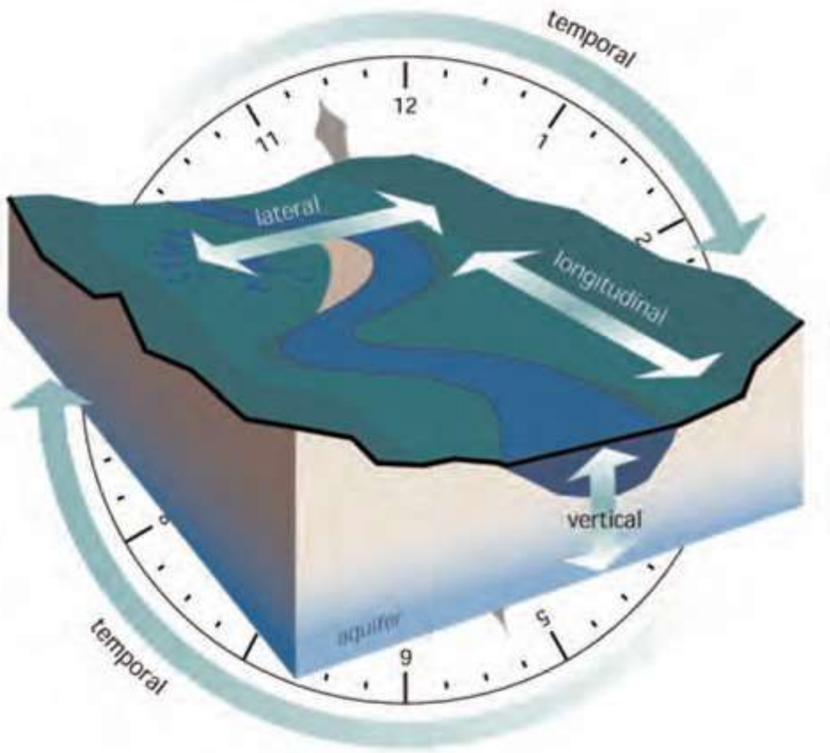
White Paper

Common Connectivity Challenges in New England Streams:

Review of current literature and an assessment of a small stream in Mid-Coast Maine



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Executive Summary

> *Riverscape management and restoration strategies should be process-oriented and embedded within a holistic framework that takes into account the driving processes and their interactions that operate at different spatial and temporal scales*. – Amoros & Bornette 2002; 771

Streams are highly interactive, dynamic ecosystems, which operate across a broad range of spatial and temporal scales that can be viewed as occurring within four dimensions: longitudinal (the main channel pathway and connecting tributaries), lateral (linkages between the stream channel and the riparian/floodplain system), vertical (linkages between the stream channel and contiguous groundwaters) and temporal (continuum of time within which the stream system operates). Traditionally, the primary focus of river management and restoration has been on the longitudinal dimension, particularly in regard to fish passage; however, in order to protect and restore aquatic biodiversity in stream ecosystems it is necessary to recognize the importance of processes operating across all four dimensions. In disturbed stream systems targeted for fisheries improvement, restoration and management must be based on knowledge of the ecological processes that govern fish populations and underlie anthropogenic influences (Mann 1995). Since the four dimensions of stream ecosystems encompass and/or influence the essential ecosystem processes that generate and maintain the physical stream habitat on which fish depend, it follows that a thorough understanding of these four dimensions is essential for diagnosing stream habitat conditions.

This paper summarizes current scientific research regarding these four dimensions of stream connectivity, specifically highlighting challenges common to New England streams, in hopes of broadening the resource manager's perspective of what constitutes stream connectivity. In order to help identify these challenges and demonstrate the scales at which they occur, a pedestrian survey of Choate Brook, a small fourth order stream located in Mid-Coast Maine, was conducted. Choate Brook is representative of small, rural New England streams that do not have the characteristic problems associated with heavily urbanized or agricultural watersheds. The survey was focused on documenting evidence of disrupted connectivity along all four dimensions. Examples from the Choate Brook study are used to demonstrate the four dimensions of a stream ecosystem, highlighting barriers, discussing their ecological implications, and where practical, suggesting recommendations for addressing these challenges.

Introduction

Sustainable management of riverine ecosystems requires a thorough understanding of the functional and structural processes operating across a range of spatial and temporal scales that support hydrologic processes and aquatic biodiversity. Recognition of a stream's natural heterogeneity, as well as its interconnectedness with the surrounding landscape, is vital to effective protection and restoration of these valuable resources (Ward 1989). The objective of this paper is to summarize current scientific research regarding stream connectivity, specifically highlighting challenges common in New England lotic systems, in hopes of broadening the resource manager's perspective of what constitutes stream connectivity.

What is Stream Connectivity?

The concept of connectivity originated in the field of landscape ecology as a means of explaining the distribution of species (Merriam 1984), and was subsequently expanded to explain flows of energy, matter and organisms across the landscape (Noss 1991). More recently the concept has been adapted to explain the dynamics of lotic systems. In regard to stream ecology, therefore, we can define connectivity as the interactions and fluxes of material, energy and organisms within and between the stream system's various components (Pringle 2001; Ward et al. 2002; Kondolf et al. 2006).

Connectivity can be further explained by dividing it into two interrelated components: structural and functional connectivity. Structural connectivity refers to the spatial arrangement and degree of connectedness within an ecosystem in regard to the ability of organisms and materials to move between constituent parts (Lake et al. 2007). Functional connectivity, on the other hand, is concerned with the ability of an ecosystem to facilitate natural processes and functions (Forman 1995).

The Four Dimensions of Stream Connectivity

Streams are highly interactive, dynamic ecosystems, which operate across a broad range of spatial and temporal scales (Ward 1989). Stream connectivity can be viewed as occurring along four interrelated dimensions: longitudinal (flow within the stream channel), lateral (linkages between the stream channel and the riparian/floodplain system), vertical (linkages between the stream channel and contiguous groundwaters) and temporal (variation over time) (Ward 1989; Jansson et al. 2007).

Traditionally, longitudinal connectivity, particularly fish passage along the longitudinal gradient, has been the primary focus for river management and restoration. However, if the goal is to protect and restore aquatic biodiversity, it is necessary to recognize the importance of processes operating across all four dimensions. It is now widely acknowledged that the four dimensions of stream connectivity and their associated variations are the foundation of nearly all stream ecosystem processes and patterns, and that disruption of ecosystem processes and patterns explain much of the ecological degradation of streams and rivers that we see today (Kondolf et al. 2006). Therefore, a better understanding of the disruptions of ecosystem process across multiple dimensions will lead to guidance on how to more effectively restore stream structure and function.

Linking Connectivity to Fisheries Management

Atlantic salmon, alewife, brook trout, and American eel have been identified as species of concern in the Sheepscot River watershed, which includes Choate Brook as a significant spawning tributary (M. Laser, Maine Department of Marine Resources, personal communication). Theoretically, effective management of stream fisheries should take into account the habitat requirements of all life history stages of each species included in the stream community (including species other than fish), however this approach is generally impractical (Garcia de Jalon 1995). A more traditional approach has been to focus on the habitat requirements of the indicator species and to assume that their habitat needs are also representative of co-existing species (Garcia de Jalon 1995). Knowing the characteristics of the stream's fish population (composition, structure, and dynamics) and habitat requirements of each species, to the greatest extent possible, is essential for effective fisheries management and restoration (Garcia de Jalon 1995). Especially when dealing with several key species, as in the Sheepscot River watershed, interactions between species need to be taken into account, and the ecological requirements of each species, life stage and population need to be categorized (Elliot 1995). This information can then inform the assessment of physical stream habitat available for the target fish community, and deteriorated features can be identified. Five primary components of stream fisheries habitat requirements include spawning areas, food production areas, refuge zones, flow regimes, and water quality. All of these requirements are closely related to the four dimensions of stream connectivity. The evaluation of physical habitat should lead to the identification of controlling factors, and therefore, the diagnosis of specific problems, which can be traced to the root cause of habitat degradation (Garcia de Jalon 1995). It is the root cause that ultimately needs to be treated, which is often related to an anthropogenic barrier to connectivity within one, several, or all of the stream's dimensions. In disturbed stream systems targeted for fisheries improvement, restoration and management must be based on knowledge of the ecological processes that govern fish populations and underlie anthropogenic influences (Mann 1995). Since the four dimensions of stream ecosystems encompass and/or influence the essential ecosystem processes that generate and maintain the physical stream habitat on which fish depend, it follows that a thorough understanding of these four dimensions is essential for diagnosing stream habitat conditions.

Choate Brook Connectivity Study

Choate Brook is a typical rural New England stream without the conspicuous problems characteristic of streams in heavily urbanized or agricultural watersheds, yet it is not supporting the fisheries that it did historically. This is presumably due to a combination of factors, including issues within the stream system itself, as well as large man-made barriers in the Sheepscot and West Branch Sheepscot Rivers that inhibit fish migration to upstream tributaries.

Studying Choate Brook in regard to connectivity presents an opportunity to investigate the more subtle workings of a stream ecosystem. Throughout the rest of this paper I will be drawing on examples from Choate Brook to demonstrate the various dimensions of connectivity as they relate to a typical stream in New England. For each barrier to connectivity I will discuss the ecological implications and, where practical, suggest recommendations for addressing these challenges. Finally, I will discuss the cumulative affects of barriers operating at various spatial and temporal scales.

Background Information

Choate Brook is located in Kennebec County in the mid-coast region of Maine. This small 4th order stream drains Savade Pond and a complex of associated wetlands and terminates at its confluence with the West Branch Sheepscot River near Windsor Station. The survey conducted on Choate Brook included a 1.25 mile stretch of this 1.5 mile long stream from the Greeley Road crossing to its confluence with the W. Branch Sheepscot (Figure 1).

Figure 1. The pedestrian survey of Choate Brook was conducted on a 1.25 mile stretch of the stream from Greeley Road to the confluence with the W. Branch Seeepscot River.

Choate Brook's drainage area above its confluence with the West Branch Sheepscot River is 5.2 square miles (3338 acres); the watershed has an average slope of six percent, with a maximum elevation of 478 feet (146 meters) and minimum elevation of 171 feet (52 meters). This small watershed is rich in aquatic resources, with almost 70 acres of open water (the majority of which can be attributed to Savade Pond), 420 acres of wetlands, and 15 miles of streams. According to the Maine Land Cover Dataset (MEGIS 2004), approximately two percent of the land cover in Choate Brook's watershed is open water and 13% are wetlands (Figure 2).

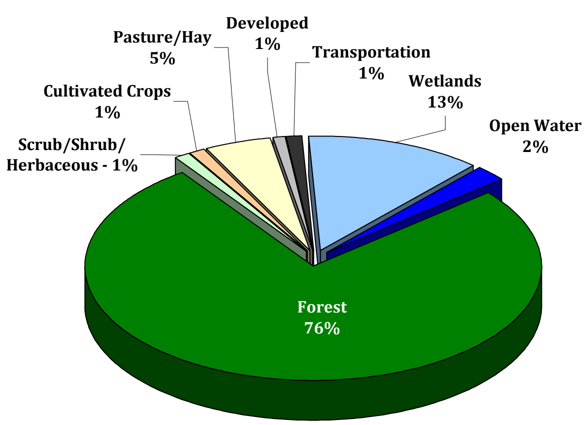

Figure 2. Land Cover in the Choate Brook Watershed

Today, over 75 percent of the drainage basin is covered by forest (Figure 2), with the vast majority being mixed hardwood and conifer forests. Very little development exists in the watershed; roads cover one percent of the drainage basin and one percent is covered by low density residential development. Hay and pasture make up five percent of land cover, much of which occurs in the lower portion of the watershed near Choate Brook and Savade Pond (Figure 3).

The shape, grade and substrate of the Choate Brook watershed are controlled by geologic factors. Bedrock exerts the dominant control on drainage patterns in the Sheepscot River basin generally, dictating the grade of streams and regulating the elevation of the stream channel (Laser 2007). The region's bedrock geology was shaped by tectonic events that occurred over 400 million years ago, resulting in the pattern of northeast trending parallel drainages that are expressed in the Choate Brook (Figure 3) and the Sheepscot River valleys today (Laser 2007).

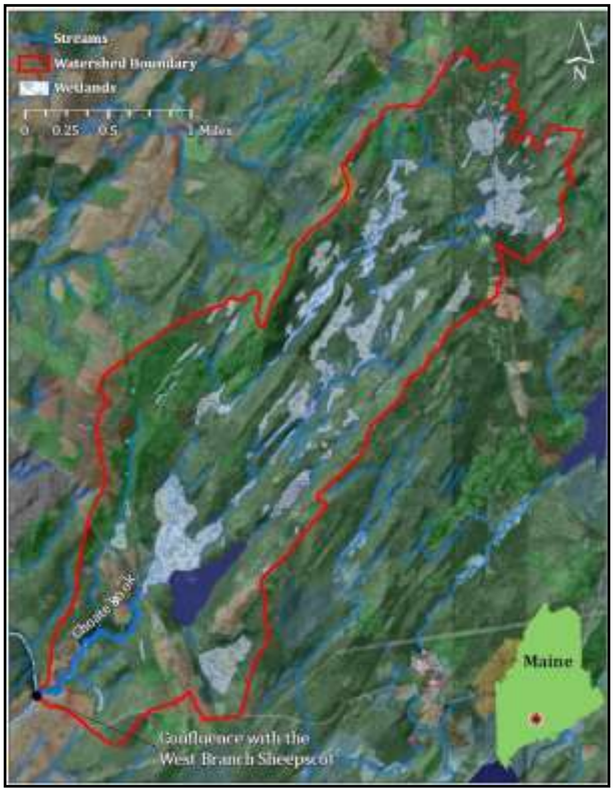

Figure 3. Choate Brook Watershed.

More recently on the geologic time scale, glaciation has shaped the regional landscape and drainage patterns. 20,000 to 14,000 years ago the Laurentide Ice Sheet flowed across New England, eroding hills and deepening and widening valleys as it advanced, depositing glacial till, and creating moraines and outwash plains as it made its slow retreat (Marvinney 2004; Marvinney and Thompson 2000; Davis 1992). Today we see the results of this glacial activity in topographic features including many of region's the lakes and soils.

A thirty-year long weather record for Augusta, Maine (the closest weather station to Choate Brook) indicates an average annual temperature of 45.8° F, average summer temperature of 68° F, and an average winter temperature of 23° F. Rainfall at this weather station is fairly consistent throughout the year with a monthly average range from 2.55 inches in February to 4.04 inches in October, and average annual precipitation of just over 42 inches. Winter months in this region see a significant amount of snow, with an annual average of 72.2 inches occurring from November through April. (NCDC 2004)

Methodology

In September and October of 2008 I conducted a pedestrian survey of Choate Brook and its riparian corridor with the help of a field assistant. The survey was focused on documenting evidence of disrupted connectivity. We used protocols and survey forms established by the State of Maine and the US Fish and Wildlife Service for assessing road-stream crossings, man-made dams, beaver dams, debris jams, and natural falls (Maine Road-Stream Crossing Survey & Maine Dam and Natural Barrier Survey). In order to assess other factors that impact stream connectivity, three additional survey logs were developed. The Adjoining Waterbody Survey log, a new form created for this study, was used to document potential impediments to connectivity between the stream channel and other waterbodies, such as ponds, wetlands, and tributaries. In order to evaluate the health and connectedness of the riparian corridor, I developed a Riparian Corridor Survey Log, which was used to keep track of changes in riparian corridor width, channel canopy, vegetative cover, and land use. Finally, the Supplemental Barrier Survey Log was designed to inventory other potential barriers or signs of impeded connectivity that were not covered by any of the other surveys. This log documented features such as bank erosion, channel alterations, diversions, low flow areas, depositional features, stream corridor encroachment, non-point source pollution, thermal pollution, and turbidity. Examples of all survey logs are included in Appendix A.

After conducting the field study, the data were entered into a database, uploaded into GIS using the GPS waypoints, and overlaid on a recent aerial photograph. This resulted in maps that spatially display the patterns of disturbance along the stream channel and areas where changes in the riparian corridor occur (see Appendix B).

The Longitudinal Dimension

In the longitudinal dimension the stream is viewed as a linear feature bounded by its bed and banks and dominated by downstream transfers of energy and material, as well as variations in flow, temperature, channel form, and biotic communities from its headwaters to mouth (Petts and Amoros 1996). Geomorphic patterns along the longitudinal gradient greatly influence the physical, chemical, and biological patterns of the stream, and therefore, the nature, diversity and stability of in-stream habitat (Roux and Amoros 1996).

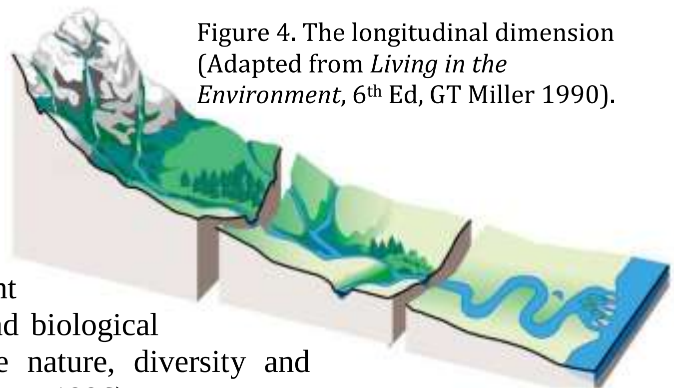

Figure 4. The longitudinal dimension (Adapted from *Living in the Environment,* 6th Ed, GT Miller 1990).

Of the four dimensions of stream connectivity, this is the most easily discernable and longest studied, on which many of today's most influential models regarding fluvial geomorphology and stream ecology are based. For example, the Strahler method (1952) of defining stream orders is widely used today as a means of classifying, comparing and examining streams of varying size and location in the stream network. Schumm's zonation (1977) is another longitudinal classification model that uses geomorphic processes such as sediment transport, channel stability and channel dimensions, to categorize streams into three zones (Figure 4: from left to right—the zone of production, zone of transfer, and zone of accumulation) (Rosgen 1994). The River Continuum Concept, which focuses on resource gradients[1], addresses the longitudinal dimension as well. This ecologically based stream flow model proposed by Vannote et al. (1980) is used to explain and predict changes in the distribution of physical, chemical and biological characteristics along the stream corridor from source to sea (Gordon et al 2004). These and other longitudinally based models provide the conceptual framework from which many modern stream assessment methods are derived.

At the watershed scale, longitudinal connectivity consists of the main channel pathway as well as the connections between the main channel and its tributaries (Muhar and Jungwirth 1998). According to Jungwirth et al. (2000), the relative influence of the longitudinal pathway is greatest in headwater streams; however, in regard to anadromous fish, longitudinal connectivity

[1] Resource gradients refer to the elicit series of responses that are expected based on the location of the stream reach within the stream continuum from headwaters to mouth. These resource responses include biotic adjustments, patterns of sediment loading, nutrient transport and utilization, and storage of organic matter.

throughout the entire catchment is vital (Northcote 1998). While fish migration is often the primary concern in regard to longitudinal connectivity, numerous vital ecosystem processes may also be disrupted by changes that occur along this dimension. Channel forming processes, resource gradients, sediment transfer, nutrient cycling, and biotic assemblages all rely on intact longitudinal pathways.

Common Barriers to Longitudinal Connectivity

Longitudinal barriers are often perceived as insurmountable transverse structures in the stream channel that literally block the movement of fish and other aquatic biota. While this is often the case in regard to such features as dams, weirs, debris jams, culverts and natural falls, other barriers are not necessarily so obvious. Furthermore, it is important to understand that structures in streams may be passable from the perspective of a fish while causing other disruptions in stream structure or function.

Dams

Dams, the most familiar and dramatic barriers to longitudinal connectivity, have served many important functions for human society, and will likely continue to do so far into the future. Unfortunately, these structures have tremendous impacts on the fluvial and ecological processes of stream systems (Pizzuto 2002). Dams act as physical barriers to the migration of fish and other aquatic biota, which in turn result in species declines, isolated populations, and disruption of food webs, nutrient transfer, and aquatic productivity (Poff and Hart 2002). In fluvial systems organisms and nutrients tend to move downstream, and the upstream movement of strong swimmers like migratory fish counters this biological displacement, returning nutrients to upstream portions of these systems (Jackson 2003). One pronounced example of this process occurs in nutrient-deficient headwater streams that are enriched with phosphorous by anadromous fish that die after spawning (Ward 1989). Dams that prevent anadromous fish from reaching their native spawning grounds, therefore, not only affect that particular species (reduced reproductive success), but the productivity of the whole stream ecosystem. Dams also act as physical barriers to the movement of macroinvertebrates, which play a major role in the stream's food web and nutrient cycle (Ward 1989).

Beyond acting as physical barriers to the movement of biota, dams disrupt longitudinal connectivity by fundamentally transforming stream ecosystems (Poff and Hart 2002). Dams alter the flow of water and sediment, subsequently modifying natural biogeochemical cycles, changing water temperatures, and altering the structure and dynamics of aquatic habitats (Poff and Hart 2002). Although downstream reaches respond to these altered fluxes of water and sediment in varied ways, some common responses include channel erosion and incision (lowering of the stream bed), loss of instream structure (e.g. pool-riffle sequence), widening of cross-section profiles, reduced gradient, increased deposition of fine-grained sediment and decreased transport of gravel resulting in degraded downstream spawning reaches and altered biotic assemblages (Pizzuto 2002; Muhar and Jungwirth 1998; Kondolf et al. 2006).

With individual dams providing ecologists with virtually unlimited opportunities for research, it is no wonder that the cumulative impacts of dams have received such little attention. While it is clear that excessive fragmentation of riverine systems caused by high dam density promotes ecosystem isolation, prevents dispersal and persistence of inland species, and prevents exchange between isolated populations of inland fish and other biota (Poff and Hart 2002), there is a lack of research regarding the cumulative abiotic impacts of dams. With dams occurring so frequently in many watersheds, however, their cumulative ecological effects are bound to be immense, and thus worthy of further research.

Even dam removal may have significant impacts on longitudinal connectivity and, therefore, must be approached with well thought-out and detailed restoration plans. Two primary considerations in regard to dam removal are the extent to which the dam is removed and the problem of sediment buildup behind the impoundment (Pizzuto 2002). If the dam is not fully removed, and parts remain in the streambed, the remaining structure may continue to control the elevation of the streambed above the dam by restricting the downstream movement of coarse sediment (bed load) (Pizzuto 2002). Therefore, while passage for specific fish species may have been restored, if bed load transport remains restricted, the streambed is not allowed to revert to its target profile, and thus restoration of connectivity is not complete because the channel is not allowed to return to equilibrium. The second consideration regarding dam removal is the accumulated sediment behind the dam, which often occurs in large volumes and contains high levels of toxicity. After the dam is removed, the sediment will be carried downstream and redeposited. The deposition of this finer grained sediment, in combination with the accumulated toxins, could rapidly degrade water quality and alter the streambed structure at the reach scale, from which the stream may require many years to recover (Pizzuto 2002).

Road-Stream Crossings

In recent years there has been growing concern about the impacts of road-stream crossings, particularly culverts, in regard to disrupting stream connectivity. A range of adverse impacts to stream ecosystems result from road-stream crossings depending on the type of crossing (bridge, ford, open-bottom/arch culvert, box culvert, or pipe culvert), its size, and the method of installation and maintenance (Jackson 2003). Both during construction and over the long-term (on-going erosion of embankments, the road surface, and drainage ways), crossings can result in excessive erosion and sedimentation, which leads to increased suspended solids in the water (turbidity) and altered downstream substrate and channel characteristics (Jackson 2003). Stormwater runoff is another impact associated with road-stream crossings. Stormwater from roads may contain excessive amounts of salt or contaminants that are toxic to stream biota; these and other pollutants that make their way into streams can act as invisible barriers to fish and other aquatic organisms moving along the longitudinal gradient.

While bridges and fords can have significant affects on stream systems, culverts tend to be the most problematic crossing structures. Culverts impact the local geomorphology of stream ecosystems because they form rigid boundaries that do not change with the stream channel through time (Norman 2006). This leads to the fragmentation of adjusting channels and a number of geomorphic effects both upstream (e.g. decreased stream bank stability, sediment deposition, and channel aggradation) and downstream (e.g. erosion) of the culvert (Norman 2006). Key problem features of culverts include inlet or outlet drops, physical obstruction, excessive water velocities, absence of bank-edge areas, excessive turbulence, insufficient water depth, flow constriction, and discontinuity of channel substrate. Inlet and outlet drops, physical obstructions and excessive flow velocities act as physical barriers to the movement of many aquatic organisms and may also result in scouring of sediments (Jackson 2003). Crossings that constrict the channel alter the hydrology of the stream, with water ponding upstream of the structure and increased flow velocities scouring the channel downstream (Jackson 2003). This change in hydrology also alters sediment transport, leading to accumulation of sediments upstream of the culvert and scour pools on the downstream side (often resulting in a perched outlet). Further, ponding of water on either side of the road crossing may have impacts on water temperatures, as these roadside areas often lack riparian vegetation (and thus a vegetative canopy) and are therefore exposed to direct solar radiation. Discontinuities in channel substrate (pipe culverts for example) present problems for many benthic organisms that are only capable of moving through appropriate substrates (Jackson 2003); since the stream's food web is dependent on such benthic organisms, disrupting their movement causes a ripple effect through the food chain. Crossing structures may also restrict the downstream movement of large woody debris, which is vital in the shaping of channel characteristics and important habitat features.

Road and stream networks, both being long linear systems, frequently intersect. As previously noted in regard to dams, it is important to consider the cumulative impacts of road-stream crossings throughout a watershed. In New England roughly 10 times as many culverts exist per basin as dams (Bechtel 2008). A high density of road-crossings leads to excessive fragmentation of stream systems, resulting in an undermining of the viability of animal populations through ecosystem isolation (Poff and Hart 2002; Jackson 2003). These small, isolated populations tend to be more vulnerable to genetic change and extinction.

Low Stream Flow

Reduced stream flow and low flow areas also have the potential to act as barriers to longitudinal connectivity. Reduced flow caused by dams, diversions, withdrawals, legacy effects and reduced baseflow can render formerly passable reaches impassable (Kondolf et al. 2006). For example, migratory fish may no longer be able to navigate over a waterfall due to insufficient water depth. Furthermore, low flows are more vulnerable to changes in temperature and can lead to reduced levels of dissolved oxygen, thus creating stress on migrating fish species (Kondolf et al. 2006). Finally, areas where the streambed is homogenous (lacks pools for refugia) may act as barriers to fish passage during periods of low flow.

Longitudinal Connectivity and Choate Brook

Within the 1.25 mile stretch of Choate Brook that was assessed for this study, we found three culverts, one ford, two remnant dams, two remnant bridges, one old train crossing that is now used as an ATV/snowmobile crossing, and one potential low flow area. In addition, there appear to be some problems with connectivity at the confluence of Choate Brook with the West Branch Sheepscot River, and temperature data from 2000 indicate that thermal barriers may exist during certain weather and flow conditions (KRIS Sheepscot 2005).

Road-Stream Crossings

Of the three culverts on Choate Brook, two occurred at paved road crossings (Greeley Road and Sampson Road) and were already included in the Maine Department of Marine Resources (DMR) road-stream crossing inventory that is currently underway. The completed data sheets for Greeley Road and Sampson Road were obtained from Maine DMR for inclusion in this assessment[2]. The third culvert occurred at a new dirt road crossing and will also be briefly discussed.

The Greeley Road crossing consists of a round five-foot diameter, tar-lined metal culvert. The culvert is flow-aligned and both inlet and outlet are at stream grade. Although the data sheet concludes that there are no significant sediment sources or wildlife barriers at this crossing, several factors indicate that the culvert may be impeding the stream's longitudinal connectivity. This culvert severely constricts the stream channel: the channel's bankfull width is 35.5 feet as measured several meters away from the crossing, but the culvert has a diameter of only 5 feet. As stated in the previous section, culverts that constrict the channel alter the hydrology of the stream, causing water to pond upstream of the structure (Jackson 2003). The upstream ponding increases the detention time of water upstream of the crossing (Jackson 2003), and therefore increases sediment deposition as well. This results in an alteration of downstream substrates and channel characteristics, which will likely also impact benthic macroinvertebrate populations and distribution. Furthermore, the constriction leads to increased velocities on the culvert's downstream side, which can result in scour pools and large drops at the outlet that act as barriers to animal movement (Jackson 2003). Both the upstream ponding of water and the downstream scour pool (in this case greater than 3 feet deep) are present at this site, as is a change in the velocity of water from the stream channel to that within the culvert.

Two other potential connectivity challenges occur at this crossing: 1) a discontinuity of channel substrate, and 2) potentially insufficient water depth within the culvert. The Greeley Road culvert lacks any natural substrate, while gravel is the predominant substrate both upstream and downstream of the crossing. This lack of substrate results in a discontinuity between streambed habitats, which impacts the benthic organisms that can travel only through appropriate streambed substrates. Thus, this crossing may be causing fragmentation of the stream's benthic communities that are vital components of the stream's food web. Finally, the data sheet indicates that the depth of water at the inlet of the culvert is 0.3 feet (3.6 inches) and at the outlet is 0.2 feet (2.4 inches). These depths were recorded in July during a period of low flow, indicating that the culvert may be passable to most fish species most of the year; however, the depth requirements of particular species will need to be investigated in order to determine if the shallow depth of flow in this culvert presents a barrier to passage. In order to minimize the impacts of this road-stream crossing, it is recommended that, when funding becomes available for infrastructure replacement or upgrades at this site, the culvert be replaced with a structure that does not constrict the stream channel and has a natural substrate bottom matching that of the stream channel, such as a large open bottom arch culvert.

During the second day of our pedestrian survey, we came across a newly installed culvert. Since we were not aware of the presence of this crossing, we lacked the proper survey form for completing a full assessment. We did, however, take enough measurements and notes to at least partially evaluate the crossing's impact on the stream's connectivity. The road crossing consists of an old metal tank (with both ends cut out) installed as a culvert under a new dirt road with gravel/cobble embankments. The old metal tank (culvert) is 5 feet in diameter, 18 feet long, and has no natural substrate. The lack of natural substrate will lead to issues similar to those discussed for the Greeley Road crossing. The primary concern at this crossing is erosion; the

[2] Copies of these data sheets are included in Appendix B.

gravel/cobble embankments as well as the dirt road itself will be vulnerable to erosion during storm events, and the culvert is not flow-aligned, which also leads to concerns about erosion and sedimentation. Figure 5 illustrates the conditions that occur at this crossing. Since this crossing has only recently been constructed, obvious signs of hydrologic change or channel adjustment are not yet visible; however, one would expect similar affects that are seen at the Greeley Road crossing to result here over time (if the culvert remains in place) from the channel constriction, potentially with more extensive impacts on the upstream side due to the skewed alignment. Furthermore, similar impacts to benthic communities will result from the lack of natural substrate in the structure. If this road is to remain permanently, its impact on the stream should be thoroughly assessed and the culvert replaced with a larger, flow-aligned structure that does not constrict flow and has a natural substrate bottom.

Figure 5. New stream crossing: dirt road off of Sampson Road. Top left: looking upstream at outlet; Bottom left: from road looking downstream; Top right: looking downstream at the inlet; Bottom right: from road looking upstream.

The Sampson Road crossing consists of a 33.5-foot long metal open bottom arch culvert that is flow-aligned and has a natural substrate bottom consistent with that of the stream. The metal culvert is corrugated and has a width of 15 feet and an average clearance of 6.8 feet. Both inlet and outlet are at stream grade, the slope is comparable to that of the channel, and the crossing's water depth and velocity match the stream's depth and velocity. The observers did not witness any visible wildlife barriers or significant sediment sources at this site. Because the culvert has a natural substrate bottom and is flow-aligned, the ecological impacts of the crossing are significantly reduced as compared to the Greeley Road and new dirt road crossings. The lack of a tailwater scour pool is a further indication of intact flow and sediment transport. However, the crossing structure is not at the recommended width for maintaining ecological function.

According to the Forest Service Stream-Simulation Working Group (2008), bankfull width is a good estimator of channel-forming flow and therefore should be used as a working criterion for defining the appropriate width of a crossing structure. The structure should be at least as wide as the bankfull width measured in a reference reach of the stream (away from the existing structure). In the case of all three road-stream crossings on Choate Brook the culvert width is significantly smaller than the measured bankfull width of the stream. The Sampson Road culvert, the widest of the three structures, is only 35% of the bankfull width of the stream channel, which was measured to be 43 feet wide; therefore, the culvert is likely to interfere with the stream's channel forming flows and natural adjustment processes.

The ford across Choate Brook appears to be an old four-wheel drive crossing with the bottom composed of natural gravel and cobble substrate. This crossing is clearly not used often, but remnants of tracks can be seen through the herbaceous vegetation. At this time the ford does not appear to be causing any problems; however, if more frequently used, it could contribute to erosion and substrate compaction.

Old Train Bridge

Figure 6 shows an old train crossing with stone masonry abutments[3]. The trains have long since ceased travel along this path, but the bridge remains, and with it impacts to the connectivity of Choate Brook. The structure's stone abutments, with a span of 9 feet, obviously constrict the 35-foot wide stream channel, leading to scouring of the streambed and erosion of the stream banks downstream, as evidenced by a tailwater scour pool and the deteriorating bridge structure on the downstream side. The bridge abutments are also not aligned to the flow of the natural stream channel and the channel slope decreases through the structure. These factors all serve to constrict the natural geomorphic processes that the stream ecosystem relies on for maintaining heterogeneity and dynamic ecological processes. This structure is located just downstream of the Sampson Road crossing. Although it is a significant historic artifact that some may wish to protect, it is recommended that this structure be removed, as it serves little purpose and creates significant challenges for the connectivity of Choate Brook, especially considering its proximity to another constricting structure just upstream.

Figure 6. Old Train Bridge that is today used as a foot path across the stream. Right: looking downstream at the bridge, and Left: looking upstream at the bridge.

[3] A copy of the data sheet for this structure is included in Appendix B.

Remnant Dams

There are two remnant dams within this 1.25 mile stretch of Choate Brook, both made of stone (Figure 7). One dam is fully breached and the other is partially breached, both have tailwater ponds with pools estimated to be less than 3 feet deep. Copies of the data sheets for these structures are included in Appendix B.

Figure 7. Remnant Dams on Choate Brook. Both views are looking at the downstream face of the dam.

Although both of these dams have been breached, significant portions of their original structure remain in the stream channel, continuing to control the elevation of the streambed. The remaining structures restrict erosion above the dam, which means that the channel is not able to revert to its target profile, thereby returning to equilibrium. In the cases of both dams, significant hydraulic drops occur at the spillway, indicating that the channel is lower below the dam than above. The dam shown on the left in Figure 7 has such a significant drop that during low flow conditions it may be a direct barrier to fish passage. This same dam also creates a constriction on the stream channel, which may result in similar issues discussed in regard to constrictions caused by culverts. An assessment to determine the degree to which the remaining dam structures restrict bed load transport and impede the passage of fish and other aquatic organisms is recommended. Since these are stone dams, removing the structure should not be very complicated or expensive as compared to concrete structures, and the large boulders may prove useful if strategically placed elsewhere in the stream to increase heterogeneity of channel structure and provide cover for fish and other aquatic organisms.

Remnant Bridges

In two places along Choate Brook we found what appear to be old stone masonry bridge abutments. In both occurrences, the abutments are composed of angled rock stacks on both right and left banks, causing channel constriction and increased water velocity. However, since these structures are located in the downstream portion of Choate Brook, which lacks diversity of channel structure, it is unclear whether the structures decrease or increase connectivity, as they provide the only channel complexity. Removing the structures would likely not improve the conditions of this segment of stream, and is therefore not recommended at this time. However, if other restoration measures are taken in this area, it may prove beneficial to include removal of the structures in the restoration plan.

Potential Low Flow Area
During the pedestrian survey we identified a stretch of stream with a wide, shallow channel and no pools, offering little structure to provide refugia during low flow. The day we assessed this reach, the stream flow was high, so it did not present a problem for longitudinal connectivity. However, this very straight, flat riffle section could become a barrier to fish passage during low flow times when water would be running through the stretch in a very thin sheet.

The Confluence with West Branch Sheepscot River
At this stream confluence, water slows down drastically as it enters a very large, open pool with no overhanging vegetation and no canopy cover. This pool is likely the remains of a mill pond formed behind the dam that was located just downstream of this confluence on the West Branch Sheepscot River. The dam has long since been removed, but the river is still impacted, as is often the case. The large open body of water that remains, with only a small amount of emergent vegetation along its edges for refuge, may create a problem for migrating fish due to the increased vulnerability to predation (lack of cover), potential for high temperatures (due to lack of canopy), and potential for low dissolved oxygen. Since this is the point of entrance to Choate Brook for migrating fish, its impact on the stream's fish populations may be dramatic. This site will require a much more thorough investigation to determine the full implications on the overall connectivity of this stream system.

Water Temperatures
Water temperatures collected in 2000 from temperature data loggers placed in two locations along Choate Brook indicate summer water temperatures outside of the optimal temperature range for juvenile Atlantic salmon feeding (Figure 8) (KRIS Sheepscot 2005). High water temperatures create barriers for aquatic organisms that have low tolerances to changing conditions, especially cold-water fish. Brook trout, for example, would also be impacted by these high summer temperatures, as their optimum temperature range is 13 to 18º C. Potential causes of the elevated temperatures and recommendations for improving the situation are included further on in the discussion of lateral connectivity issues in Choate Brook.

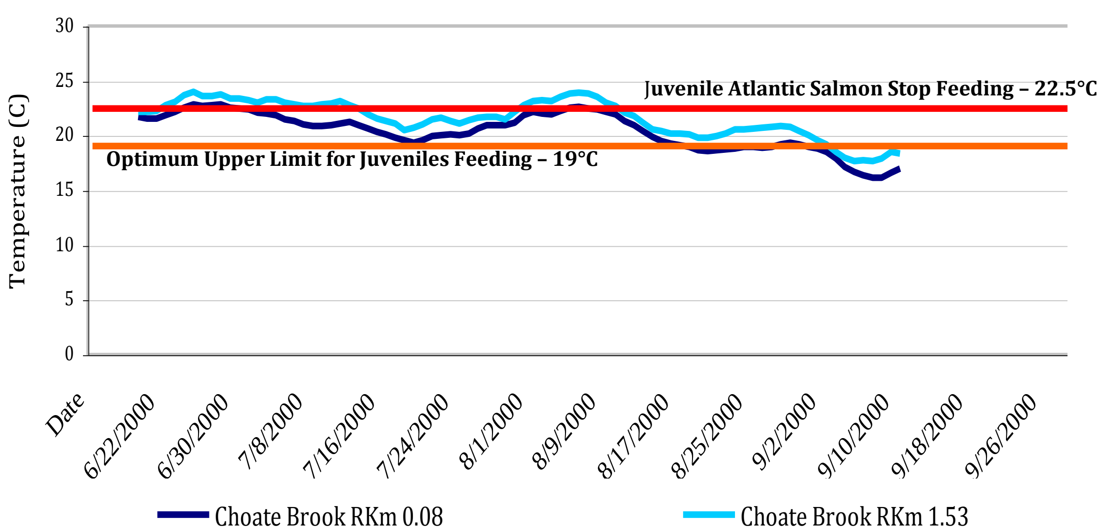

Figure 8. Floating Weekly Maximum Temperatures in Choate Brook plotted against temperature thresholds for juvenile Atlantic salmon, 2000. Adapted from the KRIS Sheepscot website (2005).

The Lateral Dimension

The lateral dimension of stream connectivity is comprised of interactions that occur within the aquatic/terrestrial interface (Junk et al. 1989). This zone relies heavily on intact flow regimes (especially high flows), which are vital for interactions such as the movement of water, nutrients, detritus, and organisms between the stream channel and adjacent terrestrial habitats (Figure 9) (Muhar and Jungwirth 1998). Key processes that take place in the lateral dimension include modifications to light, temperature and humidity (microclimate), alteration of nutrient inputs from upland areas, contribution of organic matter from riparian vegetation, and active and passive lateral movement of organisms (Gregory et al 1991; Ward 1989).

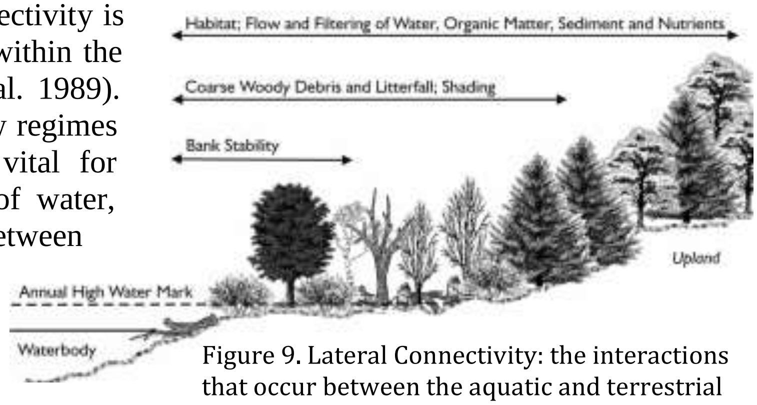

Figure 9. Lateral Connectivity: the interactions that occur between the aquatic and terrestrial interface (*Global Forest Watch,* 2003)

According to Jungwirth et al. (2000), the lateral dimension is strong in the braided middle reaches and meandering main river course but comparatively insignificant in headwater reaches. The focus of Jungwirth et al. (2000) is on floodplain dynamics, which generally are not as prominent in headwater streams. According to the River Continuum Concept, however, headwater streams are strongly influenced by and dependent upon riparian vegetation, which reduces instream primary productivity and contributes large amounts of coarse particulate matter to the stream (Vannote et al 1980). Thus, productivity within these smaller upland streams does not come from within the channel itself, but rather from lateral exchanges with adjacent riparian forests, which indicates that the lateral dimension, while functionally different, is also strong in headwater streams. Furthermore, despite the differences in flow dynamics between small headwater rivers and large floodplain rivers, many of the same fundamental ecological processes dominate the lateral zones of the stream channel; for example lateral habitats exhibit lower velocities and shallower dimensions, and therefore serve as deposition zones and refugia for aquatic organisms (Gregory et al. 1991).

It is impossible to discuss lateral connectivity without also discussing the riparian zone because the riparian zone is the area where lateral exchange processes take place. The dimensions of the riparian zone vary and are influenced by the unique spatial and temporal dynamics specific to the ecosystem in which it occurs (Gregory et al. 1991). Generally speaking, it is bounded by the outward limits of flooding and the upward limits of the streamside canopy. Abundant literature is available regarding riparian zone structure and function, which should be referenced for more detailed information on these incredibly diverse and dynamic ecosystems (e.g. *Riparia: Ecology, Conservation, and Management of Streamside Communities* by Naiman, Decamps and McClain and *Riparian Vegetation and Fluvial Geomorphology* by Bennett and Simon (eds)). This discussion will focus on the riparian zone as it relates to the lateral dimension of stream connectivity, in which riparian vegetation influences the stream channel (morphology, water temperature, and heterogeneity), and the stream in turn influences the composition, productivity, and succession of riparian vegetation (Ward 1989).

Inputs from riparian vegetation ranging from dissolved organic matter, leaves and detritus, to large pieces of woody debris are critical to the functioning of upland forested streams (Ward 1989). Such allochthonous inputs (inputs produced outside of the stream) provide the food base for invertebrate consumers, thereby determining the trophic structure of the stream community (Lake et al. 2007; Gregory et al. 1991). These inputs, particularly large woody debris (LWD), are also major determinants of channel structure, and therefore the retentive capacity of the stream (Gregory et al. 1991). A stream's capacity to retain organic matter and sediment is largely determined by the presence of major obstructions like logs, branches and boulders that trap material in transport and create pockets of slower water velocity, allowing suspended particles to be deposited (Gregory et al. 1991). This process directly influences the availability of nutritional resources and habitat for most aquatic organisms (Gregory et al. 1991). Such allochthonous inputs are especially relevant to heavily wooded New England stream systems, for example, Bear Brook in New Hampshire, which was determined to receive more than 98% of its organic matter from the surrounding forest (Fisher and Likens 1973).

Riparian vegetation is also a major determinant of stream temperature and primary productivity, both of which are related to the amount of solar radiation that reaches the stream. As solar radiation passes through the riparian canopy, it is selectively absorbed and reflected depending on the structure and composition of the streamside vegetation (Gregory et al. 1991). One of the most critical factors in determining the heat contribution to the stream from solar radiation is the density of the canopy, which is also a major determinant of the quantity and quality of light available to aquatic primary producers (Gregory et al. 1991). Canopy cover is directly related to channel size (as channel width increases, the amount of canopy over the stream decreases), therefore, the influence of streamside vegetation on solar inputs generally decreases from headwaters to mouth (Gregory et al. 1991), while primary production from aquatic plants increases, and temperature increases (although the increased volume of water helps to moderate temperatures in larger downstream reaches). Other variables that influence stream temperatures are the continuity of canopy cover along the stream, the width and density of riparian vegetation, and groundwater interactions[4].

Exchange processes and disturbance regimes occurring between the stream channel and riparian zone are vital to the enhancement of ecological connectivity and biodiversity within the stream channel and into upland areas. Natural fluvial disturbances[5] (i.e. flooding), in conjunction with topography and geologic patterns, result in a broad range of micro-habitats, and therefore high biodiversity in the riparian plant community (Ward 1998; Muhar and Jungwirth 1998). For this reason riparian areas commonly include a mixture of upland and wetland plant species, potentially contributing a major source for plant dispersal (Gregory et al 1991). These diverse streamside plant communities in turn are major determinants of the stream's nutritional resources and habitat configuration (Gregory et al. 1991), and consequently biodiversity. Abundance and composition of invertebrate assemblages in streams, for example, are largely determined by the plant communities of the riparian zone[6] (Gregory et al. 1991). Furthermore, many animal and plant species are dependent on lateral exchange processes and disturbance regimes for movement between resource patches, which is often crucial for the species' recruitment. Many fish species,

[4] See Vertical Connectivity, page 25.
[5] See also Temporal Connectivity, page 32.
[6] Inputs from the riparian zone determine functional feeding groups/method of food acquisition.

especially in large floodplain rivers depend on episodic flooding for successful reproduction (Amoros and Bornette 2002; Roux and Amoros 1996). Therefore, the relationship between the stream and the riparian zone is a reciprocal one (Lake et al. 2007).

Through flooding, lateral erosion, and long-term channel migration, the stream channel maintains an intermediate level of disturbance, whereby competitive exclusion is prevented (Amoros and Bornette 2002; Ward 1998). The slow lateral migration of the stream channel in a forested ecosystem undercuts trees growing along concave banks, creating an opening in the canopy, and promoting new growth on the recently deposited alluvium of convex banks (Ward 1998). In this way, the stream system maintains a diverse array of habitat patches and successional stages along its corridor (Amoros and Bornette 2002; Ward 1998).

Since water and other matter from upland areas are continually being transported down slope into stream channels, the riparian zone serves another very important function: that of natural buffer and filter. A healthy, intact riparian corridor of sufficient width will remove large quantities of nutrients, sediment and pollutants from water running off upland areas before it enters the stream channel, thereby protecting the stream's water quality (Gregory et al. 1991; SCS 1975). Soil, detritus, stems and roots within the vegetated buffer slow the water down, intercepting particles, which indicates that the type of vegetation in this zone has a significant affect on its filtering capacity (herbaceous vegetation has more small stems and roots to slow water down, but does not create as much leaf litter, which is a better filter for charged particles). According to Soil Conservation Service unpublished data (1975), a 100 foot vegetated buffer will remove 89% of sediment, 81% of total suspended solids, 89.5% of nitrogen and 82% of phosphorus from runoff before they enter the stream channel.

Common Barriers to Lateral Connectivity

Watershed-scale Land Conversion

Because riverine processes are closely linked to the terrestrial landscape, conversion of land within the watershed from native vegetation to agriculture or urban development may result in major changes to the normal inputs of water and matter from terrestrial habitats to the stream (Jansson et al. 2007). In general these changes include increased inputs of sediment, pollutants and nutrients to the stream. Land conversion also results in changes to the food web structure, thus modifying the composition of the stream community (Lake et al. 2007).

Riparian Zone Conversion

As previously noted the composition and width of the riparian zone is important for effective filtering of nutrients and sediment; however, the length of the riparian zone is also important, as fragmentation, even small gaps, may impair these functions (Lake et al. 2007). Conversion of riparian zone forests to agriculture, urban development, or other uses may lead to significant alteration of the stream's sources of productivity. Opening up the channel canopy results in increased primary productivity within the stream and decreased inputs of coarse particulate matter from streamside vegetation, thus leading to a complete change in stream community composition and structure (Lake et al. 2007). Furthermore, the conversion results in decreased inputs of LWD, which are vital to maintaining heterogeneous structure within the channel.

Exotic Plants
Many species of exotic plants are known to be highly invasive along riparian corridors, particularly after any sort of disturbance has taken place. Invasive plants are highly disruptive to the stream's lateral connectivity due to their ability to crowd out native vegetation, thereby changing the food web structure and modifying community composition (Lake et al. 2007) of both the riparian zone and the stream ecosystem. Furthermore, invasive plants can create major changes in sedimentation, nutrient dynamics and organic matter breakdown (Lake et al. 2007; Hancock 2002).

Livestock
Cattle grazing in riparian corridors leads to negative effects on water quality (increased nutrients and particulate matter deposited directly into the stream), compaction of channel substrate[7], and degradation of streamside vegetation through feeding, trampling and introduction of invasive plants (Hancock 2002). When at all possible, livestock should be fenced away from stream corridors.

Altered Hydrology
Altered Hydrology resulting from the construction of dams, canalization, floodplain levying, water diversions, or wetland drainage result in reduced lateral connectivity and decreased heterogeneity (Ward 1998), both in-stream and within the riparian corridor. These practices reduce the typical seasonal linkages between the main channel and its riparian zone, floodplains, and wetlands. Ultimately these changes are reflected in the reduction of species diversity and fish densities (Muhar and Jungwirth 1998).

Channel Incision
Channel incision is a common response to altered fluxes of water and sediment caused by dams and other such anthropogenic disturbances. Due to the lowered elevation of the stream bed relative to its floodplain, the same flows delivered from upstream have a reduced ability to overflow their banks, resulting in reduced frequency and depth of floodplain inundation (Kondolf et al. 2006). Channel incision results in the reduced ability of a stream to overflow its banks, leading to decreases in floodplain productivity, nutrient exchange, and dispersal of biota between the river, the riparian zone, and the floodplain wetlands (Kondolf et al. 2006).

Lateral Connectivity and Choate Brook

For the assessment of Choate Brook's lateral connectivity we focused on recording transitions within the riparian zone. The significance of these transitions is difficult to identify without more knowledge of the history of the stream (i.e. what the original structure and vegetative composition were and what series of anthropogenic uses have shaped the land around the stream)[8]. A few observations and generalizations can be made regarding lateral connectivity based on the stream's ability to overflow its banks, signs of lateral channel migration, the amount

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[7] See Common Barriers to Vertical Connectivity, page 27-28.
[8] Historic aerial photographs, topographic maps, and written records may assist in an analysis of the original structure and vegetative composition of a landscape when such documents were created prior to anthropogenic landscape alteration. However, for many areas of New England, including the region that encompasses Choate Brook, documentation of pre-settlement conditions is sparse to non-existent.

of LWD present, the presence (or absence) of invasive plants, canopy cover, water temperature, and width, length and composition of the riparian zone.

Floodplain Connection, Lateral Channel Migration & Invasive Plants

Due to the high flow conditions at the time of this study[9], we were able to clearly see that Choate Brook, throughout most of its course, is well connected with its floodplain. In many places, especially where the riparian corridor was predominantly composed of wetland vegetation, the stream overflowed its banks and saturated the surrounding land. We also saw signs of slow lateral channel migration, with areas where trees had recently fallen over due to undercutting by the stream channel. While excessive erosion and migration is unhealthy for the stream ecosystem, the natural process of slow lateral migration adds structure to the stream channel, thereby increasing heterogeneity, and also opening up space for early successional species to come in, further increasing biodiversity. An additional sign of good lateral connectivity was the complete lack of invasive plants along the stream bank (none were identified in the study stretch).

Channel Canopy Cover

The appropriate amount of canopy cover for a stream channel is generally guided by its position within the stream continuum. It is difficult to accurately identify the degree of canopy cover that Choate Brook would naturally have (e.g. whether it should have 100 percent canopy cover or 50 percent). However, since canopy cover is directly related to channel size (Gregory et al. 1991), and Choate Brook is a relatively small stream, one would expect to see a fairly influential canopy along the brook. Our survey shows that less than half of the stream has 50 to 75 percent canopy, while most of the stream's canopy ranges from 1 to 50 percent cover, and no areas over 75 percent are present (Appendix B: Choate Brook Connectivity Study Riparian Map). It is noteworthy that the transition from denser canopy to more open canopy does not occur along a continuum moving downstream, but rather in patches throughout the study area. The stream's canopy is important for the addition of LWD to the stream channel as well as for the regulation of stream temperatures.

Large Woody Debris (LWD)

Although we did not complete a LWD inventory on Choate Brook, visual observations indicate that there is not sufficient LWD to provide cover or increase the channel's structural heterogeneity. The largest amount of LWD occurred in the middle reaches, largely as a result of lateral channel migration in the forested riparian zone, where undercut trees have fallen into the stream channel. Aside from these inputs, however, LWD was severely lacking; both upstream near the Greeley Road crossing and downstream toward Sampson Road the channel lacked LWD almost completely. These observations are consistent with a recent study of LWD in low gradient rivers of Coastal Maine (in which the West Branch Sheepscot was included), which showed that on average the frequency of LWD is remarkably low is all study streams (Magilligan et al. 2007). The study further showed that large pieces of LWD (≥50 cm diameter) are highly uncommon, reflecting the relative age of the riparian forests as manifest in the small size of the trees (most < 20 cm dbh) (Magilligan et al. 2007). This lack of LWD is important in

[9] In the summer/fall of 2008 Maine experienced higher than average rainfall, with 15 inches of precipitation occurring between June and August alone (134% of normal rainfall for these months) (Northeast Regional Climate Center 2008). For this reason, Choate Brook was flowing at or near bankfull on both days of the field survey.

regard to the channel's geomorphic functioning, which depends on large, stable pieces of LWD for pool formation and sediment storage, among other things. The dominance of small sized trees in riparian forests is a result of 19th and 20th century logging as well as recent timber harvest, which has continued to remove the more mature trees likely to donate LWD to the stream (Magilligan et al. 2007). The forested areas of Choate Brook are no exception; they are relatively young and there are signs of recent logging visible near the stream channel. With logging prohibited within 100 feet of the stream, however, these forested riparian corridors should eventually mature and begin contributing LWD to the stream channel. However, the non-forested riparian corridors will require more active restoration in order to repair lateral dynamics. Active reforestation will be necessary, with recognition of the fact that it may take well over a century for the restoration effort to pay off in terms of LWD being added to the system naturally. The restoration effort may therefore require the active addition/strategic placement of structural elements such as boulders and large pieces of wood to enhance channel structure in the meantime. Active reforestation will, however, have near immediate results in regard to helping to moderate stream temperatures.

Water Temperature

The water temperature data from 2000 were introduced in the longitudinal section[10] because it is potentially a barrier to longitudinal fish migration; however, the cause of the high stream temperatures is more related to lateral dimension conditions (with some potential influence from the vertical dimension). Riparian vegetation is a major determinant of stream temperature, and the density of the canopy is one of the most critical factors in determining the heat contribution to the stream from solar radiation. Within the study reach of Choate Brook, less than half of the stream has canopy cover greater then 50%, and large stretches have virtually no canopy cover due to the predominantly grass/herbaceous riparian vegetation.

Riparian Buffer

As is apparent from Figure 10, the 100 foot riparian buffer is continually vegetated for the entire length of the study area, with only small interruptions occurring at the road-stream crossings. The length and width of the riparian zone, therefore, indicate good lateral connectivity in regard to the filtering of nutrients, sediment, and pollutants. The primary variable regarding Choate Brook's riparian zone is its composition, which changes quite often for such a short stretch of stream. The dominant riparian vegetation changes from herbaceous/shrub-sapling to deciduous forest to coniferous forest back to deciduous forest to mixed forest to herbaceous/shrub-sapling again and finally to grass (Appendix B: Choate Brook Connectivity Study Riparian Map).

Considering all of these factors, the two primary concerns related to Choate Brook's lateral connectivity are 1) inputs of LWD and coarse particulate organic matter and 2) moderation of stream temperatures. Active reforestation and restriction of logging within the 100 foot buffer should go a long way toward restoring lateral dimension functioning. Periodic monitoring of water temperature during different flow and weather conditions will provide a clearer picture of the causes of high water temperatures and the effectiveness of revegetation efforts. Further, monitoring for invasive plants should be a component of any restoration effort that requires disturbance of earth.

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[10] See Longitudinal Connectivity and Choate Brook, page 15.

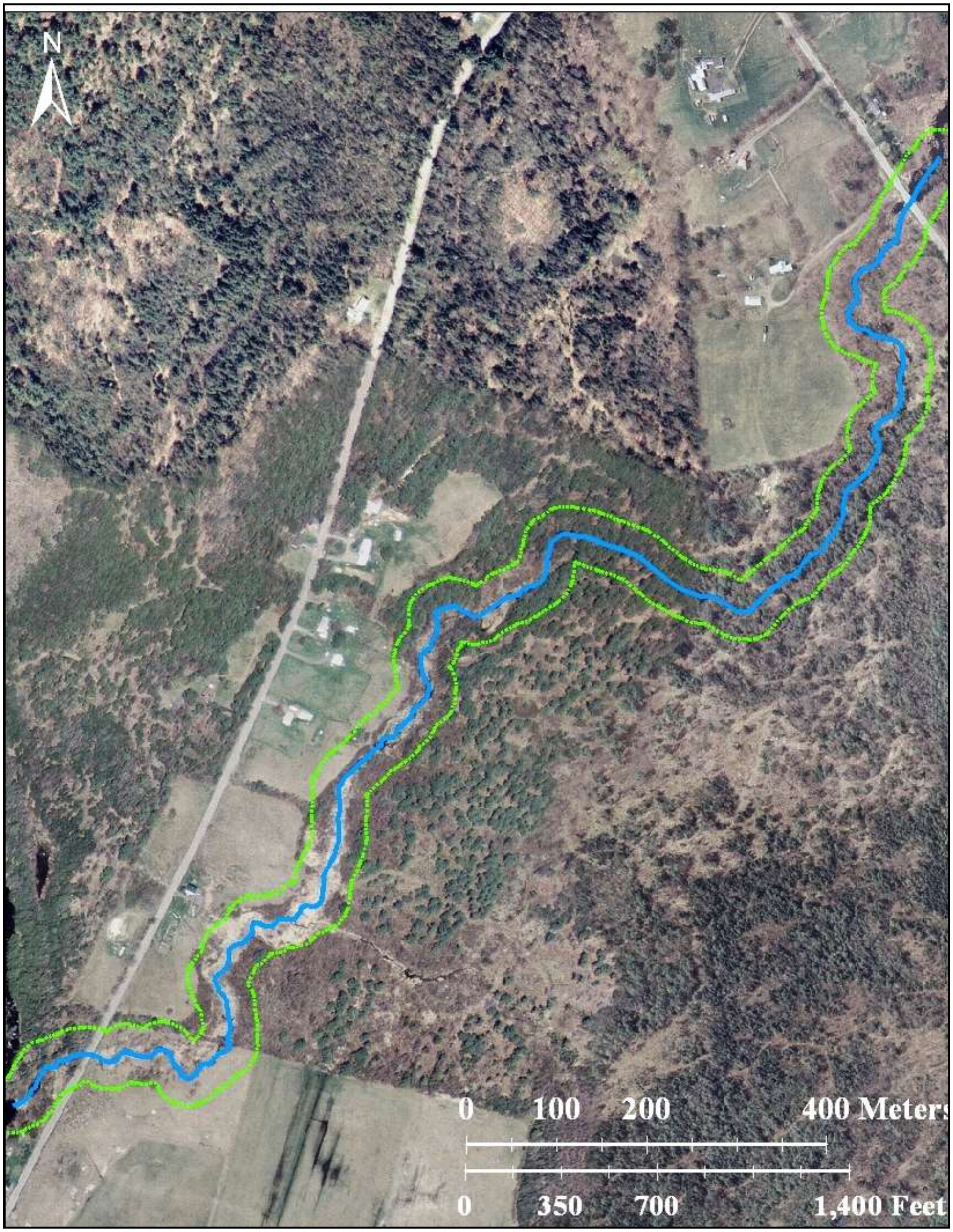

Figure 10. Choate Brook study area with 100 foot buffer indicated by green lines.

The Vertical Dimension

The vertical dimension encompasses interactions that occur at the interface between groundwater and surface water, which include exchanges of water, nutrients, biota and other materials. This groundwater-surface water interface is known as the hyporheic zone, and the flow of water through this zone is called hyporheic, or interstitial, flow (Figure 11). Although this zone can be extremely active biologically (Gordon et al. 2004), it is rather inconspicuous and consequently has been less studied than the longitudinal and lateral dimensions. Anthropogenic influences on vertical connectivity have seldom been considered (Kondolf et al. 2006).

Figure 11. Vertical Connectivity: the interface between surface water and groundwater (Alley et al. 2002)

Boulton et al. (1998; 60) present the following definition of the hyporheic zone, emphasizing its variability:

> *The hyporheic zone can be defined as a spatially fluctuating ecotone between the surface stream and the deep groundwater where important ecological processes and their requirements and products are influenced at a number of scales by water movement, permeability, substrate particle size, resident biota, and the physiochemical features of the overlying stream and adjacent aquifers.*

This definition shows the difficulty in assigning actual dimensions to the hyporheic zone due to the complex and ever shifting range of variables on which it relies. This zone may be meters thick and extend laterally away from the channel for kilometers, or it could be centimeters thick and extend only meters away from the channel, as is more often the case (Ward 1998). Hyporheic flow can be rather voluminous, in some cases equivalent to or larger than the volume of the stream itself, and can therefore have a high degree of influence regarding the proper functioning of ecosystem processes.

The hyporheic zone extends vertically into the saturated sediments below the stream channel and laterally into the sediments alongside the stream channel, which include the parafluvial zone (below the riparian zone) and alluvial aquifer (below the floodplain; often equated with groundwater) (Figure 12) (Boulton 2007; Hancock 2002; Ward 1998). Flow and exchange processes within the hyporheic zone are driven by groundwater movement and the upwelling and downwelling of stream flows, by which surface water is pushed down into the permeable stream bed, travels for some distance, and then reenters the stream (Kondolf et al. 2006; Boulton 2007). The strength of vertical connectivity is therefore heavily reliant on stream bed permeability, topography, and local flow regime. The permeability of the stream bed determines flow resistance in the hyporheic zone and is primarily controlled by substrate characteristics, particularly grain size and sorting (Kondolf et al. 2006). Bed topography influences the hydraulic gradient of the stream, which is an important driver of groundwater movement

(Kondolf et al. 2006; Boulton 2007). Pressure differences created from variations in stream flow over bed forms, for example pool/riffle sequences, and structural elements induce flow into the hyporheic zone.

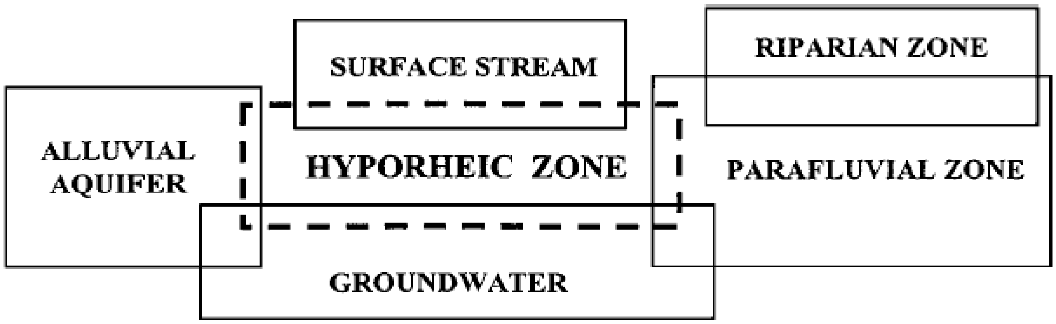

Figure 12. Simplified schematic diagram of the hydrological compartments that can interact with the hyporheic zone (Boulton 2007)

In natural stream systems vertical connectivity is predicted to be most influential in intermediate reaches with declining influence both in the headwaters and lowland rivers (Boulton et al. 1998). Although the hyporheic zone is usually less extensive in upland streams, the vertical pathway still contributes significantly to important ecosystem processes (Hancock 2002). Despite its location in the stream system, the hyporheic zone's relative significance depends on the functions it provides (e.g. thermal regulation, nutrient transformation/transportation, filtering, water storage and timing of release) and the degree of connection, which relies on the sediment characteristics and hydrology of the stream channel across a range of scales (Boulton et al. 1998). There are two primary pathways of interaction within the vertical dimension: water exchange and biologic activity (Boulton et al. 1998; Jansson et al. 2007; Ward 1998; Ward 1989).

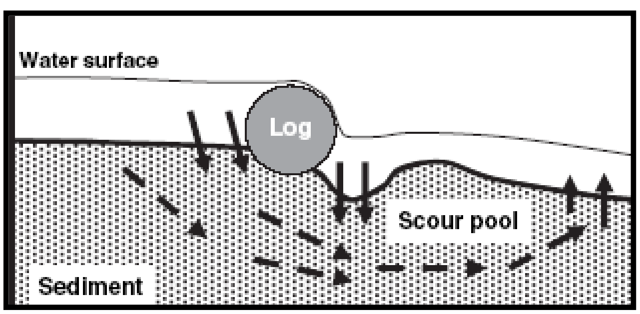

Figure 13. A log partially embedded log in the channel enhances downwelling and upwelling exchanges, indicated by the arrows. (Boulton 2007)

Hydrological exchange via upwelling and downwelling water contributes to the retention of water and nutrients, which is enhanced by reach scale heterogeneity, such as discontinuities in slope, depth, riffle-pool sequence, obstacles (e.g. logs, boulders) roughness, and permeability of streambed (Figure 13) (Boulton et al. 1998). Hydrologic retention is a delay in transport that occurs when water enters a hyporheic flow path and moves much more slowly than in the surface stream, allowing for filtration and transformation of nutrients, chemicals and dissolved metals, water storage, flood control and groundwater recharge.

The hyporheic zone plays a crucial role in maintaining water quality and nutrient cycling. During hyporheic flow, downwelling water, carrying dissolved oxygen, nutrients and organic matter (and sometimes chemicals and dissolved metals), mixes with groundwater and interacts with microbial biofilms that coat sediment particles (Boulton 2007; Boulton et al. 1998). Nutrients, chemicals and metals dissolved in the water are filtered out, taken up, or transformed by the microbial biofilms or other biogeochemical processes that are prevalent in the hyporheic zone (Hancock 2002; Boulton 2007). Microbial biofilms, in turn, are ingested by subsurface invertebrates, thus re-entering the food chain (Hancock 2002). Upon exiting the hyporheic zone, the chemically transformed, nutrient-rich upwelling water promotes growth of periphyton (tiny, aquatic organisms that live attached to the substrates on the stream bed) in localized zones of productivity along the stream bed, therefore enhancing the diversity of the surface water habitat (Boulton 2007; Boulton et al. 1998).

As previously noted, hydrologic retention also provides for water storage, flood control, and groundwater recharge (Boulton 2007). The hyporheic zone can act as a buffer to rising water levels, delaying, reducing or even preventing a flood, depending on the porosity of the river bed and stream bank sediments, as well as preexisting conditions (i.e. the degree of existing saturation at the time of the event) (Hancock 2002). This stored water is then slowly released back into stream flow during periods of lower flow, or it may slowly filter down into the water table. Upwelling groundwater serves a further function; since groundwater exhibits relatively constant, cool temperatures, as it is supplied to the surface stream via the hyporheic zone it generates cold-water refuges (thermal refugia) in the stream during the hot summer months (Amoros and Bornette 2002; Lake et al. 2007). These thermal refugia are vital to the survival of cold-water fish like salmonids when surface water temperatures increase. Furthermore, the vertical connection is essential for the incubation of salmonid embryos in stream gravels, which depends on the upwelling or downwelling water (Kondolf et al. 2006).

The second interactive pathway of the vertical dimension consists of organisms that dwell in or rely on the hyporheic zone. Many of these organisms reside in this region only temporarily, while others complete their entire life cycles here (Gordon et al. 2004). Ward and Stanford (1983), calling it a ‘faunal reservoir’, postulated that the hyporheic zone is so biologically rich it is capable of recolonizing the stream if depleted due to adverse conditions. The distribution of hyporheic organisms that occupy interstitial spaces (water-filled voids) between mineral particles is influenced by upwelling and downwelling zones, particle size, porosity, oxygen concentrations, food resources and water exchanges; and in turn, they influence all of these attributes (Ward 1998; Jansson et al. 2007). The same processes that create habitat diversity in the surface stream also result in habitat diversity within the hyporheic zone (Ward 1998). Although little research has been conducted on the subject, it is conjectured that high levels of biodiversity exist in these zones (Ward 1998).

Hyporheic organisms disturb sediments (bioturbation), generate nutrients for instream and riparian production, and assist with litter breakdown (Jansson et al. 2007). Through bioturbation, they affect substratum porosity, sediment aeration, stream metabolism, and matter and energy exchange processes between the surface and subsurface habitats (Jansson et al. 2007). It is also noteworthy that substantial connections exist between the food webs of the stream, hyporheic, and groundwater zones and therefore substantial energy is transferred among these systems (Boulton 2007). Furthermore, it is supposed that benthic macroinvertebrates seek refuge in the hyporheic zone during times of stress, such as flooding, droughts, predation, or deterioration of surface water quality (Boulton et al. 1998).

Common Barriers to Vertical Connectivity

Impairment of either of the two vertical pathways, water exchange or biological activity, will disrupt vertical connectivity, and often the disruption or collapse of one pathway will lead to impairment of the other (Hancock 2002). Vertical water exchange is affected by changes that lead to alterations of sedimentation patterns, water flow, hydraulic gradient, or overgrowth of microbial biofilms. Biological activity within the hyporheic zone can be impaired by anthropogenic pollutants, activities that lead to the clogging of interstitial pore spaces, rapid groundwater extraction, physical man-made barriers, or impaired water exchange processes. Impaired biologic activity often leads to clogging of interstitial spaces, thereby impairing water exchange.

Watershed-scale Land Conversion

Watershed-scale landscape alteration can be particularly disruptive to the vertical dimension with impacts resulting from excessive nutrients, modifications to natural riparian buffers, increased silt load, pesticides and herbicides, salinization, and hydrologic alterations such as increase runoff and decrease groundwater recharge (Hancock 2002). Since many of these changes occur simultaneously, it is difficult to isolate the individual effects of each change.

Altered Sediment Distribution

Activities that bring about changes in sediment distribution include construction of dams, roads, residential or other development, logging, mining, and changes in flow regimes (Boulton et al. 1998**).** Large-scale vegetation clearing resulting from development, logging, mining and road building, can lead to massive erosion and therefore high sediment loads transported into streams and deposited on stream beds. As the amount of fine sediments and organic matter increase on the streambed, the interstitial spaces fill in (a process known as 'colmation'), decreasing the porosity of the substratum and leading to significant reductions of water exchange (Amoros and Bornette 2002; Boulton 2007). The resultant reductions of dissolved oxygen, nutrients and organic matter entering the hyporheic zone negatively impact the functioning of hyporheic organisms (hyporheos) (Boulton 2007). In some cases newly deposited sediment or sand slugs may form a new hyporheic zone with reduced functionality, such as reduction of available carbon and surface water and altered nutrient dynamics (Lake 2007). A shift in the composition of the surface and subsurface macroinvertebrate community is a common result of the clogging of gravel-bed streams with fine sediments, such as a transition from mayflies (*Ephemeroptera*) and caddisflies (*Trichoptera*) to midgefly larvae (*Diptera*). Such changes in macroinvertebrate populations lead to a subsequent shift in the fish species compositions of the stream (Gordon et al. 2004).

Dams

Dams act as barriers to the downstream transport of sediment (Hancock 2002) and therefore reduce long-term sediment loading downstream (Boulton et al. 1998). The continuous scouring of the streambed immediately downstream of the dam wall can erode bed sediments to such an extent that the bedrock is exposed and the hyporheic zone completely removed (Hancock 2002). The impoundment created immediately upstream of the dam structure has the opposite effect on the hyporheic zone, with accumulating sediment and drastically reduced flow creating more of a lentic environment, in which many stream-dwelling macroinvertebrates cannot survive. On a larger scale, dams decrease flow dynamics within the vertical dimension by reducing the frequency and duration of high flows. This results in fewer flushing flows to dislodge accumulated fine sediment from the interstitial spaces (Kondolf et al. 2006; Hancock 2002). Without high flows to flush out fine sediments from the substrate, hyporheic organisms are left with reduced living space, low nutrient exchange, and poorly oxygenated water (Ward 1998).

Roads

Roads enhance transport of fine sediment into the streambed, leading to colmation (Boulton et al. 1998), which disrupts water exchange between the surface water and the hyporheic zone. This results in decreased dissolved oxygen, elevated nutrient concentrations, and increased ammonification in the hyporheic zone (Lake et al. 2007; Hancock 2002). Furthermore, the salting of roads in the winter can result in changes to the physicochemical conditions within the hyporheic zone, impacting biofilms and invertebrate communities (Hancock 2002).

Development

Housing construction and suburban development also lead to colmation (Lake 2007) due to increased fine sediment accumulated in runoff. The results are the same as noted for roads. Herbicides, fungicides, pesticides, heavy metals, and chemicals used in urban and suburban developments also attach to runoff as it makes its way to the stream channel. These unnatural materials are toxic to hyporheic invertebrates, interstitial bacteria, riparian vegetation, and the benthic algae and plants that assist with vertical exchange processes (Hancock 2002).

Logging

Traditional logging practices can increase transport of fine sediment into the streambed as well, clogging interstitial pore space (Boulton et al. 1998). Colmation disrupts water exchange between the surface water and the hyporheic zone, resulting in decreased dissolved oxygen, elevated nutrient concentrations, and increased ammonification in the hyporheic zone (Lake et al. 2007; Hancock 2002).

Agriculture

Likewise, common agricultural practices can lead to increased soil loss and subsequent colmation in down slope streams (Boulton et al. 1998), with impacts to vertical connectivity similar to those discussed above. Fertilizers and other nutrients that make their way into the surface stream encourage excessive algal growth on the streambed sediments, eventually leading to colmation. Pesticides, herbicides and other chemicals commonly used in agriculture are also transported down slope into streams where they may poison hyporheic invertebrates and microbes (Hancock 2002), without which the water filtration and nutrient transformation processes cease to operate. Moreover, chemicals such as those in agricultural runoff can move from the surface stream into groundwater through the hyporheic zone with little change in concentration (Hancock 2002), thus impacting groundwater faunal communities and potentially contaminating drinking water sources. The use of permeable irrigation ditches or channels further enhances the transport of contaminated water into ground- and surface waters (Hancock 2002).

Livestock

Failure to fence livestock from the stream was previously noted as being destructive to lateral connectivity, but it is destructive to the vertical dimension as well. Cattle and other livestock deposit nutrients and other organic matter directly into the stream channel (Hancock 2002), leading to excessive algal growth on the sediment surfaces that clog water exchange pathways. Livestock walking on the streambed compact gravels and resuspend silt (Hancock 2002), resulting in further disruption of vertical exchange processes both at the site and downstream where silts redeposit. The destruction of streamside vegetation due to trampling causes stream banks to become more vulnerable to erosion, which ultimately results in more sediments being deposited downstream where the fine particles settle out, clogging interstitial pore spaces.

Exotic Plants

In addition, livestock can be vehicles for the transport of invasive plants (Hancock 2002), which are often disruptive to the vertical dimension. In general, invasive plants change nutrient inputs and outtakes within the stream system[11] and displace native riparian vegetation, resulting in alteration of the normal cycling of oxygen, carbon, and other nutrients. Furthermore, in some streams, invasion by exotic plants has led to dramatic changes in gravel bar distribution.

Mining

Gravel Mining is another practice that is highly destructive to the vertical dimension, especially when it occurs directly alongside or within the stream channel. Gravel mining disturbs and physically removes sediments (Hancock 2002), potentially resulting in removal of part or the entire hyporheic zone. The mining process also resuspends silt, leading to colmation downstream. Instream mining can cause deepening of the channel, loss of channel structure (i.e. pool-riffle sequence), bank erosion, and lowering of floodplain water levels (Hancock 2002), all of which interfere with the vertical exchange of water and nutrients.

Sewage Discharge

The effects of sewage discharge on water quality have long been recognized; therefore, sewage discharges directly into surface waters of New England are a rare occurrence in today's society. However, discharges of effluent from septic tanks and leaky sewer pipes into groundwater are still a concern. Due to the vertical connection between groundwater and surface water, it is possible for contaminated groundwater from the surrounding catchment to move into the surface stream (Lake et al. 2007; Hancock 2002). If the hyporheic zone is intact and functional, the contaminated groundwater can be intercepted and most nutrients and pollutants filtered out before the water reaches the surface stream (Hancock 2002). The ability of the hyporheic zone to effectively remove coliform bacteria is yet uncertain, but preliminary studies conducted on groundwater invertebrates indicate that high levels of effluent impact the structure of the associated communities (Hancock 2002). This indicates that rather than hyporheic organisms being able to filter out such waste, the waste may harm the ability of the hyporheic communities to properly perform their normal functions.

Acid Rain

Acid rain has been a problem for much of New England. In regard to vertical connectivity, acid rain alters hyporheic physicochemical conditions, reducing precipitation of dissolved metals, and making habitat unsuitable for hyporheic fauna (Hancock 2002).

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[11] The nutrient composition of decomposing plant materials differs between native and non-native species and often invasive plants do not provide the same nutrients that the ecosystem evolved to depend on. Further, invasive plants have different water and nutrient requirements than native plants. Some invasive plants also add salinity to the soil.

Rapid Groundwater Extraction
One last consideration regarding vertical stream connectivity is the effect of rapid groundwater extraction from wells near the stream channel, which forces stream water through the hyporheic zone, reducing its residence time there. Reducing the contact time between sediments and water in the hyporheic zone is likely to reduce the effectiveness of physical and biological filtration processes, and the rapid influx of surface water into the hyporheic zone is likely to make it more vulnerable to surface water pollution (Hancock 2002).

Vertical Connectivity and Choate Brook

Although vertical connectivity within a stream cannot be seen with the naked eye, visible evidence does exist within the watershed and stream course that indicates potential disturbances currently occurring within this dimension. Current and historic landscape alterations are good indicators of disruptions that may be influencing this dimension, while the remnant dams and road-stream crossings represent specific, identifiable barriers to vertical connectivity within the study reach. Methods such as hydrometric instrumentation, tracer tests, detailed discharge measurements, or comparative analysis of temperature differences between the surface water and groundwater may be useful in future attempts to accurately assess hyporheic flow patterns and the specific impacts of potential disruptions discussed here.

Watershed-scale Land Conversion
Landscape-scale alterations in the Choate Brook watershed include conversion of forest to agricultural land (specifically hay/pasture) and logging, both of which have resulted in modifications to the natural riparian buffer. As discussed in the section on lateral connectivity, the riparian buffer is crucial for the filtering out of sediment, nutrients and pollutants transported down slope to the stream from upland areas, the prevention of massive bank erosion, and the contribution of LWD to the stream channel.

Riparian Buffers
Today the riparian buffers along the study reach appear to be of sufficient width and length to filter out most sediment, nutrients and pollutants coming from the surrounding landscape, which, in regard to vertical connectivity, means that hyporheic organisms are not being overwhelmed by excessive nutrients or poisoned by pesticides and other chemicals. For the most part the stream banks also appear to be stable, especially where dense grass and shrubs dominate them; however, in the forested stretch there are a few sites of localized, active

Figure 14. Localized bank erosion occurring in the middle, forested section of the study reach, Choate Brook, ME 2008.

erosion (Figure 14). These erosion sites may be contributing fine sediment to the stream bed, with the potential to clog interstitial pore spaces and restrict vertical flow paths. Lateral bank erosion is a naturally occurring process though, and the impacts are generally mitigated by high flows resulting from storm events (i.e. flushing flows). There is no evidence that flushing flows are being restricted in this stream; therefore, colmation of stream sediments due to such localized erosion is not likely to be a problem in Choate Brook's vertical dimension.

Riparian Zone Conversion

The large-scale conversion of the riparian zone from mature forest to the herbaceous, shrub-sapling, and young forest communities has had a major influence on channel structure and therefore an impact on vertical exchange processes. These new riparian communities are incapable of contributing sufficient LWD to the stream channel to provide channel heterogeneity, which is necessary to induce the downwelling and upwelling of water into and out of the hyporheic zone (Boulton et al. 1998). This lack of structural diversity in Choate Brook (Figure 15) is indicative of impaired vertical water exchange. As the forest stands bordering the stream channel mature, the inputs of LWD should significantly increase, creating more varied channel structure, and potentially increasing vertical connectivity. Unfortunately, the problem is not so easily solved within the areas that are not currently forested; here it may be necessary to manually restore channel structure through placement of structural elements or otherwise creating channel heterogeneity.

Figure 15. Choate Brook at different locations along the study reach showing lack of channel structure.

Also noteworthy in regard to channel structure is that the southern portion of the stream between the end of the forested riparian zone and the Sampson Road crossing has been scoured to such an extent that a clay lens is exposed in some places, meaning that the hyporheic zone has been severely reduced and in some cases completely removed. This clay lens, likely deposited during the last glacial period, is a natural characteristic, but would normally be overlain with coarse substrate such as gravel, creating a hyporheic zone. This clay lens lacks the permeability to transmit downwelling stream water or upwelling groundwater or to support hyporheic organisms; therefore the vertical pathway is disrupted here, although water may still be able to move laterally into adjacent stream banks. The causes of this scouring are not clear, but are likely related the historic transition of the riparian corridor from forest to agricultural land or possibly historic logging practices. Removal of upstream obstructions to bed load transport in conjunction with the placement of structural elements in the stream channel may eventually improve the substrate characteristics in this area, forming a new hyporheic zone.

Remnant Dams

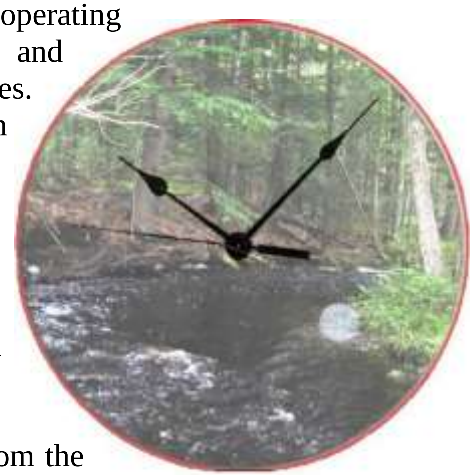
The structures of the two remnant dams that remain in Choate Brook continue to prevent the downstream transport of coarse sediment, and thus interfere with the natural bedload regime of the stream. With the remnant dams blocking the downstream transport of coarse sediment, the scoured beds downstream lack sufficient sources of coarse sediment for the replenishment of the hyporheic zone.

Road-Stream Crossings

Finally, the three road crossings on Choate Brook may be enhancing the transport of fine sediment into the stream, which, once again, could result in colmation. The dirt road in particular is a concern because its erosion potential is much greater. If the road is to remain permanently, its impact on the stream should be thoroughly assessed and actions taken to prevent erosion and subsequent transport of fine particulate matter into the channel. Winter road maintenance practices on all roads crossing the stream should also be assessed to determine if road salt is being used and transported into the stream, as the salinization will impact hyporheic organisms and thus the entire food web of the stream ecosystem.

The Temporal Dimension

All of the previously discussed processes and dynamics operating within the three spatial dimensions (longitudinal, lateral and vertical) also function within a broad range of time scales. Since time scales structure patterns and processes in a stream system, the temporal dimension can be thought of as a continuum of time within which the stream system operates. This dimension encompasses past, present and future and provides a framework through which the spatial dimensions can be evaluated. Knowing the stream system's history is essential to understanding its current state and future trajectory.



Streams function within various overlapping time scales, from the short-term to the long-term (Table 1). Stream ecologists and managers generally view streams on short time frames, such as days (e.g., a single disturbance event), seasons (e.g., changes in physicochemical factors) or years (e.g., the annual hydrologic cycle). Streams change hour by hour and day by day in response to changing flow rates and seasons; these temporary fluctuations affect the goods and services provided by the stream system because they induce behavioral responses from stream organisms. The historic time scale, on the other hand, induces adaptive responses from stream organisms and is therefore also vastly important for the management of lotic ecosystems. It operates on the order of decades to centuries and is the scale at which biotopes[12] are created, undergo regime shifts, or are destroyed (Roux and Amoros 1996). Changes such as terrestrialization, eutrophication, and ecological succession occur at the historic scale. Furthermore, the historic time scale is the level through which historic anthropogenic impacts to the system are viewed, such as the land management practices of the Native Americans or early European settlers. Thus the historic time scale is important to the long-term sustainability and adaptive capacity of the system. Finally, the long-term time scale deals with evolutionary and geologic change; this scale operates on the order of several centuries to millennia, and it encompasses the slow geologic processes through which river systems are developed, such as glacial events and tectonic activity. Understanding the geologic history of the stream system is necessary for context and to understand natural constraining characteristics within the system.

Time Scale	**Phenomenon**
Seasonal	**Spates, flow pulses, channel expansion/contraction**
Annual	**Flood pulse, seedling establishment, animal migration, reproduction, shallow ground water exchange**
Decadal	**Drought cycles, episodic events (extreme floods, debris flows), lateral channel migration, channel avulsion, island formation, channel abandonment**
Centennial	**Floodplain formation, hydrosere and riparian succession, deep groundwater exchange**
Millennial	**Terrace formation, glaciation, climate change, sea level fluctuation, orogeny**

Table 1. The phenomena that structure patterns and processes in stream systems occur over a range of time scales from short- to long-term. Adapted from Ward et al. 2002.

River ecosystem processes are emphasized by temporal changes in connectivity (Kondolf et al. 2006). This is highlighted by the fact that processes and events are frequently viewed and measured in temporal terms, for instance in regard to questions of frequency (how often?), timing (when?), duration (how long?), and rate of change (how fast?). Such temporal questions become particularly pertinent in regard to disturbance regimes (which lead to succession) and resource availability (or partitioning).

The natural disturbance regime of a riverine ecosystem consists of relatively discrete events, such as floods, droughts, debris flows, disease, and animal activities. Disturbance events open up space for colonization by individuals of the same or different species (Townsend 1989), thereby encouraging the simultaneous occurrence of temporal and spatial succession (Ward 1989). The disturbance regime, particularly the frequency of disturbance events, influences the diversity of aquatic species expected at a given site, with the highest diversity expected at moderate disturbance frequencies (Ward 1989; Ward et al. 2002). A temporal perspective is necessary in understanding the hierarchy of response times following disturbance, as organisms

[12] Biotopes are regions that have a characteristic set of environmental conditions and consequently a particular type of fauna and flora (Martin and Hine 2000).

and processes recover at varying rates (Ward 1989). The magnitude of the impact also determines the length of time required for recovery of the aquatic and terrestrial communities.

Temporal heterogeneity resulting from environmental fluctuations that allow for resource partitioning in a stream system increase the stream's potential for niche overlap (Ward 2002), and consequently biodiversity. Through environmental fluctuations such as disturbance regimes, temporal variation is able to reverse the trend toward competitive exclusion, allowing for the co-existence of an incredibly large number of species (Townsend 1989). Temporal resource partitioning, for example seasonal sequencing, further enables greater diversity by allowing ecologically similar species to utilize the same niche during different time frames (Townsend 1989). Further, seasonal fluctuations in the stream's discharge regime often correspond temporally with the reproductive cycles of fish species (Muhar and Jungwirth 1998; Ward 1989), as well as the life cycles of other aquatic and riparian organisms. The typical vegetation zonation of a riparian zone, for example, is dependent on both the frequency of flooding and the timing of discharge fluctuations throughout the year (Muhar and Jungwirth 1998). The consideration of temporal variation in the availability of resources in the stream system is essential to a complete understanding of stream ecosystem dynamics because these attributes (resource quantity and quality) are what drive the faunal response (Bissonnette 2007).

Common Barriers to Temporal Connectivity

Since the temporal dimension represents variation over time, barriers to temporal connectivity include activities that restrict or control natural variation, landscape transformations that permanently or semi-permanently alter natural variation, or management perspectives that ignore or overlook the temporal dimension of stream ecosystems. Distinguishing between anthropogenic perturbations and normal variation is often difficult, especially when knowledge of pre-existing conditions is limited and/or normal variation is due to long-term natural cycles with periodicities greater than a few years, the implications of which ecologists are only beginning to understand (Ward 1989).

Many historic and modern management practices regarding streams and their watersheds involve controlling natural variation (e.g., flood control, fire suppression, channelization, etc). Flow is the dominant driver of temporal variation in rivers; therefore, disruption of natural discharge regimes has far reaching temporal and spatial ramifications. Dams and other anthropogenic barriers to natural flows are disruptive to temporal resource partitioning and seasonal fluctuations on which many species rely (Muhar and Jungwirth 1998). The exclusion or suppression of natural disturbance regimes further reduces temporal (and spatial) diversity, resulting in fewer available niches and resources, and higher incidence of competitive exclusion, meaning considerably less biodiversity.

Ecologists and resource managers generally focus on landscape change from a spatial perspective, however, it is also vastly important for temporal repercussions to be identified. Historical events can have long-lasting impacts on ecosystem dynamics (Bissonnette 2007), with resultant legacy effects persisting for decades or centuries, even long after the landscape has seemingly recovered (With 2007). In terms of biological response, a legacy effect is essentially the delayed response of a species to ecosystem alterations; biological responses to human land use are typically not immediate, regardless of the severity of the impact (With 2007). Rather, biological communities undergo a time lag with the full impacts on some species not being realized for decades or even centuries after the human induced disturbance has ceased and the system, at least superficially, has recovered (With 2007). For example, in a study of the legacy effects of agricultural land use in Massachusetts during the 1800s, it was found that despite the large-scale return to a forested landscape, the structure and composition of the new forests are dramatically different, and significantly more homogenous, than what existed prior to agriculture (With 2007), despite having over a century to regenerate. Since natural streams are highly connected with their surrounding landscape, past land uses can also have significant effects on the biological diversity of the aquatic systems (With 2007), because the legacy effects of the surrounding landscape have a continuing impact on the stream ecosystem. Further, land use practices throughout the watershed result in changes to the stream's hydrologic regime, sediment load, organic inputs, temperature, and water chemistry, among other things, which may result in major alterations of stream function and structure and subsequent legacy effects on the aquatic community.

Resource management that ignores or overlooks the temporal dimension of stream ecosystems is potentially risky because landscape history is integral to sound environmental science and provides necessary context and guidance for ecosystem management (With 2007). Streams are inherently dynamic ecosystems operating over a broad range of spatial and temporal scales spanning decades, centuries or even millennia, but human land use activities may lie outside of the natural range of variability for the system (With 2007). Adopting a temporal perspective that integrates landscape history with natural variation may enable managers to better meet their goals of maintaining, protecting, and restoring stream ecosystems while also continuing to meet societal demands for the goods and services which they provide (With 2007).

Temporal Connectivity and Choate Brook

Like most watersheds in New England, the Choate Brook watershed has been heavily impacted by historic land use. Due to the lack of historical records or physical evidence indicating pre-European settlement conditions (Laser 2007), it is difficult to ascertain the extent to which the landscape has been altered, the degree to which the stream ecosystem has been impacted, or the amount of natural variability that has been lost. Historical records indicate that the riparian forests in most areas of the Sheepscot River basin and throughout mid-coast Maine have been harvested multiple times, either for conversion to agriculture or for the timber industry and firewood (Laser 2007). Many mills were necessary to accommodate such large scale timber harvest, and during the early 1800s they were constructed, along with accompanying dams, throughout the Sheepscot River watershed, on brooks of nearly any size. In our assessment of Choate Brook we found two remnant dams within less than a half mile from each other, indicating that this stretch was no exception to the rule. Furthermore, since streams were the major conduit for the transport of logs, structural elements, such as boulders and large woody debris, had to be removed from the channels to facilitate their transport to mills and ports (Allin and Judd 1995). Based on this information alone it is evident that major historic alterations to Choate Brook have taken place, largely resulting in homogenization of the stream channel and severing of natural dynamics.

Like Massachusetts' forests, Maine's forests have also had over a century to regenerate; however, they are likely exhibiting similar differences in composition and structure. The lack of

LWD recruitment from riparian forests is one such example, as LWD recovery lags forest recovery by centuries (Magilligan et al. 2007). Furthermore, much of Choate Brook's riparian corridor has not been allowed to revert to forest, although active agriculture is not occurring in these areas either. In light of historic events, several questions arise regarding Choate Brook's current state: 1) How long does it take for a stream to recover to a fully functional, fully connected state, after such dramatic alterations? 2) Is it necessary for the surrounding landscape to fully recover in order for stream function to fully recover? 3) What sampling strategies can be utilized to assess whether the stream has fully recovered without knowledge of its pre-disturbance condition? and 4) What is the appropriate time scale through which to evaluate stream recovery from historic land use change?

Cumulative Impacts

Although here the four dimensions of the stream system have been considered separately, they are interlinked, often in complex ways. They therefore must all be considered simultaneously and the cumulative effects of their disruptions assessed in order to fully understand the implications for ecosystem processes and the management of fish populations. Due to the interconnectedness of these dimensions and feedback within the system, it may not always be possible to separate phenomena acting at different spatial and temporal scales; moreover, events occurring at different scales or dimensions often have a net effect on the stream ecosystem. Additionally, small changes may have major impacts on the long-term evolution of the system if the conditions are right for those small changes to become amplified through positive feedback (Lane and Richards 1997).

Earlier in this paper Choate Brook was described as a typical New England stream without the conspicuous problems often associated with streams in heavily urbanized or agricultural watersheds. While it is true that Choate Brook's discharge regime is not regulated by dams and that few sources of anthropogenic nutrients or pollutants exist within the watershed, our connectivity study identified numerous potential barriers to the normal functioning of ecosystem processes. Figure 16 shows the sequence and spacing of these barriers and begins to paint a picture of what is happening in this system. However, Figure 16 does not clearly identify the land use practices that have occurred over time or the temporal variability that has been disrupted; neither does it demonstrate what is occurring vertically in the hyporheic zone. It is noteworthy that the vast majority of barriers on Choate Brook are historic in nature, remnant dams and bridges that have long since been abandoned and forgotten. The structures, however, partially remain, still exerting control over natural stream processes.

Within a 1.25 mile stretch of stream 12 potential barriers to connectivity were visibly identifiable. While many of the barriers seem insignificant individually, cumulatively they increase the impact to the natural ecological functioning of the stream ecosystem. Beyond these readily apparent barriers, factors such as canopy cover, lack of LWD, water temperature, bank erosion, bed load interference, and lack of heterogeneity in channel structure also interfere with the various dimensions of stream connectivity. Further, watershed-scale land conversion and riparian zone conversion, while not specifically identified, are visible as well; however, where forest has regenerated, past land use practices that continue to impact the stream ecosystem are not as evident. The overall effect in Choate Brook has been a substantial decrease in heterogeneity and a related suspected decrease in biocomplexity of the stream system, likely resulting in reduced capacity to support a diversity of species.

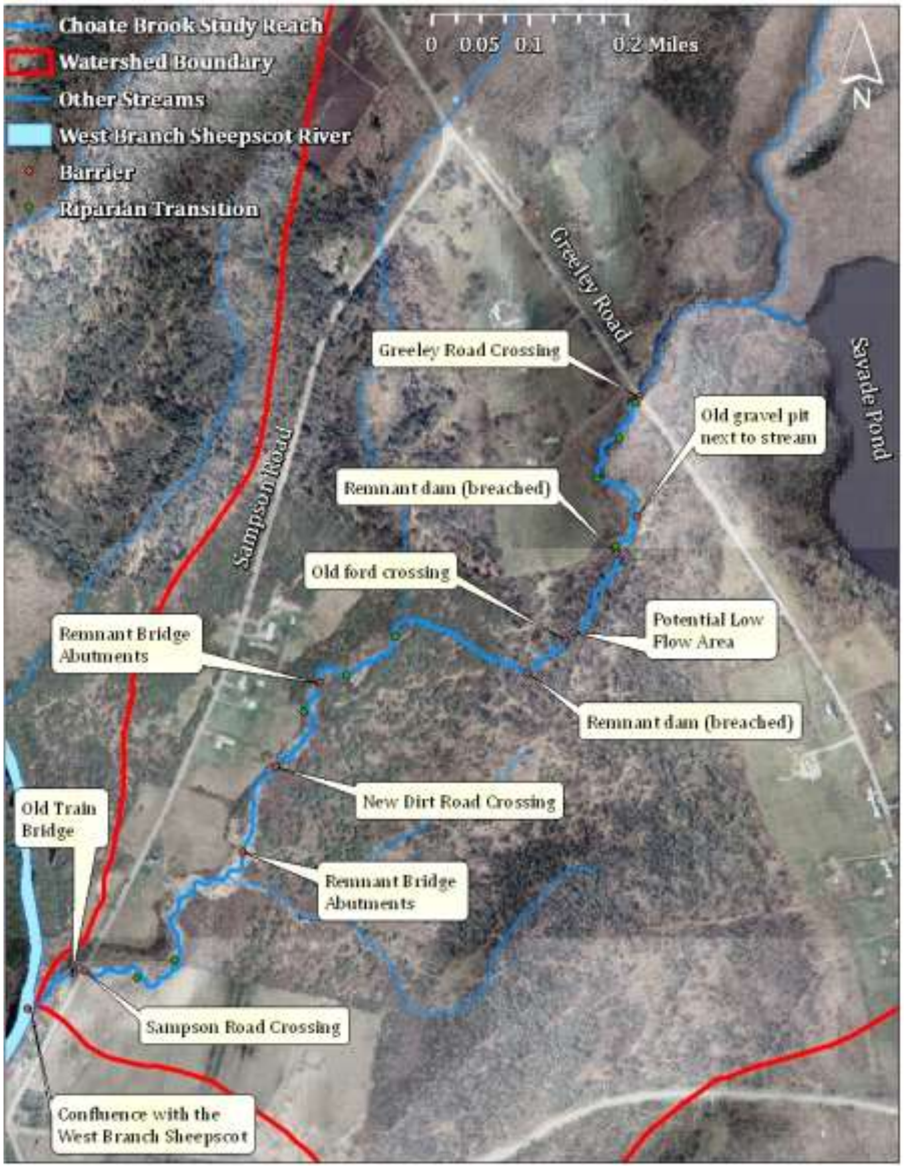


Figure 16. Map showing the sequence and spacing of barriers identified via a pedestrian survey of Choate Brook, ME 2008. More detailed information regarding these barriers can be found in Appendix B.

In brief, the cumulative effect of barriers to natural connectivity within the four dimensions of a stream ecosystem undermines natural ecosystem processes, as well as management attempts to restore physical habitat or species diversity. Interference with ecological processes impacts the stream system’s capacity as a formative and regenerative force.

Recommendations and Conclusion

Historical land use has left its mark on Choate Brook and most other streams in New England, and current land use continues to fragment these important ecosystems to the detriment of the very fisheries on which human life has depended for centuries. Resource managers seeking to improve these fisheries have tended to focus heavily on the longitudinal dimension of streams, generally from the perspective of fish passage. Effective management and restoration of streams, however, requires a shift toward the consideration of processes and interactions operating at different spatial and temporal scales and the reestablishment of environmental gradients and connectivity across all four stream dimensions, thereby reinstating the natural dynamics of these systems (Ward 1998). Focus should not be placed on a single species, a single level of diversity, or a single degree of connectivity, but rather on sustaining or restoring processes and interactions in order to increase spatial and temporal heterogeneity (Amoros and Bornette 2002), thus increasing the biodiversity of aquatic and riparian biota (Ward and Tockner 2001).

Additionally, successful management and restoration requires that the different connectivity requirements of each species, life stage, guild (group of diverse species occupying a common niche in a given community), and community are recognized and factored in to measures taken (Jungwirth et al. 2000). Evaluating the relative importance of interactions within the various dimensions, rather than the strength of connection, is critical from the fish ecology standpoint (Jungwirth et al. 2000). This approach demands a focus on the individual situation of the aquatic habitat and resident species (Jungwirth et al. 2000), recognizing that "many system dynamics cannot be understood without accounting for the context, structure and meta-structure derived from the unique combination and interactions between hierarchical elements and subsystems that make up the ecosystem" (Poole 2002). Furthermore, assessment and evaluation measures need to go beyond standardized surveying of structural-morphological habitat features and increasingly incorporate information regarding the dynamic spatio-temporal processes responsible for the formation, maintenance and regeneration of habitat features (Muhar and Jungwirth 1998). This shift will require the development of a set of informative and practical parameters that enable type-specific (e.g. alluvial, constrained, braided, meandering) processes inherent to the stream system to be recorded and assessed in all four dimensions (Muhar and Jungwirth 1998).

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Appendices