Effect of Golf Course Turfgrass Management on Water Quality of Non-tidal Streams in the Chesapeake Bay Watershed

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ABSTRACT

Turfgrass management activities on golf courses have been identified as a possible source of Chesapeake Bay nutrient pollution. Total Maximum Daily Load goals are in place to reduce nutrient amounts entering the Bay. Dissertation investigations include (1) the role of golf course turfgrass management in nutrient deposition or attenuation in local streams, (2) estimations of total nitrogen (N) discharging to the watershed from stream outlet points as a function of land use and watershed area, and (3) other factors potentially affecting water quality on golf courses, including soil characteristics and use of best management practices (BMPs). Total N, nitrate-N, ammonium-N, phosphate-phosphorus (P), streamwater temperature, specific conductance (SpC), pH and dissolved oxygen (DO) were sampled at 12-14 golf course stream sites in the James River and Roanoke River watersheds during baseflow conditions. Discharge was determined at outflow locations. Unit-area loads (UALs) were calculated from monitoring data. These UALs were then compared to UALs from Chesapeake Bay Watershed Model land use acreages and simulated loads for corresponding watershed segments. Virginia golf course superintendents were also surveyed to determine BMP use. No consistent impairment trends were detected for streamwater temperature, SpC, pH, or DO at any of the sites. Outflow NO_3-N was below the 10 mg L^{-1} EPA drinking water standard. However, some sites may be at increased risk for benthic impairment with total N concentrations >2 mg L^{-1}, as suggested by VADEQ. Significant increases in nitrate-N at OUT locations were measured at four sites, whereas decreases were measured at two sites. Ammonium-N significantly decreased at two sites. Golf course N UALs calculated from baseflow monitoring were lower than or similar to UALs estimated for forested areas in the associated watershed segment at seven out of the 12 sites. Golf course UALs ranged from 1.3-87 kg N ha^{-1} yr^{-1}. Twenty-one of 32 surveyed BMPs had an adoption rate ≥50% among survey respondents. In most cases, presence of golf courses generally does not appear to significantly degrade baseflow water quality of streams in this study. Management level appears to be an influencing factor on water quality and concerns may be heightened in urban areas.

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CHAPTER ONE: BACKGROUND, JUSTIFICATION, and OBJECTIVES

Introduction

Turfgrass systems are some of the "most intensively managed land uses in the United States" (King et al., 2001). Pesticides, water, and fertilizers are used to maintain high-quality turf for a variety of uses including home lawns, athletic fields, and golf courses. Consequently, the turfgrass industry is generally viewed to be a significant nonpoint source of water pollution (Kohler et al., 2004). This negative perception has created an interest in the quality of water associated with golf courses. There are >14,000 ha of golf course turf managed in Virginia (VGCSA, 2012). Much of this land is directly adjacent to streams, which are ultimately part of the drainage system for the Chesapeake Bay Watershed. The Chesapeake Bay has a history of severe problems with sedimentation and eutrophication, leading to production of hypoxic or anoxic waters incapable of supporting aquatic organisms (Carpenter et al., 1998; UMCES, 2014). Eutrophication of water bodies can occur as a result of excess nitrogen (N) and phosphorus (P). These two nutrients are commonly found in fertilizers and serve as important water quality indicators.

Turfgrass Species on Virginia Golf Courses

Several different turfgrass species are used on Virginia golf courses. Creeping bentgrass (*Agrostis stolonifera*) is typically used on putting greens, although some greens consist of bermudagrass (*Cynodon* spp.). Bermudagrass, creeping bentgrass, perennial ryegrass (*Lolium perenne*), or mixtures of cool-season grasses are mostly used on fairways. Zoysiagrass (*Zoysia* spp.) is infrequently used. Roughs are primarily comprised of bermudagrass, tall fescue (*Festuca arundinacea*), a mixture of cool-/warm-season, or a mixture of cool-season grasses. Kentucky bluegrass (*Poa pratensis*) use is rare (VGCSA, 2012).

Management Practices on Golf Courses

a. Nitrogen Fertilization

There are several types of N fertilizers used on turfgrasses. These sources may be inorganic or organic, fast-release or slow-release. The most commonly used N fertilizers include ammonium salts, potassium nitrate, ammonium phosphates, urea, natural organics, sulfur-coated urea, polymer-coated urea, isobutylidene diurea (IBDU), methylene urea, and urea formaldehydes (VGCSA, 2012). Timing of N fertilization depends on whether the grass is a warm- or a cool-season species. Applications will coincide with active grass growth periods during which maximum nutrient uptake occurs. Typically, cool-season grasses receive the majority of annual fertilization in the fall, with lighter applications in the spring and summer. The purpose of this scheme is to give plants a sufficient amount of N to prevent chlorosis and reduced photosynthesis levels in the spring while controlling shoot growth. Cool-season turfgrass plants fertilized in the fall will allocate more of their photosynthetic products to storage in the roots rather than to shoot growth (Christians, 2004).

Warm-season grass species grow actively during the summer months and enter dormancy in cooler climates during the winter months. Maximum growth and nutrient uptake of warm-season grasses occur in the middle of the summer. The bulk of fertilization should also occur during this period of maximum growth in climates with cold winters, or should follow a balanced approach preventing chlorosis, but avoiding rapid shoot growth in a climate where the winters are warm and the turf will not enter dormancy (Christians, 2004). In Virginia, it is recommended that N applications should occur between six weeks before the last spring average killing frost date and six weeks past the first fall average killing frost date for cool-season turfgrasses. For warm-season turfgrasses, applications should occur between the last spring average killing frost date and one month before the first fall average killing frost date (VADCR, 2005). Nitrogen application rates vary by grass type (warm- or cool-season) and use on the golf course. The Virginia Department of Conservation and Recreation provides recommendations for fertilizer application rates on golf courses (Table 1). These rates are often adjusted based on fertilizer type used (water-soluble vs. water-insoluble), wear of turf, soil type, and soil moisture status.

In terms of nutrient management, water solubility and release rate of N fertilizers are very important (VGCSA, 2012). Water-soluble N sources such as urea or ammonium salts release quickly and are immediately available for plant uptake, but may be susceptible to runoff or leaching. Slow-release, water-insoluble N sources such as IBDU, coated urea, or urea formaldehyde are slowly made available, which reduces runoff or leaching risk while slowly supplying plant nutrients over time. Fertilizer N is most likely to be lost as leachate during the establishment of turfgrasses (Stier et al., 2013). Following establishment, use of N fertilizers can pose risks to leaching and runoff if applied on sandy soils, at high application rates, in the presence of excessive precipitation or irrigation, and near water sources or high-gradient slopes (Stier et al., 2013; VGCSA, 2012). To reduce the risk of N leaching from sand-based putting greens, small, frequent applications of N are often made between 0.2-2 g m $^{-2}$ to meet plant needs while reducing environmental risk (VGCSA, 2012).

b. Phosphorus Fertilization

Phosphorus (P) fertilizers, unlike N fertilizers, are applied based on soil sufficiency and not on a calendar basis. Fertilizer P is applied as necessary based on soil testing, which is recommended every three years for native soils, and yearly on sand-based greens or tees (VGCSA, 2012). To meet turfgrass needs, P_2O_5 fertilizer can be applied at an annual rate of 10-15 g m $^{-2}$ with a soil test fertility rating of L (low), 5-10 g m $^{-2}$ with a rating of M (medium), and 2-5 g m $^{-2}$ with a rating of H (high). Phosphorus should not be applied to soils with a VH (very high) soil fertility rating because the soil can supply more P than is required by the turf plants (VADCR, 2005). Generally, plant responses to phosphorus applications are expected to occur with L ratings, whereas a response may occur with M ratings. Plant responses are not expected with phosphorus applications on soils testing H or VH (VGSCA, 2012). Some of the most common P sources used in turfgrass applications are superphosphates, ammonium phosphates, rock phosphate, or bone meal (VGCSA, 2012).

In a review by Soldat and Petrovic (2008), they identified several best management practices (BMPs) to reduce the risk of runoff and leaching from phosphorus fertilization. These include only applying P when a soil test indicates a deficiency, lowering per-application rates, watering-in fertilizer to prevent overland losses, use of slow/controlled-release sources of fertilizer, avoiding fertilization prior to large rainfall events, and using constructed wetlands to trap phosphorus. Phosphorus in runoff is generally the main concern for water quality, but the risk of leaching increases in coarse textured soils with low P sorption capacity, especially during establishment (Soldat and Petrovic, 2008; VGCSA, 2012).

c. Irrigation

Irrigation of turfgrasses is needed in climatic zones where precipitation is not adequate. Some golf courses may not use irrigation, but most courses in Virginia will need supplemental water to maintain high-quality turfgrass, especially in stressful conditions (VGCSA, 2012). Many golf course superintendents irrigate based on plant evapotranspiration (ET) demand, or use soil moisture sensors to inform their irrigation decisions. On loamy soils, deep and infrequent irrigation is typically used at slight deficit levels below ET demand to encourage rooting, reduce mowing, and balance water conservation with plant needs. Shallow, more frequent irrigation is generally needed on sand-based greens or fine-textured clays (Christians, 2004).

Irrigation frequency often varies by specific conditions on golf courses. Grass type (warm- vs. cool-season), species/cultivar, climate, soil characteristics, use of growth regulators, mowing height, and fertility can influence the water needs of turfgrasses. Warm-season grasses generally have better water-use efficiency, lower evapotranspiration rates, improved drought resistance, and need less irrigation than cool-season grasses (VGCSA, 2012). Of the species commonly used on Virginia golf courses, bermudagrass has the best drought resistance (as a function of drought avoidance and drought tolerance) followed by tall fescue and perennial ryegrass.

Creeping bentgrass has comparatively low drought resistance (Fry and Huang, 2004). Higher temperatures, lower humidity, and windy areas increase turfgrass plant evapotranspiration rates and increase the need for water (Christians, 2004).

Soil characteristics, particularly texture, organic matter content, and structure play an important role in water infiltration. Poorly structured, compacted soils with low organic matter content reduce water infiltration, inhibit rooting, encourage ponding/runoff, and reduce water availability to plants. Fine-textured soils such as clays are more prone to compaction and reduced infiltration rates. Coarse-textured soils such as sands have better infiltration rates, but may not have sufficient water-holding capacity to support plant growth in some cases. Loams often have good water holding capacities that are able to meet plant needs, support healthy rooting, and provide proper drainage (Christians, 2004).

Cultural practices also influence water use. The stress imposed by low mowing heights can reduce turfgrass ability to cope with water stress, increasing irrigation needs (Fry and Huang, 2004). It is thought that increasing mowing heights will increase rooting and allow for more efficient water use by increasing the amount of soil moisture that is available to the plant (Christians, 2004). Over-fertilization of turfgrasses, particularly with N, can result in plant succulence. This increases evapotranspiration rates, decreases water use efficiency, and creates a higher irrigation demand (Christians, 2004). Use of plant growth regulators to inhibit shoot growth may reduce evapotranspiration rates. This increases drought tolerance and decreases water demand (Kopp and Jiang, 2013).

d. Mowing

Mowing heights on golf courses vary by specific areas. Mowing heights are adjusted depending on the species of grass used, environmental conditions, aesthetic needs, and playability demands. Mowing frequency depends on mowing height, and as a general rule, no more than 1/3 of the leaf blades should be removed at a time to avoid stressing the plant (Christians, 2004). Greens are typically mown between 0.3-0.4 cm, tees at 0.6-1 cm, fairways at 1-2 cm, primary rough at 4-8 cm, and secondary rough at 5 cm or more. Warm-season turfgrass species do not need to have mowing heights adjusted during high temperature periods. Bermudagrass, a warm-season turfgrass species commonly used on Virginia golf courses, has a recommended mowing height of 0.6-8 cm (Christians, 2004). Cool-season turfgrass species should have their mowing heights adjusted during high temperature stress periods. Creeping bentgrass, tall fescue, and perennial ryegrass are cool-season turfgrass species commonly used on Virginia golf courses. Creeping bentgrass has a recommended mowing height of 0.3-2 cm during cool weather, and 1-2 cm during high temperature periods. Tall fescue's recommended mowing height range is 5-8 cm during cool weather, and 6-9 cm during high temperatures. The recommendations for perennial ryegrass are 4-5 cm during cool weather, and 5-8 cm for high temperatures (Christians, 2004).

BMPs for mowing exist that will help to protect the environment while preserving turf quality. The most important consideration is selection of a species/cultivar that can withstand the mowing heights for the intended use in an appropriate climate. Shaded turfgrass and cool-season species in higher temperatures will benefit from increased mowing heights. By raising mowing heights in the shade, stress will be offset by increased available leaf area for photosynthesis and carbohydrate availability. Increased mowing height allows for increased carbohydrate availability and increased nutrient/moisture acquisition ability as a result of a more extensive, deep root system (VGCSA, 2012). For water quality protection, increased height of cut or increased turf density from regular mowing can disrupt the channelized path of runoff, slow runoff initiation time, and encourage infiltration of water (Cole et al., 1997; Gross et al., 1990; Linde et al., 1995; Moss et al., 2006). Clippings may be returned (except on golf greens) to the turf to recycle plant nutrients and can supply up to 5 g m^{-2} annually, reducing the need for fertilizer inputs. Furthermore, varying mowing direction will reduce wear patterns and compaction, encouraging healthy growth and coverage of turfgrass over a given area (VGCSA, 2012).

e. Integrated Pest Management

Integrated pest management (IPM) is the blending of several different turfgrass management practices to maintain healthy turfgrass stands while minimizing environmental inputs. Not only will this serve to protect the environment, but also often translates to a cost savings for the turfgrass manager. A combination of ideal species/cultivar selection, use of biological controls, use of conventional pesticides as needed, reduction of stressors (pathogen pressure/weed competition), and modification of cultural practices contribute to IPM (VGCSA, 2012). The overall goal of this program is to use less pesticides and fertilizer when possible.

Healthy, dense, well-managed turf can protect water quality by increasing infiltration and reducing surface runoff (Gross et al., 1990; Linde et al., 1995; Stier et al., 2013). The most important factors affecting turfgrass health are proper planning of a site by selecting appropriate turfgrass species for the intended use, climate, and other site-specific factors (shading, soil quality, aesthetics, etc.). Turfgrass that is not initially stressed will be less subject to thinning, competition by weeds, and disease pressure. As a result, less fertilizer inputs will be needed to help maintain turfgrass color and density, while less pesticide inputs will be needed to control pathogen/weed pressure (VGCSA, 2012).

Once turfgrasses are established, use of proper irrigation, fertilization, and cultural practices will also help to reduce overall turfgrass stress and pathogen/weed pressure. These include proper application and amount/timing of irrigation, fertilizer maintenance in areas where fertility-dependent diseases are common, aerification, and use of correct mowing height in different situations (such as raising mowing height on shaded turf). When disease or weed problems occur, they can be prevented or mitigated by applications of pesticides or biological controls (VGCSA, 2012).

f. Water Quality Protection

Several BMP options targeting water quality protection are available for use on golf courses. Use of Nutrient Management Plans (NMPs) specifically aims to reduce the potential for entry of fertilizer nutrients into water supplies by highlighting site-specific, proper fertilization application amounts, timing, and recommended sources (discussed previously under Nitrogen and Phosphorus fertilization). NMPs also identify high-risk areas on golf courses for runoff and leaching, and provide guidance for proper type of management in these areas. Proper management may include use of slowly available forms of fertilizer, restriction of fertilizer use (zero-application), and use of minimum setback distances for sensitive areas such as high-gradient slopes, Karst terrain, or presence of surface water bodies (VADCR, 2005).

Specific surface runoff controls may also protect water quality by managing stormwater, preventing nutrient transport, and reducing sedimentation. These include use of features such as grassed swales, buffer strips, vegetated filter strips, constructed wetlands, and detention ponds (VGCSA, 2012).

Maintenance practices can play an equally important role in water quality protection. These include, but are not limited to, avoidance of deposition of grass clippings in surface waters, use of aquatic plants to uptake nutrients, sediment removal from ponds/forebays, proper fertilization/chemical application, use of grass carp for algae control, and mechanical aerification of ponds (VGCSA, 2012). Furthermore, many golf courses engage in regular water quality monitoring programs to assess their individual impact on surface water bodies and effectiveness of BMPs. Water quality monitoring is required for golf courses to become certified by the Audubon Cooperative Sanctuary Program for Golf, and water quality management must be documented to regain certification every three years (Audubon International, 2015). This program certifies courses that use “environmentally responsible maintenance practices” in daily golf course operations. Courses must conduct a site assessment for environmental planning, promote wildlife diversity/habitat conservation, employ chemical use reduction/safety techniques, conserve water, manage water quality, and provide outreach/educational activities to gain and retain certification (Audubon International, 2006).

Soil Types and Nutrient Loss Potential

There are several avenues of nutrient transformation and losses in an ecosystem. Nitrogen inputs from biological fixation, animal/plant tissues (or wastes), rainfall, fertilizer, irrigation, or atmospheric deposition may be immobilized into organic N forms, or mineralized into plant-available forms in a cyclic fashion. Export can occur via volatilization, runoff, leaching, denitrification, or plant tissue removal (Petrovic, 1990). Nitrogen is generally more of a leaching concern, especially in the nitrate form because it is a highly mobile anion and does not readily adsorb to negatively charged soil particles. Ammonium ions are positively charged and will bind to soil particles, bind to organic colloids, or will be rapidly used by plants as a preferred form of N (Hull and Liu, 2005).

Phosphorus inputs (both organic and inorganic) are sourced from fertilizer, sediment particles, erosion of soils, plant debris, animal wastes/tissues, and to a much lesser extent, atmospheric deposition from dust particles (Soldat and Petrovic, 2008). Phosphorus can be transported as particulate P bound to soil/sediments, or as dissolved P in surface or soil water. Phosphorus, unlike N, is generally considered to be more of a runoff risk than a leaching risk. This is because phosphorus sorbs easily to soil surfaces, or precipitates as insoluble inorganic compounds (Wong et al., 1998). This depends on the phosphorus adsorption capacity of the soil. Leaching may occur on soils with low phosphorus adsorption capacities, such as sandy soils. Risk of leaching increases with high application rates of fertilizer on these types of soils (Wong et al., 1998; Steinke et al., 2009).

Runoff poses the most risk to contamination of surface waters. Runoff is a significant avenue of nutrient loss on fine-textured, high-clay, ill-structured, compacted soils with low infiltration rates. This risk is elevated on high-gradient slopes, in proximity to impervious surfaces, and when soils are saturated. Soils with low organic matter content in the absence of vegetative cover are also more prone to runoff (Brady and Weil, 2008). Water that is not subject to runoff may become subject to leaching in certain conditions. Soils with very high infiltration rates, coarse-texture, high sand content, and loose structures are more subject to leaching, which can pose a risk for groundwater contamination. This risk is exacerbated in the presence of certain features such as Karst terrain or soils with a high percentage of cracks or biopores, which may lead to preferential flow and an easier route for groundwater contamination (Brady and Weil, 2008).

On golf courses, greens can be considered to be at a higher risk for leaching because of very high infiltration rates and coarse textures of the sandy rooting mixture. Ground drainage pipes may also serve as point sources from the greens if they lead directly to surface waters. However, the area of greens relative to the rest of the golf course is very small, and proper management of the green or its drainage water can prevent contamination of water sources (Brown et al., 1977; Kohler et al., 2004)

Nutrient Management Implications

Smith et al. (1999) have suggested that eutrophication can occur in environments with nitrate-N levels less than the 10 mg L^{-1} EPA limit for drinking water (USEPA, 1986). Others have suggested that there is no consensus that removing N will control eutrophication because "there are insufficient whole ecosystem-scale data to show that removing N will reduce eutrophication" (Schindler and Hecky, 2009). Furthermore, nutrient attenuation in natural waters can remove excess nitrate through processes such as uptake and denitrification (Allan and Castillo, 2007).

The concept of lag time is extremely important when discussing the effectiveness of nutrient management, BMP implementation, and meeting desired water quality goals. Lag time is defined as the "amount of time between an action and a response to that action", which may result in delayed detectable improvement of water quality following use of management practices (Meals et al., 2010). Magnitude of lag time or effectiveness of BMP implementation can be affected by several factors including but not limited to, degree of impairment of the water body, physical features of the landscape, chemical features of soil/water, suitability of management practices selected, hydrology, pollutant mechanism of transport, and enforcement of management practices (Meals et al., 2010). A review of lag time associated with BMPs by Meals et al. (2010) indicates that it can take up to 30 years to observe a noticeable difference in water quality of runoff by adjusting fertilizer P rates and more than 50 years by adjusting fertilizer N rates. It is important to address these lag times when formulating expectations for watershed management plans and assessing TMDL effectiveness because watershed-scale improvements may not be observed for decades despite implementation of management practices (Meals et al., 2010).

Environmental Impact of Turfgrass Management

A review of scientific evidence from plot- and small-scale turfgrass studies generally suggests that proper fertilization practices and correct maintenance result in little nutrient and sediment losses from turfgrass systems (Stier et. al, 2013). BMPs such as use of slow-release fertilizers, soil testing, construction of wetlands, maintenance or establishment of riparian buffer zones, and rerouting drainage tiles can further protect water sources from excess nutrients. Changing superintendent management preferences and the use of structural BMPs can result in an 80% reduction of nitrates and 60% reduction of phosphorus in surface waters of golf courses (Davis and Lydy, 2002). Constructed wetlands are very efficient at nitrate/nitrite removal and are capable of removing up to 95% of these inputs (Kohler et. al, 2004).

Seventeen studies comprised of 36 golf courses reviewed by Cohen et al. (1999) indicated that the EPA maximum allowable drinking water contaminant level of nitrate-N (10 mg L^{-1}) was not exceeded for surface waters and very infrequently (31 of 849 samples) for ground water. Other more recent golf course studies indicate very small contributions of nutrients (either N or P) that did not pose a significant threat to local water quality (King et al., 2001; King et al., 2007; Hindahl et al., 2009). Reviews of water quality studies on coastal golf courses indicate some potential for concern in fairway ponds, groundwater, and adjacent estuaries, especially in areas with coarse-textured sandy soils. However, effects are thought to be limited locally to “near-coastal areas”, and effects on water quality are not expected to occur on a widespread basis in other areas (Lewis et al. 2002; Cohen et al. 1999; Mallin and Wheeler, 2000).

Turfgrass use can be used as a BMP in some situations. Turfgrass can intercept surface runoff flows, increase infiltration, and reduce erosion in urban areas (Linde et al., 1995; Gross et al, 1990; Steinke et al, 2009; Stier et al., 2013). In comparison to other systems, areas with pervious turfgrass cover can protect groundwater by trapping and cycling nutrients, allowing for infiltration and groundwater recharge, and reducing water drainage volumes when serving as a buffer strip (Steinke et al, 2009).

Overall, the risk of N leaching is highest during turfgrass establishment and on coarse-textured soils, but the environmental impacts are mostly localized and are not significant in most cases (Stier et al., 2013). Runoff containing dissolved N does not appear to be a concern. Where runoff has been documented, it was found to be very low compared to agronomic crops and rarely exceeded the EPA drinking water standard of 10 mg L^{-1} of nitrate. Runoff of dissolved N varies by fertilizer source used and species of turfgrass present (Erickson et al., 2001; Gross et al., 1990; Linde et al., 1995; Petrovic, 1990; USEPA, 1986).

Literature documenting effects of phosphorus leaching and runoff is highly variable, but the general consensus appears to be that losses of phosphorus from turfgrass systems are also low. This is because phosphorus is generally adsorbed on soil surfaces or becomes precipitated as insoluble compounds. Soils covered with vegetation also have a reduced risk of erosion and an interrupted flow path/increased infiltration rate of water (Bierman et al, 2010; Gross et al., 1990; Stier et al, 2013; Wong et al., 1998). To fully assess the environmental impact of turfgrass management, there is still a need for more studies on turfgrass systems in different climactic zones, across different soil types, and under different management schemes around the world.

The Chesapeake Bay Watershed Model and TMDL

The U.S. Environmental Protection Agency (EPA) has developed and implemented Total Maximum Daily Loads (TMDL) of N, P, and sediment for all waters in the Chesapeake Bay Watershed (USEPA, 2010). The EPA mandates that each state within the Bay Watershed must develop watershed implementation plans to meet TMDL goals in an effort to reduce pollutants entering the Chesapeake Bay.

The Chesapeake Bay Watershed Model was used to construct the TMDL for the Chesapeake Bay. This model included simulations of nonpoint source pollution from several types of land uses, point sources of pollution, modes of nutrient input and reduction, hydrology, and sediment input from land area and river segments throughout the Chesapeake Bay Watershed (USEPA, 2010). However, golf courses were not included as a land use in this model.

Regulation

Nonpoint pollution of surface waters from golf courses has not been quantified by the EPA or individual states and therefore has not been subject to federal regulation. However, golf courses have been identified as a possible contributor to nonpoint-source pollution by the Commonwealth of Virginia (VADEQ, 2012). The Commonwealth of Virginia is requiring development of NMPs for golf courses before 2017 and is considering an Urban Nutrient Management Initiative aimed at reducing inputs of N and

P by golf courses and homeowners (VADEQ, 2012). The Commonwealth has the authority to revise its watershed implementation plans as necessary to meet TMDL criteria, with golf courses possibly being subjected to future regulation.

Research Justification

None of the water quality studies accessed in this review included golf courses in Virginia. Furthermore, studies in this review did not encompass a large-scale watershed-based approach. Virginia soil characteristics, hydrology, vegetation, and stream biota are likely different from the courses previously studied, which may have different influences on water quality.

The Chesapeake Bay is still impaired for water quality and continues to be subject to eutrophication and dead zones despite efforts to implement BMPs and reduce nutrient loads in the watershed. Overall, conditions appear to be improving on the Western shore and its tributaries, whereas the Eastern shore and its tributaries are generally in a state of decline (UMCES, 2014). A recent report from the Chesapeake Bay Commission indicates that there has been some improvement in water quality conditions in the Bay. United States Geological Survey monitoring data presented in the report show a consistent decrease in N across the watershed since 2003, but phosphorus has not decreased. Many sites have increasing phosphorus concentrations or show no significant signs of improvement (CBC, 2013).

The overall goal of this dissertation is to quantify the effect of golf course turfgrass cultural and environmental management on the quality of surface waters traversing the courses. As previously mentioned, no studies have been completed of this nature on

Virginia golf courses and the Chesapeake Bay Watershed Model does not include golf courses as a land use. Very few studies have been conducted at the field scale in the U.S. and even fewer studies have been completed at the watershed scale. Many studies have addressed multiple factors potentially influencing water quality, but none have fully integrated soil chemical/physical data, surface water quality data, fertilization schemes, and management practices on a large scale. A 2012 Congressional Research Service report found that the Government Accountability Office was concerned that "water quality data are so limited, particularly data for nonpoint sources, that many fear that TMDL decisions will be based on unsound information and will impose unneeded or inappropriate control mandates" with respect to the TMDLs (Copeland, 2012). This dissertation investigated whether changes in water quality are occurring in association with turfgrass cultural and environmental management and to what extent. Golf course managers will be provided with valuable information on the water quality impacts of selected golf courses in Virginia.

Objectives

The overarching objectives of this dissertation are as follows: (1) assess baseflow water quality of streams from selected golf courses in the James River Watershed (a major sub-watershed within the Chesapeake Bay Watershed) and the Roanoke River Watershed (outside of the Chesapeake Bay Watershed), (2) calculate and compare unit-area N loads associated with golf courses in this study with those estimated from other land uses in corresponding land-river segments as simulated in the Chesapeake Bay Watershed Model (CBWM), and (3) investigate other potential factors influencing water quality on golf courses.

Tables

Table 1. Virginia recommended nitrogen fertilizer application rates for golf courses (VADCR, 2005).

	Max Annual Rate g m^{-2}	**Max Per App. Rate g m^{-2}**
Greens	15-29	4
Tees	10-24	4
Fairways Without Irrigation	Cool Season: 10-15 Warm Season: 15-20	5
Irrigated Fairways	Cool Season: 15-20 Warm Season: 17-22	2
Roughs	5-15	5

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CHAPTER TWO: GOLF COURSE DESCRIPTIONS AND METHODS

Golf Courses

Representatives from each golf course assessed in this study volunteered for participation in water quality monitoring. There were three Chesapeake Bay Watershed courses located in Richmond, VA, two in Keswick, VA, one in Powhatan, VA, and one in Manakin-Sabot, VA (Figure 1). Separate monitoring outside of the Chesapeake Bay Watershed (Roanoke River Watershed) was conducted at a golf course in Blacksburg, VA. This course was chosen to allow for more frequent sampling and to present an additional case study of a course in a region different from the other courses in the James River Watershed. All courses are private-membership, high-visibility courses with robust maintenance budgets (See Table 1). These courses can afford to make more fertilizer applications and generally must meet higher membership expectations for high-quality, aesthetically pleasing, uniform turfgrass surfaces. Lower-budget courses may be more financially constrained and may not make as many fertilizer applications. Furthermore, membership or patron expectations for turfgrass quality may not be as high on these courses.

Demographics

a. Chesapeake/James River Watershed Golf Course 1: Manakin-Sabot, VA

Golf Course 1 is located within Goochland County in Manakin-Sabot, VA. It was built on land that was previously forested approximately 15 years ago. This private course has an annual maintenance budget >$1.5 million and 10-20,000 rounds of golf are played there annually. Course 1 is certified in the Audubon Cooperative Sanctuary

Program for Golf. Approximately 68 ha of turfgrass are maintained on the course (~2 ha greens, ~3 ha tees, ~15 ha fairways, ~40 ha rough, and ~8 ha native areas). The rough is comprised of mixed cool-season species of turfgrass, whereas greens and fairways consist of creeping bentgrass (*Agrostis stolonifera*). Greens are typically mown <0.3 cm, tees 0.5-0.6 cm, fairways 0.8 -1.1 cm, and primary rough 6-8 cm. Mowing heights are raised slightly in the spring for greens, tees, and fairways. Combinations of slow- and quick-release fertilizer products are typically used on this course. From 2011 to 2014, N fertilizer annual application rates were approximately 18-26 g m^{-2} on greens, 15-21 g m^{-2} on tees, 9-15 g m^{-2} on fairways, and 16-27 g m^{-2} on roughs. Annual P fertilization rates ranged from 5-8 g m^{-2} on greens, 0.2-1.7 g m^{-2} on tees, 0.3-1.8 g m^{-2} on fairways, and 3-10 g m^{-2} on roughs.

b. Chesapeake/James River Watershed Golf Course 2: Keswick, VA

Golf course 2 is located within Albemarle County, VA and was originally built on previously forested land. This private golf course has an annual maintenance budget of $1-1.5 million. Less than 10,000 rounds of golf are played annually on this golf course, which was previously certified in the Audubon Cooperative Sanctuary Program for Golf. The playable areas consisted primarily of tall fescue (*Festuca arundinacea*) rough, bermudagrass (*Cynodon* sp.) fairways, and creeping bentgrass (*Agrostis stolonifera*) greens. Greens were typically mown at 0.3 cm, tees at 0.5-0.6 cm, fairways at 1.1-1.3 cm, and rough at 6-9 cm. Fifty-90% Quick-Release N fertilizers were typically used on all areas of the course. No fertilization records were available for this course, although ranges of N fertilization were reported as 10-19 g m^{-2} on greens, 10-14 g m^{-2} on tees, 10-14 g m^{-2} on fairways, and 0-9 g m^{-2} on rough. This golf course began complete renovation in 2013, therefore data collection ended early.

c. Chesapeake/James River Watershed Golf Course 3: Richmond, VA

Golf Course 3 is located within Henrico County in Richmond, VA. This private course is >20 years old, has an annual maintenance budget >$1.5 million, and experiences >40,000 rounds of golf played per year. Approximately 44 ha of turfgrass are maintained on the course (~1 ha greens, ~1 ha tees, ~12 ha fairways, and ~30 ha rough). Roughs and fairways consist of bermudagrass (*Cynodon* sp.) and greens consist of creeping bentgrass (*Agrostis stolonifera*). Greens are typically mown at 0.3 cm, tees at 0.9-1.3 cm, fairways at 1.1-2 cm, and rough from 3.8 to >8.9 cm. Mowing heights are raised slightly during the summer months for greens. N fertilizer products with >90% quick-release formulations are typically used on this course. Approximate annual N fertilization rates from 2011 to 2014 ranged from 12-31 g m^{-2} on greens, whereas rates of 17-22 g m^{-2} were reported for all bermudagrass areas (tees, fairways, rough). Approximate annual P fertilization rates ranged from 1.4-3 g m^{-2} on greens, whereas no phosphorus was applied on bermudagrass areas.

d. Chesapeake/James River Watershed Golf Course 4: Richmond, VA

Golf Course 4 is a private course located in Richmond City, VA. Course 4 is over 20 years old, has an annual maintenance budget over $1.5 million, and has over 40,000 rounds of golf played annually. Approximately 41 hectares of turfgrass are maintained on the course (~ 1 ha greens, ~1 ha tees, ~11 ha fairways, and ~28 ha rough). Roughs and fairways consist of bermudagrass (*Cynodon* sp.) and greens consist of creeping bentgrass (*Agrostis stolonifera*). Greens are typically mown at 0.3 cm, tees at 0.9-1.3 cm, fairways at 1.1-2 cm, and rough from 3.8 to over 8.9 cm. Mowing heights are raised slightly during the summer months for greens. Fertilizer products with greater than 90% quick release N formulations are typically used on this course. Approximate annual N fertilization rates 2011 to 2014 ranged from 19-29 g m^{-2} on greens, 5-24 g m^{-2} on tees/fairways, and 5-22 g m^{-2} on rough areas. Approximate annual P fertilization rates on greens ranged from 1.4-3 g m^{-2}, while no phosphorus was applied on tees, fairways, or rough areas.

e. Chesapeake/James River Watershed Golf Course 5: Richmond, VA

Golf Course 5 is located within Henrico County in Richmond, VA. This private course is over 20 years old, has an annual maintenance budget over $1.5 million, and members play over 40,000 rounds of golf each year. Course 5 is certified in the Audubon Cooperative Sanctuary Program for Golf. Approximately 60 ha of turfgrasses are maintained on the course (~1 ha greens, ~2 ha tees, ~13 ha fairways, ~17 ha rough, and ~27 ha low maintenance fescue rough). Roughs and fairways consist of bermudagrass (*Cynodon* sp.) and greens consist of creeping bentgrass (*Agrostis stolonifera*). Greens are typically mown at 0.3 cm, tees at 0.9-1.3 cm, fairways at 1.1-2 cm, and rough from 3.8 to over 8.9 cm. Mowing heights are raised slightly during the summer months for greens. Fertilizers with greater than 90% quick-release N formulations are typically used on this course. 2011 to 2014 annual N fertilization rates ranged from approximately 14-26 g m^{-2} on greens, and 19-28 g m^{-2} on bermudagrass areas (tees, fairways, rough). Approximate annual P fertilization rates for greens were 1-2 g m^{-2}, while no phosphorus was applied to tees, fairways, or rough areas.

f. Chesapeake/James River Watershed Golf Course 6: Keswick, VA

Golf course 6 is located in Albemarle County in Keswick, VA. This private course is over 20 years old, has an annual maintenance budget between $500,000-$1 million, and experiences 10-20,000 rounds of golf played annually. Approximately 52 ha of turfgrass are maintained on the course (~2 ha greens, ~2 ha tees, ~8 ha fairways, and 40 ha rough). Bermudagrass (*Cynodon* sp.) is used in the rough and fairway areas, while creeping bentgrass (*Agrostis stolonifera*) is used on the greens. Greens are generally mown at 0.3 cm, tees 0.9-1.3 cm, fairways 1.1-1.3 cm, and rough at 2 cm or greater. A combination of slow and quick-release N fertilizers are typically used on the greens of this course, while products with greater than 90% quick-release formulations are used on other areas. 2011 to 2014 approximate annual N fertilization rates ranged from 17-22 g m^{-2} on greens, 10-19 g m^{-2} on tees, 10-19 g m^{-2} on fairways, and 7-14 g m^{-2} on rough areas. Approximate annual P fertilization rates were 0.4-3 g m^{-2} on greens, 0-1.1 g m^{-2} on tees/fairways, and 0-0.8 g m^{-2} on rough areas.

g. Chesapeake/James River Watershed Golf Course 7: Powhatan, VA

Golf Course 7 is located in Powhatan County in Powhatan, VA. This private golf course is 15-20 years old and has an annual maintenance budget of $500,000 to $1 million. Golfers play less than 10,000 rounds of golf per year. Course 7 is certified in the Audubon Cooperative Sanctuary Program for Golf. Approximately 31 ha of turfgrass is maintained on the course (~1 ha greens, ~1 ha tees, ~10 ha fairways, and ~19 ha rough. Roughs and fairways are composed of bermudagrass (*Cynodon* sp.) and greens are composed of creeping bentgrass (*Agrostis stolonifera*). Greens are typically mown at 0.3 cm, tees 0.5-0.6 cm, fairways 1.1-1.2 cm, and rough 2 cm or greater. 50-90% quick-release N products are typically used on most areas of the golf course, while slow-release products with less than 50% quick-release N are used on the greens. From 2013-2014 approximate annual N rates were 9-20 g m^{-2} on greens, 27-28 g m^{-2} on tees, and 23-27 g m^{-2} on fairways. 2013 totals of N on rough totaled 27 g m^{-2} while no N applications were made in 2014. Approximate annual P rates were 4-7 g m^{-2} on greens and 0-1.4 g m^{-2} on tees. No phosphorus applications were made on fairways or rough areas in 2013 or 2014.

h. Roanoke River Watershed Golf Course 8: Blacksburg, VA

Course 8 is not located within the Chesapeake Bay watershed, but represents a separate case study in Montgomery County, VA, within the Roanoke River watershed. This private course is located in Blacksburg, VA, is over 20 years old, and has an annual maintenance budget between $500,000 and $1 million. Members play 20,000-30,000 rounds of golf each year. The roughs and fairways of this course are composed of a mixture of cool-season species of turfgrasses, while the greens are a mix of *Poa* and creeping bentgrass (*Agrostis stolonifera*). Approximately 44 ha of turfgrass are maintained on the course (~2 ha greens, ~1 ha tees, ~13 ha fairways, and ~28 ha rough). Greens are typically mown at 0.3 cm, tees at 0.8-1.3 cm, fairways 1.1-1.3 cm, and rough 5.7-7.6 cm. Slow-release fertilizer N products (less than 50% quick-release) are typically used on this course in most areas, while a combination of slow and quick-release products are used on greens. Approximate annual N fertilization rates for 2011, 2013, and 2013 (2012 data unavailable) were 9-13 g m^{-2} on greens, 8 g m^{-2} on tees, and 8 g m^{-2} on fairways. Rates from 0-10 g m^{-2} were used on existing rough, and to establish new areas. Approximate annual P fertilization rates were 0.5-1.0 g m^{-2} on greens, 0-0.05 g m^{-2} on tees/fairways, and 0-0.2 g m^{-2} on rough.

Best Management Practices

a. Course 1

Course 1 reports use of several BMPs. In terms of water quality protection, this course utilizes detention/retention ponds, greens that drain to grassed/wooded areas, grass carp for lake management, a fill station situated away from drains to surface water, a wastewater recycling system, mechanical aeration of ponds, use of native plants in ponds/buffer zones, constructed or native wetlands, avoidance of grass clipping deposition in surface waters, and erosion control measures on stream banks. Fertilizer BMPs in use at Course 1 include use of slow release N fertilizers near water sources, applications made only during optimal turfgrass growth periods, phosphorus applications applied based on soil test need, and the use of a NMP. IPM practices are used to reduce stress and disease pressure on turfgrass, reducing the need for fertilizer, water and pesticide inputs. Cultural practices promoting the health of turfgrass are used. These include rolling of greens, raising height of cut during summer stress periods, recycling clippings (and nutrient content), aerification of high-traffic areas, regularly sharpened mower blades, irrigation system audits, and the use of soil moisture sensors to inform irrigation decisions.

b. Course 2

Before complete course renovation, the use of several BMPs was reported. To protect water quality, this course utilized mechanical aeration of ponds, native plants in ponds/buffer zones, constructed/native wetlands, sediment removal/dredging of ponds, vegetative buffer strips around flowing surface waters (streams), streambank erosion control measures, a wastewater recycling system, a wash pad that does not discharge to surface waters, and a NMP. Furthermore, phosphorus was only applied as needed through indication of a soil test. Cultural practices and IPM were also used to maintain turfgrass health with the goal of reducing fertilizer, water, and pesticide inputs. These include rolling of greens, aerification to reduce compaction in high-traffic areas, regular sharpening of mower blades, regular irrigation system audits and the use of evapotranspiration demand in conjunction with soil moisture sensors to inform irrigation decisions.

c. Course 3

This course utilizes several BMPs. Grass carp for lake management, mechanical aeration of ponds, native plant species in ponds/buffer zones, avoidance of deposition of grass clippings in surface waters (including cleaning machinery before wash pad entry), vegetative buffer strips around irrigation ponds/streams, and erosion control measures are used to help protect water quality. Slow-release fertilizers are used instead of quick-release fertilizers in proximity to water sources, and phosphorus is only applied on an as-needed basis as indicated by soil testing. IPM and cultural practices are used to maintain healthy, high-quality turfgrass with the goal of reducing pesticide, water and fertilizer inputs. These include rolling of greens, raising height of cut/lowering inputs on shaded turfgrass, raising height of cut during summer stress periods, returning grass clippings to the rough to recycle nutrients, regularly sharpening mowing blades, aerification of compacted high-traffic areas, performance of regular irrigation system audits, and the use of soil moisture sensors to inform irrigation decisions.

d. Course 4

This course utilizes several BMPs. To protect water quality, grass carp for lake management, mechanical aeration of ponds, native plant species in ponds/buffer zones, avoidance of deposition of grass clippings in surface waters (including cleaning machinery before wash pad entry), wash pad discharges kept out of surface waters, vegetative buffer strips around irrigation ponds/streams, and erosion control measures are used. Slow-release fertilizers are used instead of quick-release fertilizers in proximity to water sources, and phosphorus is only applied on an as-needed basis as indicated by soil testing. IPM and cultural practices are used to maintain healthy, high-quality turfgrass with the goal of reducing pesticide, water, and fertilizer inputs. Cultural practices include rolling of greens, raising height of cut/lowering inputs on shaded turfgrass, raising height of cut during summer stress periods, returning grass clippings to the rough to recycle nutrients, regularly sharpening mowing blades, aerification of compacted high-traffic areas, performance of regular irrigation system audits, and the use of soil moisture sensors to inform irrigation decisions.

e. Course 5

Several BMPs are used at Course 5. IPM and cultural practices are used to maintain healthy, high-quality turfgrass with the goal of reducing inputs. Cultural practices include rolling of greens, raising height of cut/lowering inputs on shaded turfgrass, raising height of cut during summer stress periods, returning grass clippings to the rough to recycle nutrients, regularly sharpening mowing blades, aerification of compacted high-traffic areas, performance of regular irrigation system audits, and the use of soil moisture sensors to inform irrigation decisions. Measures to protect water quality include, grass carp for lake management, mechanical aeration of ponds, native plant species in ponds/buffer zones, avoidance of deposition of grass clippings in surface waters (including cleaning machinery before wash pad entry), wash pad discharges kept out of surface waters, vegetative buffer strips around irrigation ponds/streams, and erosion control measures. Slow-release fertilizers are used instead of quick-release fertilizers in proximity to water sources, and phosphorus is only applied on an as-needed basis as indicated by soil testing.

f. Course 6

Several BMPs are reported to be in use at Course 6, including several measures to protect water quality. These include the use of detention ponds/basins, grass carp for lake management, greens draining to wooded/grassed areas, mechanical aeration of ponds, constructed/native wetlands, vegetative buffer strips around irrigation ponds, a NMP, and cleaning of equipment to avoid deposition of grass clippings in waters from wash pad drainage. Fertilizer is applied during optimal periods of turfgrass growth, and phosphorus is only applied when need is indicated by a soil test. Cultural practices are also used to maintain turf health and reduce inputs of pesticides, water, and nutrients. These include rolling of greens, returning grass clippings to the rough to recycle nutrients, aeration of high-traffic areas, regularly sharpening mower blades, and irrigation based on evapotranspiration demand in conjunction with soil moisture sensor use.

g. Course 7

Several BMPs are reportedly in use at Course 7. These include measures to protect water quality such as greens that drain to grassed/wooded areas, grass carp for lake management, use of native plants in ponds/buffer zones, constructed/native wetlands, fill stations situated away from drains to surface waters, wash pad discharges kept out of surface waters, vegetative buffer strips around irrigation ponds/surface waters, streambank erosion control measures, and a NMP. Fertilizer is applied during periods of optimal turf growth, and phosphorus is only applied when needed as indicated by a soil test. IPM and cultural practices are used to maintain healthy turfgrass stands while reducing inputs such as fertilizer, pesticide and water. These practices include rolling of greens, raising height of cut/lowering inputs on shaded turf or during periods of summer stress, grass clippings returned to the rough to recycle nutrients, aeration of compacted high-traffic areas, regular sharpening of mower blades, regular irrigation audits, and use of soil moisture sensors to inform irrigation decisions.

h. Course 8

Several BMPs are reported to be in use at Course 8. These include measures to protect water quality such as the use of detention ponds/basins, greens draining to grassed/wooded areas, grass carp for lake management, mechanical aeration of ponds, fill stations situated away from drains to surface waters, use of native plants in ponds/buffer zones, vegetative buffer strips along flowing surface waters, streambank erosion control measures, and a NMP. Fertilizers are applied during periods of optimal turfgrass growth, applications are avoided near high gradient slopes or water features, and phosphorus is only applied when need is indicated by a soil test. Several cultural practices and IPM are used to maintain high quality turfgrass while reducing inputs of fertilizer, pesticides, and water. These practices include rolling of greens, returning grass clippings to the rough to recycle nutrients, regularly sharpening mower blades, aerification of soils in compacted high-traffic areas, and the use of soil moisture sensors to inform irrigation decisions.

Water Sampling and Analysis

Samples were collected with respect to upstream locations where streams enter the golf course (INs) and downstream locations where streams exit the golf course (OUTs) (Figures 2-9). Sites upstream of the golf courses served as baseline "reference" conditions for comparison to sites downstream of the areas influenced by golf course management. Sites with multiple inflow locations are referred to as "systems" and sites with a single inflow and outflow are referred to as "streams".

In situ streamwater temperature, specific conductance (SpC), pH, and dissolved oxygen (DO) were determined with a calibrated multi-parameter probe (either HANNA Instruments HI 9829, Woonsocket, RI; Hydrolab Quanta, Loveland, CO; or YSI Professional Plus, Yellow Springs, OH) at in and out sites at each course. The maximum temperature for non-tidal piedmont waters is 32°C and 31°C for mountainous zones according to the Virginia Water Quality Standards (VASWCB, 2011). Stockable and natural trout water mountain zone criteria are 21 and 20°C, respectively (VASWCB, 2011). Dissolved oxygen criteria are listed as 4.0 mg L^{-1} for non-tidal waters in the coastal/piedmont zones (VASWCB, 2011). VA Water Quality Standards lists mountainous zone waters as 4.0 mg L^{-1} minimum for DO. Stockable and natural trout water criteria are 5.0 and 6.0 mg L^{-1} minimum, respectively for DO (VASWCB, 2011). No water quality standards exist in Virginia for specific conductance. Water pH criteria are between 6 and 9 for non-tidal piedmont or mountainous zone waters (VASWCB, 2011).

Grab samples were taken seasonally (4x/year) at all courses except Course 3 (monthly) and Course 8 (twice a month). Samples were taken consistently at the same location within ~15 cm of the surface in areas of predominate flow (i.e. thalweg). The largest stream (Course 5) was sampled within 2 meters of the stream bank due to accessibility limitations. Nitrate-N, ammonium-N, and phosphate-P were analyzed from samples taken in 125 mL plastic bottles and filtered at the laboratory using a 0.45-micron syringe filter. Total N was analyzed from separate samples taken in 250 mL plastic bottles and were not filtered prior to analysis. All samples were transported on ice in a cooler until delivered to the laboratory for analysis. All samples were analyzed colorimetrically for nutrient content using SEAL AutoAnalyzer III methods G-109-94 (nitrate-N), G-102-93 (ammonium-N), and G-103-93 (phosphate-P) (Bran and Luebbe, 1999). The minimum detection limits for nitrate-N, ammonium-N, and phosphate-P were 0.0108, 0.0096, and 0.0068 mg L^{-1}, respectively. Total N samples were oxidized to nitrate using an alkaline persulfate digestion (APHA, 2005) and copper-cadmium reduction to form an azo dye using SEAL AutoAnalyzer method G-200-97 (Seal Analytical, 2011). The minimum detection limit for this method was 0.001 mg N L^{-1}. No stream water quality standards exist for nitrate-N in Virginia, but the EPA lists the drinking water limit as 10 mg L^{-1} (USEPA, 1986). A draft report with probabilistic monitoring data from the Virginia Department of Environmental Quality estimates total nitrogen levels >2 mg L^{-1} and total P levels as >0.05 mg L^{-1} as suboptimal. These levels may present an increased risk for benthic impairment of streams in Virginia (VADEQ, 2014). In the Kansas State University Citizen Science Water Quality Testing Series document, nitrate-N < 1 mg L^{-1} is considered “good”, whereas 1-10 mg L^{-1} is considered “fair” water quality (Janke et al., 2006). The EPA recommends no more than 0.05 mg L^{-1} phosphate-P for streams entering lakes, or 0.10 mg L^{-1} for streams not discharging into lakes (USEPA, 1986).

Discharge was calculated for OUT locations in each stream when possible using a velocity meter (Marsh & McBirney Flo-Mate Model 2000 Portable Flowmeter, Frederick, MD) in conjunction with channel cross-sectional area measurements

(Whiting, 2003). Velocity was measured at approximately 60% of the depth of the stream. Baseflow was targeted for determination of discharge.

a. Course-Specific Methods for Course 1

Course 1 had two separate stream systems sampled, with a total a five sample sites. System A consisted of two inflow stream sample sites (IN A 1 and IN A 2) flowing into a large lake. The outflow samples (OUT A) were taken at a stream below the spillway draining the lake. IN A 2 was identified later in the study. Stream B was also identified on the course later in the study and consisted of a single inflow location (IN B) and a single outflow location (OUT B) along a separate stream (Figure 2).

In situ temperature, SpC, pH, and DO were determined at IN A 1 and OUT A beginning in the summer of 2011 and continued quarterly (spring, summer, fall, winter) through summer 2014. Sampling began at IN B and OUT B in fall 2013 and continued through summer 2014. An extra sample was taken during the fall of 2013 for the tested sites, resulting in n = 15 for System A, and n = 6 for Stream B. Grab samples were taken at all sites seasonally (4x/year) beginning summer of 2011 and ending summer of 2014 for System A, and from fall 2013 through summer 2014 for Stream B. IN A 2 was not identified until later in the study, and sampling began in summer 2013. Furthermore, an extra sample was taken during the fall of 2013 for all sites. A total of 7 total N samples were collected for System A, and 6 for Stream B.

b. Course-Specific Methods for Course 2

Course 2 had two separate stream systems sampled, with a total of four sample sites. Both Stream A and Stream B had a single inflow and a single outflow location.

Stream A was located between golf hole 18 (IN A) and hole 1 (OUT A). Stream B was located between hole 7 (IN B) and hole 5 (OUT B) (Figure 3). *In situ* temperature, SpC, pH, and DO were determined quarterly beginning in summer of 2011 and ending in winter of 2012. Data are not available for IN B and OUT A for winter 2011 and summer 2012. Grab samples of water were taken at all sites seasonally (4x/year) beginning in summer of 2011 and ending in winter of 2012, with the exception of winter 2011.

c. Course-Specific Methods for Course 3

Course 3 had three streams/systems sampled, with a total of seven sample sites. System A consisted of two inflow locations (IN A 1 and IN A 2) connected to an outflow location (OUT A). System B consisted of two inflow locations (IN B 1 and IN B 2) connected to an outflow location (OUT B). Stream C ("From Pad") only consisted of a single sample site at an outflow location draining the course's equipment wash pad (Figure 4).

Temperature, SpC, pH, and DO were determined at IN A 2, OUT A, IN B 2, and OUT B. Sampling was conducted from summer of 2011 to July 2014. Sampling was initially conducted seasonally (quarterly) until more frequent sampling (monthly) began in June 2012. No data are available for the fall of 2011 sample at System A, or IN B 1. Water grab samples were initially taken at all sites seasonally (4x/year) beginning spring of 2011 until June 2012. Samples were then collected monthly at all sites.

d. Course-Specific Methods for Course 4

Course 4 had three streams/systems sampled, with a total of nine sample sites. System A consisted of three inflow locations (IN A 1, IN A 2, and IN A 3) connected to an outflow location (OUT A). Stream B consisted of a single inflow location (IN B) connected to an outflow location (OUT B). System C consisted of two inflow locations (IN C 1, IN C 2) connected to an outflow location (OUT C) (Figure 5).

Temperature, SpC, pH, and DO were determined at IN A 2 and OUT A in System A, and IN B and OUT B in Stream B. Data were collected quarterly from summer 2011 to summer 2014. No data are available for fall and winter 2011 at System A locations, or spring 2012 at Stream B. An extra sample was taken in fall 2013 for all locations. Water grab samples were taken at all sites seasonally (4x/year) beginning spring of 2011 until summer 2014, with the exception of an extra sample taken in fall 2013.

e. Course-Specific Methods for Course 5

Course 5 had a single stream sampled with one inflow (IN) and one outflow (OUT) location (Figure 6). Sampling for temperature, DO, SpC, and pH began in summer 2011 and ended summer 2014. Sampling for nitrate-N, ammonium-N and phosphate-P began in spring 2011 and ended summer 2014. Grab samples were taken at all sites seasonally (4x/year), with the exception of an extra sample taken during the fall of 2013 for both sites.

f. Course-Specific Methods for Course 6

Course 6 had two streams sampled. Stream A had a single inflow (IN A) and outflow (OUT A) location. Stream B also had one inflow (IN B) and one outflow (OUT B) location (Figure 7). Sampling for temperature, DO, SpC, pH, nitrate-N, ammonium-N and phosphate-P began in summer 2012 and ended summer 2014. Temperature, DO, SpC, and pH were only taken at the IN and OUT locations on Stream B. Grab samples were taken at all sites seasonally (4x/year), with the exception of an extra sample taken during the fall of 2013 for both streams.

g. Course-Specific Methods for Course 7

Course 7 had a single stream sampled with one inflow (IN) and one outflow (OUT) location (Figure 8). Sampling for temperature, DO, SpC, and pH began in summer 2013 and ended summer 2014. Sampling for nitrate-N, ammonium-N and phosphate-P also began in spring 2013 and ended summer 2014. Grab samples were taken at both sites seasonally (4x/year), with the exception of an extra sample taken during the fall of 2013.

h. Course-Specific Methods for Course 8

Course 8 had a single stream sampled with one inflow (IN) and one outflow (OUT) location (Figure 9). Sampling for temperature, DO, SpC, pH, nitrate-N, ammonium-N and phosphate-P began in July 2013 and ended in July 2014. Grab samples and probe samples were taken at both sites biweekly (twice a month) during baseflow conditions. Stormflow concentrations of nitrate-N, ammonium-N, and phosphate-P were to be determined during the course of the study, but only three significant storm events were sampled. An intermediate area along the course was also sampled before and after implementation of a BMP. Streambank restoration occurred during the first week of November 2013. This restoration effort included re-grading banks, installation of erosion control netting, and planting of riparian vegetation. Samples were taken immediately upstream and immediately downstream of the restored area.

Statistical Analysis

Mean concentrations of nitrate-N, ammonium-N, and phosphate-P were calculated from each of the sample sites separately. Data below the detection limit but nonzero values were kept as nonzero values for calculation of means, whereas zeroes were used when reported from the instrument. Differences between the upstream and downstream locations were calculated by subtracting mean downstream nutrient concentrations from mean upstream nutrient concentrations for each stream. Differences were used to decrease the effect of autocorrelation within repeated measures so that the samples could be treated as independent statistical units (Eric P. Smith, Virginia Tech Department of Statistics, personal communication 10/06/2014). No upstream data were available for the wash pad discharges (Stream C/ “From Pad” on Course 3), so statistical analysis was not performed. In cases where an outflow was connected to multiple inflows, data were analyzed by averaging the means of the multiple inflow streams. The SAS UNIVARIATE procedure (SAS Version 9.3, 2011, SAS Institute, Inc., Cary, NC) was used to test for significance by comparing the calculated differences between inflow and outflow locations to zero (Mu = 0). Significance was determined using the Signed Rank test with $p = 0.05$ (Wilcoxon, 1945).

Fertilization Correlation Analysis

Fertilization records were collected from each golf course except Course 2. Individual application rates and water quality data were entered into a Microsoft Excel spreadsheet by date (Microsoft Excel Version 14.4.6, 2010, Microsoft Corporation, Redmond, WA). Total application amounts (kg) for greens, tees, fairways, and rough were summed and paired with a corresponding water quality sample. The application amounts summed included those made after the previous water quality sample and up to the day of the sample. Initial summations were made based on the timing of the water quality sampling. Those courses receiving seasonal or monthly applications were summed from the beginning of the year for the initial data point. Fertilizer applications from two weeks prior to the first water quality sample were summed and paired with that initial sample for the first data point in the correlation analysis. A simple linear regression analysis was used to determine if there were correlations between amounts of fertilizer applied (total in kg) and stream nutrient concentrations (mg L^{-1}) Analyses were performed in Excel to obtain a Pearson's correlation coefficient and a p-value. Significance was determined at the $p = 0.05$ level. Correlation analyses were performed for N fertilization, nitrate-N, and ammonium-N at all sites that provided fertilizer records. Correlation analyses were performed for phosphorus fertilization and phosphate P concentrations for Course 3 and Course 4, although movement of P would not be expected during baseflow conditions. The primary method for assessing possible influences of soil P on water quality was to determine the level of extractable phosphorus from soil sampling (methods to follow under Soil Sampling and Analysis) and to compare those levels to phosphate-P detected in stream. Course 3 had phosphorus applied only to greens and tees during the study period, and Course 4 had phosphorus applied only to the greens during the study period.

Total N Unit Area Loads

Total N UALs were calculated based on the baseflow monitoring data for each of the golf course-associated watersheds except Course 2 (no discharge data collected, study terminated early) and Course 5 (discharge data could not be collected). Because the watershed areas upstream of the outflow location drainage points varied widely in size, unit-area loads of total N were calculated. These loads represent an annual average of total N from all sources/land uses upstream of the drainage point, including the golf course. Total N concentrations and discharge data from each sample date were averaged and used to calculate loads of total N per year when possible. These loads were then multiplied by the watershed area upstream of the drainage point (the outflow locations) to obtain N unit-area loads in kg ha^{-1} yr^{-1}. Watershed drainage areas and golf course areas were estimated using ArcGIS™ (ArcGIS Desktop: Release 10. 2011. Redlands, CA: Environmental Systems Research Institute). Golf course unit-area loads calculated from monitoring data were then compared to unit-area loads calculated for a variety of other land uses from their acreages and loads simulated by the Chesapeake Watershed Model (USEPA-CBLO, 2011). The model-estimated loads were based on projections of monitoring data that could include data points from either baseflow or stormflow conditions. Total N unit-area loads were considered to be comparable to integrated unit-area loads from the model since nitrogen is mobile and movement can occur during either condition. Phosphorus is an immobile nutrient and movement dominantly occurs during stormflow conditions. For this reason, baseflow loads of phosphorus would not be comparable to model-estimated loads of phosphorus. Only baseflow conditions were monitored in this study and did not include monitoring of stormflow P. Watershed delineations, area-calculations, and model estimates were generated with the assistance of Dr. E. R. Yagow in the Biological Systems Engineering Department at Virginia Tech.

Soil Sampling and Analysis

Selected soil physical and chemical properties were assessed at each of the golf courses, with exception of Course 2. Soil sampling was our primary method to determine if the soil was a potentially significant source of phosphorus in-stream. Our site assessment included collection of soil cores for submission to the Virginia Tech Soil Testing Lab to determine particle size distribution, pH, extractable phosphorus, exchangeable potassium, magnesium, calcium and cation exchange capacity (CEC) in soils from composite samples. The CEC of natural soils in Virginia ranges from 1-12 meq $100g^{-1}$ (Maguire and Heckendorn, 2010). Soils from this study were classified as low (1-3 meq $100g^{-1}$), moderate (3.1-9.9 meq $100g^{-1}$) or high (≥10 meq $100g^{-1}$) in CEC based on this range. Soil extractable phosphorus was rated as low, moderate, high, or very high. These ratings are based on the Soil Test Recommendations for Virginia, and are as follows: 0-6 mg kg^{-1} (low), 6-18 mg kg^{-1} (moderate), 18-55 mg kg^{-1} (high) and 55+ mg kg^{-1} (very high) (Maguire and Heckendorn, 2014).

An adaptation of the transect method was used to collect soil cores and composite samples at each course (Carter and Gregorich 2008). Soil sampling was conducted along five transects perpendicular to the study stream reaches at each golf course (Figure 10). Samples were taken along each transect within 5 meters from the stream bank when possible, depending on site conditions. Composite samples (from 10-15 soil cores) were taken separately at 0 to 15 cm and 15 to 30 cm depths at each sampling location (Figures 2-9). These depths are within the range of commonly used sample depth combinations (Carter and Gregorich 2008). For chemical analyses, ten to 15 subsamples (2 cm diameter cores) were taken at each sampling location within 5 meters of the stream bank perpendicular to the transect line and then composited for each sampling location (Beatty and Stone, 1986). A portion of samples taken at the inflows and outflows only (not at intermediate distances) was analyzed for organic matter and particle size using the hydrometer method (Bouyoucos, 1962). Soil samples that tested very high for organic matter (>5%) were treated before particle-size analysis by using the hydrogen peroxide organic matter removal method (Gee and Or, 2002). Soil maps using the USDA Soil Survey were made for each site, to be used in conjunction with particle-size analysis to infer infiltration rates in addition to leaching and runoff risk. Soils with a drainage class of “A” have a high infiltration rate, low runoff potential, higher leaching potential, and a high rate of water transmission. Soils with a drainage class of “B” have moderate infiltration rates, drainage, and rates of water transmission. Those with a rating of “C” have a slow infiltration rate when wet and a slow rate of water transmission. Soils with a drainage class rating of “D” have a very slow infiltration rate, high potential for runoff, and a slow rate of water transmission (USDA NRCS, 2013).

a. Method Exceptions

A 15-30 cm soil sample could not be taken at site 1 on Course 3. Soil samples were only taken at five locations along the stream on the golf course side at Course 5 due to inaccessibility. A sample at 15-30 cm could not be taken at sites 19 and 20 at Course 6. Samples at site number 2 could not be taken at Course 7 due to inaccessibility.

Survey of Golf Course Superintendents

Virginia golf course superintendents were surveyed online using Qualtrics software (Qualtrics, Version 58509, 2014, Provo, UT) to assess management levels and adoption of BMPs on their golf courses. The survey was distributed to all members of the Virginia Golf Course Superintendents Association via email (Appendix A). Superintendents were asked to provide demographic information about their courses (location, maintenance budgets, number of rounds played annually, classification, membership in the Audubon Cooperative Sanctuary Program for Golf and age of course), water quality testing information, turfgrass species used on each part of the course, fertilization type/approximate rates of N applied, mowing heights, and whether the courses utilize several BMPs found in the Environmental Best Management Practices for Virginia's Golf Courses manual (VGCSA, 2012).

Tables and Figures

Table 1. Golf courses participating in water quality monitoring.

Course	City	County	Maintenance Budget	Age (Years)	Annual # Rounds	Audubon Certified
1	Manakin-Sabot	Goochland	>$1.5 Million	15-20	10,000-20,000	Yes
2	Keswick	Albemarle	$1.0- $1.5 Million	<1*	< 10,000	Yes
3	Richmond	Henrico	>$1.5 Million	20+	> 40,000	No
4	Richmond	Richmond City	>$1.5 Million	20+	> 40,000	No
5	Richmond	Henrico	>$1.5 Million	20+	> 40,000	Yes
6	Keswick	Albemarle	$0.5-$1 Million	20+	10,000-20,000	No
7	Powhatan	Powhatan	$0.5-$1 Million	15-20	< 10,000	Yes
8	Blacksburg	Montgomery	$0.5-$1 Million	20+	20,000-30,000	No

*Sampling ceased in 2013 due to complete course renovation

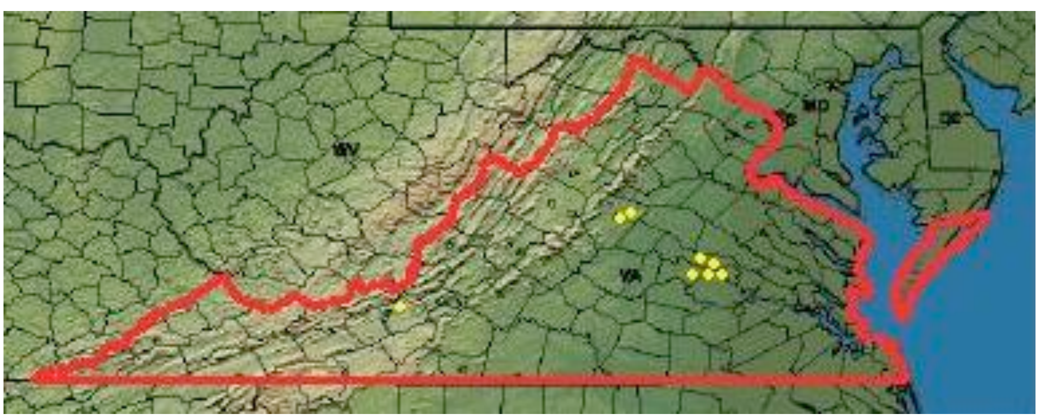

Figure 1. Approximate locations of golf courses sampled. Aerial imagery courtesy USDA FSA APFO NAIP, Accessed Feb. 27, 2015.

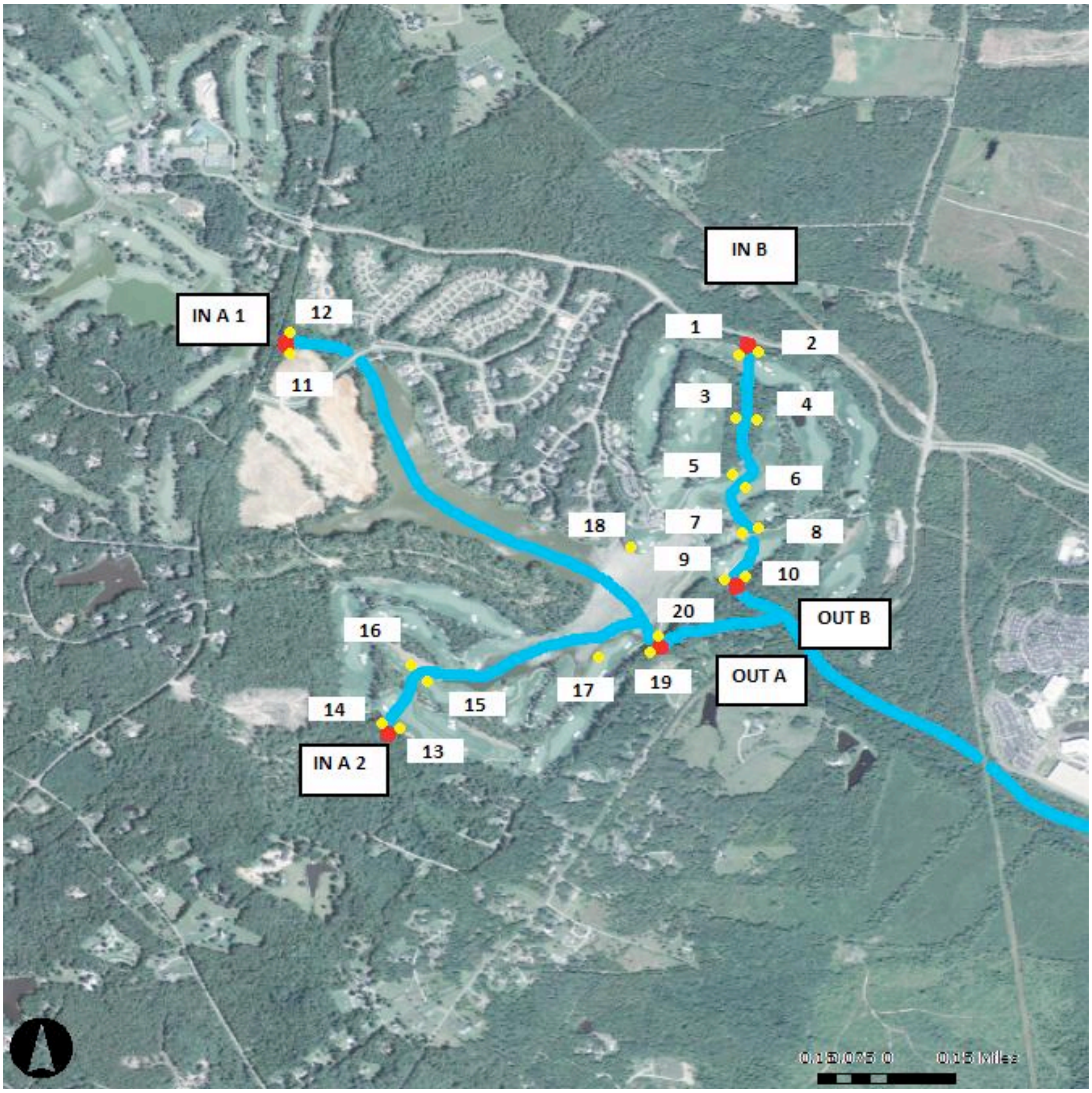

Figure 2. Course 1 site map. Water sampling locations (red dots) in System A consist of IN A 1, IN A 2, and OUT A. Stream B consists of IN B and OUT B. Numbers 1-20 (yellow dots) indicate soil sampling locations. Aerial imagery courtesy USDA FSA APFO NAIP, Accessed Dec. 17, 2014.

Figure 3. Course 2 map. Map does not reflect course conditions at the time of water quality sampling due to renovation. Aerial imagery generated from USDA FSA APFO NAIP Coverage Viewer, Dec. 17, 2014.

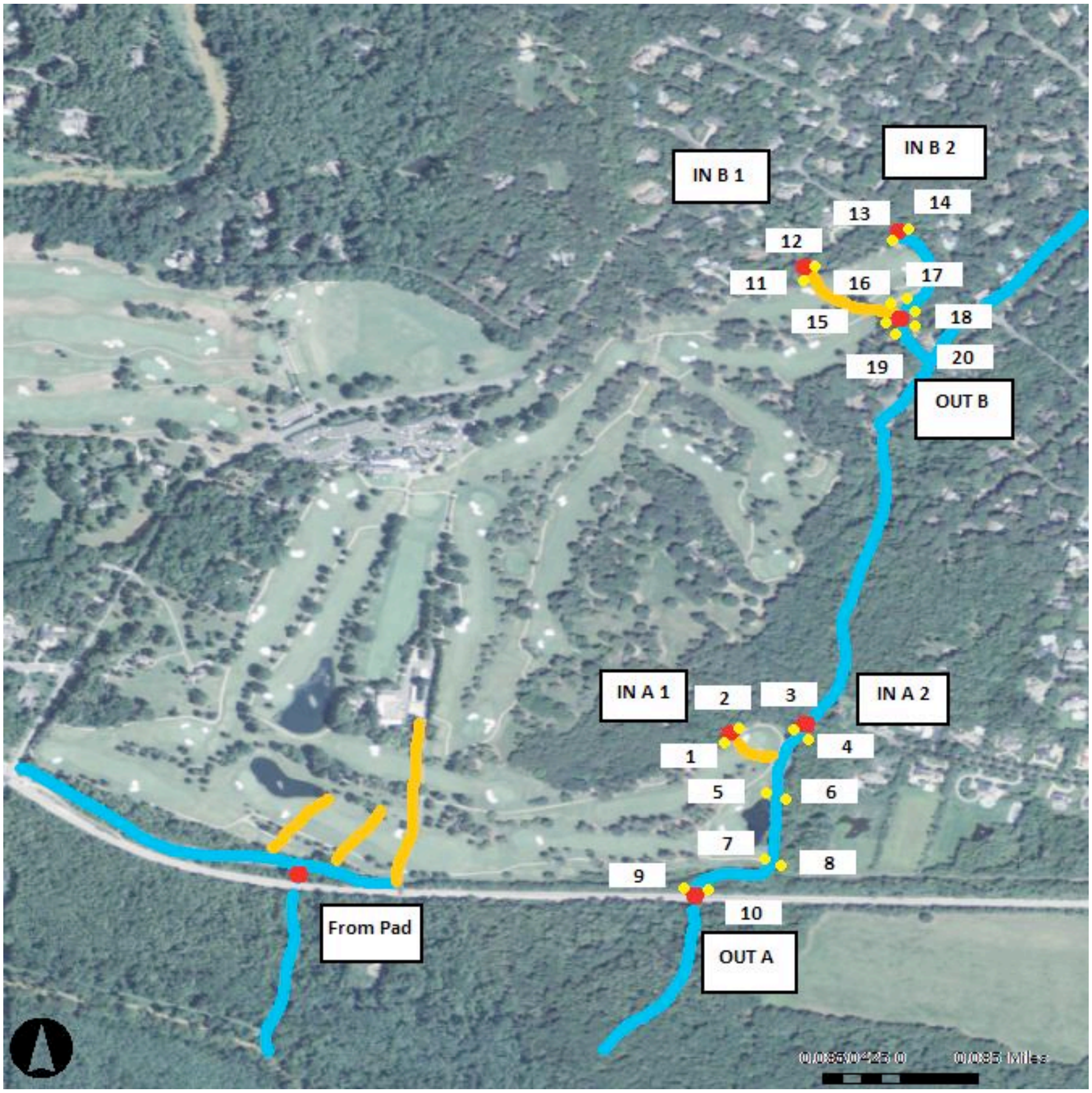

Figure 4. Course 3 site map. Water sampling locations (red dots) in System A consist of IN A 1, IN A 2, and OUT A. System B consists of IN B 1, IN B 2 and OUT B. Stream C ("From Pad") indicates an area receiving wash pad discharges. Numbers 1-20 indicate soil sampling locations (yellow dots). Orange lines represent estimated underground stream flows. Aerial imagery courtesy USDA FSA APFO NAIP. Accessed Dec. 17, 2014.

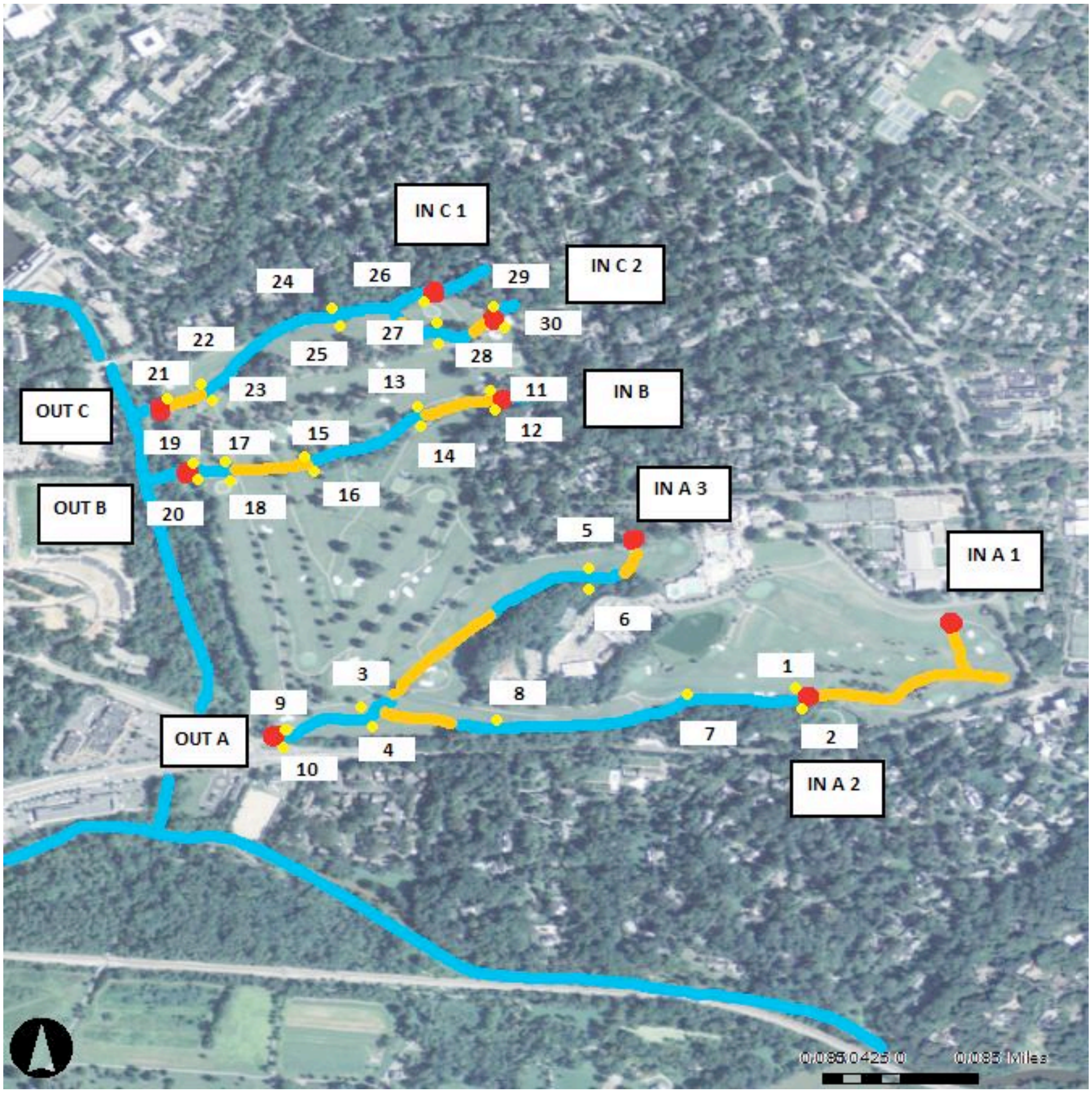

Figure 5. Course 4 site map. Water sample locations are indicated by red dots. System A consists of IN A 1, IN A 2, IN A 3 and OUT A. Stream B consists of IN B and OUT B. System C consists of IN C 1, IN C 2, and OUT C. Numbers 1-30 indicate soil sampling locations. Orange lines represent estimated underground stream flows. Aerial imagery courtesy USDA FSA APFO NAIP. Accessed Dec. 17, 2014.

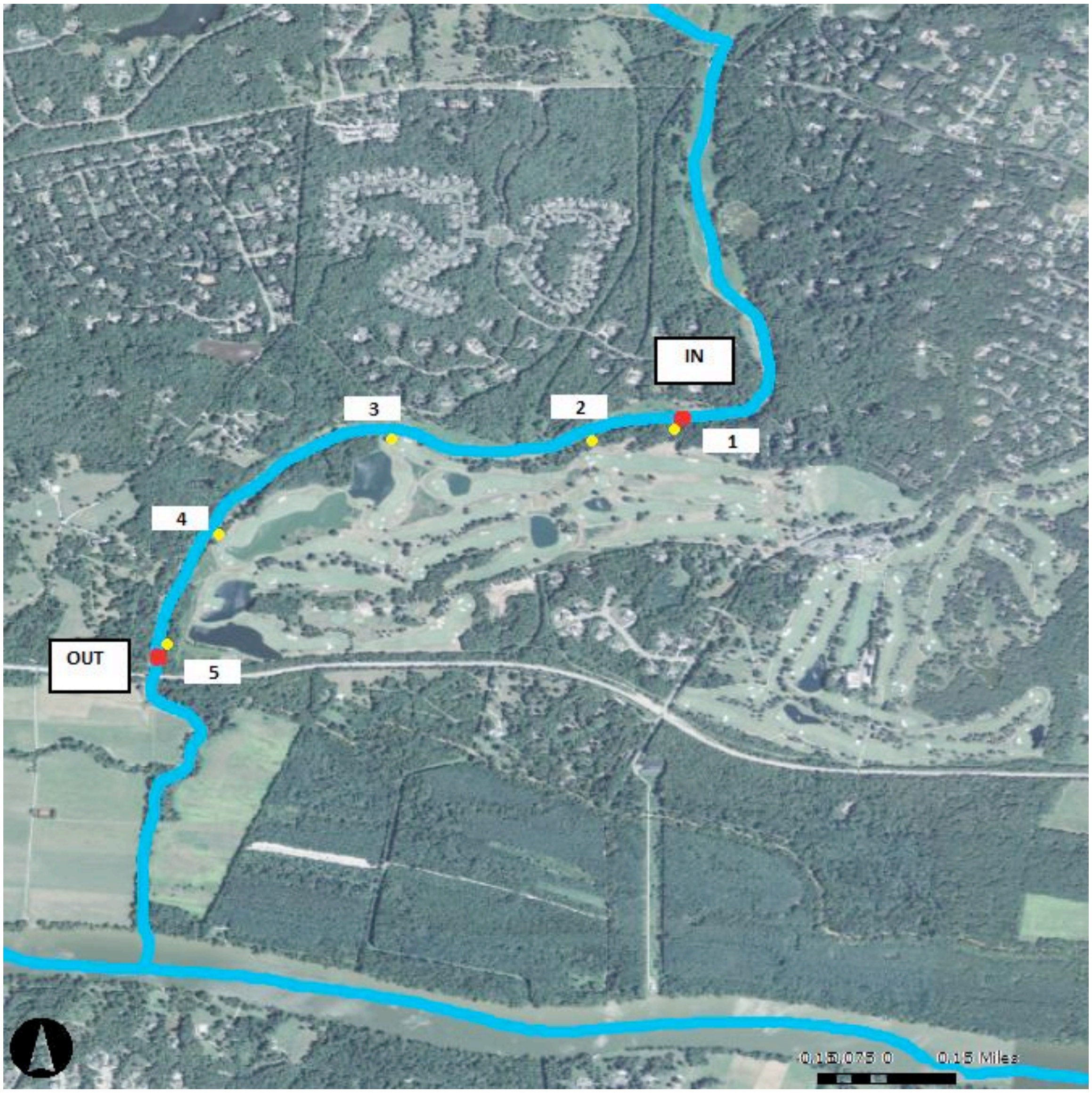

Figure 6. Course 5 site map. The IN and OUT water sampling locations are represented by red dots. Numbers 1-5 indicate soil sampling locations (yellow dots). Aerial imagery courtesy USDA FSA APFO NAIP. Accessed Dec. 17, 2014.

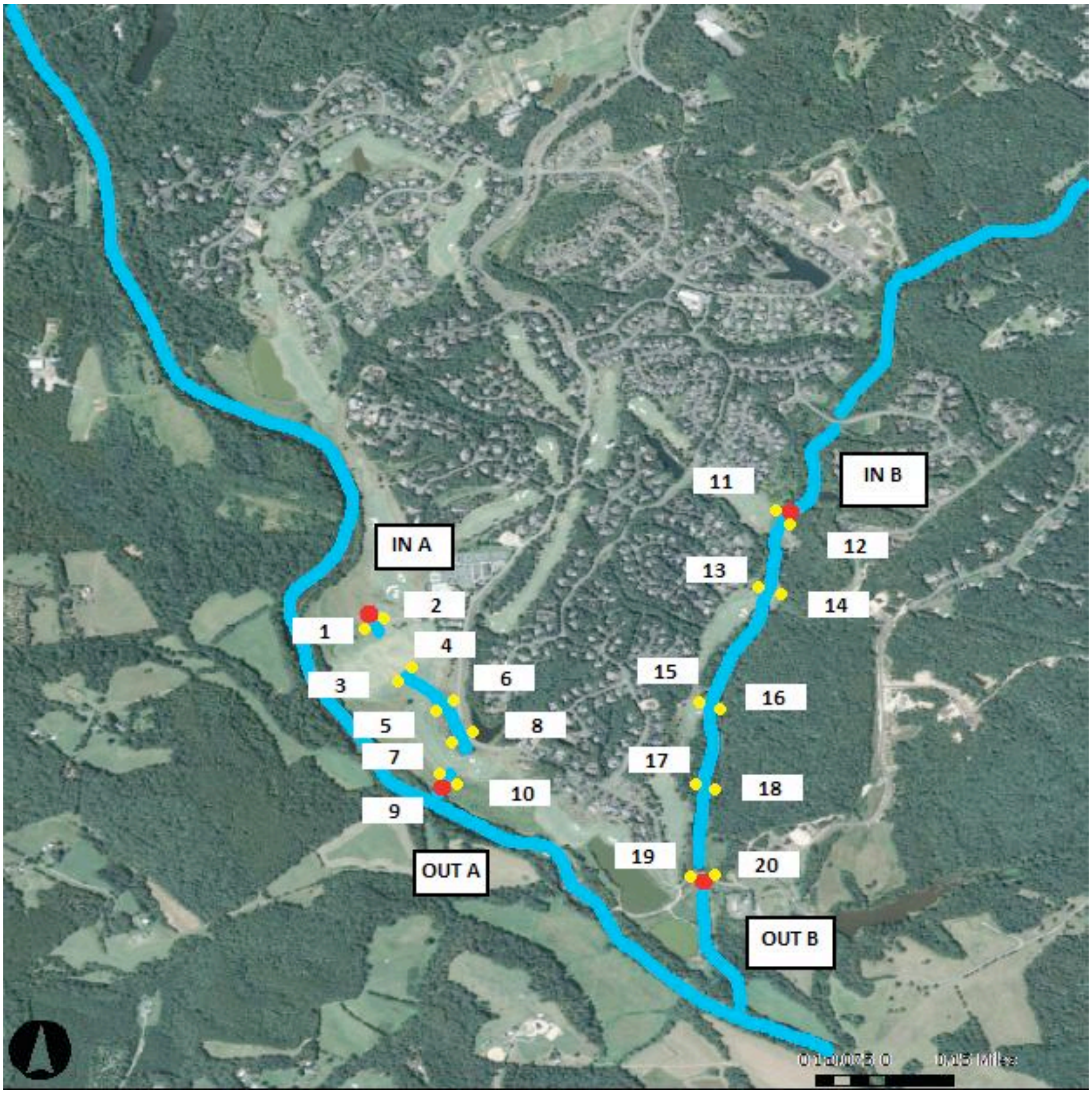

Figure 7. Course 6 site map. Water sampling locations are indicated by red dots. These consist of Stream A (IN A, OUT A) and Stream B (IN B, OUT B). Numbers 1-20 indicate soil sampling locations (yellow dots). Aerial imagery courtesy USDA FSA APFO NAIP. Accessed Dec. 17, 2014.

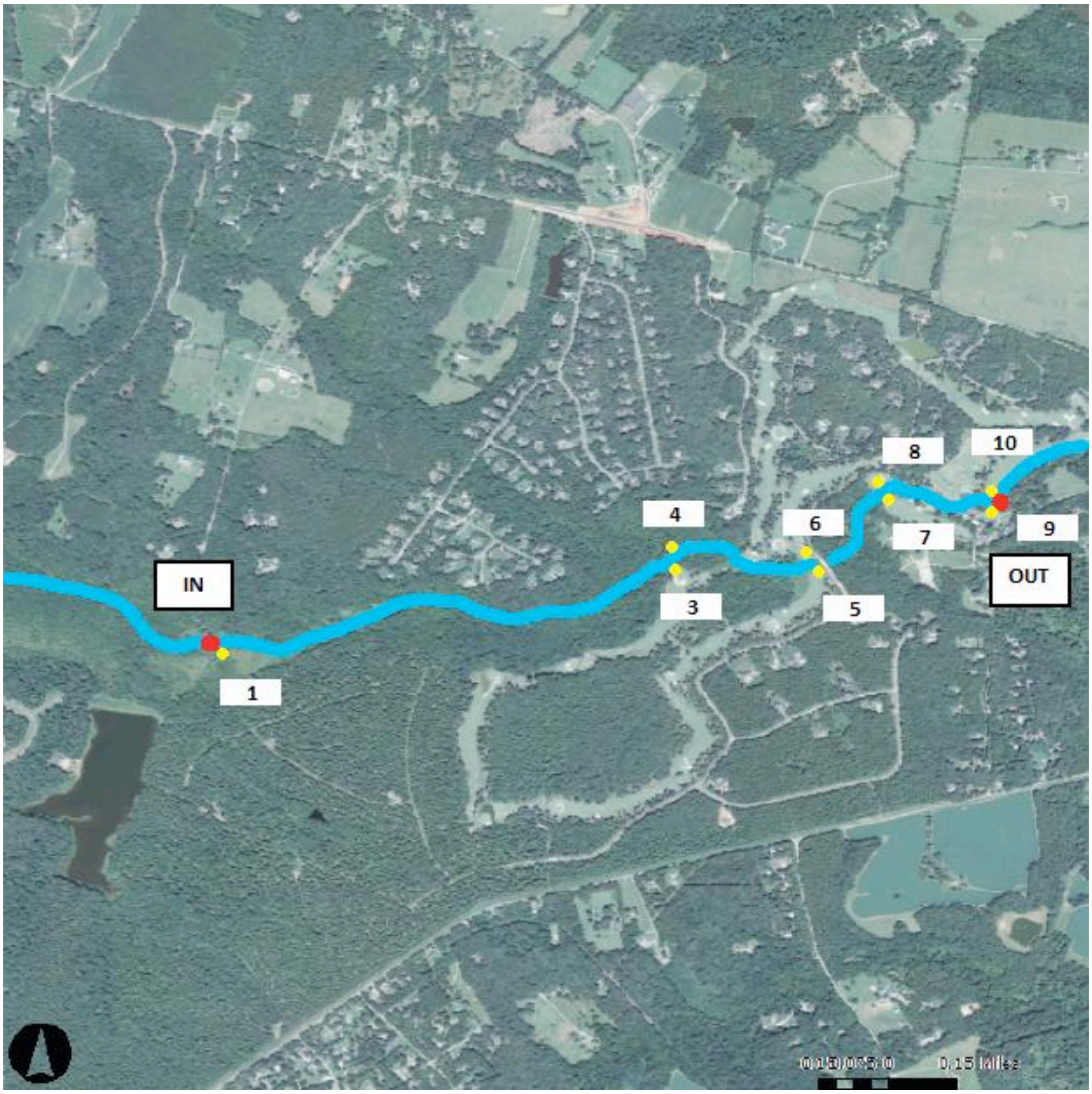

Figure 8. Course 7 Site map. Water sampling locations are indicated by red dots. Numbers 1-10 indicate soil sampling locations (yellow dots), although sample 2 was not taken. Aerial imagery courtesy USDA FSA APFO NAIP. Accessed Dec. 17, 2014.

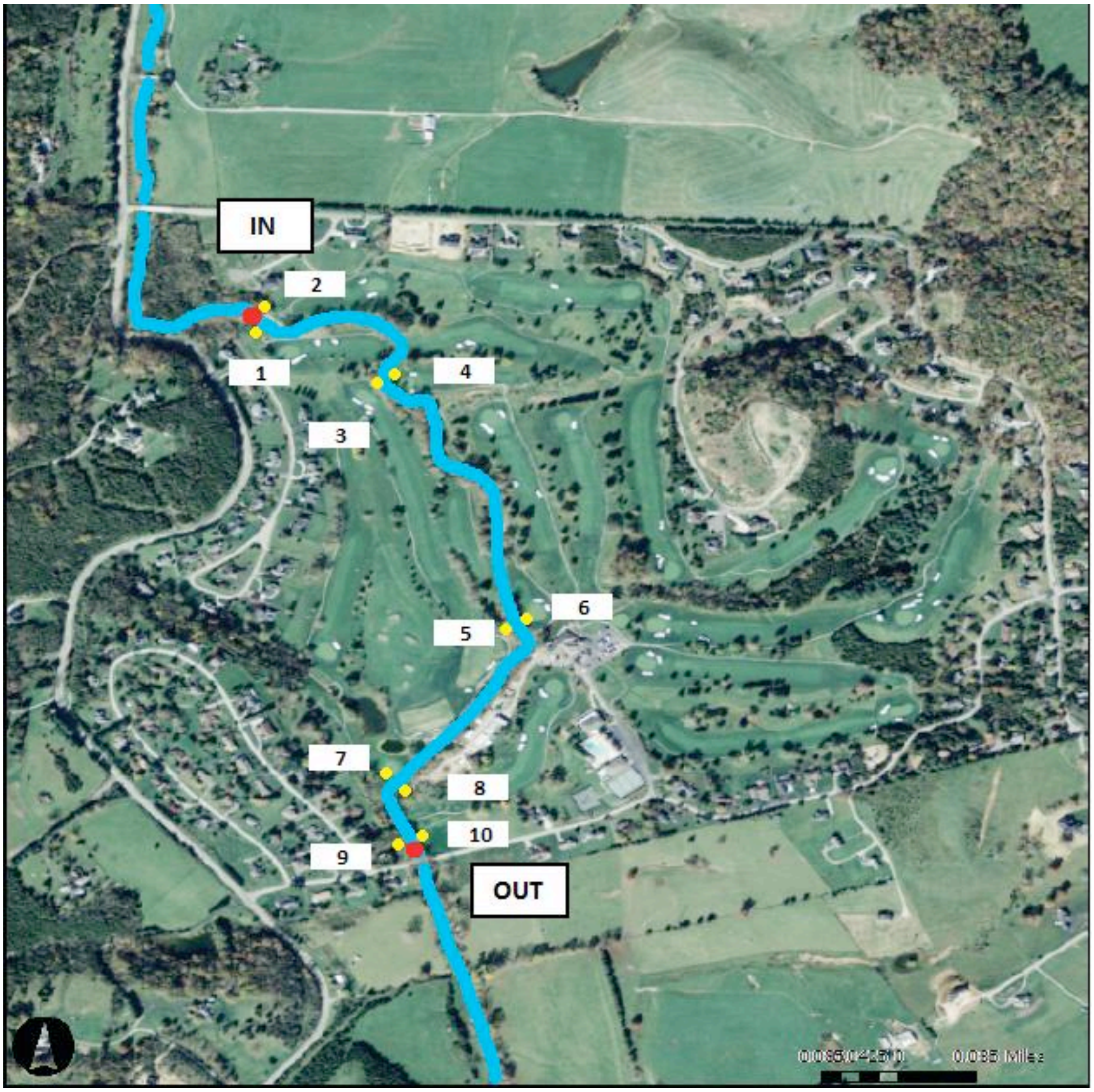

Figure 9. Course 8 site map. Numbers 1-10 indicate soil sampling locations. Aerial imagery courtesy USDA FSA APFO NAIP. Accessed Dec. 17, 2014.

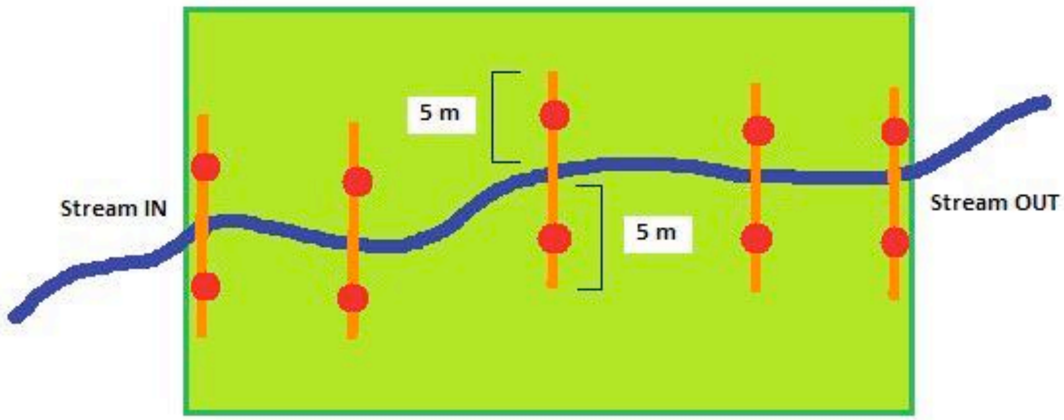

Figure 10. Diagram representing transect sampling method. Five transects (orange lines) were used to divide the stream along the golf course property. Composite samples of 10-15 cores each were taken at 0-15 cm and 15-30 cm depths within 5 meters from the stream bank (red dots).

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CHAPTER THREE: RESULTS

Temperature, pH, Dissolved Oxygen, and Specific Conductance (Appendix B)

a. Temperature

The non-tidal Piedmont waters temperature criterion was not exceeded except for one instance (33.6°C) at the OUT location in System A of Course 1 during summer of 2011. The temperature criterion for mountainous zones (31°C) was not exceeded at either sampling site for Course 8. Both inflow and outflow locations slightly exceeded natural trout waters criteria in the last sample (July 24, 2014) at Course 8 (20.8 at inflow and 21.2 °C at outflow)

b. pH

Water pH criteria were generally met. Exceptions and notable observations include: (a) Water pH was outside of the acceptable range (low at 5.6) at both IN A 1 and OUT A in fall of 2012 at Course 1; (b) Water pH was high at OUT A in summer of 2011 (excessive at 9.2) and spring of 2013 (excessive at 9.6) at Course 1; (c) All sites were below the acceptable range at Course 2 in fall 2012 and ranged from 5.2 to 5.6; (d) Deviations at IN A 2 during April and May 2013 (elevated to 9.2 and 9.6), all sites in August 2012 (low pH from 5.5 to 5.7), and both IN A 2/OUT A (low at 5.6 and 5.1) in September 2012 at Course 3; (e) Excessive pH of 9.1 at the outflow location during spring 2013 on Course 6; and (f) pH was elevated to 9.8 at the inflow location of Course 7 during one of the fall 2013 sample intervals.

c. Dissolved Oxygen

Although the dissolved oxygen (DO) water quality concentrations were occasionally below established criteria, no sustained impairment trends were observed. Occasions below established criteria and notable observations include: (a) Levels were low at the inflow location of System A (3.5 mg L^{-1}) as well as the IN location in System B (3.0 mg L^{-1}) of Course 1 during fall of 2013. DO concentrations were low (2.0 mg L^{-1}) at the IN location for System B in summer of 2014, but were sufficient in other samples; (b) The OUT in System B of Course 3 was below acceptable DO criteria September-November 2012 (ranging from 2.9-3.9 mg L^{-1}), September and November 2013 (2.8 and 0 mg L^{-1}), and May 2014 (2.8 mg L^{-1}); (c) Dissolved oxygen concentrations were generally lower at inflow locations than outflow locations for both System A and Stream B of Course 4. DO was below acceptable criteria at IN B (1.1 mg L^{-1}) during Summer 2012; (d) Dissolved oxygen fluctuated seasonally and was generally low during the summer at Course 5. Although there were no consistent differences between outflow locations, DO was below acceptable levels at both the IN and OUT locations in summer 2011 (2.8 and 1.9 mg L^{-1}), fall 2012 (2.4 and 3.0 mg L^{-1}), summer 2013 (1.5 and 1.7 mg L^{-1}), and summer 2014 (2.6 and 3.3 mg L^{-1}). The inflow location was below DO criteria during Fall 2011 (3.7 mg L^{-1}); and (e) Dissolved oxygen was consistently higher at the outflow location at Course 7, although this is likely attributable to the fact that flow was much slower at the swampy inflow sampling location.

d. Specific Conductance

Significant changes in specific conductance indicating pollution or runoff events were generally not reported. Exceptions and notable observations include: (a) Elevations at OUT A in fall (133 versus 98 $\mu s\ cm^{-1}$ at IN A 1) and winter of 2012 (224 versus 134 $\mu s\ cm^{-1}$ at IN A 1) on Course 1; (b) Elevation at IN A 1 in summer (219 versus 117 $\mu s\ cm^{-1}$ at OUT A). and fall of 2013 (251 versus 110 $\mu s\ cm^{-1}$ at OUT A in the Fall A sample, and 177 versus 64 $\mu s\ cm^{-1}$ at OUT A in the Fall B sample) as well as summer 2014 (235 versus 119 $\mu s\ cm^{-1}$ at OUT A). at Course 1; (c) A spike in SpC was detected at OUT B in April 2013 and May 2014 of Course 3 (1350 and 1823 $\mu s\ cm^{-1}$), but there were no consistent significant differences at other times for both systems; (d) SpC was generally elevated at the downstream locations when compared to the inflow locations at both System A (253 versus 226 $\mu s\ cm^{-1}$ on average) and Stream B (192 versus 222 $\mu s\ cm^{-1}$ on average) on Course 4; (e) The inflow location of Course 5 during winter 2012 was significantly elevated as compared to the downstream site; (f) An elevation at the inflow location of Course 7 during the summer of 2014 (308 versus 194 $\mu s\ cm^{-1}$ at the inflow location); and (g) SpC at Course 8 was generally high on average at both the inflow and outflow locations (413 and 419 $\mu s\ cm^{-1}$).

Dissolved Nitrate

Nitrate-N concentrations were generally low or below detection limits at all golf course sites (Figures 1-8). Statistical analysis generally did not reveal significant differences between inflow and outflow locations. Notable exceptions include: (a) There was a significant reduction of nitrate-N between the inflow and outflow location on

Stream A of Course 2, suggesting an improvement in water quality; (b) In System B of Course 3, there was a significant increase in nitrate-N when both inflow locations (IN B 1 and IN B 2) were averaged together and compared with the outflow location (OUT B); (c) In Stream B on Course 4, there was a significant increase of nitrate-N detected between the inflow and outflow location; (d) An analysis with the averaged inflow concentrations in System C on Course 4 revealed an increase in nitrate-N between inflow and outflow locations; (e) There was a significant reduction of nitrate-N concentrations at Stream A on Course 6 between the inflow and outflow locations; and (f) A significant increase was detected between the inflow and outflow location for nitrate-N on Course 8 (Table 1). The stream receiving wash pad discharges (Course 3, Stream C/“From Pad”) did not exceed the 10 mg L^{-1} EPA drinking water standard for nitrate-N for the duration of the study, but did frequently exceed the >2 mg L^{-1} total N concentrations which may indicate increased risk to benthic macroinvertebrate health.

As for stormflow samples on Course 8, storms occurred on 7/3/13 and 4/7/14 with approximately 2.5 cm of precipitation, but nitrate concentrations were similar to those taken at baseflow. No significant differences were measured between the inflow and outflow location. A more significant storm occurred on 10/7/13 with approximately 5.7 cm. Higher concentrations of nitrate-N (inflow 0.784 vs. outflow 1.348 L^{-1}) were detected. A baseflow sample three days later indicated that nitrate-N decreased back down to baseflow levels.

The streambank restoration at Course 8 appeared to have little effect on concentrations of nitrate-N. Concentrations at the upstream and downstream locations remained consistent with those found at the overall inflow and outflow locations.

Dissolved Ammonium

Ammonium- N concentrations were generally very low or below detection limits at all courses (Figures 9-16). Statistical analyses rarely revealed significant differences between inflow and outflow locations (Table 2). Notable observations are: (a) A significant reduction of ammonium-N was detected between the averaged inflow location concentrations (IN A 1 and IN A 2) and the outflow location (OUT A) of System A on Course 3; and (b) A significant reduction of ammonium-N was detected in the analysis averaging the inflow locations together as compared to the outflow location in System A on Course 4 (Table 2).

As for stormflow samples on Course 8, storms occurred on 7/3/13 and 4/7/14 with approximately 2.5 cm of precipitation. Ammonium-N concentrations were similar to those taken at baseflow. No significant differences were apparent between the inflow and outflow location. Furthermore, the streambank restoration appeared to have little effect on concentrations of ammonium-N at Course 8. Concentrations at the upstream and downstream locations generally remained consistent with those found at the overall inflow and outflow locations. An exception includes two sample occasions in December 2013 and January 2014. Ammonium-N appeared to increase in the stream between the sample site upstream of stream restoration and the site downstream.

Dissolved Phosphate

Phosphate-P concentrations were generally low or below detection limits at the golf course sites (Figures 17-24). There were no significant differences in phosphate-P concentrations between inflow and outflow locations (Table 3). Outflow concentrations of phosphate-P were always below EPA recommendations for streams not discharging into lakes except for one occurrence in June 2012 at the Course 3 wash pad site (0.152 mg L^{-1}), and three occurrences at OUT B of Course 3 (0.124 in June 2012, 0.189 in April 2013, and 0.487 in May 2014. However, IN B 1 connected to OUT B frequently had phosphorus concentrations above 0.10 mg L^{-1}.

Soil Properties

Soils were generally slightly acidic at Courses 1-7 in the James River watershed. Soil pH was higher and slightly basic at the sites in Course 8 in the Roanoke River watershed (Tables 4 and 5). Soil samples from 0-15 cm had low mean extractable phosphorus at System A sample sites on Course 3, sites on Course 7, and sites on Course 8 (Table 4). Moderate levels of mean extractable phosphorus from 0-15 cm samples were detected at System B on Course 3, System C on Course 4, sites on Course 5, and both Stream A and Stream B on Course 6 (Table 4). Mean extractable phosphorus levels were high in 0-15 cm samples on Course 1, and both System A and Stream B on Course 4 (Table 4). As for 15-30 cm samples, extractable phosphorus levels were low on Course 1, Course 3, Course 5, Stream B on Course 6, Course 7, and Course 8 (Table 5). Mean extractable phosphorus levels were moderate in 15-30 cm samples on Course 4, and Stream A on Course 6 (Table 5). Some sample sites had very high levels of phosphorus on Course 1 and System A of Course 4 (Table 4). CEC was generally moderate and within the normal range for Virginia soils at all sites except for Course 8, where CEC was very high (Tables 4 and 5).

USDA Web Soil Survey Maps constructed for each course indicated the major soil types and hydrologic drainage classes for each golf course site (Table 6). No soils at any of the golf course sites were characterized as having class “A” drainage with high infiltration rates, water transmission, and higher leaching risk. The majority of course sites had “C” drainage classes. System A on Course 3 and the site on Course 7 had a drainage class rating of “D” with very slow infiltration rates, high potential for runoff, and slow rates of water transmission. Other sites had mixed drainage classes. Native soil maps may not reflect the current site conditions after development, so particle size analyses (PSA) were performed on soil samples from the IN and OUT locations. These PSAs indicated that soils were generally moderately textured loams or heavier-textured clays, although some sites had sandy soils present (Table 6).

Nitrogen Loads as a Function of Land Use

Drainage areas within each golf course and the corresponding watershed areas were determined, along with the associated land uses as estimated by the Chesapeake Bay Watershed Model (Table 7). Half of the studied golf course sites were associated with watersheds dominated by forest cover, and half were more developed. Agriculture did not comprise >26% of the land uses in the watersheds associated with the golf course drainage points. The watershed area associated with the drainage point (OUT) on Course 5 was the largest (16029 ha), whereas the smallest associated watershed area was 10 ha for the Course 4 OUT B drainage point (Table 7).

Both OUT A and OUT B at Course 1 had UALs of total N that were less than half of loads estimated to be generated from forested land in the associated watershed segments (Table 8). Course 3 OUT A had a total N UAL that was higher than UALs expected from pasture, pervious urban, forested, or hay without manure. The N load was closer to the UAL estimated for "hay with nutrients" land use, which was 11.4 kg ha^{-1} yr^{-1}. The UAL associated with Course 3 OUT B was similar to that expected from forest in the associated watershed. The drainage point associated with wash pad discharges had a UAL higher than those associated with pasture, pervious urban, forested, or hay without manure land uses. This load was also similar to those that would be expected from "hay with nutrients". Both sites on Course 6 had UALs lower than those estimated for forest, although OUT B had UALs comparable to those estimated for "hay without manure" land use in the associated watershed. The UAL for the drainage point on Course 7 was also less than half of the UAL expected from forests in the associated watershed (Table 8).

Course 4 is situated in an urban setting in the city of Richmond. The drainage points associated with the watershed segments generally had the highest UALs of the sites studied and all exceeded the UALs expected from forest. The N loads from OUT A and OUT C were most similar to those that would be expected to be generated from atmospheric deposition in non-tidal waters (13.3 kg ha^{-1} yr^{-1}) as estimated by the model. The highest UAL in this study was from the drainage point associated with OUT B on

Course 4. The UAL of 86.9 kg N ha^{-1} yr^{-1} was higher than those modeled in other watershed segments for pasture corridors, up to 73 kg N ha^{-1} yr^{-1} (Table 8). These corridors are highly disturbed riparian areas compacted and trampled by cattle.

Assuming discharge does not change significantly along the reach between inflow and outflow locations at Course 8 in the Roanoke River watershed, a difference in nutrient loads can be calculated between the inflow and outflow points. According to data in Table 9, there is an addition of 0.042 kg ha^{-1} yr^{-1} of total N between the inflow and outflow locations at this course.

Fertilizer Correlation Analysis

In most cases, phosphate in streams was below detection limits, or a single detection occurred, therefore a correlation analysis was not completed. It is assumed that there is no detectable correlation between phosphorus applications used on these golf courses and stream concentrations because phosphorus applications were made on each course and phosphate remained below the limit of detection at most sites. No consistent trend directions were observed and no significant correlations between fertilizer applications and nutrient concentrations were detected at any site except for nitrate-N at Course 4 OUT A and ammonium-N at the Course 3 wash pad (Table 10),. However, Pearson correlation coefficients were still very low for these sites (0.57 and 0.45, respectively). Pearson correlation coefficients closest to 1 would indicate a stronger correlation between fertilizer applications and in-stream nutrient concentrations. All Pearson correlation coefficients (r) were <0.58 (Table 10).

Golf Course Management Survey

An electronic survey was distributed to Virginia Golf Course Superintendents Association members. The purpose of this survey was to determine the characteristics, management, and levels of BMP adoption on Virginia golf courses. A total of 70 complete responses were gathered representing 42 counties. Eighty-two percent of golf courses had an annual maintenance budget of <$1 million, whereas 19% had a budget >$1 million. Fifty-eight percent of golf courses identified as private clubs, 29% public, and 12% municipal. Most courses were >20 years old. About half of the golf course managers routinely test the water quality of their irrigation ponds. Furthermore, 21% test the quality of waters flowing through or adjacent to their courses, whereas 17% had no streams present. Twenty-one of the golf courses surveyed were members of the Audubon Cooperative Sanctuary for Golf program. Of courses that were not members of the program, 13 were either in the process of gaining certification or planning to obtain certification. Fifteen managers identified that they were unsure about their future plans for certification.

Most golf course managers are annually fertilizing their greens with 15-19 g m^{-2}, tees and fairways at 10-14 g m^{-2}, and rough at 0-9 g m^{-2}. These rates are within the Virginia Nutrient Management Standards and Criteria recommendations (VADCR, 2005). Many practices as recommended in the Environmental Best Management Practices of Virginia Golf Courses manual (VGCSA, 2012) are reportedly in use. The adoption rate of practices directly influencing water quality is presented in Figure 25. Water quality protection BMPs with a 50% or higher adoption rate include: (1) Use of slow release nitrogen fertilizers near water sources; (2) Greens drain to grassed or wooded areas; (3) Vegetative buffer strips are used around most irrigation ponds; (4) Fill stations are situated away from drains to surface water; (5) Control of streambank erosion; (6) Vegetative buffer strips are used around most flowing surface waters; (7) Use of detention/retention ponds or basins, (8) Use of native plants in ponds/buffer zones; (9) Grass clippings removed from equipment before washing; and (10) Wash pad discharges are kept out of surface waters. Cultural practices to maintain turfgrass health, or those indirectly affecting water quality, are presented in Figure 26. All cultural practices/selected turfgrass BMPs had an adoption rate of 50% or higher except performance of irrigation audits, irrigation based on evapotranspiration demand, and height of cut is raised while lower inputs are used on shaded turf. Sharpening and checking mower blades regularly was the only BMP reported in use at all surveyed golf courses.

Tables and Figures

Table 1. Comparison of nitrate concentration differences between inflow locations and outflow locations at eight golf courses in Virginia.

Analysis	Course/Site	N	Nitrate-N mg L^{-1} Mean Difference	Nitrate-N mg L^{-1} Median Difference	Signed Rank P-Value	Effect
Averaged INs	1 System A	15	0.02	0	0.52	NS*
IN-OUT	1 Stream B	6	0.02	0.02	0.31	NS
Averaged INs	2 Stream A	7	0.26	0.27	0.02	RED**
	2 Stream B	7	0.2	0.19	0.16	NS
Averaged INs	3 System A	31	-0.14	-0.07	0.23	NS
	3 System B	31	-0.87	-0.73	< .0001	INC***
Averaged INs	4 System A	15	-0.36	0	0.8	NS
IN-OUT	4 Stream B	15	-2.94	-3.44	0	INC
Averaged INs	4 System C	15	-1.63	-1.83	0	INC
IN-OUT	5 Stream	15	0.04	-0.01	0.09	NS
IN-OUT	6 Stream A	11	1.87	1.8	0	RED
	6 Stream B	11	0.1	0.05	0.17	NS
IN-OUT	7 Stream	7	-0.02	-0.03	0.38	NS
IN-OUT	8 Stream	29	-0.04	-0.03	0	INC

*NS indicates not significant
**RED indicates a reduction of nitrate between inflow and outflow
***INC indicates an increase of nitrate between inflow and outflow

Table 2. Comparison of ammonium concentration differences between inflow locations and outflow locations at eight golf courses in Virginia.

Analysis	Course/Site	N	Ammonium-N mg L^{-1} Mean Difference	Ammonium-N mg L^{-1} Median Difference	Signed Rank P-Value	Effect
Averaged INs	1 System A	15	0.03	0.02	0.06	NS*
IN-OUT	1 Stream B	6	0.04	0	0.25	NS
Averaged INs	2 Stream A	7	-0.04	-0.02	0.13	NS
	2 Stream B	7	0.04	-0.02	0.58	NS
Averaged INs	3 System A	31	0.03	0.01	0.04	RED**
	3 System B	31	-0.05	0	0.5	NS
Averaged INs	4 System A	15	0.03	0.03	0.03	RED
IN-OUT	4 Stream B	15	-0.08	0	0.2	NS
Averaged INs	4 System C	15	0	0	0.3	NS
IN-OUT	5 Stream	15	0	0	0.81	NS
IN-OUT	6 Stream A	11	-0.01	-0.01	0.14	NS
	6 Stream B	11	-0.01	0	0.46	NS
IN-OUT	7 Stream	7	0.01	0	0.31	NS
IN-OUT	8 Stream	29	0	0	0.07	NS

*NS indicates not significant

**RED indicates a reduction of ammonium between inflow and outflow

Table 3. Comparison of phosphate concentration differences between inflow locations and outflow locations at eight golf courses in Virginia.

Analysis	Course/Site	N	Phosphate-P mg L^{-1} Mean Difference	Phosphate-P mg L^{-1} Median Difference	Signed Rank P-Value	Effect
Averaged INs	1 System A	15	0.01	0	0.25	NS*
IN-OUT	1 Stream B	6	0	0	-	NS
Averaged INs	2 Stream A	7	-0.01	0	1	NS
	2 Stream B	7	0	0	-	NS
Averaged INs	3 System A	31	0	0	0.15	NS
	3 System B	31	-0.01	0.04	0.07	NS
Averaged INs	4 System A	15	-0.01	0	0.13	NS
IN-OUT	4 Stream B	15	0.01	0	0.08	NS
Averaged INs	4 System C	15	0	0	0.63	NS
IN-OUT	5 Stream	15	0	0	1	NS
IN-OUT	6 Stream A	11	0.02	0	1	NS
	6 Stream B	11	0	0	-	NS
IN-OUT	7 Stream	7	0	0	-	NS
IN-OUT	8 Stream	29	0	0	1	NS

*NS indicates not significant

Table 4. Soil test results from 0-15 cm samples at seven golf courses in Virginia.

#[a]	Site	Mean pH	SD	pH Range	Mean P[b]	SD[c]	P Range[b]	Mean CEC[d]	SD	CEC Range[d]
1	System A	5	0.60	5-6	21	20.79	3-62	6.6	2.05	4.7-11
1	Stream B	6	0.73	5-7	20	21.76	1-64	7.2	1.61	4.3-9.8
3	System A	5	0.54	4-6	5	2.54	3-11	7.3	1.34	5.4-10
3	System B	5	0.54	4-6	9	7.30	2-21	6.5	1.74	3.6-9.1
4	System A	6	0.44	5-6	20	19.34	5-59	5.4	0.67	4.6-6.8
4	Stream B	5	0.51	4-6	19	6.65	5-30	6.2	1.50	4.8-9
4	System C	5	0.48	4-6	16	7.55	7-29	6.9	1.91	4.2-10
5	Stream	5	0.39	4-5	8	5.27	5-17	8.0	1.48	6-9.4
6	Stream A	5	0.33	5-6	8	3.08	4-14	6.0	0.58	4.8-6.8
6	Stream B	6	0.62	5-7	9	8.89	2-31	7.3	1.62	6.1-11.3
7	Stream	5	0.33	4-5	3	1.62	1-6	5.0	0.95	3.7-7.1
8	Stream	8	0.07	8-8	2	1.45	1-5	27.5	0.67	26.7-28.8

[a] Course number
[b] Units mg kg $^{-1}$
[c] Standard deviation
[d] Units meq 100g^{-1}

Table 5. Soil test results from 15-30 cm samples at seven golf courses in Virginia.

#[a]	Site	Mean pH	SD	pH Range	Mean P[b]	SD[c]	P Range[b]	Mean CEC[d]	SD	CEC Range[d]
1	System A	5	0.54	5-6	5	4.90	1-18	6.2	4.68	3.5-19.3
1	Stream B	6	0.65	5-7	6	3.70	2-11	5.3	1.25	3.3-6.9
3	System A	5	0.61	4-6	4	2.28	2-8	5.1	1.39	3.1-7.7
3	System B	5	0.42	4-6	6	4.50	1-13	4.2	1.17	2.6-6.4
4	System A	5	0.34	5-6	14	17.39	3-55	4.8	1.54	3.4-8.3
4	Stream B	5	0.47	4-6	11	4.95	3-19	4.5	1.19	3.5-6.6
4	System C	5	0.32	5-6	13	5.48	4-19	4.1	0.68	2.8-5
5	Stream	5	0.16	4-5	5	1.58	3-7	7.3	0.93	6.1-8.3
6	Stream A	5	0.27	5-6	7	2.95	3-12	4.8	0.25	4.3-5
6	Stream B	6	0.79	5-7	3	1.91	1-6	6.0	1.40	4.9-9.2
7	Stream	5	0.35	5-6	2	0.73	1-3	3.9	1.03	2.6-5.7
8	Stream	8	0.08	8-8	2	1.27	1-5	27.1	1.63	22.9-29

[a] Course number
[b] Units mg kg^{-1}
[c] Standard deviation
[d] Units meq $100g^{-1}$

Table 6. Major soil types and drainage classes at seven golf courses in Virginia determined from USDA Soil Survey maps as compared to soil textures determined by particle size analysis.

#[a]	Site[b]	Major Soil Types at Sample Sites	Class[c]	IN PSA	OUT PSA
1	Syst. A	Monacan Complex Soils Wedowee Fine Sandy Loam Georgeville Fine Sandy Loam	C	Loam Sandy Clay Loam Sandy Clay	Sandy Clay Sandy Clay Loam
1	Strm. B	Monacan Complex Soils Fluvanna Fine Sandy Loams	C	Sandy Clay Sandy Clay Loam	Clay Sandy Clay Loam
3	Syst. A	Pouncey Sandy Loam Loamy Udorthents	D	Sandy Loam	Sandy Loam Clay
3	Syst. B	Colfax Fine Sandy Loam Appling Fine Sandy Loam Pouncey Sandy Loam	B/C	Sandy Loam Sandy Clay Loam	Sandy Loam Loamy Fine Sand
4	Syst. A	Wateree-Wedowee Complex Johnston Mucky Loam Chewacla Loam Udorthents Dumps Complex	B/D	Sandy Loam Sandy Clay Loam Loamy Fine Sand	Sandy Loam Loamy Fine Sand
4	Strm. B	Wateree-Wedowee Complex Udorthents Dumps Complex Chewacla Loam	B	Sandy Loam	Sandy Loam Loamy Fine Sand
4	Syst. C	Wateree-Wedowee Complex Chewacla Loam Turbeville-Urban Land Complex	B/C	Loamy Fine Sand	Sandy Loam
5	Strm.	Appling Fine Sandy Loam Chewacla Silt Loam	C	Clay Loam	Silty Clay Loam
6	Strm. A	Chewacla Silt Loam Riverview Loam Wahee Silt Loam	C	Loam Silt Loam	Sandy Loam
6	Strm. B	Chewacla Silt Loam Riverview Loam	C	Sandy Clay Loam	Loam
7	Strm.	Forestdale Silty Loam Toccoa Silt Loam	D	Sandy Clay Loam	Sandy Loam Fine Sand
8	Strm.	Ross Soils Weaver Soils Wumo-Caneyville Complex	B	Sandy Clay Loam	Sandy Clay Loam Sandy Loam

[a] Course Number
[b] Syst. = System, Strm. = Stream
[c] Dominant Drainage Class

Table 7. Areas of seven golf course sites in Virginia, watershed segment areas, and land use percentages associated with the watershed segment as estimated by the Chesapeake Bay Watershed Model.

Site	Area (ha)*	Watershed Area (ha)	Agriculture (%)	Developed (%)	Forested (%)	Water (%)
Course 1 OUT A	97.5	912.1	9.8	41.7	44.1	4.3
Course 1 OUT B	42.7	113.7	11.1	34.9	53.9	0.0
Course 3 OUT A	53.4	234.7	12.4	53.8	33.8	0.0
Course 3 OUT B	4.2	25.7	19.2	47.6	33.2	0.0
Course 3 Pad	15.3	15.3	14.8	80.5	4.7	0.0
Course 4 OUT A	35.0	47.1	14.1	74.6	11.1	0.2
Course 4 OUT B	3.6	9.9	4.5	54.4	41.1	0.0
Course 4 OUT C	3.2	26.6	0.3	48.7	51.0	0.0
Course 5 OUT	89.8	16029.8	14.3	44.5	40.4	0.8
Course 6 OUT A	34.7	34.7	25.7	53.2	20.8	0.3
Course 6 OUT B	163.9	1494.8	23.9	21.0	54.7	0.4
Course 7 OUT	136.4	5656.6	18.1	4.3	75.7	1.9
Course 8 IN	3.5	11727.6	22.7	5.7	71.6	0.0
Course 8 OUT	80.7	12025.5	22.9	6.3	70.8	0.0

*Golf course area within the total watershed

Table 8. Unit-area loads (kg N ha^{-1} yr^{-1}) for five Chesapeake Bay golf courses as compared to unit-area loads for different land uses as simulated in the corresponding watershed area by the Chesapeake Bay Watershed Model.

	GC/WS[b]	GC as WS[c]	Pasture	Pervious Urban	Forested	Hay w/o Manure
	UAL N	%	UAL N	UAL N	UAL N	UAL N
#1[a] OUT A	1.5	10.7	8.4	9.6	3.2	3.7
#1 OUT B	1.6	37.6	8.4	9.6	3.2	3.7
#3 OUT A	12.5	22.8	6.4	9.8	3.6	4
#3 OUT B	3.5	16.2	6.4	9.8	3.6	4
#3 PAD	13	100	6.4	9.8	3.6	4
#4 OUT A	9.8	74.4	N/A	N/A	4.2	N/A
#4 OUT B	86.9	36.5	N/A	N/A	4.2	N/A
#4 OUT C	24.4	12.1	N/A	N/A	4.2	N/A
#6 OUT A	1.5	100	7.845	10.7	2.9	3.7
#6 OUT B	3.1	11	7.8	10.7	2.9	3.7
#7 OUT	1.3	2.4	5.6	10.7	3.2	3.6

[a]Course number
[b]Golf Course Load/Watershed Area
[c]Percentage of golf course area in the watershed segment

Table 9. Unit-area loads (kg N ha^{-1} yr^{-1}) for the Roanoke River watershed golf course drainage sites as compared to unit-area loads for different land uses as simulated in the corresponding watershed areas by the Chesapeake Bay Watershed Model.

	GC/WS[b]	GC as WS[c]	Pasture	Pervious Urban	Forested	Hay w/o Manure
	UAL N	%	UAL N	UAL N	UAL N	UAL N
#8[a] IN	1.5	0	5.9-6.8	9.6-10.4	2.8-3.1	3.4-3.7
#8 OUT	1.6	0.7	5.9	9.6	3.1	3.4

[a]Course number
[b]Golf Course Load/Watershed Area
[c]Percentage of golf course area in the watershed segment

Table 10. Stream nutrient (Nitrate-N, Ammonium-N, and Phosphate-P) concentration correlations with fertilizer applications for seven golf courses Virginia. Greens, tees, fairways, roughs included except where noted.

	Nitrate-N r[1]	Ammonium-N r	Phosphate-P r	Notes
Course 1 OUT A	0.30	0.12	N/A	No stream P detected
Course 1 OUT B	0.35	0.37	N/A	No stream P detected
Course 3 OUT A	0.01	0.30	0.19	P applied to Greens & Tees Only
Course 3 OUT B	0.30	0.22	0.06	P applied to Greens & Tees Only
Course 3 Pad	0.02	0.45*	0.07	P applied to Greens & Tees Only
Course 4 OUT A	0.57*	0.01	0.20	P applied to Greens Only
Course 4 OUT B	0.02	0.18	0.33	P applied to Greens Only
Course 4 OUT C	0.35	0.23	0.21	P applied to Greens Only
Course 5 OUT	0.09	0.12	N/A	No stream P detected
Course 6 OUT A	0.38	0.15	N/A	No stream P detected
Course 6 OUT B	0.15	0.27	N/A	No stream P detected
Course 7 OUT	0.55	0.32	N/A	No stream P detected
Course 8 OUT	0.33	0.02	N/A	Only one stream P detection

*Significance at $p = 0.05$.
[1]Pearson correlation coefficient.

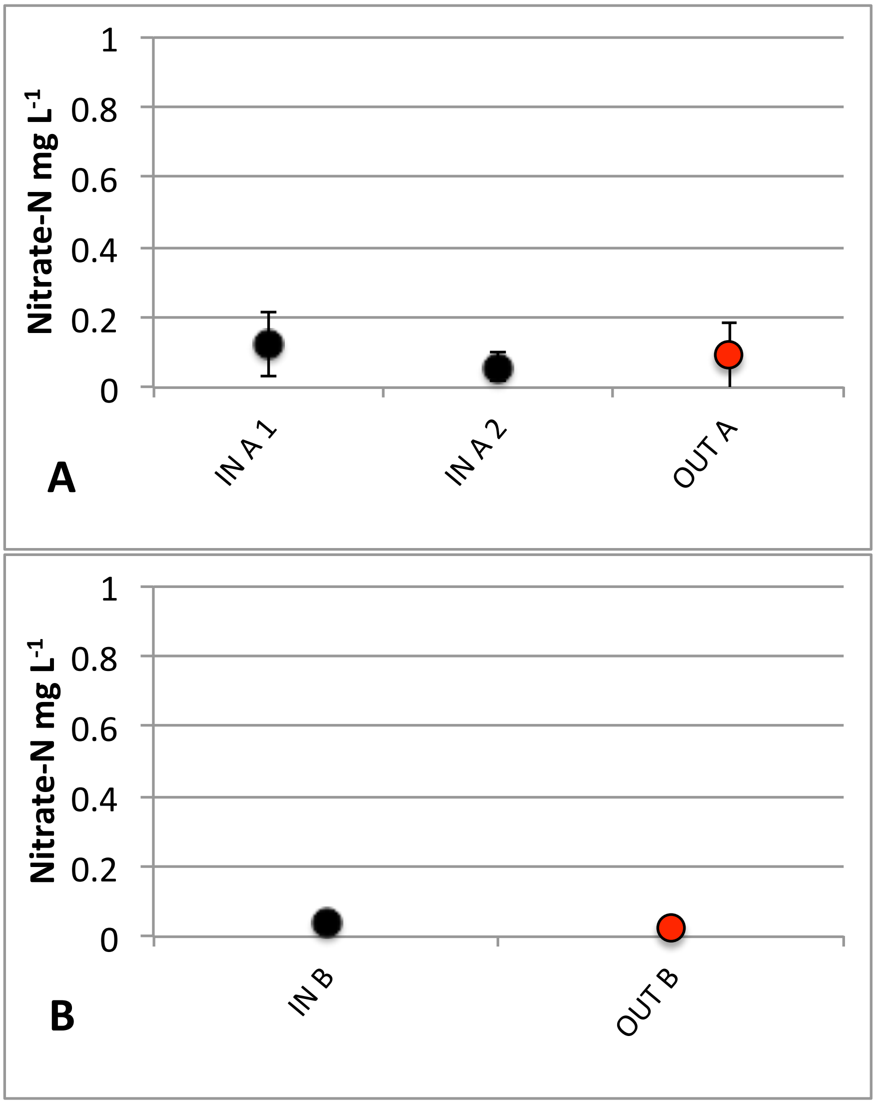

Figure 1. Mean nitrate-N concentrations over all samples from System A (A; n = 15) and Stream B (B; n = 6) of Course 1. Error bars represent standard deviation.

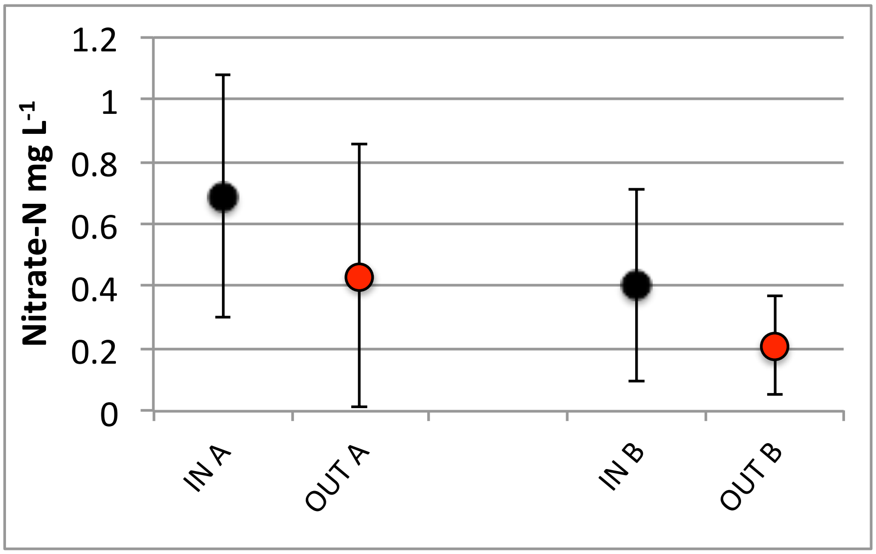

Figure 2. Mean nitrate-N concentrations over all samples for Stream A and Stream B of Course 2 (n = 7 for each site). Error bars represent standard deviation.

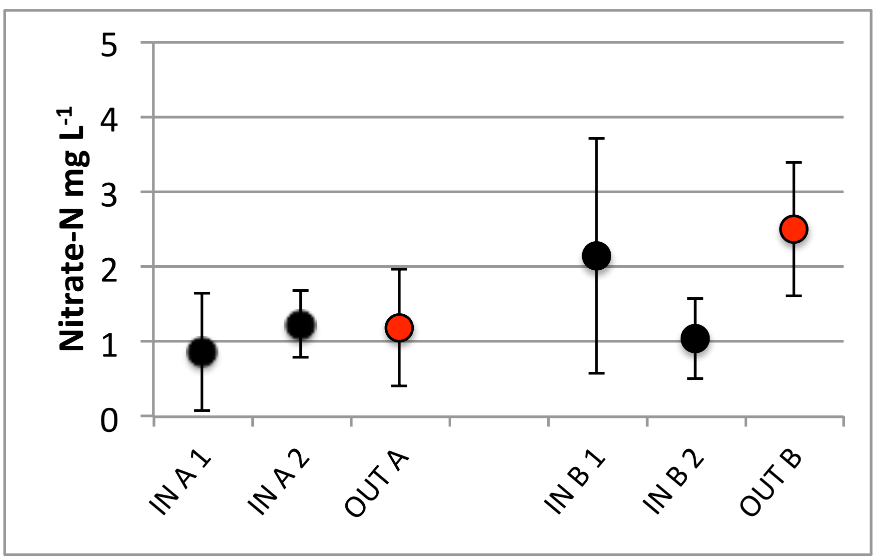

Figure 3. Mean nitrate-N concentrations over all samples from stream System A and System B of Course 3 (n = 31 for all sites). Error bars represent standard deviation.

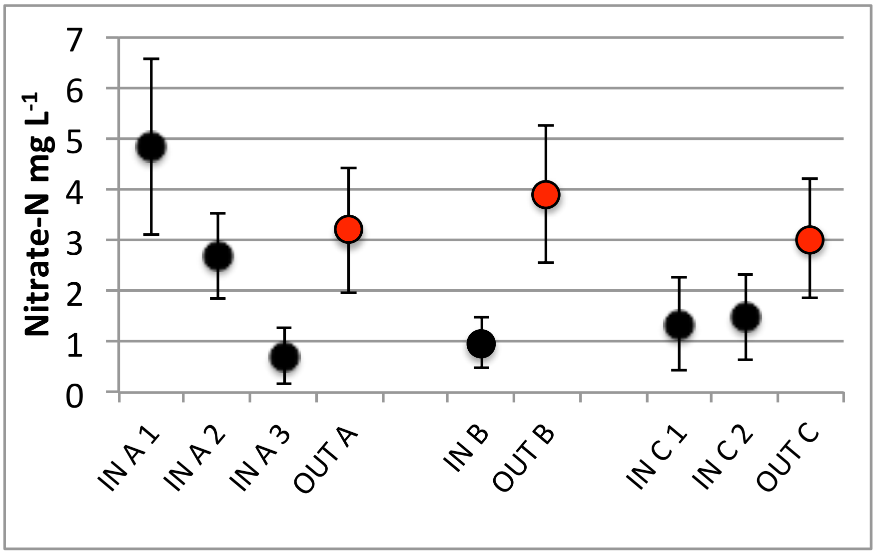

Figure 4. Mean nitrate-N concentrations over all samples from stream System A, Stream B, and System C on Course 4 (n = 15 for all sites). Error bars represent standard deviation.

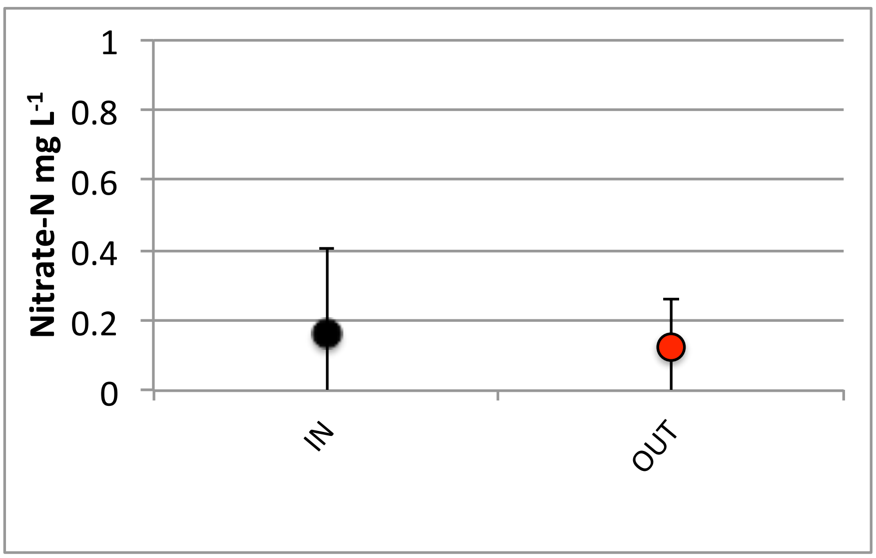

Figure 5. Mean nitrate-N concentrations over all samples from the inflow and outflow locations on Course 5 (n = 15). Error bars represent standard deviation.

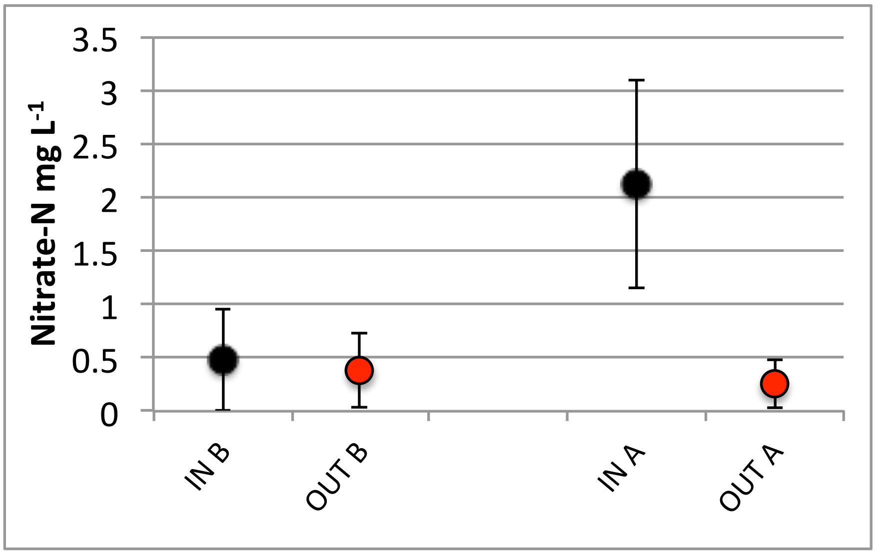

Figure 6. Mean nitrate-N concentrations over all samples from the inflow and outflow locations on Course 6 (n = 11 for all sites). Error bars represent standard deviation.

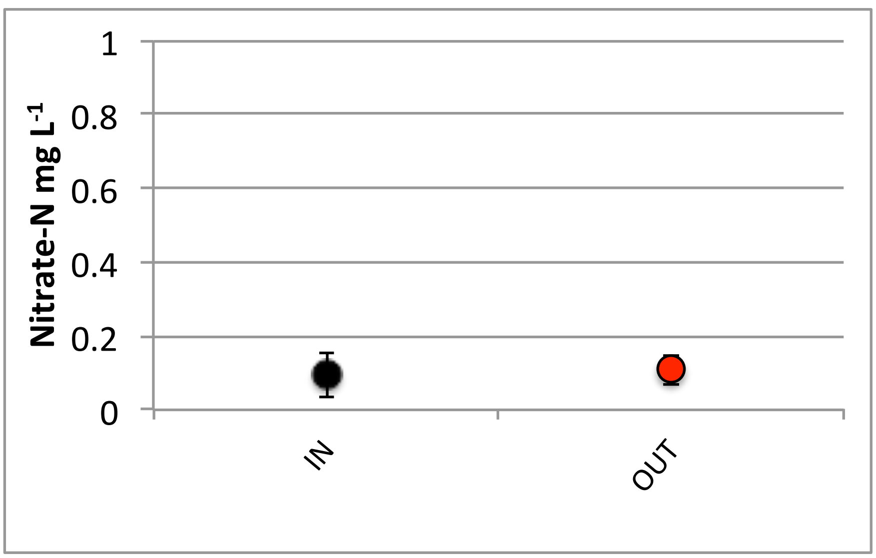

Figure 7. Mean nitrate-N concentrations over all samples from the inflow and outflow locations on Course 7 (n = 7). Error bars represent standard deviation.

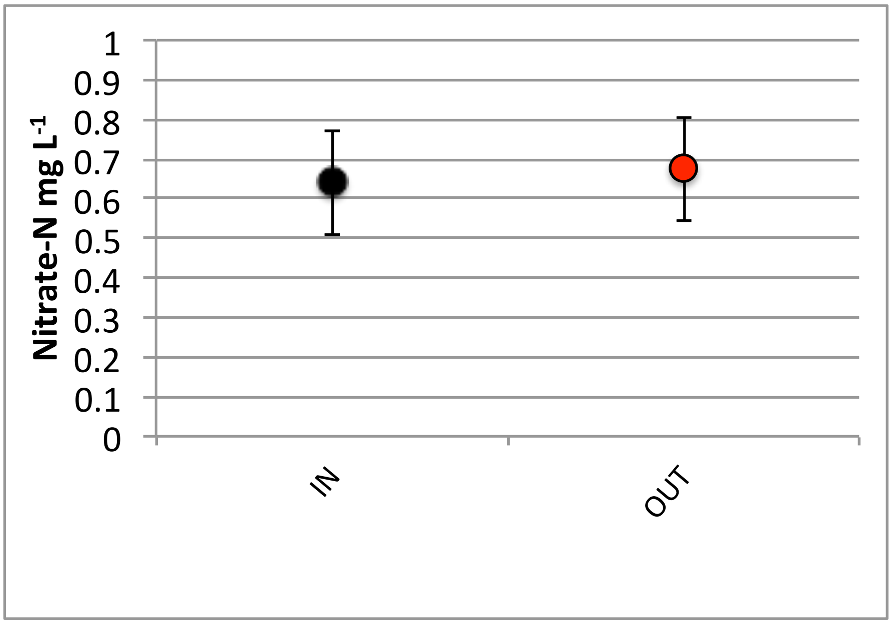

Figure 8. Mean nitrate-N concentrations over all samples from the inflow and outflow locations on Course 8 (n = 29). Error bars represent standard deviation.

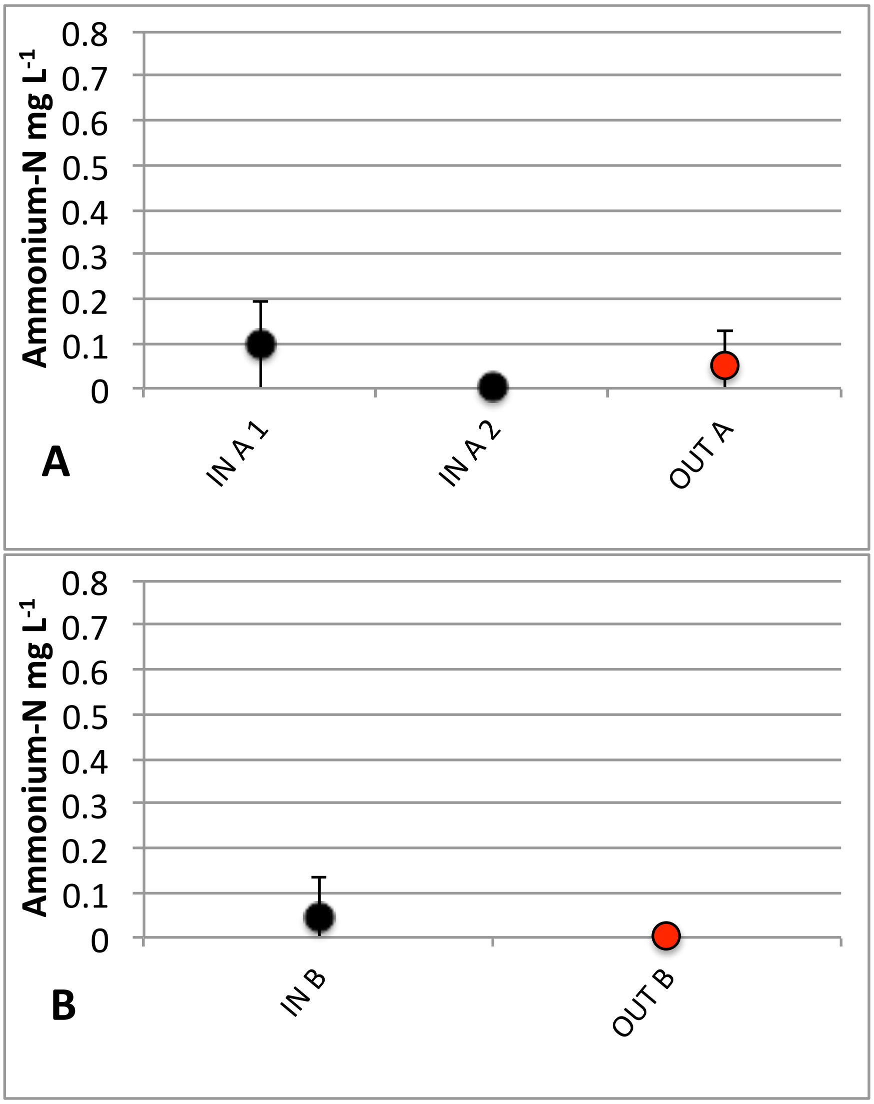

Figure 9. Mean ammonium-N concentrations over all samples from System A (A; n = 15) and Stream B (B; n = 6) of Course 1. Error bars represent standard deviation.

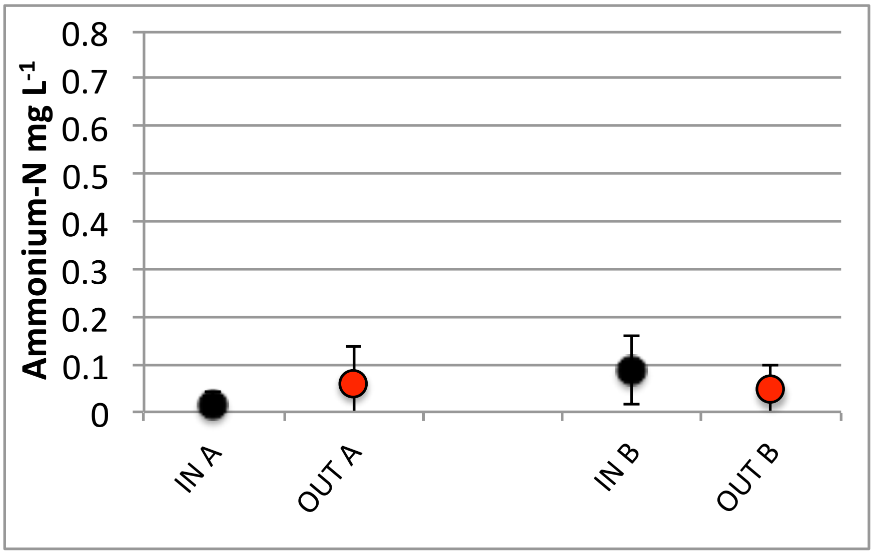

Figure 10. Mean ammonium-N concentrations over all samples for Stream A and Stream B of Course 2 (n = 7 for each site). Error bars represent standard deviation.

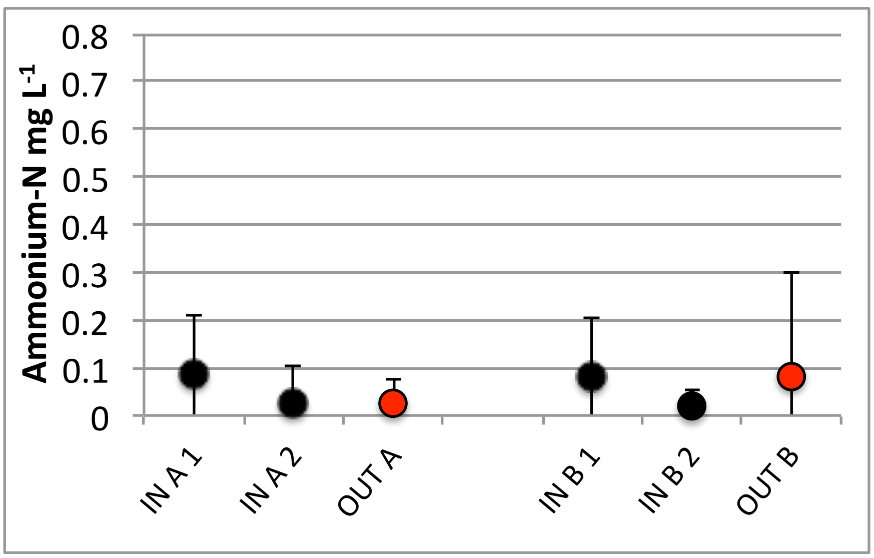

Figure 11. Mean ammonium-N concentrations over all samples from stream System A and System B of Course 3 (n = 31 for all sites). Error bars represent standard deviation.

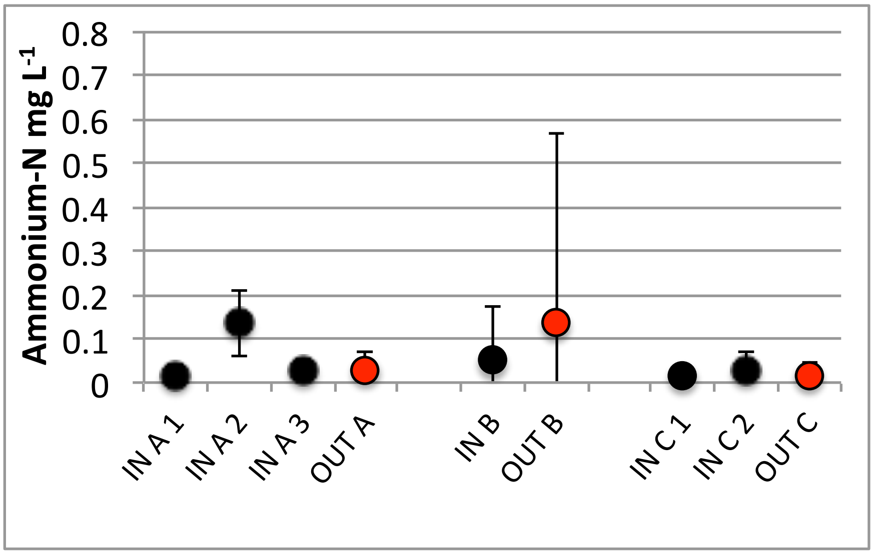

Figure 12. Mean ammonium-N concentrations over all samples from stream System A, Stream B, and System C on Course 4 (n = 15 for all sites). Error bars represent standard deviation.

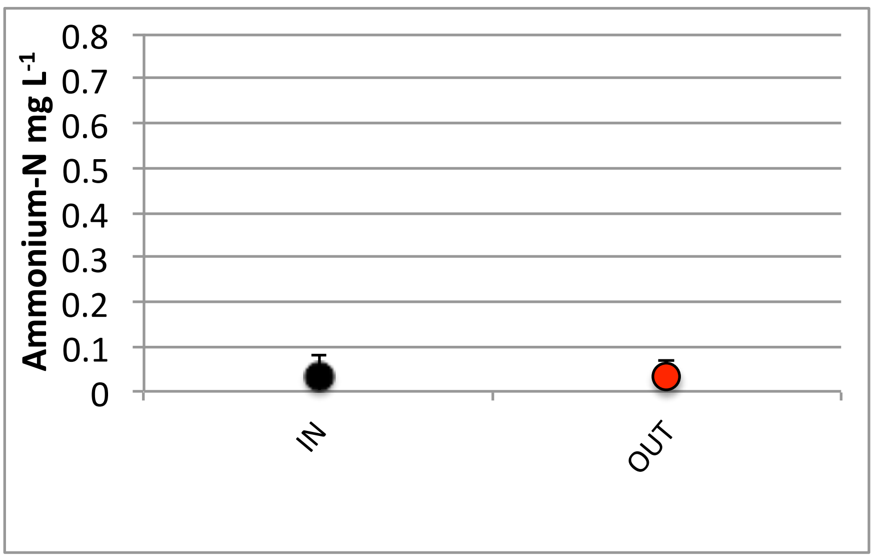

Figure 13. Mean ammonium-N concentrations over all samples from the inflow and outflow locations on Course 5 (n = 15). Error bars represent standard deviation.

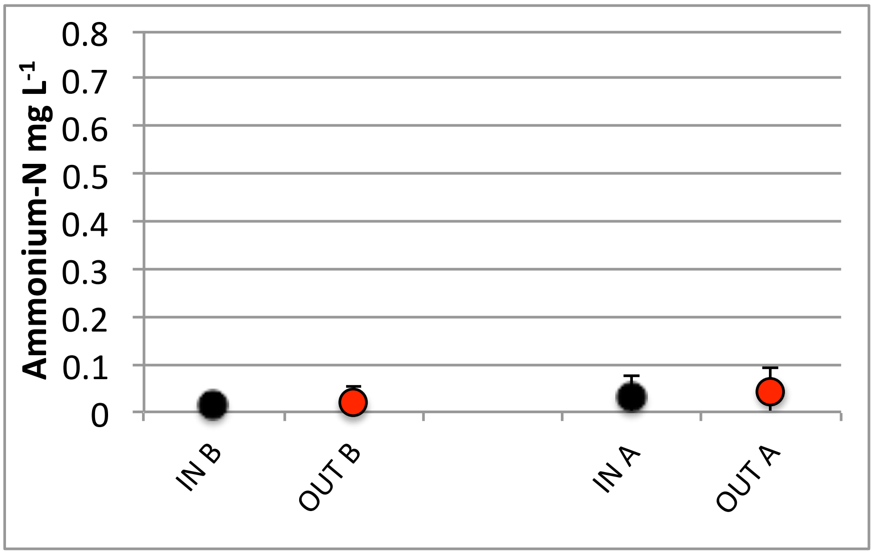

Figure 14. Mean ammonium-N concentrations over all samples from the inflow and outflow locations on Course 6 (n = 11 for all sites). Error bars represent standard deviation.

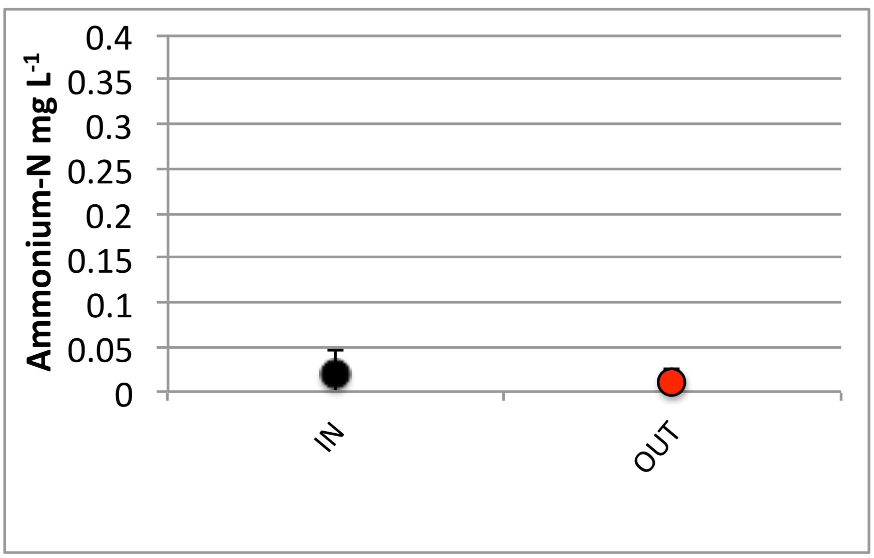

Figure 15. Mean ammonium-N concentrations over all samples from the inflow and outflow locations on Course 7 (n = 7). Error bars represent standard deviation.

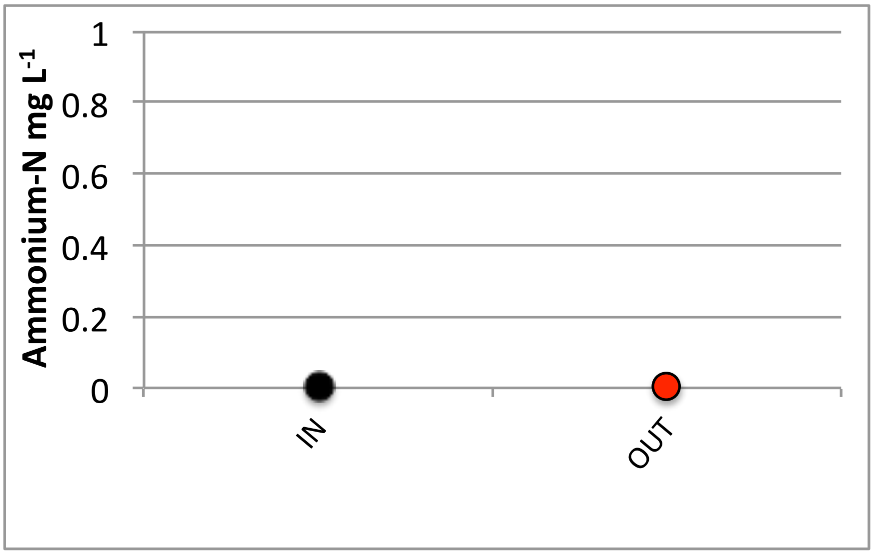

Figure 16. Mean ammonium-N concentrations over all samples from the inflow and outflow location on Course 8 (n = 29).

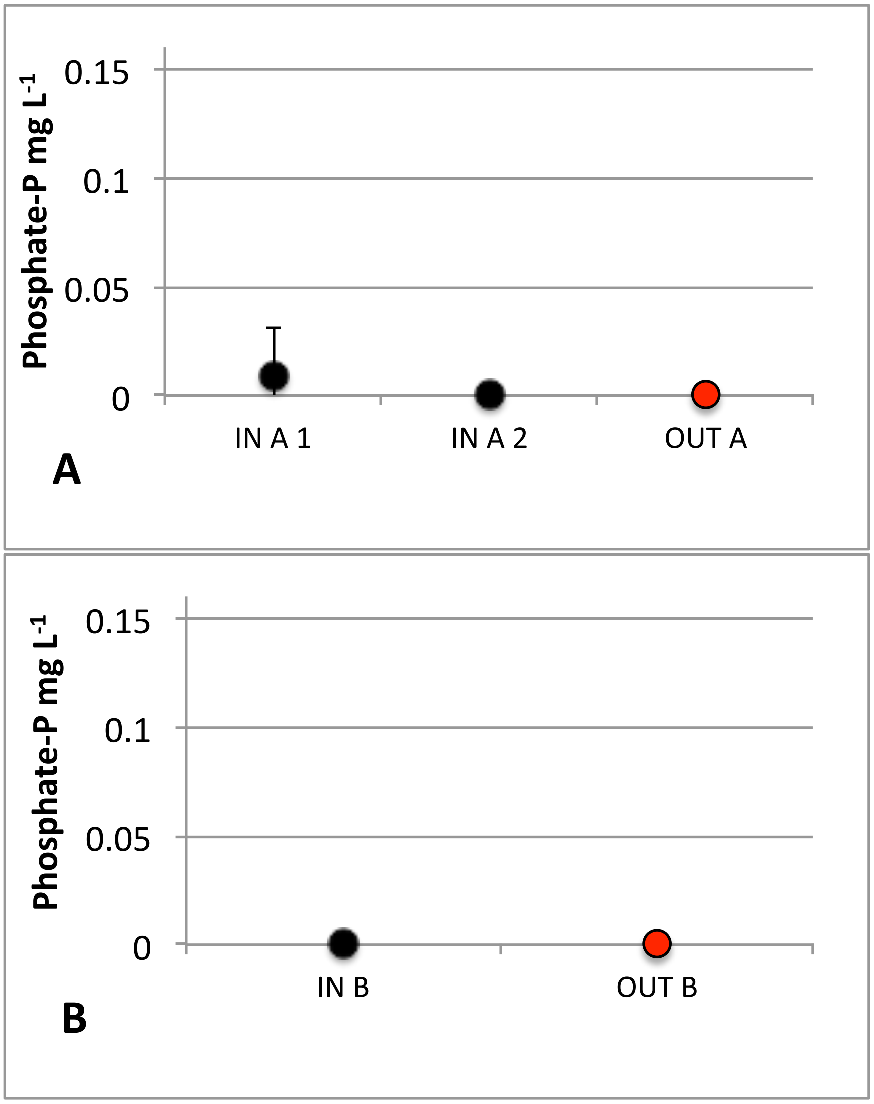

Figure 17. Mean phosphate-P concentrations over all samples from System A (A; n = 15) and Stream B (B; n = 6) of Course 1. Error bars represent standard deviation.

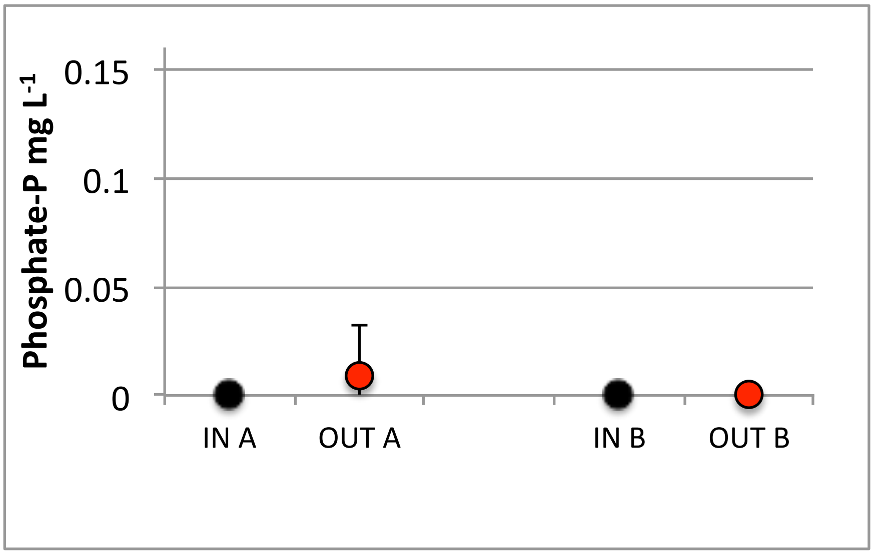

Figure 18. Mean phosphate-P concentrations over all samples for Stream A and Stream B of Course 2 (n = 7 for each site). Error bars represent standard deviation.

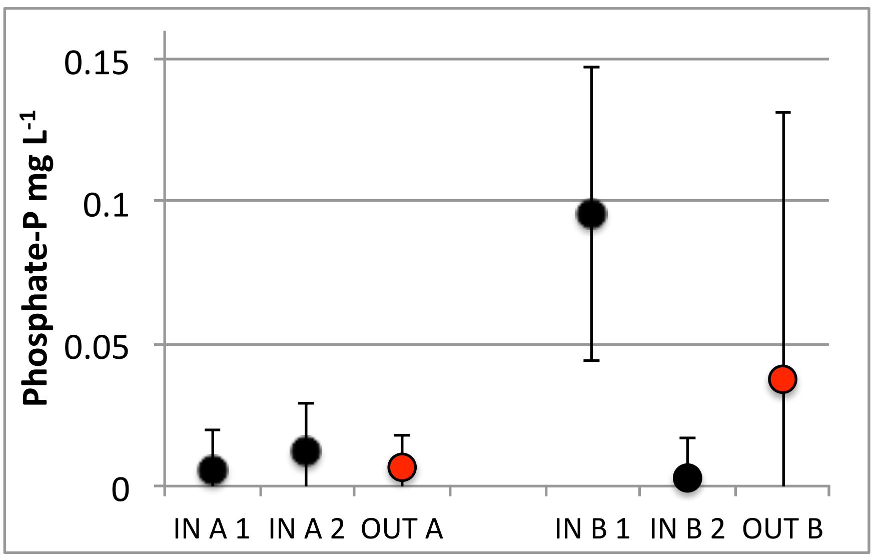

Figure 19. Mean phosphate-P concentrations over all samples from stream System A and System B of Course 3 (n = 31 for all sites). Error bars represent standard deviation.

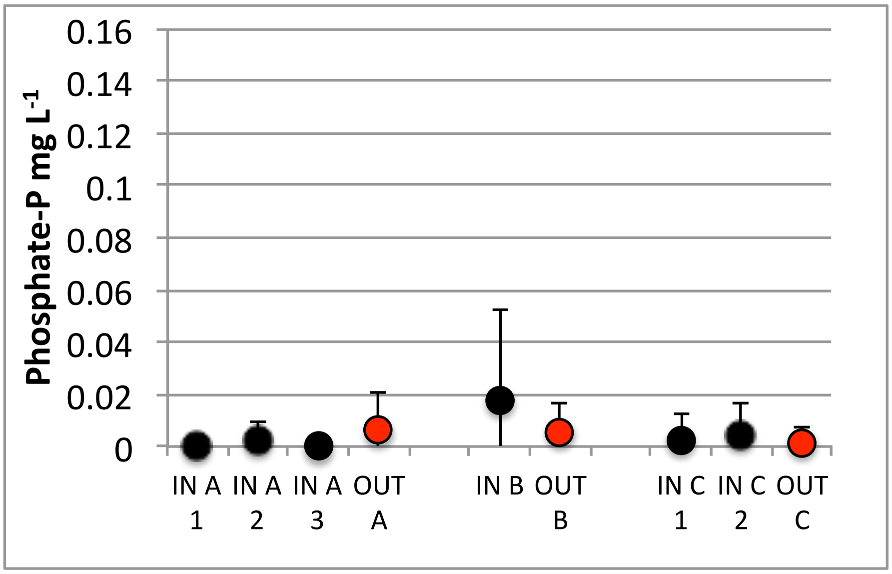

Figure 20. Mean phosphate-P concentrations over all samples from stream System A, Stream B, and System C on Course 4 (n = 15 for all sites). Error bars represent standard deviation.

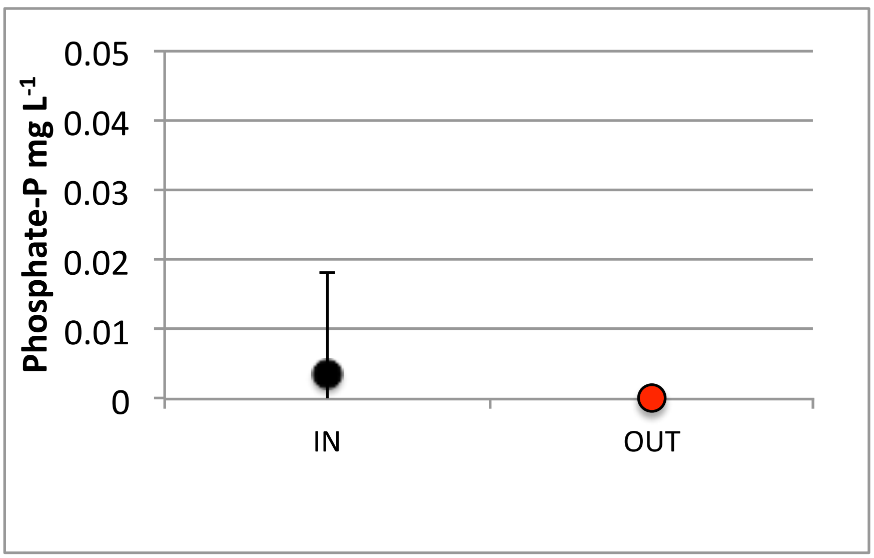

Figure 21. Mean phosphate-P concentrations over all samples from the inflow and outflow locations on Course 5 (n = 15). Error bars represent standard deviation.

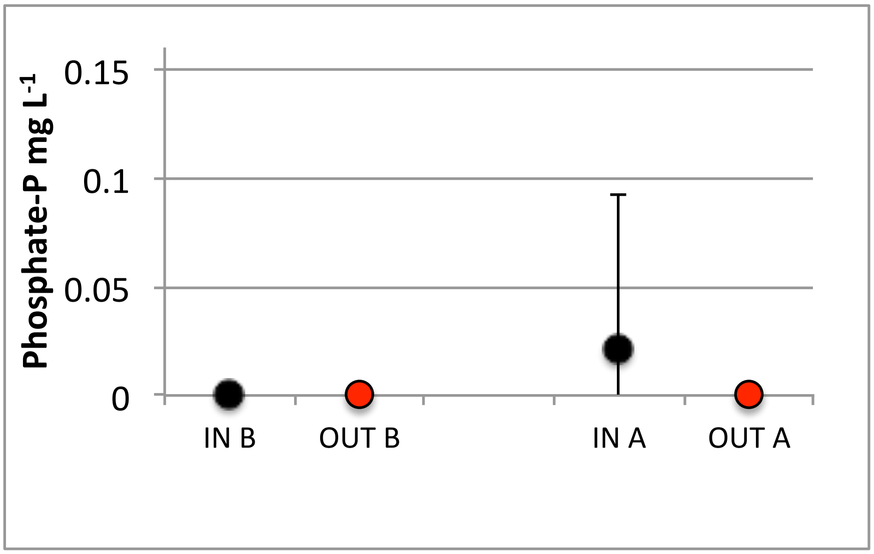

Figure 22. Mean phosphate-P concentrations over all samples from the inflow and outflow locations on Course 6 (n = 11 for all sites). Error bars represent standard deviation.

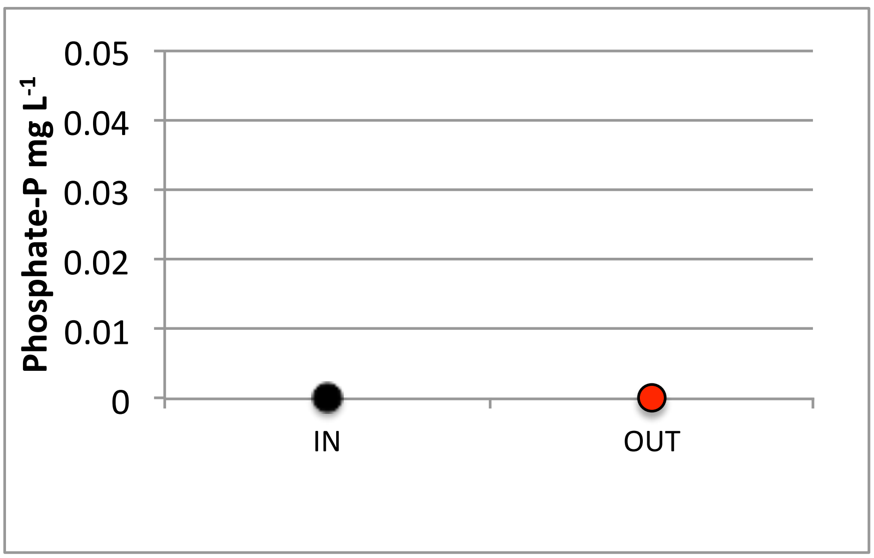

Figure 23. Mean phosphate-P concentrations over all samples from the inflow and outflow locations on Course 7 (n = 7 for all sites).

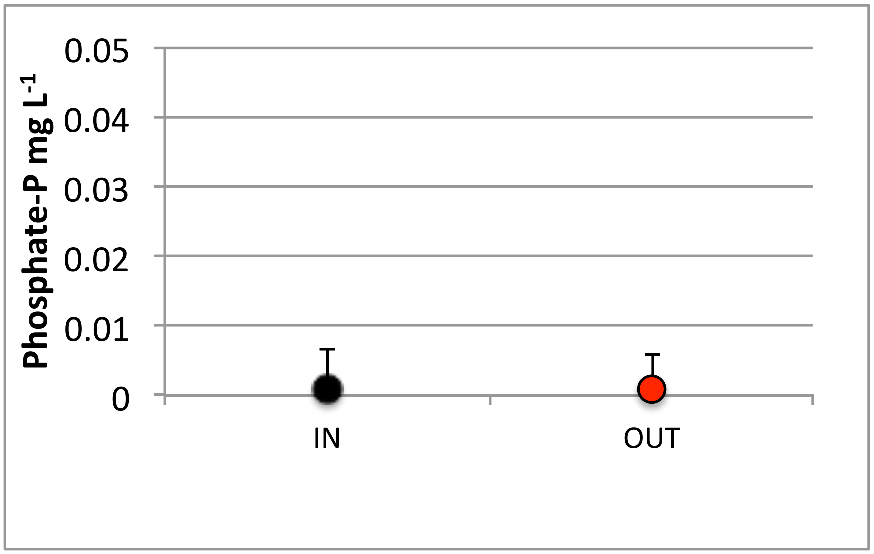

Figure 24. Mean phosphate-P concentrations over all samples from the inflow and outflow location on Course 8 (n = 29). Error bars represent standard deviation.

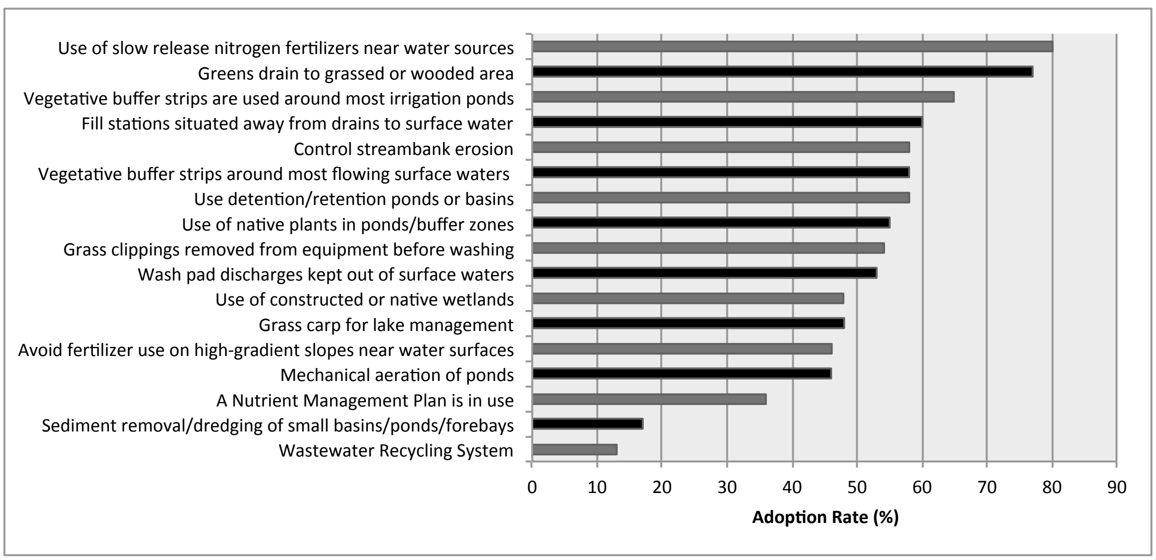

Figure 25. Adoption rate of selected water quality protection BMPs on Virginia golf courses.

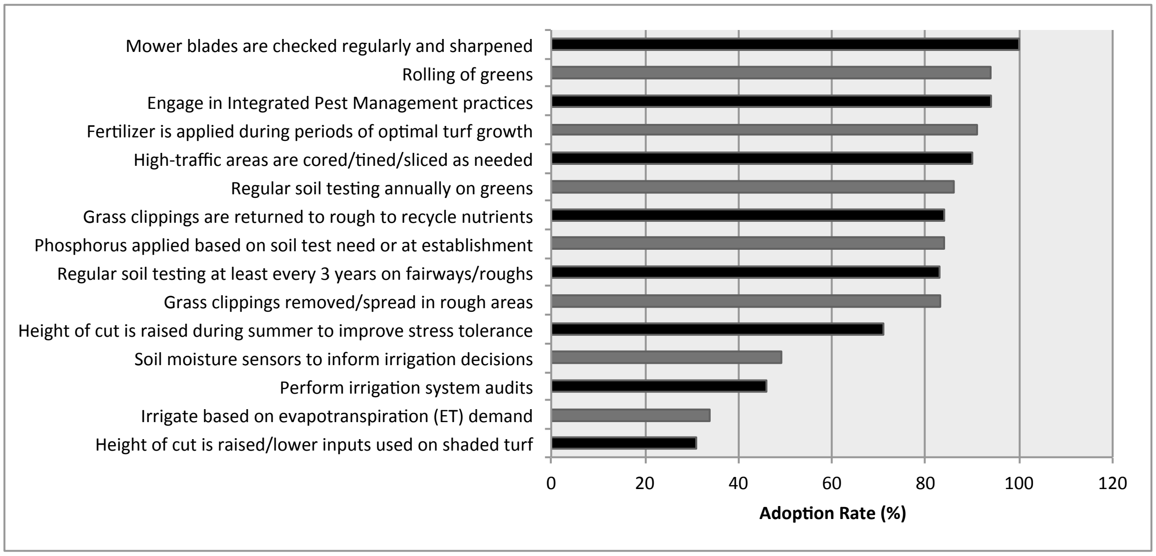

Figure 26. Adoption rate of selected turfgrass BMPs influencing water quality on Virginia golf courses.

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CHAPTER FOUR: DISCUSSION AND CONCLUSIONS

Indicators, Nitrate-N, Ammonium-N and Phosphate-P

Golf course management in the Chesapeake Bay Watershed and the Roanoke River Watershed investigated in this study generally does not appear to be having a significant negative impact on the water quality of local streams within the timeframe of this study. Sustained impairment trends for temperature, pH, DO, and SpC were not observed at any of the golf course sites, although deviations outside of the acceptable criteria range did occasionally occur. Low DO concentrations in the summer and fall at some sites may have been influenced by extremely low flows, high temperatures, or the presence of decomposing leaves in the stream. However, higher DO concentrations were often observed at the outflow locations as compared to the inflow locations, most notably on Course 1, 4, and 7. Some of the higher DO concentrations at outflow locations can be attributed to differences in stream morphology (slope, baseflow velocity, water volume). For example, the inflow at Course 7 was very slow moving and swampy compared to the higher-gradient, rocky outflow allowing for more mixing and oxygenation.

The majority of fertilizer correlation analyses comparing the total kg of fertilizer applied on the golf course with stream nitrate-N and ammonium-N concentrations did not reveal any significant correlations. When a correlation was found in two instances, correlation coefficients were very low. In other studies, it has been found that fertilizer N losses in leaching and runoff are generally very low from established turfgrass sites, especially on heavier-textured soils and when slow-release fertilizer sources are used

(Gross et al., 1990; Linde and Watschke, 1997; Petrovic, 2004; Erickson et al., 2008; Spence et al., 2012; Stier et al., 2013). The low losses may be caused by rapid uptake by turfgrass, absorption by soil microorganisms, and/or denitrification processes (Hull and Liu, 2005; Young and Briggs, 2007; Stier et al., 2013). These reasons, coupled with nutrient attenuation processes such as assimilation and denitrification occurring in the streams or wetland areas, could explain the lack of correlations observed between fertilizer N and stream N concentrations in this study (Allan and Castillo, 2007).

No significant correlations between the amount of phosphorus fertilizer applied and in-stream phosphate-P were found. In many cases, phosphorus was not applied to the majority of the golf course area or was applied at low rates. Movement of phosphorus is not expected during baseflow conditions and in-stream phosphorus likely would be from other sources such as soil from eroding stream banks (Allan and Castillo, 2007). Soil sampling was the primary method to investigate if the soil was a potentially significant source of phosphorus in-stream. However, soil sample sites along the stream that tested high in phosphorus did not translate to high concentrations of phosphate downstream. Water phosphate-P was not detected at most outflow locations, regardless of the soil phosphorus status in areas sampled along the stream corridors. A specific example includes Course 1. Course 1 had a few sites that tested very high for soil extractable phosphorus. However, no phosphate-P was detected at either outflow location. Previous research by Soldat et al. (2009) suggested that testing for soil phosphorus levels is not an accurate way to predict runoff from turfgrass areas. Also, phosphate-P is often attached to soil particles and relatively immobile. Movement should not occur as readily in baseflow conditions as opposed to stormflow conditions when erosion and runoff potential are higher (Allan and Castillo, 2007). In a review by Soldat and Petrovic (2008), they summarize that leaching is generally more of a concern on coarse-textured soils/those with a low P sorption capacity, or when phosphorus is applied at high rates (especially before a storm). These conditions were generally not present on the sites studied.

In some cases, the USDA soil survey data suggested that the drainage classes might be different than those suggested by our PSAs. The PSA of soils would only be appropriate for the IN and OUT locations characterized, and may only represent the site conditions in the immediate area of the sampling. USDA soil survey maps are presented at a larger scale and may not accurately reflect microsite conditions. Use of PSA may be useful to determine the actual texture of soils along the golf course streams, but the USDA soils maps are useful to determine the general site conditions of the native soils. The PSA and USDA soil survey data generally agree and suggest that the soil textures are generally not coarse and should not pose as high of a risk for nutrient leaching. The soil sampling data from the courses also indicate that most sites are moderate or high in CEC for Virginia soils. Very sandy soils with a CEC 1-3 meq $100g^{-1}$ are expected to have a reduced ability to hold nutrients, and are at a higher risk for leaching (Maguire and Heckendorn, 2010). Soils with a high pH can produce “erroneously high” CEC soil test values, and this may explain why CEC values were high and outside of the normal range of Virginia soils at Course 8 (Maguire and Heckendorn, 2010).

With respect to the data including the sites with a single IN-OUT location or those with averaged inflow locations, there were no significant differences between inflow and outflow locations for nitrate-N at eight of the 14 tested sites. There was a reduction in nitrate-N at two sites, and an increase of nitrate-N at four of the 14 tested sites. When considering the averaged inflow locations and those sites with only a single IN and OUT, 12 of the 14 tested sites had no significant differences between inflow and outflow locations for ammonium-N. There were reductions of ammonium-N between the inflow and outflow locations at two sites. According to the analysis considering streams with a single IN-OUT or those with averaged inflow locations, there were no significant differences between inflow and outflow locations for phosphate-P at any of the 14 sites tested. In the cases where systems had multiple inflow locations, it is important to point out that it was possible for a high amount of nutrients to be contributed by a single inflow location that may not be reflected in the analysis of differences. A single inflow location could have a high concentration of nutrients with low discharge, or a higher amount of discharge with a low nutrient concentration. Reduction in nutrients may be explained by the presence of riparian vegetation or the turfgrass may be serving as a BMP in urban areas by removing nutrients. Turfgrass buffer strips have been found to reduce drainage water volumes and to reduce nutrient concentrations of runoff from impervious surfaces. Furthermore, these turfgrass buffer strips perform on a level similar to that of mixed forb/grass prairie buffer strips (Steinke et al., 2009).

The sites that had an increased amount of nitrate-N between the inflow and outflow locations had concentrations that were always below the EPA drinking water limit of 10 mg L^{-1} (USEPA, 1986). No water quality standards exist in the state of Virginia for stream nitrate-N, although < 1 mg L^{-1} is considered "good", while 1-10 mg L^{-1} is considered "fair" water quality in Kansas State University Citizen Science Water Quality Testing Series document (Janke et al., 2006). Eutrophication can occur at concentrations much less than 10 mg N L^{-1} in the right conditions, but each stream site will differ in its ability to attenuate nutrients and avoid the effects of eutrophication (Smith et al., 1999). Mean nitrate-N concentrations were higher than the 2 mg L^{-1} total N value estimated to pose a risk to benthic organisms at some of the inflow and outflow locations on Courses 3 and 4 (VADEQ, 2014). The mean concentrations of nitrate-N at these and other locations were 2.50 mg L^{-1} at Course 3 OUT B (2.14 and 1.05 mg L^{-1} at the inflow locations), 3.90 at Course 4 OUT B (0.97 mg L^{-1} at the inflow location), 3.03 mg L^{-1} at Course 4 OUT C (1.35 and 1.47 mg L^{-1} at the inflow locations), and 0.68 mg L^{-1} at the Course 8 OUT (0.64 mg L^{-1} at the inflow location). Nitrate contributions may be either attributable to lower levels of golf course management, location in high-risk areas for nutrient runoff/leaching from urban areas (especially Course 4), or the presence of a wastewater treatment plant on site (Course 8). Sites with at least one inflow with mean nitrate-N concentrations above the total N screening value of 2 mg L^{-1} include Course 3 System B, Course 4 System A, and Course 6 System A. This suggests that there may be a pre-existing risk to benthic macroinvertebrate populations regardless of the influence of golf course turfgrass cultural and environmental management. Otherwise, concentrations of nitrate were generally low and should not pose a significant threat to local water quality on most golf course sites. Individual streams would need to be studied in order to make a clear judgment as to whether or not current nutrient concentrations are sufficient to cause local eutrophication and benthic impairment.

A technical bulletin report from the Virginia Department of Environmental Quality suggests that the screening value for nitrate-N should be 1.5 mg L^{-1} for streams in the montane ecoregions of the state (VADEQ, 2004). Above this value, probabilistic monitoring reveals correlations with impaired benthic macroinvertebrate statuses of streams. Course 8 was located within a montane ecoregion of Virginia. Nitrate-N did not exceed the suggested 1.5 mg L^{-1} screening value for the duration of the study at Course 8. This implies that nitrate-N concentrations found at the Course 8 outflow location would not be threatening to aquatic biota. It is also important to revisit the concept of lag time that applied to this study. No apparent differences in nitrate-N or phosphate-P concentrations were detected as a result of stream restoration activities at Course 8. It can take several years for noticeable in-stream reductions of nutrients as a result of BMP installation (Meals et al., 2010). It is possible that water quality changes were not detected at this site due to the relatively short amount of time elapsed following BMP implementation and within the timeframe for water quality testing during this study.

Nutrient Loads: Total N

Because nutrients may travel downstream into sensitive waters such as the Chesapeake Bay, it was important to determine the loads coming from the discharge locations at the golf courses. It was not possible to take discharges at many of the inflow locations, so the nutrient load was calculated including the entire upstream watershed draining to the outflow point on the golf course (UALs). It was not possible to pinpoint changes in loading as directly attributable to the golf course. However, it was possible to compare the loads calculated from golf course monitoring data to loads estimated from other land uses in the Chesapeake Bay Watershed Model, to compare to literature values, and then to infer changes based on the differences seen in nitrate-N and ammonium-N (USEPA, 2010). Of the 12 outflow locations for which unit-area loads (UALs) were calculated, seven had UALs less than or similar to those generated from forested areas as estimated by the Chesapeake Bay Watershed Model (USEPA, 2010). Nutrient loads associated with other golf courses have been reported in the literature. These include 13.5 kg ha^{-1} yr^{-1} total N for continuous monitoring of a course in Japan and approximately 4.7 kg ha^{-1} yr^{-1} nitrate + nitrite-N during baseflow conditions for a course in Austin, TX (Kunimatsu, et al., 1999; King et al., 2001). Seven of 12 sites had total N UALs lower than the nitrate + nitrite-N load reported for the Texas course, and 10 of 12 sites had total N UALs lower than the total N UAL reported for the Japan course. Significant increases in nitrate-N suggest that some inputs may be occurring on some of the golf course sites, although it is difficult to determine what the source is, given that there are housing/developed areas adjacent to some streams, there were generally no correlations between water quality and fertilizer applications, and stream nutrient concentrations may be influenced by lag time from previous land use. Furthermore, Course 8 was likely influenced by presence of a wastewater treatment plant on site between the inflow and outflow locations sampled. This is likely an important source of N in the stream. Even with the influence of the wastewater treatment plant, the UALs associated with the discharge point are still less than half of those expected from forest, and are very similar to the UAL from the inflow location.

Most of the courses in this study have a NMP. Courses 3, 4, and 5 did not have these plans during the study. Two of these courses may have had a higher risk for impaired water quality to begin with, since they are present in urban/developed areas (Course 4 more so than Course 3). It is also possible that the risk for nutrient loading may be higher on courses without NMPs, although this risk will be minimized in the near future because all golf courses will be required to have a NMP in the Commonwealth of Virginia by 2017.

Virginia Golf Course Management

Based on the results gathered from the golf course superintendent survey, respondents appear to be environmentally focused and are voluntarily using several different types of BMPs to grow high-quality turfgrass stands while protecting water resources. Twenty-one out of 32 of the selected golf course BMPs suggested in the Environmental Practices for Virginia's Golf Courses manual (VGCSA, 2012) and presented in the survey had an adoption rate of 50% or greater. Most golf course superintendents use slow-release nitrogen fertilizers near water sources, greens draining to grassed/wooded areas, control streambank erosion, and use vegetative buffer strips around surface waters as direct measures to protect water quality. The majority of superintendents also use cultural management of turfgrasses to indirectly protect water quality such as use of integrated pest management, applying fertilizers during periods of optimal growth, and regular soil testing to determine phosphorus needs. The courses monitored as part of this research used a combination of the water quality and turfgrass BMPs mentioned above, but it is unclear which of those measures were most important for water quality protection.

Many Virginia golf courses are certified or are planning to become certified members of the Audubon Cooperative Sanctuary Program for Golf. Data from the eight golf courses in this study suggest that courses participating in the program (Course 1, 2, 5, 7) may have better water quality than those that do not. These types of programs not only serve to protect the environment on golf courses, but provide a public service by educating membership on environmental stewardship. Audubon International has reported several benefits recognized by member courses, including improvements in chemical use reduction, wildlife habitat availability, decreased water consumption, increased water quality monitoring efforts, better financial performance, and increased golfer satisfaction (Audubon International, 2009). Course participation in the Audubon Cooperative Sanctuary Program for Golf and use of NMPs may have been associated with improvements in water quality relative to those not participating. Thirty percent of survey respondents were members of the Audubon program and 36% had a NMP in use. More golf courses in Virginia may have increased water quality protection as suggested by the data presented in this dissertation if superintendents participate in the Audubon program and/or develop nutrient management plans.

Golf courses with high annual maintenance budgets would be expected to have the funds to apply more fertilizers annually than lower-budget or municipal courses. Fertilization may pose a risk to water quality, but pollution risks are lowered if proper management and application practices are used. Proper fertilization is not only critical to grow healthy turfgrass stands and to protect the environment, but it serves an economic purpose as well. Golf course managers do not have an incentive to apply fertilizers beyond turfgrass needs or in a manner that would result in runoff/leaching losses because it will not result in any added benefit to the turfgrass and will cost the course money in terms of wasted fertilizer and labor. The golf courses studied in this dissertation appear to be properly managing their turfgrass systems and do not appear to pose a risk to local water quality or to downstream areas such as the Chesapeake Bay by generating significantly excessive nutrient loads during normal baseflow conditions. Elevated nutrient loads were present at some sites on Courses 3 and 4, which could possibly be attributed to sources from urban/residential areas, but it is not possible to rule out elevations as a result of turfgrass management decisions. The overall contribution of nutrient loads calculated for this study (baseflow only) may also be increased by stormflow contribution of nutrients not measured in this study.

Environmental Stewardship Implications

This research suggests that the Virginia golf industry is committed to environmental stewardship and is voluntarily taking action to use BMPs to protect water quality. The nutrient and indicator status of most sites in this study appear to not be significantly affected by turfgrass cultural management practices, although there are some exceptions, which may be influenced by the presence of golf courses. Three of the sites with moderate nitrate-N levels and higher UALs were on two golf courses without NMPs, but not all sites on these two courses had significant increases in nutrient concentrations, and correlations with fertilizer applications were not evident. Sources other than fertilizer nutrients such as runoff, subsurface flows, or underground drainage/sewage pipes from urban areas may be a contributing factor. Overall, this research suggests that management on golf courses evaluated in this study generally does not degrade water quality, but the level of management and locations of courses may be a significant factor for the water quality of associated streams. Impervious surfaces and residential areas may contribute a significant amount of nutrients to golf course sites through runoff, leaching, and underground drainage/sewer systems, but golf courses can serve as green spaces in these urban areas. Urban courses may need more careful attention to cultural and environmental management strategies to protect water quality. Utilization of NMPs and water quality BMPs, such as incorporation of wetlands or using buffer strips around surface waters may be key to mitigating risk in urban areas, and may help to reduce elevated nutrient loads from multiple possible sources as observed on Course 3 and 4 (Kohler et al., 2004 and Steinke et al., 2009). Effectiveness of BMPs are generally determined by site-specific conditions, and state-approved NMPs will further highlight any possible risk areas on golf courses and allow managers to use more targeted, effective implementation of water quality protection measures. Whenever these measures are utilized, it is important to note that it can be many years before noticeable water quality changes occur in the body of interest (Meals et al., 2010). Future establishment of water quality standards for nitrogen and phosphorus in Virginia streams will allow for a more complete assessment of impacts from multiple land uses on stream health.

Future Research

The research presented here was limited by several constraints. Travel capacity was limited and funds were not available to pursue all avenues that could have further informed this research. Future studies should include additional factors to more fully assess the impacts of turfgrass systems on non-tidal streams. Additions of biological studies are highly desirable. Monitoring benthic macroinvertebrate communities to determine condition of the aquatic systems would be an effective approach to quantifying if nutrient concentrations at a particular stream are associated with impairments of wildlife. An attempt was made to collect macroinvertebrates for this study, but it was quickly determined that suitable reference conditions were not available at the majority of sites, and many of the locations were not suitable for sampling using currently accepted methods for macroinvertebrate sampling.

Another extremely important aspect would be to determine the nutrient assimilation capacity of the golf course streams and the point at which eutrophication occurs. Algal species naturally found in the streams could be collected and subjected to controlled laboratory conditions to determine the concentrations of nutrients necessary for the eutrophication process. Although it has been previously suggested that turfgrass systems do not generally pose a significant risk for runoff and leaching when properly managed, it may be beneficial to determine and compare stormflow concentrations at these same golf course sites to get a more accurate picture of loading and confirm the evidence in the existing literature. This is especially true for those cases during more rare, significant storms that may produce runoff events. An attempt was made to collect stormflow samples at Course 8 during this study, but only three events occurred. Nutrient concentrations in two of the three samples were similar to those collected during baseflow conditions, but one had evidence for elevations in nutrient concentrations between the inflow and outflow sites. Furthermore, the source of nutrients was unclear, due to the presence of a wastewater treatment plant on the golf course that influenced the stream between the inflow and outflow locations. If a storm was significant enough to exceed the capacity of the plant, discharges may have occurred to the stream. Discharge taken at inflow locations would be helpful in determining more accurate loads coming from the golf course, and would allow for more accurate comparison of nutrient concentrations between upstream and downstream areas, particularly in those systems that had more than one inflow location. Streams were highly variable, and most were unsuitable for discharge determination (lack of depth or little flow, for example). It would be informative to compare golf courses in other major river watersheds of the Chesapeake, and to have more frequent sampling data capturing both stormflow and baseflow concentrations as well as discharge amounts. A preliminary ANOVA analysis of the majority of the data revealed that seasonality was not an important factor for nutrient concentrations at our sites, but this may not be the case for data that includes stormflow concentrations (Appendix C).

A final interesting aspect for comparison would be to investigate possible differences between high-visibility, high-budget golf courses with increased membership expectations as studied in this research and lower-budget public or private courses. The rationale behind targeting high-end golf courses in this study was the expectation that those courses have the funds available for larger fertilizer application amounts and may do so to meet higher membership expectations. However, the superintendents hired by these clubs may be more informed about proper turfgrass management strategies and environmental BMPs to protect water quality. They may also have more funds available to incorporate BMPs on their courses. Lower-budget courses may have lower membership or patron expectations for turfgrass quality. Lack of funds or awareness may prevent superintendents from implementing certain BMPs in some situations. In a worst-case scenario, mismanagement or poor turfgrass coverage/density could possibly result in more opportunities for nutrient leaching and runoff, although this would generally be unexpected since many superintendents from all types (municipal, public, private) of golf courses indicated (in the Superintendent Survey) that they are using BMPs on their courses and are fertilizing at appropriate rates (Easton and Petrovic, 2004; Gross et al., 1990; Linde et al., 1997; Stier et al., 2013).

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APPENDICES

APPENDIX A. SUPERINTENDENT'S GOLF COURSE MANAGEMENT SURVEY

Name of Course:________Course Address________ Course County________

Demographics (Please select one answer per question)

1. What is the annual maintenance budget of your course (non-capital)?

_ $500,000 or less　　_ $500,001-$1 Million
_ $1,000,0001- $1.5 Million　　_ Over $1.5 Million

2. What is the approximate number of rounds played at your course annually?

_ Less than 10,000　　_ 10,000-20,000　　_ 20,001-30,000
_ 30,001-40,000　　_ Greater than 40,000 annually

3. What would you classify your golf course as:

_ Municipal　　_ Public　　_ Private　　_ Other _______

4. What is the approximate age of your course?

_ Less than one year　　_ 1-5 years　　_ 5-10 years
_ 10-15 years　　_ 15-20 years　　_ Over 20 Years

Water Quality Testing (Please select one answer per question)

1. Do you routinely test the water quality of your irrigation ponds?

_ Yes　　_ No　　_ Unsure

2. Do you routinely test the water quality of streams flowing through or next to your course?

_ Yes　　_ No　　_ No Streams Present　　_ Unsure

a. If yes, would you be willing to share this data with Virginia Tech? Water quality data will be used in aggregate anonymously and will not be uniquely identifiable to your course.

_ Yes　　_ No　　_ Unsure

Course Characteristics (Please select one answer per question)

1. Is this golf course certified by the Audubon Cooperative Sanctuary Program for Golf?

_ Yes _ No _ Unsure

-If not, is this course in the process of certification or are there plans to obtain certification?

_ Yes _ No _ Unsure

2. What type of turfgrass is primarily used on your roughs?

_Bermudagrass _Tall Fescue _Kentucky Bluegrass
_Mixed Cool-Season _Mixed Cool/Warm-Season _ Other_______

3. What type of turfgrass is primarily used on your fairways?

_Bermudagrass _Zoysiagrass _Creeping Bentgrass
_Perennial Ryegrass _Kentucky Bluegrass _Mixed Cool-Season
_Other _______

4. What type of turfgrass is primarily used on your greens?

_Creeping Bentgrass _Bermudagrass _*Poa*/Bentgrass Mix
_Other _______

5. Would you be willing to share your fertilization records with Virginia Tech?
_Yes _ No _Unsure

6. What is the primary type of N fertilizer used on your roughs?

_Greater than 90% Quick Release _50-90% Quick Release
_Less than 50% Quick Release or Slow Release _Combination

7. What is the primary type of N fertilizer used on your tees?

_Greater than 90% Quick Release _50-90% Quick Release
_Less than 50% Quick Release or Slow Release _Combination

8. What is the primary type of N fertilizer used on your fairways?
_Greater than 90% Quick Release _50-90% Quick Release
_Less than 50% Quick Release or Slow Release _Combination

9. What is the primary type of N fertilizer used on your greens?

_Greater than 90% Quick Release _50-90% Quick Release
_Less than 50% Quick Release or Slow Release _Combination

10. What was the approximate N annual fertilization rate (lbs N/1000ft^2) for your course for the past three years? **Please select one answer per Year**

	Year One	Year Two	Year Three
a. Greens	_0-1.9	_0-1.9	_0-1.9
	_2.0-2.9	_2.0-2.9	_2.0-2.9
	_3.0-3.9	_3.0-3.9	_3.0-3.9
	_4.0-4.9	_4.0-4.9	_4.0-4.9
	_5.0-greater	_5.0-greater	_5.0-greater
b. Tees	_0-1.9	_0-1.9	_0-1.9
	_2.0-2.9	_2.0-2.9	_2.0-2.9
	_3.0-3.9	_3.0-3.9	_3.0-3.9
	_4.0-4.9	_4.0-4.9	_4.0-4.9
	_5.0-greater	_5.0-greater	_5.0-greater
c. Fairways	_0-1.9	_0-1.9	_0-1.9
	_2.0-2.9	_2.0-2.9	_2.0-2.9
	_3.0-3.9	_3.0-3.9	_3.0-3.9
	_4.0-4.9	_4.0-4.9	_4.0-4.9
	_5.0-greater	_5.0-greater	_5.0-greater
d. Primary Rough	_0-1.9	_0-1.9	_0-1.9
	_2.0-2.9	_2.0-2.9	_2.0-2.9
	_3.0-3.9	_3.0-3.9	_3.0-3.9
	_4.0-4.9	_4.0-4.9	_4.0-4.9
	_5.0-greater	_5.0-greater	_5.0-greater
e. Secondary Rough			
	_0-1.9	_0-1.9	_0-1.9
	_2.0-2.9	_2.0-2.9	_2.0-2.9
	_3.0-3.9	_3.0-3.9	_3.0-3.9
	_4.0-4.9	_4.0-4.9	_4.0-4.9
	_5.0-greater	_5.0-greater	_5.0-greater
f. Tertiary Rough	_0-1.9	_0-1.9	_0-1.9
	_2.0-2.9	_2.0-2.9	_2.0-2.9
	_3.0-3.9	_3.0-3.9	_3.0-3.9
	_4.0-4.9	_4.0-4.9	_4.0-4.9
	_5.0-greater	_5.0-greater	_5.0-greater

11. What mowing heights (or frequency) do you generally use? **Please select one answer per season**

	Spring	Summer	Fall
a. Greens	_Under .100”	_Under .100”	_Under .100”
	_.100-.115”	_.100-.115”	_.100-.115”
	_.116-.125”	_.116-.125”	_.116-.125”
	_.126-.140”	_.126-.140”	_.126-.140”
	_Greater than .140”	_Greater than .140”	_Greater than .140”
b. Tees/Collars			
	_.185-.249”	_.185-.249”	_.185-.249”
	_.250-.350”	_.250-.350”	_.250-.350”
	_.351-.500”	_.351-.500”	_.351-.500”
	_Greater than .500”	_Greater than .500”	_Greater than .500”
c. Fairways	_.300-.450”	_.300-.450”	_.300-.450”
	_.451-.500”	_.451-.500”	_.451-.500”
	_.501-.750”	_.501-.750”	_.501-.750”
	_Greater than .750”	_Greater than .750”	_Greater than .750”
d. Primary Rough			
	_.75-1.50”	_.75-1.50”	_.75-1.50”
	_1.51-2.25”	_1.51”-2.25”	_1.51”-2.25”
	_2.26-3.0”	_2.26-3.0”	_2.26-3.0”
	_Greater than 3.0”	_Greater than 3.0”	_Greater than 3.0”
e. Secondary Rough			
	_2.0-2.5”	_2.0-2.5”	_2.0-2.5”
	_2.6-3.0”	_2.6-3.0”	_2.6-3.0”
	_3.1-3.5”	_3.1-3.5”	_3.1-3.5”
	_Greater than 3.5”	_Greater than 3.5”	_Greater than 3.5”
f. Tertiary Rough			
	_1x/year	_1x/year	_1x/year
	_2x/year	_2x/year	_2x/year
	_3x/year	_3x/year	_3x/year
	_Other_____	_Other_____	_Other_____

Management Practices
Please indicate if the following Management Practices are in use at your facility. **Check all that apply to your facility**

1. Surface Waters
_ Detention/retention ponds or basins
_ Greens drain to surface waters
_ Greens drain to grassed or wooded area
_ Grass carp for lake management
_ Mechanical aeration of ponds
_ Use of native plants in ponds/buffer zones
_ Use of exotic plants in ponds/buffer zones
_ Constructed or native wetlands
_ Sediment removal/dredging of small basins, ponds, and/or forebays
_ Grass clippings deposited into surface waters
_ Grass clippings removed/spread in rough areas
_ Vegetative buffer strips are used around most irrigation ponds
_ Turf is maintained to edge of most irrigation ponds
_ Vegetative buffer strips are used around most flowing surface waters (creeks, streams)
    _ Check here if flowing waters not present
_ Turf is maintained to the edge around most flowing surface waters (creeks, streams)
    _ Check here if flowing waters not present
_ Do you attempt to control streambank erosion by reducing slope, stabilization with sod/native plants, netting, or other means?

2. Fertilizer Considerations
_ Use of slow release nitrogen fertilizers near water sources
_ Use of quick release nitrogen fertilizers near water sources
_ Fertilizer is applied during turf dormancy periods
_ Fertilizer is applied during periods of optimal turf growth
_ Phosphorus is only applied based on soil test need or at establishment
_ Phosphorus is applied on a calendar-based or seasonal basis
_ A Nutrient Management Plan is in use
_ Non-application of fertilizers on high-gradient slopes near water surfaces
_ Does your facility engage in regular soil testing annually on greens?
_ Does your facility engage in regular soil testing at least every 3 years on fairways/roughs?

3. Maintenance Considerations
_ Do you engage in Integrated Pest Management practices to reduce stress and disease pressure on turf?
_ Are fill stations in the same physical location as drains to surface water?

_ Are fill stations situated away from drains to surface water?
_ Are grass clippings removed from equipment before washing (to prevent clippings from entering drains?)
_ Does the wash pad drain to surface waters?
_ Are wash pad discharges kept out of surface waters?
_ Are wastewater recycling systems in use?

4. Cultural Practices:

Rolling of greens
_ Height of cut is raised/lower inputs used on shaded turf
_ Height of cut is lowered/higher inputs used on shaded turf
_ Height of cut is raised during summer to improve stress tolerance
_ Height of cut is lowered during summer to improve stress tolerance
_ Grass clippings are returned to rough to recycle nutrients
_ High-traffic areas are cored/tined/sliced as needed to increase aeration, infiltration and reduce compaction
_ Mower blades are checked regularly and sharpened
_ Do you irrigate based on evapotranspiration (ET) demand?
_ Do you perform irrigation system audits?
_ Do you use soil moisture sensors to inform your irrigation decisions?

History

1. Are you aware of the past land use for the area of your golf course before construction? **Please list if known.** Examples: forested, agriculture, pasture, mining, residential, etc.

_ Yes ____________________ _ No

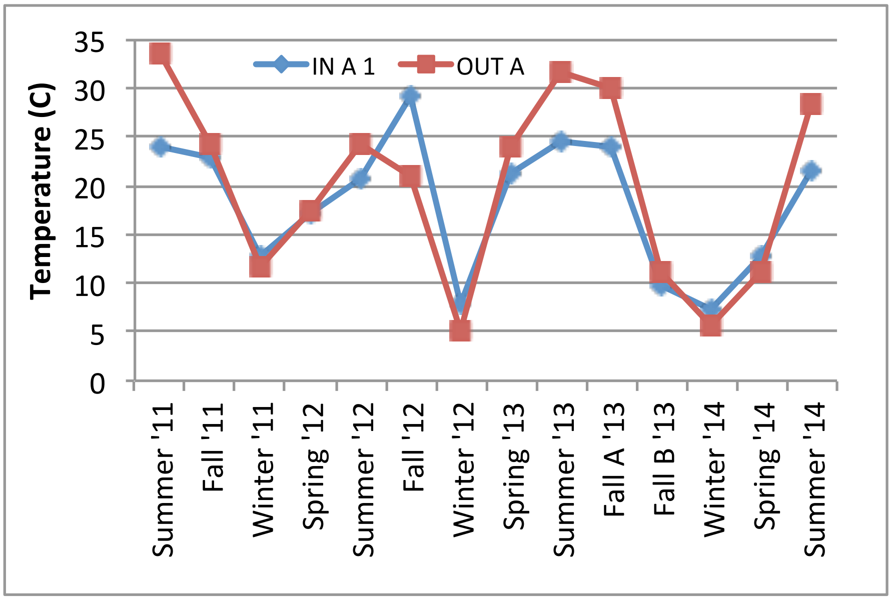
Comments

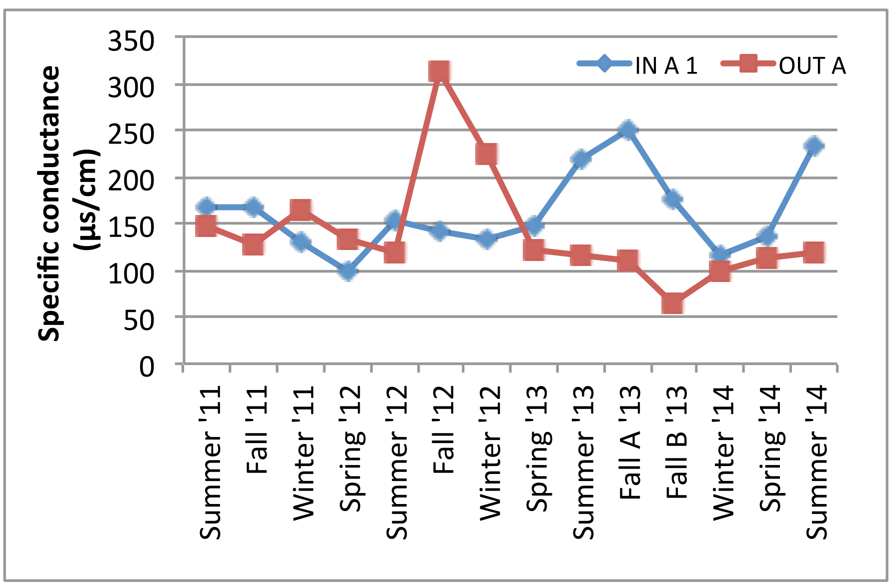
Do you have any additional comments regarding the questions above which would help us to determine the water quality, environmental status, or best management practice use of your course?

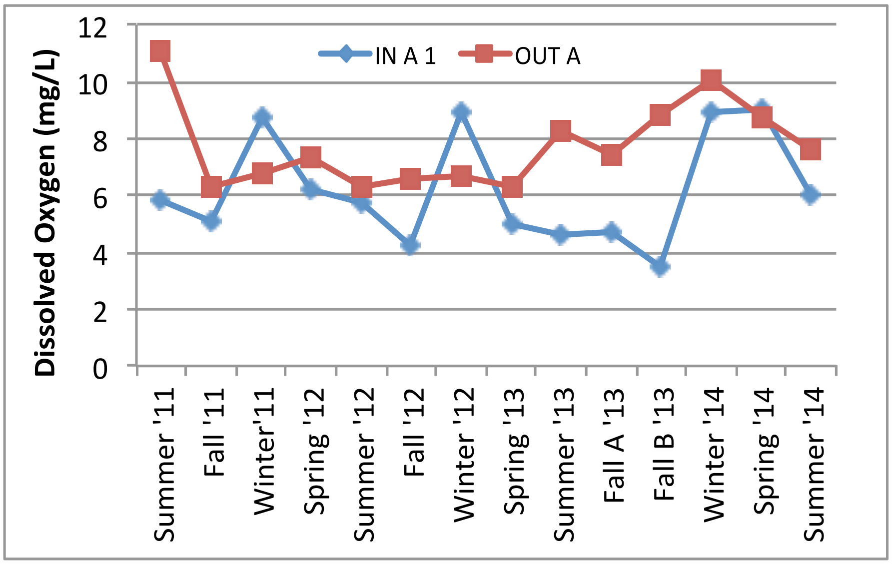
____

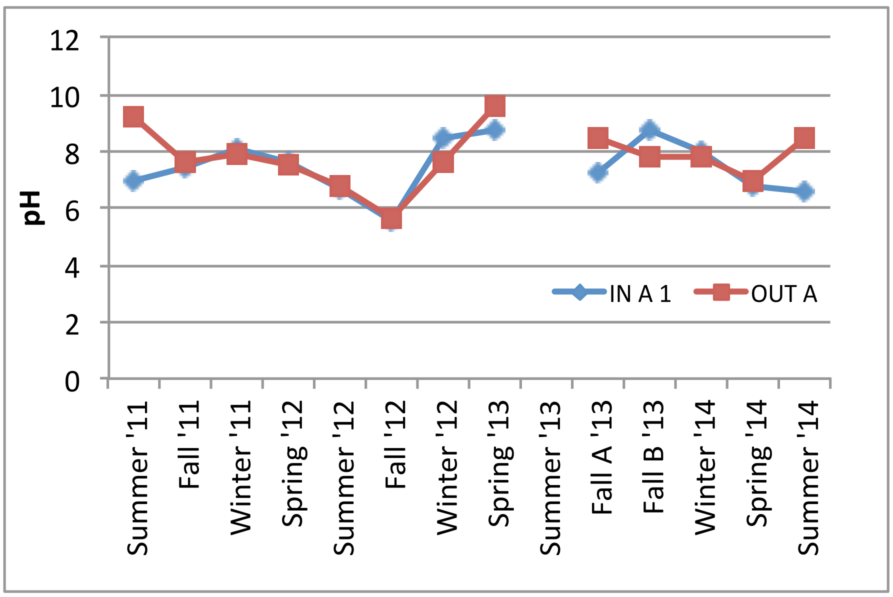
APPENDIX B. TEMPERATURE, pH, DISSOLVED OXYGEN, AND SPECIFIC CONDUCTANCE FIGURES FROM STREAM SAMPLES FOR EIGHT VIRGINIA GOLF COURSES

Course 1 System A

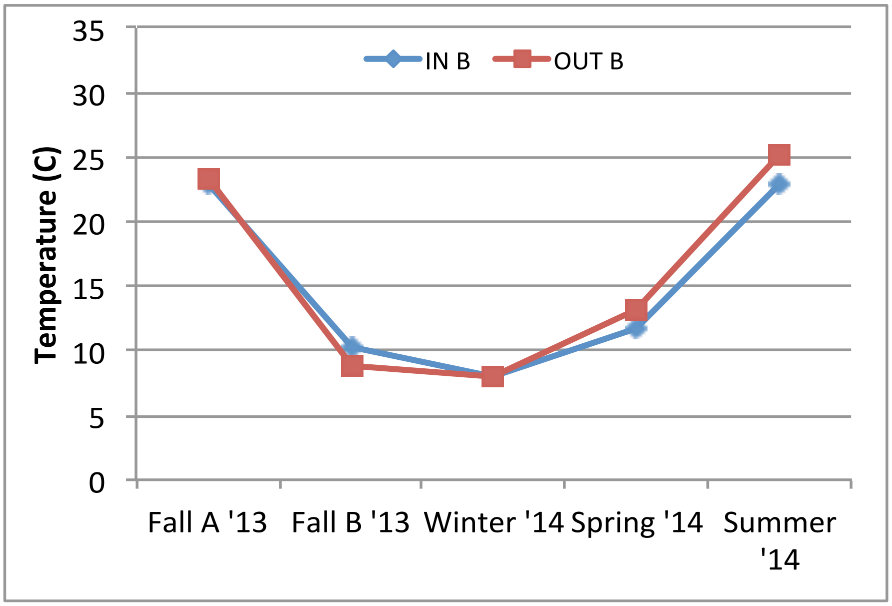


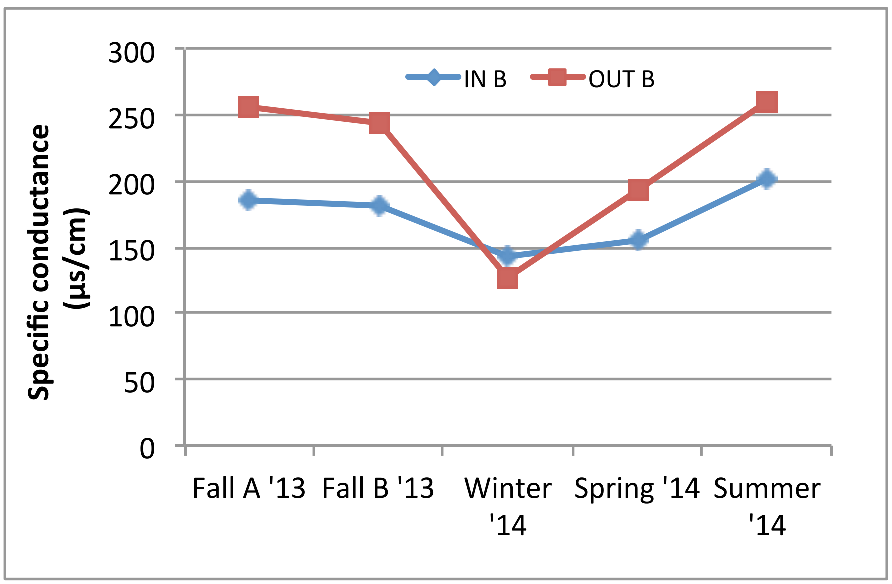


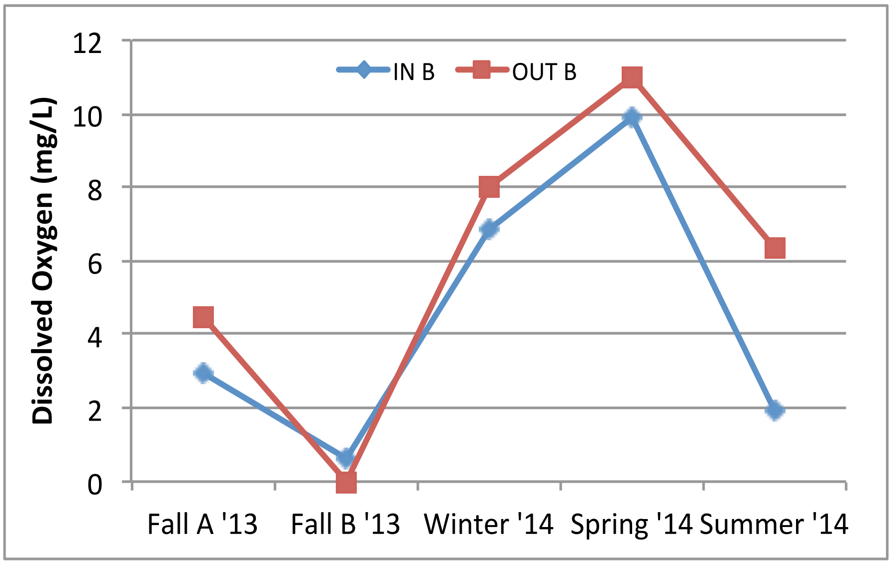

Dissolved Oxygen (mg/L)
IN A 1
OUT A
12
10
8
6
4
2
0
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14


pH
IN A 1
OUT A
12
10
8
6
4
2
0
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

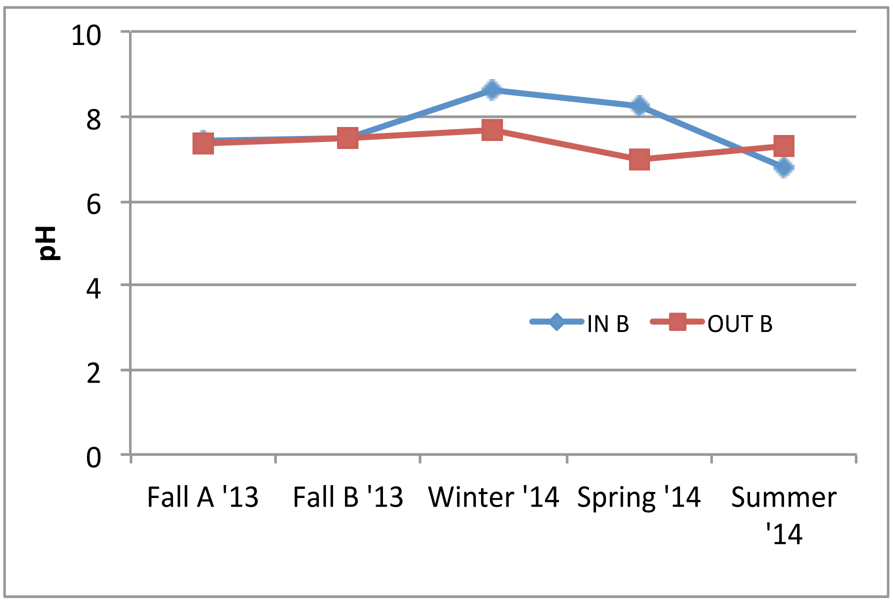
Course 1 Stream B





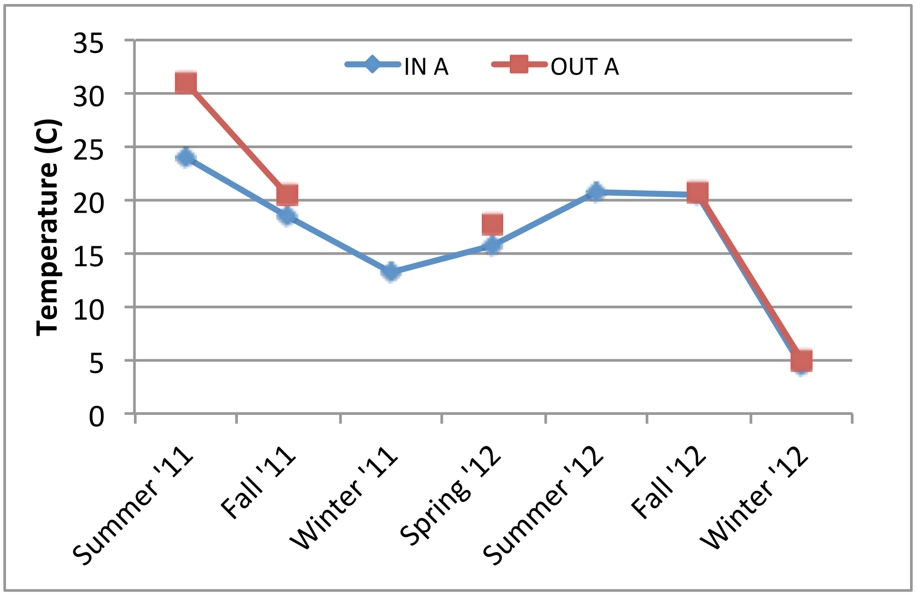


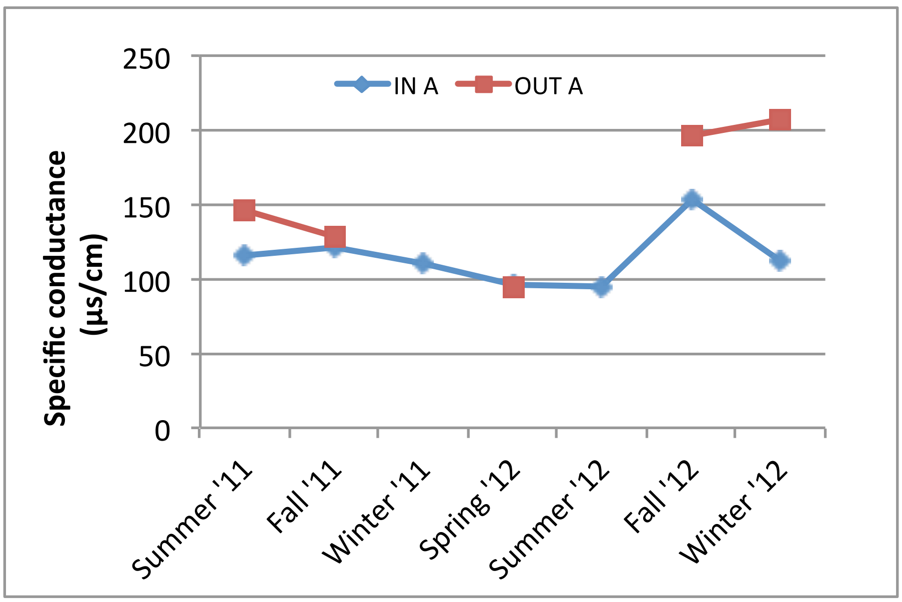
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
IN B
OUT B
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

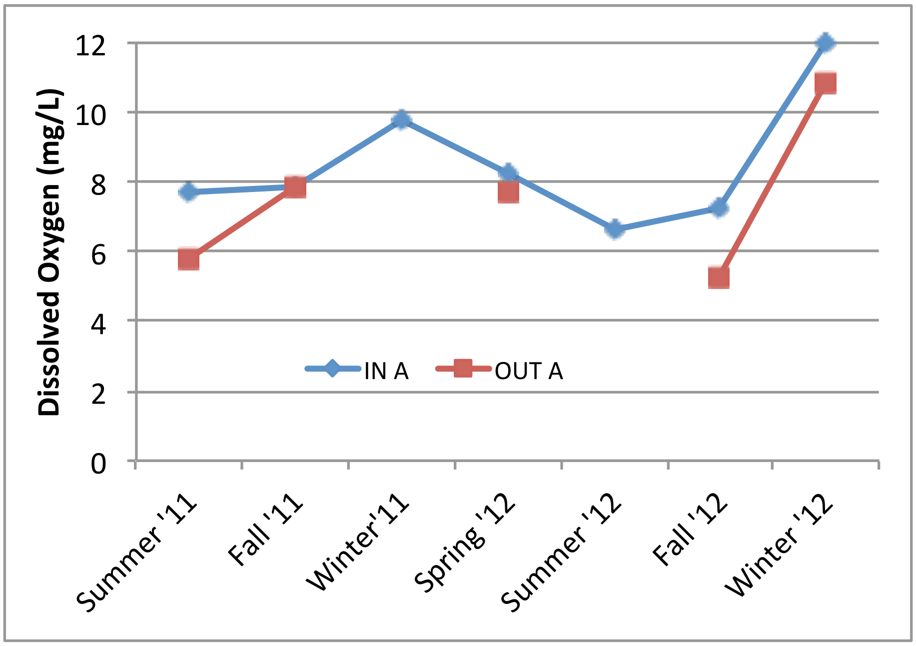


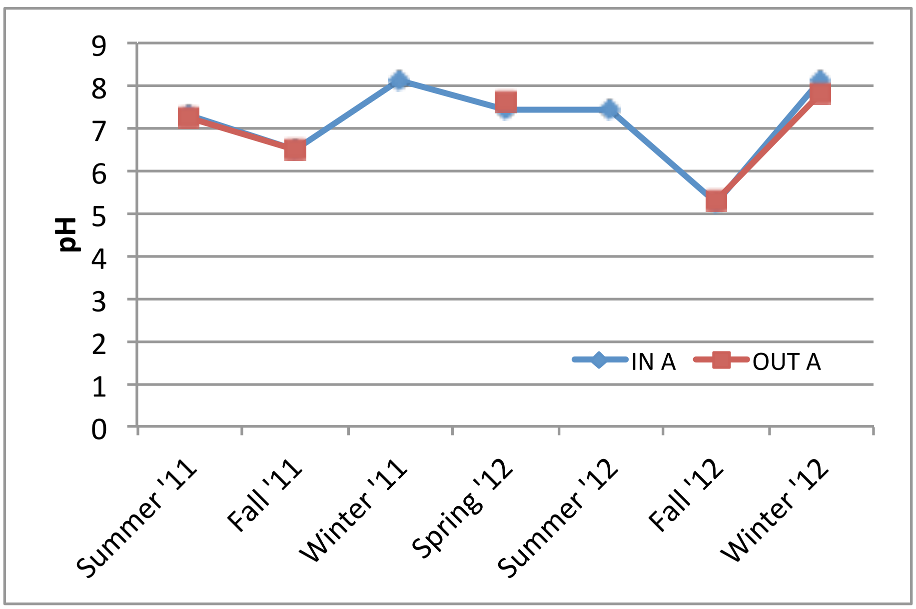
pH
10
8
6
4
2
0
IN B
OUT B
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

Course 2 Stream A

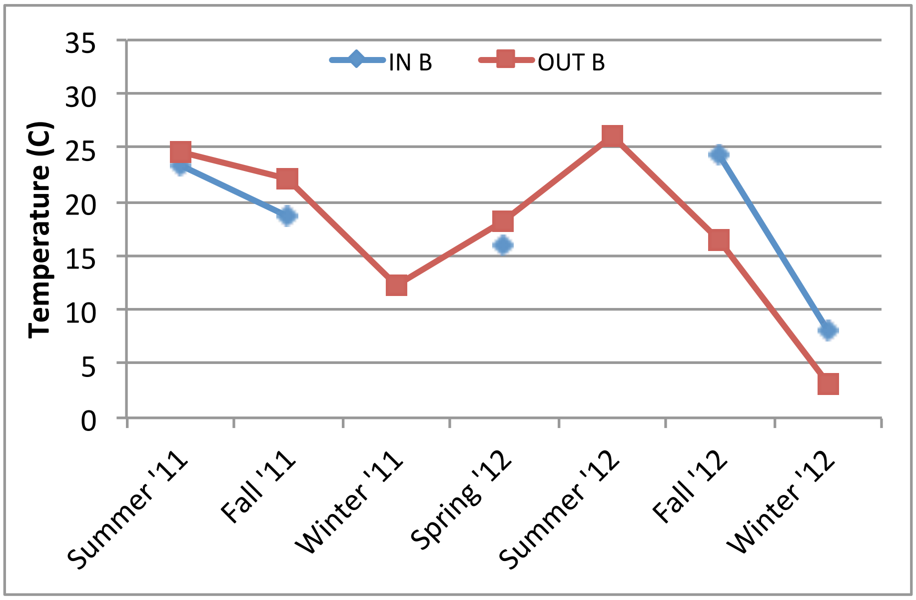


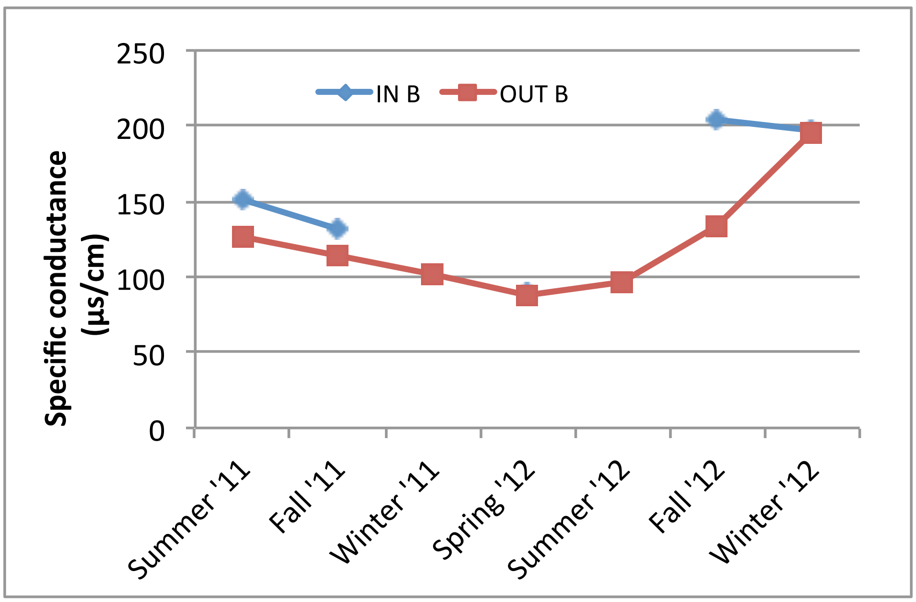


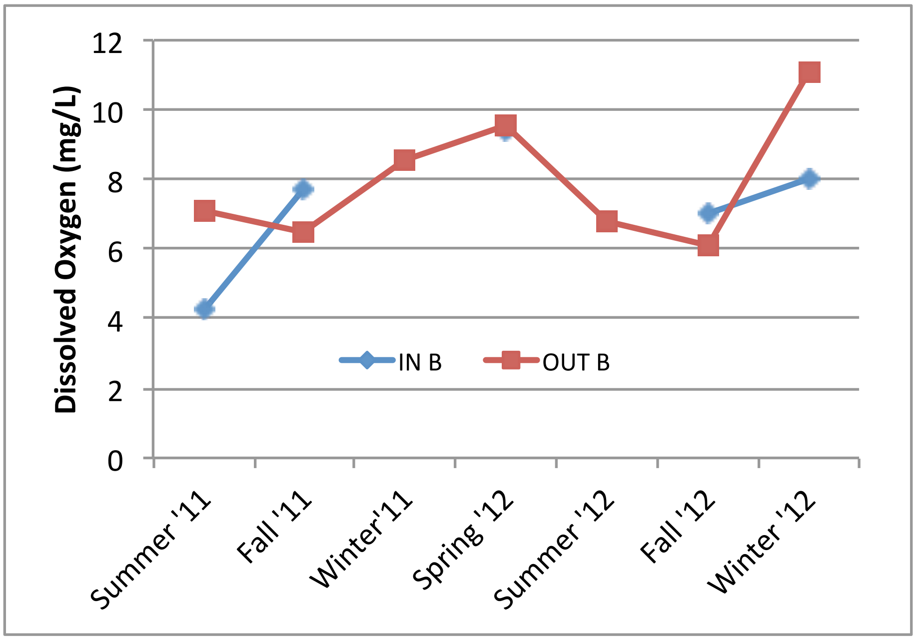

Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
IN A
OUT A
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12
Fall '12
Winter '12

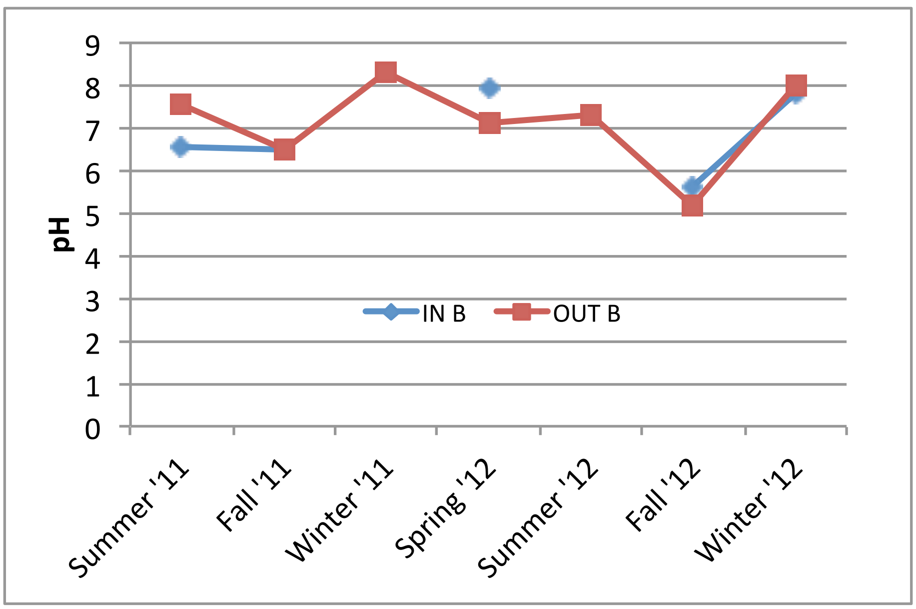

pH
9
8
7
6
5
4
3
2
1
0
IN A
OUT A
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12
Fall '12
Winter '12

Course 2 Stream B

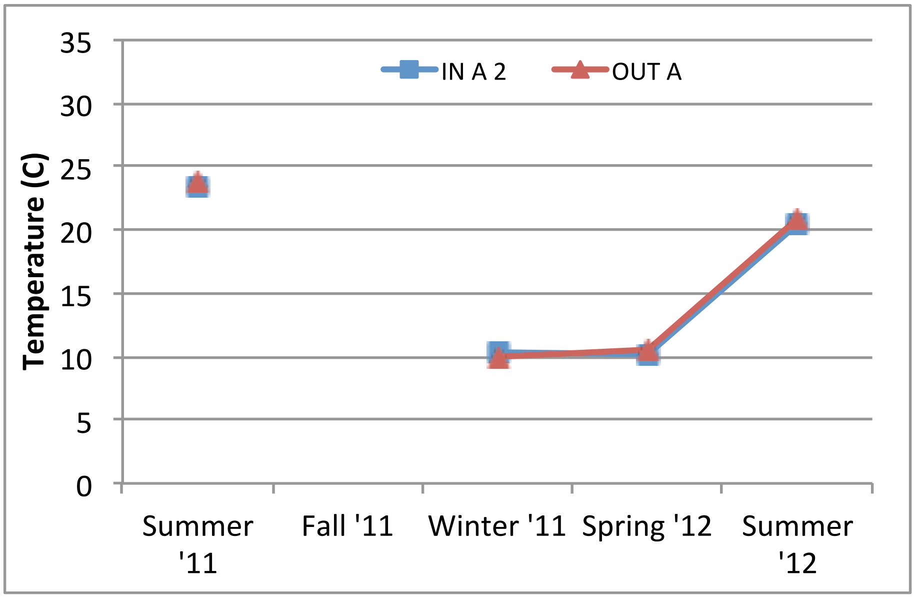


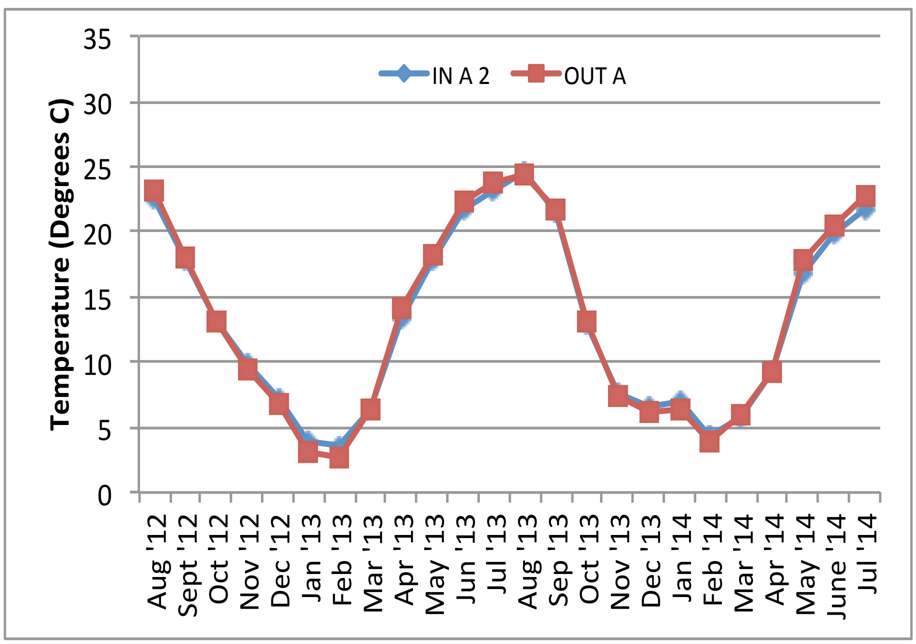


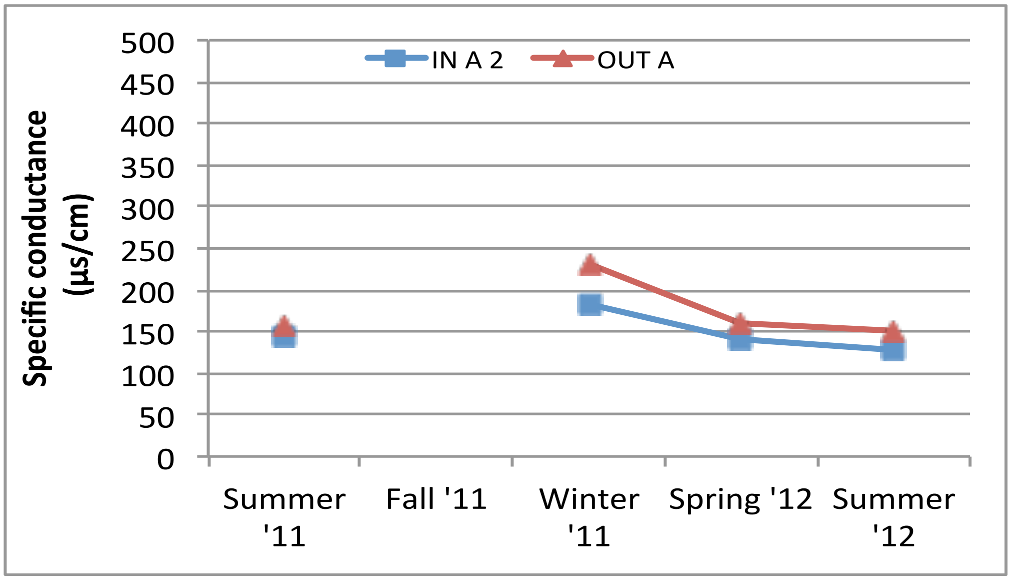

Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
IN B
OUT B
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12
Fall '12
Winter '12

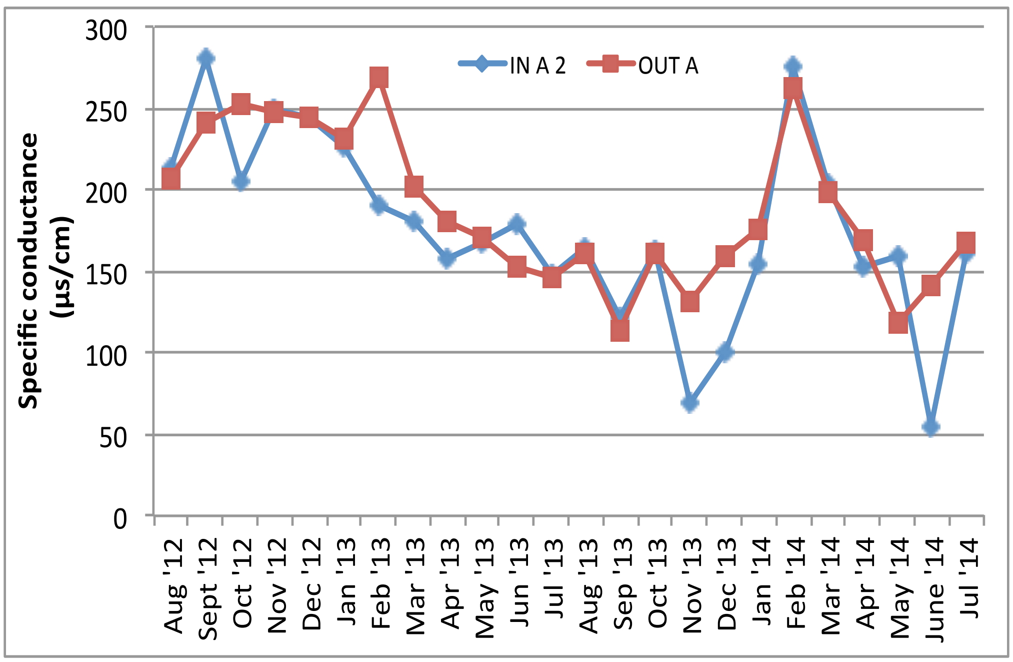

pH
9
8
7
6
5
4
3
2
1
0
IN B
OUT B
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12
Fall '12
Winter '12

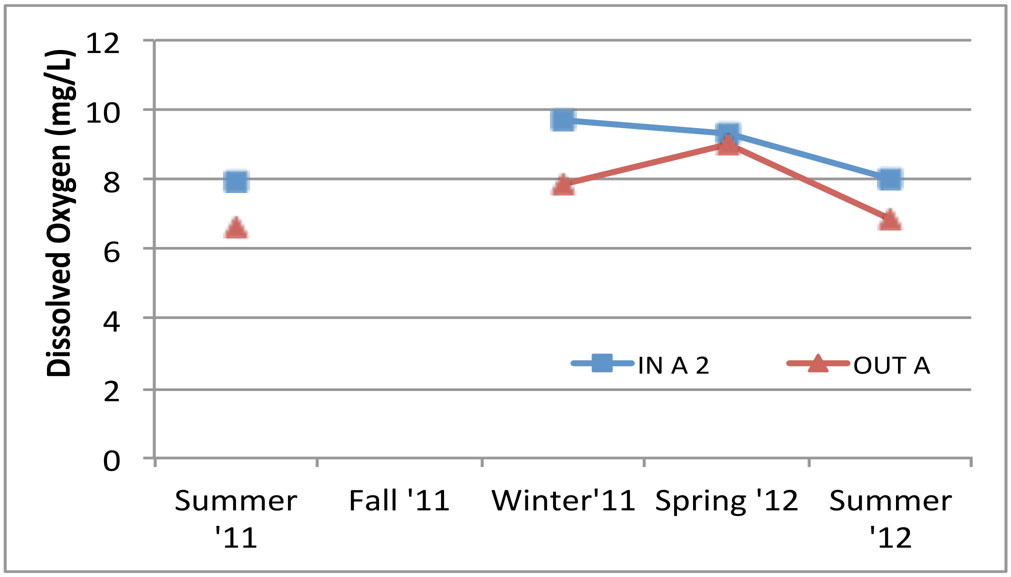
Course 3 System A

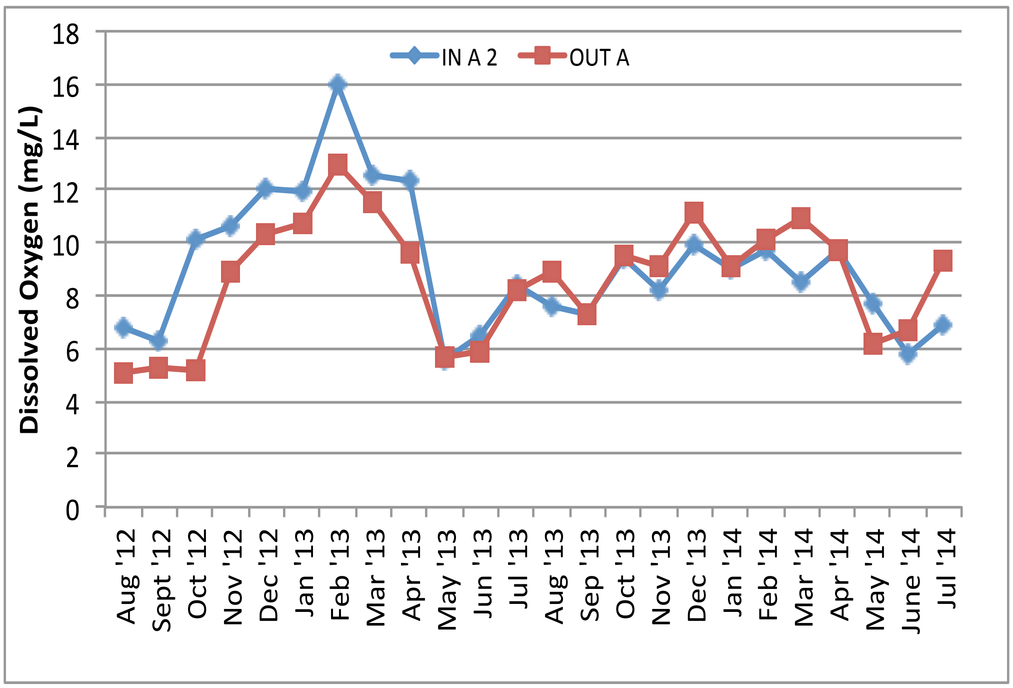


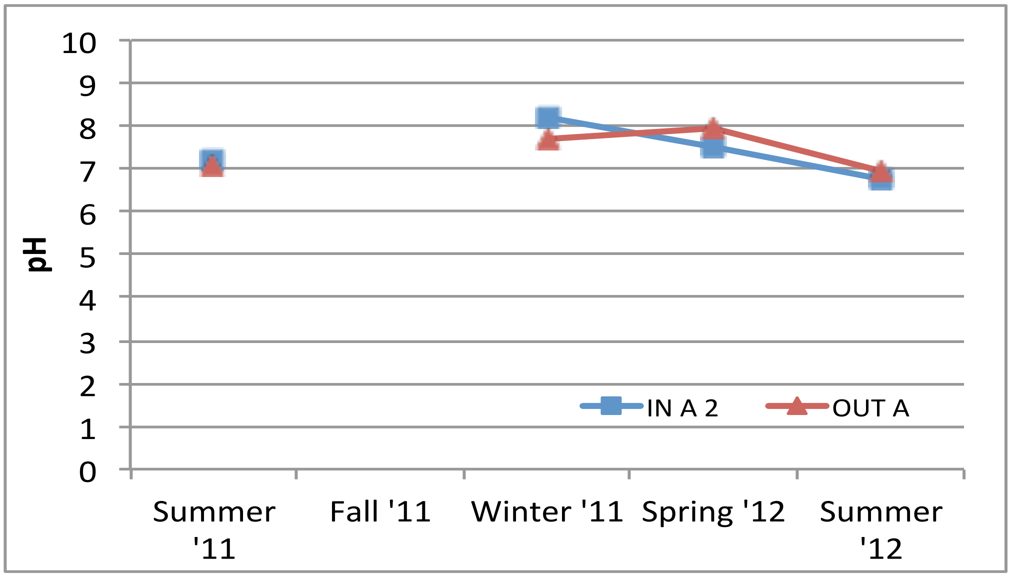



IN A 2
OUT A
Specific conductance (µs/cm)
500
450
400
350
300
250
200
150
100
50
0
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12

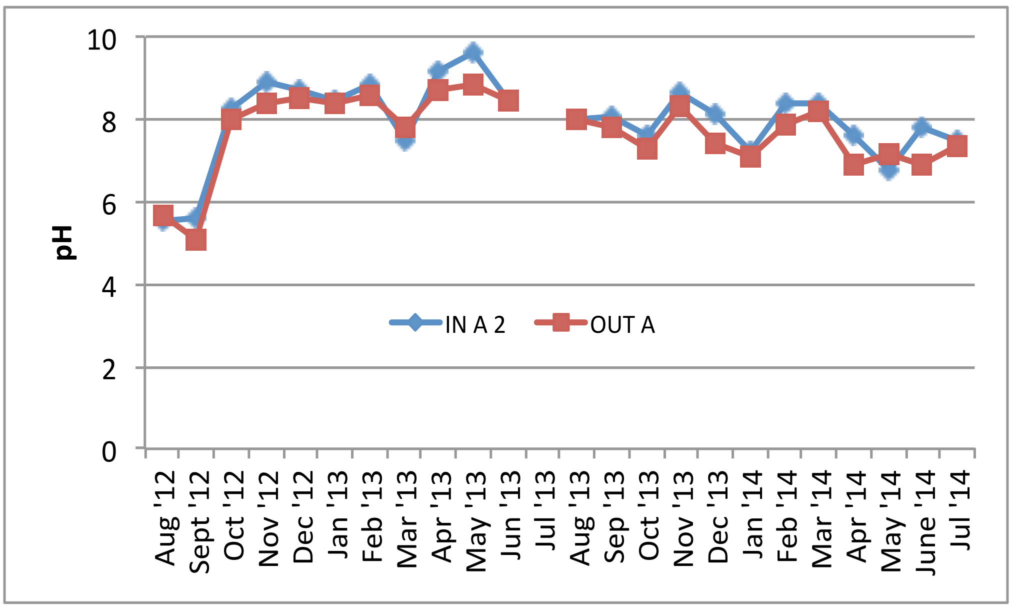

IN A 2
OUT A
Specific conductance (µs/cm)
300
250
200
150
100
50
0
Aug '12
Sept '12
Oct '12
Nov '12
Dec '12
Jan '13
Feb '13
Mar '13
Apr '13
May '13
Jun '13
Jul '13
Aug '13
Sep '13
Oct '13
Nov '13
Dec '13
Jan '14
Feb '14
Mar '14
Apr '14
May '14
June '14
Jul '14


Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
IN A 2
OUT A
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12


Dissolved Oxygen (mg/L)
18
16
14
12
10
8
6
4
2
0
IN A 2
OUT A
Aug '12
Sept '12
Oct '12
Nov '12
Dec '12
Jan '13
Feb '13
Mar '13
Apr '13
May '13
Jun '13
Jul '13
Aug '13
Sep '13
Oct '13
Nov '13
Dec '13
Jan '14
Feb '14
Mar '14
Apr '14
May '14
June '14
Jul '14

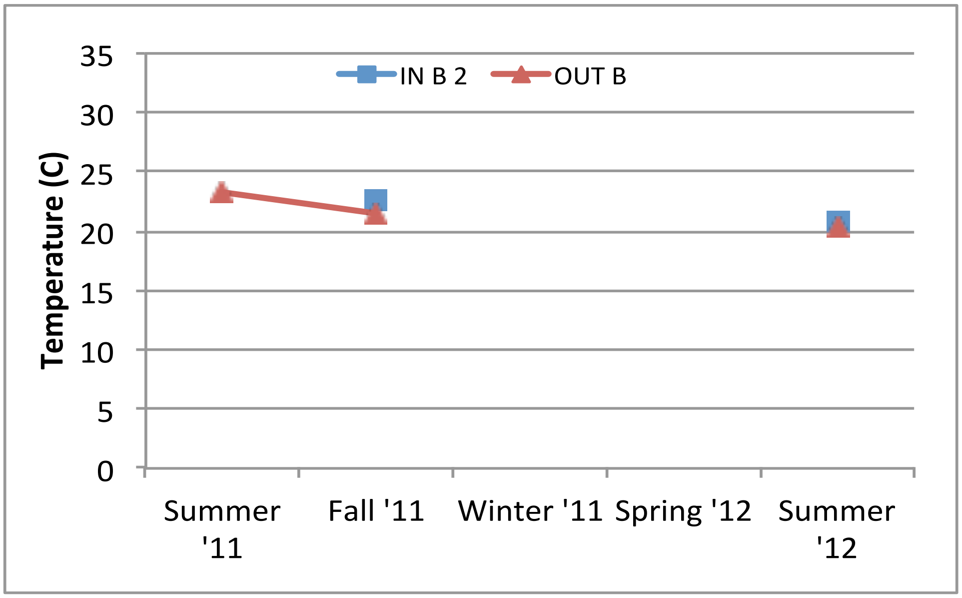


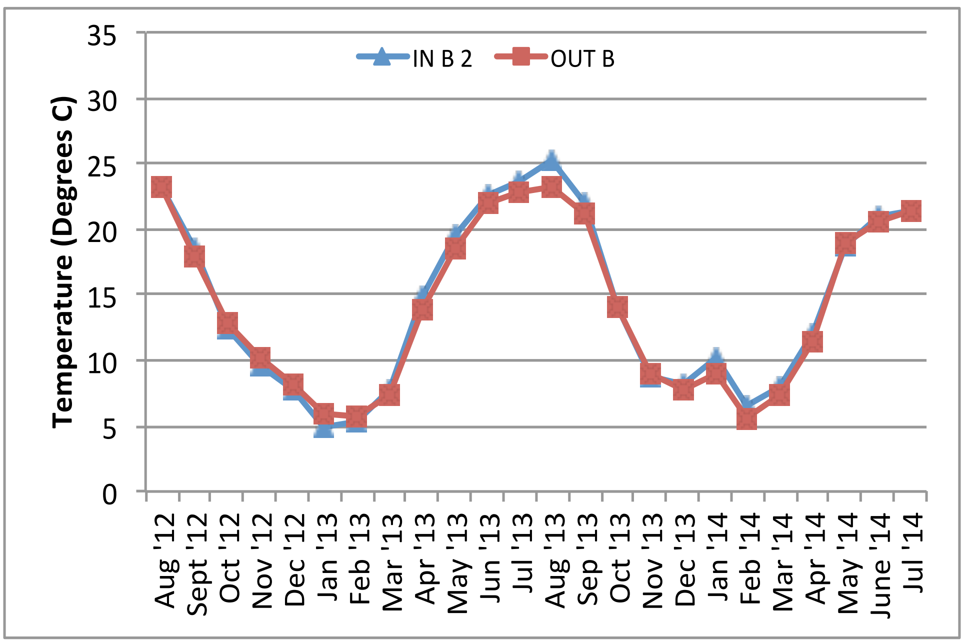
pH
10
9
8
7
6
5
4
3
2
1
0
IN A 2
OUT A
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12

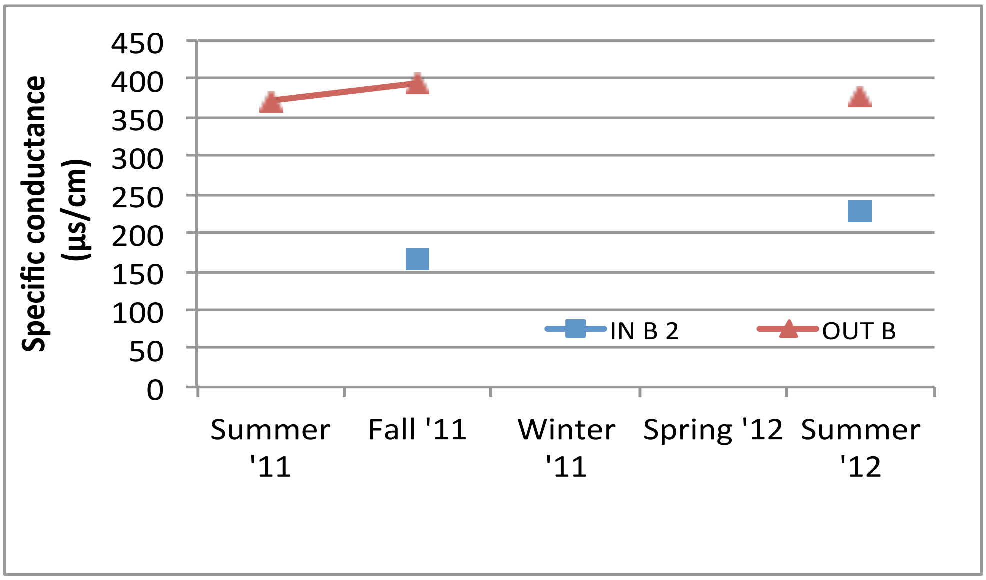


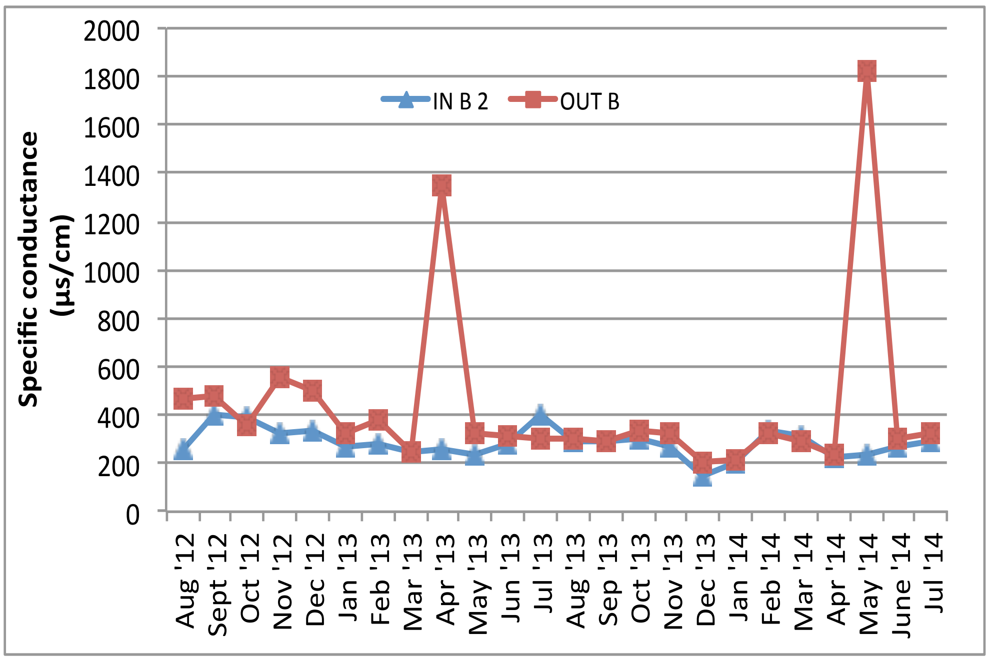
pH
10
8
6
4
2
0
IN A 2
OUT A
Aug '12
Sept '12
Oct '12
Nov '12
Dec '12
Jan '13
Feb '13
Mar '13
Apr '13
May '13
Jun '13
Jul '13
Aug '13
Sep '13
Oct '13
Nov '13
Dec '13
Jan '14
Feb '14
Mar '14
Apr '14
May '14
June '14
Jul '14

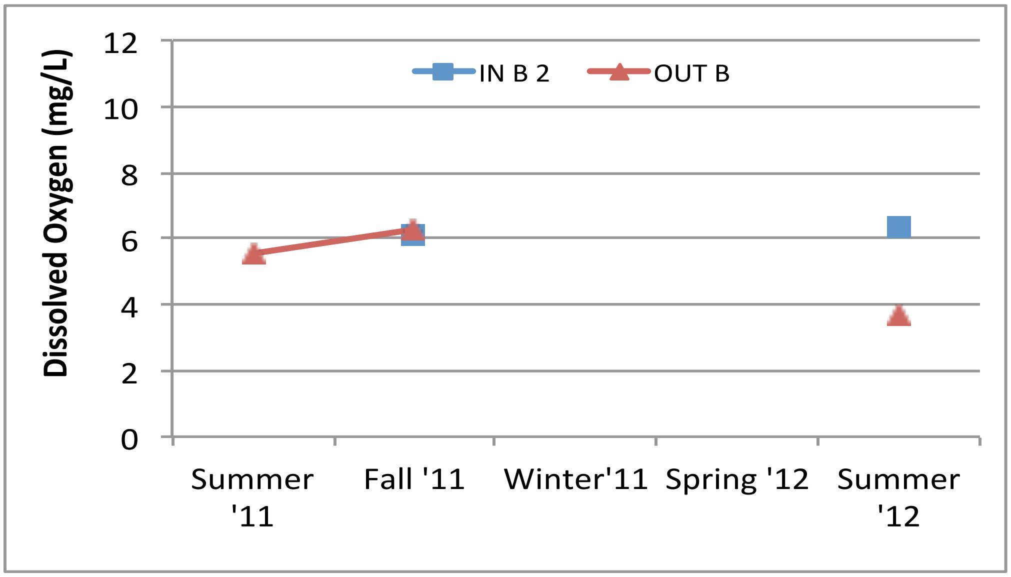
Course 3 System B

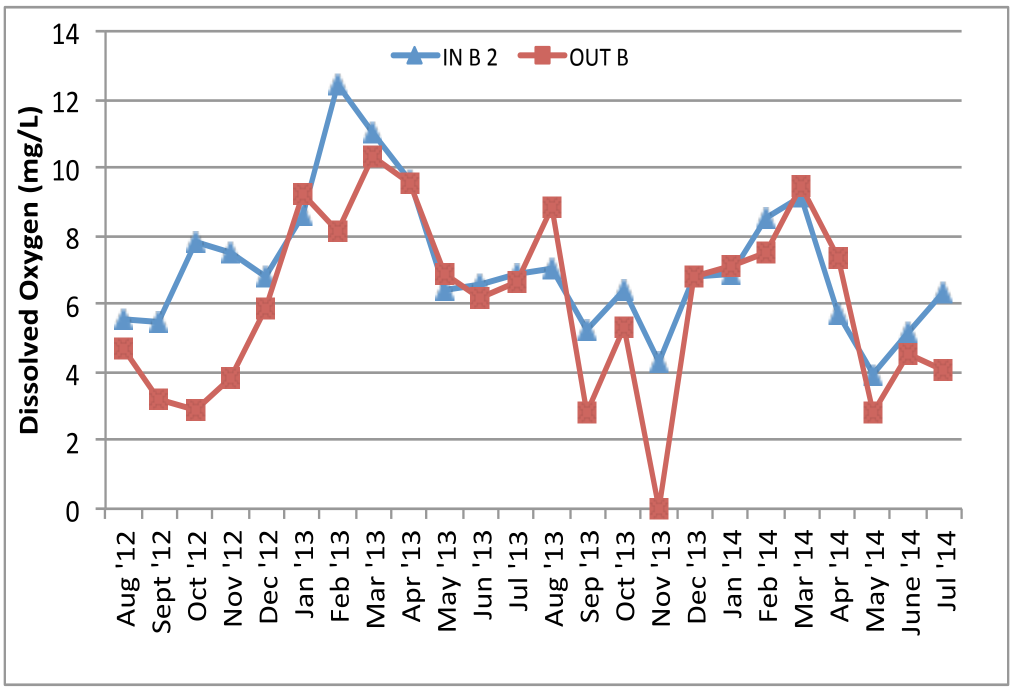


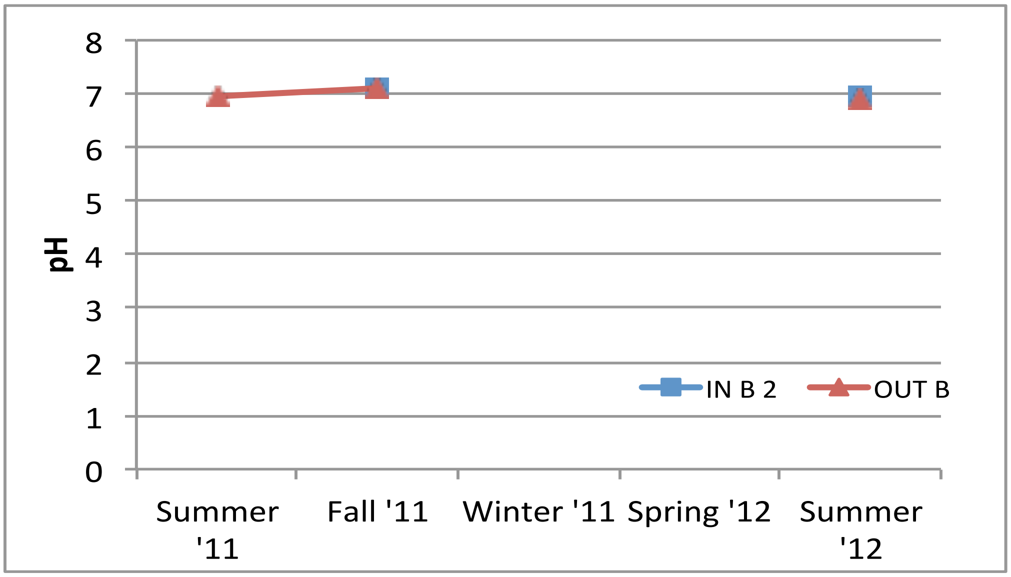



Specific conductance (µs/cm)
450
400
350
300
250
200
150
100
50
0
IN B 2
OUT B
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12

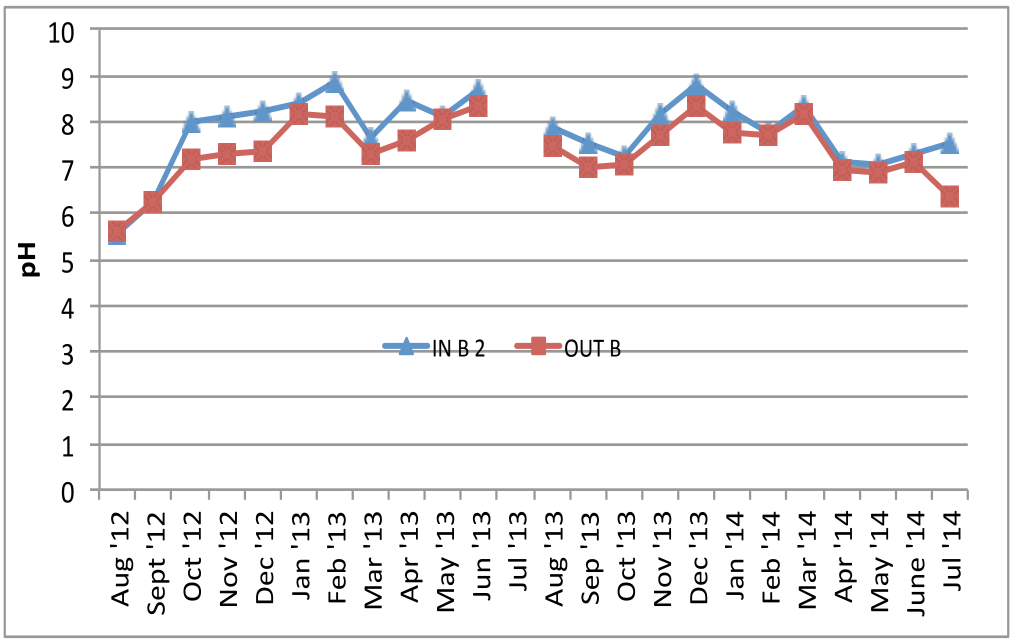

Specific conductance (µs/cm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
IN B 2
OUT B
Aug '12
Sept '12
Oct '12
Nov '12
Dec '12
Jan '13
Feb '13
Mar '13
Apr '13
May '13
Jun '13
Jul '13
Aug '13
Sep '13
Oct '13
Nov '13
Dec '13
Jan '14
Feb '14
Mar '14
Apr '14
May '14
June '14
Jul '14


Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
IN B 2
OUT B
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12


Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
IN B 2
OUT B
Aug '12
Sept '12
Oct '12
Nov '12
Dec '12
Jan '13
Feb '13
Mar '13
Apr '13
May '13
Jun '13
Jul '13
Aug '13
Sep '13
Oct '13
Nov '13
Dec '13
Jan '14
Feb '14
Mar '14
Apr '14
May '14
June '14
Jul '14

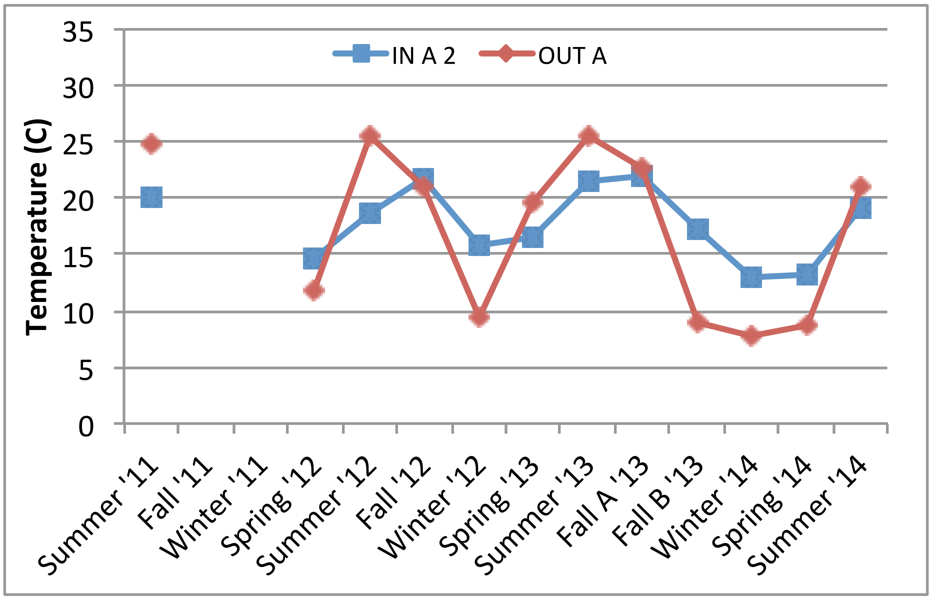


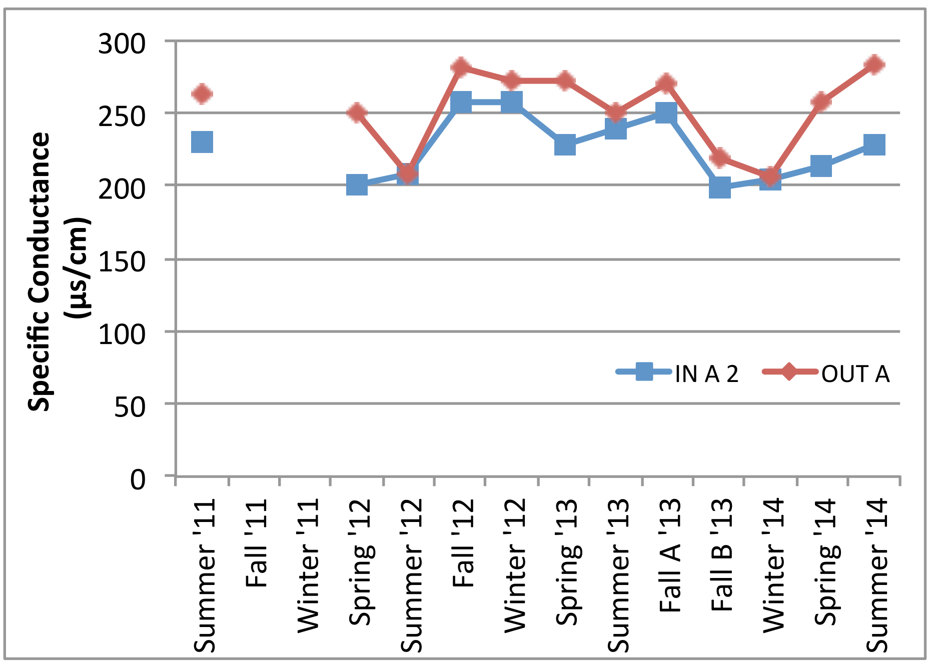
8
7
6
5
pH
4
3
2
1
0
IN B 2
OUT B
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12

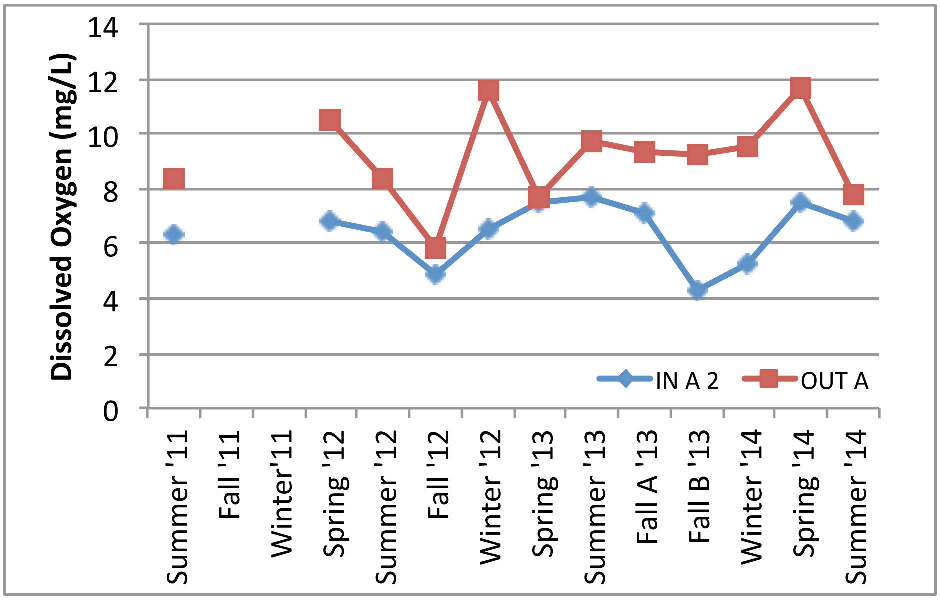


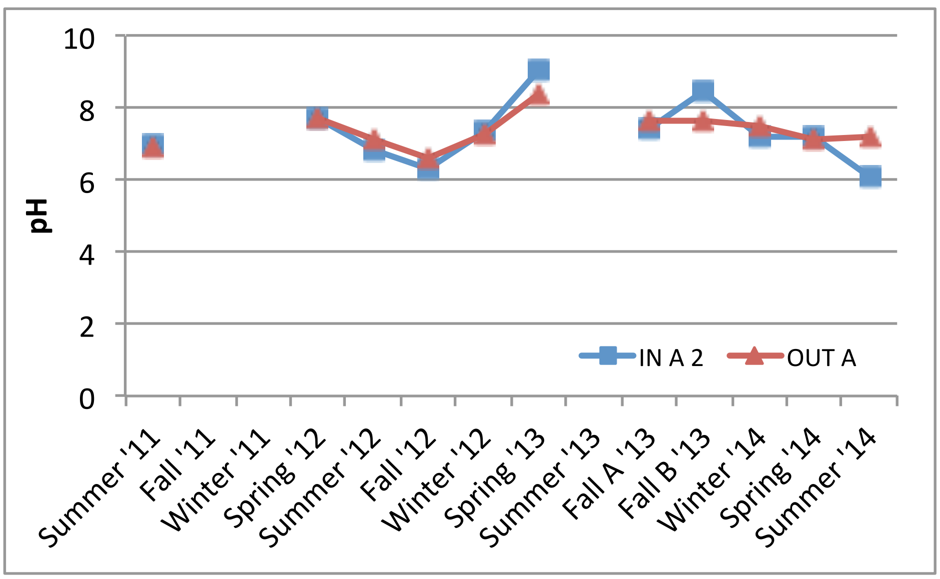
10
9
8
7
6
pH
5
4
3
2
1
0
IN B 2
OUT B
Aug '12
Sept '12
Oct '12
Nov '12
Dec '12
Jan '13
Feb '13
Mar '13
Apr '13
May '13
Jun '13
Jul '13
Aug '13
Sep '13
Oct '13
Nov '13
Dec '13
Jan '14
Feb '14
Mar '14
Apr '14
May '14
June '14
Jul '14

Course 4 System A

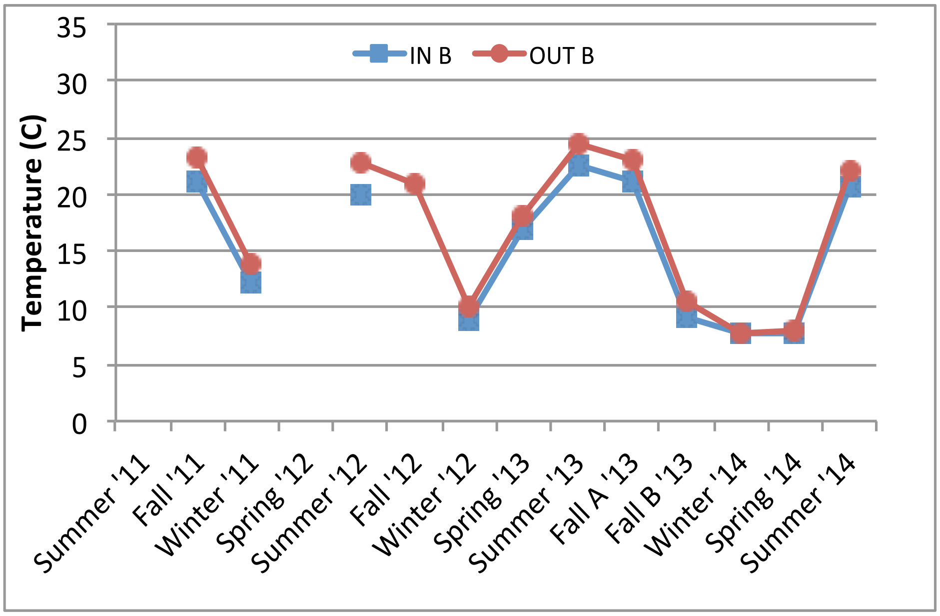


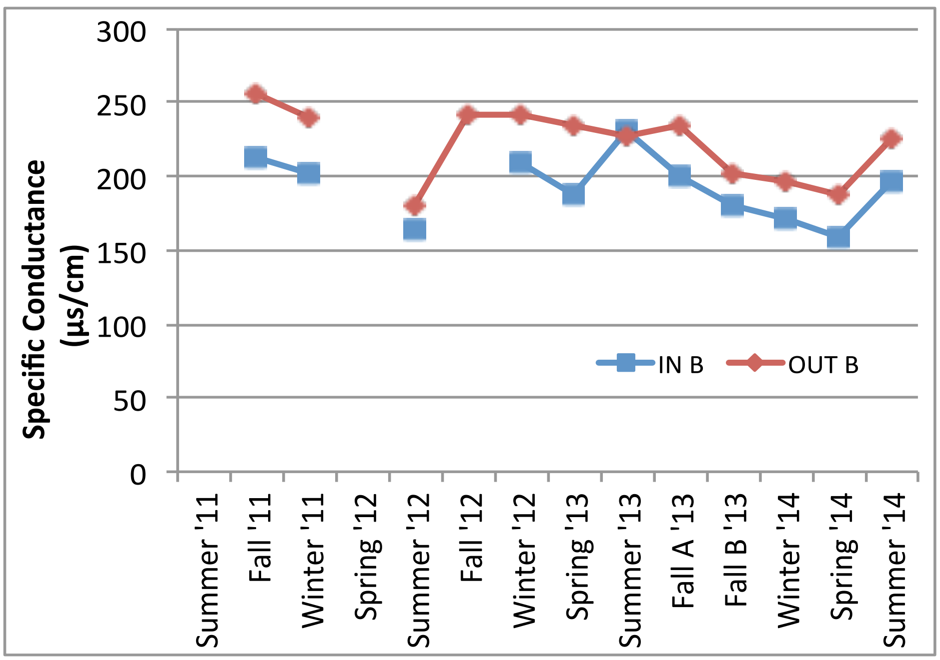


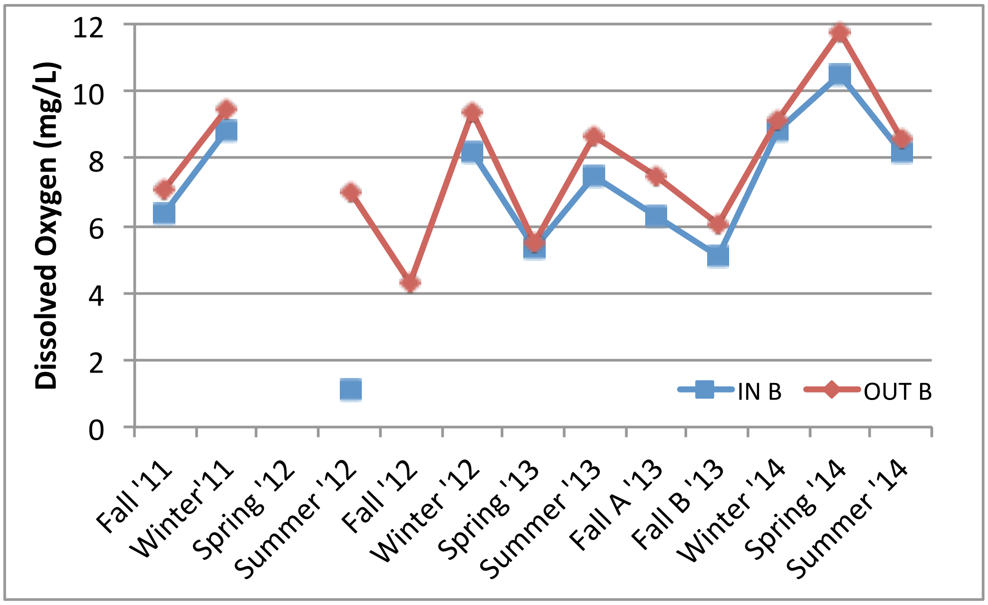

Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
IN A 2
OUT A
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14


pH
10
8
6
4
2
0
IN A 2
OUT A
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

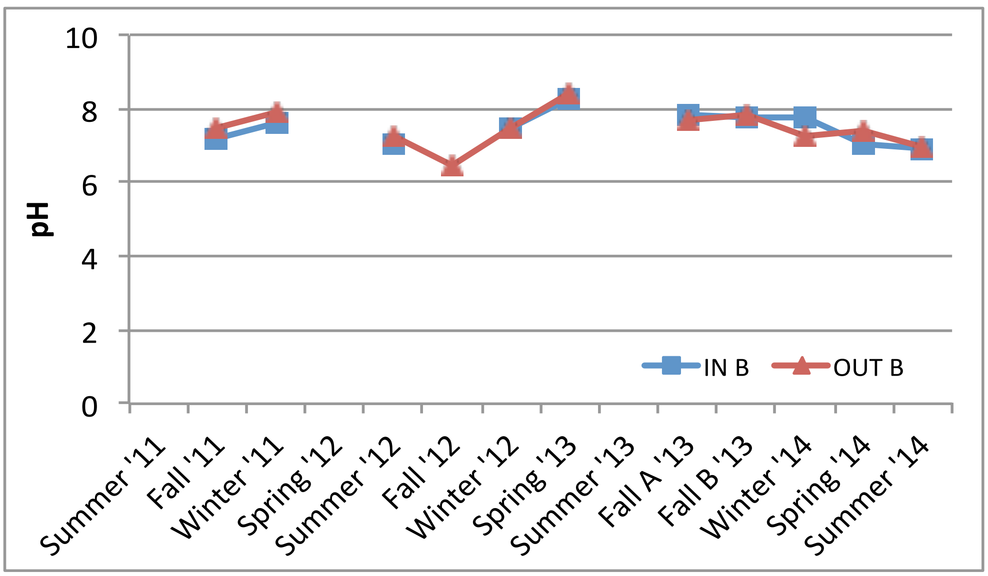
Course 4 Stream B





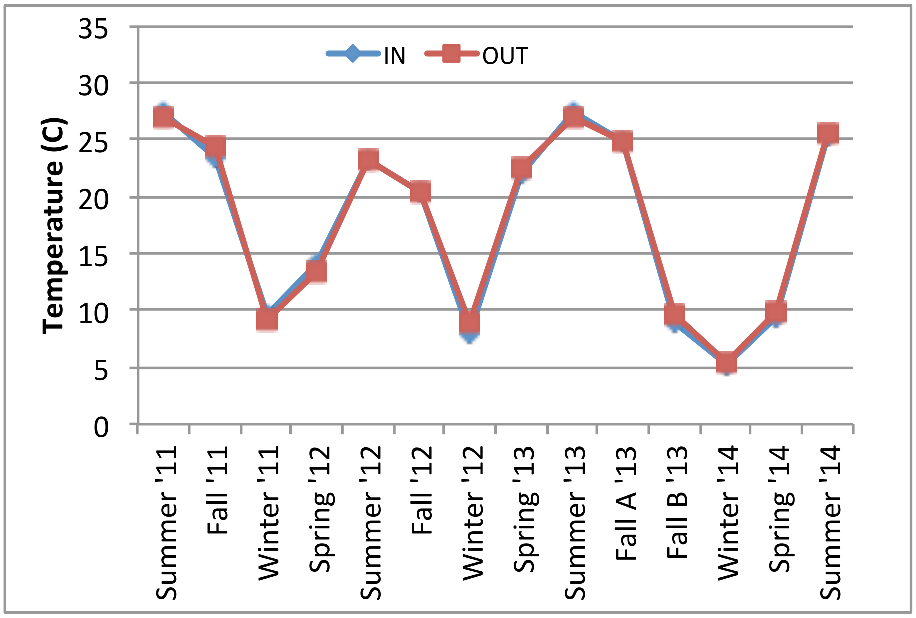


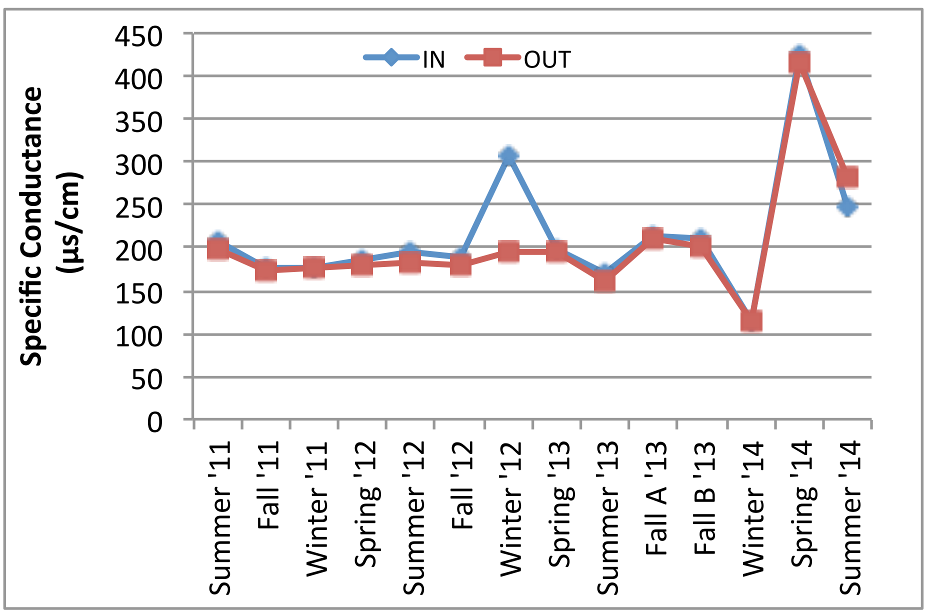
Dissolved Oxygen (mg/L)
12
10
8
6
4
2
0
IN B
OUT B
Fall '11
Winter'11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

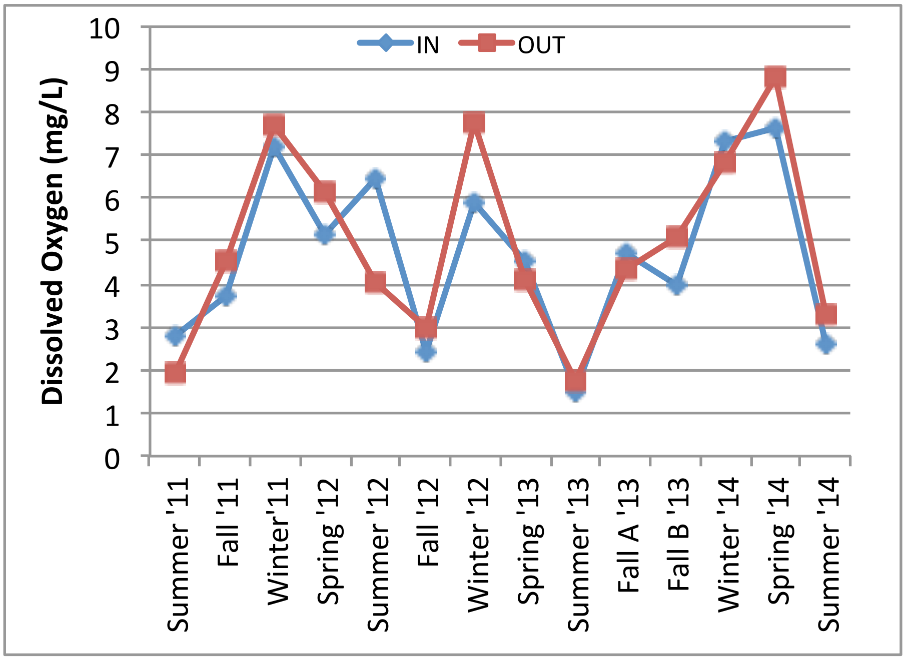


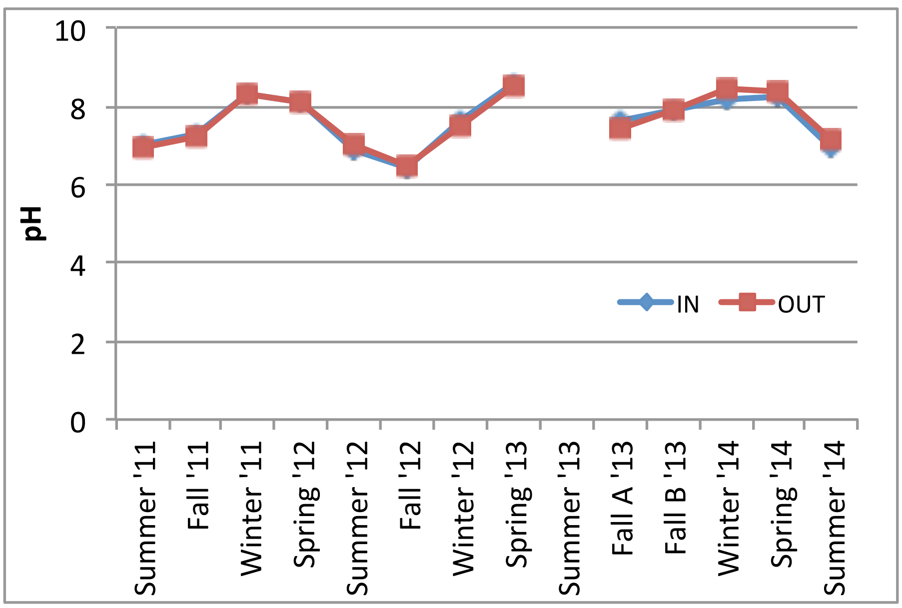
pH
10
8
6
4
2
0
IN B
OUT B
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

Course 5 Stream

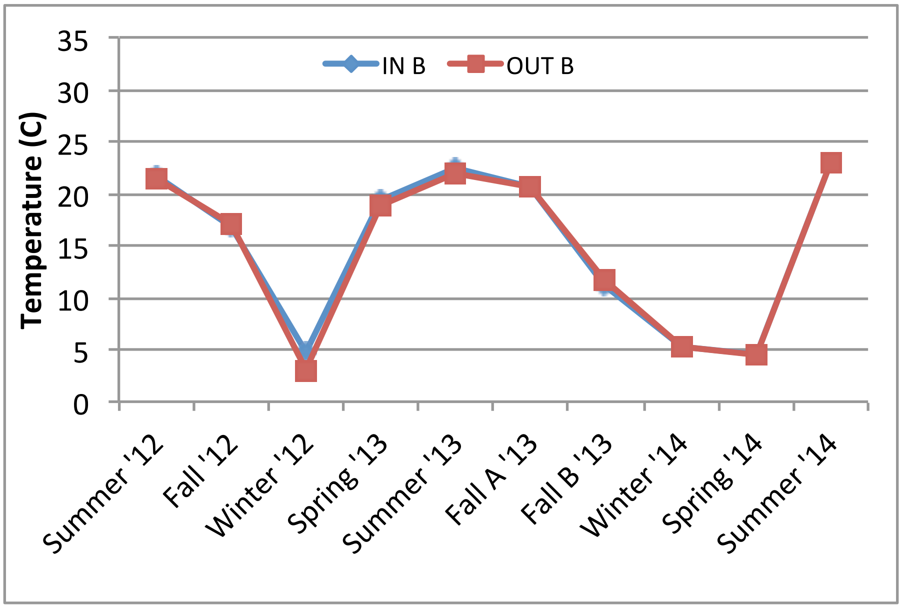


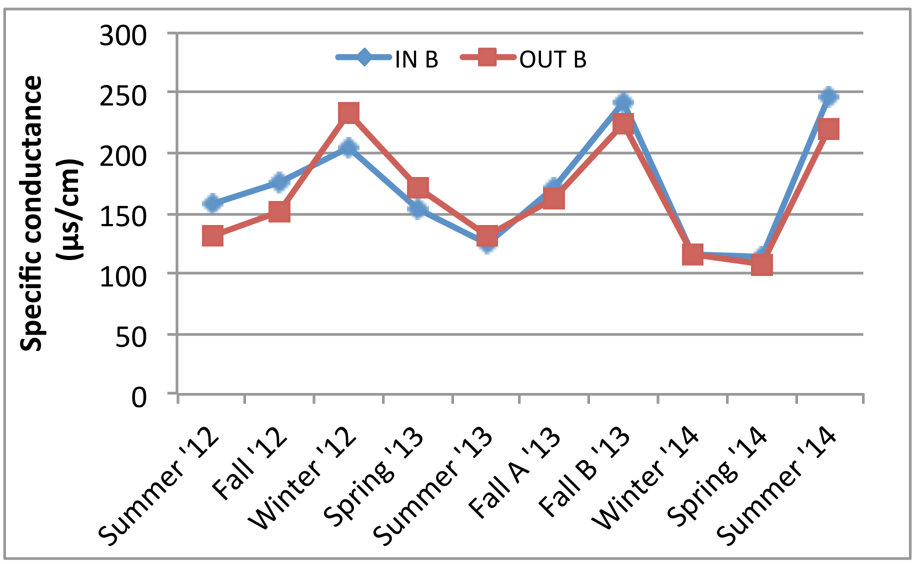


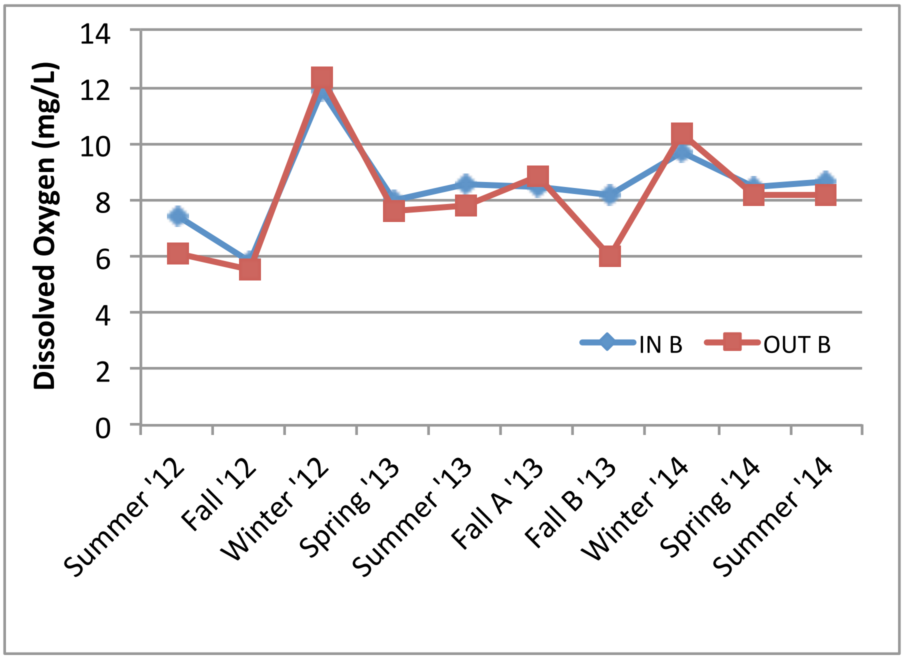

Dissolved Oxygen (mg/L)
IN
OUT
10
9
8
7
6
5
4
3
2
1
0
Summer '11
Fall '11
Winter'11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14


pH
IN
OUT
10
8
6
4
2
0
Summer '11
Fall '11
Winter '11
Spring '12
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

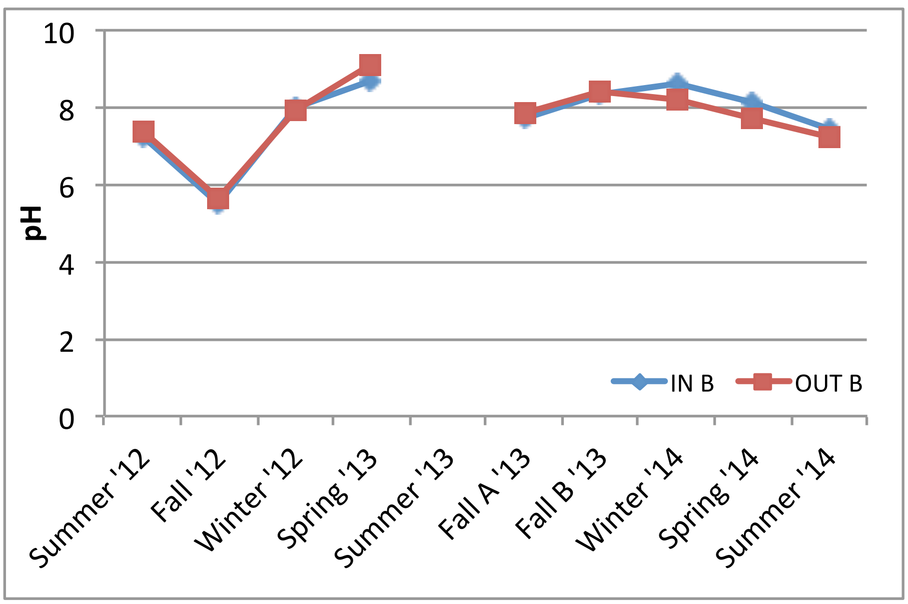
Course 6 Stream B





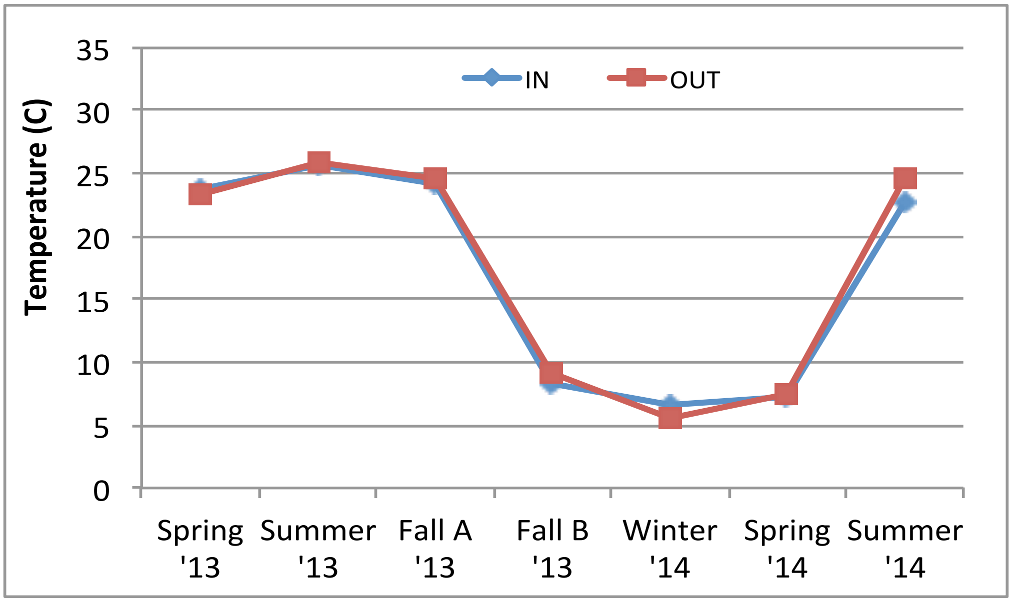


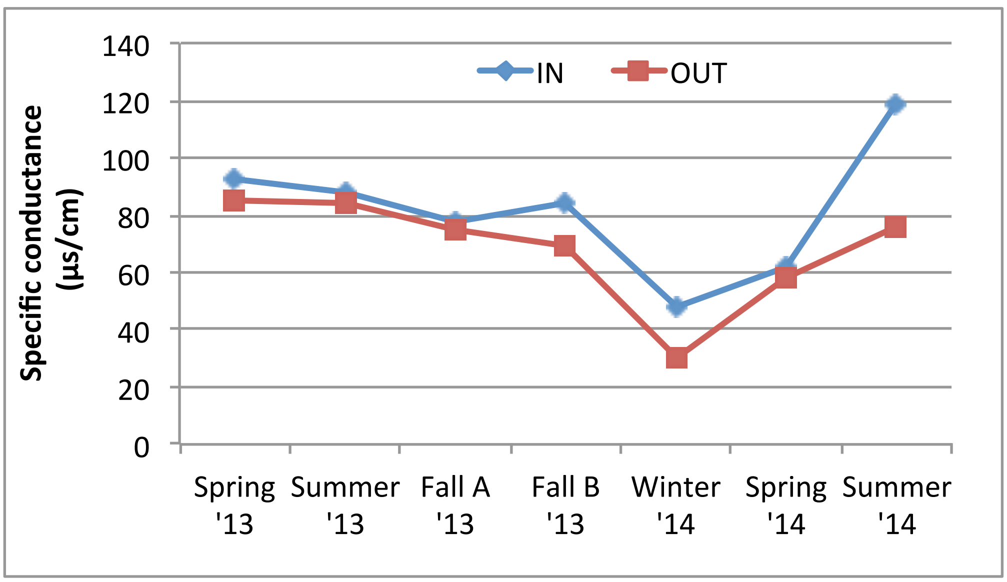
Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
IN B
OUT B
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

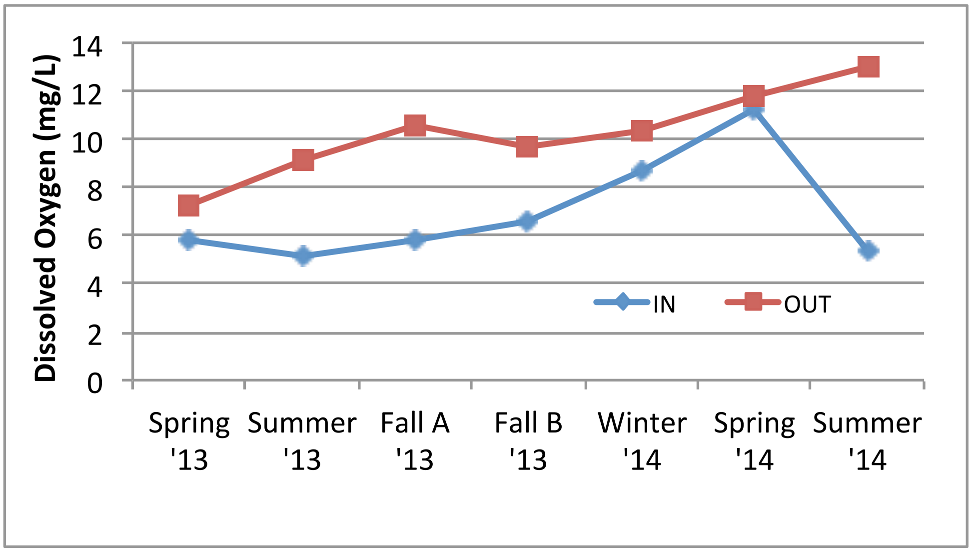


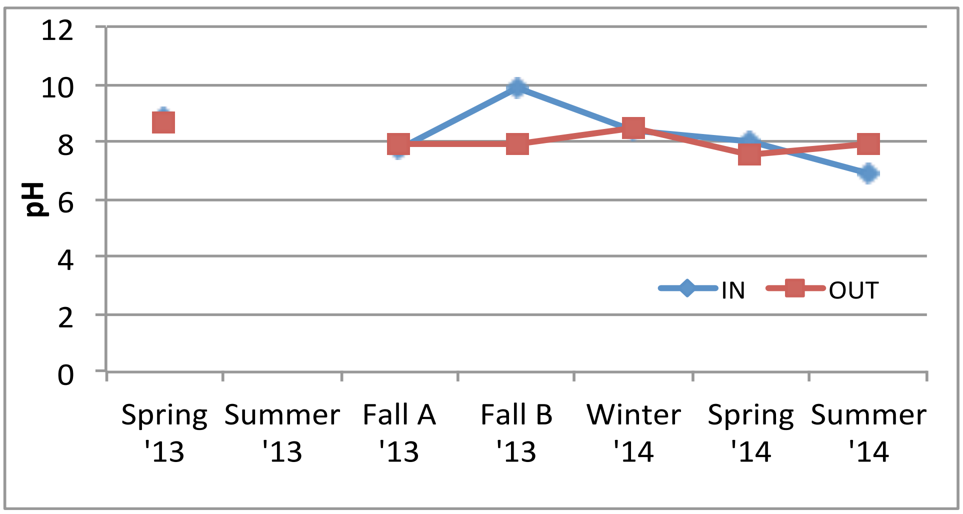
pH
10
8
6
4
2
0
IN B
OUT B
Summer '12
Fall '12
Winter '12
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

Course 7 Stream

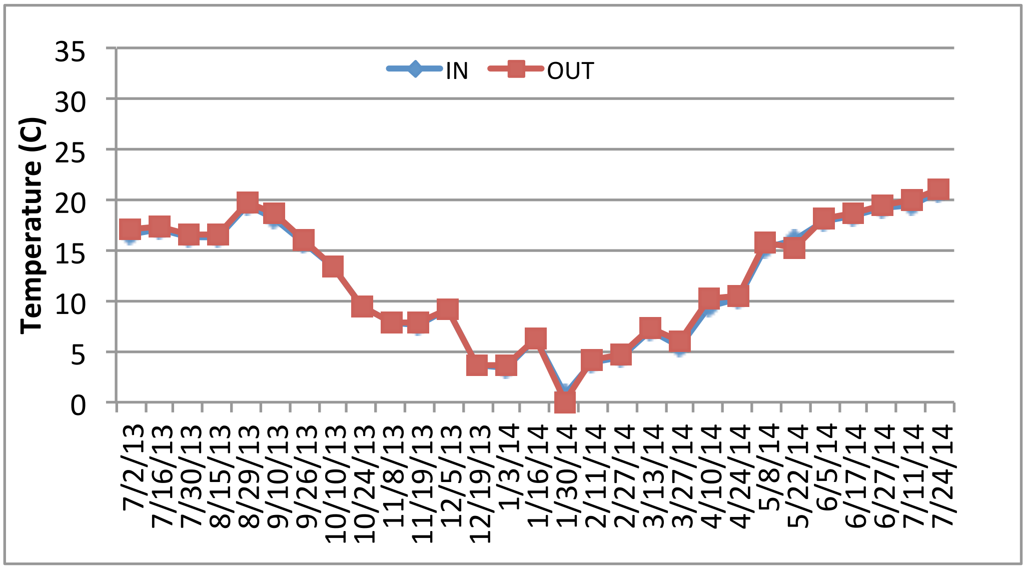


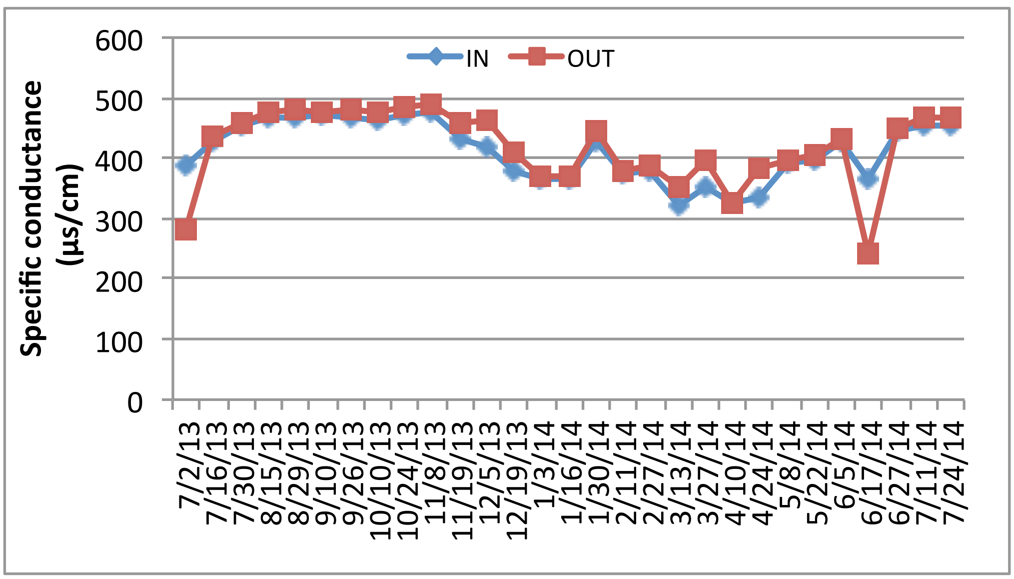


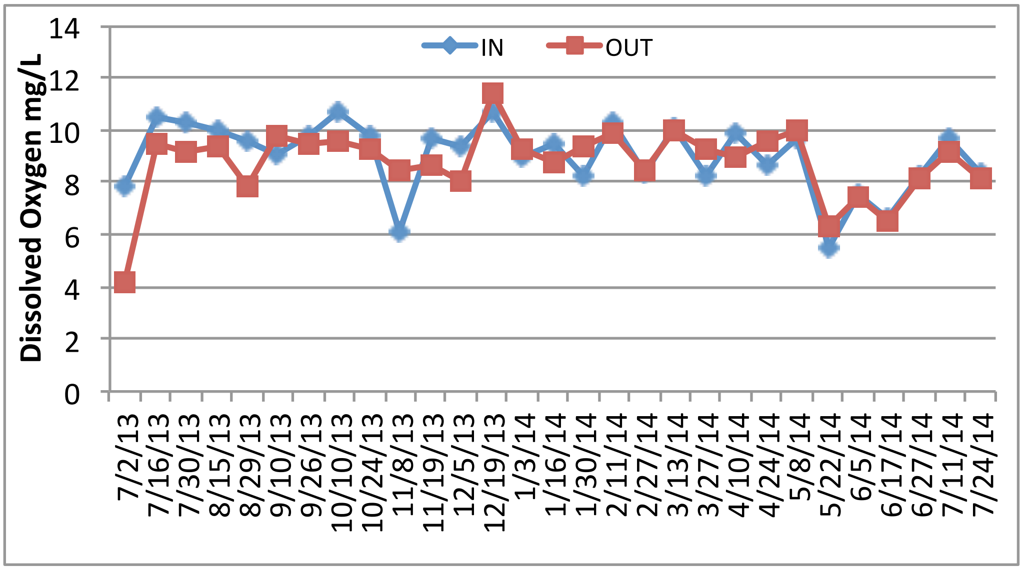

Dissolved Oxygen (mg/L)
14
12
10
8
6
4
2
0
IN
OUT
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14


pH
12
10
8
6
4
2
0
IN
OUT
Spring '13
Summer '13
Fall A '13
Fall B '13
Winter '14
Spring '14
Summer '14

Course 8 Stream






Dissolved Oxygen mg/L
IN
OUT
14
12
10
8
6
4
2
0
7/2/13
7/16/13
7/30/13
8/15/13
8/29/13
9/10/13
9/26/13
10/10/13
10/24/13
11/8/13
11/19/13
12/5/13
12/19/13
1/3/14
1/16/14
1/30/14
2/11/14
2/27/14
3/13/14
3/27/14
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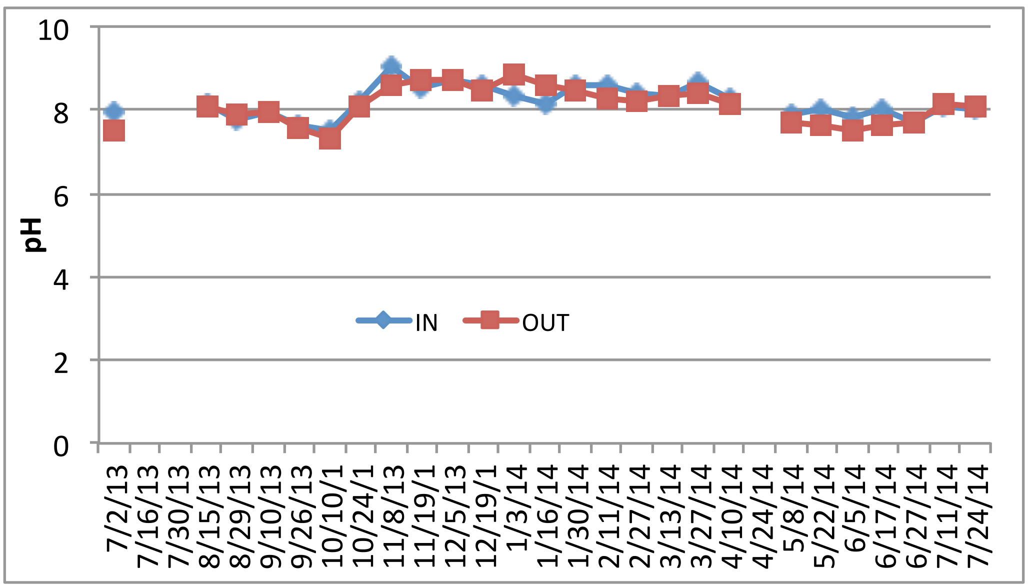
6/17/14
6/27/14
7/11/14
7/24/14


pH
IN
OUT
10
8
6
4
2
0
7/2/13
7/16/13
7/30/13
8/15/13
8/29/13
9/10/13
9/26/13
10/10/1
10/24/1
11/8/13
11/19/1
12/5/13
12/19/1
1/3/14
1/16/14
1/30/14
2/11/14
2/27/14
3/13/14
3/27/14
4/10/14
4/24/14
5/8/14
5/22/14
6/5/14
6/17/14
6/27/14
7/11/14
7/24/14

APPENDIX C. PRELIMINARY ANOVA ANALYSIS INDICATING NON-SIGNIFICANCE OF SEASONALITY

SAS analysis based on partial seasonal data collected at James River Watershed courses at all course sites except Course 1 Stream B and the Course 3 Wash Pad. Data included through Winter 2014.

The SAS System
Statistical analysis on nitrate value

The GLM Procedure

Class Level Information

Class	Levels	Values
InOut	4	1 2 3 4
Site	12	1 2 3 4 5 6 7 8 9 10 11 12
Season	4	1 2 3 4

Number of Observations Read 314
Number of Observations Used 314

The SAS System
statistical analysis on nitrate value

The GLM Procedure

Dependent Variable: Nitrate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	40	491.7833120	12.2945828	19.55	<.0001
Error	273	171.6561264	0.6287770		
Corrected Total	313	663.4394383			

R-Square	Coeff Var	Root MSE	Nitrate Mean
0.741263	58.85263	0.792955	1.347356

Source	DF	Type I SS	Mean Square	F Value	Pr > F
InOut	3	9.3641429	3.1213810	4.96	0.0023
Site	11	356.4152280	32.4013844	51.53	<.0001
Season	3	9.5414073	3.1804691	5.06	0.0020
InOut*Site	14	112.5951539	8.0425110	12.79	<.0001
InOut*Season	**9**	**3.8673798**	**0.4297089**	**0.68**	**0.7238**

Source	DF	Type III SS	Mean Square	F Value	Pr > F
InOut	3	79.0872554	26.3624185	41.93	<.0001
Site	11	355.5190073	32.3199098	51.40	<.0001
Season	3	7.0397350	2.3465783	3.73	0.0118
InOut*Site	14	112.6582643	8.0470189	12.80	<.0001
InOut*Season	**9**	**3.8673798**	**0.4297089**	**0.68**	**0.7238**

The SAS System 1
Statistical analysis on Ammonium

The GLM Procedure

Class Level Information

Class	Levels	Values
InOut	4	1 2 3 4
Site	12	1 2 3 4 5 6 7 8 9 10 11 12
Season	4	1 2 3 4

Number of Observations Read 314
Number of Observations Used 314

The SAS System
Statistical analysis on Ammonium

The GLM Procedure

Dependent Variable: Ammonium

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	40	0.68811392	0.01720285	0.93	0.6027
Error	273	5.07476552	0.01858888		
Corrected Total	313	5.76287944			

R-Square	Coeff Var	Root MSE	Ammonium Mean
0.119405	234.5389	0.136341	0.058132

Source	DF	Type I SS	Mean Square	F Value	Pr > F
InOut	3	0.01534011	0.00511337	0.28	0.8434
Site	11	0.23725808	0.02156892	1.16	0.3149
Season	3	0.02104372	0.00701457	0.38	0.7694
InOut*Site	14	0.37490131	0.02677867	1.44	0.1339
InOut*Season	**9**	**0.03957070**	**0.00439674**	**0.24**	**0.9889**

Source	DF	Type III SS	Mean Square	F Value	Pr > F
InOut	3	0.01935235	0.00645078	0.35	0.7913
Site	11	0.23725770	0.02156888	1.16	0.3149
Season	3	0.00583873	0.00194624	0.10	0.9573
InOut*Site	14	0.37987152	0.02713368	1.46	0.1259
InOut*Season	**9**	**0.03957070**	**0.00439674**	**0.24**	**0.9889**

Statistical analysis on P value

The GLM Procedure

Class Level Information

Class	Levels	Values
InOut	4	1 2 3 4
Site	12	1 2 3 4 5 6 7 8 9 10 11 12
Season	4	1 2 3 4

Number of Observations Read	314
Number of Observations Used	314

Statistical analysis on P value

The GLM Procedure

Dependent Variable: P

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	40	0.13377526	0.00334438	8.80	<.0001
Error	273	0.10376869	0.00038011		
Corrected Total	313	0.23754395			

R-Square	Coeff Var	Root MSE	P Mean
0.563160	216.9324	0.019496	0.008987

Source	DF	Type I SS	Mean Square	F Value	Pr > F
InOut	3	0.00602127	0.00200709	5.28	0.0015
Site	11	0.05335569	0.00485052	12.76	<.0001
Season	3	0.01030309	0.00343436	9.04	<.0001
InOut*Site	14	0.06203483	0.00443106	11.66	<.0001
InOut*Season	**9**	**0.00206038**	**0.00022893**	**0.60**	**0.7948**

Source	DF	Type III SS	Mean Square	F Value	Pr > F
InOut	3	0.00793798	0.00264599	6.96	0.0002
Site	11	0.05371441	0.00488313	12.85	<.0001
Season	3	0.00249682	0.00083227	2.19	0.0896
InOut*Site	14	0.06220462	0.00444319	11.69	<.0001
InOut*Season	**9**	**0.00206038**	**0.00022893**	**0.60**	**0.7948**

APPENDIX D. PERMISSIONS

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