ratio of the sediment transport along gravel bed channels in forested settings occurs in the form of bedload transport. The authors believe that the thermal nature of the March 2012 spring breakup event and the relatively low freshet runoff (about 330 $m^3/s$) in the M watershed did not generate a significant amount of bedload transport. However, in April 2014, a dynamic breakup event characterized by a succession of seven measurable javes [60] and a high Q (about 600 $m^3/s$) apparently moved a significant amount of sediment in the same watershed: two anchored instruments were lost (the local bed geometry had completely changed), and one instrument had been flipped over and buried under 200 mm-diameter stones. Further downstream, piles of gravel had been deposited on ice floes laying on the floodplain (Figure 12A), and a 300-mm rock was found in the thermal ice portion of an ice floe in the forest (Figure 12B). An observation from the Ste. Anne River also demonstrates that ice runs can mobilize 1.5-m boulders (Figure 12C). This highlights the fact that, beyond the complexity of estimating bedload transport during winter, quantifying ice rafting and ice pushing sediment transport is also very challenging, but necessary to understand how dynamic winter fluvial processes can impact the channel stability and aquatic habitats. It is known by river ice scientists and engineers that tributaries can trigger breakup [54] that can in turn generate bank and bed scour (e.g., [53]), which can directly cause mortality among the aquatic community. This highlights one of the potential impacts of the environmental continuum on aquatic species through sediment transport.

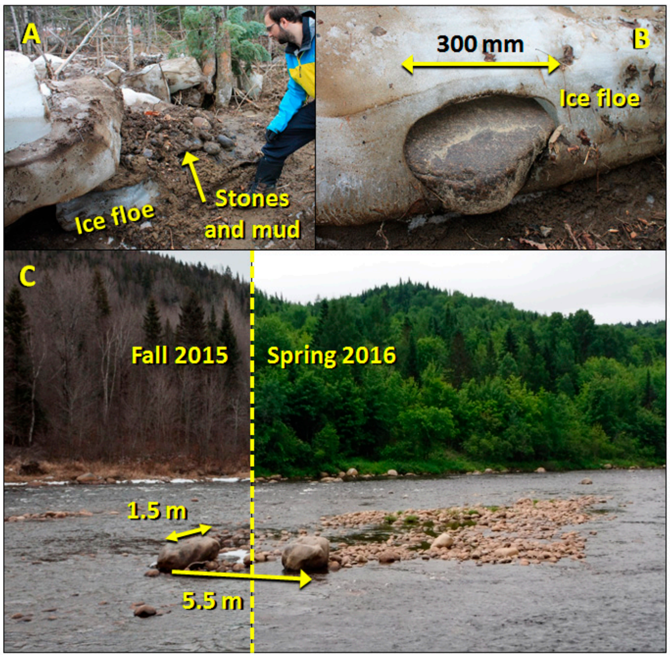


**Figure 12.** (**A**) Stones and mud found on an ice floe deposited in the floodplain after the 2014 breakup in the Montmorency River; (**B**) 300-mm stone trapped in thermal ice deposited on the floodplain after the 2014 breakup in the Montmorency River; and (**C**) 1.5-m boulder pushed by an ice run (1 April 2016) in the Ste. Anne River (left and right photographs respectively taken before and after winter at a similar discharge).

In the E watershed where a significant ratio of sediment transport takes place in the form of suspended load, Figure 6 and the data interpretation revealed that sediment transport rates were higher in smaller channels and that dilution tended through the drainage system. This could either be due to a decreasing proportion of agricultural land use (i.e., sediment supply; Table 1) or to a reduced sediment transport capacity (Site E4 being located in a small reservoir and Stream E3 presenting the lowest gradient). A change in land use from forest to agricultural (or logging) can substantially modify sediment transport modes and intensities in river systems by increasing fine sediment supply. Knowing that fine sediment can transport contaminants and obstruct gravel bed habitats [17], further investigation should reveal how this can impact the fluvial environment.

From a temporal point of view, Figure 6 shows that low sediment transport rates (although higher than expected; Figure 8) occurred in the presence of stationary ice, whereas a significant amount of suspended sediment transited through Sites E2–E4 during the moderately mechanical breakup event combined with the spring freshet. This result is consistent with other studies, e.g., [41,43], but additional winters of research should investigate how varying hydro-climatic conditions can impact the distribution of the annual sediment transport budget. For instance, in August 2011, the extratropical storm Irene generated an open water flow of 660 $m^3/s$ at Site E4 (return period of 20–50 years), and a significant amount of suspended sediment was transported during the event (roughly 48% of the annual suspended load at Site E4 in three days), thus impacting the annual sediment transport budget distribution. Additional research should also investigate the net impact of a dynamic breakup on sediment transport and aquatic life. For instance, the newly formed gravel bar presented in Figure 7C was probably caused by significant water velocity variations under an ice jam.

### *5.7. Environmental Continuum Research Avenues*

The data presented in Figures 4 and 6 were measured or estimated continuously during a single winter. Additional winters of field investigation at the same sites, data monitoring in distinct aquatic environments, as well as indirect approaches should expose how climate change (warmer $T_{air}$, shorter winters, more frequent mid-winter breakup events and consequent frazil production intensification) and anthropic activities (e.g., hydroelectric production, hydraulic structures, urbanization, agricultural practice, logging, etc.) can impact the hydrological, thermal, cryologic and morphological regimes of river systems and, more comprehensively, the environmental continuum. Their respective effect on the multiple parameters and factors that determine water and aquatic habitats quality should be documented.

From what has been learned through this study, in a climate change perspective involving warmer winters, more frequent rain-on-snow events and additional freeze-thaw cycles, the following winter environmental impacts could be expected at the watershed scale:

- Higher Q with more frequent runoff events in all channel orders;
- Lower $I_c$ at all channel orders and a more fragile ice cover;
- Lower $T_w$ in steep headwater channels (reduced $I_c$ insulation) and warmer $T_w$ in larger channels (reduced winter intensity and duration);
- The use of more de-icing salt that would potentially lead to more frequent Sp.C winter spikes downstream of roads and bridges;
- Higher sediment transport rates and more frequent sediment transport pulses in the drainage system that would eventually contribute in destabilizing cold region channels.

In turn, as an example of human impact, if the land use would change from forest (e.g., M watershed) to agriculture in a low gradient watershed (E watershed), the following winter environmental impacts could be anticipated:

- Higher runoff maximum Q at all channel orders (reduced response time in the absence of intercepting vegetation);

- Higher $T_W$ in small channels (windblown [13] snow insulation);
- Potentially higher Sp.C (annual and) levels at all channel orders for reasons that would need to be identified (as measured at site E2);
- Potentially lower DO levels prior and during the breakup period (as detected at site E2);
- An increased sediment supply (absence of stabilizing vegetation) and transport capacity (consequent of higher Q) involving a change in channel bed characteristics and contaminant transport rates.

## 6. Conclusions

In cold and temperate regions river systems, winter may have been overlooked as a period during which aquatic life can be directly or indirectly impacted by cold air temperatures and by the consequent various forms of freshwater ice cover types and processes. This paper has presented a global portrait of environmental conditions in channels of different sizes in two distinct watersheds during the winter of 2011–2012 and made links from upstream to downstream conditions, as well as between various water quality parameters (discharge, ice coverage, water temperature, water conductivity, dissolved oxygen and turbidity) forming the watershed environmental continuum. The paper has also referred to key events, including some obtained during subsequent winters and in other rivers. The potential environmental impact of a number of hydrothermal events, ice processes and human activities on aquatic habitats has been highlighted and discussed.

Overall, this research has demonstrated that a multi-parameter, watershed scale, continuous environmental investigation campaign can provide information that facilitates the interpretation of specific water quality parameter variations and extremes. It furthermore proves that upstream to downstream, temporal and biophysical or biochemical interactions occur in watersheds during the winter period, that these interactions can directly or indirectly affect aquatic life and that streams and rivers are not as sleepy as they seem under their white cover. Finally, this paper suggests that including (representative) tributaries in freshwater aquatic investigation projects is necessary to obtain a comprehensive understanding of the aquatic habitat and species behavior.

Further data investigation, including the use of statistical tools, could reveal additional relationships among the various hourly datasets that were collected in this study (and subsequent studies). Although monitoring the aquatic environment in the presence of ice is challenging, today's technology enables the deployment of automated sensors that can monitor an increasing amount of parameters with suitable accuracy. However, preserving the instruments' integrity and reducing the occurrence of unexpected results or sensor readings will probably always imply the knowledge of river processes, as well as strategically planned presence in the field.

**Acknowledgments:** The authors would like to thank Shahrzad Bazri for the work done in the field in 2013 and for the analysis of environmental data. Thomas Simard-Robitaille provided field support in the Etchemin Watershed in 2011–2012, and Mathieu Dubé, as well as Félix Pigeon provided support in the Montmorency Watershed between 2011 and 2015. The reviewers and editor have provided comments that contributed to improving the content and structure of the paper. This research was made possible by the financial support of the Canada Foundation for Innovation (CFI) shared by François Anctil (Université Laval) and the Natural Sciences and Engineering Research Council of Canada (NSERC).

**Author Contributions:** The initial idea of this research was proposed by Brian Morse. Benoit Turcotte and Brian Morse did the research project planning; Benoit Turcotte completed the field work and analyzed the data; Benoit Turcotte proposed the structure of the paper and wrote each section with Brian Morse.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Prowse, T.D. River-ice ecology. I. Hydrologic, geomorphic, and water-quality aspects. *J. Cold Reg. Eng.* **2001**, *15*, 1–16. [CrossRef]
2. Prowse, T.D. River-ice ecology. I. Biological aspects. *J. Cold Reg. Eng.* **2001**, *15*, 17–33. [CrossRef]

3. Prowse, T.D.; Culp, J.M. Ice Breakup: A Neglected Factor in River Ecology. In *River Ice Breakup*; Beltaos, S., Ed.; Water Resources Publications: Highland Ranch, CO, USA, 2008; pp. 349–376.
4. Strahler, A.N. Quantitative Analysis of Watershed Geomorphology. *Trans. Am. Geophys. Union* **1957**, *8*, 913–920. [CrossRef]
5. Turcotte, B.; Morse, B.; Anctil, F. Cryologic continuum of a steep watershed. *Hydrol. Process.* **2012**. [CrossRef]
6. Turcotte, B.; Morse, B.; Anctil, F. The hydro-cryologic continuum of a steep watershed at freezeup. *J. Hydrol.* **2014**, *508*, 397–409. [CrossRef]
7. Beltaos, S. Freezeup Jamming and Formation of Ice Cover. In *River Ice Formation*; Beltaos, S., Ed.; Committee on River Ice Processes and the Environment, Canadian Geophysical Union, Hydrology Section: Edmonton, AB, Canada, 2013; pp. 181–256.
8. Prowse, T.D.; Carter, T. Significance of ice-induced storage to spring runoff: A case study of the Mackenzie River. *Hydrol. Process.* **2002**, *16*, 779–788. [CrossRef]
9. Cunjak, R.A.; Prowse, T.D.; Parrish, D.L. Atlantic salmon in winter; the season of parr discontent. *Can. J. Fish. Aquat. Sci.* **1998**, *55*, 161–180. [CrossRef]
10. Jasek, M.; Beltaos, M. Ice-Jam Release: Javes, Ice Runs and Breaking Fronts. In *River Ice Breakup*; Beltaos, S., Ed.; Water Resources Publications: Highland Ranch, CO, USA, 2008; pp. 247–304.
11. Hicks, F.E. *An Introduction to River Ice Engineering for Civil Engineers and Geoscientists*; CreateSpace Independent Publishing Platform: Charleston, SC, USA, 2016; p. 159.
12. Malenchak, J.; Clark, S. Anchor Ice. In *River Ice Formation*; Beltaos, S., Ed.; Committee on River Ice Processes and the Environment, Canadian Geophysical Union, Hydrology Section: Edmonton, AB, Canada, 2013; pp. 135–158.
13. Turcotte, B.; Morse, B.; Dubé, M.; Anctil, F. Quantifying steep channels freezeup processes. *Cold Reg. Sci. Technol.* **2013**, *94*, 21–36. [CrossRef]
14. Ashton, G.D. Thermal processes. In *River Ice Formation*; Beltaos, S., Ed.; Committee on River Ice Processes and the Environment, Canadian Geophysical Union, Hydrology Section: Edmonton, AB, Canada, 2013; pp. 19–76.
15. Daly, S.F. Aufeis. In *River Ice Formation*; Beltaos, S., Ed.; Committee on River Ice Processes and the Environment, Canadian Geophysical Union, Hydrology Section: Edmonton, AB, Canada, 2013; pp. 159–180.
16. Power, G.; Brown, R.S.; Imhof, J.G. Groundwater and fish—Insights from northern North America. *Hydrol. Process.* **1999**, *13*, 401–422. [CrossRef]
17. Bergeron, N.E.; Enders, E.C. Fish Response to Freezeup. In *River Ice Formation*; Beltaos, S., Ed.; Committee on River Ice Processes and the Environment, Canadian Geophysical Union, Hydrology Section: Edmonton, AB, Canada, 2013; pp. 411–432.
18. Turcotte, B.; Morse, B. A global river ice classification model. *J. Hydrol.* **2013**, *507*, 134–148. [CrossRef]
19. Nafziger, H.; Hicks, F.; Thoms, P.; McFarlane, V.; Banack, J.; Cunjak, R.A. Measuring supercooling prevalence on small regulated and unregulated streams in New-Brunswick and Newfoundland, Canada. In Proceedings of the 17th CGU HSE CRIPE Workshop on River Ice, Edmonton, AB, Canada, 21–24 July 2013.
20. Daly, S.F.; Ettema, R. Frazil Ice Blockage of Water Intakes in the Great Lakes. *J. Hydraul. Eng.* **2006**, *132*, 814–824. [CrossRef]
21. Marsh, P.; Prowse, T.D. Water Temperature and Heast Flux at the Base of River Ice Covers. *Cold Reg. Sci. Technol.* **1987**, *14*, 33–50. [CrossRef]
22. Parkinson, F.E. Water temperature observations during break-up on the Liard–Mackenzie River system. In Proceedings of the 2nd Workshop on Hydraulics of Ice-Covered Rivers, Edmonton, AB, Canada, 1982.
23. Stewart, M.; Cimino, J.; Ross, M. Calibration of Base Flow Separation Methods with Streamflow Conductivity. *Ground Water* **2007**, *45*, 17–27. [CrossRef] [PubMed]
24. Hamilton, A.S.; Moore, R.D. Winter streamflow variability in two groundwater-fed sub-Arctic rivers, Yukon Territory, Canada. *Can. J. Civ. Eng.* **1996**, *23*, 1249–1259. [CrossRef]
25. Guesdon, G.; Santiago-Martin, A.; Raymond, S.; Messaoud, H.; Michaux, A.; Roy, S.; Galvez, R. Impact of Salinity on Saint-Augustin Lake, Canada: Remediation Measures at Watershed Scale. *Water* **2016**, *8*, 285. [CrossRef]
26. Schreier, H.; Erlebach, W.; Albright, L. Variations in water quality during winter in two Yukon rivers with emphasis on dissolved oxygen concentration. *Water Res.* **1980**, *14*, 1345–1351. [CrossRef]

27. Whitfield, P.H.; McNaughton, B. Dissolved-Oxygen Depressions under Ice Cover in Two Yukon Rivers. *Water Resour. Res.* **1986**, *22*, 1675–1679. [CrossRef]
28. Chambers, P.A.; Brown, S.; Culp, J.M.; Lowell, R.B.; Pietroniro, A. Dissolved oxygen decline in ice-covered rivers of northern Alberta and its effects on aquatic biota. *J. Aquat. Ecosyst. Stress Recovery* **2000**, *8*, 27–38. [CrossRef]
29. Hou, R.; Li, H. Modelling of BOD-DO dynamics in an ice-covered river in northern China. *Water Res.* **1987**, *21*, 247–251.
30. McBean, E.; Farquhar, G.; Kouwen, N. Predictions of ice-covered development in streams and its effect on dissolved oxygen modelling. *Can. J. Civ. Eng.* **1979**, *6*, 197–207. [CrossRef]
31. Demers, S.; Buffin-Bélanger, T.; Roy, A.G. Macroturbulent coherent structures in an ice-covered river flow using a pulse-coherent acoustic Doppler profiler. *Earth Surf. Process. Landf.* **2012**. [CrossRef]
32. Clark, S.P.; Peters, M.; Dow, K.; Malenchak, J.; Danielson, D. Investigating the effects of ice and bed roughness on the flow characteristics beneath a simulated partial ice cover. In Proceedings of the 23rd IAHR International Symposium on Ice, Ann Arbor, MI, USA, 31 May–3 June 2016.
33. Tsai, W.-F.; Ettema, R. Ice cover influence on transverse bed slopes in a curved alluvial channel. *J. Hydraul. Res.* **1994**, *32*, 561–581. [CrossRef]
34. Allard, G.; Buffin-Bélanger, T.; Bergeron, N.E. Fluvial and ice dynamics at a frazil-pool. *River Res. Appl.* **2011**. [CrossRef]
35. Ettema, R.; Daly, S.F. Sediment transport under ice. In *Cold Regions Research and Engineering Laboratory Report TR-04-20*; U.S. Army Engineer Research and Development Center: Hanover, NH, USA, 2004.
36. Sui, J.Y.; Wang, D.S.; Karney, B.W. Suspended sediment concentration and deformation of riverbed in a frazil jammed reach. *Can. J. Civ. Eng.* **2000**, *27*, 1120–1129. [CrossRef]
37. Ettema, R.; Zabilansky, L. Ice influences on channel stability: Insights from Missouri's Fort Peck reach. *J. Hydraul. Eng.* **2004**, *130*, 279–292. [CrossRef]
38. Tywonik, N.; Fowler, J.L. Winter measurements of suspended sediments. In Proceedings of the Banff International Symposium on the Role of Snow and Ice on Hydrology, Banff, AB, Canada, 1972.
39. Best, H.; McNamara, J.P.; Liberty, L. Association of ice and river channel morphology determined using ground-penetrating radar in the Kuparuk River, Alaska. *Arct. Antarct. Alp. Res.* **2005**, *37*, 157–162. [CrossRef]
40. Ettema, R. Review of alluvial-channel responses to river ice. *J. Cold Reg. Eng.* **2002**, *16*, 191–217. [CrossRef]
41. Beltaos, S.; Burrell, B.C. Suspended sediment concentrations in the Saint John River during ice breakup. In Proceedings of the Conference of the Canadian Society for Civil Engineering, London, ON, Canada, 7–10 June 2000.
42. Prowse, T.D. Suspended Sediment Concentration during River Ice Breakup. *Can. J. Civ. Eng.* **1993**, *20*, 872–875. [CrossRef]
43. Milburn, D.; Prowse, T.D. The effect of river-ice break-up on suspended sediment and select trace-element fluxes. *Nordic Hydrol.* **1996**, *27*, 69–84.
44. Gatto, L.W. Soil freeze-thaw effects on bank erodibility and stability. In *US Army Cold Regions Research and Engineering Laboratory Special Report 95-24*; USACE: Hanover, NH, USA, 1995.
45. Beltaos, S. Significance of javes in transporting suspended sediment during river ice breakup. In Proceedings of the 18th CHU-HS CRIPE Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, QC, Canada, 18–20 August 2015.
46. Uunila, L.S. Effects of river ice on bank morphology and riparian vegetation along the Peace River, clayhurst to fort vermilion. In Proceedings of the 9th Workshop on River Ice, Fredericton, NB, Canada, 24–26 September 1997.
47. Hicks, F.E. Ice as the geomorphologic agent in an anastomosing river system. In Proceedings of the NHRI Workshop on Environmental Aspects of River Ice, National Hydrology Research Institute, Saskatoon, SK, Canada, 18-20 August 1993.
48. Beltaos, S.; Calkins, D.J.; Gatto, L.W.; Prowse, T.D.; Reedyk, S.; Scrimgeour, G.J.; Wilkins, S.P. Physical effect of river ice. In *Environmental Aspects of River Ice*; Prowse, T.D., Gridley, N.C., Eds.; Environmental Aspects of River Ice; National Hydrology Research Institute: Saskatoon, SK, Canada, 1993.
49. Kempema, E.W.; Reimnitz, E.; Clayton, J.R.; Payne, J.R. Interactions of Frazil and Anchor Ice with Sedimentary Particles in a Flume. *Cold Reg. Sci. Technol.* **1993**, *21*, 137–149. [CrossRef]

50. Kempema, E.W.; Ettema, R. Anchor ice rafting: Observations from the Laramie River. *River Res. Appl.* **2010**. [CrossRef]
51. Larsen, P.; Billfalk, L. Ice problems in Swedish hydro power operation. In Proceedings of the IAHR Symposium on Ice Problems, Delft, The Netherlands, 1978.
52. Martin, S. Frazil ice in rivers and oceans. *Annu. Rev. Fluid Mec.* **1981**, *13*, 379–397. [CrossRef]
53. Turcotte, B.; Morse, B.; Bergeron, N.E.; Roy, A.G. Sediment transport in ice-affected rivers. *J. Hydrol.* **2011**, *409*, 561–577. [CrossRef]
54. Turcotte, B.; Morse, B.; Anctil, F. Impacts of precipitation on the cryologic regime of stream channels. *Hydrol. Process.* **2012**, *26*, 2653–2662. [CrossRef]
55. Harper, P.P. Ecology of streams and high latitudes. In *Perspectives in Running Water Ecology*; Lock, M.A., Williams, D.D., Eds.; Plenum: New York, NY, USA, 1981; pp. 313–337.
56. Schallock, E.W.; Lotspeich, F.B. Low winter dissolved oxygen in some Alaskan rivers. In *Office of Ressources and Development*; U.S. Environmental Protection Agency: Corvallis, OR, USA, 1974.
57. Hicks, F.E.; Healy, D. Determining winter discharge based on modeling. *Can. J. Civ. Eng.* **2003**, *30*, 101–112. [CrossRef]
58. Morse, B.; Hamaï, K.; Choquette, Y. River discharge measurements using the velocity index method. In Proceedings of the 13th CRIPE Workshop on the Hydraulics of Ice Covered Rivers, Hanover, NH, USA, 15–16 September 2005.
59. Andrishak, R.; Hicks, F. Working safely on river ice. In Proceedings of the 18th CGU-HS CRIPE Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, QC, Canada, 18–20 August 2015.
60. Pigeon, F.; Leclerc, M.; Morse, B.; Turcotte, B. Breakup 2014 on the Montmorency River. In Proceedings of the 18th CGU-HS CRIPE Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, QC, Canada, 18–20 August 2015.
61. Ribeiro, K.H.; Favaretto, N.; Dieckow, J.; De Paula Souza, L.C.; Gomez Minella, J.P.; De Almeida, L.; Ribeiro Ramos, M. Quality of Surface Water Related to Land Use: A Case Study in a Catchment with Smal Farms and Intensive Vegetable Crop Production in Southern Brazil. *Rev. Bras. Cienc. Solo* **2014**, *38*, 656–668. [CrossRef]