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[Article]

Large Woody Debris Structures and Their Influence on Atlantic Salmon Spawning in a Stream in Nova Scotia, Canada

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Abstract.—Although large woody debris from streamside vegetation has profound influences on channel morphology and habitat for salmonid fishes, it has often been depleted by channelization or deforestation of the riparian zone. We installed artificial structures mimicking naturally fallen trees in a third-order stream in northern Nova Scotia from 1992 to 2004 to determine whether the structures enhanced spawning success of Atlantic salmon *Salmo salar*. In total, 250 digger logs (which mimic fallen tree trunks and stimulate formation of pools) and bank deflectors (which encourage meandering) were constructed in degraded reaches of Brierly Brook beginning at the downstream end. We monitored spawning each year by counting redds during the fall spawning season. Spawning rates (redd counts) in the whole brook increased exponentially for the first 4 years after restoration work began, from 43 in 1992 to 592 in 1996. By 1996, the entire length of Brierly Brook contained redds, and Atlantic salmon were using gravel that accumulated behind digger logs to build redds. Thereafter, redd counts remained high (502–605) but no longer increased, suggesting that restoration near the mouth of the brook removed an impediment to upstream migration. In 2004, reaches with artificial structures had significantly more redds (336) than reaches without the structures (280). In reaches with artificial structures, 48% of the redds were associated with gravel pool tails or the heads of riffles, 44% were near artificial structures, and 7% were near natural large woody debris. In reaches without artificial structures, almost 89% of the redds were associated with pool tails and the remainder were associated with natural large woody debris. Large woody debris, whether natural or artificial, appears to be an important source of spawning habitat for Atlantic salmon. Artificial structures mimicking naturally fallen wood are effective in the restoration of spawning habitat.

Fallen tree trunks, branches, and rootwads, collectively referred to as large woody debris, influence channel morphology and habitat for salmonid fishes in many streams (Bustard and Narver 1975; Keller and Swanson 1979; Bilby and Likens 1980; Cederholm et al. 1997). Large woody debris has been classified as organic matter longer than 2 m and having a diameter of at least 10 cm (Cederholm et al. 1997). This heavy, semipermanent material profoundly affects stream morphology by reducing or redirecting the flow of water. For example, logs falling across the channel impound water upstream and create a high-energy jump as water crests the log; wood along the bank deflects current toward midchannel and reduces bank erosion. Large woody debris can influence salmonid fishes by scouring pools; redistributing gravel, fine sediments, and organic matter; creating spawning areas; providing refuge from predators and ice scour; and providing cover during high winter flows (Bustard and Narver 1975; Bilby and Likens 1980; Cederholm et al. 1997; Merz 2001).

Historically, woody debris has been removed from many streams in eastern North America during channelization for road building or log driving or to improve drainage (House and Boehne 1986; Crispin et al. 1993; Gore and Shields 1995). Without the channel-shaping influence of large wood, stream habitat tends to simplify, as complex riffle–pool sequences are replaced by long, and long-lasting, homogeneous stream reaches (Fausch and Northcote 1992; Crispin et al. 1993). The loss of wood and the habitat created by it may have contributed to the population declines in Atlantic salmon *Salmo salar* currently observed in many river systems (Montgomery et al. 1995; Crook and Robertson 1999).

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Artificial structures that mimic the effects of natural woody debris can help restore habitat complexity in streams where wood has been lost. Several studies (House and Boehne 1986; Cederholm et al. 1997; Crook and Robertson 1999) have shown substantial increases in salmon abundance in stream reaches modified by instream structures. However, although some studies have indicated increased spawner and spawning densities after additions of large woody debris, the effects of such artificial structures on salmon spawning have not been thoroughly evaluated. Moreover, most evaluations of channel restoration have been short term and have been concentrated in the Pacific Northwest region of North America. Van Zyll de Jong et al. (1997) and Mitchell et al. (1998) reported short-term benefits of instream structures in restoration of degraded habitat in Newfoundland streams. However, no studies have discussed the long-term effects of artificial woody structures on Atlantic salmon spawning in the Atlantic Northeast region.

In 1992, Brierly Brook, a degraded tributary of West River in northern Nova Scotia, Canada, was selected for a restoration project aimed at rebuilding the historical run of Atlantic salmon in the brook. Restoration concentrated on recreating the natural pool–riffle sequence in the brook, which had a very uniform channel, by installing artificial structures made of large woody debris (Andrus et al. 1988; Robison and Beschta 1990a, 1990b). The most effective structures were digger logs, which mimic fallen trees, and bank deflectors, which narrow the channel.

Rutherford et al. (1994) examined the short-term effects of digger logs and deflectors in Brierly Brook over the first 3 years. The present study was intended to evaluate the long-term benefits of restoration. Specifically, we wanted to determine (1) whether reaches restored with artificial wood structures supported more Atlantic salmon spawning than before restoration and (2) whether spawning in unrestored, degraded reaches was still limited by a lack of large wood in the channel. Because Brierly Brook is more or less typical of the many small, midgradient streams draining the Atlantic provinces of Canada, results here should be generally applicable to other regional streams.

Study Area

Brierly Brook is a 20-km-long, third-order tributary of the West River, located west of Antigonish, Nova Scotia (45°36′N, 62°04′W). The brook originates on Browns Mountain (elevation = 350 m) and drains an area of approximately 35 km^2 (Figure 1). The brook flows through alluvial deposits of gravel and fine material (2–15 m thick) on top of unsorted glacial till (Davis and Browne 1996).

Brierly Brook can be divided into three unequal sections based on gradient and surrounding land use. The brook flows first through a 6.5-km-long upper section of Acadian mixed forest that was logged intermittently from 1920 to 1970. Predominant vegetation in this reach (including the riparian zone) consists of white spruce *Picea glauca* intermixed with white birch *Betula papyrifera*, gray birch *B. populifolia*, red maple *Acer rubrum*, speckled alder *Alnus incana*, and balsam fir *Abies balsamea*. The gradient is approximately 3.5% in the upper section. Unlike the rest of the brook, the stream channel in the upper section contains abundant woody debris and good habitat for Atlantic salmon.

The next 10.5 km of Brierly Brook (middle reach; gradient = 1.5%) flows through a mixed rural landscape of farmland, alder swale, and new-growth forest. Much of the middle section is braced by pasture with a narrow, early successional riparian zone (0–10 m). Woody vegetation is dominated by speckled alder along with white spruce, trembling aspen *Populus tremuloides*, and large-toothed aspen *P. grandidentata*. The middle section of the brook supports an abundant population of American beavers *Castor canadensis*, which have built nine dams. The brook here contains little woody debris beyond that contributed by American beavers. A flood control dam located 15 km from the headwaters (Figure 1) retains water during major floods; otherwise, the stream flows unrestricted through a culvert at the base of the dam.

Of special interest is a 2-km-long stream segment (hereafter, the farmed segment) within the middle section that runs through a cattle farm. The farmed segment has a minimal riparian zone (0–5 m) and is heavily degraded by cattle. Before restoration, many parts of the farmed segment were uniformly wide and shallow (depth = 15 cm or less at low flow); had slumping, unvegetated banks; and were clogged with fine sediment.

The lower 2.5 km of the brook flows through the densely developed urban landscape of Antigonish. Much of the brook in this lower section is constrained by streamside development, is modified by bridges and drains, and has a very narrow riparian zone (0–5 m). Before restoration, the urban section was straight, wide, and uniformly shallow (depth often <10 cm in summer) and was characterized by eroding banks, little woody debris, and an embedded substratum.

The entire length of Brierly Brook is accessible to anadromous fishes, including brook trout *Salvelinus fontinalis*, brown trout *Salmo trutta,* and Atlantic salmon. Nonanadromous fish include threespine stick-

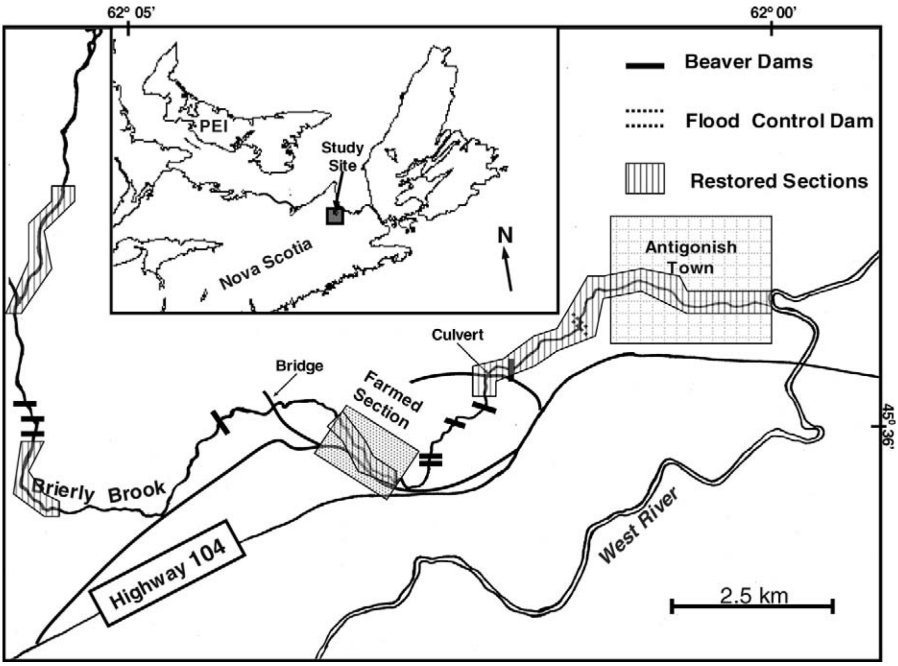


FIGURE 1.—Location of Brierly Brook in northeast Nova Scotia, Canada, where the effects of stream restoration (addition of artificial structures) on Atlantic salmon spawning were studied (PEI = Prince Edward Island).

lebacks *Gasterosteus aculeatus*, white suckers *Catostomus commersoni*, and creek chub *Semotilus atromaculatus*.

Bank-full width in upper Brierly Brook is nearly 6 m, broadening to 8 m in the middle and urban reaches, but wetted width at summer low flow ranges from 3 to 4 m. Mean maximum monthly discharge in Brierly Brook is about 3.0 m^3/s (April); mean minimum monthly discharge is 0.5 m^3/s (July). The 30-year-average annual precipitation for Brierly Brook basin is 1,380 mm.

We used the James River, another West River tributary that drains the basin adjacent to Brierly Brook, as a control to evaluate the success of restoration in the brook. James River is about 15 km long and also begins on Browns Mountain. For most of its length, the river flows through second-growth forest similar to that surrounding upper Brierly Brook and the river is similarly lacking in large woody debris. James River is a larger system (drainage area = 50 km^2) than Brierly Brook, and its mean slope (3%) is steeper. Consequently, only the upper 5 km of James River is comparable physically and hydrologically with Brierly Brook. In this section, the bank-full width of the river averages 11 m and the wetted width at summer low flow is about 7 m. Bank-full flow in James River is roughly twice that in Brierly Brook, but summer low flows are similar between the two systems.

Methods

Sequence of restoration.—Spawning habitat of Atlantic salmon varied considerably along the length of Brierly Brook at the outset of the restoration project. Undisturbed reaches with good habitat are characterized by the following: a relatively narrow, shaded, meandering channel with a typical riffle–pool sequence; a gravel or cobble substratum without embedding in silt or sand; stable, vegetated banks; conspicuous accumulations of woody debris in the channel; and an undisturbed riparian zone of mature forest. Degraded reaches are characterized by relatively wide, straight, open channels with uniformly shallow water and few pools; a highly embedded substratum; eroding banks with exposed soil; little or no large wood in the channel; and a disturbed or discontinuous riparian zone of early successional species, such as speckled alder or chokecherry *Prunus virginiana*.

At the outset of the project, we qualitatively judged the severity of degradation in each section of the brook according to the criteria above. Except for a few kilometers in the headwaters, essentially the entire length of the brook had undergone some degradation of salmon spawning habitat. However, the severity of

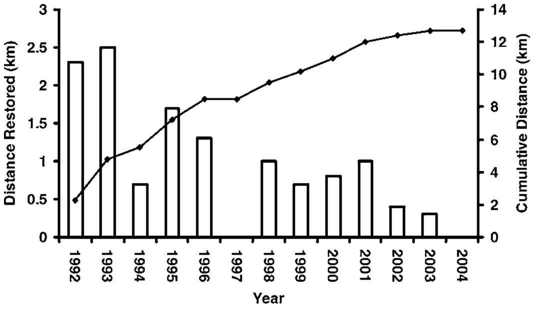


FIGURE 2.—Annual progress of restoration (bars; km restored by addition of artificial structures) and cumulative distance restored (diamonds) in Brierly Brook (total length = 19.5 km), Nova Scotia, 1992–2003. Restoration began at the mouth and proceeded upstream.

habitat degradation varied along the length of the brook. We did not modify mildly disturbed reaches that already supported good habitat. However, we restored most of the severely degraded reaches (12.7 km of the brook, more than 60% of its length) in a continuing effort from 1992 to 2003, beginning at the mouth of the brook and working upstream (Figure 2). Because of the continuing nature of the work, the total length of restored habitat increased each year and the length of degraded habitat diminished. Therefore, although we did not maintain degraded reaches specifically as controls for comparison, several degraded reaches were not restored until near the end of the restoration project.

Design and construction of restoration structures.— The placement of our restoration structures was intended to restore the natural pool–riffle sequence, which in most rivers leads to pools forming every five to seven bank-full river widths (Leopold 1994; Rosgen 1996). Therefore, to estimate the pool spacing that was appropriate for Brierly Brook, we needed to estimate the natural bank-full width of Brierly Brook before degradation. To do so, we measured bank-full width and discharge in 30 undisturbed, gravel-bed streams with moderate slopes in mainland Nova Scotia. For these streams, the daily mean storm flow with a 2-year return period most closely matched the bank-full widths and discharges. Hence, we used hydrographic data to calculate the 2-year mean daily storm flow for the lower reach of Brierly Brook and then estimated the undisturbed channel width of the brook from a plot of storm flow against bank-full width for the 30 reference watercourses. Multiplying the result (8 m) by 6 (because pools form naturally every 5–7 stream widths), we determined that restoration structures should be placed every 48 m in the middle and lower reaches of the brook. To test our calculations, we measured bank-full width and pool spacing at six places in the least disturbed section of the middle reach of Brierly Brook. The measured bank-full width (8.0 $\pm$ 1.0 m; mean $\pm$ SD) and pool spacing (48.0 $\pm$ 2.6 m) in this section were in agreement with calculated values.

Bank-full discharge and stream width normally increase as a stream flows downstream. Therefore, the structure spacing calculated above for the lower reaches was decreased to 35 m in the upper 10 km of the brook to reflect the narrower channel width. No such correction was necessary in the lowest reach, because in Brierly Brook the flood control dam regulates bank-full discharge for the lowest 4 km. Therefore, the structure spacing of 48 m was applied throughout the lower 10 km of the brook.

Before restoring a degraded reach, we surveyed the reach to find the largest naturally occurring pool and any evidence of the natural pool–riffle pattern. The first artificial structure was placed just above the largest pool in the reach. We then placed structures every six stream widths (35 or 48 m) upstream and downstream from the first structure.

Restoration of Atlantic salmon habitat in Brierly Brook primarily involved the use of two structures: digger logs and bank deflectors (Figure 3). A digger log is a tree trunk lodged across the stream channel in a manner simulating a fallen bankside tree (Figure 3A, B). The log creates a low-stage check dam (Rosgen 1996), impounding water on the upstream side and creating a plunge pool on the downstream side from the erosive energy of water flowing over the log. Deflectors are triangles of large wood filled with rocks. Deflectors are constructed against the bank with one side angled outward into the channel in the downstream direction (Figure 3C). Deflectors redirect water flow toward the far bank, thereby narrowing the channel and encouraging the formation of meanders.

Early experiments with several designs soon revealed that one particular digger log orientation (see below), when combined with a bank deflector, was the most effective in digging pools and narrowing the stream channel (Rutherford et al. 1994). We placed deflectors on the upstream side of most digger logs, opposite the side of the stream where the pool was to be formed (Figure 3D). We installed deflectors alone in places where it was not feasible to install digger logs.

To make digger logs, we placed straight, freshly cut logs (diameter = 15–20 cm) in a trench across the entire stream at a 30° angle to the perpendicular bisector of the streambanks (Figure 3B). We most often used hardwood logs, usually red maple, to maximize longevity of the structures; we used white spruce logs at sites where no hardwoods were growing nearby. To

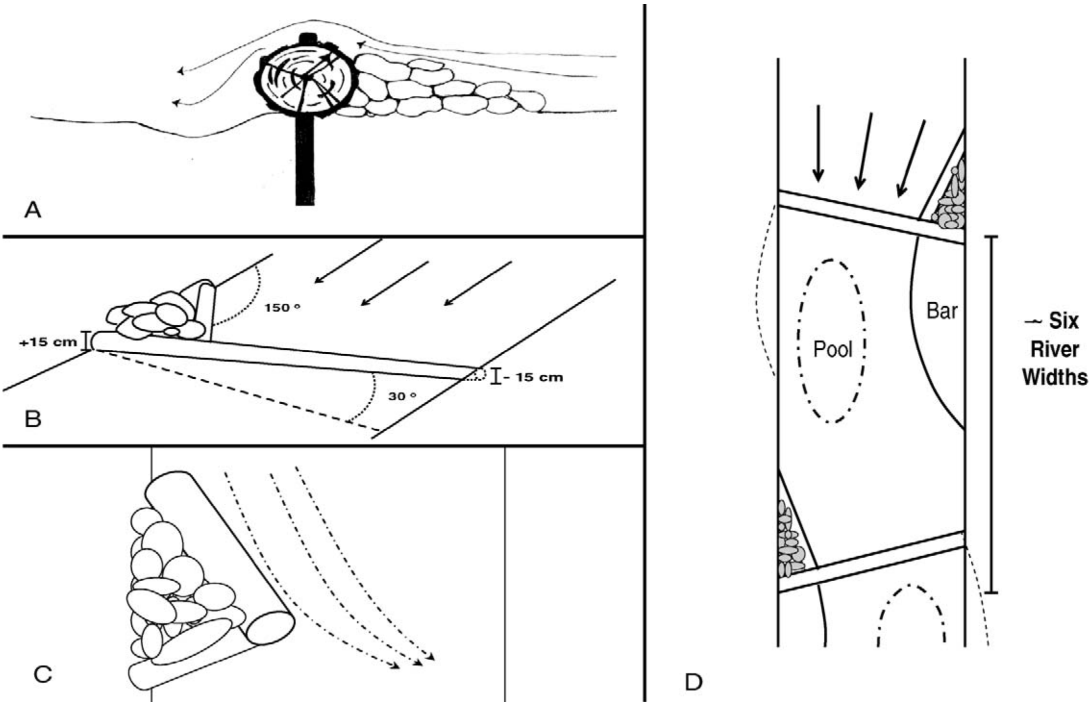


FIGURE 3.—Placement of digger logs and deflectors in the restoration of Brierly Brook, Nova Scotia (arrows indicate direction of flow): **(A)** digger log side profile; **(B)** plan of typical digger log placement, in which logs were placed at a 30° angle from the streambank, the upstream end was buried 15 cm into the streambed, and the downstream end was placed 15 cm above the streambed; **(C)** design of deflectors, which were oriented 30° from the streambank and were placed on the opposite side of the stream from where the pool was to be formed; and **(D)** anticipated locations of gravel bars and pools downstream from a digger log, and an illustration of digger log spacing (i.e., 6 river widths).

concentrate flows on one side of the stream, we set the upstream end of the log about 30 cm lower than the downstream end. We secured each log in place with four pieces of rebar (length = 1.25 m; diameter = 1.5 cm) driven into holes drilled at 2-m intervals along the log. To further secure the log, we placed stream cobble and small boulders on both ends of the log to the height of the streamside vegetation. We built a cobble ramp with a 2:1 slope against the upstream side of the log using material from the downstream side or from elsewhere (Figure 3A). This ramp protected the log from ice and debris and formed a base on which gravel and fine sediments could accumulate.

We inspected and maintained all the structures each spring to repair damage from ice scour. A few other structures required repairs or replacement after floods. Maintenance consisted of rebuilding the cobble ramp and adding stones to refurbish deflectors to their original shape. In the farmed segment, where eroding and slumping banks were a particular problem, fieldstone was placed on unvegetated banks to help stabilize them.

Data collection and analysis.—To monitor Atlantic salmon spawning each year, we counted all salmon redds in Brierly Brook and James River starting in 1992. Once we observed adult Atlantic salmon in the brook, usually after a high flow between late October and early November, we surveyed the entire length of the brook and the river twice each week until no new redd digging was observed. Newly dug redds are easily recognized by the lighter color of the newly exposed gravel and the large pit at the upstream end. Where overlapping redds were difficult to count, we looked for upstream pits to separate one large redd from two smaller ones. We did not differentiate between redds with one egg pocket and those with more than one egg pocket. We also did not count smaller test redds that had been excavated by Atlantic salmon but that typically contained no eggs.

We divided the entire length of Brierly Brook (19.5 km) into 390 contiguous 50-m segments to quantify the amount of spawning occurring in each reach. On each stream survey, we recorded the total redd count for each segment. The redd count from the last survey (when all spawning was apparently completed) was used in subsequent analysis. Each 50-m segment therefore contributed one replicate measurement of the number of redds, which could be combined to calculate means and variances for any defined length of stream. This method allowed spawning activity to be statistically compared among reaches and years. Redd counts in James River followed the same methods.

While conducting the 2003 spawning survey, we noticed that most beaver dams in Brierly Brook were slowing or blocking upstream migration of Atlantic salmon. Beaver dams were notched repeatedly throughout the spawning season to allow the Atlantic salmon to access the entire length of the brook. High flow from a storm during the middle of the 2001 spawning survey moved gravel about and obscured many of the redds in the middle reach of Brierly Brook. The redd count for 2001 is therefore incomplete. Because Atlantic salmon had not reached the upper parts of Brierly Brook before the storm, we still know how far up the brook they ultimately moved.

Atlantic salmon redds were not counted over the length of Brierly Brook in the years immediately preceding restoration. Therefore, we could not employ a true before–after control–impact design to test whether restoration improved spawning activity. However, coincident redd counts in upper James River from 1992 to 1998 provided control data to account for variations in spawning activity that were attributable to weather or other factors. Restoration work began in upper James River in 1999. We compared total redd counts in upper James River against counts in Brierly Brook with a chi-square test using 1992–1998 data.

Similarly, using data from 2004 (i.e., when restoration work was complete), we tested whether reaches of Brierly Brook with artificial structures had greater redd counts than reaches without structures. For this analysis, we used final redd counts from 50-m segments in restored and unrestored reaches staggered along the length of Brierly Brook (Figure 1). We omitted the unrestored segments above 15.5 km because few Atlantic salmon spawned this far up the brook in 2004. For balance, we also omitted the lowest 2 km of restored habitat within Antigonish so that the lengths of restored and unrestored stream segments were approximately equal. Because segments just downstream from beaver dams supported relatively high levels of spawning but segments just upstream from beaver dams had no spawning, we did not use data from segments that were 200 m downstream or 200 m upstream from beaver dams in this analysis. The resulting data set included redd counts from 100 restored segments and 104 unrestored segments.

Because the data were strongly nonnormal and contained many counts of zero, we could not use parametric statistics to compare restored with unrestored segments. Instead, we used a chi-square test based on the total number of redds in all 50-m segments in each treatment. Expected counts for comparison were based on the null assumption that Atlantic salmon spawning would be distributed equally among restored and unrestored reaches. If instead Atlantic salmon preferred to spawn in restored segments, the proportion of total redds would be greater in restored than in unrestored reaches, leading to a significant difference by chi-square (Zar 1996).

During fall 2004, we conducted a more detailed survey of Atlantic salmon spawning in Brierly Brook. We counted redds the same way as above, but we noted whether each redd was located near the tail of a gravel pool (head of a riffle), near a piece of natural woody debris, or near an artificial structure. A redd was classified as associated with natural or artificial large woody debris only if it was situated within 2 m of a woody structure and was not located in a pool tail.

Results

Between 1992 and 2003, 250 restoration structures were built in Brierly Brook. In the lower, urban section of the brook, one structure failed because of ice scour in 1993 and one failed because of a large flood in 2003. The same flood destroyed six structures in the upper part of Brierly Brook. Approximately 20 structures were damaged in one 5-km upstream reach after extensive American beaver activity and a large flood in 2003 altered the flow and scoured a new channel. In total, of 250 structures, only 28 failed over a period of 12 years, giving an overall success rate of 89%.

Although we did not track the total annual returns of adult Atlantic salmon, we did find substantial increases in Atlantic salmon spawning in Brierly Brook after restoration began in 1992 (Figure 4A). In 1992, we counted only 43 redds in the entire 20-km length of Brierly Brook. In each successive year between 1992 and 1996, the total number of redds increased and Atlantic salmon spawned farther up the brook. From 1996 to 2004 (excluding 2001 because the redd count was incomplete), the total number of redds ranged from 502 (1998) to 616 (2004) and averaged 541 $\pm$ 41 (mean $\pm$ SD). In 1992, the farthest upstream redd in Brierly Brook was 12.7 km from the mouth. By 1995, that distance increased to 17.1 km. In 1997, the entire length of Brierly Brook contained redds. By contrast, over the same period, there was no change in the number of redds in upper James River (Figure 4A). Consequently, the chi-square test comparing trends in number of redds between Brierly Brook and James

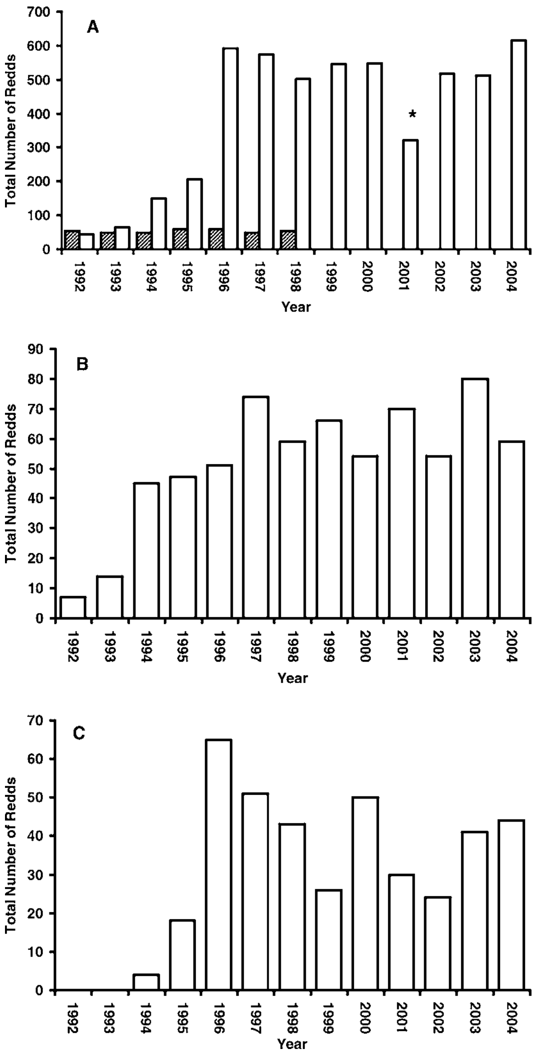


FIGURE 4.—Counts of Atlantic salmon redds in Brierly Brook, Nova Scotia, after stream restoration work began in the summer of 1992: **(A)** total redds in the entire brook (open bars; 1992–2004; asterisk indicates an incomplete count) and in the unrestored upper 5 km of the James River (hatched bars; 1992–1998 only, as restoration began there in 1999); **(B)** total redds in a lower, 2.5-km-long, urban reach of the brook; and **(C)** total redds in a farmed segment (1.0-km agriculturally disturbed segment; its downstream end was located 9.3 km from the mouth), where restoration began in summer 1995.

River showed a significant difference ($\chi^2 = 283.9$, $P < 0.001$, $N = 14$).

In 1992, only seven redds were found in the lower, urban section of Brierly Brook (first 2.5 km; Figure 4B). By 1994, just 2 years after restoration began, the redd count in the urban reach had increased to 45. The total redd count in this reach ranged from 45 in 1994 to

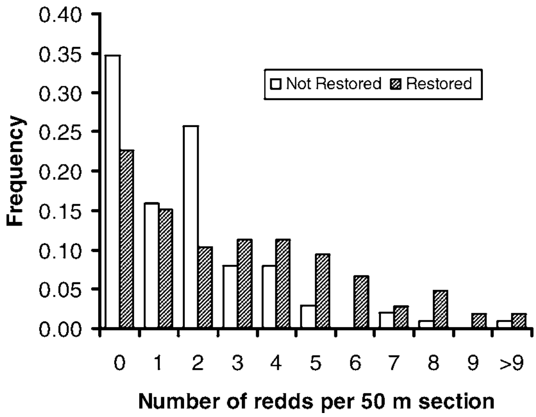
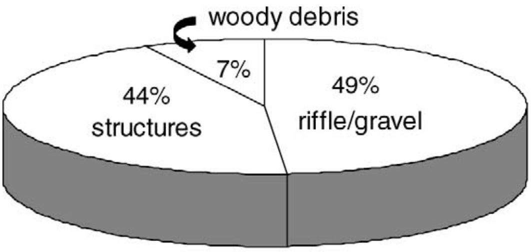


FIGURE 5.—Frequency distribution of Atlantic salmon redd counts per 50-m stream segment in 100 unrestored segments (open bars) and 104 restored segments (hatched bars) of Brierly Brook, Nova Scotia, 2004.

80 in 2003 and averaged 60 ± 11 (mean ± SD). In 1995, we restored 1 km of the farmed segment, a 2-km-long, agriculturally disturbed reach. Before 1995, very little spawning occurred within this reach; counts were zero in both 1992 and 1993. After restoration, there was a major increase in spawning activity (Figure 4C). Between 1995 and 2004, total redd count in this reach ranged from 18 in 1995 to 65 in 1996 and averaged 39 ± 15.

For the brook as a whole, the increase in the number of redds from 1992 (when restoration began) to 1996 could be described by a linear regression ($R^2 = 0.77$) that was significant ($P < 0.05$) despite the small number of data. The trend was even better described by an exponential model (estimated by fitting log-transformed counts to a linear model) for which R^2 was 0.97 ($P < 0.005$, $N = 5$). Thus, over this period, there was a consistent, exponential increase in redd counts that coincided with continuing restoration efforts in the brook. From 1996 to 2004, however, no significant trend in total redd counts was apparent ($R^2 = 0.03$), although counts remained higher than at any time prior to 1996 (Figure 4A). A similarly exponential increase in redd counts was evident for the farmed segment during 1992–1996 ($R^2 = 0.94$, $P < 0.01$, $N = 5$) but not thereafter ($R^2 = 0.07$; Figure 5). For 1992–1997, redd counts in the farmed segment and the whole brook were highly correlated ($r = 0.99$, $P < 0.01$, $N = 6$). In the downstream, urban section, the increase in number of redds from 1992 to 1997 was better described by a linear model ($R^2 = 0.92$, $P < 0.01$, $N = 6$), but again there was no significant trend from 1997 to 2004 ($R^2 = 0.01$; Figure 4B).

The difference in the distribution of redd counts



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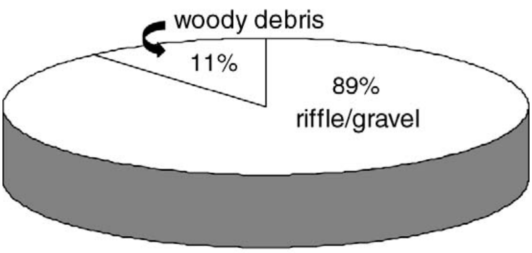

B

FIGURE 6.—Percentages of the total number of Atlantic salmon redds associated with restoration structures, pool tails, and large woody debris (>2 m in length and >10 cm in diameter) in **(A)** restored reaches and **(B)** unrestored reaches of Brierly Brook, Nova Scotia.

between restored and unrestored segments in 2004 was significant ($\chi^2 = 13.1$, $P < 0.001$, $N = 2$). Restored reaches had conspicuously fewer segments with no redds than did unrestored reaches (23% versus 35%), and restored reaches had a greater percentage of segments with five or more redds than did unrestored reaches (27% versus 7%; Figure 5). Restored segments contained a median of three redds (90% range = 0–7), whereas unrestored segments had a median of one redd (90% range = 0–4).

Of the 616 Atlantic salmon redds counted in Brierly Brook in 2004, 410 (67%) were associated with pool tails, 149 (24%) with artificial structures, and 57 (9%) with natural woody debris. There were 336 redds in reaches with artificial structures; of these redds, 162 (48%) were associated with pool tails, 149 (44%) were associated with artificial structures, and 25 (7%) were associated with natural large woody debris (Figure 6). There were 280 redds in reaches of the brook that did not have structures. Of these, 248 (89%) were associated with pool tails and 32 (11%) were associated with natural large woody debris (Figure 6).

Discussion

Salmonid spawning has increased substantially since restoration began in Brierly Brook. Spawning increased exponentially in each of the 4 years after restoration began in 1992. One must partly attribute this increase to the creation of new spawning areas and holding pools by the restoration structures. Although the increases in spawning in Brierly Brook could be part of a general increase in salmonid abundance in the West River system or a coincidental improvement in survival at sea, the complete lack of a parallel change in spawning activity in James River strongly argues against these possibilities. Since restoration of James River began in 1999, spawning has dramatically increased there also (C.M., unpublished data). Crispin et al. (1993) found that the abundance of spawning coho salmon *Oncorhynchus kisutch* in Elk Creek, Oregon, increased fourfold in the years after placement of instream structures, whereas spawner abundance elsewhere in the Nestucca River basin remained the same or decreased.

In addition to sparse spawning habitat, the lack of adequate rearing habitat in Brierly Brook is another factor that may have caused a population bottleneck. Before restoration, a paucity of rearing habitat could have reduced the survival of fry, parr, and smolts or the fitness of adults. This limitation could easily result in few adults returning and low spawning activity. If the instream structures improved the quality of rearing habitat, they would necessarily improve the survival and fitness of fry, parr, and smolts, resulting in more returning adults and more spawning activity in succeeding years. The spike in total redds observed in 1996 was produced in part by adult stages of fry and parr from 1992 and 1993. Hence, both greater spawning activity by adult Atlantic salmon and, eventually, greater numbers of returning adults may have contributed to the observed increases in spawning activity after restoration.

The substantial increase (from 7 in 1992 to 80 in 2003) in total number of redds in the urban reach of the brook shows that even badly degraded reaches flowing through an urban setting can be sufficiently restored for use by spawning Atlantic salmon. Before restoration in 1992, the urban reach of the brook was channelized, very wide, and uniformly flat-bottomed and contained few pools; it would have been classified by Montgomery et al. (1995) as a plane-bed channel. This type of channel does not support large salmonid populations (Montgomery and Buffington 1997). Our structures narrowed some reaches, dug pools, and increased the sinuosity of the urban part of Brierly Brook, changing this reach into a forced pool–riffle channel, which supported greater salmonid spawning.

Restoration in the farmed segment was also successful in boosting spawning. This reach, which was disturbed by cattle, was wide, flat-bottomed, and embedded with fine sediments and had slumping streambanks. The artificial structures dug pools, scoured fine sediments from around embedded cobble and gravel, and created spawning areas. This segment was so badly degraded that Atlantic salmon dug only four redds there in three spawning seasons between 1992 and 1994. In summer 1995, we built artificial structures in this reach; during that fall, the number of redds increased to 18. This response by spawning fish in both reaches suggests that our restoration structures had immediate physical effects on the channel that were detectable by Atlantic salmon. On the other hand, the increase in spawning activity in the farmed segment may reflect a general increase in the number of fish in the middle reaches of the brook; correlation in redd counts suggests that spawning activity was already increasing in the farmed segment when restoration began there.

Since restoration began, Atlantic salmon spawning has increased in reaches with and without artificial structures. Given that not all reaches of the brook were severely degraded at the outset of this project and that some reaches with reasonably good habitat were not restored, improving the quality of the degraded habitat appears to have had a beneficial impact on other reaches of the brook. Also, long reaches of degraded habitat, especially at the mouth of the brook, may have acted as barriers and deterred migrating Atlantic salmon from taking advantage of good spawning habitat farther upstream. Therefore, improving large reaches of degraded habitat might have decreased habitat fragmentation and given spawning Atlantic salmon greater access to the entire brook.

This latter possibility could explain why the number of redds in Brierly Brook increased so rapidly in the first 4 or 5 years after restoration began but not thereafter even though restoration efforts continued. Because the lower, urban reach was the most seriously impaired and given that restoration progressed upstream from the mouth, the first few years of restoration would have removed the most significant barriers to migration and allowed incrementally better access to upstream habitat. By 1996, Atlantic salmon were observed spawning over the whole length of the brook for the first time; that year also marked the point at which the number of redds in the brook abruptly ceased to increase.

The more or less constant number of Atlantic salmon redds in Brierly Brook after the first 5 years is also consistent with the stream reaching carrying capacity, either for spawning Atlantic salmon or for fry and parr. However, from 1996 onward, when redd counts had stabilized, many 50-m stream segments in apparently good habitat lacked redds; clearly, the capacity of the brook to accept spawners has not been reached. Moreover, densities of fry and parr are much greater in reaches with artificial structures than in degraded reaches that lack the structures (T.A.F., unpublished data). The continued construction of new structures after 1996 would therefore have produced an increase in carrying capacity that eventually should have led to increases in returning adults and redd counts. The absence of such increases strongly argues that carrying capacity is not a factor limiting Atlantic salmon spawning in Brierly Brook, a conclusion that accords with historical information on Atlantic salmon runs in Nova Scotia.

The finding that only the first few years of restoration efforts increased the number of redds in the brook calls into question the efficacy of the digger logs and deflectors that were later installed upstream. There is no evidence that these structures further augmented the number of spawning Atlantic salmon in the brook. However, analysis of redd distribution in 2004 demonstrated that along the entire length of the brook, reaches with artificial structures contained more redds than those without the structures. If the total number of redds is constant, then the Atlantic salmon must be preferentially selecting restored reaches over unrestored ones. Indeed, it appears that the structures themselves, as well as the pools they create, are preferred spawning habitat at the small scale. Reaches with pools provide cover and resting places for adult Atlantic salmon and good-quality spawning habitat in the pool tails. Presumably, this preference is aligned with a greater probability of hatching and rearing success and should lead to greater adult recruitment in the long term. Hence, installation of digger logs and deflectors throughout the brook is still an effective restoration strategy even if the total number of redds is no longer increasing.

Atlantic salmon redds are usually found in relatively shallow water above a place where the current accelerates, such as the head of a riffle or pool tail; where the current converges between two obstructions; or where the current is deflected by a single obstruction (White 1942). In Brierly Brook, we found many instances where this was true. Atlantic salmon spawned near the head of a riffle or pool tail, behind natural and artificial digger logs where the current was converging, and beside pieces of natural woody debris and deflectors where the current was deflected. It appears that our artificial structures mimic natural spawning locations. Similar to the findings of House and Boehne (1986), House (1996), and Cederholm et al. (1997) for coho salmon and steelhead *O. mykiss*, we found that Atlantic salmon frequently chose to spawn directly behind or adjacent to restoration structures. In fact, spawning sites near artificial structures and natural woody debris were often the first sites selected for redd construction, indicating that these were preferred spawning locations.

We also found the reaches with artificial structures had more redds than reaches without them, indicating that spawning in reaches without artificial structures is limited by the lack of large woody debris. Merz (2001) found that 29% of the 733 Chinook salmon *O. tshawytscha* redds he surveyed in the lower Mokelumne River, California, during 1994–1995 were associated with natural large woody debris. Brierly Brook has very little natural woody debris, and similar streams that contain few woody debris structures apparently are lacking preferred spawning habitat, which results in fewer redds.

Other studies have shown increases in salmonid spawning after the addition of structures meant to mimic large woody debris. House (1996) reported that gravel trapped above and below channel-spanning gabions in Lobster Creek, Oregon, increased suitable spawning habitat by 115%. After the construction of structures, 56% of coho salmon adults in East Fork Lobster Creek spawned near structures, whereas before construction only 18% of coho salmon redds were located in the treatment area (House 1996). Similarly, Anderson et al. (1984), Moreau (1984), and House et al. (1989) found that salmonid adults spawned in gravels that accumulated near weir and deflector structures. Taking these studies into account, Roni et al. (2002) suggested that using structures or supplementing gravels for salmon spawning enhancement should be used as a short-term measure until natural watershed processes are restored. Further work on the survival of embryos in redds located near woody debris compared with that of embryos located in redds near the head of a riffle or pool tail would help us better understand the importance of spawning locations near woody debris.

The 89% success rate and good endurance of our restoration structures over 12 years shows that a large percentage of the structures may persist for the expected useful life of 25 years. These types of structure are very cost effective for restoration projects with limited budgets. A crew of three can install one structure in 3 h, and the only expenses other than labor are for the rebar, wood, and hand tools. Diagonal weirs or V-weirs appear to be the most effective structures for enhancing salmonid spawning in lower-gradient (<3%) streams (House and Boehne 1986; Roni et al. 2002). However, in a long-term evaluation, House (1996) noted that artificial structures, such as weirs made of wire gabions, deteriorated and began to fail after 10 years and no longer performed as intended. After 12 years, our inexpensive structures are still performing well.

The high success rate, persistence, and low cost of our structures have shown them to be effective stream restoration tools for Brierly Brook. The artificial structures should provide spawning habitat until the young riparian forest along the stream matures and begins to contribute natural woody debris. To this end, the restoration of Brierly Brook included the planting of more than 500 trees, predominantly disease-resistant American elm *Ulmus americana*, in the most severely degraded areas.

This study has demonstrated the importance of instream large woody debris in creating Atlantic salmon spawning habitat. Streams of the northeastern region of North America and other regions that are devoid of large woody debris may lack an important type of spawning habitat and therefore might be less productive than streams containing such debris.

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