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Stream Water Quality and Quantity Effects from Select Timber Harvesting of a Streamside Management Zone

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ABSTRACT

A naturally regenerated, even-aged, mixed pine/hardwood, streamside management zone (SMZ) was selectively harvested in May 2006. The 27.8-ha SMZ buffered an intermittent headwater stream draining a 98-ha watershed. The harvest complied with Texas, US best management practices (BMP) by maintaining a minimum SMZ width of 15 m on either side of the channel, retaining a minimum basal area (BA) greater than 11.47 m^2 ha^{-1}, and minimizing forest floor and stream channel disturbance. No changes in soil bulk density were measured with only a slight increase in bare soil. No changes in water quality or quantity were detectable after harvest, in part because of dry posttreatment conditions. The Agricultural Environmental/Policy Extender (APEX) model was used to simulate treatment effects under different harvesting and weather conditions. APEX provided reasonable estimates of water yield, sediment, and nutrient losses and was found to be an effective tool for estimating the relative impacts of alternative BMP scenarios. Results indicate that maintaining a minimum BA of 11.47 m^2 ha^{-1} and SMZ width of 15 m on intermittent streams will protect water quality even in wet years and that not retaining any residual BA can result in over 10 times more sediment loss.

Keywords: best management practices, water quality, hydrology, streamside management zone, riparian buffers

Protection of riparian areas with forested buffers called streamside management zones (SMZ) is a major component of successful best management practice (BMP) programs (National Council of the Paper Industry for Air and Stream Improvement [NCASI] 2000, Aust and Blinn 2004, Carroll et al. 2004). Riparian areas are the most sensitive portions of watersheds to disturbance (Dunford and Fletcher 1947, Rivenbark and Jackson 2004). There have been numerous studies examining the impacts of forest management with and without BMPs (Edwards et al. 1996, Arabi and Govindaraju 2004, Azevedo et al. 2005, McBroom et al. 2008a). Furthermore, studies have examined the effectiveness of SMZ in the southeast United States for reducing water quality impacts from silviculture (Nutter and Gaskin 1988, Comerford and Mansell 1992, Keim and Schoenholtz 1999, Clinton 2011). However, the effects of select harvest in the riparian area as a separate activity from other silvicultural practices occurring in the watershed have not been studied as extensively. Management of riparian buffers, including timber harvesting, is necessary to enhance commercial value, maintain or enhance forest health, and provide ecosystem services such as wildlife habitat. With different management objectives considered, timber harvests may occur in the watershed at a different time than timber harvests in adjacent upland stands in the watershed. Better understanding of SMZ harvesting and water quality impacts is very important for successful nonpoint source pollution control (Anderson and Lockaby 2011).

Because long-term data on flow and water quality within watersheds are not generally available, programs to evaluate the long-term effectiveness of BMP implementation often rely on hydrologic models. Hydrologic models also are helpful tools for understanding complex hydrologic processes (Anderson and Lockaby 2011). Several studies have used modeling to assess BMP effectiveness (Edwards et al. 1996, Mostaghimi et al. 1997, Saleh et al. 2004, Azevedo et al. 2005, Wang et al. 2007). The Agricultural/Policy Extender (APEX) model was developed for agricultural studies, as a tool for assessing manure management strategies and a wide range of livestock, and farm and nutrient management studies (Gassman et al. 2005). The model was modified to assess forested watersheds and silvicultural practices (Saleh et al. 2004, Wang et al. 2007). The modified model enhanced hydrologic processes associated with forests including rainfall interception by canopy, litter, subsurface flow, nutrient movement, and routing enrichment ratios (Saleh et al. 2004).

The purpose of this study was to measure the in-stream water quantity and quality impacts of an operational SMZ thinning on commercial forestlands as a separate operation from upland harvesting. An additional goal of this study was to simulate harvesting effects with the APEX model to predict hydrologic and water quality responses under different harvest and weather conditions. Finally, the APEX model was used to simulate water quality and quantity for

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This article uses metric units; the applicable conversion factors are: millimeters (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.39 in.; cubic centimeters (cm^3): 1 cm^3 = 0.155 $in.^3$; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac; grams (g): 1 g = 0.035 oz; kilograms (kg): 1 kg = 2.2 lb.

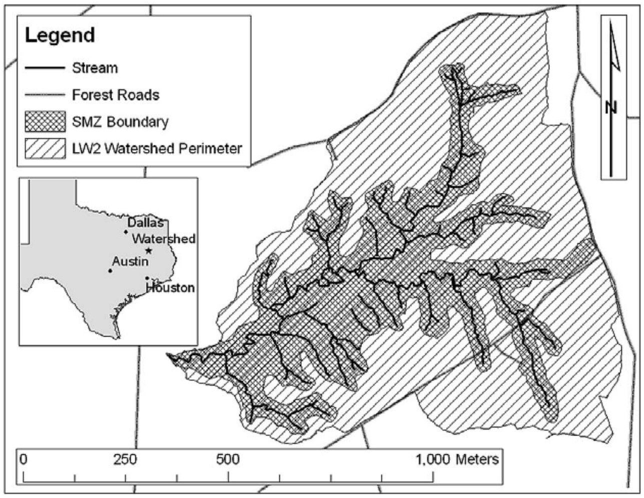


Figure 1. The 27.8-ha SMZ buffering the intermittent headwater stream channel on 98-ha large watershed 2 (LW2) at the Alto Experimental Watersheds in East Texas.

this watershed using guidelines from other southeastern BMP programs to determine if guidelines from those states would have been effective in protecting water resources.

Methods

Study Watershed

The treatment watershed (large watershed 2, LW2) is located at the Alto Experimental Watersheds in the Neches River basin, approximately 16 km west of Alto, Texas (Figure 1). Alto is about 90 km west of Nacogdoches with climatic conditions similar to Nacogdoches.

East Texas is in the Western Gulf Coastal Plain and has a humid subtropical climate. In Nacogdoches, Texas, average summer temperatures are 27.2° C (81° F) and average winter temperatures are 9.5° C (49° F), with a mean annual temperature of 18.7° C (66° F). Annual rainfall in Nacogdoches is 120 cm (47 in.). Rainfall is distributed fairly evenly throughout the year with an average of 89 rain days a year, with April and May receiving the largest amount of rainfall (Chang et al. 1996).

Study watersheds formed in the Sparta Sand and the Cook Mountain Formation in the Claiborne Group (University of Texas at Austin Bureau of Economic Geology 1968). The watershed has a dendritic drainage system formed by random headward erosion. Watershed topography is dominated by rolling hills, with flat floodplains associated with larger streams. Watershed elevation ranges from 115 to 76 m above sea level. Dominant soils include the Cuthbert and Kirvin series, which comprise most of the watershed areas. Cuthbert and Kirvin soils are classified as clayey, mixed, thermic Typic Hapludults with a fine-textured, sandy loam A-horizon up to 250 mm thick and a clay-textured B-horizon. The Kirvin series dominates the upper slopes and Cuthbert the side slopes, with Kirvin soils being slightly deeper and Cuthbert soils having more ironstone in upper horizons. Both soils have severe erosion hazard on steeper slopes. Other soil series found on the site are Lilbert, Tenaha, Rentzel, Briley, and Darco—all Ultisols and typified by deep fine sandy A-horizons (Mowery 1959).

Watershed Treatments

In 2002, a loblolly pine (*Pinus taeda* L.) plantation in Alto, Texas, on a 98-ha watershed was clearcut with the retention of an undisturbed SMZ of 27.7 ha buffering an intermittent headwater stream. The harvest area was replanted in 2003 with a loblolly pine plantation. Because of steep sloping stream banks, erodible soils, and the spatial distributions of ephemeral drains, the SMZ width buffering the harvest was larger than the Texas BMP minimum of 15 m on each side of the channel and above the head. The SMZ is a naturally regenerated, even-aged mixed stand containing mature loblolly and shortleaf pine (*Pinus echinata* Mill.) and mixed upland hardwoods. Total storm runoff and sediment rates were not significantly greater in the years after this clearcut in 2002 on LW2 (McBroom et al. 2008a) and treatment effects on these watersheds lasted only 1 year even when statistically significant (Blackburn et al. 1986).

In May 2006, this SMZ was selectively cut (thinned) in compliance with Texas BMP (Texas Forestry Association 2004) by harvesting marked pines to use the timber, improve stand health, reduce wildfire hazard, create a more open canopy to facilitate natural regeneration, and to provide more growth potential for residual trees. A forester with the landowner, Temple-Inland Forest Products Corp., wrote the stand prescription and laid the harvest out according to what was considered a normal operational SMZ thinning. Trees were harvested using a rotary shear mounted on an articulating tractor, a chainsaw crew, and two log skidders. Sets (log landings) were established outside of the SMZ, upslope of the ephemeral heads. The logging crew was experienced in SMZ thinning operations and exercised appropriate care in felling and removing harvested trees with as little damage to the residual stand and stream banks as possible. Marked pines that required felling across the channel were left standing. Other marked pines on steep sloping ridges, which provided limited access, were often left standing. For these reasons, there were about five marked pines per ha left standing. The rotary shear operator was able to transport many of the cut pines outside the SMZ before dropping them and this greatly reduced the amount of skidder traffic in the SMZ and residual damage to remaining trees. The two skidder operators worked in different areas, not passing over the same skid trail more than two or three times. The chainsaw crew removed the tops of felled trees before the trees were taken to the set; the tops were left in the SMZ. The lower density of large overstory trees allowed the skidder and shear operators more maneuverability and access to marked trees and provided for multiple paths in and out of the SMZ as opposed to using the same trail for many passes. Streams were not crossed during the harvest operation.

After harvest, the operation was inspected by the Texas Forest Service to evaluate BMP compliance. The operation scored 83% implementation, with tops and debris in the stream channel being in excess of allowable BMP limits. The landowner removed some of this logging residue to reduce potential water quality risks and to bring the operation into BMP compliance.

Water Sample Collection and Analysis

The two watersheds (LW1 = untreated control and LW2 = thinned SMZ) were instrumented in March 1999. Two years of calibration data were collected before the SMZ thin. A concrete control structure with an established stage discharge rating curve (McBroom et al. 2008a) was used for flow measurements. Stream stage was measured using an intermountain environmental potentiometric float and pulley level recorder and stored in a Campbell Scientific CR500/510 datalogger (Campbell Scientific Corp., Logan, VT). Rainfall was measured with a network of ISCO Model

674 tipping-bucket (Teledyne ISCO Corp., Lincoln, NE) recording rain gauges and standard National Weather Service nonrecording gauges.

Discrete storm flow samples were taken using an ISCO 3700 pumping sampler (Teledyne ISCO Corp.). Storm samples were taken every 30 minutes until stage fell below the initiation level or until all 24 bottles in the ISCO sampler are filled. Water samples were collected as soon as possible after each storm and handled according to project quality control protocols and standard operating procedures.

After collection, samples were composited in sets that represent the rising limb, the peak, and the recession limb of the storm hydrograph. Sample analysis methods corresponded to established American Public Health Association (American Public Health Association 2005) and US Environment Protection Agency (US Environment Protection Agency 2003) methodology (See McBroom et al. 2008a for more details).

Vegetation Inventory

SMZ vegetation was inventoried before, immediately after, and 1 year after the thin to determine changes in overstory and understory woody plants, percentage of canopy cover, and condition of ground cover. Thirty-two 0.04-ha plots were established in the SMZ on an 80.4 × 100.6-m grid spacing, covering 4.6% of the total SMZ. All stems within the 0.04-ha plot with dbh (1.4 m, 4.5 ft) of >5.1 cm were tallied by species, dbh to the nearest 0.3 cm, and total height to the nearest 0.3 m. Tallied pines that were marked for harvest were measured to ensure compliance with the Texas BMP guideline of a minimum stand density of 11.48 $m^2\ ha^{-1}$ basal area (BA).

Ground surface conditions were measured using the Shugart Method (James and Shugart 1970). Using the 0.04-ha plot center, nested 0.004-ha plots were established. Four transects were run from plot center with the cardinal directions. Along each transect, a point sample was taken every 71.6 cm, recording ground surface condition. Parameters included litter, course woody debris, rock, mineral soil, and vegetation including woody or herbaceous/grass. At each transect point, the presence or absence of canopy cover was noted. All woody vegetation with dbh < 0.3 cm was tallied as understory vegetation by species and total height. Each plot center was marked with PVC pipe driven into the ground with plot number marked on the pipe. A Trimble Pro XRS global positioning systems unit (Trimble Navigation Ltd., Sunnyvale, CA) was used to record coordinates at each plot center.

Soil Compaction

Soil bulk density was measured before and after the SMZ thin, to evaluate soil compaction. Using a 100-m grid across the SMZ, a 30.5-cm^3 core was extracted using an impact core sampler. A total of 20 cores were extracted from the SMZ. Samples were taken at depths of 0–10.2 cm, 10.2–20.3 cm, and 20.3–30.5 cm. Samples were dried in the laboratory at 105° C to constant mass and weighed to measure dry mass in grams. Dry mass in grams was divided by sample volume in cm^3 to calculate bulk density in grams per cm^3.

Data Analysis

Watershed treatment effects were to be analyzed with the analysis of covariance (ANCOVA) procedure. However, because of very low winter rainfall in 2006 and the subsequent low number of samples collected from the treatment and control watersheds, statistical analysis of the postharvest data using ANCOVA was not possible. This drought did not compromise other study objectives, however, and water quality and quantity effects from the selective cutting were modeled using the APEX model. Long-term average rainfall from the APEX weather generator (based on the Lufkin, Texas, climate station), ±20% rainfall (added to or subtracted from daily values in the long-term average rainfall dataset), and observed daily rainfall amounts at the Alto Experimental Watersheds during the study period were used in separate simulations. The watershed was divided into two subareas: upland and floodplain (SMZ and stream channel).

To simulate the SMZ thin, tree density (trees per ha) was the adjusted parameter based on APEX modifications for forestry and availability of measured data. Tree density influences the water balance in relation to watershed input, storage, and usage. Stand density was reduced in the model input from 919 trees ha^{-1} prethin to 799 trees ha^{-1} postthin. Trees per ha were further reduced to simulate alternative harvest scenarios. The modified Hargreaves method (Hargreaves and Samani 1985) was used for potential evapotranspiration (ET) estimations and the Natural Resources Conservation Service curve number method (Mockus 1969) was used for runoff volume estimates. Loblolly pine was used for APEX crop parameters with a leaf area index of 5.0. Daily maximum and minimum temperature, daily total solar radiation, average relative humidity, and average wind velocity were generated using long-term monthly weather statistics in the APEX weather generator parameter database for Lufkin, Texas. Other parameters were defaults in the APEX parameter database and conformed to the calibration conducted by Saleh et al. (2004). Various simulations were compared using different values for width, stems per ha, and canopy interception efficiency (EF) of the SMZ.

The model results were compared with observed flow and sediment data on LW2 from 1999 to 2007. Simulated and observed values for flow and sediment losses were compared using means, R^2, and Nash-Sutcliffe (1970) EF. The satisfactory criteria of $EF > 0.3$ and $R^2 > 0.5$ was used by Chung et al. (1999) for assessment of EPIC annual output comparison and was used in this study. Paired *t*-tests were performed for sediment and streamflow to assess if the measured and predicted values were significantly different from each other. Additional details for APEX calibration for these watersheds and simulation methodology can be found in a study by Wang et al. (2007) and Saleh et al. (2004).

Results and Discussion

Vegetation Effects

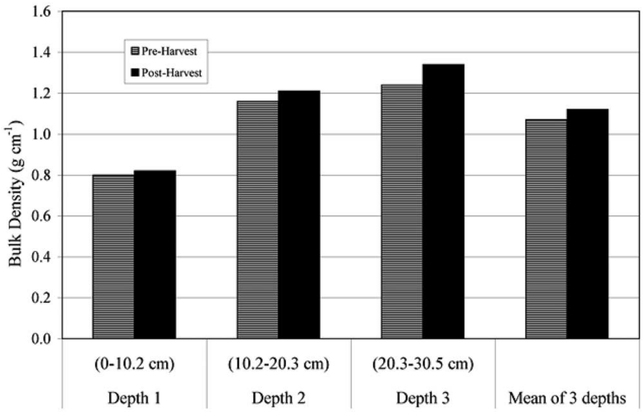
Overstory

SMZ vegetation structure was typical of a lower mesic, species-rich, riparian area in this region. The overstory consisted of a diverse mix of hardwoods, loblolly, and shortleaf pine. A total of 23 overstory species were tallied with loblolly pine, sweetgum (*Liquidambar styraciflua* L.), black tupelo (*Nyssa sylvatica* Marsh.), and oaks (*Quercus* spp.) occupying most of the dominant position in the canopy. Most prevalent species in the intermediate canopy were bitternut hickory (*Carya cordiformis* K.), green ash (*Fraxinus pennsylvanica* Marsh.), and eastern hop-hornbeam (*Ostrya virginiana* Mill.). Marked pines had an average height of 30.64 m and dbh of 43.95 cm. Although only 6.26% of the trees per ha were marked pines, they accounted for 26.45% of the SMZ BA (Table 1). Pines were selected for a thinning from above, which means more of the

Table 1. Preharvest (March 2006) and postharvest (June 2006) density and BA for overstory pines (loblolly and shortleaf) and mixed-upland hardwoods and midstory density in the SMZ on the treatment watershed (LW2) at the Alto, Texas, Experimental Watersheds.

	Overstory pine		Overstory hardwood		
	(stems ha^{-1})	BA (m^2 ha^{-1})	(stems ha^{-1})	BA (m^2 ha^{-1})	Midstory[a] (stems ha^{-1})
Preharvest	317.03	25.03	602.90	9.44	2,026.30
Postharvest	221.50	16.80	577.5	9.51	1,284.90
1-year postharvest					1,546.80

[a] Only midstory vegetation was sampled 1-year postharvest.



Means were not significantly different at $\alpha = 0.05$ by the paired t-test.

Figure 2. Pre- and postharvest soil bulk density by depth and mean of three depths for an SMZ select harvest at the Alto Experimental Watersheds in East Texas in 2006.

larger and more valuable trees were harvested. This accounts for the small ratio of trees per ha^{-1} to BA per ha^{-1}.

After harvest in June 2006, the SMZ was reduced from 34.60 to 26.31 m^2 ha^{-1} BA, exceeding the Texas BMP minimum recommendation of 11.47 m^2 ha^{-1} of BA. This higher BA was retained because the forester representing the landowner was concerned that reducing stand density by more than 25–35% in a single harvest may result in excess mortality due to wind and ice. Furthermore, this landowner rarely targets the minimum BA in an SMZ thin to allow for the inevitable natural mortality that will occur after SMZ harvesting (Brian Gowin, Campbell Group, pers. comm., May 5, 2006). One of the goals of this study was to monitor an operational SMZ thin on commercial timberlands. Site-specific SMZ management based on professional judgment is necessary for effective BMP implementation. Therefore, the investigators did not interfere with the planning and implementation of treatments.

Although there was a 24% reduction in BA, trees per ha were only reduced by 13%, with 799.0 trees ha^{-1} remaining from the original 920.9 trees ha^{-1} before harvest. This percentage of overstory trees per ha were removed, nearly all of which held a dominate canopy position, correlated to a 30% reduction from the complete canopy coverage of the SMZ before harvest. Percent BA removed was more closely associated with the percentage of canopy harvested than the percent of trees per ha removed. Again, minimum BMP guidelines were exceeded by maintaining 70% canopy coverage in the SMZ, where the recommendation calls for a minimum of 50% coverage.

Midstory and Groundcover

The thinning operation reduced midstory vegetation from 2,026 to 1,285 trees ha^{-1}. This cover provided interception, energy dissipation, and storage during rain events that helped offset the increased throughfall as a result of the reduced canopy (Table 2). Increases in bare soil along with decreases in litter layer and canopy coverage were the major watershed physiographic changes after harvest that have the potential to increase soil erosion. However, these same factors facilitate vigorous recruitment and regeneration, helping to quickly reduce the probability for increased sediment loss after harvest (NCASI 2000).

Bulk Density

Soil compaction, measured by soil bulk density, did not show any significant ($P > 0.10$) increases at any depth (Figure 2). Overall surface soil bulk density (0- to 10.2-cm depth), with values of 0.80 g cm^{-3} preharvest and 0.82 g cm^{-3} postharvest had the smallest mean difference, followed by 0.05 g m^{-3} difference at a depth of 10.2–20.3 cm and a 0.10-g cm^{-3} at the deepest depth of 20.3–30.5 cm.

Observed Water Quantity and Quality

Precipitation

Before harvest in 2005 and after harvest in 2006 and 2007, total annual precipitation was 36, 12, and 30% below normal, respectively. In 2006, rainfall amounts in the months of January and October accounted for 36% of the annual total. Excluding January and October, total annual rainfall was 33% below average. October had the most precipitation with 24.99 cm from five events. The watershed received 12.26 cm of rainfall from five events in January of 2006, which was 19% above average. In November through February, immediately after harvest, precipitation was 25% below normal (Table 3). In addition to less total winter precipitation in both 2006 and 2007, the precipitation was less evenly distributed.

Water Quantity

In East Texas, streamflow is typically intermittent in headwater streams on small forested watersheds. The majority of annual flow occurs during winter storm events when there is a moisture surplus (McBroom et al. 2008a). Virtually all the stream discharge in 2005 occurred in January and February, when watershed conditions were

Table 2. Watershed ground cover conditions at preharvest (March 2006), postharvest (June 2006) and 1 year after postharvest on the treatment SMZ at the Alto, Texas, Experimental Watersheds, 2006–2007.

	Woody plants	Herbaceous plants	Coarse woody debris	Litter	Bare soil	Canopy	Average litter depth (cm)
	................................% coverage						
Preharvest	5.00	22.22	8.10	99.00	0.37	100.00	4.05
Postharvest	2.74	11.50	26.82	90.00	3.70	70.00	3.25
1-year postharvest	6.20	44.3	27.2	94.00	2.2	74.00	3.89

Table 3. Mean monthly measured precipitation (cm) at the Alto Experimental Watersheds compared with published long-term averages for Nacogdoches, Texas.

Month	2004	2005	2006	2007	Average
	. . . .		.cm		
January	16.24	14.87	12.26	16.18	10.31
February	18.30	13.13	8.10	3.08	10.10
March	7.31	7.02	7.75	5.77	9.80
April	12.60	2.75	8.74	7.14	11.70
May	3.99	6.24	3.93	15.33	13.00
June	19.35	0.18	8.10	1.87	9.70
July	16.61	5.28	2.96	10.73	9.00
August	10.05	12.48	5.38	0.00	6.60
September	6.40	10.15	9.42	3.25	8.30
October	18.34	2.26	24.99	4.39	8.60
November	23.55	0.72	5.89	5.38	10.70
December	5.21	2.08	7.30	9.33	12.19
Total	157.95	77.15	104.82	83.74	120.00

Source: Chang et al. 1996.

Table 4. Measured and APEX simulated total annual discharge (Q) and total annual sediment from 1999 to 2007 on LW2 at the Alto Experimental Watersheds in East Texas.

	Annual Q (mm yr^{-1})		Sediment (kg ha^{-1} per yr)	
Year	Observed	Simulated	Observed	Simulated
1999	40	22	125	20
2000	43	47	24	0
2001	102	302	1005	1910
2002	211	83	60	330
2003	104	84	240	390
2004	101	81	30	10
2005	41	45	0	0
2006	51	54	14	20
2007	89	38	35	40
Average	87	84	196	302

Table 5. Observed base-flow and storm-flow concentrations and mass losses for the 1st year after thinning a SMZ (2007 water year) on LW2 at the Alto Experimental Watersheds, Texas.

Parameter	Mean base flow	Mean storm flow	Total storm flow loss (kg ha^{-1})
	Concentration . . . . .(mg L^{-1})		
Total dissolved solids		270.00	3.435
Totals suspended solids	1.00	456.70	6.045
Total kjeldahl nitrogen	0.25	1.70	0.029
Nitrate nitrogen		0.88	0.015
Ammonia nitrogen		0.09	0.002
Total phosphorus	0.05	0.12	0.001
Orthophosphate		0.01	0.000

Note: Base flow samples were not analyzed for TDS, NO_3, NH_4, and PO_4.

wet from the previous years of above-average rainfall (Table 4). During the winter, when PET rates decline, winter storms are expected to recharge soil moisture deficits, providing a surplus for the next growing season (Newman and Schmidt 1980). If a lack of precipitation in the growing season persists through the winter and into the next growing season, streamflow can become more ephemeral. This was the case in 2006, when the unusually dry winter conditions in 2005 carried over, resulting in no winter base flow and minimal streamflow response to the few storms in January and February of 2006 (Table 4). Again, most of the annual flow in 2006 was generated by a small number of storms during the winter.

In 2007, total annual discharge resulted from a January storm event, followed by high base flow throughout the spring and above-average streamflow in July. Although rainfall was less in 2007, rainfall was distributed more evenly and the watershed began the year with much wetter conditions than in 2006. Overall, total flow was low on this watershed during the study period, with only 4.12, 5.07, and 8.93 cm of runoff for 2005, 2006, and 2007, respectively (Table 4). Total annual flow in 2005 and 2006 were comparable with amounts from 1999 to 2000 (McBroom et al. 2008a), when precipitation amounts and watershed conditions were similar.

Water Quality

Because of the unusually dry year, only two storm runoff events were measured for water quality variables during the 1st year after harvest (Table 5). Mass losses were also very low, much lower than would have been expected from these watersheds during average rainfall (Blackburn et al. 1986, McBroom et al. 2008a). For example, only 6 kg ha^{-1} of sediment were measured from LW2 in 2007, comparable with the 2000 drought when 24 kg ha^{-1} was measured (Table 4). However, in a wet year such as 2001, over 1,000 kg ha^{-1} was measured from LW2 without any treatments. These watersheds display a great deal of natural variation in losses depending on rainfall (McBroom et al. 2003). With only two storms, it was not possible to conduct an analysis to determine if the observed treatment effect was statistically significant.

APEX Results

Model Performance

Nash-Sutcliffe EF value for annual flow and total sediment (2005–2007, postclearcut recovery period) were −0.99 and 0.90, respectively, meeting the criteria used by Chung et al. (1999) of $EF > 0.3$ for sediment, but not for flow. The R^2 value for sediment for 2005–2007 was 0.98, well above the Chung et al. (1999) threshold of $R^2 > 0.5$. The R^2 for flow was slightly below this threshold at 0.49 for this period. When the full period (1999–2007) was used, APEX performance was less reliable. EF for flow and sediment were −1.54 and −0.21, respectively, and R^2 values were 0.08 and 0.90 for flow and sediment, respectively. However, predicted and measured sediment values were not significantly different ($P = 0.33$). The same was observed for predicted versus measured flow ($P = 0.46$). APEX predictions were more accurate when winter precipitation was closer to normal. In addition, APEX was less effective in predicting the effects of an extreme event, Tropical Storm Allison in 2001 (McBroom et al. 2003).

SMZ Thin (Observed Precipitation)

Using observed daily rainfall amounts at the Alto Experimental Watersheds, APEX did not simulate any differences in total annual discharge or sediment—N and P losses between simulations run with and without an SMZ thinning. For forested watersheds, stream channels can be the greatest source of sediment loss (Chang 2006, McBroom et al. 2008a), although additional research is needed to partition sediment sources (Anderson and Lockaby 2011). In this study, because streamflow did not increase after harvest, neither did sediment losses.

SMZ Thin (Alternative Weather Scenarios)

As mentioned earlier, the seasonal and annual timing of rainfall after treatment is the major factor determining increased water and sediment yields after treatment. Using rainfall amount 20% above and below long-term averages (on a daily time step), the model was

Table 6. APEX simulated water quantity (streamflow) and quality after SMZ thinning at the Alto Experimental Watersheds in East Texas for decreasing SMZ BA and for average total annual rainfall and ±20% of the normal (1,200 mm) rainfall in the year after thinning.

Rainfall	Residual BA (m^2 ha^{-1})	Streamflow (mm)	Sediment yield	N yield	P yield
			. . . .(kg ha^{-1})		
+20%	26.31	38.69	90.00	0.41	0.04
Average		35.48	10.00	0.15	0.00
−20%		4.94	0.00	0.03	0.00
+20%	11.47	40.21	550.00	0.94	0.16
Average		38.88	10.00	0.15	0.02
−20%		4.98	0.00	0.03	0.00
+20%	9.18	42.67	670.00	1.09	0.21
Average		39.17	10.00	0.15	0.02
−20%		5.02	0.00	0.03	0.00
+20%	6.88	46.32	1460.00	1.72	0.38
Average		39.79	10.00	0.17	0.02
−20%		5.10	0.00	0.03	0.00
+20%	4.60	54.65	1810.00	2.01	0.49
Average		41.95	40.00	0.27	0.03
−20%		5.34	0.00	0.04	0.00
+20%	2.30	69.15	3690.00	3.23	0.92
Average		54.92	170.00	0.58	0.08
−20%		6.56	0.00	0.08	0.00
+20%	0.00	192.21	6350.00	7.40	0.94
Average		81.23	1450.00	1.74	0.61
−20%		10.00	350.00	0.30	0.07

run with and without the SMZ thin. These model results indicate that even with a wet year after treatment, total flow, sediment, and nutrient losses were not affected by this SMZ thin (Table 6).

Alternative Harvest Scenarios

Using long-term monthly averages for rainfall amounts (Table 3), there were no differences in pretreatment and posttreatment flow or water quality parameters. With the Texas BMP minimum SMZ BA of 11.47 m^2 ha^{-1} maintained after thinning, values for total discharge, sediment, and N yield were similar (Table 6). Total annual discharge increased by 0.29 and 0.62 mm with SMZ BAs of 9.10 and 6.88 m^2 ha^{-1}, respectively. However, these slight increases in discharge did not result in any increase in sediment loss. Sediment losses were similar below the recommended minimum SMZ BA of 11.47 m^2 ha^{-1}. Increased sediment yield did not occur until the SMZ BA was reduced to 4.66 m^2 ha^{-1}, which correlated to 140 trees ha^{-1}. Reducing the SMZ BA from 6.88 to 4.66 m^2 ha^{-1} increased total annual flow by 5% and annual sediment yield from 10.00 to 40.00 kg ha^{-1} (Table 6).

Total N losses from the watershed remained at 0.150 kg ha^{-1} when the simulated SMZ BA was reduced from 26.31 m^2 ha^{-1} postharvest to the Texas BMP minimum of 11.47 m^2 ha^{-1}. Total nitrogen did not increase with a BA of 9.18 m^2 ha^{-1} before slightly increasing to 0.17 kg ha^{-1} when reduced to 6.88 m^2 ha^{-1} BA (Table 6). Although APEX results show an increase in annual flow and no increase in sediment loss, the increase in total N came from sediment transported nitrogen with soluble nitrogen losses remaining the same. With SMZ BA reduced to 4.60 m^2 ha^{-1}, total N losses increased to 0.27 kg ha^{-1}, and then to 0.58 kg ha^{-1} at 2.30 m^2 ha^{-1} BA (Table 6), with the largest increases coming from sediment bound N, and only 0.01 kg ha^{-1} of each increase coming from soluble N. Total P losses increased slightly until sediment transported P increased from no loss to 0.05 kg ha^{-1} at BA 2.30 m^2 ha^{-1} (Table 6).

Complete harvest of the SMZ increased total flow by 108%, which correlated to 1450.00, 1.59, and 0.59 kg ha^{-1} increases in sediment, total N, and total P losses, respectively. Annual flow and sediment loss remained similar until reduced below 40% of the Texas BMP minimum BA (Figure 3).

Using ±20% of average monthly rainfall, the same BA harvest scenarios were run. With the SMZ BA reduced below the Texas BMP minimum of 11.47–2.30 m^2 ha^{-1}, predicted sediment losses remained at 0.00 with 20% below normal rainfall in the year after the simulated thin. Using 20% below normal rainfall, total annual flow increased only 1.62 mm when reduced to 20% of Texas BMP minimum SMZ BA of 11.47 m^2 ha^{-1}. Using 20% above-normal rainfall, sediment losses and total flow increased more drastically. Annual sediment loss increased by 22, 165, 230, and 571% when BA was reduced to 80, 60, 40, and 20% below Texas BMP minimum, respectively (Table 6).

Modeled annual flow and sediment loss show sensitivity to tree density when reduced past the threshold of about 200 trees ha^{-1}, which correlated to a BA of 6.88 m^2 ha^{-1}. At this tree density, the reduction of canopy intercepted rainfall and ET was significant enough to cause a sharp increase in total flow and sediment loss.

Southeast US State BMP

One of the criticisms of the voluntary BMP program that exists is that BMPs vary between states in the United States, suggesting that water quality may not be adequately protected nationwide. For perennial streams, all southeastern states required residual BA in the SMZ. However, for intermittent streams, there is more variability in minimum guidelines, with several states not having permanent BA requirements (Table 7). APEX was used to simulate the effects on water quality and quantity of an SMZ thin on LW2 with normal rainfall using the different state minimum guidelines. Retaining no residual cover resulted in much higher sediment losses, with 1450 kg ha^{-1} simulated from total harvest versus 10 kg ha^{-1} with 11.47 m^2 ha^{-1} residual BA (Table 6). Nutrient losses were also greater under this scenario.

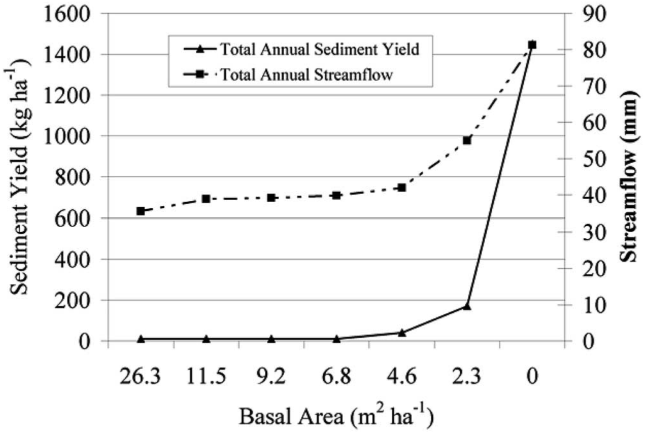


Figure 3. APEX simulated total annual flow and sediment loss using average monthly precipitation with decreasing SMZ BA. Simulation was conducted on an intermittent headwater stream (LW2) draining a 70-ha watershed at the Alto Experimental Watersheds in East Texas.

Table 7. Minimum state guidelines for SMZ width (slope <20%), tree density, and overstory canopy coverage on an intermittent stream for southeastern states in the United States.

State	SMZ width (m)	Tree/canopy coverage
Alabama	10.6	[a]No permanent tree cover requirements
Arkansas	24.4	Maintain 11.47 m^2 ha^{-1} of BA
Florida	10.6	[a]No permanent tree cover requirements
Georgia	10.6	Maintain 5.74 m^2 h^{-1} of BA and 25% canopy coverage
Louisiana	12.2	[a]No permanent tree cover requirements
Mississippi	9.1	[a]No permanent tree cover requirements
North Carolina	15.2	Maintain 75% of canopy coverage along the channel
South Carolina	12.2	[a]No permanent tree cover requirements
Tennessee	30.4	Maintain 50% canopy coverage
Texas	15.2	Maintain 11.47 m^2 ha^{-1} of BA and 50% canopy coverage
Virginia	15.2	Maintain 50% of existing BA or canopy coverage

[a] Although no permanent trees must be maintained, each state calls for maintaining some level of vegetation and/or soil protection. Furthermore, each state recommends not harvesting trees where in sensitive areas and limiting harvest in intermittent SMZs to minimize disturbance.

Based on results from APEX, SMZ width alone was not found to be as sensitive of a parameter within the range of guidelines recommended by southeastern state BMP programs. States such as Arkansas (24.4 m) and Tennessee (30.4 m) require wider SMZs than Texas (15.2 m) with the same basal requirements. Using these wider SMZ widths did not result in a corresponding decrease in predicted sediment or nutrients for this stream. Wider SMZs may be needed in more mountainous states and in states that have trout-bearing streams, such as Arkansas or Tennessee. Other states such as Georgia have narrower SMZs (10.6 m) on intermittent streams than Texas with the same BA. Simulating sediment and nutrient losses with a 10.6-m SMZ on this stream did not result in a significant change.

However, one of the components not accounted for in this analysis is the fact that in establishing the minimum guidelines, all the state BMPs rely on professional judgment to be the overriding factor in decisionmaking. Areas of steeper topography, with deeply incised ephemeral streams in erodible soils would require additional protection beyond the BMP minimums. Additional research is needed to determine how often in the South these intermittent and even ephemeral streams are, in fact, being protected by forest managers who are sensitive to this. In addition, several states (Florida, Georgia, and South Carolina) have provisions for primary and secondary SMZs under certain conditions, which were not simulated as part of this analysis. Finally, additional protection is required for trout-bearing streams in many of these states, which was not taken into account for this analysis.

Conclusions

SMZs are managed to prevent or reduce the transport of sediment, nutrients, and herbicides from silvicultural operations into streams (NCASI 1992). Select harvesting of SMZs is often necessary to provide economic return, maintain forest health, reduce wildfire risk, and enhance other ecosystem services such as wildlife habitat. However, harvesting must not significantly compromise the beneficial hydrologic functions of the SMZ. The Texas BMP compliant select harvest conducted in this study reduced canopy coverage by 30% and stand BA by almost 25% (from 34 to 26 m^2 ha^{-1}). Damage to residual timber as a result of the harvest was minimal. Less than 4% bare soil was exposed, and ground cover and understory vegetation regrowth was rapid after harvest. Soil bulk density did not increase significantly after harvest.

Below-average annual precipitation in the year before harvest resulted in minimal streamflow and thus low sediment and nutrient losses in the 1st-year posttreatment. The APEX model was used to simulate hydrologic effects under various precipitation and harvesting scenarios. Using observed rainfall and tree density, APEX results were similar with and without the SMZ thin. APEX was found to be an effective tool for determining the relative impacts of different treatments and BMP.

Based on output from APEX, with the SMZ BA reduced below the Texas BMP minimum of 11.47–2.30 m^2 ha^{-1}, predicted 1st-year sediment losses remained at 0.00 kg ha^{-1} using 20% below-normal rainfall amounts. With the same rainfall scenario, total annual flow increased only 1.58 mm when reduced to 20% of the Texas BMP minimum. Simulated sediment losses increased along with flow using 20% above-normal rainfall amounts. Simulated annual sediment loss increased by 22, 165, 230, and 571% when BA was reduced to 80, 60, 40, and 20% of the Texas BMP minimum, respectively (Table 6). With minimum Texas BMP requirements for BA and width, APEX predictions for total annual flow were 4% higher and sediment losses increased from 90 to 550 kg ha^{-1} after harvest. Total annual flow becomes sensitive to tree density when reduced past the threshold of about 200 trees ha^{-1}, which correlated to a BA of 6.88 m^2 ha^{-1}. The reduction of canopy intercepted rainfall and ET was significant enough to cause an increase in total flow and sediment loss. Nutrient losses remained minimal, indicating that these forests have the capacity to effectively retain nutrients made available through forest harvesting (McBroom et al. 2008b).

Based on these results, SMZ harvesting should be planned and executed with sound professional judgment on a site-specific basis to ensure minimal disturbance to the forest floor, stream channel, and runoff contributing areas. These results indicate that maintaining a minimum BA of 11.47 m^2 ha^{-1} and SMZ width of 15 m on intermittent streams will protect water quality even in wet years, and that not retaining any residual BA on intermittent streams can result in about 10 times more sediment loss.

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