MITIGATING IMPACTS OF NEW FOREST ACCESS ROADS ON WATER LEVELS IN FORESTED WETLANDS: ARE CROSS-DRAINS ENOUGH?

by

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ABSTRACT

New forest access roads are routinely constructed across sections of forested wetland in Canada's maritime provinces. Seven such roads in southwestern Nova Scotia and central New Brunswick were examined. Treatments of 20 m and 40 m culvert spacing were used to determine which spacing would best maintain natural wetland hydrology under the road after construction. Water table depths on both sides of each road were measured, with shallow wells, before and after the road was constructed. In six of seven sites, the part of the wetland upslope from the road had a significantly higher water table than the adjacent wetland downslope, after right-of-way clearing (before road construction). This condition continued after road construction regardless of treatment. These results suggest that natural wetland hydrology had been altered during right-of-way clearing and that alternative approaches to right-of-way clearing seem warranted to maintain natural wetland hydrology. In addition, further testing of culvert installation or other methods to maintain natural hydrology under roads through wetlands is needed.

LIST OF ABBREVIATIONS USED

SFI	Sustainable Forestry Initiative
ROW	Right –of -Way
GPS	Global Positioning System
BMP	Best Management Practice
Pre	Pre-Road Construction Measurement
PC1	First Post -Road Construction Measurement
PC2	Second Post -Road Construction Measurement

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Chapter 1. Introduction

Wetlands have been described as imperative landscapes for economies and ecosystems on both a national and global scale (Government of Canada, 1991). The Federal Policy on Wetland Conservation (Government of Canada, 1991) estimated that Canada possessed one quarter of the world's remaining wetland (127 million hectares), and Canadian wetlands are valued in the billions of dollars based on land value and their numerous ecological functions. With this in mind, conservation of these landscapes has become increasingly more important due to improved knowledge of the extensive ecological services they provide (Woodward & Wui, 2000). The unique ability of a wetland to retain water in its organic layer is one reason that wetlands are so highly valued. Water retention capabilities of wetlands reduce the erosive potential of water run-off from the surrounding area and allow sediment and heavy metal capture to occur throughout the soil profile (Gren et al., 1994). While doing so, they also act as nutrient sinks within the environment, capturing, holding and cycling many nutrients including nitrogen, phosphorus, sulphur, and carbon (Greb et al., 2006; Mitsch and Gosselink, 2000). These water- and nutrient-rich areas result in habitat for a diverse array of plant and animal species.

The general definition of a wetland which is used in The Canadian Wetland Classification System (National Wetlands Working Group, 1997) is:

> "Land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment" (p. 12).

Although the national definition of a wetland is broad, wetlands are generally categorized throughout North America a similar manner. Regional jurisdictions have developed their own definitions of wetland to fit their specific geographic area; such is the case with Nova Scotia and New Brunswick. Thus, a wetland is:

> "(An area that) either periodically or permanently has a water table at, near or above the land's surface, or that is saturated with water; and sustains aquatic processes as indicated by the presence of poorly drained soils, hydrophytic vegetation, and biological activities adapted to wet conditions" (Nova Scotia Department of Environment, 2011, p. 1).

> "Land that has the water table at, near, or above the land's surface, or which is saturated, for a long enough period to promote wetland or aquatic processes as indicated by hydric soils, hydrophytic vegetation, and various kinds of biological activities adapted to the wet environment" (New Brunswick Department of Natural Resources, 2006, p. 12).

Within these regional definitions, classifications such as fens, bogs, marshes, and shallow open water would be identified wetlands. The provincial governments of Nova Scotia and New Brunswick also have specific descriptions for a particular wetland type classified as a swamp, which is also commonly referred to as forested wetland (New Brunswick Department of Natural Resources, 2006; Nova Scotia Department of Environment, 2011).

According to the Canadian Wetland Classification System, the water table in swamps are normally at or below the surface of the soil, which is normally mineral-based (National Wetlands Working Group, 1997). Typically, the mineral soil layer limits the drainage of water through the soil profile resulting in wet soil conditions. Swamps are dominated by trees or shrubs, which often provide greater than 30% canopy cover (National Wetlands Working Group, 1997). Non-coniferous vegetation most commonly occurs in swamps which are drier and have more nutrient-rich soils, while lower-lying shrubs are found in wetter areas, and coniferous vegetation can occur across a spectrum of these saturation levels due to their ability to survive in both rich and poor soils (National Wetlands Working Group, 1997).

Conservation of wetlands, including forested wetlands, in Nova Scotia and New Brunswick is guided by each province's wetland conservation policy. Both of these provincial policies are relatively new, with Nova Scotia first implementing its policy in 2011 and New Brunswick in 2002. The backbones of both provinces' wetland conservation policies are the "no loss" objectives for wetlands which have been classified to be "significant," and the prevention of net loss in total wetland area and ecological function for all other wetlands (Government of New Brunswick, 2002; Government of Nova Scotia, 2011).

In order to reach these objectives, Nova Scotia and New Brunswick have outlined hierarchical processes for wetland conservation when any type of development occurs in or near a wetland. First, proponents of the development must avoid disturbing the wetland, which would therefore avoid any adverse effects to the wetland. If avoidance is not possible, proponents must minimize the adverse effects to the best of their abilities (Government of New Brunswick, 2002; Government of Nova Scotia, 2011). The Government of Nova Scotia also requires compensation for any unavoidable adverse effects that may occur during development (Government of Nova Scotia, 2011). In addition to the "avoid-minimize-compensate" mitigation sequence mentioned above, Nova Scotia and New Brunswick require wetland alteration approvals when a proposed development will impact a wetland.

The creation and implementation of wetland policies in Nova Scotia and New Brunswick have the potential to influence the way industry operates within the respective provinces, including the forestry sector. Forestry companies in these provinces encounter wetlands on a regular basis when harvesting and transporting wood products and equipment (J. Gilbert, personal communication, May 2011). Like many areas of the world, the forest industry in the Maritimes relies on the construction of new roads to access remote sections of timberland that would otherwise be inaccessible, while also enabling harvested timber to be transported over large distances efficiently (Rummer, 2004). Although road construction provides access to harvestable trees and neighbouring harvest blocks, the roads also often impact forested wetlands in a variety of negative ways, quite commonly by flooding large areas of the adjacent wetland, killing trees and ultimately reducing harvest potential.

When preparing a site for typical road installation, forestry companies in the Maritimes first clear-cut a narrow stretch of forest to and through the area selected for harvest. The timber from these sites is removed and the remaining stumps are excavated from the soil and used to build a base for the new road. The stumps are then covered with the soil excavated directly adjacent to the road. This soil acts as the surface for the new road and its excavation creates a ditch that allows water movement away from the walls of the road. These road construction practices are often applied when companies cross forested wetlands, resulting in damming of the sub-surface water (Anderson, 2007; R. Badcock, personal communication, May 2011). Disruptions of water tables in forested wetlands have been assumed to be caused by the impermeable barrier created by the compaction of the road materials and the use of ditches. This disruption can raise the water table on the higher side of the road, which can lead to flooding of the road area and drowning of vegetation. At the same time, the lower side of the road can experience a lowered water table where the drying of the soil can also lead to mortality of vegetation (Anderson, 2007; J. Gilbert, personal communication, May 2011). It is in the best interest of provincial governments and the forest industry to work collaboratively to develop methods that can maintain forested wetlands while still allowing forest operations to take place in the landscape.

1.1 Objective of the Study

The objective of this study was to determine the effect that culvert (or cross drain) spacing in newly constructed access roads had on water table levels in forested wetlands. This would be achieved by experimenting with two separation distances between cross-drains: 20 m (most commonly used in the Maritimes) and 40 m. This information could then be used by organizations to help develop new best management practices (BMPs) when constructing access roads across forested wetlands.

The null hypothesis for this test states that responses of water table levels should not be different for the two culvert spacings. This null hypothesis was developed because it was expected that a set of data collected before road construction would be representative of natural water table levels in the selected wetland, and the subsequent data collected would show how the road construction and culvert spacing would affect the movement of water. With some prior knowledge of the impacts of roads in wetlands, it was expected that post-road construction measurements would reveal variation in water table levels associated with different culvert spacing. The treatment that differed least from the natural water table levels would be deemed the most effective culvert spacing for the movement of water across the road.

1.2 Partnerships

Funding for this project was provided by SFI Inc., a non-profit organization that administers the Sustainable Forestry Initiative certification program. Many forest product companies in North America are members in this certification program, including J.D. Irving Limited and the former Bowater Mersey Paper Company (henceforth referred to as J.D. Irving and Bowater Mersey).

At the outset of the project, J.D. Irving and Bowater Mersey offered to be involved in the project. These companies own a large amount of land in each province and J.D. Irving also operates on large sections of Crown land in New Brunswick. Both J.D. Irving and Bowater Mersey agreed to help develop new BMPs for forest access road construction when working in forested wetlands, in conjunction with researchers at Dalhousie University.

The road construction associated with this study was carried out as an in-kind contribution of J.D. Irving and Bowater Mersey. In-kind contributions have also come in the form of professional assistance from John Brazner (Nova Scotia Department of Environment; currently with Nova Scotia Department of Natural Resources), John Drage (Nova Scotia Department of Natural Resources), and Mark Partington (FP Innovations) as well as members at Ducks Unlimited Canada. During the study, Bowater Mersey sold its entire landholdings to the Government of Nova Scotia, and it no longer functions as a forest product company in Atlantic Canada.

1.3 Organization of the Thesis

The next chapter “Background and Literature Review” describes current literature from various areas of the world, regarding related studies and application of BMPs. The “Methods” chapter describes the study sites and the methods used in this study. The “Results” and “Discussion” outline and examine the findings of the study and lastly, Appendices and References are provided at the end of the report.

Chapter 2. Background and Literature Review

The presence of a wetland in a particular landscape is dependent on the climate, hydraulic properties of the soil, and local topography of an area. Wetlands develop in locations where these characteristics form and maintain an elevated water table, which result in hydric soils and hydrophytic vegetation (Tiner, 1999). Water enters and exits wetland systems through precipitation and evaporation, as well as inputs and outputs from both surface and groundwater sources (United States Geologic Survey, 1999; Winter, 2000). The movement of water and the length of time that a wetland will remain saturated are dependent on soil characteristics such as porosity, permeability, and amount of organic material present, as well as temperature and microbial activity (Verpraskas et al., 2002). Many of these hydrologic processes are also seasonally dependant, meaning that the existing water table levels are directly related to seasonal variability in such variables as precipitation and temperature (Tiner, 1999; United States Geologic Survey, 1999).

Due to the accumulation of water in a wetland, soils are often anaerobic (Brinson et al. 1981; Hammer, 1989). These anaerobic conditions result in different physical and chemical characteristics in the soil when compared to surrounding upland areas (Mitsch and Gosselink, 2007). Physical characteristics such as high bulk density and low porosity allow consistent presence of water in the soil and creates conditions that are anaerobic and reducing instead of aerobic and oxidizing, as would be found in soil that is not saturated (Bridghman et al. 1998; Hammer, 1989). Over time, these anaerobic and reducing environments create soils that have a high percentage of organic material, while having low pH and available nutrients (Hammer, 1989; Johnson, 1991). The slow rates of water flow and decreased rates of decomposition cause wetlands to collect sediments and also act as sinks for nutrients such as nitrogen, phosphorus, and sulphur as well as metals (Bridghman et al. 1998; Hammer, 1989; Johnson, 1991; Woodward & Wui, 2000).

Anaerobic conditions in hydric soils impact vegetation and can cause species in wetlands to be different from the surrounding upland areas (Verpraskas et al., 2002). Species of hydrophytic vegetation are adapted to complete or partial anaerobic environments where their roots can survive without aerobic respiration (National Wetlands Working Group, 1997; Scott et al., 1989). Many of these species can also occur in upland areas (Scott et al., 1989; Welsch et al., 1995); however, individuals would likely experience more growth and deeper root systems than they would if they were in a wetland environment (Mitsch and Gosselink, 2007; U.S. Army Corps of Engineers, 1987). Wetland conditions cause vegetation to have shallow root systems, but the same conditions can promote high growth rates in certain species. Larger plants can impact the hydrology of the wetland by decreasing water levels during the growing season and when harvested, water levels can rise as a result (Tiner, 1999).

2.1 Ecological Effects of Roads

Roads have become a necessary component of human transportation and the number of roads is increasing to enhance movement of people and goods. Unfortunately, the introduction and expansion of road systems in landscapes have many negative impacts on surrounding habitats. Roads alter a multitude of the physical and chemical characteristics of a landscape, as well as modifying the actions and movement of the biota in a particular region.

Roads fragment the landscapes in which they are placed, physically separating sections of land from each other. This physical partition disrupts natural horizontal processes such as surface and groundwater flow (Forman and Alexander, 1998). Groundwater and surface run-off water are intercepted by interruptions in the organic layer such as ditches and are diverted alongside the road and typically moving the water into a surface channel or stream (Trombulak and Frissell, 2000). The connecting of road structures to the hydrology within a landscape through culverts and ditches typically causes larger and earlier discharges, resulting in decreased amounts of water in higher elevation areas of the water table and flooding at lower elevations (Forman et al., 1995). In contrast, if methods of installing cross-drains are not performed properly during road construction, the upper-gradient areas will experience higher than normal water table levels while drying the lower-gradient sections (Forman et al., 1995; Forman and Alexander, 1998).

Increased rates of water movement can lead to increased amounts of erosion in landscapes (Forman et al., 1995; Forman and Alexander, 1998; Spellerberg, 1998). Erosion increases the amount of sediments that enters a watercourse and can have impacts many kilometres away from the area where they originated (Trombulak and Frissell, 2000). In addition to sediments, altered water flows can move and release nutrients affecting the overall water quality in the ecosystem (Trombulak and Frissell, 2000).

Aside from water quality issues that may affect aquatic biota, roads impact terrestrial biota as well. Roads are a source of contact between humans and animals, resulting in animal-vehicle collisions (Andrews, 1990; Spellerberg, 1998). These animal-vehicle collisions often result from animals using roads as travel corridors. Other species will avoid these areas because vehicle noise restricts movement within a landscape patch (Andrews, 1990). Movement of some types of natural vegetation species can also become restricted when coming in contact with roads (Robinson et al, 2010). These species can become inhibited further by the introduction of invasive species along roadsides where early successional species typically have little competition (Andrews, 1990; Trombulak and Frissell, 2000).

. Construction of forest access roads is an important aspect of timber harvesting and management, providing a means for transporting timber and equipment as well as creating fire barriers and access for other activities. Although the construction of roads is necessary for the survival of the forest industry, the health of the surrounding ecosystems needs to be considered when planning and installing these structures (Robinson et al, 2010).

On average, from 2010 to 2012, J.D. Irving constructed 519 kilometres of new forest access roads per year in Nova Scotia, New Brunswick and Maine. This is in addition to the ~25,000 kilometres that were installed previously and are currently being maintained (J.D. Irving, Limited, 2012). When installing sections of forest access roads J.D. Irving constructs the roads straight and in a grid-like pattern to make travel and removal of timber more efficient.

Bowater Mersey sold 224,600 hectares of land to the province of Nova Scotia in 2012. While operating, Bowater Mersey constructed 2,500 kilometres of road in its operating areas from 1929 to 2012 (Nova Scotia Department of Natural Resources, 2014). Existing road networks and the continued construction of new forest access roads outline the need for practices which decrease the impacts on wetland function.

The series of processes that have been found to work best during day-to-day operations (road construction, harvesting, etc.) are outlined in a company's BMP documents. Although many companies already have basic guidelines in place regarding road construction in wet areas, members of the research team for this project questioned their effectiveness and efficiency. It was suggested by members of the research team at initial meetings that road construction methods might be improved so that the natural hydrology of forested wetlands is maintained with minimal impact on forestry operations.

2.2 J.D. Irving and Bowater Mersey Road Construction Methods

Road networks are one of the most important assests of forestry companies such as J.D. Irving and Bowater Mersey. These companies rely on road systems for all transportation in woodlands, including withdrawal of wood, and must be designed to be both safe and efficient. To maintain safety and efficiency, installation of forest access roads is performed differently depending on whether the area being crossed is classified as a wetland or as a dry landscape (i.e., upland). The first step of road installation, regardless of the type of landscape being crossed, begins with planning and site assessment. Site assessment is normally conducted on foot, and is used to determine whether there are major obstacles to the road construction process, which include the presence of wetlands (Rummer, 2004). A recently developed depth-to-water table model has aided J.D. Irving in assessments in New Brunswick but was not applied to Bowater Mersey's assessment processes in Nova Scotia (Murphy et al., 2007). This method uses a combination of elevation modeling combined with hydrographic data from the area to identify areas that have high water tables (i.e. wetlands), often with more accuracy than obtained using maps and aerial photographs. This tool can also detect the hydrologic connectivity of water tables across the landscape that may not be apparent with other methods (Murphy et al., 2007). The accuracy of results for the site assessments is especially important for J.D. Irving and Bowater Mersey because road construction is typically permanent (roads are not decommissioned) to allow for continued access to operating areas.

After site assessment is completed and any necessary changes are made to the road layout plan, construction can commence. The first stage of road construction in any type of landscape is the clearing of a narrow strip of trees (i.e. the right -of -way) where the road surface will eventually be placed. The right -of -way (ROW) is normally cleared mechanically using a feller-buncher, which cuts the trees at their base and places them in the wooded area outside of the ROW. The feller-buncher typically makes two passes to clear the ROW in order to achieve the desired width necessary for the type of road, clearing one side of trees on the way into the harvest block and the other side on the way back. The clearing of the ROW does not take into account the type of landscape being encountered unless the machinery encounters an unforeseen obstacle (e.g. an exceptionally wet area or watercourse).

2.2.1 J.D. Irving and Bowater Mersey Best Management Practices for Road Construction in Upland Areas

Upland areas with good soil drainage are ideal for road construction. If the landscape allows, site assessment will ensure that the majority of road construction will occur in these areas. Upland road construction methods are completed with the use of an excavator and bulldozer. The excavator removes stumps of harvested trees and flips them upside down so that the section once attached to the tree trunk is pointing into the ground; this is used at the base of the road. The excavator then removes soil adjacent to the roadbed and places it on top of the overturned stumps until it is able to move forward. The bulldozer follows behind the excavator, smoothing out the soil used for the surface of the road. The area from which the soil was removed can now act as a ditch for removal of water away from the base of the road. These ditches typically move water to an area of the road where there is a natural depression and the water can be displaced across the road through a culvert.

The placement of the road in the ROW varies depending on the forestry company. Roads constructed by J.D. Irving are typically placed on what appears to be the higher side of the ROW, resulting in one side of the road being adjacent to the standing forest and the placement of the ditch in what is remaining of the ROW. Roads constructed by Bowater Mersey are typically placed in the middle of the ROW, allowing for soil used for the surface of the road to be taken from both sides, resulting in two ditches.

During road construction at Bowater Mersey and J.D. Irving sites, all movement and transportation of machinery takes place within the 20 m width of the ROW. This includes the two passes of the feller-buncher, followed by installation of the road which is performed by an excavator, bulldozer and any other machinery necessary (e.g. dump trucks). Once the road has been installed on a portion of the ROW, processors move within the remaining exposed section of the ROW to process the trees and place them on the road surface for collection. Forwarders are then used in the same exposed section of the ROW to collect the processed timber from the road surface and move the timber off site. The movement of the processors and forwarders occurs on the exposed section of organic layer in the ROW to prevent damage to the surface of the newly constructed road.

2.2.2 J.D. Irving and Bowater Mersey Best Management Practices for Road Construction in Forested Wetlands

When constructing road networks, companies inevitably have to cross wetlands in order to gain access to other areas of the forest or to harvest in forested wetlands with marketable timber. Using upland road construction methods while crossing a wetland poses numerous problems, both to the health of the wetland and the functionality of the road. Methods for upland road construction often result in the removal of organic soil layers and compaction of the soil profile beneath the surface of the road. This compaction of material creates an impermeable barrier that has a damming effect on the sub-surface water flowing through the soil (Anderson, 2007). Disruption of the water table on the upslope side of a road can lead to flooding of the road area and flooding of nearby vegetation. Additionally, the downslope side of the road can also experience vegetation mortality through the drying of the soil (Robinson et al, 2010).

Constructing roads in wetlands also negatively affects the integrity of the road. A constant presence of water near the base of the road and the movement of heavy machinery on the road can result in erosion and rutting of the road surface, ultimately causing the road to become impassable over time (Welsch et al, 1995). The use of upland road construction methods in wetlands eventually results in additional costs to timber harvest and maintenance of the road (Wisconsin Department of Natural Resources, 2010). In attempts to maintain wetlands and roads, companies such as J.D. Irving and Bowater Mersey have created BMPs for road construction specific to these areas.

The primary aspect of these BMPs is to avoid wetland whenever possible and place roads on well drained soil. Proper road placement is a result of having prior knowledge of the landscape and is effectively done during planning and site assessments. If avoiding an area of wetland is not a viable option (e.g. distance around the wetland is too great to be deemed economically feasible), companies will often place the road across the wetland at its narrowest point, which is normally perpendicular to the direction of water flow. By crossing at the narrowest point, the companies not only try to minimize the road impact and footprint on the wetland, but also minimize the cost associated with using the special techniques to build roads through wetlands. The narrowest section of the wetland is ideally found through proper wetland delineation. In addition to proper road placement, wetland delineation can also identify species that may be at risk, soil types, and inputs and outputs of ground and surface water.

If the narrowest point of a wetland still results in a substantial distance to be crossed, or if the organic layer of the wetland is determined to be too deep, Bowater Mersey and J.D. Irving commonly construct these sections of road using a "push" technique. This technique does not involve the construction of ditches through the wetland area and is commonly used in many areas of North America (Minnesota Forest Resources Council, 1999). The "push" method of road construction involves the surface material being imported from another location or through the excavation of a borrow pit (a pit from which suitable roadbed materials are excavated). The imported material is placed on top of the organic layer and pushed along by a bulldozer to complete the section of road (Welsch et al, 1995).

Similar to their upland road construction methods, Bowater Mersey and J.D. Irving use culverts to transport water under the road. The companies differ slightly in approach. During construction, Bowater Mersey typically anticipated sections of the road where water is likely to pool and places culverts in these areas during the construction process. Wetlands naturally tend to occur in depressions in the landscape; therefore, Bowater Mersey normally placed culverts in the wetland to prevent flooding in the future. J.D. Irving employs a different technique and constructs the entire length of road without the placement of culverts. The water is allowed to pool and that section of road is revisited at a later date, at which time the culverts are then placed where the water has naturally collected.

The size and spacing of culverts used during road construction processes normally depends on the amount of water that is being moved under the road surface. When construction occurs in situations of low water flow (i.e. no year-round surface flow) such as forested wetlands, and it appears that multiple culverts may be required, Bowater Mersey and J.D. Irving typically use 46 cm diameter pipe (18'') and space them 20 m apart. This spacing is a generally accepted approach used by forestry companies in the Maritimes. The ends of the culverts extend only a metre or less beyond the edges of the road to prevent damage by machinery and are normally placed to accommodate surface water but not subsurface flows. In order to prevent the culverts from bending over time due to the high volume of heavy traffic on the road, Bowater Mersey and J.D. Irving ensure that all culverts are placed on solid material (i.e., on mineral soil). This involves excavating all the organic material directly below the length of culvert (perpendicular to the road) and building the culvert base up with mineral soil or rock material until the height of the culvert allows surface water flow without the risk of blockage.

2.3 Best Management Practices for Road Construction in Forested Wetlands Used Elsewhere

In the United States, all wetlands are classified as federally protected waterways in section 404 of the United States Environmental Protection Agency's Clean Water Act which was developed in 1977. The Clean Water Acts outlines the need for permits to be used when construction, agriculture, or timber-harvesting operations are taking place in or near wetlands. The Clean Water Act does, however, exempt the construction and maintenance of roads from needing a permit in wetlands as long as the road is constructed and maintained using the following mandated BMPs (Mississippi Forestry Commission, 2008).

> "1. Permanent roads, temporary access roads and skid trails in waters of the U.S. shall be held to the minimum feasible number, width and total length consistent with the purpose of specific silvicultural operations and local topographic and climatic conditions.
>
> 2. All roads, temporary or permanent, shall be located sufficiently far from streams or other water bodies (except portions of such roads that must cross water bodies) to minimize discharge of dredged or fill material into waters of the U.S.

3. The road fill shall be bridged, culverted or otherwise designed to prevent the restriction of expected flood flows.

4. The fill shall be properly stabilized and maintained to prevent erosion during and following construction.

5. Discharges of dredged or fill material into waters of the U.S. to construct a road fill shall be made in a manner that minimizes the encroachment of trucks, tractors, bulldozers or other heavy equipment within waters of the U.S. (including adjacent wetlands) that lie outside the lateral boundaries of the fill itself.

6. In designing, constructing and maintaining roads, vegetative disturbance in the waters of the U.S. shall be kept to a minimum.

7. The design, construction and maintenance of the road crossing shall not disrupt the migration or other movement of those species of aquatic life inhabiting the water body.

8. Borrow material shall be taken from upland sources whenever feasible.

9. The discharge shall not take, or jeopardize the continued existence of a threatened or endangered species as defined under the Endangered Species Act, or adversely modify or destroy the critical habitat of such species.

10. Discharges into breeding and nesting areas for migratory waterfowl, spawning areas and wetlands shall be avoided if practical alternatives exist.

11. The discharge shall not be located in the proximity of a public water supply intake.

12. The discharge shall not occur in areas of concentrated shellfish population.

13. The discharge shall not occur in a component of the National Wild and Scenic River System.

14. The discharge of material shall consist of suitable material free from toxic pollutants in toxic amounts.

15. All temporary fills shall be removed in their entirety and the area restored to its original elevation." (pg. 28)

Beyond U.S. federally imposed BMPs, a range of different techniques has been developed as part of state BMPs for road construction in forested wetlands, many of which are similiar to those used by J.D. Irving and Bowater Mersey operations. Almost all state and provincial BMPs note that all wetlands should be avoided when feasible and roads should affect only the smallest area possible when crossing is necessary. In order to minimize the footprint of the road on the wetland, it is suggested that all roads be installed perpendicular to the flow of the ground water (Gillies, 2011).

In most BMPs, the recommended construction and installation techniques differ based on the soil profile present in the forested wetland, which are generally sub-divided into three categories: mineral, shallow peat, and deep peat (Welsch et al., 1995). The standard classification of a mineral wetland type is the presence of a thin peat layer (up to 40 cm deep) with underlying clay or silt material. Shallow and deep peat wetlands have deeper organic layers than mineral forested wetlands, and are classified based on the depth of these organic layers. Shallow peat wetlands are classified to have organic layers between 40 cm and 4 m in depth while deep peat wetlands have an excess of 4 m of organic layer (Wiest, 1998). Due to the anaerobic conditions that are present in areas that have significant organic layers, forested wetlands typically only occur in mineral and shallow peat wetlands (Wiest, 1998; Welsch et al., 1995).

Road Construction in Swamps (Mineral Based):

When roads are placed in forested wetlands that have a mineral base, upland road construction techniques are used as BMPs for most forestry companies (Welsch et al., 1995). This includes creating the base of the road from the material remaining from the harvesting of the ROW (this may include any part of the tree), and installing ditches on one or both sides of the road. The material from the ditches is then used as the material for the road surface. In cases where large amounts of fill are removed from ditches, coarse material from offsite is used to backfill them to a reasonable depth. Using this method, ditches are only intended to protect the road from water overflow and are not constructed in a manner that intentionally causes the drainage of a wetland (Wiest, 1998).

Road Construction in Shallow Peat Forested Wetland:

If the peat layer is shallow enough for machinery to safely operate, upland construction methods are also used as BMPs for road installation in shallow peat forested wetlands (Wiest, 1998). However, as an alternative to upland methods, forestry companies commonly use the same “push” method that J.D. Irving and Bowater Mersey employ, which uses imported fill material over the organic layer to create the surface of the road.

Other BMPs used in shallow peat wetlands include the use of a geotextile material to support the weight of the push material. Using this method, the geotextile material is rolled out along the surface of the organic layer and imported soil is pushed along the surface of the material (Figure 1). The use of the geotextile material is intended to allow the road to reduce compaction of the organic layer under the road; this normally results in the use of less soil for the surface of the road (Virginia Department of Forestry, 2009). A brush mat, coarse rock, or log corduroy can be used above, below, or between two layers of geotextile material to promote water flow and permeability below the surface of the road (Gillies, 2011). BMPs that utilize these push techniques, with or without geotextile material, state that ditches can still be used during construction in order to move water to the nearest culvert if desired (Welsch et al., 1995).

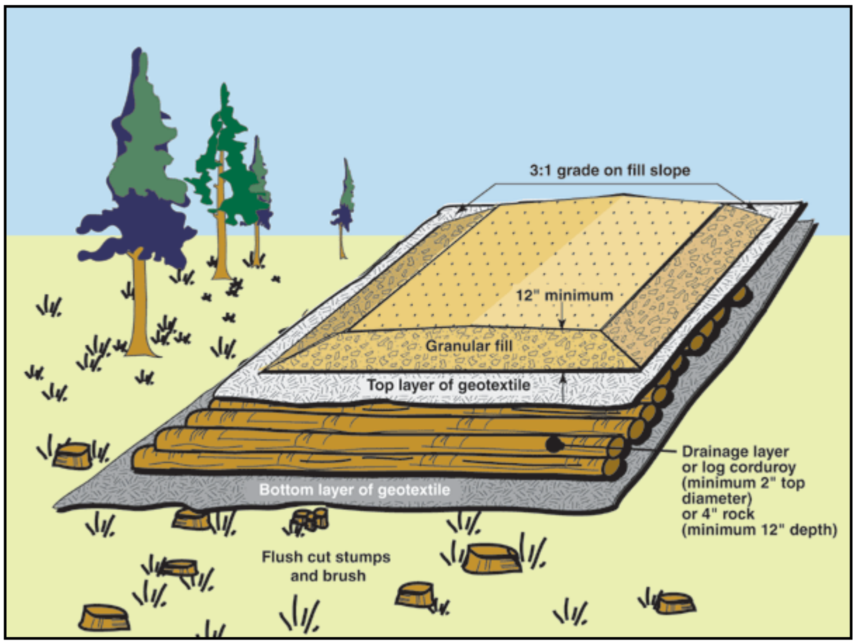


Figure 1. Combination of geotextile layers and log corduroy to float access road (Bassel, 2002)

Use of Culverts:

The goal of culverts as cross-drains is to prevent structural damage to the base of the road caused by the pooling of water (Welsch et al., 1995) while maintaining hydrologic connectivity within the wetland bisected by the road. Keeping the water away from the road can be done by controlling factors such as the size, depth of placement in the soil, and spacing at which multiple culverts are placed along the road. The key is to find a balance of these factors in order to prevent the flow of water from becoming constricted at the inlets and/or outlets of the culverts (Cox and Cullington, 2009). The suggested sizing and spacing of culverts placed in wetlands varies depending on which jurisdiction has created the BMP. Federally, Canada and the U.S. do not have a suggested sizing or spacing for culverts, stating that each case may differ and that culverts should be placed wherever necessary (Welsch et al., 1995), leaving the responsibility to the provinces, states, and companies. Other jurisdictions (e.g. Alberta Sustainable Resource Development, 2010; Nebraska Forest Service, n.d., etc.) have general guidelines and BMPs in place for culvert sizing and spacing but are not designed specifically for forested wetlands (See Table 1).

Table 1: Provincial/state/company BMP guidelines for culvert size and spacing

Jurisdiction	**Diameter of Culvert**	**Spacing of Culverts**
(Bowater Mersey/J.D. Irving) - **Nova Scotia/New Brunswick**	46 cm (18'')	20 m
(Virginia Department of Forestry, 2009) - **Virginia**	61 cm (24'')	Regular Intervals
(Cox and Cullington, 2009) – **British Columbia**	No Suggested Size	20 m
(Mississippi Forestry Commission, 2008) - **Mississippi**	53 – 61 cm (21 – 24'')	152 m (500 ft)
Wisconsin Department of Natural Resources, 2011) - **Wisconsin**	No Suggested Size	91 m (300 ft)
(Gillies, 2011) – **FP Innovations**	230 – 450 mm	15 – 100m
(Illinois Department of Forest Resources, 2000) - **Illinois**	No Suggested Size	91 m (300ft)

Although the number and spacing of culverts seem to vary, some BMPs agree that culverts should be installed in the wetland in a manner in which they are able to accommodate both surface and sub-surface water flow. This requires the culverts to be placed partially submerged in the organic material of the wetland, deep enough so that half of the exposed end of the culvert is covered or until the top 30 cm of organic material can be drained (Phillips, 1997; Virginia Department of Forestry, 2009; Wiest, 1998). To prevent surface blockage of these culverts, some BMPs suggest that they should be installed at a 30-45 degree angle to the surface of the road (Virginia Department of Forestry, 2009; Wisconsin Department of Natural Resources, 2010). To prevent an influx of offsite water from the upland areas from entering the wetland through any nearby ditches (Wisconsin Department of Natural Resources, 2010), culverts should be installed just beyond the outer edges of the wetland in the upland area of the road.

Road Construction in Deep Peat Forested Wetland:

BMPs do not suggest using upland road construction methods when crossing deep peat wetlands. Upland construction methods in these wetlands are expensive and harmful to natural hydrology. Instead, the road should be floated on top of the organic layer using methods similar to floating the road in shallow peat conditions (Wiest, 1998; Welsch, 1995). Culverts should also be placed in similar locations and depths as the shallow peat wetlands for flow of water under the road. These crossings are difficult to construct and it is suggested that an engineer design the project to prevent the road from sinking into the wetland (Wiest, 1998).

To avoid interfering with wetlands altogether, winter roads are a viable alternative to the permanent construction of forest access roads in any type of wetland landscape, as long as temperatures remain cold enough to maintain the road structure. These structures do not use any soil material and culverts are only temporarily placed to maintain natural water flow. Using this method, bridges are constructed with ice and snow which allow harvest operations to continue even during the winter months (Wiest, 1998). If permanent roads are still desired, companies can avoid crossing through wetlands by coupling upland road construction with the construction of wooden bridges when a wetland is encountered (Gillies, 2011). This option is not commonly used due to the cost of the construction and maintenance associated with bridge crossings.

2. 4 Compaction and Rutting of Organic Material

At the outset of this project, it was originally thought that road installation and the lack of a proper, consistent, drainage system were the primary issues resulting in the change in hydrology commonly observed when roads cross forested wetlands. However, upon further investigation, it was found that other factors such as rutting and compaction of the wetland outside of the footprint of the road structure can also impact surface and groundwater flow.

As mentioned previously, forest access road construction requires a number of different types of machinery to prepare the land and construct the road surface. Feller-bunchers and cut-to-length processors (Figure 2) are similar machines that move with the use of a track system instead of tires. Forwarders (Figure 3) and skidders are able to use tires, tracks, or a combination of both. Each of these pieces of machinery is designed for operation in forested areas; however, all are large and heavy pieces of machinery that can cause rutting and compaction of organic material in wetlands. Disturbances caused by machinery can have a number of adverse effects on wetlands, including restricting the flow of the water through the soil profile (Sutherland, 2003). In addition to hindering the flow of water, soil compaction and rutting can damage root systems and decrease future growth of vegetation, while acting as potential entry points for insects and diseases (Greacen and Sands, 1980; Wisconsin Department of Natural Resources, 2010).

Figure 2. Standard John Deere K-Series Feller Buncher/Processor (953K) - 31,820 kg (John Deere, 2014)

Figure 3. Standard John Deere 1110E Forwarder – 12,000 kg (John Deere, 2014)

The effects of machinery on forested wetlands often extend beyond the footprint of the machine tracks. Aust and Lea (1992) found that impacts of skidder traffic during harvesting affected the top 50 cm of the soil profile, which decreased hydraulic conductivity of the soil and thus resulted in reduced oxygen levels and decreased soil pH levels. Depending on the weight of the machinery and soil type, Danfors (1974) found that these impacts can have long-term effects on the soil profile. Danfors (1974) study found that impacts can be detected up to 50-60 cm in the soil profile three years after a small (14,515 kg) skidder was used to remove timber from an area of forested wetland.

The most common BMP used to try to mitigate the short-term and long-term effects of machinery movement in forested wetlands is the use of low-ground-pressure equipment such as floating or wide tires (Aust, 1994; Greacen and Sands, 1980; Wisconsin Department of Natural Resources, 2010). In addition to using the modified machinery, it is suggested that all work in these environments take place during dry or low-flow seasons and be evaluated on a day-to-day basis (Decker, 2003; Wisconsin Department of Natural Resources, 2010). To prevent rutting, woody mats created from harvested tree material can also be placed on top of the organic layer to act as a buffer between the soil and the running gear of the machinery (South Carolina Forestry Commission, 1994; Wisconsin Department of Natural Resources, 2010). This method can use whole logs, similar to that of log corduroy used in road construction, or brush from the limbs of the timber that was harvested previously on site. If at any point rutting from machinery becomes greater than 15 cm deep or the water table is becoming visibly disrupted, operations in the area should cease and time should pass to allow the site to dry sufficiently so that travel can continue (Phillips, 1997).

2.5 Related Research

A thorough literature review found few scientific findings outlining how road installation and spacing of cross-drains affects groundwater in wetland systems as a whole, and most BMPs are not specific to wetland type, soil type, or region. However, studies have been done on the effects of road construction on groundwater in sloped and non-wetland settings that show this is a problem in a number of landscape types. Wemple et al. (1996), Kahklen (1999) and Wigmosta and Perkins (2001) all show that the flow of water is altered up-gradient and down-gradient of the road after installation has occurred. While these results are not specific to wetlands, they highlight the need for research to increase understanding about the potential impacts on the hydrology of wetland ecosystems. My project, and a number of other SFI-funded projects that are ongoing across Canada, are designed to address this lack of understanding and provide science-based recommendations that, if adopted, could potentially reduce industry impacts from road construction through wetlands.

Chapter 3. Methods

3.1 Study Area

All sites used in the study were sections of forested wetland that intersected forest access roads planned and built by Bowater Mersey or J.D. Irving. Forested wetland sites that had a mineral base and a relatively shallow organic layer (i.e. no deeper than approximately 1.0 m) were determined to be suitable for the project. This depth was chosen to keep the amount of push material to a minimum when crossing a site. Sites also had to be long enough to allow for a minimum of two cross-drains to be spaced 20 m apart. The single Nova Scotia site is located in the southwestern portion of the province, on land once owned by Bowater Mersey, in close proximity to the town of Liverpool. The six study sites in New Brunswick are located near Chipman and Fredericton on Crown land operated by J.D. Irving.

Each study site was a newly constructed section of forest access road that had been included in the respective company's road construction plan. The local operations manager and machinery operators had prior knowledge of the landscape where construction was to occur. With their expertise and the help of wetland inventory mapping and aerial photographs, these individuals were able to determine, with confidence, the presence of forested wetland in the area. When a construction area was thought to contain a section of forested wetland, the proposed road area was walked to confirm the presence of the wetland and its suitability for the study. In five sites, the ROW for the road was cleared before the initial visit to the site, making identification of the wetland relatively easy. For two other sites, the ROW was not cleared and the proposed road corridor was walked with the local operations manager with the aid of global positioning systems (GPS).

To assist in locating the sites in the future, latitude and longitude coordinates were recorded with GPS; soil types (Fahmy et al., 2010; Nova Scotia Department of Natural Resources, 2011) and dominant vegetation were also documented (Appendix C).

3.2 Study Design

Once the ROW had been cleared of timber for the proposed road and the presence of a suitable forested wetland was found, the length of wetland crossing was determined (Table 2). The boundaries of the wetland along the length of the road were determined using vegetation, soil and topographic indicators. The boundaries of the wetland were clearly marked with flagging tape to ensure that machine operators knew the length of the site that had been selected. All findings were communicated to the local operations manager and the machine operators to ensure that the site was constructed to the specifications of the study and the proper number of cross drains would be used for each site (Table 2).

Table 2. Length of wetland crossings and culvert spacing at study sites

Site	Length of Crossing (m)	Cross-drain Spacing (m)
Acadia Road	54	20
Bowater Mersey	52	40
Drifters	108	40
G4 Main Branch	84	40
G4 Upper Branch	63	20
Harcourt	92	40
Minto (K-road)	51	20

This study's objective was to test two cross-drain spacings to evaluate which treatment maintained water table levels closest to that of the natural forested wetland. A high-density treatment (cross-drain every 20 m) was compared to a low-density treatment (cross-drain every 40 m). The minimum length of wetland crossing was chosen to be 50 m so that each site could be allocated a treatment of one or two cross-drains. The maximum length of crossing was determined to be 150 m. This maximum distance was determined by the forestry companies. Due to the geography in the study regions, lengths of forested wetlands larger than 150 m long were uncommon and if encountered would most likely be avoided in road-construction plans.

Plastic culverts (46 cm diameter) were used as cross-drains at all study sites. This size is the current industry standard used in settings of low water flow. Most aspects of road construction remained consistent for all study sites, but some variability was inevitable due to unique site conditions at individual sites. Staff for the forestry companies used their discretion in making specific installations decisions. All ROWs were narrowed to 10 m in width while crossing the forest wetland sections to reduce the amount of wetland surface area affected. Roads were constructed using the push technique where the road surface material was imported from borrow pits. This method was used instead of the traditional ditching technique which would have excavated the road surface material from the mineral layer in the wetland along the roadside.

The culverts were installed at the designated densities along the road and were fully submerged in the wetland organic layer, just on top of the mineral soil layer (Figure 4), extending approximately 1 m out from the edge of the roadbed (Figure 5). This depth was chosen to ensure that water could flow through the cross-drains at times when the water table was below the surface of the peat layer. Placing the culverts on the mineral layer also provided structural support for the culvert and prevented the culvert from bending under the pressure of the road materials and the weight of machinery travelling the road so that water flow was not impeded.

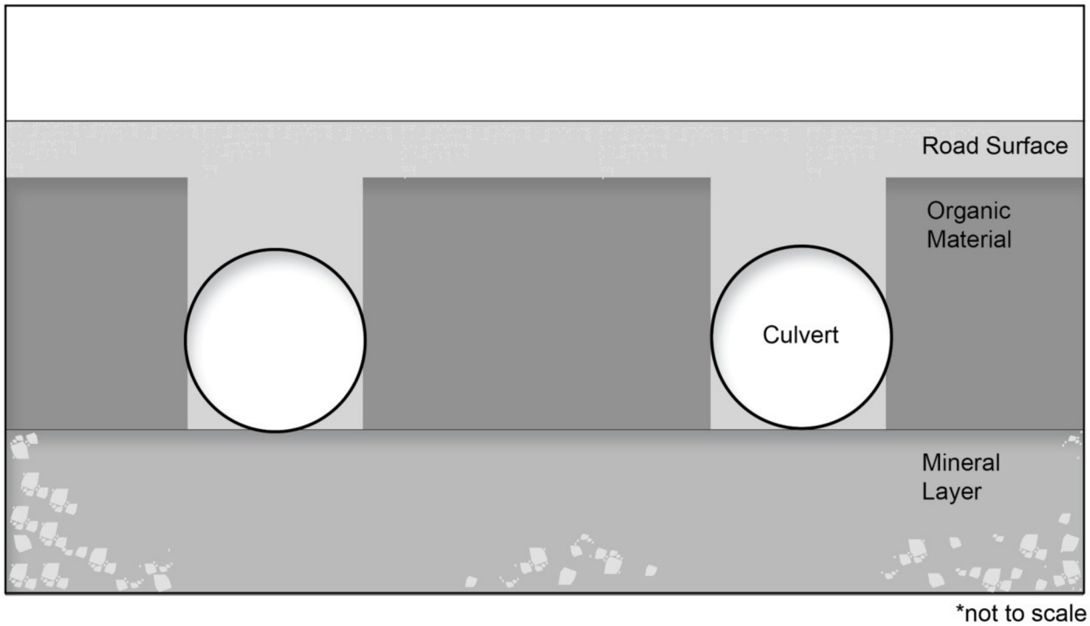


Figure 4. Cross-sectional view of culvert installation

To measure the water tables accurately in these locations, the shallow wells were placed other either side of the road. The number of shallow wells used on each side of the road was dependent on the length of wetland being crossed and shape of the wetland selected. Combinations of three and four shallow wells per side of road were used for shorter wetland crossings, while sets of five were used for longer crossings. The first rows of shallow wells were placed at least 10 m away from the edge of the road, evenly spaced throughout the wetland according to the size of the wetland crossing. All other shallow wells were placed in the wetland at least 10 m apart from each other (Figure 5). This distance between shallow wells allowed for differences in water table depths to be easily identified. At each site, each shallow well was designated a number based on its location in the landscape to ensure that all measurements for each pipe could be compared over time.

No additional sites were used as control sites for this study. The research team determined that spatial controls were not necessary because of the presumed low gradients across short distances of wetland. During planning of the project, the pre-road construction data were intended to act as a temporal control. The data collected from the shallow wells before the road was installed were presumed to identify natural water table levels and give a baseline to compare pre- and post-road construction water table levels.

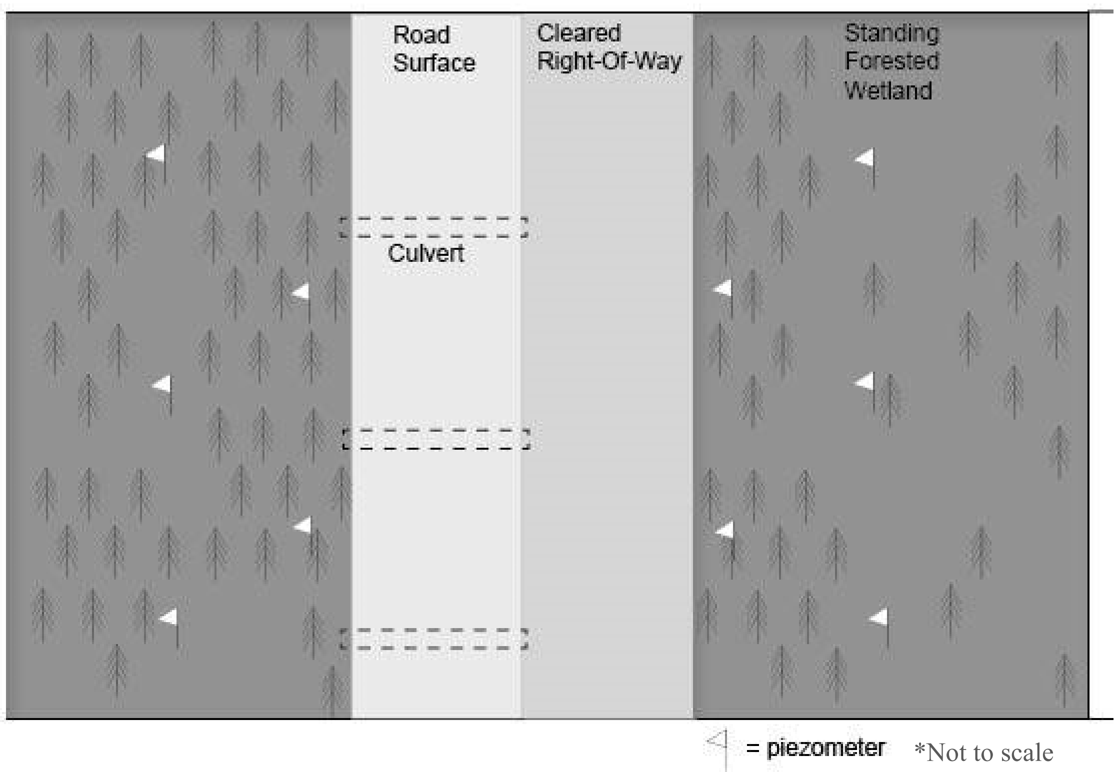


Figure 5. Culvert placement and site context for large wetland crossing

3.3 Shallow Well Design

Water table levels within the forested wetlands were the primary data collected for this study. Water level data were gathered with the use of shallow wells. The shallow well design used for this project was adapted from methods of Lee and Cherry (1978) and the Clinton and MacQuarrie (1992).

The shallow wells were constructed using one-metre lengths of 38 mm ABS pipe. The lower 50 cm of these pieces of pipe were perforated with eighteen 9.5 mm holes to allow for rapid flow of groundwater into the pipe (Figure 6). Rows of holes were drilled in each quarter of the circumference of the pipe and were vertically spaced approximately 8 cm apart. Two rows of holes had four holes each and the other two rows had five holes each. The section of pipe that was perforated was covered with two layers of light-duty (0.034 kg/m^2) landscaping fabric using industrial tie wraps to keep the fabric in place (Figure 7 and 8). The fabric allowed for water to flow freely into the pipe while preventing sediments and soil from entering.

The shallow wells were pushed, by hand, vertically into the organic layer so that the lower 50 cm of the pipe was below the surface of the sphagnum or until the shallow well encountered a mineral layer of soil (Figure 9).

Figure 6. Shallow well without landscape fabric covering

Figure 7. Shallow well with landscaping fabric covering

Figure 8. Constructed shallow wells

Figure 9. Shallow well installation in organic layer

3.4 Data Collection

A metal tape measure covered in water soluble dye from a marker was used to measure the water levels in the shallow wells. When measuring the water levels, the dye-covered tape was lowered to the bottom of the shallow well, and the water inside the tube removed the dye from the surface of the tape measure (Figure 10). When the tape was removed, the dissolved dye indicated how much water was in the well. The distance of the water away from the surface of the soil could be determined by comparing the amount of water in the well to the depth at which the well was buried in the soil.

Figure 10. Water soluble ink removed by water on metal tape measure

The measurement process was completed for each shallow well at each site before road construction. This pre-road construction measurement was intended to give an indication of the natural water table levels in the wetland at that given time of year. The same process was repeated on two occasions after the road had been constructed and the cross-drains had been installed. These post-road construction measurements were taken to determine the effects of the road and culvert system on the water levels in the vicinity of the road.

Following installation of the shallow wells, 18 to 24 hours were allowed to pass before water levels were measured to ensure that levels had reached equilibrium with the surrounding wetland water table. Due to time restrictions and the long distances to travel to some sites, it seemed sensible to determine how long it would take for water levels to reach equilibrium. This investigation determined that approximately one hour was sufficient.

Although the water levels in the shallow wells are indicative of the water tables at individual points in the wetland, these points had to be corrected for variations in elevation across the wetland. Site-specific elevation measurements were completed with a Trimble R10 GNSS System (Trimble Navigation Limited, 2012), which was accurate within a millimetre. Elevation measurements were collected at a base station on the surface of the road and at ground level of each shallow well. The elevations collected at each shallow well were then compared to that of the elevation at the base station on the road. This comparison gave the relative elevations of each shallow well in relation to the base station at that site. The result of this comparison gives a negative value that is indicative of the water table depth in relation to the elevation point on the road, not of the water depth below the surface of the forest wetland.

The water table measurements collected at each shallow well were then corrected against the relative elevation of the ground level at each shallow well point. The end results of all corrections are the water table levels relative to each other in the wetland. Complete sets of data were not able to be collected at the Bowater Mersey site and at the J.D. Irving site on Acadia

Road. One pipe at each location was knocked over and therefore could not be used for data collection.

Time of collection for the pre-road construction data was determined by the installation of the road, decided by the forestry companies. The post-road construction data were collected based on ability to access the sites and an effort was made to sample multiple sites per trip. The majority of post-road construction data was collected during the summer months when the water table would be at its lowest point (Table 3).

Table 3: Date of site visits in which data was collected from shallow wells

Site	**Pre-Construction Mesurements**	**1st Post-Construction Measurements**	**2nd Post-Construction Measurements**
Acadia Road	August 2011	August 2012	August 2013
Bowater Mersey	July 2011	August 2012	August 2013
Drifters	September 2011	July 2012	August 2013
G4 Main Branch	August 2011	May 2013	August 2013
G4 Upper Branch	August 2011	May 2013	August 2013
Harcourt	August 2012	May 2013	August 2013
Minto Road	September 2012	August 2013	N/A

3.5 Data Analysis

Two sample T-tests were performed to analyze the difference in means of the water table levels between the two sides of the road for each site for each individual site visit. Analysis of variance was used to compare the mean water table levels on each side of the road to determine if they varied over the span of the three site visits. Two sample T-tests were also used to determine whether culvert spacing influenced differences between upslope and downslope water table levels for pre-construction and post-construction measurements.

3.6 Study Limitations

There were several limitations of this study, regarding both site selection and data collection. First, because there was difficulty finding sites that were appropriate for the study, the wetlands selected varied in both size and type (Appendix C). Pre-road construction measurements of these sites were performed as the sites became available, which resulted in these data sets being collected during different times of year and under varying weather conditions. An effort was made to collect post-road construction measurements during the summer months. However, in the interest of time, some post-construction measurements were collected in May when the water table may have been higher than in July and August.

During data collection in the first pre-road construction period, the water table levels were measured in relation to the surface of the soil. After discussing this data collection method with professionals in the field, it was determined that these measurements should have been taken in relation to the top of the shallow well. Measurements are commonly taken in relation to the top of the well because the well is a more flat and stable surface than the surface of the soil/peat layer. The soil/peat layer is soft and could have potentially moved between times of data collection. Measuring the depth of the culvert in relation to the shallow wells would have also been a piece of data that could have aided analysis to help determine if water was flowing from one side of the road to the other.

It should also be noted that only one post-road construction measurement was taken at the Minto (K-Road) site. This site was the last to be installed and time did not allow for a second set of post-road construction measurements to be collected.

Chapter 4. Results

Differences in water table depths in a natural wetland setting over a short distance, like that of the study sites, were expected by the research team to be between approximately 2 and 5 cm. Using the hypothesis that water table levels on opposing sides of the road would be equal, the two sample T-test showed a much larger difference than anticipated at six of the seven sites (p value: <0.05) (For actual values see Appendix A). Thus, the null hypothesis was rejected. The differences in water table depths on opposing sides of the road for these six sites ranged from 11.3 cm at the G4 Main Branch site (Table 4) to 75.3 cm at the G4 Upper Branch site (Table 4). The Bowater Mersey site was an exception which showed a small (2.8 cm) difference between the upslope and downslope portions of the wetland before the road was installed (p-value: >0.05) (For actual value see Appendix A).

The two sample T-tests (using the same hypothesis) conducted on post-road construction data continued to show differences in upslope and downslope sides of the road among the six sites that displayed the differences in the pre-road construction data. An analysis of variance conducted on the data collected over the course of the three site visits showed water table depths on the same side of the road were not statistically different throughout the study period for all sites ($p>0.05$; Appendix A).

To test the null hypothesis that responses of water table levels were not different for the two culvert spacings, a two sample T-test of the average differences between upslope and downslope water table levels for all three measurements was performed. The results showed p-values greater than 0.05 (Table 5), leading to acceptance of the null hypothesis and indicating that the two treatments were not statistically different.

4.1 Water Table Measurements

Table 4: Differences of average water table level on opposite sides of road (m)

Site	Culvert Spacing	Pre-road Construction*	Post-road Construction (1)*	Post-road Construction (2)*
Acadia Road	20	-0.658	-0.737	-0.593
Bowater Mersey	40	-0.028	-0.001	-0.006
Drifters	40	-0.363	-0.336	-0.299
G4 Main Branch	40	-0.113	-0.119	-0.109
G4 Upper Branch	20**	-0.753	-0.793	-0.803
Harcourt	40	-0.634	-0.644	-0.632
Minto (K-Road)	20	-0.206	-0.115	N/A

* Values determined by calculating average downslope water table depths minus average upslope water table depths.

** The Irving site, G4 Upper Branch, was intended to have culverts placed 20 m apart but no culverts were ever installed at the site. This site was looked over during a changeover in supervisory personnel for the company.

Table 5: Comparison of averages of the two treatments over the duration of the three data collection dates and the associated p-values

Treatment	Pre-road Construction Average (m)	P-value	Post-road Construction (1) Average (m)	P-value	Post-road Construction (2) Average (m)	P-value
20 m Spacing	-0.539	0.307	-0.530	0.384	-0.698	0.086
40 m Spacing	-0.285		-0.275		-0.262	

*Values determined by calculating average differences between upslope and downslope water table depths.

Figure 11. Acadia Road water table levels (H=Upslope side of road, L=Downslope side of road)

*An eighth pipe installed at the site was knocked over and a full set of data was not able to be collected.

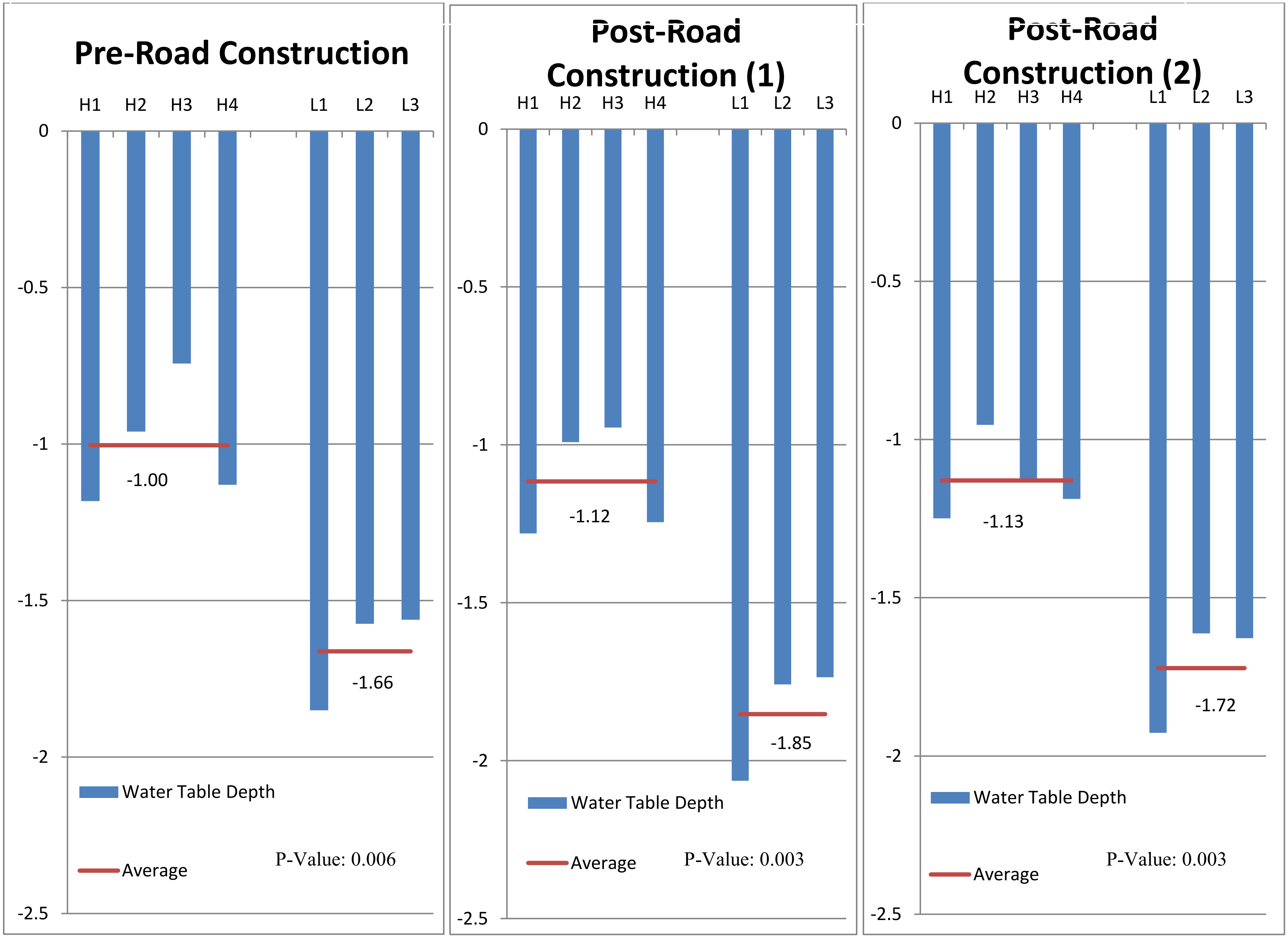


Figure 12. Bowater Mersey water table levels (H=Upslope side of road, L=Downslope side of road)

*The pipe represented by L2 was knocked over and a full set of data was not able to be collected.

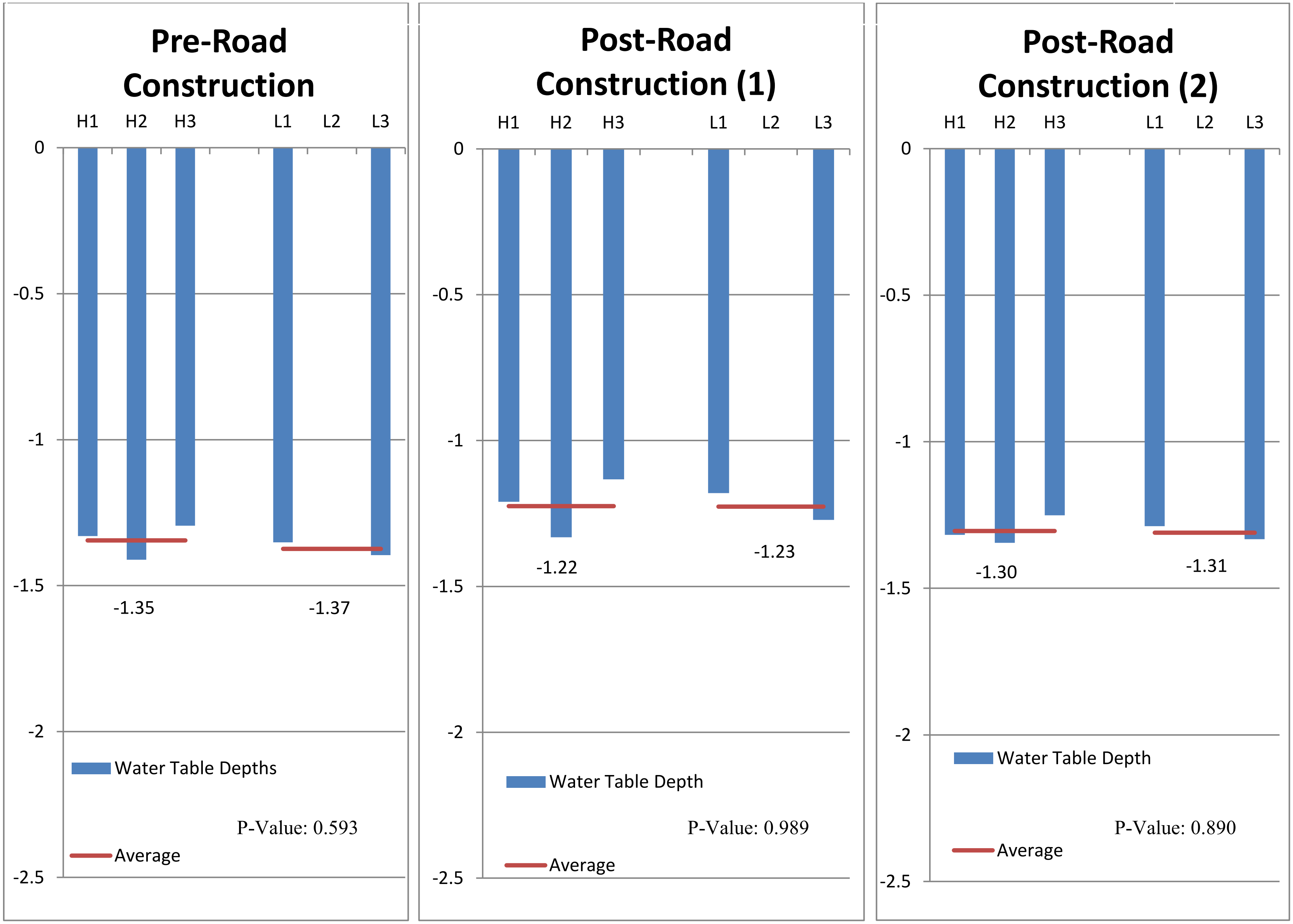


Figure 13. Drifters water table levels (H=Upslope side of road, L=Downslope side of road)

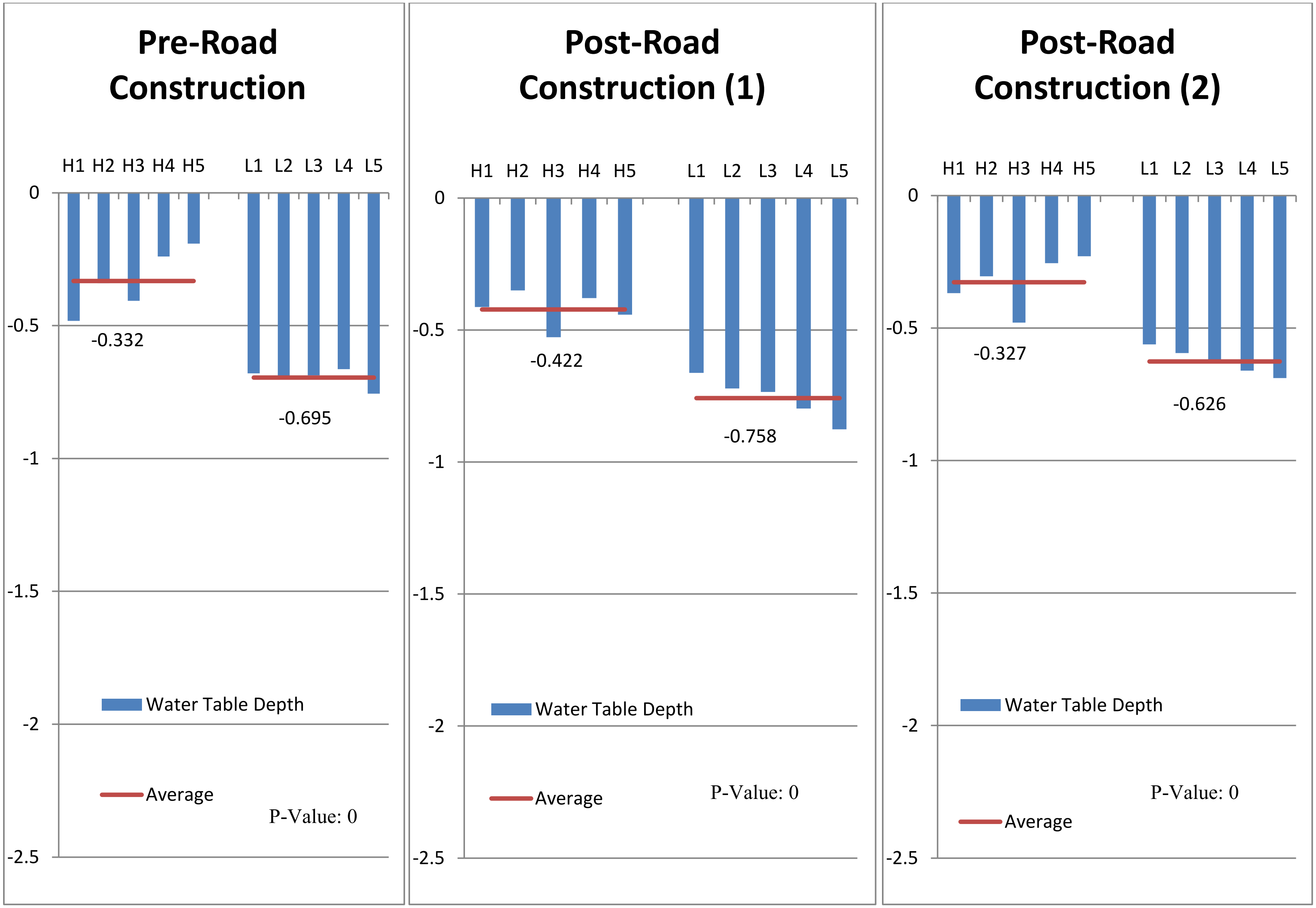


Figure 14. G4 Main Branch water table levels (H=Upslope side of road, L=Downslope side of road)

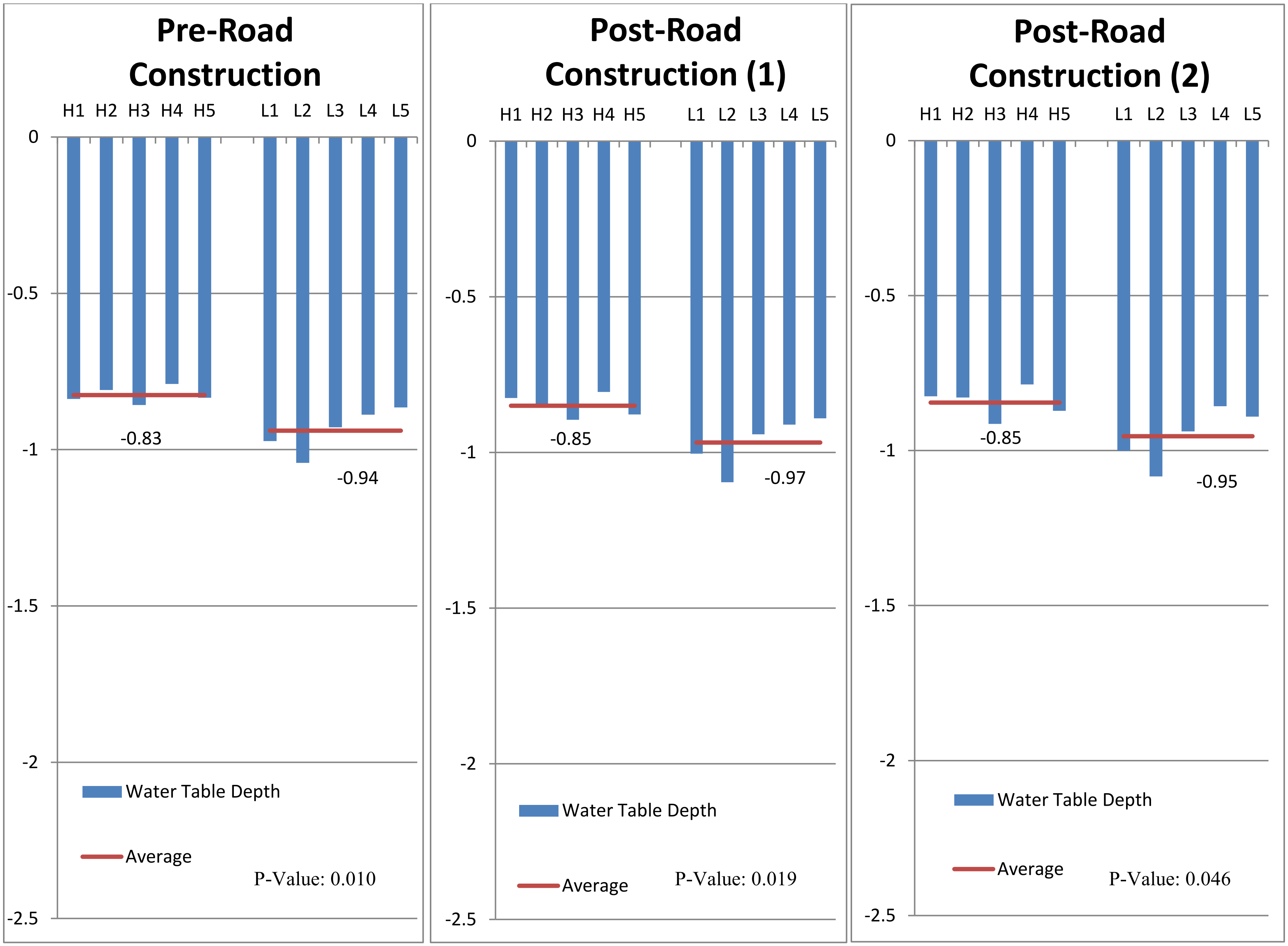


Figure 15. G4 Upper Branch water table levels (H=Upslope side of road, L=Downslope side of road)

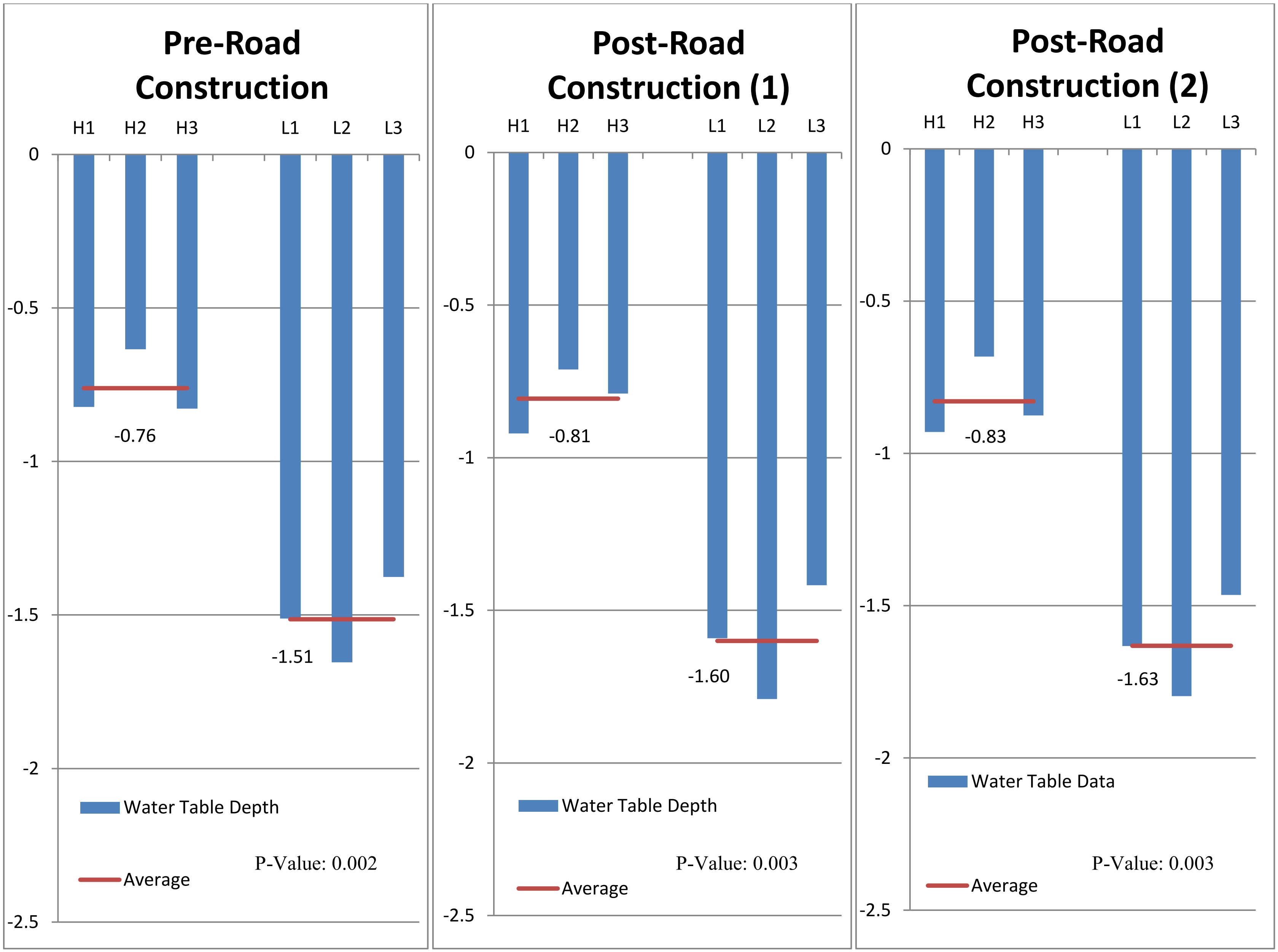


Figure 16. Harcourt water table levels (H=Upslope side of road, L=Downslope side of road)

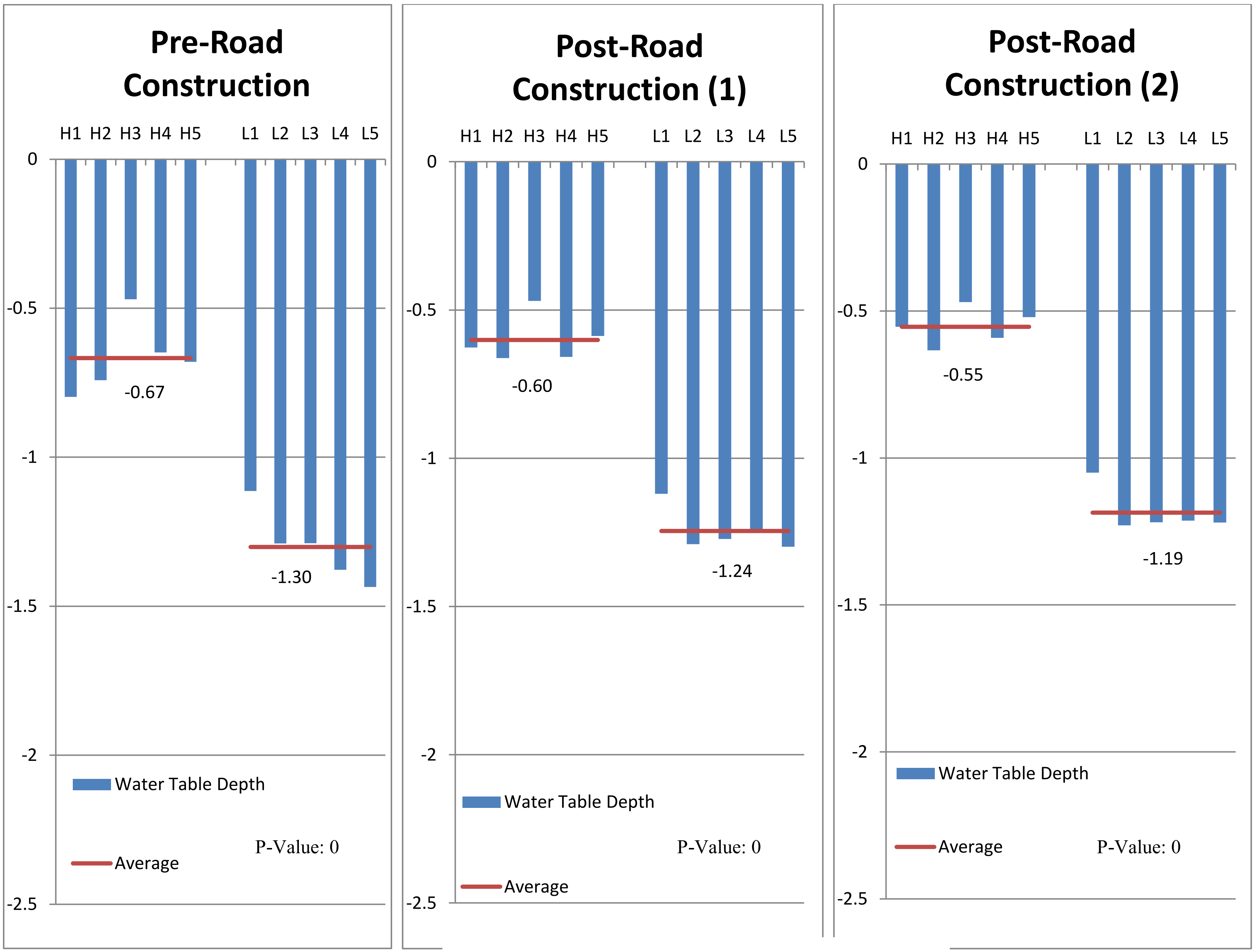
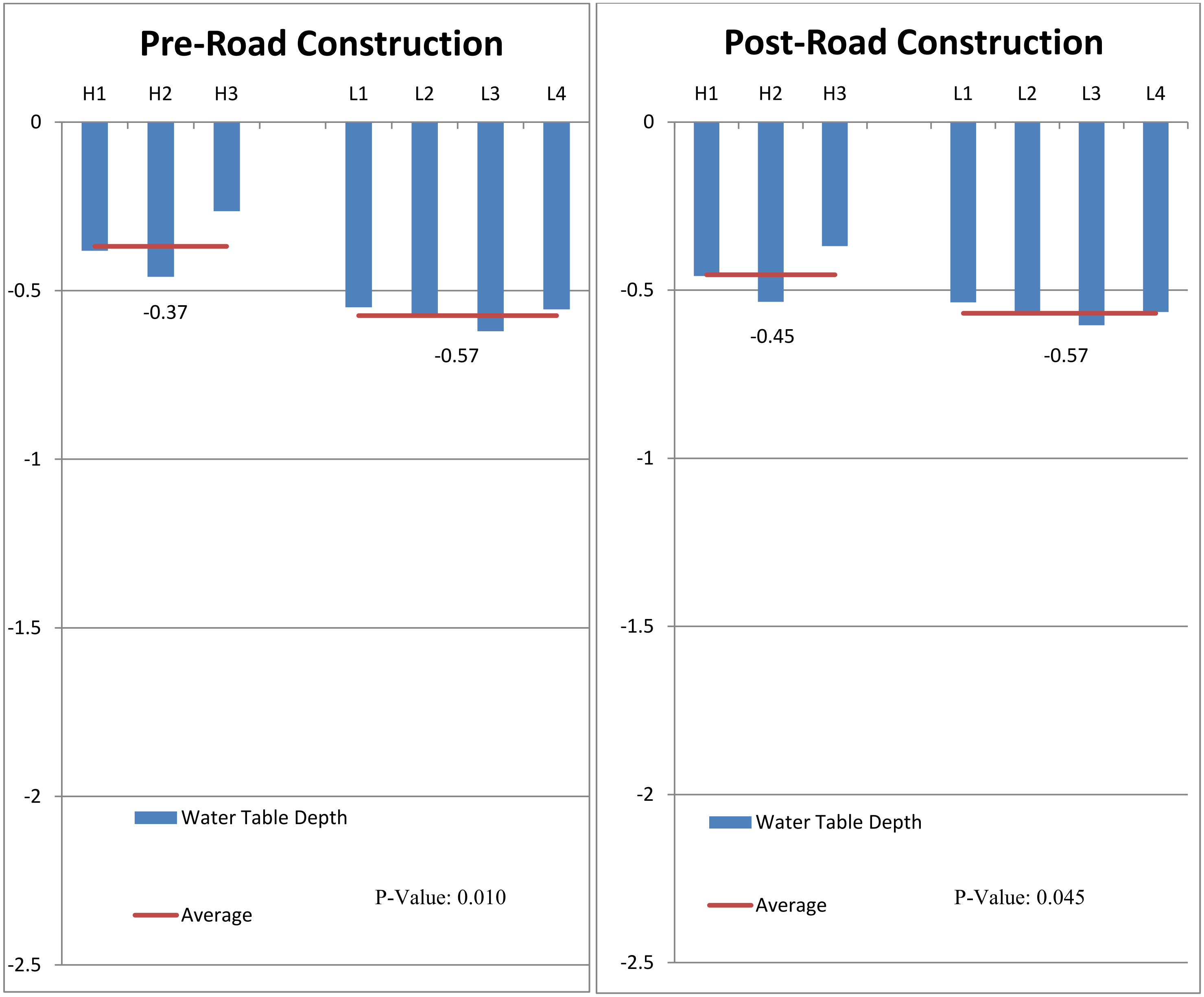


Figure 17. Minto (K-Road) water table levels (H=Upslope side of road, L=Downslope side of road)



Chapter 5. Discussion

The data collected before road construction were expected to be the baseline data used to observe changes in water table levels after road construction and across treatments. When a two sample T-test was performed on pre-road construction data, it showed that upslope and downslope water table levels were statistically different from each other at six of the seven sites. These differences were larger than expected and seem to suggest that there is at least one variable, which was unaccounted for, that affected the water table levels before the installation of the road bed.

The clearing of the ROW and the collection of the timber from the road side were the only activities which took place in the area before the building of the road surface started. With the luxury of hindsight, and forest harvesting BMP literature (Aust, 1994; Aust and Lea, 1992; Danfors, 1974; Decker, 2003; Greacen and Sands, 1980; Sutherland, 2003; Wisconsin Department of Natural Resources, 2010) from a number of jurisdictions, it seems reasonable to suggest that the combined movement of a feller-buncher and forwarder may have been enough to compact the organic material in the wetland portion of the ROW. The compacted material appears to have created enough of a disturbance in the forested wetland to observe some of the impacts in the disruption of natural horizontal processes (Forman et al., 1995; Forman and Alexander, 1998; Spellerberg, 1998) even before the installation of the road bed took place. Unfortunately, this issue was not raised by stakeholders during the initial planning meetings for this project.

The six sites that showed differences between upslope and downslope water table levels in pre-road construction measurements continued to show statistical differences throughout both post-road construction measurements. Although the road had been constructed and the culverts installed, the data continued to show a gradient in which the upslope side of the road displayed higher water tables while the downslope side of the road had lower water table levels. The three measurements collected at each, the upslope and downslope portions of these sites, did not significantly vary over the course of the study, suggesting that the problem encountered before road construction continued after the road was installed.

An explanation as to why water table levels did not begin to equalize over time through the culverts placed in the roadbed is not clear. However, the ROW, culvert placement, and the placement of the road in the ROW could account for the continued water table difference between the upslope and downslope sides of the ROW (Forman et al., 1995; Forman and Alexander, 1998). Due to the road being placed on one side of the cleared area, the road sits on less than half of the exposed area of the ROW. After the road is constructed, the culverts are installed only as long as the road is wide. The result of this construction method would mean that water needs to move from non-compacted soil (i.e., forested wetland), through compacted soil in the upper-gradient portion of the ROW, and then through the culvert in order to reach non-compacted forested wetland again on the low-gradient side of the ROW. Although the culverts may be performing properly, in respect to the roadbed, the movement of water from the uncut portion of the wetland may be inhibited due to soil disturbance on the upslope side of the road. If this scenario is true, the water would ultimately move parallel to the road and ultimately move off-site along the surface of the exposed soil or through ruts left by the machinery to nearby ditches or borrow pits (Kahklen, 1999).

The Bowater Mersey site behaved differently than the six J.D. Irving sites. There were no significant statistical differences between the upslope and downslope water table levels in the pre- or post-road construction data suggesting that construction did not affect the water table levels and culverts were working properly.

The reason the Bowater Mersey site responded differently than the J.D. Irving sites may be due to the nature of the soil profile (Appendix C). This site had a much deeper organic soil layer than the other six sites and there was no desirable timber present in the wetland to harvest. These factors likely resulted in the machinery operators making passes through a much narrower corridor of the wetland for fear of getting the machinery stuck in the wet soil. It appeared that by traveling in this manner, the footprint of the roadbed was similar in area to that of the cut ROW, and that the installed culvert moved water effectively from the upslope to the downslope section of the wetland.

In addition to the ROW, culvert placement, and the placement of the road in the ROW, the location of a wetland in the local topography and the construction of ditches may provide some insight as to why water table levels behaved as they did over the course of this study. It appears that the J.D. Irving sites at G4 Upper Branch and Acadia Road may be perched wetlands and are situated at higher elevations than the surrounding area along the road. The construction of ditches to the edge of the wetland may have caused water to leave the area and move down the ditch or drain into a nearby borrow pit. Although there are no ditches through the wetland itself, this movement of water off-site may be preventing water from flowing through the culverts that were installed for this study. Research by Forman et al. (1995) supports this possibility. J.D. Irving sites only had ditches constructed on one side of the road. Having a ditch on one side of the road and not the other may have contributed to the differences in water table levels between the two sides of the wetlands.

J.D. Irving wetlands at G4 Lower Branch, Drifters and Minto appear to be wetlands located in the low point of the local topography. In these instances, there are ditches along the road that are visibly moving off-site drainage water toward the wetlands. As mentioned above, having a ditch on one side of the road and not the other may again have contributed to the differences in water table levels between the two sides of the wetlands. At these sites, the ditches on one side of the road bringing water into the wetland may have caused that side of the wetland to experience larger amounts of water than the other. At the Bowater Mersey site, the wetland had ditches entering the low-lying push area from both sides of the road. The presence of two ditches at this site likely resulted in both sides of the wetland receiving similar amounts of surface water from off-site sources, possibly contributing to similar water table levels on both sides of the road and (under the circumstance of this site at this time) implying that a 40 m culvert spacing may be adequate.

The result of the two sample T-test comparing differences in upslope and downslope water table levels between treatments determined that there was no significant statistical difference between the two treatments. Despite the culvert spacing differences, the upslope water levels differed from the downslope water levels regardless of treatment. The application of this analysis should be considered limited because of the water table differences in the pre- and post-road construction data over time even with the treatments in place.

When observing the data in this study, some consideration should be given to the ability of wetlands to adjust to environmental pressures. Water table levels in wetlands are dependent on precipitation, temperature, and seasonal variability, resulting in fluctuations through exceptionally wet and dry periods of the year (Tiner, 1999; United States Geologic Survey, 1999). Upslope and downslope water table levels at the G4 Main Branch and Minto sites were determined to be statistically different from each other. However, the differences at these two sites (as well as Bowater Mersey) appear to be smaller than those of the other J.D. Irving sites and there does not appear to be a clear reason. These two sites differ in soil type, length of wetland crossing and the treatment used.

Of the two J.D. Irving sites mentioned, the lowest difference between upslope and downslope sides of the ROW was 10.9 cm while the largest difference was 20.6 cm. If one assumes that the water table difference is caused equally by flooding of one side of the wetland and drying of the other, a difference of 20.6 cm would mean that the upslope side of the wetland is experiencing a 10.3 cm increase in water table level while the downslope side is experiencing a 10.3 cm decrease. These differences in water tables may not be biologically significant for the species in these wetlands and may allow the wetland to exist in its current state. To determine the impacts on the wetlands ecology caused by the differences in water table levels, the study sites will have to be monitored over a longer period of time. These impacts may be more rapid at sites where the water table differences are greater.

Improper road installation disrupts natural horizontal processes such as surface and groundwater flow (Forman and Alexander, 1998) causing changes in the hydrology within the landscape (Trombulak and Frissell, 2000). This disruption can raise the water table on the upslope side of the road, which can lead to flooding of the road area and drowning of vegetation. Alternately, the downslope side of the road can experience a lowered water table where the drying of the soil can also lead to mortality of vegetation (Anderson, 2007; Mitsch and Gosselink, 2007; Verpraskas et al., 2002). Flooding of the area next to the roadbed increases erosion, sediment travel, and nutrient storage while negatively impacting the surface of the road causing the road to become impassable over time (Forman et al., 1995; Spellerberg, 1998; Welsch et al, 1995).

Disruptions of surface water and ground-water caused by roads have been documented in studies by Wemple et al. (1996), Kahklen (1999) and Wigmosta and Perkins (2001). Although these studies make no mention of the specific impacts of the sections of ROW that are not being used for transportation purposes, and are not specific to forested wetlands, it appears that findings from this study are relatable and support their conclusions that roads do impact the natural hydrology of wetlands. In order to fully understand what is taking place in these forested wetlands crossings, it seems that the remaining section of exposed ROW that was not used for placement of the road and the ditch structures must be included in BMPs and construction plans to better manage the hydrology in the area.

5.1 Recommendations

Several reasons explain the unexpected nature of the results in this study. This study's original hypothesis was based on the presumption that road construction methods are causing problems with the natural hydrology after the construction of the roadbed. In order to test this presumption, an alternative hypothesis would have to be developed to determine whether the clearing of the ROW is affecting water table levels before the road is constructed. Testing of this alternative hypothesis should include installation of shallow wells on either side of the proposed road, similar to this study. However, measurements from these wells should be taken before the ROW is cleared, preventing compaction and rutting by the machinery. Data associated with this alternative hypothesis should be able to determine whether the water table levels are naturally much larger than we expected or if the ROW construction is the root cause of the problem.

If the results associated with the alternative hypothesis, mentioned above, shows that this study's presumptions were correct, further testing of the ROW clearing and road construction methods can be conducted. Each of the following techniques would have to be tested separately or in different combinations before the original hypothesis related to proper culvert spacing could be revisited. Each of these techniques could be tested using the same monitoring system as this original study.

A test should be developed to determine whether narrowing the ROW, so that it is the same footprint at the road, would allow water table levels to equalize over time. This would have to be achieved during the site assessment, and boundaries of each wetland would have to be marked before the movement of any machinery into the area. Narrowing the ROW would keep the footprint of the machinery and road bed on the same section of forest floor, similar to practices used when crossing watercourses such as streams. The narrower section of ROW may cause more disruption to a smaller section of the wetland initially, but would allow the length of the culvert to remain the same as the width of the road to move water from one side of the wetland to the other.

If narrowing the footprint of the ROW is not plausible, another option could be to use longer sections of culvert that would span the entire width of the cleared area (Figure 18), allowing the water to bypass the compacted ROW soils altogether. Approximately half the total length of the culvert in the ROW would be held down by the weight of the road but the remaining half would have to be buried to prevent the culvert from lifting due to frost.

In an effort to continue current construction practices, building ditches/trenches may be another effective way to bypass the compacted area of the ROW. This method would be similar to that of extending the length of culvert, but as an alternative, companies could dig a ditch/trench that would extend from the mouth of the culvert and run across the ROW to the other side of the wetland. This would move water from the upslope section of wetland, through the culvert under the road, into the trench and theoretically back into the downslope section of the wetland.

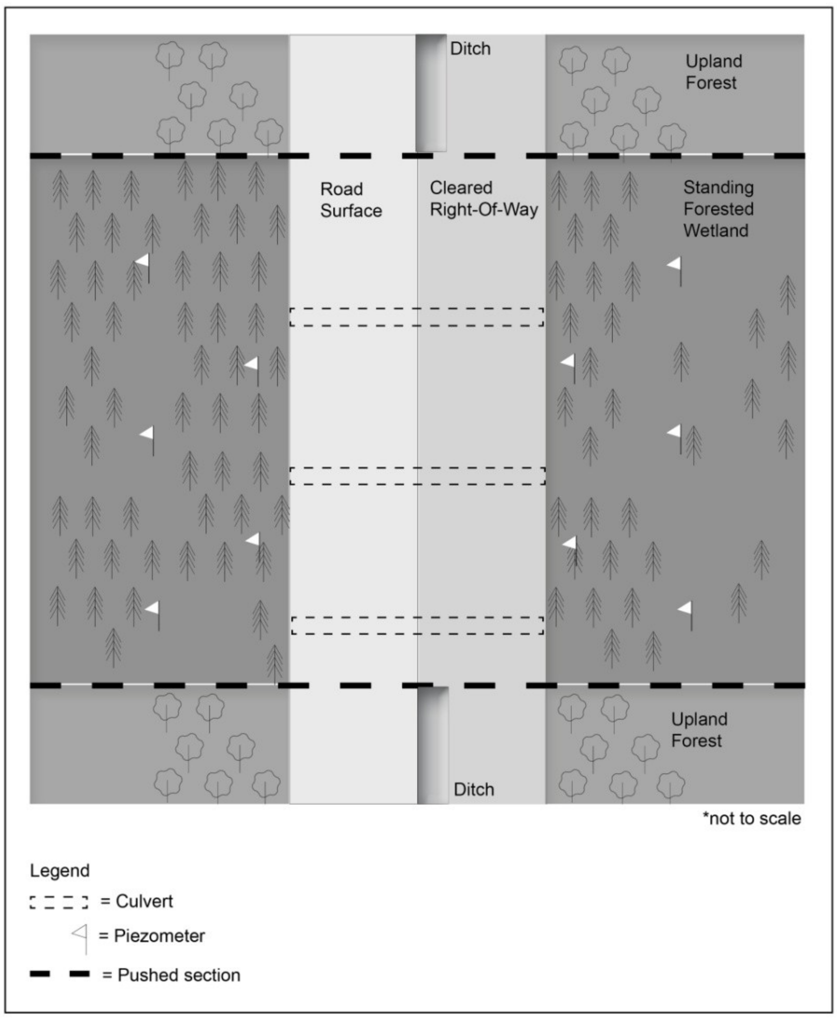


Figure 18. Culvert extension to bypass right-of-way

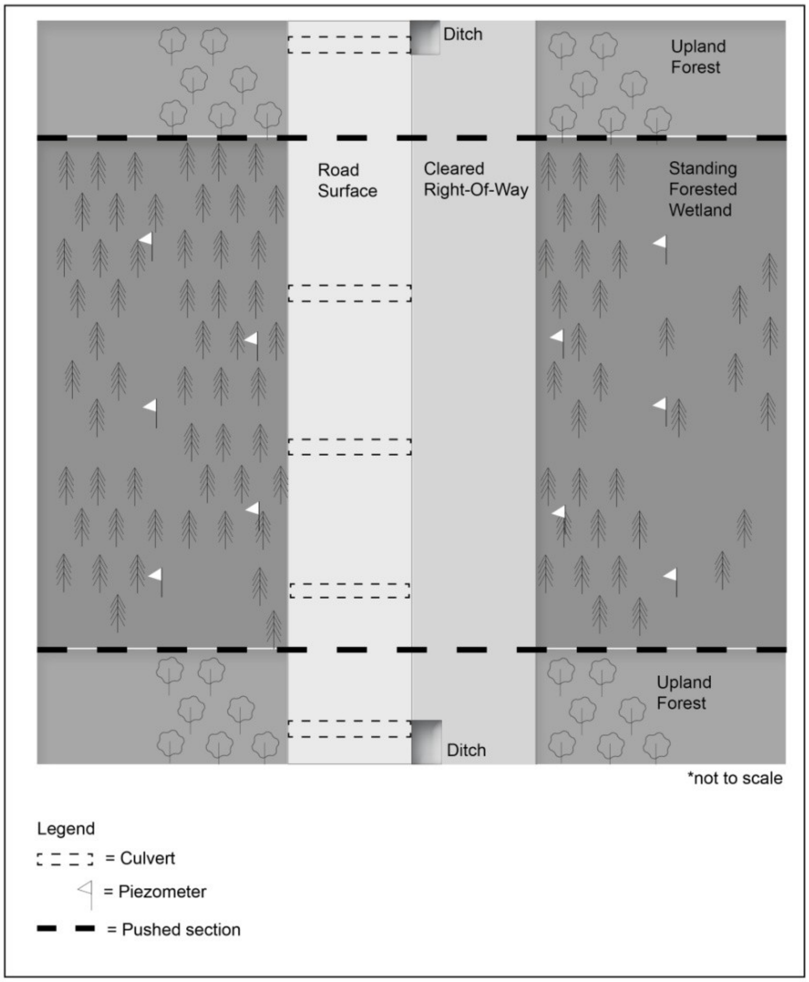


Figure 19. Extension of "push" area different placement of ditches

The data collected from narrowing or bypassing the cleared area of ROW could help determine which aspect of forest access road construct is contributing to the differences in water table levels. If results from the changing of ROW construction do not clarify the issue, another alternative hypothesis may be that the addition of offsite surface water is contributing to the problem. To test this alternative hypothesis, the ditch structure of the road in the area would have to be altered. One possible way of performing this test would be to extend the section of road without constructing ditches on either side, which essentially amounts to "pushing" an additional section of road at either end of the identified wetland crossing (Figure 19). Placing culverts at the end of each ditched section would allow water to move to the proper side of the road while leaving the area of wetland that had been “pushed” across free from any offsite effects.

Chapter 6. Conclusion

The data and results from this study indicated a number of issues that were not known at the outset of the project. The differences in water table levels found in pre-road construction measurements on opposing sides of the road were found to be much different than what was expected in a natural wetland setting for six of the seven sites. Upslope water table levels remained higher than the downslope water table levels but did not significantly vary over the duration of the three site visits. This may suggest that the research team's presumptions regarding pre-road construction water table levels were wrong or that there may be an impact on the site before the installation of the roadbed, but after the ROW had been cleared.

Results from the study were able to determine that there were no significant statistical differences between 20 m or 40 m cross-drain spacing using the current road construction methods. Although the testing of culvert spacing may have been affected by other variables, the results still appear to demonstrate a significant finding regarding the cause of disrupted water tables during road construction practices in forested wetlands. Future studies will have to build on the results and challenges that were discovered during this study. Despite the challenges, this study's findings support previous literature that concludes that there appears to be an underlying problem with forest access road construction in respect of water movement aside from the number and orientation of culverts. With this information in hand, the future research will hopefully be able to determine a set of construction methods that creates a functional road while preventing damage to wetland ecosystems.

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APPENDIX – A

Statistical Analysis

Pre – Pre-Road Construction Measurement

PC1 – First Post-Road Construction Measurement

PC2 – Second Post-Road Construction Measurement

H – Upslope Section of Forested Wetland

L – Downslope Section of Forested Wetland

Acadia Road:

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N    Mean  StDev  SE Mean
Pre H  4  -1.004  0.198    0.099
Pre L  3  -1.662  0.164    0.095


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.658
95% CI for difference:  (0.294, 1.022)
T-Test of difference = 0 (vs not =): T-Value = 4.65  P-Value = 0.006  DF = 5
Both use Pooled StDev = 0.1854
```

Two-Sample T-Test and CI: PC1 H, PC1 L

```
Two-sample T for PC1 H vs PC1 L

       N    Mean  StDev  SE Mean
PC1 H  4  -1.116  0.171    0.086
PC1 L  3  -1.853  0.183     0.11


Difference = mu (PC1 H) - mu (PC1 L)
Estimate for difference:  0.737
95% CI for difference:  (0.391, 1.083)
T-Test of difference = 0 (vs not =): T-Value = 5.47  P-Value = 0.003  DF = 5
Both use Pooled StDev = 0.1763
```

Two-Sample T-Test and CI: PC2 H, PC2 L

```
Two-sample T for PC2 H vs PC2 L
```

```
       N    Mean  StDev  SE Mean
PC2 H  4  -1.129  0.127    0.064
PC2 L  3  -1.722  0.178     0.10


Difference = mu (PC2 H) - mu (PC2 L)
Estimate for difference:  0.593
95% CI for difference:  (0.300, 0.887)
T-Test of difference = 0 (vs not =): T-Value = 5.20  P-Value = 0.003  DF = 5
Both use Pooled StDev = 0.1494
```

One-way ANOVA: Pre H, PC1 H, PC2 H

```
Source  DF      SS      MS     F      P
Factor   2  0.0379  0.0190  0.67  0.536
Error    9  0.2549  0.0283
Total   11  0.2929

S = 0.1683   R-Sq = 12.95%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N     Mean   StDev  --------+---------+---------+---------+-
Pre H  4  -1.0038  0.1985          (------------*------------)
PC1 H  4  -1.1157  0.1715   (------------*-----------)
PC2 H  4  -1.1292  0.1272  (------------*-----------)
                           --------+---------+---------+---------+-
                               -1.20     -1.05     -0.90     -0.75

Pooled StDev = 0.1683
```

One-way ANOVA: Pre L, PC1 L, PC2 L

```
Source  DF      SS      MS     F      P
Factor   2  0.0569  0.0284  0.93  0.445
Error    6  0.1838  0.0306
Total    8  0.2407

S = 0.1750   R-Sq = 23.63%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N     Mean   StDev  -----+---------+---------+---------+----
Pre L  3  -1.6620  0.1637            (-----------*-----------)
PC1 L  3  -1.8526  0.1832  (-----------*------------)
PC2 L  3  -1.7224  0.1775         (-----------*-----------)
                           -----+---------+---------+---------+----
                             -2.00     -1.80     -1.60     -1.40

Pooled StDev = 0.1750
```

Bowater Mersey:

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N     Mean   StDev  SE Mean
Pre H  3  -1.3456  0.0595    0.034
Pre L  2  -1.3738  0.0310    0.022


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.0282
95% CI for difference:  (-0.1223, 0.1787)
T-Test of difference = 0 (vs not =): T-Value = 0.60  P-Value = 0.593  DF = 3
Both use Pooled StDev = 0.0518
```

Two-Sample T-Test and CI: PC1 H, PC1 L

```
Two-sample T for PC1 H vs PC1 L

       N     Mean   StDev  SE Mean
PC1 H  3   -1.225   0.100    0.058
PC1 L  2  -1.2261  0.0647    0.046


Difference = mu (PC1 H) - mu (PC1 L)
Estimate for difference:  0.0012
95% CI for difference:  (-0.2601, 0.2625)
T-Test of difference = 0 (vs not =): T-Value = 0.01  P-Value = 0.989  DF = 3
Both use Pooled StDev = 0.0899
```

Two-Sample T-Test and CI: PC2 H, PC2 L

```
Two-sample T for PC2 H vs PC2 L

       N     Mean   StDev  SE Mean
PC2 H  3  -1.3043  0.0484    0.028
PC2 L  2  -1.3103  0.0310    0.022


Difference = mu (PC2 H) - mu (PC2 L)
Estimate for difference:  0.0060
95% CI for difference:  (-0.1200, 0.1319)
T-Test of difference = 0 (vs not =): T-Value = 0.15  P-Value = 0.890  DF = 3
Both use Pooled StDev = 0.0434
```

One-way ANOVA: Pre H, PC1 H, PC2 H

```
Source  DF       SS       MS     F      P
Factor   2  0.02256  0.01128  2.13  0.201
Error    6  0.03185  0.00531
Total    8  0.05441

S = 0.07286   R-Sq = 41.47%   R-Sq(adj) = 21.95%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N     Mean   StDev  -----+---------+---------+---------+----
Pre H  3  -1.3456  0.0595  (---------*----------)
PC1 H  3  -1.2249  0.1002              (----------*---------)
PC2 H  3  -1.3043  0.0484      (----------*---------)
                           -----+---------+---------+---------+----
                             -1.40     -1.30     -1.20     -1.10

Pooled StDev = 0.0729
```

One-way ANOVA: Pre L, PC1 L, PC2 L

```
Source  DF       SS       MS     F      P
Factor   2  0.02194  0.01097  5.39  0.102
Error    3  0.00611  0.00204
Total    5  0.02805

S = 0.04512   R-Sq = 78.23%   R-Sq(adj) = 63.71%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N     Mean   StDev  --------+---------+---------+---------+-
Pre L  2  -1.3738  0.0310  (----------*---------)
PC1 L  2  -1.2261  0.0647                 (---------*----------)
PC2 L  2  -1.3103  0.0310         (---------*---------)
                           --------+---------+---------+---------+-
                                -1.40     -1.30     -1.20     -1.10

Pooled StDev = 0.0451
```

Drifters:

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N     Mean   StDev  SE Mean
Pre H  5   -0.332   0.119    0.053
Pre L  5  -0.6951  0.0353    0.016


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.3632
95% CI for difference:  (0.2353, 0.4911)
T-Test of difference = 0 (vs not =): T-Value = 6.55  P-Value = 0.000  DF = 8
Both use Pooled StDev = 0.0877
```

Two-Sample T-Test and CI: PC1 H, PC1 L

```
Two-sample T for PC1 H vs PC1 L

       N     Mean   StDev  SE Mean
PC1 H  5  -0.4221  0.0681    0.030
PC1 L  5  -0.7584  0.0815    0.036


Difference = mu (PC1 H) - mu (PC1 L)
Estimate for difference:  0.3364
95% CI for difference:  (0.2268, 0.4459)
T-Test of difference = 0 (vs not =): T-Value = 7.08  P-Value = 0.000  DF = 8
Both use Pooled StDev = 0.0751
```

Two-Sample T-Test and CI: PC2 H, PC2 L

```
Two-sample T for PC2 H vs PC2 L

       N     Mean   StDev  SE Mean
PC2 H  5   -0.327   0.100    0.045
PC2 L  5  -0.6259  0.0508    0.023


Difference = mu (PC2 H) - mu (PC2 L)
Estimate for difference:  0.2984
95% CI for difference:  (0.1827, 0.4141)
T-Test of difference = 0 (vs not =): T-Value = 5.95  P-Value = 0.000  DF = 8
Both use Pooled StDev = 0.0793
```

One-way ANOVA: Pre H, PC1 H, PC2 H

```
Source  DF       SS       MS     F      P
Factor   2  0.02851  0.01425  1.49  0.265
Error   12  0.11517  0.00960
Total   14  0.14368

S = 0.09797   R-Sq = 19.84%   R-Sq(adj) = 6.48%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level  N      Mean    StDev  -----+---------+---------+---------+----
Pre H  5  -0.33190  0.11891              (-----------*----------)
PC1 H  5  -0.42208  0.06813  (-----------*-----------)
PC2 H  5  -0.32746  0.10006              (-----------*-----------)
                             -----+---------+---------+---------+----
                               -0.480    -0.400    -0.320    -0.240

Pooled StDev = 0.09797
```

One-way ANOVA: Pre L, PC1 L, PC2 L

```
Source  DF       SS       MS     F      P
Factor   2  0.04396  0.02198  6.31  0.013
Error   12  0.04183  0.00349
Total   14  0.08579

S = 0.05904   R-Sq = 51.24%   R-Sq(adj) = 43.11%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level  N      Mean    StDev  -------+---------+---------+---------+--
Pre L  5  -0.69510  0.03530           (--------*-------)
PC1 L  5  -0.75844  0.08146  (--------*-------)
PC2 L  5  -0.62588  0.05076                    (--------*-------)
                             -------+---------+---------+---------+--
                                 -0.770    -0.700    -0.630    -0.560

Pooled StDev = 0.05904
```

G4 Main Branch:

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N     Mean   StDev  SE Mean
Pre H  5  -0.8256  0.0261    0.012
Pre L  5  -0.9393  0.0704    0.031


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.1137
95% CI for difference:  (0.0363, 0.1912)
T-Test of difference = 0 (vs not =): T-Value = 3.39  P-Value = 0.010  DF = 8
Both use Pooled StDev = 0.0531
```

Two-Sample T-Test and CI: PC1 H, PC1 L

```
Two-sample T for PC1 H vs PC1 L

       N     Mean   StDev  SE Mean
PC1 H  5  -0.8498  0.0369    0.016
PC1 L  5  -0.9686  0.0832    0.037


Difference = mu (PC1 H) - mu (PC1 L)
Estimate for difference:  0.1188
95% CI for difference:  (0.0250, 0.2126)
T-Test of difference = 0 (vs not =): T-Value = 2.92  P-Value = 0.019  DF = 8
Both use Pooled StDev = 0.0643
```

Two-Sample T-Test and CI: PC2 H, PC2 **L**

```
Two-sample T for PC2 H vs PC2 L

       N     Mean   StDev  SE Mean
PC2 H  5  -0.8453  0.0489    0.022
PC2 L  5  -0.9540  0.0904    0.040


Difference = mu (PC2 H) - mu (PC2 L)
Estimate for difference:  0.1087
95% CI for difference:  (0.0027, 0.2146)
T-Test of difference = 0 (vs not =): T-Value = 2.36  P-Value = 0.046  DF = 8
Both use Pooled StDev = 0.0726
```

One-way ANOVA: Pre H, PC1 H, PC2 H

```
Source  DF       SS       MS     F      P
Factor   2  0.00165  0.00082  0.56  0.586
Error   12  0.01772  0.00148
Total   14  0.01937

S = 0.03843   R-Sq = 8.51%   R-Sq(adj) = 0.00%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level  N     Mean    StDev  -----+---------+---------+---------+----
Pre H  5  -0.82562  0.02610            (--------------*--------------)
PC1 H  5  -0.84975  0.03687  (--------------*--------------)
PC2 H  5  -0.84531  0.04889    (--------------*--------------)
                             -----+---------+---------+---------+----
                               -0.875    -0.850    -0.825    -0.800

Pooled StDev = 0.03843
```

One-way ANOVA: Pre L, PC1 L, PC2 L

```
Source  DF       SS       MS     F      P
Factor   2  0.00213  0.00107  0.16  0.854
Error   12  0.08017  0.00668
Total   14  0.08230

S = 0.08174   R-Sq = 2.59%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on Pooled StDev
Level  N    Mean   StDev     +---------+---------+---------+---------
Pre L  5  -0.9393  0.0704          (---------------*---------------)
PC1 L  5  -0.9686  0.0832     (---------------*---------------)
PC2 L  5  -0.9540  0.0904        (---------------*---------------)
                             +---------+---------+---------+---------
                           -1.050    -1.000    -0.950    -0.900

Pooled StDev = 0.0817
```

G4 Upper Branch:

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N    Mean  StDev  SE Mean
Pre H  3  -0.761  0.110    0.064
Pre L  3  -1.514  0.139    0.080


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.753
95% CI for difference:  (0.469, 1.037)
T-Test of difference = 0 (vs not =): T-Value = 7.36  P-Value = 0.002  DF = 4
Both use Pooled StDev = 0.1253
```

Two-Sample T-Test and CI: PC1 H, PC1 **L**

```
Two-sample T for PC1 H vs PC1 L

       N    Mean  StDev  SE Mean
PC1 H  3  -0.807  0.106    0.061
PC1 L  3  -1.600  0.187     0.11


Difference = mu (PC1 H) - mu (PC1 L)
Estimate for difference:  0.793
95% CI for difference:  (0.449, 1.137)
T-Test of difference = 0 (vs not =): T-Value = 6.40  P-Value = 0.003  DF = 4
Both use Pooled StDev = 0.1519
```

Two-Sample T-Test and CI: PC2 H, PC2 L

```
Two-sample T for PC2 H vs PC2 L

       N    Mean  StDev  SE Mean
PC2 H  3  -0.829  0.130    0.075
PC2 L  3  -1.632  0.166    0.096


Difference = mu (PC2 H) - mu (PC2 L)
Estimate for difference:  0.803
95% CI for difference:  (0.464, 1.141)
T-Test of difference = 0 (vs not =): T-Value = 6.59  P-Value = 0.003  DF = 4
Both use Pooled StDev = 0.1492
```

One-way ANOVA: Pre H, PC1 H, PC2 H

```
Source  DF      SS      MS     F      P
Factor   2  0.0072  0.0036  0.27  0.775
Error    6  0.0807  0.0134
Total    8  0.0878

S = 0.1159   R-Sq = 8.15%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N     Mean   StDev  ---------+---------+---------+---------+
Pre H  3  -0.7613  0.1100        (----------------*---------------)
PC1 H  3  -0.8068  0.1061    (---------------*----------------)
PC2 H  3  -0.8290  0.1303  (---------------*---------------)
                           ---------+---------+---------+---------+
                                -0.90     -0.80     -0.70     -0.60

Pooled StDev = 0.1159
```

One-way ANOVA: Pre L, PC1 L, PC2 L

```
Source  DF      SS      MS     F      P
Factor   2  0.0222  0.0111  0.41  0.683
Error    6  0.1635  0.0272
Total    8  0.1856

S = 0.1651   R-Sq = 11.94%   R-Sq(adj) = 0.00%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level  N     Mean   StDev  ----+---------+---------+---------+-----
Pre L  3  -1.5141  0.1390          (--------------*---------------)
PC1 L  3  -1.5998  0.1867    (--------------*---------------)
PC2 L  3  -1.6316  0.1660  (--------------*---------------)
                           ----+---------+---------+---------+-----
                            -1.80     -1.65     -1.50     -1.35

Pooled StDev = 0.1651
```

Harcourt:

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N    Mean  StDev  SE Mean
Pre H  5  -0.667  0.125    0.056
Pre L  5  -1.301  0.122    0.055


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.6334
95% CI for difference:  (0.4536, 0.8132)
T-Test of difference = 0 (vs not =): T-Value = 8.12  P-Value = 0.000  DF = 8
Both use Pooled StDev = 0.1233
```

Two-Sample T-Test and CI: PC1 H, PC1 L

```
Two-sample T for PC1 H vs PC1 L

       N     Mean   StDev  SE Mean
PC1 H  5  -0.6007  0.0792    0.035
PC1 L  5  -1.2450  0.0730    0.033


Difference = mu (PC1 H) - mu (PC1 L)
Estimate for difference:  0.6442
95% CI for difference:  (0.5332, 0.7553)
T-Test of difference = 0 (vs not =): T-Value = 13.38  P-Value = 0.000  DF = 8
Both use Pooled StDev = 0.0762
```

Two-Sample T-Test and CI: PC2 H, PC2 L

```
Two-sample T for PC2 H vs PC2 L

       N     Mean   StDev  SE Mean
PC2 H  5  -0.5538  0.0631    0.028
PC2 L  5  -1.1859  0.0763    0.034


Difference = mu (PC2 H) - mu (PC2 L)
Estimate for difference:  0.6322
95% CI for difference:  (0.5300, 0.7343)
T-Test of difference = 0 (vs not =): T-Value = 14.27  P-Value = 0.000  DF = 8
Both use Pooled StDev = 0.0700
```

One-way ANOVA: Pre H, PC1 H, PC2 H

```
Source  DF       SS       MS     F      P
Factor   2  0.03262  0.01631  1.90  0.192
Error   12  0.10309  0.00859
Total   14  0.13572

S = 0.09269   R-Sq = 24.04%   R-Sq(adj) = 11.38%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level   N      Mean    StDev  -----+---------+---------+---------+----
Pre H   5  -0.66742  0.12462  (-----------*----------)
PC1 H   5  -0.60075  0.07915           (----------*----------)
PC2 H   5  -0.55375  0.06308                (-----------*----------)
                              -----+---------+---------+---------+----
                                -0.720    -0.640    -0.560    -0.480

Pooled StDev = 0.09269
```

One-way ANOVA: Pre L, PC1 L, PC2 L

```
Source  DF       SS       MS     F      P
Factor   2  0.03303  0.01652  1.90  0.191
Error   12  0.10411  0.00868
Total   14  0.13714

S = 0.09314   R-Sq = 24.09%   R-Sq(adj) = 11.43%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N     Mean   StDev  ----+---------+---------+---------+-----
Pre L   5  -1.3008  0.1219  (----------*-----------)
PC1 L   5  -1.2450  0.0730         (----------*-----------)
PC2 L   5  -1.1859  0.0763                (-----------*----------)
                            ----+---------+---------+---------+-----
                             -1.360    -1.280    -1.200    -1.120

Pooled StDev = 0.0931
```

Minto (K-Road):

Two-Sample T-Test and CI: Pre H, Pre L

```
Two-sample T for Pre H vs Pre L

       N     Mean   StDev  SE Mean
Pre H  3  -0.3681  0.0978    0.056
Pre L  4  -0.5739  0.0322    0.016


Difference = mu (Pre H) - mu (Pre L)
Estimate for difference:  0.2058
95% CI for difference:  (0.0748, 0.3367)
T-Test of difference = 0 (vs not =): T-Value = 4.04  P-Value = 0.010  DF = 5
Both use Pooled StDev = 0.0667
```

Two-Sample T-Test and CI: PC H, PC L

```
Two-sample T for PC H vs PC L

      N     Mean   StDev  SE Mean
PC H  3  -0.4539  0.0829    0.048
PC L  4  -0.5692  0.0279    0.014


Difference = mu (PC H) - mu (PC L)
Estimate for difference:  0.1153
95% CI for difference:  (0.0039, 0.2266)
T-Test of difference = 0 (vs not =): T-Value = 2.66  P-Value = 0.045  DF = 5
Both use Pooled StDev = 0.0567
```

Two-Sample T-Test and CI: Pre H, PC H

```
Two-sample T for Pre H vs PC H

       N     Mean   StDev  SE Mean
Pre H  3  -0.3681  0.0978    0.056
PC H   3  -0.4539  0.0829    0.048


Difference = mu (Pre H) - mu (PC H)
Estimate for difference:  0.0857
95% CI for difference:  (-0.1199, 0.2913)
T-Test of difference = 0 (vs not =): T-Value = 1.16  P-Value = 0.311  DF = 4
Both use Pooled StDev = 0.0907
```

Two-Sample T-Test and CI: Pre L, PC L

```
Two-sample T for Pre L vs PC L

       N     Mean   StDev  SE Mean
Pre L  4  -0.5739  0.0322    0.016
PC L   4  -0.5692  0.0279    0.014


Difference = mu (Pre L) - mu (PC L)
Estimate for difference:  -0.0048
95% CI for difference:  (-0.0568, 0.0473)
T-Test of difference = 0 (vs not =): T-Value = -0.22  P-Value = 0.830  DF = 6
Both use Pooled StDev = 0.0301
```

Between Treatments:

Two-Sample T-Test and CI: Pre 20, Pre 40

```
Two-sample T for Pre 20 vs Pre 40

        N    Mean  StDev  SE Mean
Pre 20  3  -0.539  0.292     0.17
Pre 40  4  -0.285  0.272     0.14


Difference = μ (Pre 20) - μ (Pre 40)
Estimate for difference:  -0.254
95% CI for difference:  (-0.856, 0.348)
T-Test of difference = 0 (vs ≠): T-Value = -1.17  P-Value = 0.307  DF = 4
```

Two-Sample T-Test and CI: PC1 20, PC1 40

```
Two-sample T for PC1 20 vs PC1 40

        N    Mean  StDev  SE Mean
PC1 20  3  -0.530  0.360     0.21
PC1 40  4  -0.275  0.282     0.14


Difference = μ (PC1 20) - μ (PC1 40)
Estimate for difference:  -0.255
95% CI for difference:  (-1.055, 0.544)
T-Test of difference = 0 (vs ≠): T-Value = -1.02  P-Value = 0.384  DF = 3
```

Two-Sample T-Test and CI: PC2 20, PC2 40

```
Two-sample T for PC2 20 vs PC2 40

        N    Mean  StDev  SE Mean
PC2 20  2  -0.698  0.148     0.11
PC2 40  4  -0.262  0.275     0.14


Difference = μ (PC2 20) - μ (PC2 40)
Estimate for difference:  -0.436
95% CI for difference:  (-0.987, 0.114)
T-Test of difference = 0 (vs ≠): T-Value = -2.52  P-Value = 0.086  DF = 3
```

APPENDIX – B

Raw data: Averages of Upslope/Downslope Sides of Wetland

Pre-road construction measurement:

Site	Culvert Spacing	Average of "Upslope" Side of Road (m)	Average of "Downslope" Side of Road (m)	Difference (m)
Acadia Road	20	-1.004	-1.662	-0.658
Bowater Mersey	40	-1.346	-1.374	-0.028
Drifters	40	-0.332	-0.695	-0.363
G4 Main Branch	40	-0.826	-0.939	-0.113
G4 Upper Branch	20*	-0.761	-1.514	-0.753
Harcourt	40	-0.667	-1.301	-0.634
Minto (K-Road)	20	-0.368	-0.574	-0.206

First post-road construction measurement:

Site	Culvert Spacing	Average of "Upslope" Side of Road (m)	Average of "Downslope" Side of Road (m)	Difference (m)
Acadia Road	20	-1.116	-1.853	-0.737
Bowater Mersey	40	-1.225	-1.226	-0.001
Drifters	40	-0.422	-0.758	-0.336
G4 Main Branch	40	-0.850	-0.969	-0.119
G4 Upper Branch	20*	-0.807	-1.600	-0.793
Harcourt	40	-0.601	-1.245	-0.644
Minto (K-Road)	20	-0.454	-0.569	-0.115

Second post-road construction measurement:

Site	Culvert Spacing	Average of "Upslope" Side of Road (m)	Average of "Downslope" Side of Road (m)	Difference (m)
Acadia Road	20	-1.129	-1.722	-0.593
Bowater Mersey	40	-1.304	-1.310	-0.006
Drifters	40	-0.327	-0.626	-0.299
G4 Main Branch	40	-0.845	-0.954	-0.109
G4 Upper Branch	20*	-0.829	-1.632	-0.803
Harcourt	40	-0.554	-1.186	-0.632
Minto (K-Road)	20	N/A	N/A	N/A

* Note: The Irving site, G4 Upper Branch, was intended to have culverts placed 20 m apart but no culverts were ever installed at the site. This site was over looked during a changeover in supervisory personnel for the company.

APPENDIX – C

Co-ordinates, Soil Types and Dominant Vegetation of Study Sites

Site	Longitude	Latitude
Acadia Road	-65.95791184	46.43868337
Bowater Mersey	-65.20192194	44.05314136
Drifters	-65.87715776	46.23013032
G4 Main Branch	-65.8740096	46.33297606
G4 Upper Branch	-65.86816446	46.33738162
Harcourt	-65.43549752	46.61025791
Minto (K-road)	-66.2568019	46.03925012

Site	Soil Type	Drainage Characteristics	Dominant Vegetation
Acadia Road	RE – 02 – 1	Dominantly well drained with significant rapidly or moderately well drained	Red Spruce, Balsam Fir, Cinnamon fern, Sphagnum
Bowater Mersey*	ST14	Moderate to Imperfect Drainage	Red Maple, Tamarack, Black Spruce
Drifters	SB – 05 – 3	Dominantly poorly drained with significant imperfectly or very poorly drained	Tamarack, Black Spruce, Lambkill, Sphagnum
G4 Main Branch	HT – 04 – 2	Dominantly imperfectly drained with significant moderately well or poorly drained	Tamarack, Black Spruce, Sphagnum
G4 Upper Branch	HT – 04 – 2	Dominantly imperfectly drained with significant moderately well or poorly drained	Red Spruce, Balsam Fir, Cinnamon fern, Sphagnum
Harcourt	RE – 04 – 2	Dominantly imperfectly drained with significant moderately well or poorly drained	Black Spruce, Lambkill, Labrador Tea, Sphagnum, Huckleberry
Minto (K-road)	HT – 03 – 1	Dominantly moderately well drained with significant well or imperfectly drained	Tamarack, Black Spruce, Sphagnum, Huckleberry

*Note: Different soil classification systems for Nova Scotia and New Brunswick.

APPENDIX - D

Figures of Shallow Well Placement at Individual Sites

Acadia Road:

Characteristics of Site

- 54 m long crossing (20 m spacing treatment, 2 culverts)

Dates

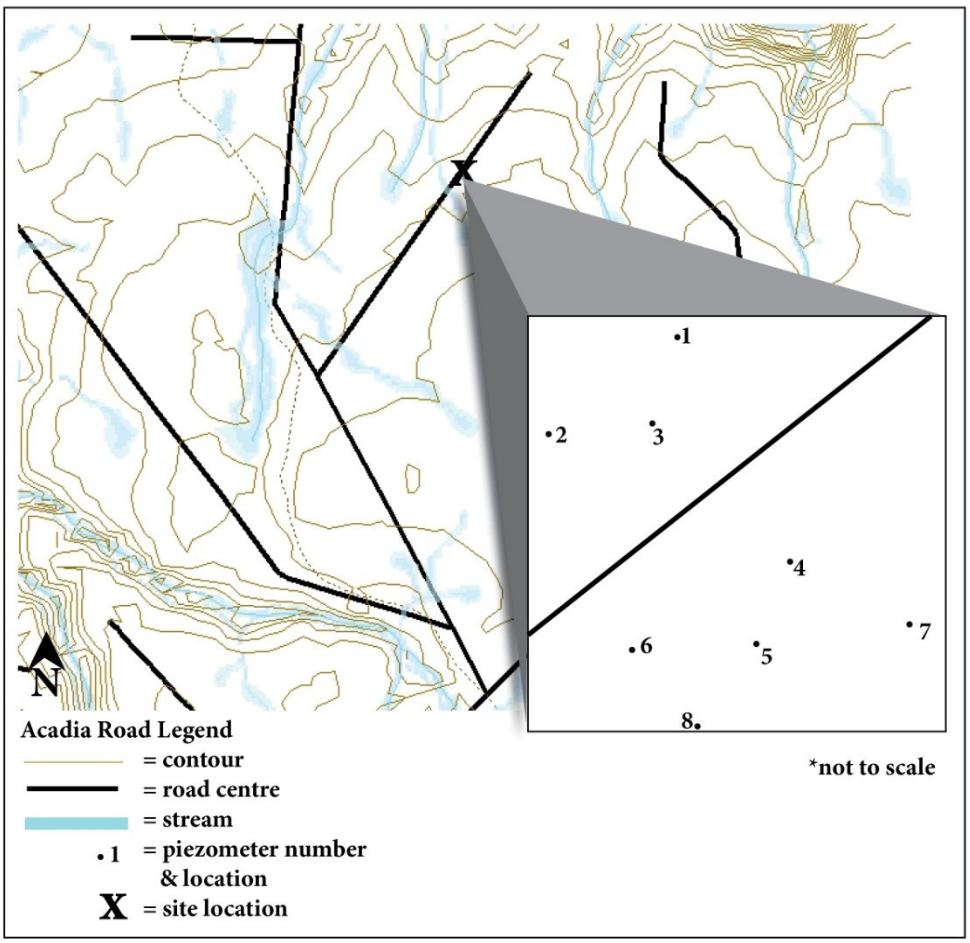
ROW Cleared - August 2011

Pre-construction Measurement – August 2011

Road Installation – Fall 2011

1st Post-construction Measurement – August 2012

2nd Post-construction Measurement – August 2013


N
•1
•2
•3
•4
•5
•6
•7
8•
Acadia Road Legend
= contour
= road centre
= stream
•1 = piezometer number & location
X = site location
*not to scale

Bowater Mersey:

Characteristics of Site

- 52 m long crossing (40 m spacing treatment, 1 culvert)

Dates

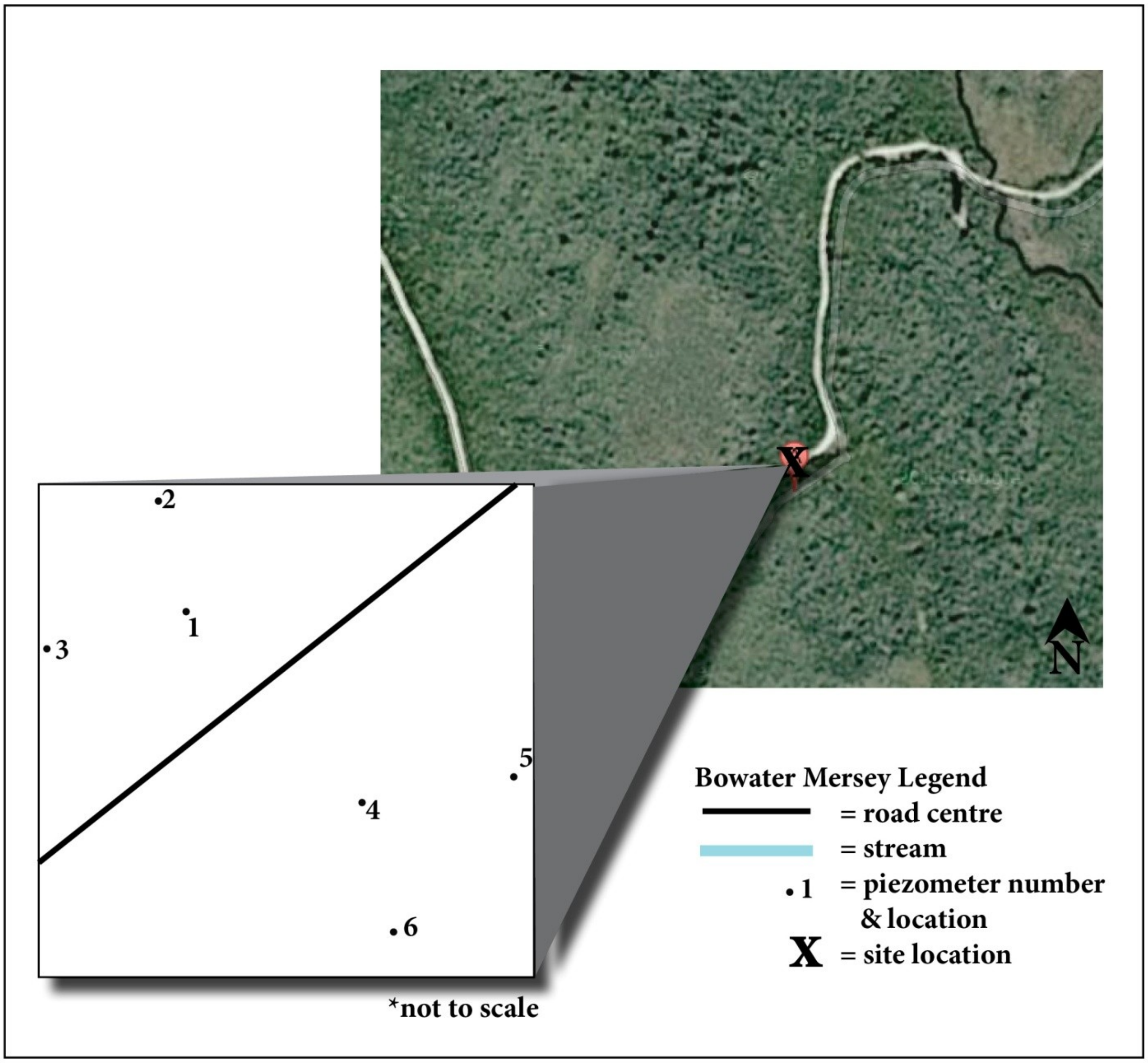
ROW Cleared – Summer 2011, After pre-construction measurements had been collected

Pre-construction Measurement – July 2011

Road Installation – Fall 2011

1st Post-construction Measurement – August 2012

2nd Post-construction Measurement – August 2013



2
1
3
5
4
6
X
N
Bowater Mersey Legend
= road centre
= stream
1 = piezometer number
& location
X = site location
*not to scale

Drifters:

Characteristics of Site

- 108 m long crossing (40 m spacing treatment, 3 culverts)

Dates

ROW Cleared - August 2011

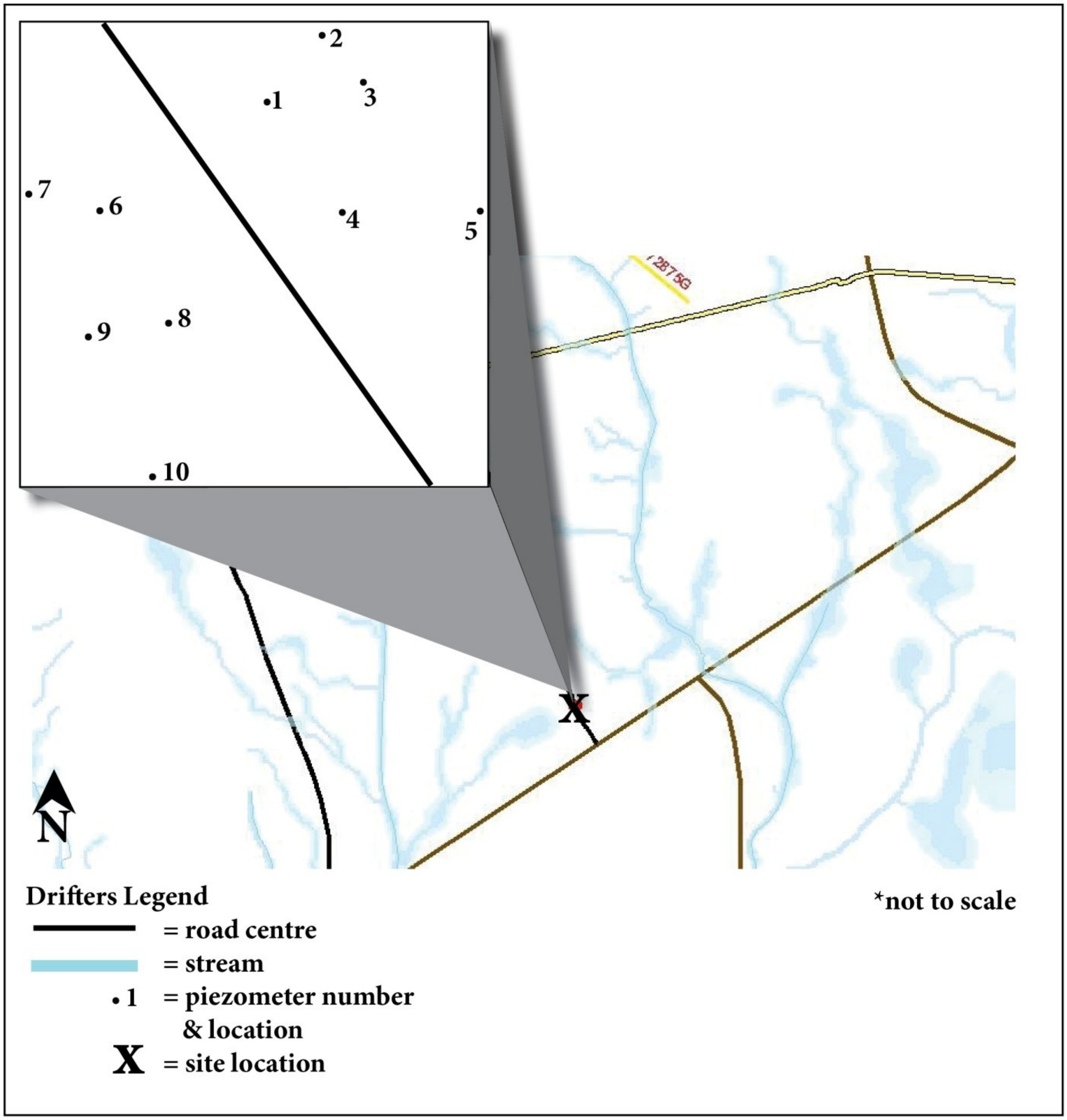
Pre-construction Measurement – September 2011

Road Installation – Fall 2011

1st Post-construction Measurement – July 2012

2nd Post-construction Measurement – August 2013





2
1
3
7
6
4
5
9
8
10
N
Drifters Legend
= road centre
= stream
• 1 = piezometer number
& location
X = site location
*not to scale

G4 Main Branch:

Characteristics of Site

- 84 m long crossing (40 m spacing treatment, 2 culverts)

Dates

ROW Cleared - August 2011

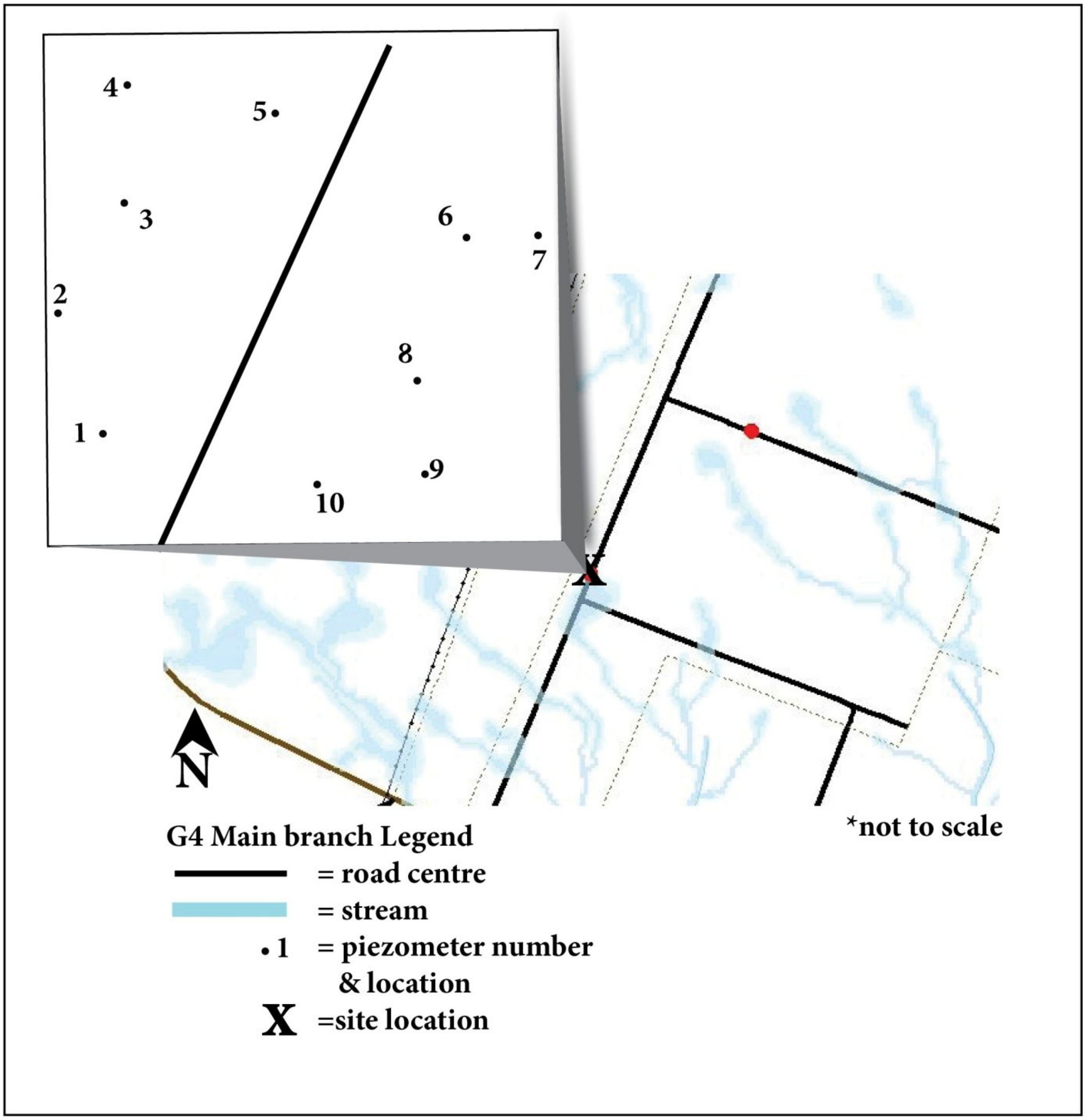
Pre-construction Measurement – August 2011

Road Installation – Fall 2011

1st Post-construction Measurement – May 2013

2nd Post-construction Measurement – August 2013





4
5
3
6
7
2
8
1
9
10
N
*not to scale
G4 Main branch Legend
= road centre
= stream
1 = piezometer number
& location
X =site location

G4 Upper Branch:

Characteristics of Site

- 63 m long crossing (20 m spacing treatment, 2 culverts)

Dates

ROW Cleared - August 2011

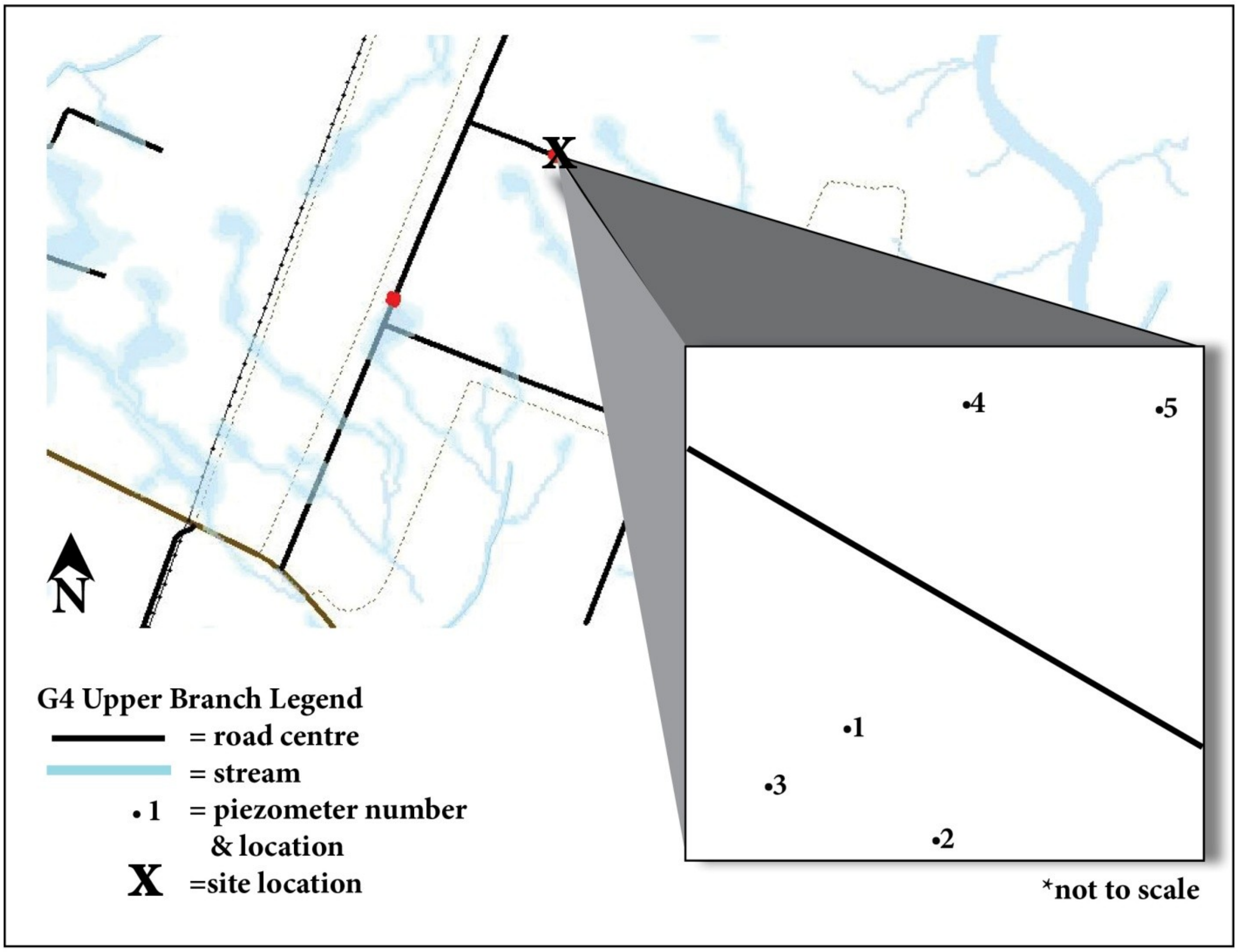
Pre-construction Measurement – August 2011

Road Installation – Fall 2011

1st Post-construction Measurement – May 2013

2nd Post-construction Measurement – August 2013



N
•4
•5
•1
•3
•2
*not to scale
G4 Upper Branch Legend
= road centre
= stream
• 1 = piezometer number
& location
X =site location

Harcourt:

Characteristics of Site

- 92 m long crossing (40 m spacing treatment, 2 culverts)

Dates

ROW Cleared - August 2012

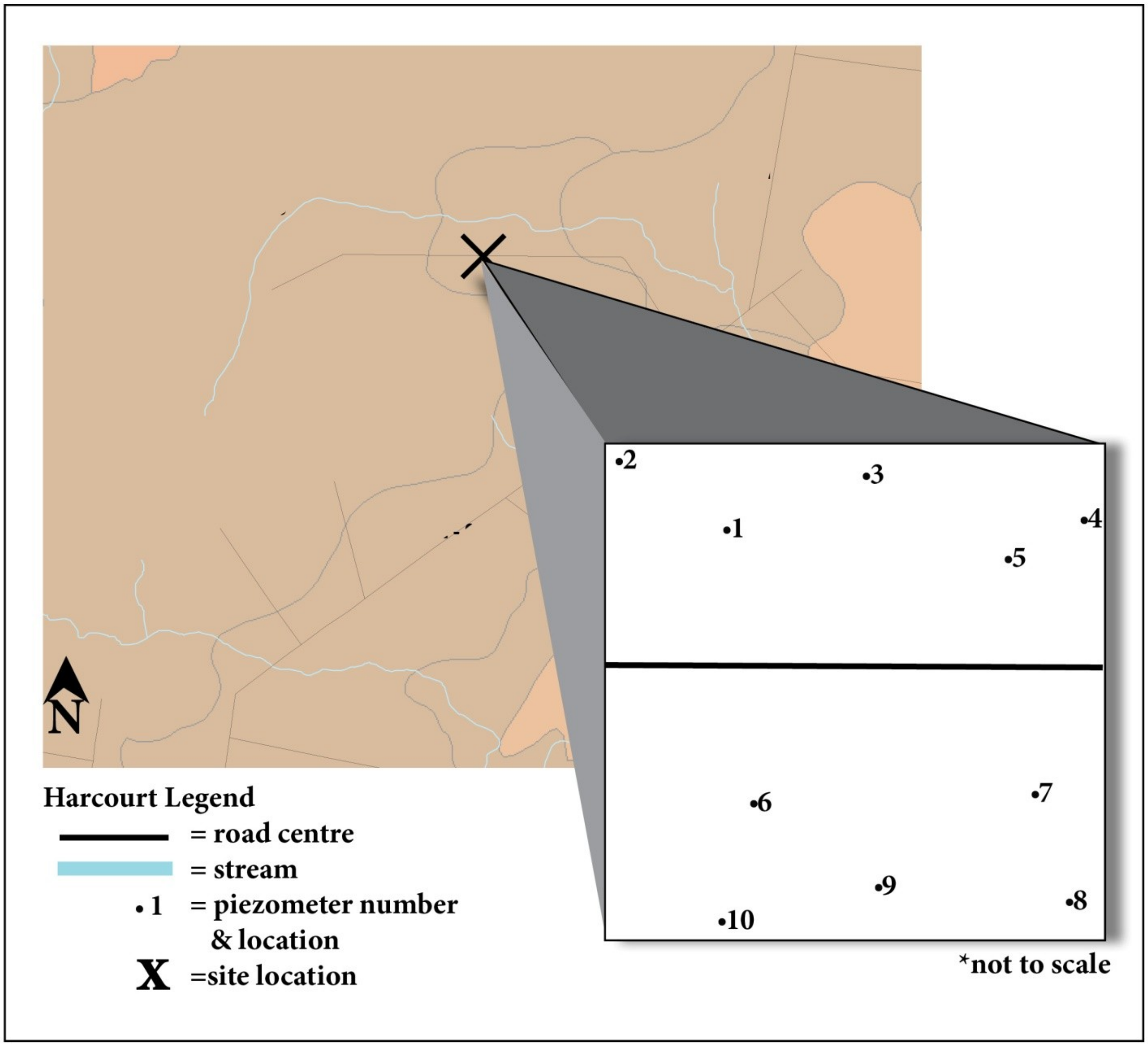
Pre-construction Measurement – August 2012

Road Installation – Fall 2012

1st Post-construction Measurement – May 2013

2nd Post-construction Measurement – August 2013





•2
•3
•1
•4
•5
•6
•7
•9
•8
•10
*not to scale
Harcourt Legend
= road centre
= stream
• 1 = piezometer number
& location
X =site location
N

Minto (K-Road):

Characteristics of Site

- 51 m long crossing (20 m spacing treatment, 1 culvert)

Dates

ROW Cleared - September 2012

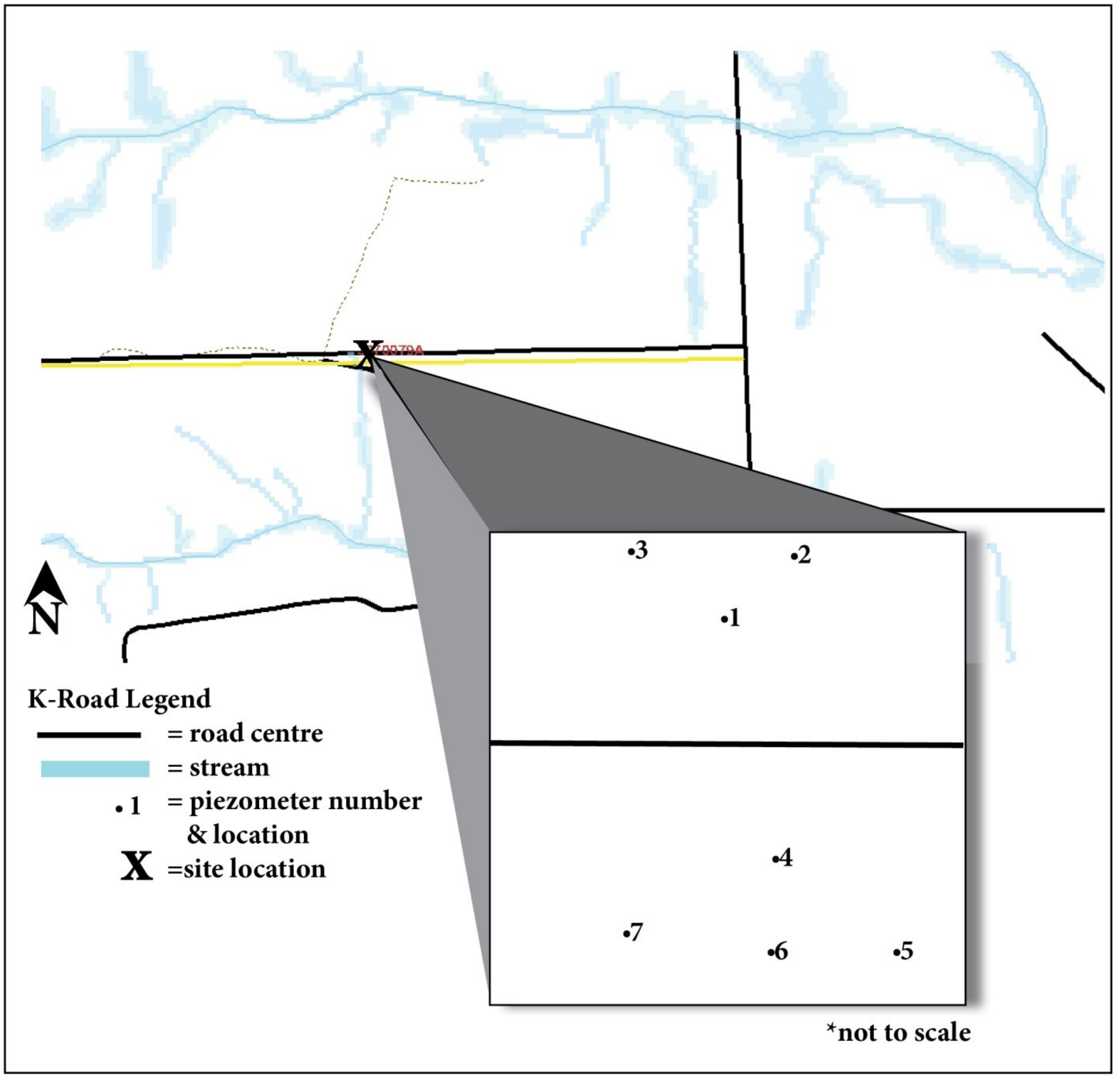
Pre-construction Measurement – September 2012

Road Installation – July 2013

Post-construction Measurement – August 2013

** Only one post-construction measurement was collected at this site due to late installation of the road **



N
K-Road Legend
= road centre
= stream
• 1 = piezometer number & location
X =site location
•3
•2
•1
•4
•7
•6
•5
*not to scale