Suspended solid yield from forest harvesting on upland blanket peat

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Abstract

Forest harvesting activities, if not carefully carried out, can disturb the forest soils and can cause significant suspended solid concentration increases in receiving waters. This study examined how harvesting, following forestry guidelines, influenced suspended solid concentrations and loads in the receiving waters of a blanket peat salmonid catchment. The study site comprised two forest coupes of 34-year old conifers drained by a first order stream. The upper coupe was not felled and acted as a baseline 'control' catchment; the downstream coupe was completely harvested in summer 2005 and served as the 'experimental' catchment. Good management practices such as proper use of brash mats and harvesting only in dry weather were implemented to minimize soil surface disturbance and stream bank erosion. Stream flow and suspended solid measurements at an upstream station (US) and a downstream station (DS) in the study stream commenced over a year before felling took place. The suspended solid concentrations, yields and release patterns at US and DS were compared before and after harvesting. These showed that post-guideline harvesting of upland blanket peat forest did not significantly increase the suspended solid concentrations in the receiving water and the aquatic zone need not be adversely affected by soil releases from sites without a buffer strip.

Key words: Suspended solid; solid rating curve; forest clearfelling and harvesting; blanket peat; best management practice; salmonid catchment.

1. Introduction

Soil erosion is a two-phase process consisting of the detachment of individual soil particles from the soil mass and their subsequent transport by erosive agents such as runoff (e.g. Rose, 1993). Erosion of upland blanket peat is widespread in British and Ireland (Bradshaw and McGEE, 1988; Evans and Warburton, 2007). In a survey of erosion across the upland of England and Wales, McHugh *et al.* (2007) found that peat soils in the uplands are the most severely eroded soil class. In Ireland, Bradshaw R. and McGEE (1988) carried out a survey of blanket peat in five mountain areas and reported extensive erosion in all areas. The erosion of peatlands is the greatest from very wet peatlands and from areas where there are layers of mud or highly decomposed peat (Paavilainen and Päivänen, 1995). Peatland erosion results in the increase of suspended solid concentrations in the receiving water, which could cause damage to the water ecology. Solid organic matter silts up watercourses more than inorganic matter. Moreover, organic matter is biologically active, thus consuming the oxygen resources of watercourses as it is decomposed (Paavilainen and Päivänen, 1995). In a review, Greig *et al.* (2007) suggested that organic material deposited in gravels had a greater deleterious effect on salmon spawning grounds because of its oxygen demand. The causes of peat erosion have included human disturbance and changes in the mechanical stability of the peat mass through time (Evans and Warburton, 2007).

Most forest operations including forest harvesting could create some mechanical disturbance of the ground surface that can lead to the release of soil to river systems (Everest *et al.*, 1987; Robinson and Blyth, 1982). Erosion from timber harvesting and reforesting operations can be significant in the absence of good management practice (Swank *et al.*, 2001). In a catchment study in Arkansas and Oklahoma, Scoles *et al.* (1996) found that where no specific erosion control measures were applied, annual soil losses in the first year were statistically significantly greater on clearfelled and harvested sites than on selectively harvested and control sites. In a study by Ahtiainen *et al.* (1988), a combination of clear-cutting, ditching, soil preparation in peatland catchment increased the amount of annual suspended solids from 4 kg/ha to 1010 kg/ha at its highest. 5 to 8 years later, the amount of annual suspended solids was still approx 60 kg/ha.

Since the 1950s, large areas of upland peat were afforested in northern European countries. In the UK, between the 1950s and 1980s, forests were planted on about 500,000 ha of peatland (Hargreaves *et al.*, 2003). In Ireland, it was estimated that in 1990 about 200,000 ha of forest were on peatland (Farrell, 1990) and between 1990 and 2000, about 98,000 ha of peat soils were afforested (EEA, 2004). Before the 1980s, most of the Irish peatland forests were planted without riparian buffer strips in upland areas that contain the headwaters of rivers, many of them salmonid. These forests are now reaching harvestable age. Peatland is defined as a forest soil type which has a greater risk of erosion in the Irish Forest and Water Quality Guidelines (Forest service, 2000a). Due to the sensitive of the upland water and blanket peat to the disturbance, concerns have been raised about the possible impacts of harvesting these forests and associated activities on the receiving aquatic systems (Coillte Teo, 2007).

In order to minimize the amount of suspended solids entering watercourses, good management practices were introduced in the UK (Forestry Commission, 1988) and in Ireland (Forest Service, 2000a, 2000b and 2000c). These practices targeted the process of soil erosion, and included proper harvesting methods and the use of thick brash mats to limit surface disturbance. The findings of earlier harvesting studies in the UK and Ireland were not relevant for the impact assessment of forestry operations carried out under the new forest and water guidelines (Stott *et al.*, 2001). To date, few studies have focused on the impact of post-guideline harvesting on suspended solid yields (Nisbet, 2001; Stott *et al.*, 2001).

In this study, an assessment of the impact of post-guideline harvesting on the suspended solid release was carried out in an upland blanket peat catchment that had been afforested in the 1970s without buffer strips - typical of most Irish forests now approaching harvestable age. It comprised a control area upstream of an experimental area. The experimental area was harvested in summer 2005. The measurement of suspended solid concentrations and stream flows, upstream and downstream of the experimental area, commenced over a year earlier in summer 2004 and the suspended solid concentrations were intensively monitored. By pre-harvesting monitoring and comparing the experimental data from the experimental and upstream control areas, the impact of the harvesting on suspended solid increase could be accurately estimated (Ferguson, 1987).

The bedload in the flashy study stream was sand, stones and rocks. The average annual bedload mass of less than 50 kg, which accumulated and was cleared from the measuring flume just downstream of the experimental area, was several orders smaller than the suspended solid mass released from the whole study area. In this study, suspended solids refer to organic and inorganic matter that occurs in water in suspended or particle form (Paavilainen and Päivänen, 1995; Joensuu *et al.*, 1999). More than 80% of suspended solids weight was lost after ignition at 550^{o}C (APHA, 1995), indicating that the main content of the suspended solids was organic matter, which was considered to be the main threat to fauna in this salmonid catchment.

The objectives of this study were to examine the impact of post-guideline harvesting the blanket peat forest on the suspended solid concentrations and yields.

2. Study site description

The Burrishoole catchment, located in County Mayo, Ireland, in the west of Ireland, consists of important salmonid productive rivers and lakes (Figure 1). About 18% of the catchment is covered by forests that were planted in the 1970s and which are now being, or are about to be, harvested. The study site (9°55'W 35°55'N), which is a sub-catchment of the Burrishoole catchment drained by a small first order stream (Figure 1a), was planted with Lodgepole Pine (*Pinus contorta*) between January and April 1971. The stream is equipped with two flow monitoring stations at stable channel sections, one upstream (US) and the other downstream (DS) of the experimental area (Figure 1b). The US measures flows from the control area (area A in Figure 1b) of 7.2 ha and the DS covers the control coupe and the experimental coupe (coupes B in Figure 1b) with a total combined area of 17.7 ha. Before the start of this study, road drainage into the channel near the US gauge was diverted into an adjoining sub-catchment. In August 2005, a wind-blown tree blocked one of the collector drains, resulting in an increase of the upstream forest control area (coupe D), to about 10.8 ha (coupes A plus D in Figure 1b). Meanwhile the downstream harvested area increased to about 14.5 ha due to the blockage of a drain by brash mat during the harvesting, incorporating another part of the total harvested area (coupe C). Fortunately, in both cases the additional area had the same characteristics of vegetation and soils, and the *relative* sizes of US and DS remained unchanged – US increasing only marginally from 41% of the total area to DS before harvesting and 43% afterwards. All unit area depths in this paper have been calculated using these values. The blanket upland peat soil in all four areas A - D had been double mouldboard ploughed by a Fiat tractor on tracks creating furrows and ribbons (overturned turf ridges) with a 2 m spacing, aligned down the main slope, together with several collector drains aligned close to the contour. The trees were planted on the ribbons at 1.5 m intervals, giving an approximate soil area of 3 m^2 per tree. The initial stand density was about 2800 trees per ha but was reduced to about half by thinning and natural die-off before harvesting. The catchment had an average peat depth of more than 2 m above the bedrock of quartzite, schist and volcanic rock, and the peat typically had a gravimetric water content of more than 80%. Close to the DS station there is a deep incision, where the depth of the peat is about 0.5 meter and rocks are found in the bed of the study stream. Comparing with the study catchment, this incision section is very small, with the area of less than 0.1 hectare. In the catchments, the mean annual rainfall is more than 2000 mm and the mean air temperature is about 11 ^{o}C. Hillslope gradients in areas B and C average 8^0 and range between 0^o – 16^o. Bole-only harvesting was conducted in area B and C from July 25th to September 22nd 2005. The timber was harvested using a Valmet 941 harvester, and the residues (i.e. needles, twigs and branches) were left on the soil surface and collected together to form windrows. During harvesting, the boles were stacked beside the windrow for collection. A Valmet 840 forwarder delivered the boles to truck collection points beside the forest service road. To minimise soil damage, the clearfelling and harvesting were conducted only in dry weather conditions during the period from July to September 2005. That time period is recommended for harvesting in the Irish Forest Harvesting and the Environment Guidelines since ground conditions tend to be drier (Forest Service, 2000a). Mechanised operations were suspended during and immediately after periods of particularly heavy rainfall. Another important good management practice used during the harvesting operation was the proper use of brash mats for machine travelling. Tree residues (i.e. needles, twigs and branches) were collected together to form brash mats on which the harvesting machines travelled, thus protecting the soil surface, and reducing erosion. In the lowest part of the site where the stream is deeply incised, the trees were cut with a chain saw and left behind. The non-harvested upstream area of A and D, was used as a control area in this study as it had the same type and age of trees, similar soil, hydrologic characteristics and size, as the harvested experimental area of B and C. In the experimental area, the furrows and windrows/brash mats - formed from the harvest residues – are, in general, parallel with the study stream, which is at right angles to the contours. The surface water flows along the furrows, is collected by collector drains (arrows in Figure 1c) and joins the study stream.

3. Sampling, measurement

From April 2004 - March 2005, continuous water levels in the study stream were recorded at both the upstream station (US) and downstream station (DS), and converted to flows by a rating equation based on dilution gauging and current meter measurements. In April 2005, H-flume flow gauges were installed at the sites for flow measurement. At US and DS, water samples were taken: (i) manually every 20 minutes from April 2004 to March 2005 during flood events; (ii) hourly from April 2005 to March 2006 using ISCO automatic water samplers and (iii) manually in base flow conditions through the study period. Suspended solid concentrations of the water samples were measured at the Marine Institute in Newport, Co. Mayo in accordance with the Standard Methods (APHA, 1995) using Whatman GF/C (pore size 1.2 μm) filter papers.

4. The possible longevity of the impact

Harvesting activities could immediately increase solid yield (Cornish and Binns, 1987). The longevity of impact of harvesting on suspended solid concentrations depends on the recovery of the catchments from soil disturbance, which could depend on: (i) weather conditions, (ii) soil properties and ground slopes and (iii) the growth of vegetation. Previous studies reported that the impact of harvesting on solid concentrations could last from a few months to a few years (Macdonald *et al.*, 2003; Stott, 2005). Figures 2a and 2b show the daily mean and peak suspended solid concentrations at US and DS stations during the study period. The daily mean suspended solid concentration was calculated based on Ferguson (1987). Harvesting didn’t result in obvious increase in daily suspended solid mean concentrations at DS station. However, daily peak suspended solid concentrations at DS station increased after harvesting and lasted for about 7 months (September 2005 to March 2006) before returning to the US station levels. Comparing with the previous and following periods, no increase in monthly rainfall in the period from September 2005 to March 2006 was found (Figure 2c). The 7-month increase in peak concentrations after harvesting could be due to flushing out of loose material exposed by the felling activities. Short-term elevation in suspended solid concentrations could damage the water ecology and result in reduction of survival rates of salmonid eggs and newly hatched alevins. This paper focused on assessment of the impact of harvesting on the suspended solid concentrations in the first 7 months post-harvesting. Intensive monitoring the suspended solid concentrations in this period would allow us to detect any possible increases in soil release after harvesting.

5. Analysis methods

To determine the harvesting effect on soil release, a calibration equation was established between US and DS suspended solid concentration data for the pre-harvesting period. The dependent variable was suspended solid at DS and the independent variable was suspended solid at US. After harvesting, the same equation was used to estimate ‘no-felling’ suspended solid concentrations at DS for the observed values of suspended solid at US. This should allow for the effect of weather conditions, so that the impact of the harvesting on the soil release can be established from: (i) comparing the measured and estimated suspended solid concentrations and (ii) determining the statistical significance of any concentration differences by, for example, using a t-test

The characteristics of solid yields were examined by using the solid yield rating curve. In this study, the solid yield rating curve was defined as a simple power function (Hotta et al., 2007) and used for suspended solid yield estimation:

$$Q_S = \alpha Q^{\beta} \qquad \text{Equation 1}$$

Where Q_S represents the solid yield, Q is the water discharge, and α and β are obtained by the least squares method using observed solid yield and water discharge data. The values of α and β were calculated and compared before and after harvesting for the study and control catchments. Monthly suspended solid yields in storm events at DS and US before and after harvesting were calculated using Equation 1.

6. Results

6.1 Suspended solid concentrations before and after harvesting

During base flow conditions, suspended solid concentrations at the US and DS stations were generally low before and after harvesting and ranged from 0.1 to 5 mg/l. Stream suspended solid are usually episodic – most solid is carried in high flows - so this study focused on the storm events. Table 1 lists the studied storm events before and after harvesting. A rainfall event was defined as a block of rainfall that was preceded and followed by at least 12-hours of no rainfall (Hotta *et al.*, 2007). A total of 23 events were studied in this paper: 8 before and 15 after harvesting. 114 and 394 water samples were collected at both stations before and after harvesting, respectively. Figure 3 shows the suspended solid concentrations and flows in some storm events before and after the harvesting period. As expected, variations in suspended solid concentration roughly correlate to the temporal profile of water discharge, and bigger storm events generally result in higher suspended solid concentrations. The biggest storm event in the pre-harvesting period occurred on the 22nd June 2004 with 86.8 mm rainfall, having a maximum intensity of 2.2 mm/5 min and duration of about 32 hours (Table 1). The highest suspended solid concentrations during this storm were 37.8 mg/l at US station and 65 mg/l at DS station, respectively, which were the maximum suspended solid concentrations observed during the pre-harvesting period. During the post-harvesting study period, the biggest storm event occurred on 01 November 2005 with a total rainfall of 67.2 mm, maximum rainfall intensity of 3.2 mm/5 min, and duration of 82 hours (Table 1). Suspended solid concentrations at US station increased from 0.1 mg/l to 25.8 mg/l and then dropped back to 0.5 mg/l. At DS station, suspended solid concentrations increased from 0.3 mg/l to a peak of 97.5 mg/l towards the beginning of the flood event as the flow rate increased from about 4.5 l/s to 12.5l/s, which was the highest suspended solid concentration observed during the post-harvesting study period (Figure 3c). Three water discharge peaks of (i) 140 l/s, greater than (ii) 150 l/s, and (iii) 57 l/s occurred in this storm event, with the three corresponding sediment concentration peaks of 97.5 mg/l, 44 mg/l and 15 mg/l, respectively. Much higher solid concentrations were observed in the first peak, though the second peak had a much higher water discharge, indicative of a lack of available eroded source material during the following flow peak. In most of the studied storms, suspended solid increased quickly at the beginning of the water discharge and reached the maximum prior to the water discharge peak, which could be due to the build-up of the soil fraction available for release and erosion prior to rainfall. Similar phenomena were also observed by Drewry *et al.* (2008) and Baca (2002).

Figures 4a and 4b show the relationships between suspended solid concentrations of the US and DS before and after harvesting, respectively. Larger scatter was found in the correlation of US and DS suspended solid concentrations after harvesting. Almost all of the highest post harvesting concentrations occurred in storm event on 2nd November 2005 – the first high storm event after harvesting - and its following storm event on 11th November 2005, which could be due to the flushing out of loose material exposed by the felling. In most of the storm events the peak flows passed US earlier than DS with the time difference of less than 30 minutes. Simple power equations were used to describe the solid relationships between the two stations:

$$C_{DS} = a.C_{US}{}^{b} \qquad \text{Equation 2}$$

Where C_{DS} and C_{US} are the suspended solid concentrations at DS and US stations, and *a* and *b* were obtained by the least squares method.

Parameter *a* increased from about 1.35 before harvesting to about 1.98 after harvesting and *b* decreased from 1.01 to 0.81. In Equation 2, an increase in *b* may result in more significant increases in solid at DS than an increase in a. In order to examine the impact of the harvesting activities on the sediment release, the solid at DS was estimated as the dependent variable by using the pre-harvesting power function equation (a = 1.35 and b = 1.0) and the observed post-harvesting solid at US as the independent variable. The estimated and measured solid concentrations at DS were compared using a paired samples t-test at the 95% significance level (P=0.05) (http://www.spss.com), which indicated that there was no statistically significant difference between the estimated and measured concentrations.

6.2 Pre- and post- harvesting solid rating curves

Figures 5a and 5b show the relationship between solid loads and water discharge calculated using suspended solid concentrations and water discharge data during the pre- and post-harvesting study periods, respectively, which reveal no detectable post harvest increase. Combining all the storms, before and after harvesting, α and β in Equation 1 were obtained by applying the least squares method (Table 2). At the US station, α and β decreased from 8.1 and 1.08 before harvesting to 5.94 and 1.01 after harvesting, respectively. At the DS station, α decreased from 11.95 before harvesting to 6.0 after harvesting and β slightly increased from 1.11 to 1.17.

Figures 6 and 7 show the relationship of monthly water discharges and solid yields respectively. The solid yield in storm events was calculated by placing the water discharge and the values of α and β in Table 2 into Equation 1. The monthly solid yield was achieved by accumulating the solid yields in all the storm events in the month. As shown in Figure 6, the water discharge per unit area increased after harvesting, which was probably due mainly to lower interception losses (Calder, 1986; Robinson and Dupeyrat, 2005). The water discharge at DS and US had a very good linear relationship during the pre- and post- harvesting period. The linear factors were similar and close to 1 during the pre- harvesting and post- harvesting periods. A linear relationship was also found between the solid yields at DS and US as shown in Figure 7. The slopes for pre- harvesting and post- harvesting were similar. Solid yields slightly increased after harvesting (Figure 7), which could be attributed to the increase in runoff. In order to examine the impact of the harvesting activities on the solid yield, the sediment at DS was estimated as the dependent variable by using the pre-harvesting linear regression equation and the observed post-harvesting sediment yield at US as the independent variable. The estimated and measured sediment yield at DS were compared using a paired samples t-test at the 95% significance level (P=0.05) (http://www.spss.com), which indicated that there was no significant difference between the estimated and measured sediment yield.

7. Discussion

The pair of parameters α and β in the solid rating curve in Equation 1 represent the erosion characteristics of the catchment. The two parameters fluctuate from storm to storm (Marehead *et al.*, 2003). The values of these parameters in each of the studied storms are presented in Figures 8a and 8b for before and after harvesting, respectively, which indicated that the erosion characteristics of the study site were the same as the control site and didn't change significantly after harvesting.

Though higher daily peak suspended solid concentrations were observed, there was no significant suspended solid concentrations increase after harvesting in this study. Hotta *et al.* (2007) indicated that if appropriate measures are undertaken to prevent surface disturbance, there may not be an increase in sediment concentrations during and following harvesting; they used skyline harvesting treatment and found there were no sediment concentration or yield increases after harvesting. In this Burrishoole study, the soil disturbance and stream bank erosion during the harvesting operation were minimized as much as possible by applying best management practices (Forest Service, 2000a): harvesting was conducted only in dry weather conditions; brash mats were properly used and maintained; the harvester had a 10 metre reach which minimized the soil disturbance within 10 metres of the study stream; and hand cutting was used on steep slopes and the felled tree boles were left behind. No stream bank erosion due to the forest activities was observed in this study site. In their post-guideline harvesting study, Stott *et al.* (2001) emphasized the importance of the timing of harvesting work and recommended that the forestry guidelines should also include the hydrological and meteorological conditions under which work can be undertaken near watercourses. A preliminary study carried out by the authors - using laboratory flume technology (Rose, 1993) to monitor the effect of the harvest machine disturbance - indicated that suspended solid concentrations (data not shown) could increase by two orders of magnitude from dry to wet conditions. Owende *et al.* (2002) investigated the progression of ground disturbance on a peat site during forwarder extraction on a brash mat, and found that when maintenance of the brash mat was conducted on an on-going basis, the deterioration of weak areas in the brash mat was prevented and, as a consequence, deep disturbance and rutting was minimised.

The hillslopes and stream banks are considered to be the main solid sources in a catchment (Egashira and Ashida, 1981; Hotta *et al.*, 2007). Soil erosion generally does not occur in an undisturbed forest because during most rainfall events runoff only flows within the humic layer. Smith (2008) reported that channels dominate solid supply in sub-catchments. Smith and Dragovich (2008) investigated the solid sources by using radionuclides and found that 81% of the solid flux was from the channel and gully wall in an upland catchment. In their study, Hotta *et al.* (2007) concluded that the stream banks/riparian zone, rather than the forest area, were the solid source in their catchment. When a stream serves as the solid source area, the solid released patterns differ depending on whether the water discharge is in the rising or falling stage. As the water level rises, most of the erodible material on the surface of a stream bank can be readily transported by flushing, creating a suspended solid concentration peak in the early stage of rising. In this present study, higher suspended solid concentrations were also always in the rising stage in most of the storms at the control site and study site before and after harvesting (Figure 2). Therefore, the stream, drain and furrow banks were considered to be the most likely the main pre- and post-harvesting solid source.

The solid yield was determined from the suspended solid concentrations and water discharge data. An increase in either or both could result in an increase of solid yield. Good management practice could prevent the suspended solid concentration increase by minimizing the disturbance of the soil, but can't prevent the increase of water discharge after harvesting, due to the lower evaporation from the harvested area. This is especially the case in temperate maritime climates such as Britain and Ireland where frequent light rainfall means tree canopies are often wet and the interception losses are high (Robinson and Dupeyrat, 2005). In this study, the slight increase in solid yields after harvesting could be due to the increase in water discharge, since no significant suspended solid concentration increases were observed.

8. Conclusions

The results of this study indicated that post-guideline harvesting did not have long-term impact on the suspended solid concentrations and did not change the erosion characteristics of the catchment. Solid yields slightly increased after harvesting could be due to the increase in water discharge from the experimental area. The stream, drain and furrow banks were considered to be the principal solid sources before and after harvesting. The study indicated that it is possible to prevent the solid concentration increase after harvesting if good management practices are strictly followed.

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9. References

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Table 1. Rainfall events during which samples were taken

Storm events	Rainfall duration (dd/mm/yyyy)	Total rainfall (mm)	Maximum runoff rate at DS station (l/s)	Maximum rainfall intensity (mm/hour)
1	17/04/2004 - 18/04/2004	13.2	41.6	6
2	22/06/2004 - 23/06/2004	86.8	100.3	5.8
3	20/07/2004 -20/07/2004	22.2	48	5.6
4	19/08/2004 - 20/08/2004	16.2	12.6	5.8
5	27/11/2004 - 28/11/2004	17.8	100.3	8.0
6	09/12/2004 - 10/12/2004	14.4	91.9	3.2
7	14/03/2005 -15/03/2005	35.8	87.8	5.0
8	05/05/2005 - 05/05/2005	9.8	14.5	4.0
	Clearfelling and harvesting (July – early September 2005)			
9	21/09/2005 -22/09/2005	7.8	8.8	7.0
10	29/09/2005 - 01/10/2005	22.8	20.8	2.8
11	07/10/2005 -10/10/2005	56.8	32.1	7.4
12	28/10/2005 - 30/10/2005	18.6	43.6	6.2
13	01/11/2005 - 04/11/2005	67.2	>158	8.8
14	07/11/2005 -10/11/2005	56.8	93.6	7.4
15	10/11/2005 - 13/11/2005	24.4	34.9	4.0
16	30/11/2005 - 01/12/2005	8.4	22.3	1.6
17	07/12/2005 - 07/12/2005	23.2	107.1	5
18	22/12/2005 - 23/12/2005	15.4	86.1	2.6
19	09/01/2006 -11/01/2006	35.6	59.8	7.0
20	17/01/2006 - 19/01/2006	17.4	88.4	4.4
21	13/02/2006 - 14/02/2006	38.8	152.1	9.0
22	06/03/2006 - 08/03/2006	21.8	69.3	3.0
23	13/03/2006 -14/03/2006	29.4	154.5	6.4

Table 2 Pre- and post– harvest α and β in the control and study catchments for all storms

Time	Catchment	α	β	r^2
Pre- harvesting	Control (US)	8.1	1.08	0.71
	Study (DS)	11.95	1.11	0.83
Post- harvesting	Control (US)	5.94	1.01	0.56
	Study (DS)	6	1.17	0.76

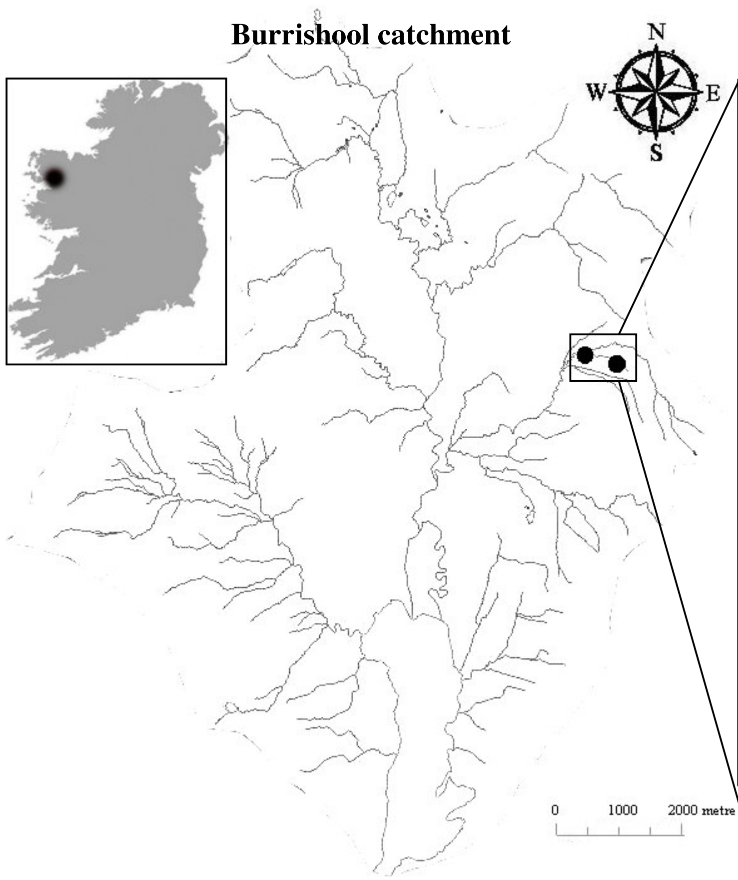

Figure 1a Location of the Burrishool catchment

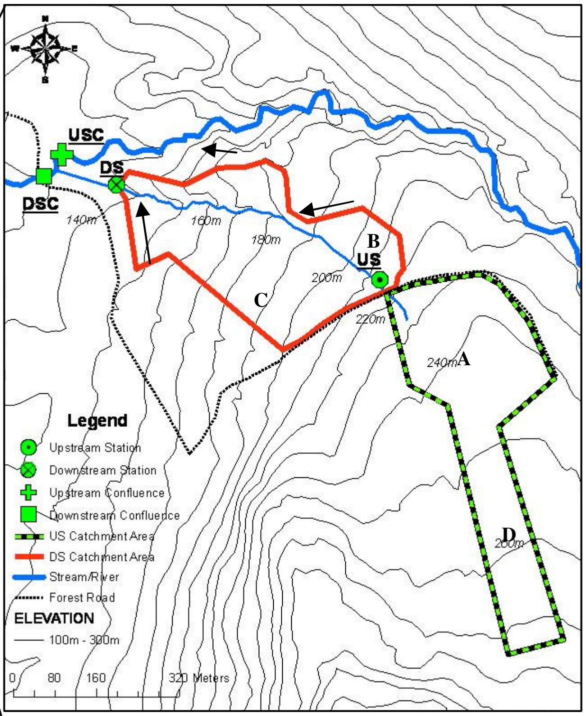

Figure 1b. Location of the study stream

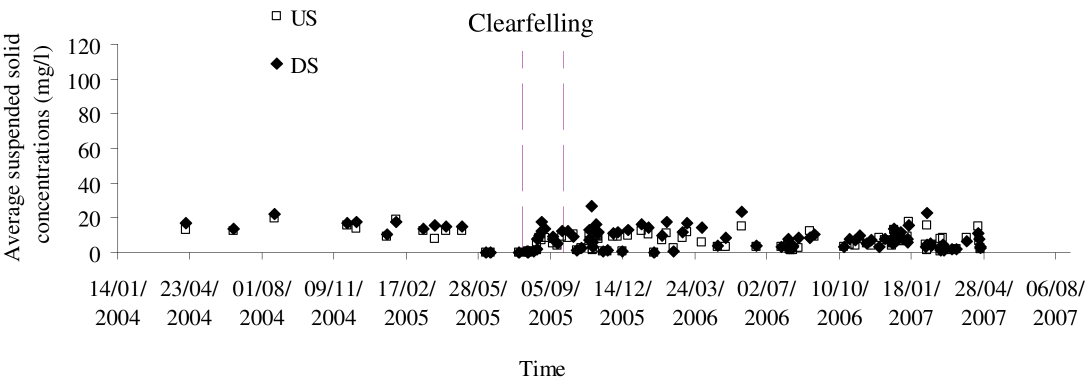

Figure 2a. Daily average suspended solid concentrations at US and DS stations before and after harvesting

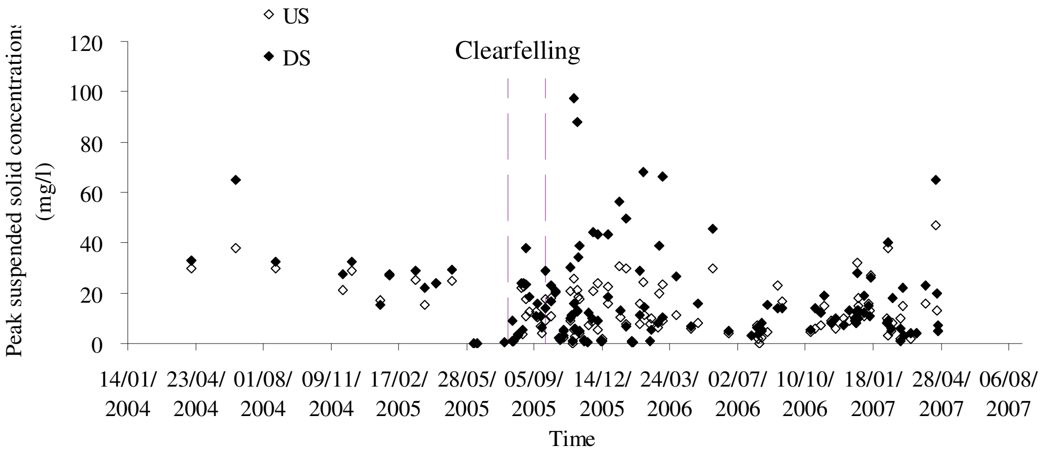

Figure 2b. Daily peak suspended solid concentrations at US and DS stations before and after harvesting

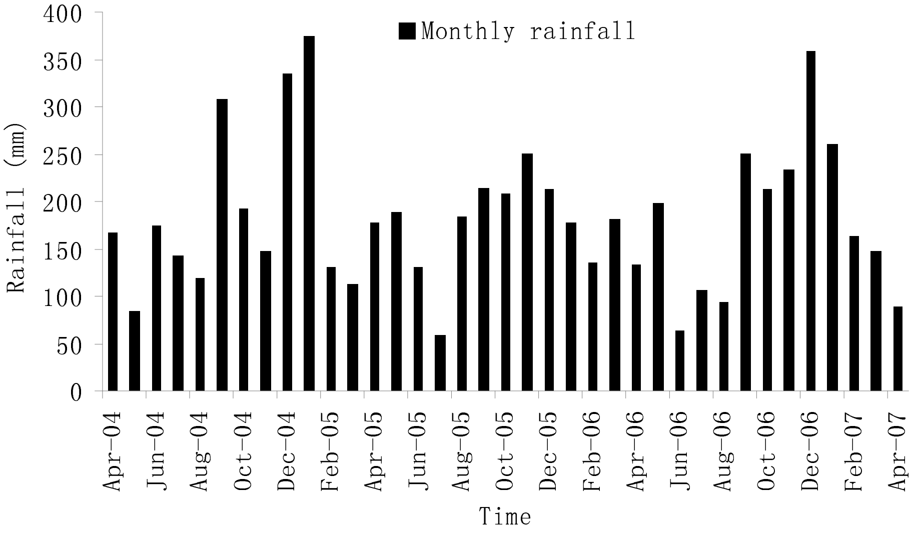

Figure 2c. Monthly rainfall before and after harvesting

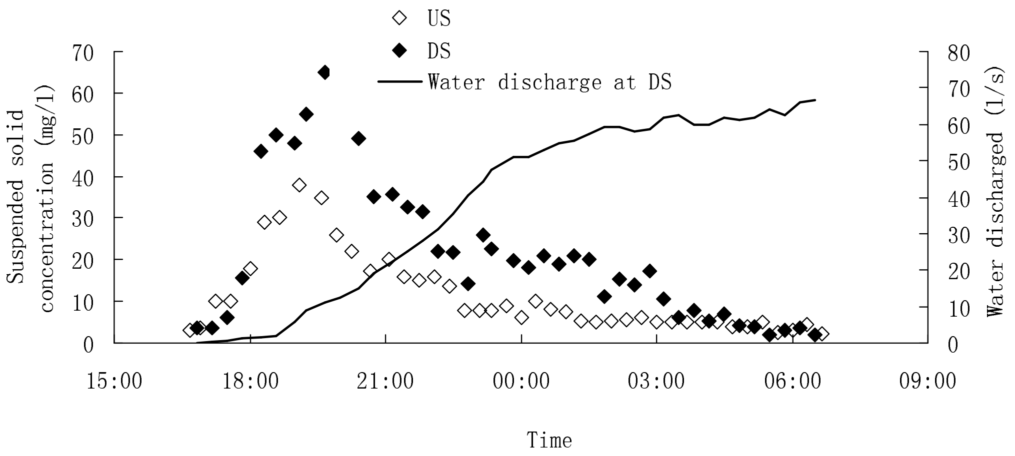

Figure 3a. Pre-harvesting (22/06/2004)

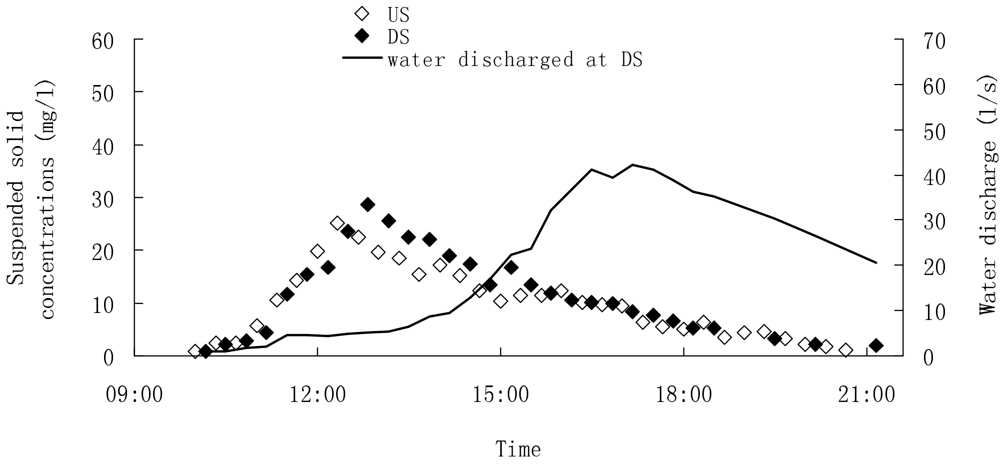

Figure 3b. Pre-harvesting (14/03/2005)

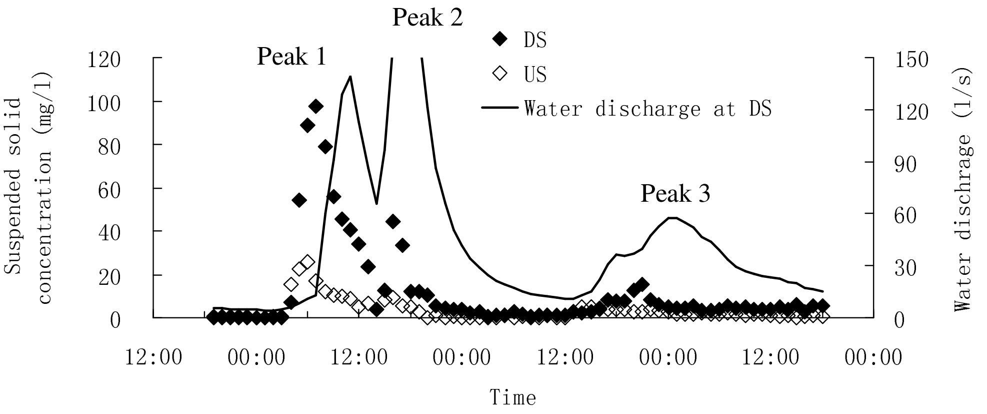

Figure 3c. Post-harvesting (1-4/11/2005) (The flume capacity was about 158 l/s)

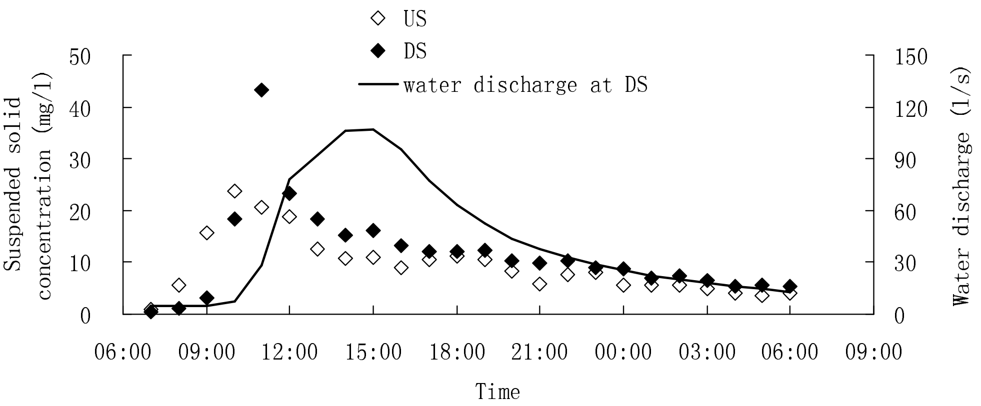

Figure 3d. Post-harvesting (7/12/2005)

Figure 3. Suspended solid concentrations (SS) in the storms at US and DS before and after harvesting

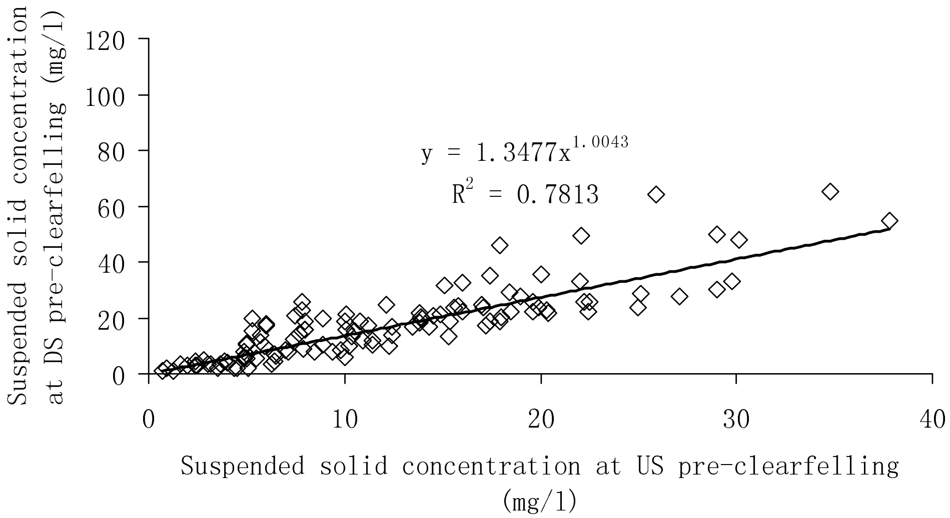

Figure 4a. Pre- harvesting

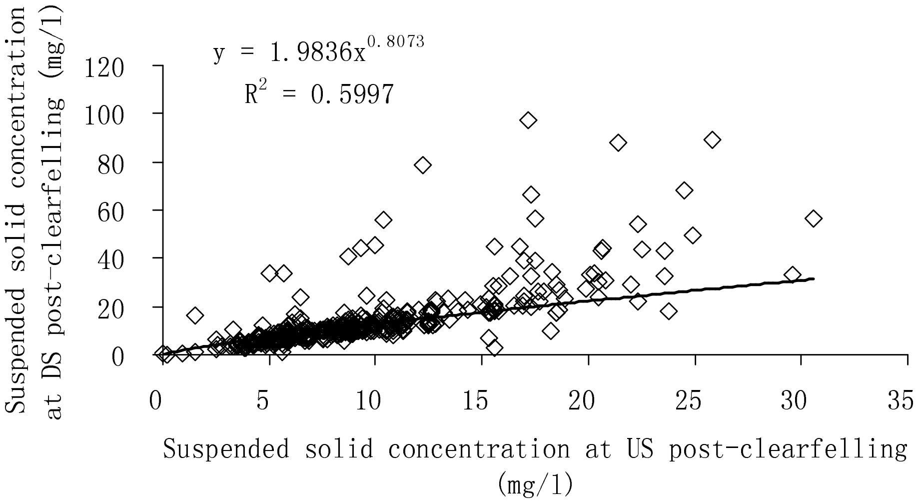

Figure 4b. Post - harvesting.

Figure 4. The relationship between the suspended solid concentrations at US and DS stations before and after harvesting.

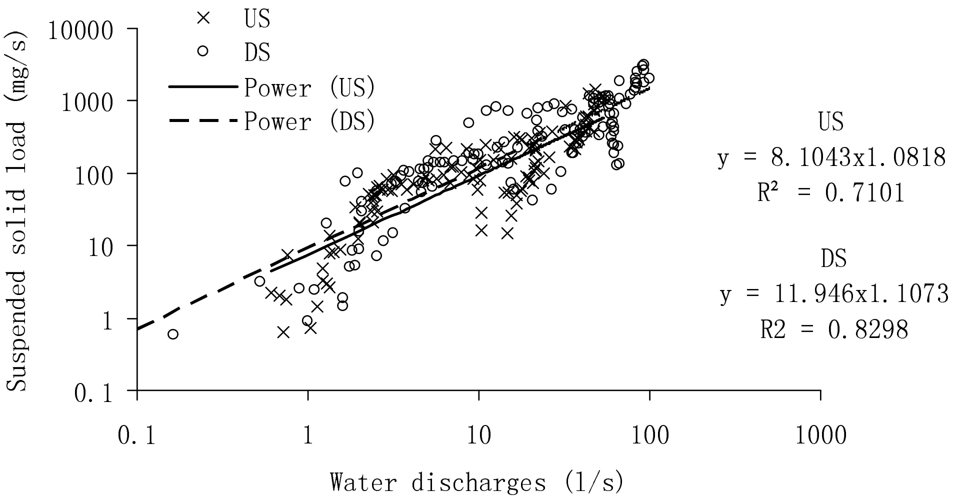

Figure 5a. Pre-harvesting

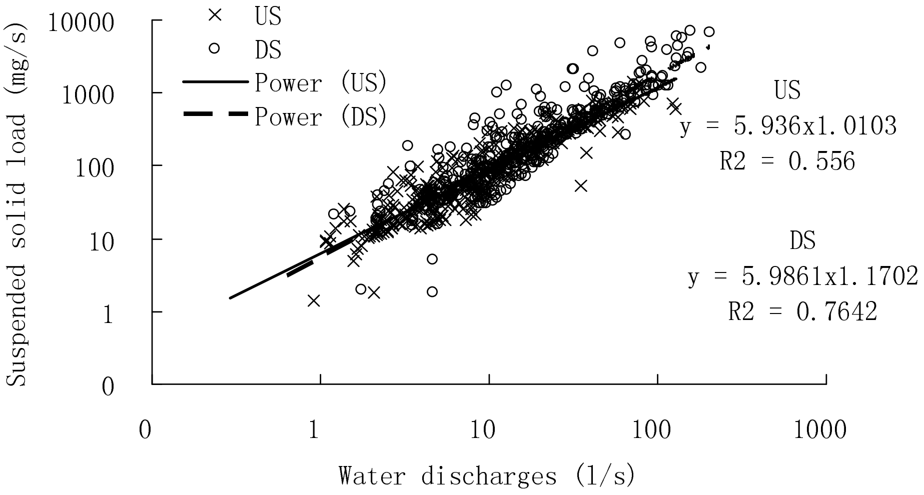

Figure 5b. Post- harvesting

Figure 5. The relationship between water discharge and solid loads calculated using suspended solid concentrations and water discharge data in the pre- and post-harvesting study periods

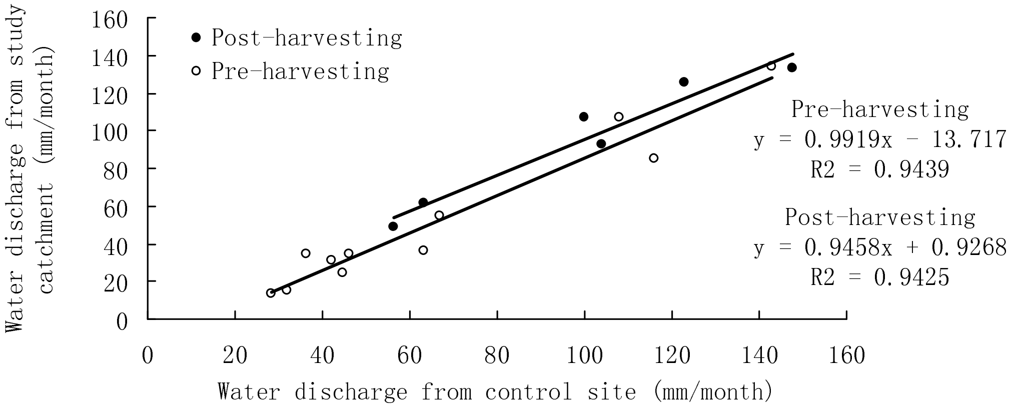

Figure 6. The relationship of monthly water discharge of US and DS pre- and post-harvesting. (Pre- harvesting: April 2004 to June 2005, except January 2005, March 2005 and April 2005 due to lack of data; post-harvesting: October 2005 to March 2006)

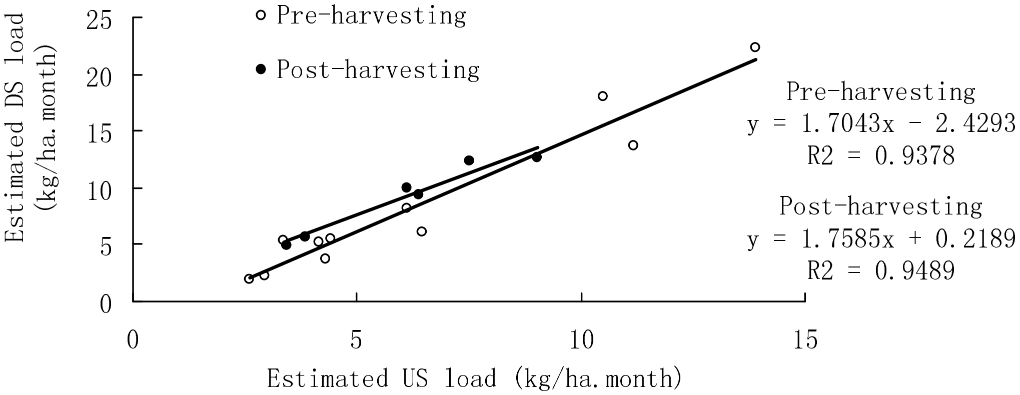

Figure 7. The relationship of calculated monthly solid loads of US and DS pre- and post- harvesting. (Pre- harvesting: April 2004 to June 2005, except January 2005, March 2005 and April 2005; post- harvesting: October 2005 to March 2006)

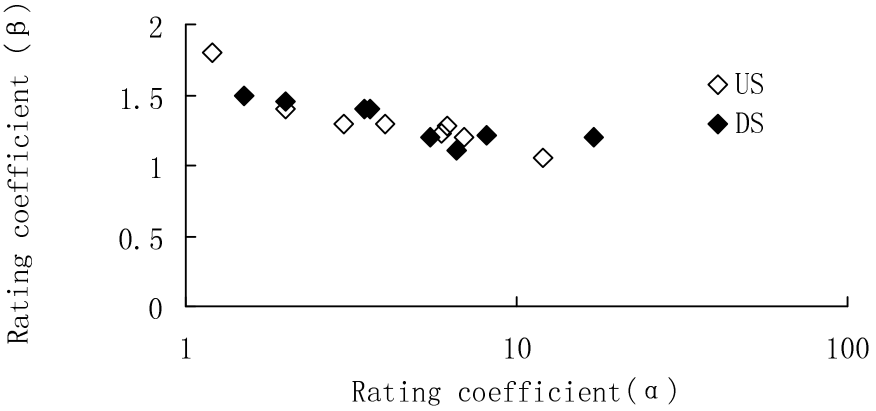

Figure 8a. Pre- harvesting

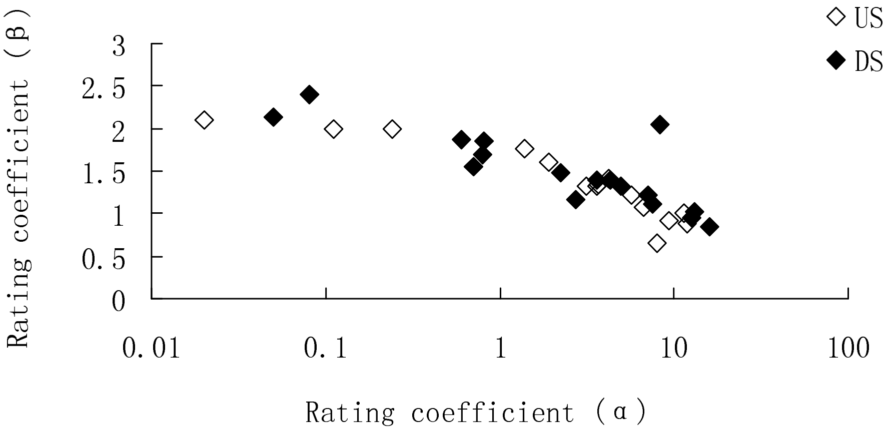

Figure 8b. Post- harvesting

Figure 8. The relationships between the solid load rating curve parameters for individual storms before and after harvesting