Creation and functioning of a buffer zone in an upland peat forest

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Abstract

Buffer zones can be used to reduce nutrient and suspended sediment export following forest clearfelling by directing runoff over a vegetated area. This study demonstrates the achievability of constructing a buffer zone by initially clearfelling the standing forest, seeding with two native grass species and directing the water from a semi-natural stream draining an upstream 10 ha forested peatland site through it. Following the clearfelling of the upstream study site this study tested the efficacy of this management practice in reducing nutrient and suspended sediment concentration in the receiving water. The buffer zone reduced total reactive phosphorus (TRP) and suspended sediment (SS) loads by 18% and 33%, respectively. Phosphorus (P) retention efficiency was dependent on inlet concentrations, loading and hydraulic loading rates. In storm events with a loading rate of >28 g P ha^{-1}, a flow rate higher than 88.5 L s^{-1} and an inlet concentration of <17 μg L^{-1} the buffer zone became a TRP release source. The maximum P concentration in the buffer zone did not exceed 40 μg L^{-1} during this study demonstrating that the buffer zone method could be used efficiently in peatland forestry to moderate the high P concentrations and assist in protecting salmonids and freshwater pearl mussels.

Key words: peatland forest, buffer zone, phosphorus, retention, grass seeding

1. Introduction

Buffer zones are widely used for water management in urban and agricultural catchments (Correll, 2005). The fundamental concept is to prevent erosion, increase sedimentation and improve water quality by directing outflow through a vegetated area retaining storm runoff and reducing peak discharge. Similarly, buffer zones have been used in forestry (Aust and Blinn, 2004; Luke et al.,2007; Parkyn et al., 2005) and more specifically peatland forestry in boreal conditions (Ihme, 1994; Heikkinen et al., 1995; Kubinet al., 2000; Nieminen et al., 2005; Väänänen et al., 2008). In this study we applied the buffer zone method for the first time to peat-land forestry in moderate oceanic climatic conditions where forests were established without buffer zones and trees planted to the stream edge (Broadmeadow and Nisbet, 2004; Ryder et al., 2011).Approximately 3.75% of the world's peatlands have been drained for commercial forestry (Joosten and Clarke, 2002). In the northern hemisphere peatland afforestation was practiced extensively during the late 20th century (Paavilainen and Päivänen,1995) and with many of these peatland forests now reaching harvestable age, concerns have been raised about the potential impact of forest harvesting on the receiving aquatic systems. Peatland forest harvesting operations in temperate maritime climatic conditions are particularly environmentally challenging due to high annual precipitation (Müller, 2000; Rodgers et al., 2010), high soil water content, (Long and Jennings, 2006), low ground bearing capacity (Owende et al., 2002) and typically high ecological sensitivity of the receiving waters (O'Driscoll et al., 2012). Increases in nutrient and suspended sediment concentrations have been well documented (Cummins and Farrell, 2003a; Nieminen, 2003; Rodgers et al., 2010, 2011) associated with the degradation of logging residues and mechanical disturbance on the ground (Cummins and Farrell, 2003a; Nieminen, 2003; Rodgers et al., 2010). Excess nitrogen (N) and phosphorus (P) input to receiving waterbodies can trigger eutrophication thus deteriorating water quality (European Union, 2000). Similarly, high organically derived sus-pended sediment (SS), could consume oxygen resources further damaging the ecological status of receiving water (Paavilainen and Päivänen, 1995; Greig et al., 2007). With timber production set to increase across Europe, supported by governments for its potential to mitigate climate change through carbon sequestration and fossil fuel substitution (Forest Service, 2008; Riipinen et al.,2009; Laudon et al., 2011), and the future of the afforested blanket peats uncertain, there is an urgent need for more evidence to underpin evidence based sustainable forestry policy developments (European Union, 2000; Laudon et al., 2011; Coillte, 2012). Mitigation methods such as felling smaller plantation coupes at one time, whole-tree harvesting and the use of buffer zones have been suggested (Forest Commission, 1988; Forest Service, 2000), however, they are not as of yet supported by extensive scientific evidence. Many of the earlier afforested blanket peat catchments in Ireland and the UK were established without any buffer areas, and trees were planted to the stream edge (Broadmeadow and Nisbet, 2004; Ryder et al., 2011). Establishing buffer zones by harvesting the peatland forest alongside water bodies before harvesting the main coupe behind has been recommended (Forestry Commission,1988; Forest Service, 2000) as a best management practice (BMP) however, there is limited data available to forest managers on the efficacy of this practice (see Ryder et al., 2011; Finnegan et al., 2012). A fundamental concern for the creation of buffer zones following harvesting is the slow vegetation recovery (Connaghan, 2007;O'Driscoll et al., 2011). The novel grass seeding method described by O'Driscoll et al. (2011) presents a solution to overcoming this concern. In addition, the effectiveness of peatland buffers relies to an extent on factors such as buffer size, hydraulic load and inlet concentrations (Väänänen et al., 2008).Given that (1) most of the nutrients released after harvesting occur in soluble form during storm events (Rodgers et al., 2010);(2) peat has low hydraulic conductivity (Lewis et al., 2011) and P adsorption capacity (Tamm et al., 1974); and (3) the spate nature of peatland forested catchments in Ireland and the UK (Müller,2000; Holden and Burt, 2003) the efficacy of buffer zones for these blanket peat sites is questionable. Based on the findings of earlier studies, four hypotheses were addressed in this present study. These hypotheses were that: a recently harvested peatland forest site would serve as a vegetated buffer zone if a novel grass seeding method was implemented at the site and runoff was directed through this buffer zone area by blocking the stream (H1); forest clearfelling the upstream 10 ha catchment would increase total reactive phosphorus (TRP), total oxidised nitrogen (TON), ammonium (NH4-N) and SS concentrations in the receiving water (H2);the buffer zone would be efficient in removing SS but not TRP, TON and NH4-N (H3); and factors such as inlet concentrations, loading and hydrologic loading rates would play an important role in percentage retentions (H4). From an international perspective the findings of this study will contribute important qualitative and quantitative data on the creation and functioning of buffer zones in blanket peat forested catchments in moderate climates receiving high and frequent precipitation.

2. Materials and Methods

2.1 Sites description and buffer zone construction

Buffer zone construction was carried out in the Glennamong, a sub-catchment of the Burrishoole Catchment, Co. Mayo (53°58’ N - 9°37’ E, 69 m a.s.l.) (Fig. 1). An upstream forest catchment (10 ha) which was to be felled during the study period was used as the study site and a 1 ha area downstream of this study site was used for the establishment of the buffer zone. The study site and buffer zone are drained by a semi-natural stream. The Glennamong catchment was planted in 1972 with a combination of lodgepolepine (*Pinus contorta*) (86%) and sitka spruce (*Picea sitchensis*) (13%) using spaced-furrow ploughing, manually applied rock phosphate fertiliser (at a rate of 13.2 kg P ha^{-1}) and nursery-grown transplants. Thinning was not generally carried out on upland western blanket peats due to windthrow risk (Cummins and Farrell, 2003a).The average depth of the peat in the buffer zone was circa 0.5 m and the peat profile also contained sand deposits of varying thick-ness. These layers were probably formed of the material that was displaced from the ditches during the initial drainage in the early1980s. A more detailed description of soil characteristics can be found in Asam et al. (2012).The buffer zone was constructed by initially clearfelling the standing forest in August 2009. Brash material (branches and logging residues) was removed from the site and drainage channels were defined around the 1 ha area. Two months after clearfelling, five plots were identified within the buffer zone, three of which could potentially have stream water from the study site diverted through them (buffer plots P1, P2, P3) and two of which could not(C1, C2) and would serve as controls. The buffer plots areas were as follows: 0.01 ha (P1 in Fig. 1), 0.036 ha (P2 in Fig. 1), and 0.066 ha (P3 in Fig. 1) accounting for 1.12% of the area of study site. Each buffer plot received the same sowing treatment, which comprised fifty: fifty ratios of *Holcus lanatus* L. and *Agrostis capillaris* L. The two control plots were left un-seeded. The seed was distributed evenly by hand at an initial rate of 36 kg ha^{-1} on top of the undisturbed old forest residue layer in October 2009. December 2009 and January2010 were exceptionally cold months, and a layer of snow measuring 30 cm in depth was recorded on the ground above the seeded area. To eliminate the risk of seed establishment failure, the plots were re-seeded in February 2010 at the same rate of 36 kg ha^{-1}. The stream was diverted through the buffer zone in September 2010. Areas of preferential flow and furrows were identified and blocked using either peatbags or corrugated recycled plastic. Bole only harvesting was conducted on the upstream forest (~10 ha) between February 2011 and April 2011. The timber was harvested using a Timberjack 1470D harvester and the boles (merchantable timber) were stacked beside the windrow for collection. Some of the brash material was laid out in mats to protect the soil surface and reduce erosion and the remainder was collected into windrows and left onsite to degrade. During harvesting an 8-wheeled

Timberjack 1110forwarder delivered the boles to truck collection points beside the forest road.

2.2 Instrumentation setup and water sampling analysis

In January 2010 the stream was instrumented with two flow and water quality monitoring stations at stable channel sections, one downstream of the study site and at the inflow to the bufferzone (GSS) and the second further downstream at the outflow of the buffer zone (BZS). An H-flume, a water level recorder and a datalogger were installed at each station, along with a tipping bucket rain gauge. Readings were recorded every 5 min. Water samples were taken for TRP, TON, NH4-N and SS analysis at each station during storm events, on a weekly basis over the study period using an ISCO automated water sampler. All water samples were frozen at −20°C in accordance with the standard methods (APHA, 1998) until water quality analyses were conducted. The TRP, TON andNH4-N were analysed using a Konelab 20 Analyser (Konelab Ltd.,Finland). SS was analysed based on the standard methods (APHA,1998).

2.3 Soil water extractable (WEP) and total (TP) content measurement

20 cm deep soil cores were collected using a 3 cm diameter gouge auger in the buffer zone area. 4, 8, and 14 soil samples were taken from plot 1, 2, and 3, respectively, and 4 samples were taken from the control areas in April 2009, 2010 and 2011. Soils samples were analysed for gravimetric water content, WEP and TP. The core samples were placed in bags, mixed by hand until visually homogenised, and subsamples of approximately 0.5 g (dry weight) were removed and extracted in 30 ml of deionised water on a reciprocating shaker at 250 rpm for 30 min. The supernatant was then filtered (0.45 μm) and measured for P using a Konelab20 Analyser. Second subsamples of approximately 5 g (wet weight) were removed and dried to determine their gravimetric moisture content (Macrae et al., 2005). The dried subsamples were then put into a furnace at a temperature of 550°C for 24 h. 5 ml of 2 N HCl was added to extract the TP and they were subsequently diluted to50 ml with deionised water. P in the solution was analysed using a Konelab 20 Analyser (Konelab Ltd.) to determine the TP content. As this study was conducted in the year immediately following harvesting and N increases are typically observed one year after harvesting (Cummins and Farrell, 2003b), nitrogen analyses were not conducted on the soil and grass samples.

2.4 Aboveground vegetation biomass and P content measurement

To estimate the aboveground vegetation biomass in the buffer zone, 32 25 cm × 25 cm quadrats were randomly sampled (8 in plot1; 11 in plot 2; 9 in plot 3 and 4 in the control plots) in August 2010,and again in August 2011. All vegetation lying within the quadrat was harvested to within 1 cm and dried at 80°C in the laboratory on the day of collection for 48 h. Samples were then weighed, for above ground biomass calculation. Dried samples were milled to pass a 0.2 cm sieve and TP content of the vegetation was measured in accordance with Ryan et al. (2001). About 1 g (dry matter) of milled sample was weighed, and put into a furnace at a temperature of 550°C overnight, then 5 ml of 2 N HCl was added to extract the

TP and subsequently diluted to 50 ml with deionised water. P in the solution was analysed using a Konelab 20 Analyser (Konelab Ltd.).

2.5 Data analyses

It has been reported that in the peatland forest 70% of the Prelease occurred during episodic storm events (Rodgers et al., 2010, 2011). In addition, the performance of buffer zone on P retention is significantly affected by the hydrological conditions. Therefore this study mainly focused on storm events. A storm event was defined as a block of rainfall that was preceded and followed by at least 12 h of no rainfall (Hotta et al., 2007). As the flow is variable during a storm event, it is difficult to determine the hydraulic retention time at a certain flow rate using tracers. This buffer zone has a slope of 2–5°and has a relatively small volume of stored water which could be exchanged with the runoff. The assumption has therefore been made that the faster the runoff water passing through the buffer zones the lower the hydraulic retention time. The time that the runoff needed to pass through the buffer zone is estimated as the time difference of the peak flow passing through GSS and BZS in storm events (Fig. 2).In this study, the nutrient and SS loads in the first year after harvesting were estimated using the methods described in Rodgers et al. (2010, 2011). The nutrient and SS loads during each sampled storm event were also estimated using the following equation:

$$L = \frac{\sum C_i * Q_i}{\sum Q_i} * Q_T$$

where L is the load, C_i and Q_i are the instantaneous concentration and flow at time *i* and Q_T is the total flow during the storm event. To further investigate the relationship between the retention efficiency and the flow rate and input concentrations, the peak flow instantaneous retention efficiency was calculated for each sampled storm event using the following equation:

$$\%\ retention = \left(1 - \frac{Q_{t2}C_{t2}}{Q_{t1}C_{t1}}\right) * 100$$

where Q_{t1} and Q_{t2} are the peak flow rates at the GSS and the BZS during a storm event, respectively; Ct1and Ct2are the concentrations in the peak flows at the GSS and the BZS during a storm event. Comparisons of discharge and precipitation in the year's pre-and post-buffer construction were made using two sample t-tests or Mann–Whitney U-tests (where data were non-normal, and transformations were not appropriate). The software package R(R Development Core Team, 2008) was used to examine the variation in the TP and the WEP concentrations in the soil samples. Differences in WEP and TP were examined using analysis of variance (ANOVA) to determine the subset of explanatory variables that best explained the variation in the data. Model selection was based on AIC (Akaike information criterion). The data were tested for normality, homogeneity and independence to check whether the assumptions of linear modelling were met. Where conditions for normality were not fulfilled the analysis was performed on log transformed data. Significance was determined at the 95% level unless otherwise noted.

3. Results

3.1 Precipitation and runoff retention pre- and post-buffer water spreading

Total precipitation from a nearby Met Eireann weather station(circa 5.5 km south of the study site) was 1736 mm pre-buffer water spreading (September 2009–August 2010) and 1962 mm post-buffer water spreading (September 2010–August 2011) (Marine Institute, unpublished data) and precipitation was not significantly higher in the post-buffer water spreading period (Mann–Whitney U-test, $P = 0.9004$). However, due to a larger number of outliers in the rainfall data post-buffer water spreading, further investigation was carried out on the variation of daily and monthly precipitation for these periods (Fig. 3). The number of wet days (>1 mm of precipitation/ day (Hundecha and Bárdossy, 2005)) recorded pre-buffer water spreading was 226 and post-buffer water spreading was 213.The average daily precipitation pre-buffer water spreading was4.8 mm and post-buffer water spreading was 5.4 mm. Precipitation data indicates that there were 14 heavy precipitation (>20 mm/ day (Ryder et al., 2011)) occurrences pre-buffer water spreading and 25such occurrences post-buffer water spreading (Fig. 3). Whilst the numbers of heavy precipitation events were greater post-buffer water spreading (Fig. 3), overall, daily precipitation pre- and post-water spreading were similar indicating that rainfall is not likely to impact on the results. The time it took for the storm to pass through the buffer zone and its peak flow rate in both before and after water spreading was described by an exponential relationship ($R^2 = 0.65$, before water spreading and $R^2 = 0.55$ after water spreading (Fig. 4)). Diverting the stream water through the buffer zone significantly increased the passing through time (t-test, $P < 0.01$) (Fig. 4). Storm peak flow rates were not significantly reduced (Fig. 5a). Monthly runoff passing through buffer zone was marginally higher than that of study site (Fig. 5b).

3.2 Suspended sediment (SS) retention

The average SS concentrations measured before clearfelling were 43.47 ± 51 SS mg L^{-1} and 11.99 ± 28.55 SS mg L^{-1} at the GSS and BZS, respectively (Fig. 6). After clearfelling, the average SS concentrations were 27.47 ± 27 SS mg L^{-1} at the GSSand14.65 ± 11 SS mg L^{-1} at the BZS. The values observed were not typical of reported baseline values for upland peat sites (Rodgers et al., 2011). The most likely causes of these high values were (1) buffer zone construction, (2) buffer water spreading, and (3) the development of an old forest road during the study site pre-felling baseline data collection period. Further investigations into the nature of the SS released from the buffer zone over the study period indicated that the majority of SS released pre-felling was derived from inorganic material (i.e. the road material) and the majority of SS released post-felling was organic in nature (i.e. disturbance from felling activities on the upstream study site) (Fig. 7). A total of 3780.5 kg of SS were released from the study site in the year following clearfelling (February 2011 to January 2012), giving the SS input loading rate to the buffer zone of 33,754 kg $SSha^{-1}$. From February 2011 to January 2012, a total of 11051.5 kg $SSha^{-1}$ was retained by the buffer zone, with the retention efficiency of ~33%.

3.3 Nutrient runoff and retention

The average P concentration measured in the rainfall during the study period was 4 ± 3 $\mu g\ L^{-1}$TRP. Total reactive phosphorus (TRP) concentrations at the GSS and BZS stations were low before clear-felling, with average values of 13 ± 4 $\mu g\ L^{-1}$ and 12 ± 3 $\mu g\ L^{-1}$ at the GSS and BZS, respectively (Fig. 9). Four weeks after the clearfelling operations began, daily discharge weighted mean P concentrations at the GSS station started to increase and increased gradually to a maximum of 101.7 $\mu g\ L^{-1}$ by the end of the felling period. During the same period the maximum P concentration in the buffer zone outflow did not exceed 40 $\mu g\ L^{-1}$ (Fig. 8). A total of 6.17 kg of TRP were released from the study site in the year following clearfelling (February 2011 to January 2012). The TRP input loading rate to the buffer zone was 55 kg TRP ha^{-1}. From February 2011 to January2012, a total of 9.7 kg TRP $ha^{-1}$was retained by the buffer zone, the retention efficiency of ~18%. Analyses from 20 storm events over the duration of the study period highlighted that higher TRP loading rates resulted in lower retention percentages (Fig. 9a). In storm events with a loading rate of >28 g P ha^{-1}, the buffer zone became a TRP release source (Fig. 9a). The buffer zone started to release P when the flow rate was higher than 88.5 L s^{-1} (Fig. 9b) and when the inlet P concentration was lower than 17 $\mu g\ L^{-1}$ (Fig. 9c).

WEP concentrations were significantly lower in both the buffer and control plots ($p < 0.001$) before felling (Fig. 10a). In 2011, the soil WEP continued to increase in the control plots, but decreased in the buffer plots. Soil TP concentrations were significantly reduced ($p < 0.05$) to 0.27 ± 0.06 mg g^{-1}dry soil and0.28 ± 0.06 mg g^{-1}dry soil in the buffer and control plots, respectively (Fig. 10b), after clearfelling. In 2011, soil TP increased in the buffer plots (0.30 ± 0.07 $\mu g\ L^{-1}$) and remained the same in the control plots (0.28 ± 0.01 $\mu g\ L^{-1}$). Aboveground vegetation biomass and P content increased one year after grass seeding (Fig. 11). In 2011, the vegetation in the buffer zone had increased 5-fold in the buffer plots (6043, 7438 and 9992 kg ha^{-1}in P1, P2 and P3, respectively) compared to the control plots (1200 kg ha^{-1}). The corresponding P content was 9.73 ± 1.14 kg ha^{-1}, 7.80 ± 0.72 kg ha^{-1}, and 7.61 ± 0.87 kg ha^{-1}in P1, P2, and P3, respectively, in comparison to the control plots which contained only 1.00 ± 0.1 kg ha^{-1}.The average TON concentration measured in the rainfall during the study period was 69 ± 28 $\mu g\ L^{-1}$, however, TON concentrations at the GSS and BZS were below the limits of detection (<50 $\mu g\ L^{-1}$) before and after clearfelling. These values were less than the average TON in the rainfall. Similarly, the average NH_4-N concentration measured in the rainfall during the study period was74 ± 38 $\mu g\ L^{-1}$ which was greater than the NH_4-N concentrations measured at the GSS and BZS before and after clearfelling.

4. Discussion

4.1 Runoff and suspended sediment (SS)

This study demonstrated that two years after clearfelling and seeding, the constructed buffer zone was well vegetated and the blocking of the semi-natural stream that passed through the buffer zone increased the passing through time of the diverted water. However, storm peak flow rates were not significantly reduced and it is likely that the main flow path in the buffer zone was overland flow, due to the low vertical hydraulic conductivity (10–4m

s^{-1}to10−8m s^{-1}) of the peat soil (Lewis et al., 2011). Dahl et al. (2007) proposed four major flow path types – diffuse flow, overland flow, direct flow and drainage flow – in riparian buffer areas. Hoffmann et al. (2009) found that compared with the other three flow path types; the overland flow had a lower residence time. Addition-ally, the creation of sheet flows has been considered a primary condition for buffer zones (Väänänen et al., 2008). However, in artificially drained forested peatland the presence of furrows con-tributes to higher flow velocity and lower residence times in the buffer (Väänänen et al., 2008). Although the buffer did not reduce storm peak flows it did reduce SS concentrations in the runoff considerably with 33% retention efficiency. The reduction in SS is likely a result of the successful vegetation growth in the buffer zone which allows the suspended particles to efficiently settle down among ground vegetation and surface soil (Nieminen et al., 2005).The smaller SS retention efficiency observed in this study compared to the 70% observed by Nieminen et al. (2005) for a buffer with the same % of watershed area (1.1%) is likely a direct result of relatively higher flow rates in our study sites, the slope of the buffer area and the furrows with preferential flow. While best management practices (BMPs), such as the laying of geotextile material beneath the road were implemented during the road development period this data highlights the ongoing and un-resolved issue of the impacts of forest road construction and the importance of pre-felling data collection in inflow versus outflow studies.

4.2 P retention

The values of total TRP released from the study site after felling are comparable to similar studies which examined the impacts of clearfelling peatland catchments on water quality (Nieminen,2003; Cummins and Farrell, 2003a; Rodgers et al., 2010). The TRP input loading rate reported for this study was high in comparison to comparison to studies reviewed by Hoffmann et al. (2009). The high loading rate was primarily due to the high runoff from the upstream study site which is characteristic of blanket peat catchments (Müller, 2000; Holden and Burt, 2003), combined with the high P concentrations and the relatively small buffer zone area (1.1% of the study site). The P retention result (18%) observed in the current study is lower than comparable studies (see Väänänen et al., 2008), how-ever, it supports the findings of Asam et al. (2012) which used the laboratory flume approach to assess the phosphorus retention efficiency of blanket peat buffers. The lower retention observed in this study is likely a result of preferential flow in the furrows during high hydraulic loading which increased flow velocity and reduced the residence time (Koskiaho et al., 2003). The longer the water residence time the longer time available for P-consuming processes such as microbial immobilisation, soil sorption and vegetative uptake, to be involved in P retention (Väänänen et al., 2008).During buffer zone establishment, soil WEP increased, reflecting the leaching P caused by the decomposition of fallen needles on the forest floor (Hyvönen et al., 2000; Piirainen et al., 2004) and lowered plant uptake after clearfelling (Walbridge and Lockaby, 1994; Herz, 1996). Consequently, due to the leached P after clearfelling, soil TP reduced in the buffer and control plots. The grass seeding resulted in increased aboveground vegetation biomass in the buffer plots compared to the control in 2010 and this increased 5-fold in 2011 highlighting that the novel seeding practice (O'Driscoll et al., 2011) on clearfelled blanket peat was successful in improving buffer zone function. Vegetation has an important role in P retention, not only through P accumulation in the living biomass (Silvan et al., 2004) but also because the living vegetation slows down the water flow in the buffer zones and thereby reduces the formation of preferential flow paths (Braskerud, 2001). Initially added P in wet-lands and peatlands is rapidly allocated into the litter-microbial pool and uptake by vegetation and adsorption in soil will follow within the time scale of several days (Richardson and Marshall, 1986; Kellogg and Bridgham, 2003). However, although the buffer retained 18% of P, when the loading rate was >28 g P ha^{-1}, the flow rate was higher than 88.5 L s^{-1}, and the inlet P concentration was lower than 17 μg L^{-1} the buffer became a source of P. This finding contrasts with the findings of Braskerud et al. (2005) and Syversen and Borch (2005) where higher P retention with a higher load was reported. Though the P retention efficiency is relatively low (18%), the buffer zone does appear to moderate the high P con-centration efficiently. During the course of the study, even though the highest input TRP concentrations were more than 100 μg L^{-1}, the maximum TRP concentration in the buffer zone did not exceed40 μg L^{-1}.

4.3 Nitrogen

Both TON and NH_4-N concentrations did not exceed the rain-fall values measured during the study period. Increased levels of N are typically associated with forest clearfelling (Nieminen, 1998; Cummins and Farrell, 2003b) and are linked to the biological mineralisation of organic matter and the reduced uptake from biomass following the removal of the trees (Nieminen, 1998; Cummins and Farrell, 2003b). However, these increases typically occur several years after clearfelling (Lundmark-Thelin and Johansson, 1997; Cummins and Farrell, 2003b; Palviainen et al., 2004). The delayed release of N is reportedly due to the initial high N immobilisation of the brash material, which has a high carbon C:N ratio (Nieminen,1998). Both ammonium and nitrate are absorbed from bulk precipitation by tree canopies (Hyvärinen, 1990). Enhanced leaching of inorganic nitrogen from drained peatlands after clearfelling is most likely due to nitrification and the production of nitrate (Vitousek et al., 1982). However, increased nitrification after clearfelling does not necessarily lead to leaching of nitrate from clearfelled areas as the production of nitrate may stimulate the production of N_2O and N_2O which are emitted to the atmosphere (Nieminen, 1998) and were not measured by this study.

A similar study examining the nitrogen retention by peatland buffer areas applied nitrogen additions to the inflow (Vikman et al., 2010) rather than rely on an expected increase from a clearfelled catchment as was the case in this study. Further work could focus on using applied nitrogen additions to the inflow and measure gaseousN2O and N2which can account for 15% of the total N removed in a peatland buffer (Silvan et al., 2002).

4.4 Implications for forestry and water quality management

Two major concerns from forest clearfelling to water quality were highlighted by this study, increased SS and P concentration. The P concentration in water from pristine peatlands rarely exceeds 20 μg L^{-1} (Kenttämies, 1981), which is marginally higher than thePO_4-P found in rain water (Soveri and Peltonen, 1996; Rodgers et al., 2010). Additionally, the P concentration in water draining afforested peatlands (drained and with fertiliser applications) did not exceed 20 μg L^{-1} at 40 sites (O'Driscoll et al., 2012). Many of these peatland rivers are ecologically sensitive, containing IUCN Red List species (salmonids and fresh water pearl mussels) which make them important biodiversity refuges (O'Driscoll et al., 2012).BMPs such as clearfelling smaller plantation sizes at one time have been shown to reduce the concentration in the larger receiving rivers (Rodgers et al., 2010; O'Driscoll et al., 2013). However, this management strategy does not reduce the total P load leaving the harvested catchment (Rodgers et al., 2010) which is particularly important for catchments draining into sensitive lakes that act as a natural sink for any increased run off of nutrients and sediment (Drinan et al., 2013). Yanai (1998) reported negligible P loss to streams over 3 years from harvesting using the whole tree harvesting method and the by-products of WTH are gaining increasing value due to the rising demands for renewable energy (Vanguelova et al., 2010; Laudon et al., 2011). However, in the peatland forest catchments that are to receive a second rotation of forestry, there is a concern that WTH may deplete the nutrient pools and affect the growth of second rotation (Kaarakka, 2013).The buffer zone in the current study retained 9.7 kg TRP $ha^{-1}$and 11051.5 kg SS ha^{-1} released due to forestry operations including road development and clearfelling. However, the sustainabilityof the buffer zone retention capacity is of great importance because the increased P load from clearfelled peatlands continues for up to 4 years after the clearfelling ceases (Ahtiainen and Huttunen,1999; Rodgers et al., 2010). The P retention capacity of vegetated buffers is limited and no biogeochemical transfer in buffer areas is able to reduce the quantity of P stored (Dorioz et al., 2006). High DRP losses have been recorded from grassed buffer zones (Uusi-Kämppä, 2005) and management practices such as grass cultivation or low impact temporary sheep grazing need to be investigated for the peatland buffer zone. Additionally, given that the majority of P is released in storm events and the buffer became a release source in higher flows, investigation of peak runoff control (PRC) methods also warrants further investigation. The PRC method has been shown to effectively reduce peak runoff rate, peak concentrations and subsequently SS and nutrients (Martilla and Kløve, 2010).The buffer in the current study was created by harvesting the trees from a strip beside the stream a year before clearfelling the main coupe and allowing the area to revegetate. A buffer zone can also be created by leaving an intact strip of forest adjacent to the stream and clearfelling the main coupe of trees behind it, a method which has been shown to be successful in the UK (Broadmeadow and Nisbet, 2004). It is thought that the buffer allowed sedimentation to sedimentation to occur because of a slowing down of surface runoff due to the well-structured and drier character of forest soils, the increased macroposity from tree roots and soil fauna (Goudie, 2006) and the damming effect created by falling debris and protruding roots. However, this option has not been pursued for peatland forests in the west of Ireland due to thin soil depths, exposure and high winds, leading to the increased risk of windthrow (Finnegan et al., 2012).

5. Conclusion

Of the four study hypotheses outlined in the introduction, the data presented here fully support H1, H3 and H4, and partially sup-port H2. Two years after clearfelling and seeding, the constructed buffer zone was well vegetated and the blocking of the semi-natural stream that passed through the buffer zone increased the passing through time of the diverted water, in line with H1. Forest clearfelling the upstream 10 ha catchment increased the TRP concentration in the receiving water. However, SS concentrations were much higher before felling highlighting the ongoing and unresolved issue of the impacts of forest road construction. Thus, H2 was only partially supported, as the data did not indicate an increase in SS after clearfelling. The buffer zone was efficient in removing SS with retention efficiency of 33% but less efficient in removing P with the retention efficiency of 18% as hypothesised in H3. Finally, Pretention efficiency was dependent on inlet concentrations, loading and hydraulic loading rates (H4). From an international perspective the findings of this study contributes important scientific qualitative and quantitative data on the creation and functioning of buffer zones in blanket peat forested catchments in moderate climates receiving high and frequent precipitation.

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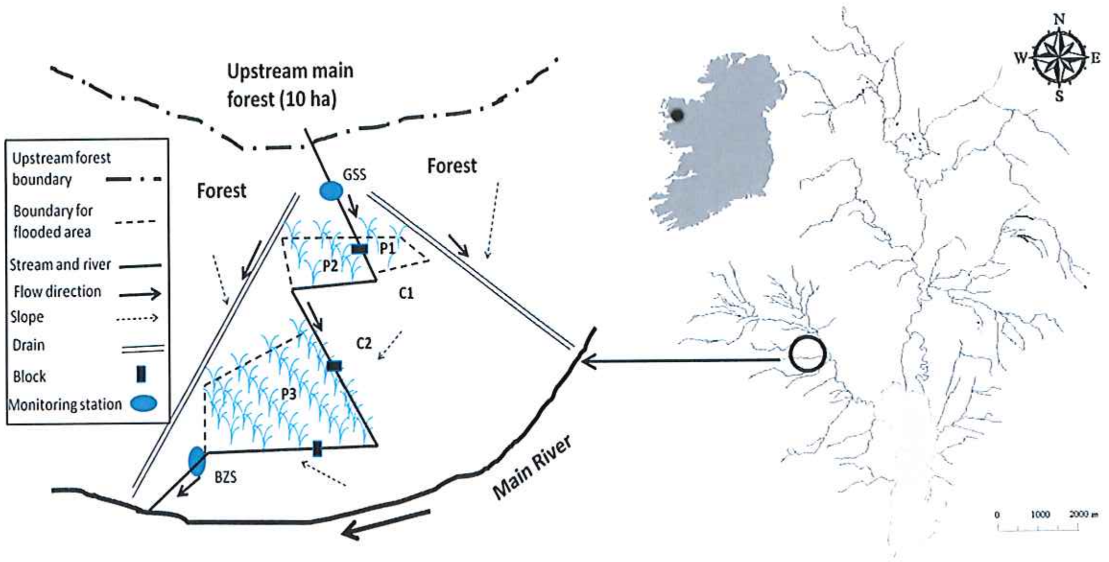


Figure 1 Location of the Burrishoole catchment and the buffer zone catchment boundaries and seeded plots (P1, P2, P3) and control plots (C1, C2) are presented in detail.

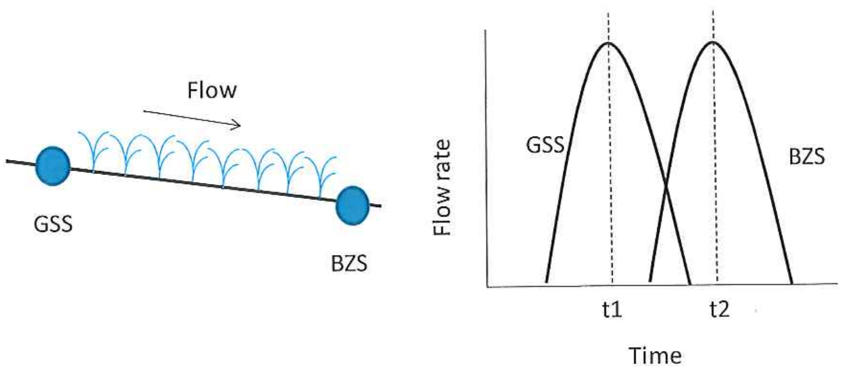
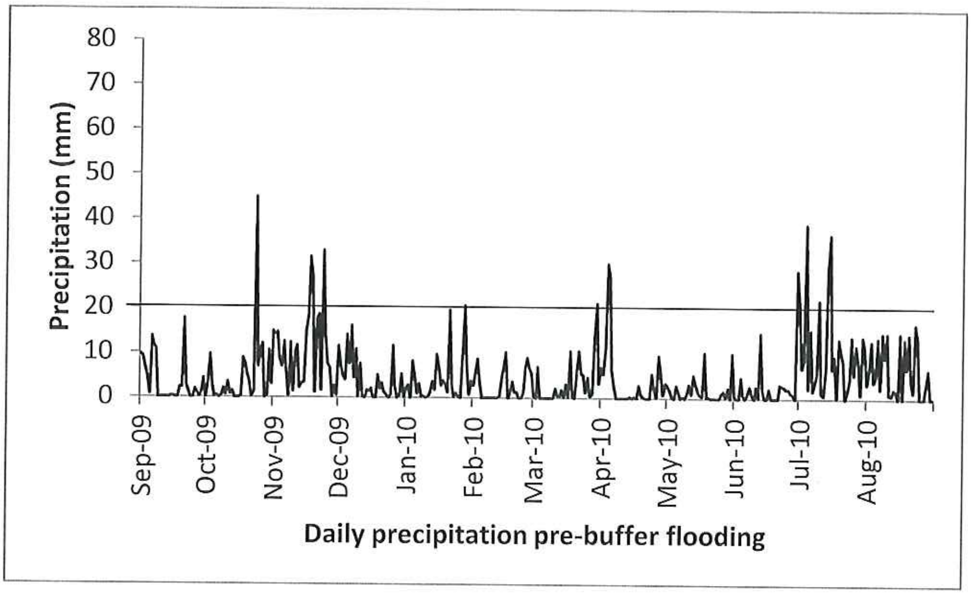


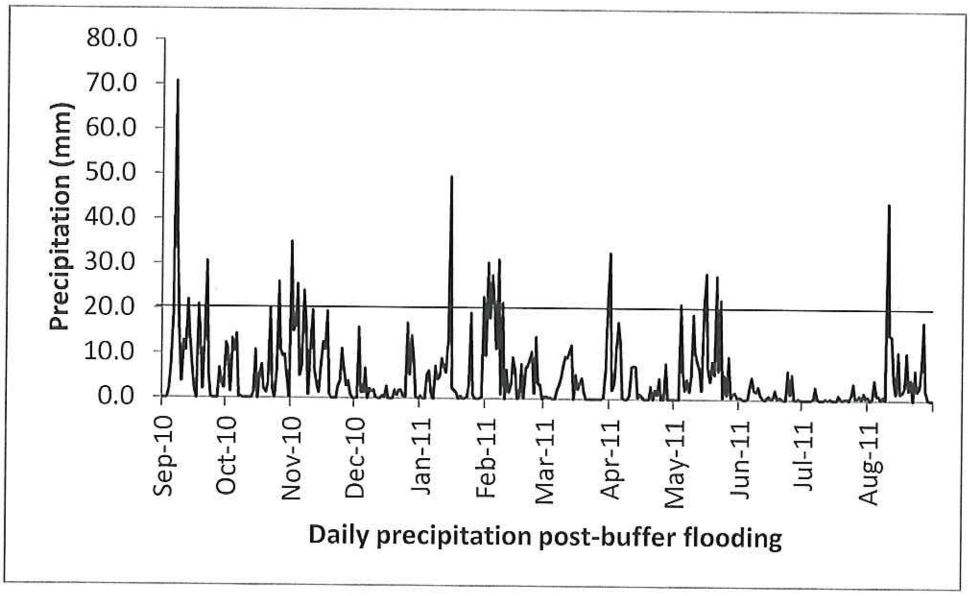
Figure 2. In a storm event the peak flow passed GSS at t1 and BZS at t2. The time difference (t2-t1) is considered at the time that the runoff needed to pass through the buffer zone.

a



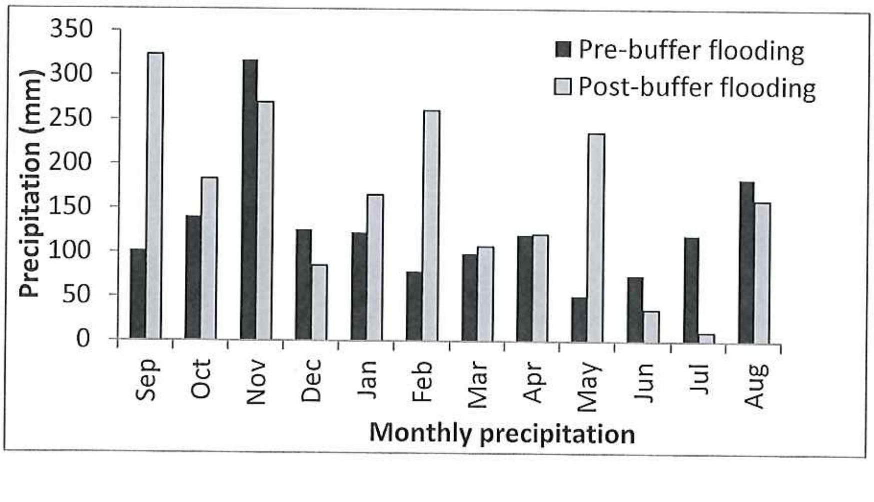
Precipitation (mm)
80
70
60
50
40
30
20
10
0
Sep-09
Oct-09
Nov-09
Dec-09
Jan-10
Feb-10
Mar-10
Apr-10
May-10
Jun-10
Jul-10
Aug-10
Daily precipitation pre-buffer flooding

b



Precipitation (mm)
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Sep-10
Oct-10
Nov-10
Dec-10
Jan-11
Feb-11
Mar-11
Apr-11
May-11
Jun-11
Jul-11
Aug-11
Daily precipitation post-buffer flooding

c



Precipitation (mm)
350
300
250
200
150
100
50
0
Pre-buffer flooding
Post-buffer flooding
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Monthly precipitation

Figure 3 Daily precipitation recorded at the Marine Institute for a) the pre-buffer flooding, b) the post-buffer flooding and c) the monthly periods. The gray line indicates the threshold for storm occurrence.

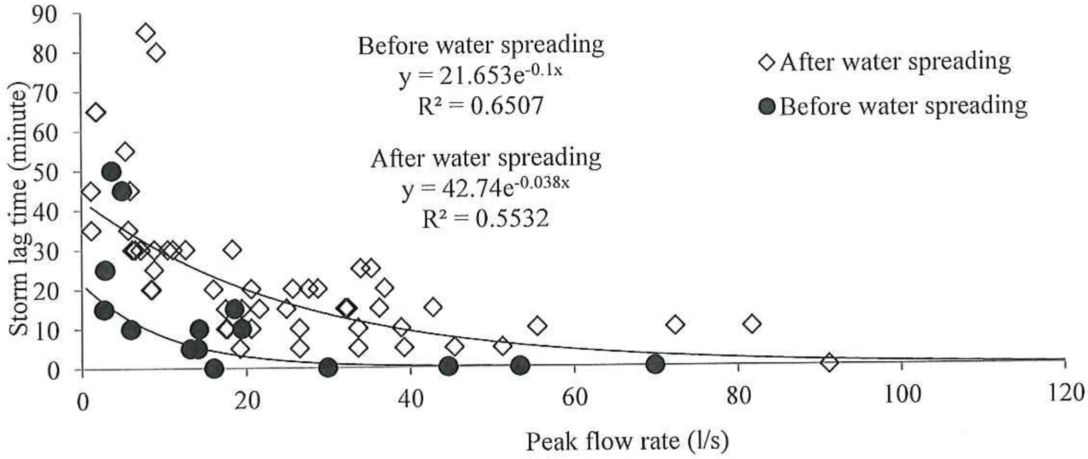
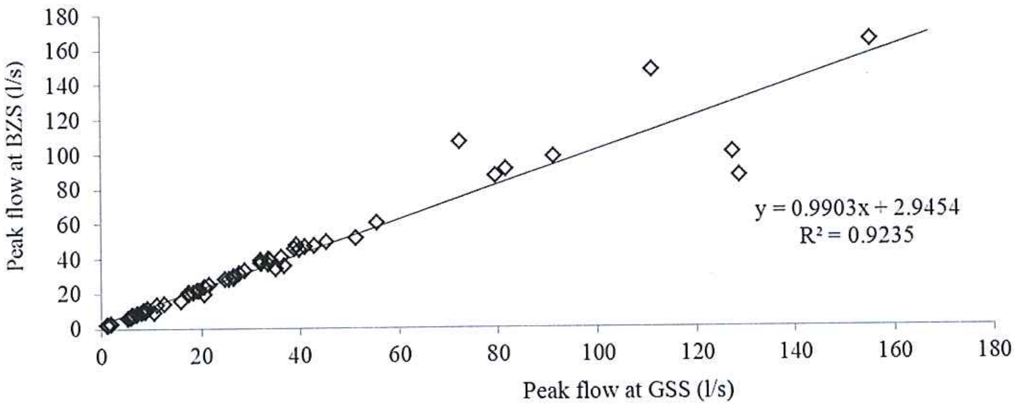


Figure 4. Runoff passing through the buffer zone in different storm events before and after water spreading; 15 and 65 storm events were included before and after water spreading, respectively.



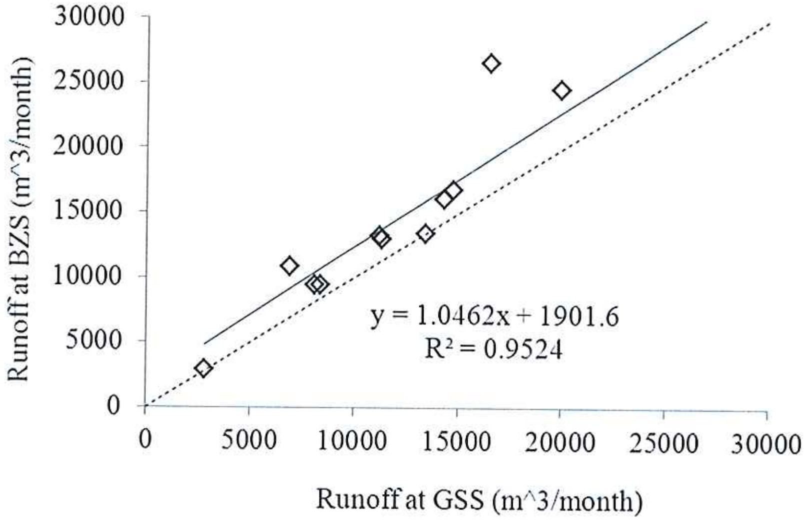


Figure 5a) Storm peak flows at the GSS and the BZS after water spreading, b) monthly runoff passing through the GSS and the BZS after water spreading (Dash line represents 1:1).

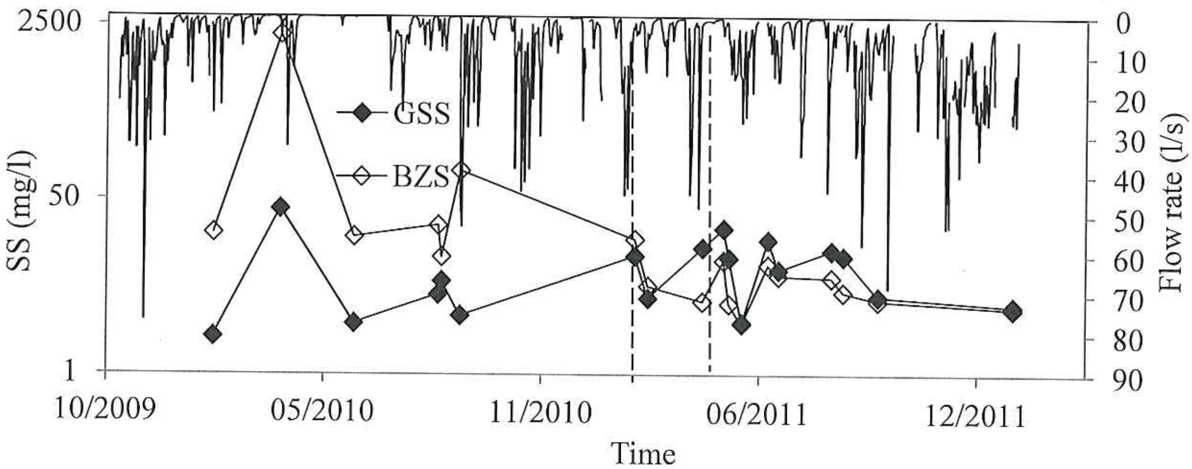


Figure 6. The daily discharge-weighted mean SS concentrations at the GSS and the BZS during the study period. Dash lines indicate the harvesting period (February – April 2011) and the y-axis is expressed in the logarithmic scale.

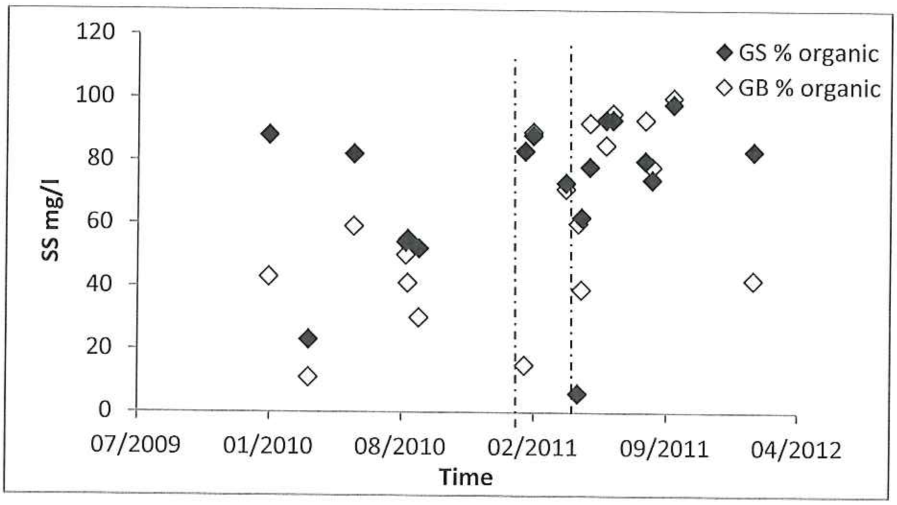


Figure 7 The % or organic matter content measured in the SS samples. The dash lines indicate the felling period (February – April 2011).

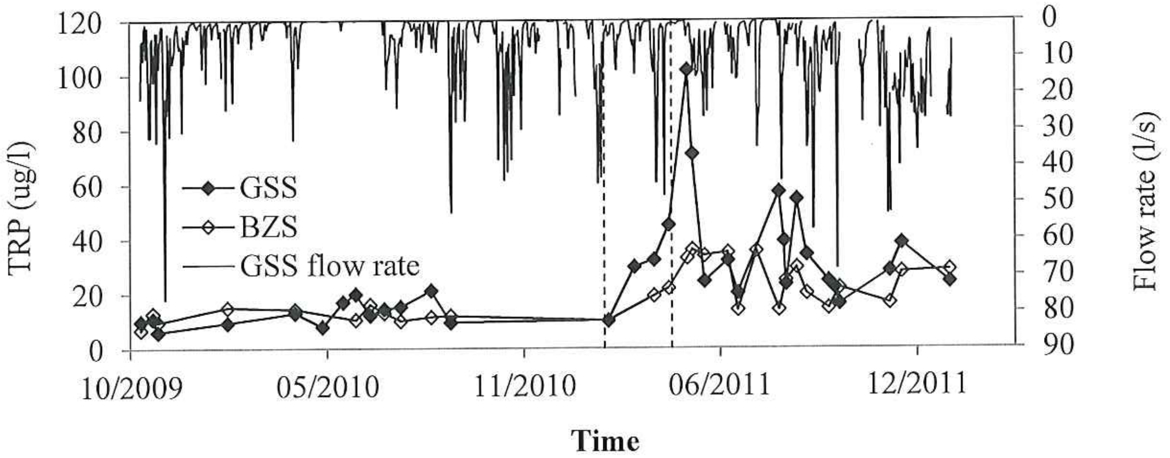
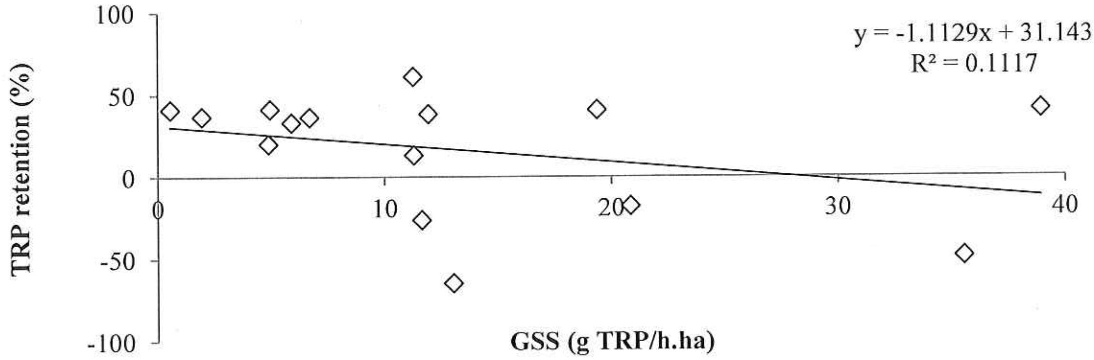
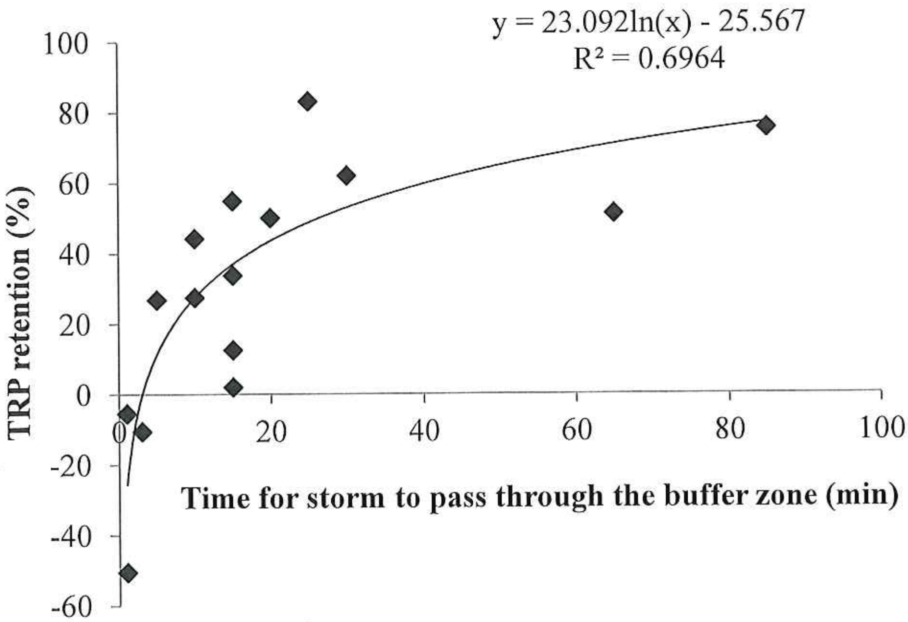


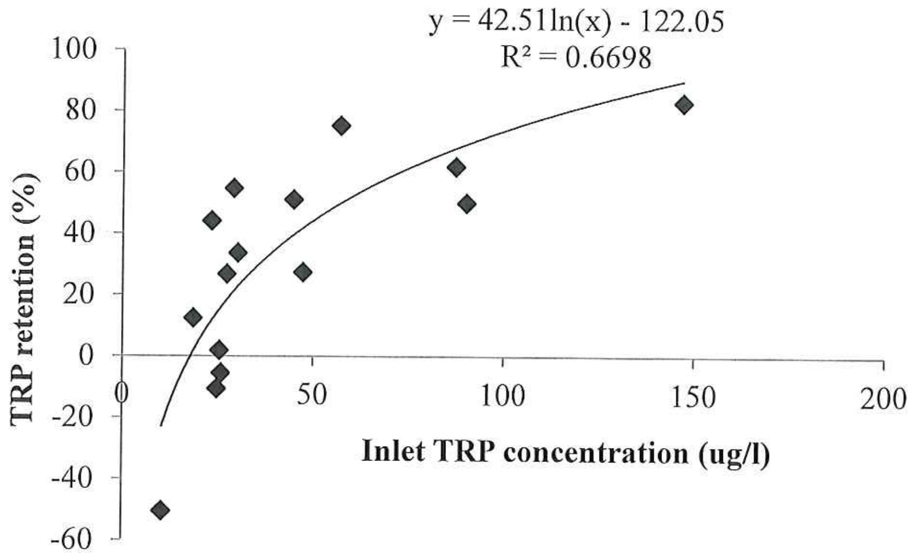
Figure 8. The daily discharge-weighted mean TRP concentrations at the GSS and the BZS during the study period. Dash lines indicate the harvesting period (February – April 2011).



a



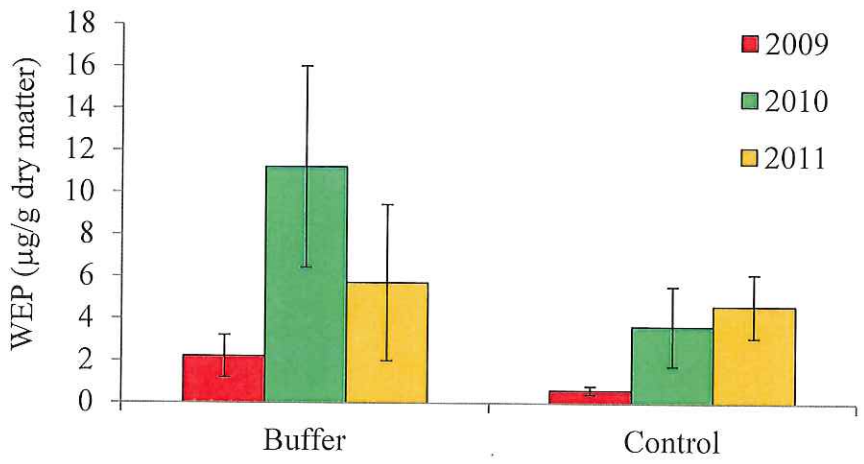
b



c

Figure 9 a) The relationships between retention efficiency and loads during storm events; b) the relationship between % retention and times for storm to pass through the buffer zone and c) the relationship between % retention and inlet concentrations.

a



b

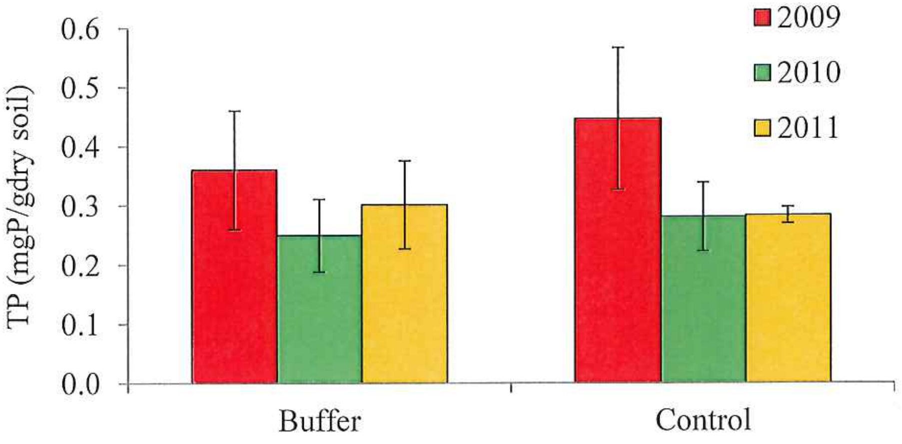
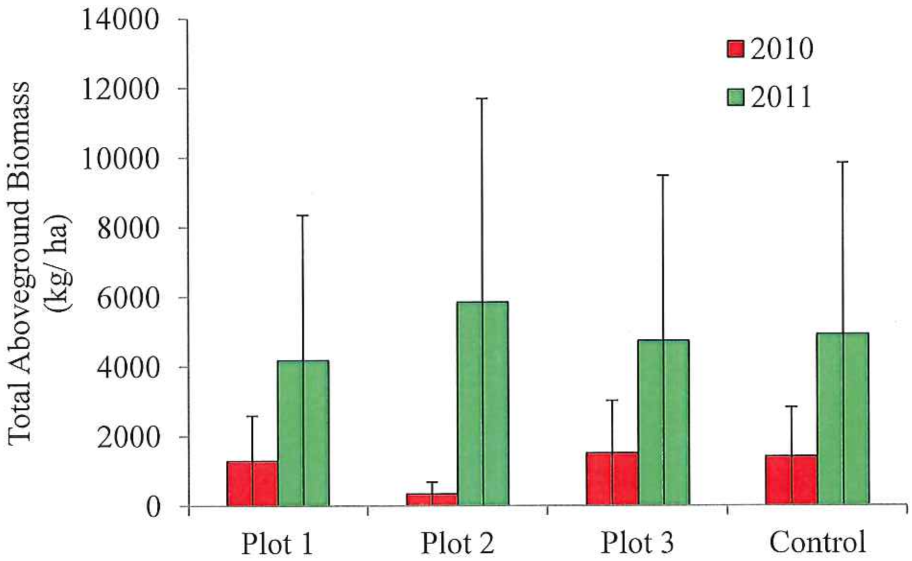


Figure 10 a) Soil water extractable (WEP) and b) total (TP) phosphorus in the buffer zone and control area.

a



b

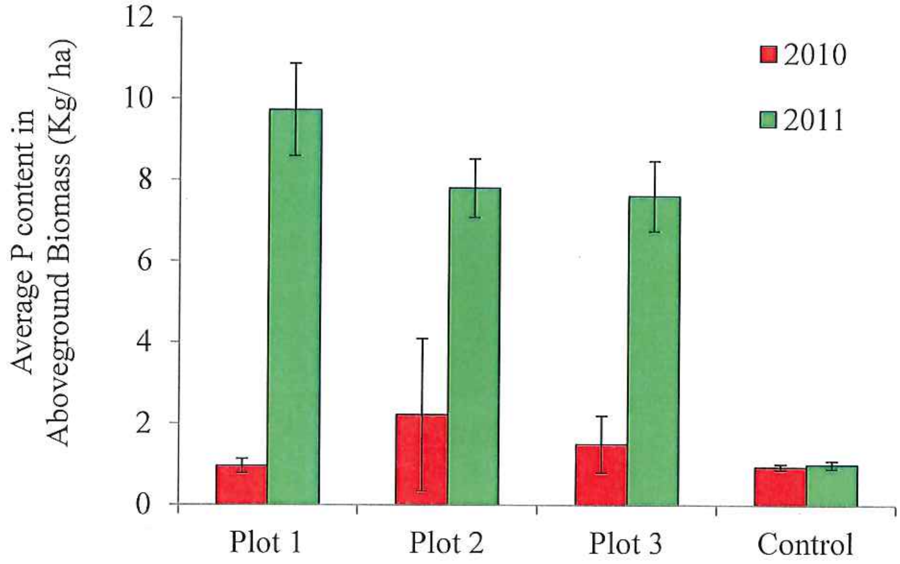


Figure 11 a) Above ground biomass and b) P content in the buffer zone in 2010 and 2011. Error bars indicate standard deviation.