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[Article]

Temporal and Spatial Quantification of Fine-Sediment Accumulation Downstream of Culverts in Brook Trout Habitat

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Abstract.—We quantified fine-sediment accumulation annually from 2000 to 2003 after culvert construction in five Laurentian Shield streams containing brook trout *Salvelinus fontinalis*. A significant spatial pattern (section effect) was observed in which the accumulation was lowest upstream of the culvert (section 1), peaked in the section directly below the culvert (section 2), and slightly decreased in sections further downstream (sections 3–5) without returning to upstream levels. The accumulation was always significantly higher downstream of the culvert than in section 1. The temporal pattern (period effect) was also significant; accumulation was lowest several weeks after construction, peaked at one full year after construction, and decreased at 2–3 years postconstruction. Fine-sediment accumulation differed significantly among all periods. The downstream distance at which sediment accumulation returned to upstream levels varied from 358 and 1,442 m below the culvert. Owing to the accumulated sediment, which probably originates primarily from construction sand or road erosion, habitat downstream of a culvert is in many cases of lower quality for brook trout incubation and rearing. Recommendations for minimizing culvert impacts on fish habitat are discussed.

On Québec public lands, some 10,000 culverts are built annually in the course of road development for logging or recreational purposes (FAPAQ 2002). Culvert construction can increase suspended matter in the water column and lead to subsequent sedimentation (Clarke and Scruton 1997; St-Onge et al. 2001), which is detrimental to spawning sites of fish species such as brook trout *Salvelinus fontinalis* (Young et al. 1991; Castro and Reckendorf 1995; Argent and Flebbe 1999). Low abundance of accessible, good-quality spawning sites can limit the recruitment of this species (Hunt 1988; Schofield and Keleher 1996). Although upwellings are among the most important characteristics in brook trout choice of spawning sites (Fraser 1985; Curry and Noakes 1995), substrate type is also a criterion. Brook trout prefer a gravel-type substrate (diameter $>$ 9 mm) with less than 20% sand (diameter = 1–2 mm; Witzel and MacCrimmon 1983).

The relationship between fine-sediment accumulation in salmonid spawning gravels and incubation or emergence success has been well documented. It is now clear that accumulation of fine sediment can severely limit reproductive success of salmonids (Cederholm and Reid 1987; Scrivener and Brownlee 1989; Argent and Flebbe 1999). A high percentage of fine sediment limits emergence of fry, either by suffocation or through the creation of a compact surface layer that can only be traversed with great difficulty (Morantz et al. 1987; Scruton and Gibson 1993; Waters 1995).

Though small streams play an important role in salmonid reproduction, this should not be the only criterion for protecting permanent or intermittent streams from the impacts of crossings, roads, and timber harvesting. Small watercourses also play a key role in downstream ecosystems. Sediment accumulation is known to have an adverse impact on the abundance and diversity of benthic organisms in streams, thus affecting an important food resource that is necessary for the growth and production of fish (Scrimgeour et al. 2000; Gayraud et al. 2002, Liljaniemi et al. 2002; Williams et al. 2002) and other

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vertebrates, such as salamanders (Lowe et al. 2004). For example, one study reported that the majority of aquatic invertebrates exported from 52 small, forested headwater streams represented a sufficient energy input to support 2,000 age-0 juvenile salmonids per kilometer of fish-bearing downstream habitat (Wipfli and Gregovich 2002). Cummins and Wilzbach (2005) reviewed the importance of very small streams and pointed out the benefits of watershed-level management. Given that invertebrates fed by detrital material from first-order and intermittent streams can constitute a significant food source for juvenile salmonids, establishment of protection zones along these streams and use of measures to minimize sedimentation should be components of watershed management plans focused on downstream fish.

Roads and culverts can be significant sources of fine sediment in streams (Clarke and Scruton 1997; Clarke et al. 1998; Wellman et al. 2000; Lachance and Dubé 2004). However, despite the attention given to this subject in the literature, questions about the effects of roads and culverts remain. How much sediment do roads and culverts bring into riverine systems? Is the quantity enough to be detrimental? Is there a continuous input through road upkeep, or is sedimentation only an issue during the construction phase? How far downstream does a significant impact extend? This paper addresses these issues based on the results of a study launched in 2000 by the Québec Ministry of Natural Resources and Wildlife (Ministère des Ressources Naturelles et de la Faune du Québec [MRNF]). The MRNF implements provisions for minimizing the impact of road construction and logging operations on forest resources and aquatic environments. These provisions are included in Québec regulations that address standards of forest management for forests in the public domain (RSFM; Québec Government 1996). Several of these regulatory provisions are directly concerned with specific aspects of culvert construction, including minimum culvert diameter, stabilization of streambanks, and proper slopes and embedding to ensure fish passage. One provision prohibits the positioning of culverts within 50 m upstream of a spawning area identified in Québec's Annual Forest Management Plans (AFMPs). The present study was initiated to validate the effectiveness of this 50-m protective distance.

Our general objective was to quantify sediment accumulation that was directly related to RSFM-prescribed culvert construction and that occurred on brook trout spawning beds over a period of several years. More specifically, we wanted to (1) measure surface sediment accumulation, (2) determine sediment accumulation at spawning depth, and (3) validate the 50-m rule.

Methods

Study sites.—Five streams were selected for the study: Roza, Bernier, and Saunier streams in the Laurentides Wildlife Reserve; Aux Canards Stream in the Buteux-Bas-Saguenay Controlled Exploitation Zone (Zone d'Exploitation Contrôllée [ZEC]); and Aubé Stream in the Bessonne ZEC (Figure 1). All streams are located on the Laurentian Shield, typified in these areas by forests that primarily contain balsam fir *Abies balsamea* and paper birch *Betula papyrifera*. General characteristics of the study sections within each stream were typical of potential brook trout spawning grounds. Superficial substrate was a mixture of gravel, cobble, and some coarse sand. Study sections varied in slope from 0.5% to 4.0% and in width from 2 to 10 m (Table 1). Major habitat quality criteria for brook trout are upheld year-round in these streams; water flow is permanent, temperatures generally remain under 18°C, and oxygen content is high even at the peak of summer.

Culverts were built in the summer of 2000 except at Aubé Stream, where the culvert was built in 2001. Structures were constructed in accordance with most RSFM provisions. Provisions to protect the aquatic environment were attained in 11 out of 13 cases. Experimental areas for each stream, inclusive of all study sections, were selected because potential brook trout spawning habitat was present at least 10 m upstream and at least 100 m downstream of the culvert installation point. For each stream, we chose study sections with similar flow and substrate conditions, as validated by velocity measurements and visual estimation. In addition, we made sure that the experimental area located between the upstream section and the downstream-most section could not be influenced by any tributary. Section 1, located at least 10 m upstream of the proposed culvert, was regarded as a control, whereas the other sections were located approximately 20 m (section 2), 50 m (section 3), 100 m (section 4), and, if possible, 200 m (section 5) downstream of culvert construction site. In Roza Stream, section 2 was not studied because of the bedrock substrate and fast flow observed there. Preliminary results in Saunier Stream in 2000 indicated that a fifth section could be studied at around 200 m from the culvert without a large increase in field work time. Section 5 was hence added to the Bernier and Roza streams in 2001 to measure impacts further downstream when possible. Precise distance from each section to the culvert was measured after construction.

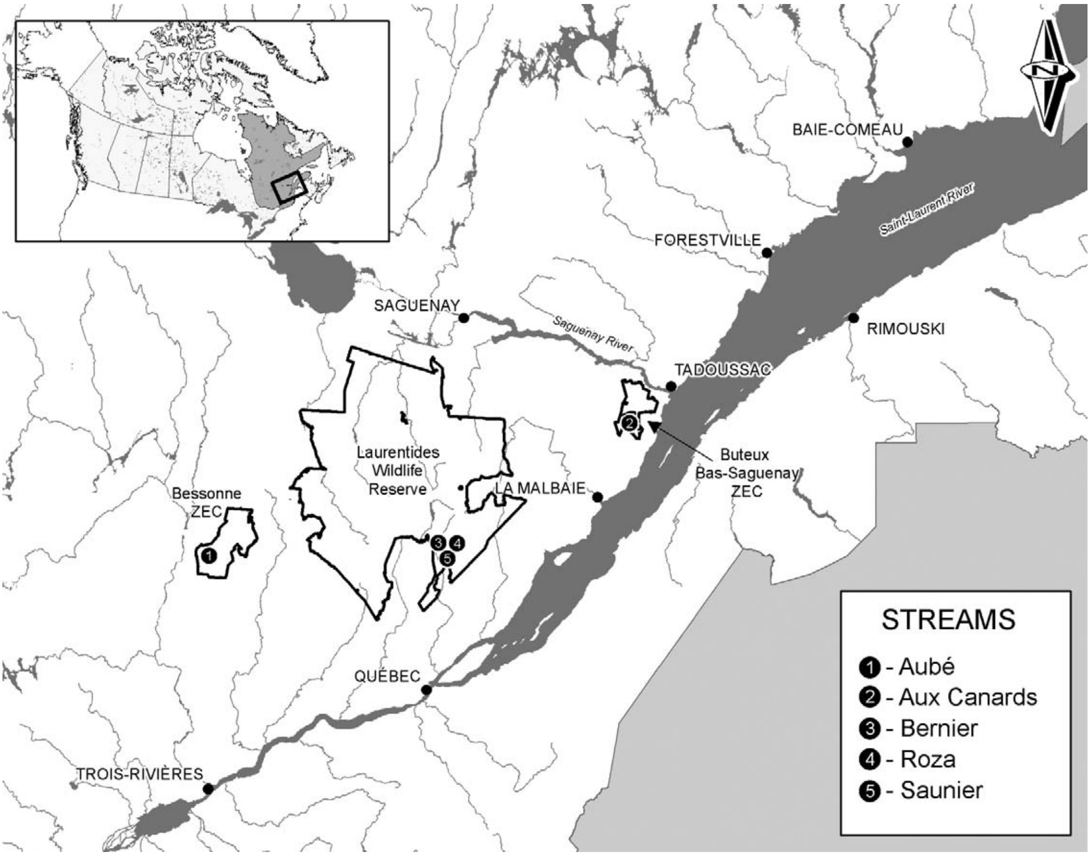

FIGURE 1.—Locations of five Laurentian Shield (Québec) study streams selected for measurement of sediment accumulation after culvert construction, 2000–2003.

Sediment accumulation on surface substrate.—Sediment accumulation at the surface of the riverbed was measured using the particle count method (Wolman 1954). This method estimates the size distribution of surface particles. One-hundred particles in each study section were measured using a template or gravelometer (Bunte and Abt 2001). Across the section, particles were taken at a distance of 25 cm on each side of 10 equally interspersed points along five transects. Particle measurements were made prior to construction and in September at intervals of several weeks, 1, 2, and 3 years postconstruction.

Data describing sediment accumulation on the surface of the substrate were analyzed using multivar-

TABLE 1.—General characteristics of study sections in five Laurentian Shield (Québec) streams where sediment accumulation after culvert construction was measured from 2000 to 2003.

Study section characteristic	Aubé Stream	Aux Canards Stream	Bernier Stream	Roza Stream	Saunier Stream
Width (m)	2–4	6–8	5–10	3–4	4–7
Length (m)	3–6	3–6	5	4–5	3–5
Water depth (cm)	10–25	15–36	7–21	18–43	18–39
Distance from culvert (m)					
Upstream (section 1)	32	33	25	106	37
Downstream (sections 2–5)	28, 58, 100, –	16, 36, 75, –	21, 45, 90, 200	–, 65, 111, 200	33, 43, 109, 171
Slope (%)	1.0–2.0	2.0–2.5	0.5–1.0	0.5–2.0	1.5–4.0
Water velocity (cm/s)	6–23	1–44	1–55	9–67	NA[a]
Culvert position (latitude/longitude)	47°20′30″N, 72°35′30″W	48°00′39″N, 69°57′72″W	47°23′13″N, 71°06′85″W	47°25′98″N, 71°03′85″W	47°22′01″N, 71°04′95″W

[a] Value not available.

iate, repeated-measures analysis of variance (ANOVA) in a randomized block design. The multivariate response variables corresponded to the percentage of sediment accumulation in five size-classes (0.0–2.0, >2.0–2.5, >2.5–4.0, >4.0–5.0, and >5.0 mm). The five streams were considered blocks in the analysis and were the replicates of study sections 1–5 (approximately 10 m upstream and 20, 50, 100, and 200 m downstream). The control section was compared with the downstream sections via contrast analysis. Wilk's lambda statistic was used to test the overall effect of the different sources of variation. If a significant effect was detected, univariate analyses were performed and Fisher's least-significant-difference test was used to compare the levels of any significant factor. All analyses were performed using the Statistical Analysis System (SAS Institute 2003). Normality and variance homogeneity hypotheses were tested, and data were transformed as necessary.

Sediment accumulation at spawning depth.—The detailed methodology used for this part of the study is described by Lachance and Dubé (2004). Eight SÉDIBAC 45 collectors per section were installed prior to culvert construction (between June and August 2000 or 2001). The collectors were filled with clean gravel (particle diameter = 1.5–3.0 cm). The top of the collector, which remained uncovered to permit infiltration of fines, was set slightly below the natural surface of the streambed to reconstitute the natural arrangement of stream pavement.

The collectors were retrieved and replaced in September 2000, 2001, and 2002, and the final retrieval took place in 2003. The sampling period thus spanned several weeks, 1, 2, and 3 years postconstruction for all streams except Aubé Stream, which was not sampled in the third year because it was constructed in 2001 instead of 2000. Samples were dried (60°C for 2–7 d until total water evaporation) and then put through a set of standard nested sieves (5.000, 2.000, 0.850, 0.500, 0.250, and 0.075 mm). Each fraction was then recovered and weighed. The mesh sizes of the sieves were selected to account for the fine-particle sizes known to hinder salmonid egg survival or fry emergence (Wesche et al. 1989; Avery 1996; Knapp and Vredenburg 1996; Kondolf 2000). Three classes of fine particles ($\leq$5.00, $\leq$2.00, and $\leq$0.85 mm) were subsequently analyzed.

Total fine sediments ($\leq$5 mm) from all eight collectors per section were combined, and three subsamples from this composite sample were chosen to estimate the organic matter ratio (g/kg) using a combustion method (Carter 1993). Percent weight of organic matter was used as a natural marker of the origin of the fine sediment that accumulated downstream (Kreutzweiser and Capell 2001). Due to the origin of sand used for road and culvert construction, we hypothesized that accumulated sediment derived from human activities would be less organic in nature than the sediment that naturally occurred in the stream.

Sediment accumulation at spawning depth and organic matter content data were analyzed with univariate, repeated-measures ANOVA in a randomized block design for which stream was the blocking factor. Accumulation in collectors on each section of each stream was measured at several weeks or 1–3 years after culvert construction; measurements were pooled for data analysis because the collectors were pseudoreplicates. Upon detection of a significant effect, univariate analyses were performed and Fisher's least-significant-difference test was used to compare the levels of a significant factor.

Since we wanted to validate the 50-m protection rule, it was necessary to determine the distance at which fine-sediment accumulation downstream of the culvert returned to upstream levels. A multiple-regression model between accumulated fine sediment at spawning depth and distance from the culvert (sections 2–5) was originally developed with data from all streams and periods. However, this model was nonsignificant due to high variation among streams and periods. The most important problem was that for some streams or periods, sediment accumulation continued to rise with distance from the culvert instead of decreasing. To evaluate the pertinence of the 50-m rule, simple linear regression was applied to a few streams and periods individually. Though they are not as strong as a general model describing all data, these individual estimations of distance at which upstream sediment conditions resumed provide an interesting basis for discussion.

The use of upstream controls on every stream was intended to account for sediment accumulation that was solely attributable to extreme hydrological circumstances; however, we wanted to examine whether hydrology was exacerbating or undermining the dynamics measured during our study. Hydrological data from each month of the study were obtained from permanent monitoring stations in the Montmorency River (Bernier, Roza, and Saunier streams), Malbaie River (close to Aux Canards Stream), and Vermillon River (close to Aubé Stream). Monthly averages for 2000–2003 were compared with the monthly averages for 1980–1999 (Figure 2). By qualitative appreciation of Figure 2, it appears that flow regimes were generally lower than average; however, higher-than-usual spates were detected in December 2001, April 2002, and August 2003. Overall, we estimate that the pattern and quantity of sediment accumulation measured in this

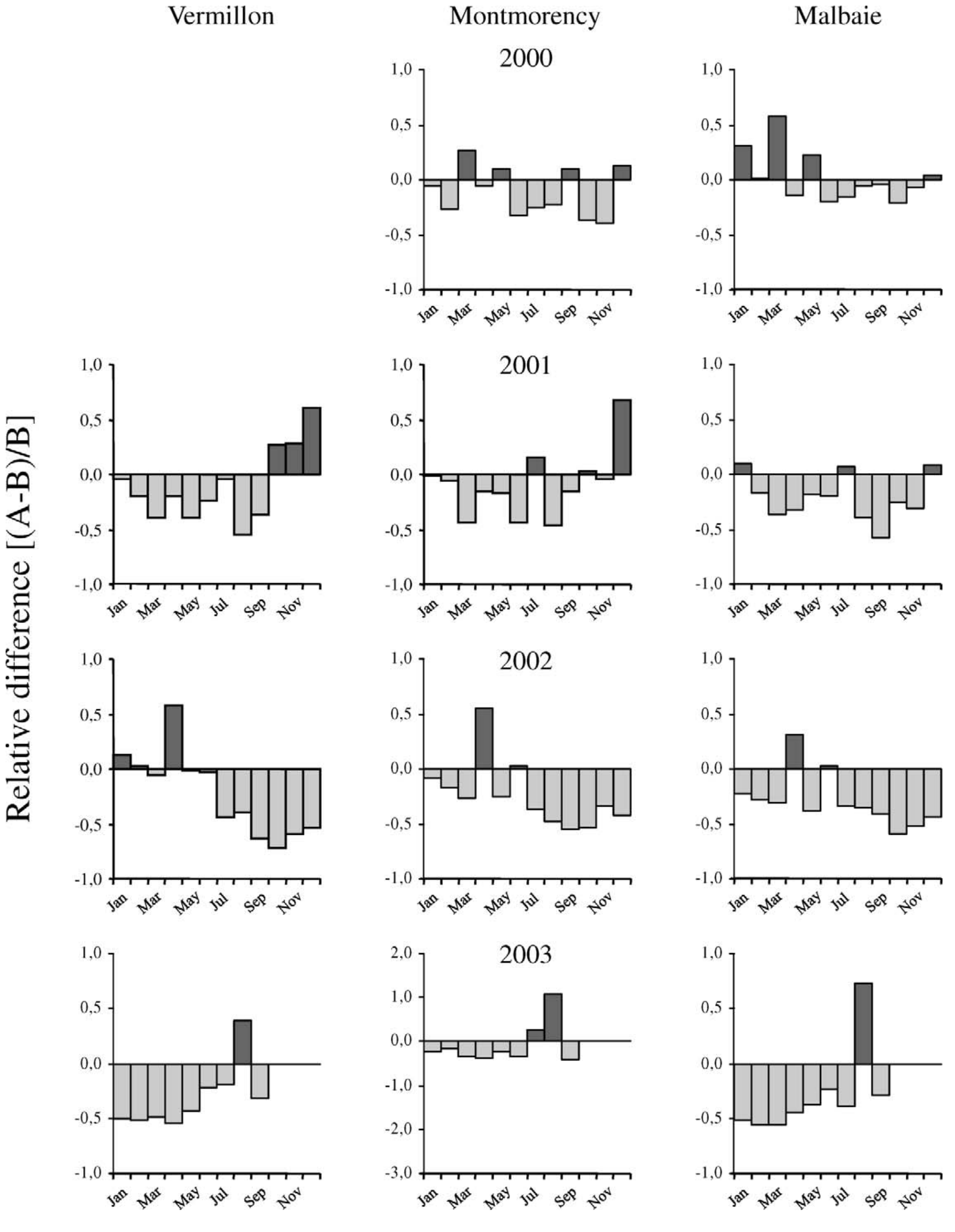

FIGURE 2.—Relative difference between average monthly flow rates in the Montmorency, Malbaie, and Vermillon rivers, Québec, during the study period (*A*; August 2000–September 2003) and from 1980 to 1999 (*B*).

TABLE 2.—Results of multivariate analysis of variance examining the particle size distribution of surface sediment measured by the pebble count method before culvert construction and at several weeks or 1–3 years after construction (period effect) in four to five study sections (section 1 was upstream of the culvert; sections 2–5 were downstream) within five Laurentian Shield (Québec) streams (Table 1), 2000–2003. Overall results and the results for individual particle size-classes (mm) are presented.

		Overall results		0.0–2.0 mm		>2.0–2.5 mm		>2.5–4.0 mm		>4.0–5.0 mm		>5.0 mm	
Source of variation	df	F (df[a])	P	F	P	F	P	F	P	F	P	F	P
Stream	4	2.37 (16, 31.2)	0.0193	5.12	0.0106	1.06	0.4135	0.12	0.9744	0.93	0.4743	2.86	0.0668
Section	4	0.62 (16, 31.2)	0.8451	0.29	0.8812	0.35	0.8374	2.34	0.1094	0.96	0.4607	0.46	0.7665
Stream × section (main-plot error)	13												
Period	4	2.91 (16, 174.8)	0.0003	3.68	0.0096	1.82	0.1364	4.36	0.0037	1.78	0.1455	4.68	0.0024
Section × period	16	0.70 (16, 225.4)	0.9522	0.39	0.9800	0.40	0.9762	0.91	0.5669	0.90	0.5776	0.75	0.737
Subplot error	60												
Corrected total	101												

[a] Degrees of freedom determined by the Satterthwaite method.

study were realistic for the conditions and were not due to extreme hydrological situations.

Results and Discussion

Sediment Accumulation on Surface Substrate

Visible changes in surface substrate were noted at all postconstruction periods upstream and downstream of the culverts. Signs of deposition and erosion attributable to human activity and to the normal dynamics of a stream environment were observed. For example, some collectors were covered by up to 25 cm of sediment composed of a mixture of sand, gravel, and pebbles, whereas other collectors were 50% visible and half of the depth of substrate around them had been washed away.

Analysis of the size-class structure of surficial substrate, as estimated by particle count, revealed a significant overall period effect on particle size distribution (Table 2). The particle size distribution measured before culvert construction differed significantly from that observed at several weeks ($F = 3.11$; df = 4, 57; $P = 0.022$), 1 year ($F = 3.28$; df = 4, 57; $P = 0.0172$), or 2 years ($F = 3.69$; df = 4, 57; $P = 0.0096$) postconstruction but did not differ from the distribution observed at 3 years postconstruction ($F = 2.22$; df = 4, 57; $P = 0.0778$). Two particle size-classes were subject to this period effect. Of major interest to this study, particles smaller than 2 mm (i.e., sand or finer material) were significantly more abundant at several weeks and 1 year postconstruction than during the preconstruction period (Table 3; Figure 3). Moreover, particles greater than 5 mm (not considered fine material) were significantly less abundant at several weeks, 1 year, and 2 years postconstruction than during the period prior to construction (Figure 3).

For all streams in general, this shift in surface particle size distribution cannot be attributed simply to culvert construction, as in many cases the temporal increase was greater upstream of the culvert than downstream. However, surficial downstream accumulation of fine sand was obvious to the eye in Bernier Stream and Aux Canard Stream at several weeks and 1 year postconstruction. Up to 5 cm of compact fine sand could cover the normal riverbed. These were the only study streams for which a downstream increase in surficial sediment could be attributed to culvert construction sand. It is difficult to determine whether this short-term surficial sand accumulation affected brook trout emergence. Crisp (1993) mentioned that coho salmon *Oncorhynchus kisutch* and rainbow trout *O. mykiss* in redds were able to emerge through a layer of coarse sand (diameter = 1 to >4 mm) up to 8 cm thick. Brook trout are smaller, especially in these northern streams, and thus it is possible that a sand layer of this thickness could impede emergence.

The fact that construction sand disappears from sight after a few strong spates leads the untrained observer to believe that fine material from culvert construction disappears quickly from the system. This, in turn, gives rise to the idea that the effect, if any, is relatively short lived. Examination of data taken at spawning depth allowed us to evaluate whether fine sediments stayed in the system and the duration for which they were retained.

Sediment Accumulation at Spawning Depth

Overall, only 4 out of 636 collectors were lost over the course of the study. Some were lost to high spates, whereas others were buried too deeply to find. High performance of the sediment collectors and the positioning techniques described by Lachance and Dubé (2004) were maintained throughout the study, confirming the consistency of the method. For all three analyzed particle size-classes (≤5.00, ≤2.00, and ≤0.85 mm), results led to the same conclusions. To simplify the presentation, only results for fine sediments of 5 mm or less are presented.

TABLE 3.—Percentage of fine particles smaller than 2 mm in surface sediment measured by the pebble count method before culvert construction and at several weeks or 1–3 years after construction in five Laurentian Shield (Québec) streams (4–5 study sections/stream), 2000–2003.

Stream	Section[a]	Preconstruction	Postconstruction			
			Several weeks	1 year	2 years	3 years
Aubé Stream	1	15	34	19	36	ND[b]
	2	7	14	31	33	ND
	3	10	29	22	43	ND
	4	5	26	16	21	ND
Aux Canards Stream	1	0	0	3	0	1
	2	0	32	5	1	0
	3	1	24	10	0	2
	4	3	40	11	9	4
Bernier Stream	1	0	0	1	8	7
	2	10	53	3	3	6
	3	2	26	2	12	4
	4	4	6	3	14	11
	5	ND	ND	0	3	2
Roza Stream	1	0	1	1	2	4
	3	1	4	4	1	9
	4	2	5	3	8	10
	5	ND	ND	11	6	1
Saunier Stream	1	6	12	14	20	8
	2	2	1	18	21	7
	3	1	2	18	21	3
	4	0	1	6	5	1
	5	0	2	18	20	17

[a] Section 1 was approximately 10 m upstream and served was the control; sections 2–5 were approximately 20, 50, 100, and 200 m downstream of the culvert.

[b] Not determined; Aubé Branch study began in summer 2001. Section 5 was only added to Bernier and Roza Streams in the second autumn after construction.

From data measured in the collectors, overall significant section and period effects on postconstruction fine-sediment accumulation were found (Table 4). For the spatial pattern (section effect), the lowest accumulation was observed in the control section upstream of the culvert, the peak in accumulation occurred in section 2 directly below the culvert, and a slight decrease was detected for sections 3–5 but

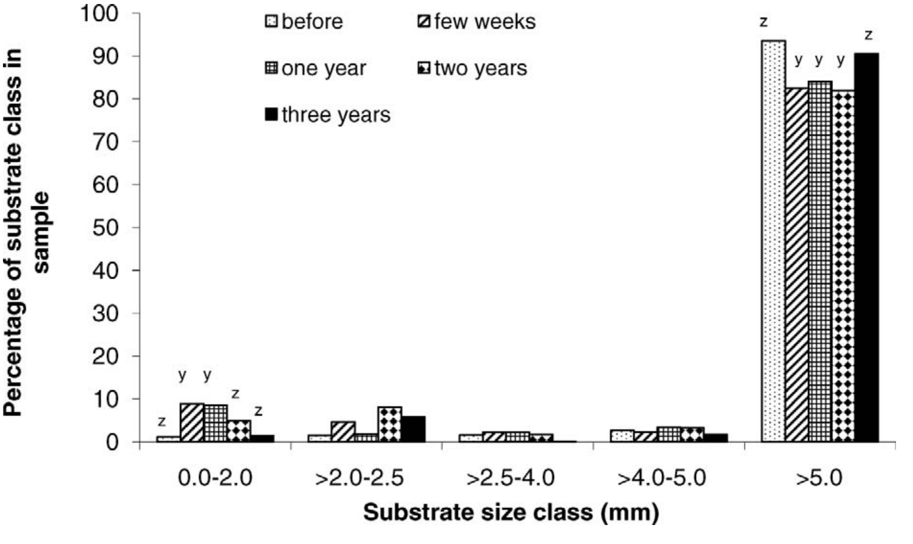

FIGURE 3.—Percentages of various particle size-classes in surface sediment measured by the pebble count method before culvert construction, at several weeks postconstruction, and at 1–3 years postconstruction on five Laurentian Shield (Québec) streams. For a given particle size-class, percentages identified by the same letter are not significantly different (Fisher's least-significant-difference test: $P > 0.05$).

TABLE 4.—Results of analysis of variance examining sediment accumulation at brook trout spawning depth (percentage of sediment weight consisting of 5-mm or smaller particles) and the organic matter content (g/kg) of sediment measured at several weeks or 1–3 years after culvert construction (period effect) in five Laurentian Shield (Québec) streams (4–5 study sections/stream; section 1 was upstream of the culvert, and sections 2–5 were downstream), 2000–2003.

		Sediment accumulation at spawning depth		Organic matter content	
Source of variation	df	F	P	F	P
Stream	4	5.50	0.0082	9.59	0.0008
Section	4	5.70	0.0071	4.80	0.0135
Stream × section (main-plot error)	13				
Period	3	40.50	<0.0001	12.00	<0.0001
Section × period	12	0.62	0.8125	0.60	0.8358
Subplot error	43				
Corrected total	79				

TABLE 6.—Results of a posteriori Fisher's least-significant-difference tests examining section and period effects on the percentage of accumulated fine-sediment weight consisting of 5-mm or smaller particles in SÉDIBAC 45 collectors placed at brook trout spawning depth within areas of culvert construction in five Laurentian Shield (Québec) streams, 2000–2003. Four to five study sections were present in each stream; section 1 was upstream of the culvert, and sections 2–5 were downstream. Study periods were several weeks and 1–3 years after culvert construction.

Effect	Comparison	df	t	P
Section	1 *v.* 2	13	−4.40	0.0007
	1 *v.* 3	13	−3.46	0.0042
	1 *v.* 4	13	−3.12	0.0081
	1 *v.* 5	13	−2.49	0.0271
	2 *v.* 3	13	1.18	0.2575
	2 *v.* 4	13	1.50	0.1574
	2 *v.* 5	13	0.85	0.4093
	3 *v.* 4	13	0.34	0.7388
	3 *v.* 5	13	−0.02	0.9834
	4 *v.* 5	13	−0.26	0.7959
Period	Several weeks *v.* 1 year	11	−10.49	<0.001
	Several weeks *v.* 2 years	11	−6.98	<0.001
	Several weeks *v.* 3 years	11	−3.30	0.0071
	1 year *v.* 2 years	11	2.32	0.0402
	1 year *v.* 3 years	11	5.22	0.0003
	2 years *v.* 3 years	11	4.26	0.0013

without a return to the upstream accumulation level (Tables 4, 5). Accumulation was always significantly higher downstream of the culverts than in upstream sections. However, no significant difference was observed between individual downstream sections (Table 6). The temporal pattern (period effect) was characterized by lowest accumulation several weeks after construction, a peak at 1 year postconstruction, and a decrease at 2 and 3 years postconstruction (Table 5). The accumulation differed significantly among all periods (Table 6).

The significantly higher accumulation of sediments downstream of the culverts is consistent with results obtained by Clarke and Scruton (1997), Clarke et al.

TABLE 5.—Mean (±SD) percentage of accumulated fine-sediment weight consisting of 5-mm or smaller particles in SÉDIBAC 45 collectors (Bio Innove 2005; 8 collectors/section; 4–5 study sections/stream), as measured at several weeks or 1–3 years after culvert construction in five Laurentian Shield (Québec) streams, 2000–2003.

Stream	Section[a]	Several weeks	1 year	2 years	3 years
Aubé Stream	1	1.27 ± 0.42	8.53 ± 1.35	4.11 ± 1.04	ND[b]
	2	2.63 ± 2.01	13.19 ± 5.41	11.29 ± 7.72	ND
	3	2.9 ± 3.12	13.5 ± 8.12	6.51 ± 2.21	ND
	4	7.02 ± 5.49	13.23 ± 3.36	10.62 ± 3.04	ND
Aux Canards Stream	1	0.30 ± 0.08	8.44 ± 5.33	6.57 ± 2.95	10.05 ± 3.54
	2	14.76 ± 4.00	29.94 ± 6.26	18.44 ± 4.53	21.2 ± 4.99
	3	6.98 ± 3.80	24.72 ± 4.38	16.25 ± 3.12	16.42 ± 2.02
	4	2.59 ± 1.54	17.09 ± 2.99	10.5 ± 1.65	13.74 ± 3.65
Bernier Stream	1	0.89 ± 0.14	4.48 ± 1.44	5.58 ± 1.54	2.11 ± 0.81
	2	17.90 ± 5.36	25.59 ± 3.62	13.05 ± 3.31	2.4 ± 0.51
	3	5.75 ± 1.42	14.04 ± 5.02	7.93 ± 1.64	2.58 ± 1.07
	4	3.48 ± 0.56	11.41 ± 2.35	10.85 ± 2.13	2.98 ± 1.58
	5	ND	ND	16.03 ± 3.66	7.11 ± 2.30
Roza Stream	1	0.35 ± 0.06	14.15 ± 2.91	11.79 ± 4.11	2.96 ± 1.36
	3	1.87 ± 0.76	15.37 ± 2.01	13.73 ± 3.17	9.42 ± 3.21
	4	1.08 ± 0.28	19.77 ± 7.39	11.61 ± 1.93	4.07 ± 0.86
	5	ND	ND	16.32 ± 2.35	13.86 ± 2.33
Saunier Stream	1	4.74 ± 2.70	10.67 ± 3.22	9.81 ± 4.04	9.29 ± 3.41
	2	10.07 ± 3.83	20.65 ± 10.08	19.63 ± 6.11	14.09 ± 4.67
	3	11.65 ± 4.22	25.07 ± 9.52	26.61 ± 8.16	16.66 ± 4.21
	4	8.67 ± 7.22	30.2 ± 10.35	29.19 ± 3.29	19.45 ± 5.38
	5	5.34 ± 4.43	23.1 ± 8.40	21.00 ± 6.31	10.62 ± 2.85

[a] Section 1 was approximately 10 m upstream of the culvert and served as the control; sections 2–5 were approximately 20, 50, 100, and 200 m downstream of the culvert.

[b] ND = Not determined; sediment collectors were not installed in the given section given during that year.

TABLE 7.—Mean (±SD) organic matter content (g/kg) of accumulated fine sediment (diameter ≤ 5 mm) in SÉDIBAC 45 collectors, as measured at several weeks or 1–3 years after culvert construction in five Laurentian Shield (Québec) streams, 2000–2003.

Stream	Section[a]	Several weeks	1 year	2 years	3 years
Aubé Stream	1	171.3 ± 17.33	28.16 ± 0.78	99.33 ± 13.87	ND[b]
	2	144.9 ± 18.97	24.77 ± 0.10	28.33 ± 1.53	ND
	3	91.1 ± 13.33	24.25 ± 1.79	62.33 ± 3.79	ND
	4	22.93 ± 0.65	22.35 ± 0.78	37.00 ± 2.65	ND
Aux Canards Stream	1	141.20 ± 21.06	23.67 ± 0.12	28.5 ± 2.51	15.33 ± 2.31
	2	40.35 ± 3.46	11.07 ± 0.12	14.99 ± 0.46	9.67 ± 0.58
	3	41.49 ± 4.85	11.30 ± 0.17	16.44 ± 0.43	15.33 ± 1.53
	4	83.55 ± 3.92	13.33 ± 0.42	22.24 ± 3.90	18.00 ± 1.00
Bernier Stream	1	352.33 ± 39.14	37.43 ± 0.68	79.02 ± 4.10	186.33 ± 31.94
	2	28.89 ± 3.01	45.1 ± 0.50	24.31 ± 2.60	205.33 ± 15.88
	3	62.12 ± 8.51	114.87 ± 2.63	51.89 ± 3.46	166.67 ± 17.79
	4	123.29 ± 2.66	17.80 ± 0.78	35.17 ± 3.01	127.00 ± 16.46
	5	ND	ND	25.4 ± 4.14	55.00 ± 5.29
Roza Stream	1	144.15 ± 5.96	25.03 ± 1.25	25.11 ± 1.01	116.67 ± 7.02
	3	65.62 ± 1.93	18.83 ± 0.50	22.76 ± 0.62	41.67 ± 5.51
	4	109.73 ± 5.60	20.20 ± 0.26	26.26 ± 0.88	74.00 ± 13.45
	5	ND	ND	21.49 ± 0.53	29.33 ± 2.52
Saunier Stream	1	60.86 ± 7.85	42.53 ± 1.80	48.79 ± 1.08	43.67 ± 6.03
	2	31.60 ± 2.74	22.83 ± 0.15	16.55 ± 0.34	25.00 ± 1.00
	3	32.80 ± 4.38	16.50 ± 3.57	12.01 ± 0.50	17.67 ± 1.53
	4	56.79 ± 10.99	18.33 ± 0.47	14.37 ± 0.87	17.33 ± 2.08
	5	44.82 ± 3.82	24.67 ± 0.70	14.71 ± 0.26	22.00 ± 1.00

[a] Section 1 was approximately 10 m upstream of the culvert and served as the control; sections 2–5 were approximately 20, 50, 100, and 200 m downstream of the culvert.
[b] Not determined; no collectors were installed in the given stream during that year.

(1998), and Wellman et al. (2000) for experimental designs with upstream–downstream data. Further comparison of sediment accumulation results between our study and theirs is hindered by differences in collectors, downstream spacing of experimental sections, and time periods between samples.

TABLE 8.—Results of a posteriori Fisher's least-significant-difference tests examining section and period effects on organic matter content (g/kg) of accumulated fine sediment (diameter ≤ 5 mm) in SÉDIBAC 45 collectors placed at brook trout spawning depth within areas of culvert construction in five Laurentian Shield (Québec) streams, 2000–2003. Four to five study sections were present in each stream; section 1 was upstream of the culvert, and sections 2–5 were downstream. Study periods were several weeks and 1–3 years after culvert construction.

Effect	Comparison	df	*t*	*P*
Section	1 *v* 2	13	3.66	0.0029
	1 *v* 3	13	3.33	0.0054
	1 *v* 4	13	3.41	0.0047
	1 *v* 5	13	2.40	0.0321
	2 *v* 3	13	−0.59	0.5663
	2 *v* 4	13	−0.52	0.6142
	2 *v* 5	13	−0.26	0.8012
	3 *v* 4	13	0.08	0.9391
	3 *v* 5	13	0.16	0.8738
	4 *v* 5	13	0.11	0.9144
Period	Several weeks *v* 1 year	11	4.94	0.0004
	Several weeks *v* 2 years	11	5.31	0.0002
	Several weeks *v* 3 years	11	2.63	0.0235
	1 year *v* 2 years	11	−0.12	0.9064
	1 year *v* 3 years	11	−2.55	0.0268
	2 years *v* 3 years	11	−2.74	0.0192

Section and period effects on the organic matter content of postconstruction sediment accumulation in the collectors were detected (Table 4). The organic matter content analysis reveals a pattern opposite to that of sediment accumulation in the collectors (Table 7). Upstream of the culvert, the collectors displayed an organic matter content that was more typical of natural bank erosion, organic soil, and plant debris carried by the stream. The fact that sediments collected downstream contained less organic matter indicates that their source is most likely the sand used for culvert construction, although alteration of slope and water velocity after culvert construction may also lead to sediment erosion and accumulation downstream.

Overall, organic content exhibited a spatial pattern (section effect) in which the highest level occurred in the control section upstream of the culvert, the lowest level was observed in section 2 directly below the culvert, and a slight increase was measured for sections 3–5 without a return to upstream levels (Table 7). The organic matter content was always significantly higher upstream of the culverts than in downstream sections. However, no significant difference was noted between individual downstream sections (Table 8). For the temporal pattern (period effect), the highest organic content was detected several weeks after construction and was significantly different from those observed in all other periods (Table 7). Organic matter content measured at 1 or 2 years postconstruction was significantly lower than that measured at 3 years postconstruction (Table 8).

Although there were more discrepancies in the organic matter content patterns (Table 7) than in sediment accumulation patterns (Table 5), we are confident in the results. We conclude that the change in organic matter content and the accumulation of fine sediment downstream and over time are attributable to culvert construction, culvert presence, and erosion of the road surface leading to the culvert. The greater mineral content of downstream accumulated sediments points to a source other than erosion of the natural riverbed, such as the sand used for culvert and road construction or the materials from road surface erosion. The presence of such sand in the collectors could be the result of certain practices—for example, leaving piles of construction sand on the riverbank for several days before work begins or waiting too long to stabilize the banks around the culvert. Moreover, the fact that culverts were built in moving water and not under dry conditions may have accounted for a large portion of the accumulation of inorganic sediments. Kreutzweiser and Capell (2001) also noted that inorganic sediment in streams was mostly produced by road construction associated with timber harvest.

The shift from organic to mineral deposition may indicate a shift from food-producing fine particulate organic matter (<1 mm) to sterile sand. Fine particulate organic matter, which includes fragments of terrestrial plants, periphytic algae, bacteria, and very small invertebrates, is good-quality food for filtering and gathering organisms. These organisms, in turn, are among the most common and abundant food items for juvenile fish (Cummins and Wilzbach 2005).

These fine sediments obviously accumulated at spawning depth at significantly higher levels downstream than upstream; are these quantities impairing the quality of brook trout spawning and rearing habitat and therefore detrimentally affecting the fish? Downstream levels were generally 2–5 times the levels found upstream (Table 5) for at least 3 years postconstruction. A major accumulation of 20–49 times the upstream level was observed several weeks postconstruction. Without detailed studies of in situ incubation success, survival, and growth, this question is difficult to answer with certainty. However, sediment accumulation data from our study and other studies offer a realistic portrait. Upstream fine-sediment percentages ranged from 0.30% to 14.15% (Table 5), whereas downstream percentages averaged 1.08–29.94%. A threshold of 15–20% fines is considered problematic for salmonid incubation and emergence (Witzel and MacCrimmon 1983; Raleigh and Nelson 1985; Argent and Flebbe 1999). Alexander and Hansen (1986) noted that even small amounts of moving sand bed load had major impacts on brook trout populations and that the removal of sand to levels below 10% increased brook trout population abundance significantly for several years. Sand bed load increases of 4–5 times, as much as the increases measured in some of our samples, were shown to result in a significant reduction (up to 50%) of brook trout numbers (Alexander and Hansen 1986). Our results and those of Alexander and Hansen (1986) indicate that the habitats downstream of culverts are of lower quality for brook trout incubation and rearing in many cases. However, the variability among microsites and the possible presence of upwelling waters downstream could still permit successful reproduction of brook trout but at fewer microsites than upstream.

Although sediment accumulation occurred downstream of culverts in all streams, the quantity of the accumulation diminished with distance from the culvert in some cases and increased in other cases. Even in a given stream, the pattern of accumulation can evolve over time in relation to fluctuations in the equilibrium between the sediment entering the system from the road and culvert and the sediment being transported downstream. Because of this, it was impossible to use a regression model that included all data to validate the 50-m protective distance rule. However, since we needed to estimate whether the 50-m protective distance was adequate, we used the individual linear regression models for Aux Canards Stream (1, 2, and 3 years postconstruction) and for Bernier Stream (1 year postconstruction). The Bernier Stream model predicted that at 1 year postconstruction, the safe downstream distance would be 398 m (Table 9). Aux Canard Stream was described by a systematic linear model with a negative slope (Table 9) that generated safe distances of 1,442 m at 1 year postconstruction, 460 m at 2 years, and 358 m at 3 years (Table 9).

Normal rainfall events precluded manipulation of collectors downstream of culverts, because turbidity was so high that we were unable to see at depths greater than 30 cm. The stream became opaque and cream colored from sand associated with road erosion; this phenomenon was not observed upstream. Although we did not specifically address the problem of increased turbidity downstream of culverts, these observations indicate a potential impact. Precise measurement of turbidity downstream of culverts should be addressed. The potential increase in turbidity can have a variety of behavioral, sublethal, and lethal effects on fish, and sedimentation of spawning beds is but one effect of many. Growth rate reductions, homing impairment, physiological stress, and histological

TABLE 9.—Significant linear regression models describing the relation between the percentage of accumulated fine-sediment weight consisting of 5-mm or smaller particles (PCT5; measured in SÉDIBAC 45 collectors placed at brook trout spawning depth) and distance from culverts (DIST) at 1–3 years postconstruction in the Aux Canards River and Bernier Stream on the Laurentian Shield, Québec, 2000–2003. Four to five study sections were present in each stream; section 1 was upstream of the culvert, and sections 2–5 were downstream. The safe distance at which downstream PCT5 was predicted to return to the average level measured in section 1 is also given.

Stream	Period	Model	R^2	F	P	df	Safe distance (m)
Aux Canards Stream	1 year	$\text{Log}_e(\text{PCT5}) = 0.0500 - 0.0136\log_e(\text{DIST})$	0.5471	25.37	0.0001	22	1,442
	2 years	$\text{Log}_e(\text{PCT5}) = 0.0648 - 0.0177\log_e(\text{DIST})$	0.5176	23.60	0.0001	23	460
	3 years	$\text{Log}_e(\text{PCT5}) = 0.0473 - 0.0130\log_e(\text{DIST})$	0.4218	16.05	0.0006	23	358
Bernier Stream	1 year	$\text{Log}_e(\text{PCT5}) = 0.2497 - 0.5579\log_e(\text{DIST})$	0.5754	28.46	0.0001	22	398

changes in response to higher turbidity have all been documented (Newcombe and MacDonald 1991).

The impact of recent culverts is significant; of even more concern is that culverts built in the past (before 1996) probably exerted even greater impacts, as their construction was based on much-lower environmental standards. Of the 10,000 culverts built each year in Québec, many are constructed to cross gravel–cobble-type streams that are characteristic of brook trout habitat. Based on this study, we can conclude that even when culverts are built in accordance with present environmental rules, they bring significant amounts of fine sediment into hydrographic systems. Given the large dispersal of brook trout on the Laurentian Shield, it is likely that substantial amounts of fine sediment have been infiltrating good-quality brook trout habitat in Québec for many years. Our results concur with those of Lane and Sheridan (2002), who estimated that 2–3 metric tons of bed load material were added to an Australian stream from crossing construction and subsequent road erosion. During the first 5 months after construction of a crossing, the downstream increase in sediment load was 3.5 times the upstream sediment load (Lane and Sheridan 2002).

Due to the sediment increases detected up to 200 m downstream of the culverts in our study, we believe that the protective distance between spawning beds identified in the AFMP and proposed culverts should be greater than the 50 m currently stipulated in the RSFM. Even though they are limited to a few cases, the distance estimates in Table 7 provide a better approximation of ideal protective distance. The estimates are 5–30 times greater than the protective distance specified in the RSFM. Elsewhere in Canada, Alberta and Manitoba have adopted (1) guidelines that provide for a distance of 500 m to protect major spawning beds and (2) an assessment procedure that makes it possible to propose other, case-specific protection measures (DFO and MNR 1996; Alberta Environment 2001). Based on their approach and our own findings, we agree that a distance of 500 m between identified spawning beds and proposed culverts should be implemented. If this is not possible, a distance of less than 500 m can be accompanied by additional protective measures (building a bridge or an arch culvert, working under dry conditions, etc.). Such practices would be beneficial for all fish species, other aquatic vertebrates (i.e., salamanders), and benthic organisms and would preserve the investments made in habitat enhancement projects for increasing the productivity of species coveted by fishing enthusiasts.

More in situ studies that clarify the effect of fine-sediment accumulation on brook trout incubation, emergence success, growth, and recruitment would prove very useful. However, this study and other studies clearly demonstrate that the construction and upkeep of roads and road crossings cause large amounts of fine sediment to enter good-quality aquatic habitats every year. Given the problems created by high turbidity on rainy days and the eventual fish movement limitations associated with culverts (e.g., Gibson et al. 2005), we can conclude that fish of all life stages and species and a great variety of other organisms are being significantly and continuously affected year after year. Sport fisheries and their associated economic benefits are also being affected. However, economically viable solutions to these well-documented problems are available to those who choose to apply them.

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