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Seasonal Ground Water Table Changes Following Forest Harvesting in Small Headwater Riparian Areas[1]

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산지계류 수변지역에서 산림벌채 후 지하수위의 계절 변화[1]

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ABSTRACT

This study addressed the influence of forest harvesting on seasonal water table dynamics in small headwater riparian areas. Four treatments including potential Best Management Practices(BMPs) for ephemeral and intermittent streams were implemented(BMP1, BMP2, clearcut and reference). Water table measurements were obtained at bi-monthly intervals for 3 years including one year of pre- and two years of post-harvest observations. Overall, water table responses affected largely by rainfall amount. In addition, significant increases in water table levels following harvesting occurred throughout the two post-harvest years. Water table levels increased up to 28.2㎝ in the clearcut treatment during 2008 and up to 54.2㎝ in BMP2 during 2009. However, increase in water table elevation was not directly related to basal area removal despite considerable differences in basal area removed between BMP2 and clearcut treatments. Water table rises were apparent in that water table were more elevated during dry season(June through November) than during wet season(December through May). These seasonal fluctuations were presumably driven by changes in evapotranspiration caused by differences in leaf area of overstory canopy and understory following harvest.

KEY WORDS: BEST MANAGEMENT PRACTICES, WATERSHED, HYDROLOGY, EPHEMERAL STREAMS, INTERMITTENT STREAM

요 약

본 연구에서는 산림유역의 최상류지역에 위치한 일시하천(ephemeral stream)과 간헐천(intermittent stream)이 상존하는 수변지역을 대상으로 지하수위의 계절적인 변화 양상을 파악하였다. 3곳의 산림유역(총 12개 소유역)에서 일시하천 및 간헐천의 수변구역 보호를 위한 최적관리기법을 포함하는 4개의 처리구(BMP1, BMP2, clearcut, reference)를 적용하였다. 지하수위는 각 소유역별 25개소(총 300개소)에서 2주 간격으로 측정되었으며, 벌채 전 1년과 벌채 후 2년, 총 3년 동안 관측되었다. 전체적으로 지하수위의 반응은 강우량의 영향이 큰 것으로 관찰되었다. 또한, 산림벌채전과 비교하여, 벌채 후 2년 동안 지하수위는 유의적으로 증가하였다. 특히, 벌채 1년 후(2008) 개벌처리구에서 28.2㎝, 벌채 2년 후(2009) BMP2에서 54.2㎝로 가장 크게 증가하였다. 그러나, 개벌처리구와 BMP2의 지하수위 변화 특성을 비교할 때, 벌채된 목재의 재적과 지하수위의 변화는 직접적인 연관성이 없는 것으로 나타났다. 산림벌채로 인한 지하수위의

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증가는 습윤기간 보다 건조기간 동안 더 크게 나타났으며, 이러한 계절적인 추이는 산림벌채 후 식생구조의 차이에서 야기되는 증발산양의 변화에 기인하는 것으로 사료된다.

주요어: 최적관리기법, 유역, 수문, 일시하천, 간헐천

INTRODUCTION

Headwaters are often considered as the greatest contributor to nonpoint sources of sediment in natural conditions and are a crucial part of overall watershed dynamics(Doppelt *et al*., 1993; Meyer and Wallace, 2001) because they occupy topographically high positions and a substantial portion of drainage basins at points of stream initiation(Choi et al., 2012). However, their actual functional role in the context of downstream hydrology has not been well quantified (Gomi et al., 2002).

The boundaries between terrestrial and aquatic systems represent dynamic habitats which link ecosystem processes that influence the movement of organisms, nutrients, materials and energy throughout the stream ecosystem(Naiman and Decamp, 1997). Disturbance through silvicultural practices on such boundary areas can impact all of these processes within an ecosystem at local and landscape levels. In an effort to reduce the impacts of silvicultural practices on water quality and preserve the biological integrity of U.S. waters, most states have developed guidelines known as forestry best management practices(BMPs) for preventing or reducing water pollution from nonpoint sources. Numerous studies have been conducted to evaluate forestry BMPs effectiveness on water quality, the biological integrity of streams, and wetlands in southern U.S(Ursic, 1991; Keim and Schoenholtz, 1999; Ice *et al*., 2003; Carroll *et al*., 2004; Rivenbark and Jackson, 2004). Most results indicate that properly installed forestry best management practices provide adequate protection on riparian ecosystems. However, many studies into environmental impacts of forest management operations such as timber harvesting have usually focused on the water quality. Little is known about the effects on water quantity, thus there are still critical gaps in our knowledge base, especially with respect to forest harvesting effects on water table dynamics in these headwater systems. Moreover, in many states forestry BMP guidelines, only intermittent and perennial streams receive forested buffer protection while ephemeral streams are often ignored in terms of management prescriptions (Choi, 2011).

Forested watersheds are storage-based hydrologic systems where surface runoff occurs mainly when the soil profile is saturated and the water table reaches the soil surface(Sun *et al*., 2000). Changes in water table can affect hydrologic responses in surface runoff and subsurface flow. Also, ground water is the major source of stream baseflow which dominates stream discharge during summer; therefore it is relevant to consider the impact of forest management on water table levels.

The fluctuation of the water table over time has a substantial influence on the type and productivity of plant communities (Glaser *et al*., 1990; Xu *et al*., 2002; Pothier *et al*., 2003) and is dependent on the balance between rainfall and evapotranspiration with lateral and subsurface drainage playing a limited role(Ewel and Smith, 1992). Studies have demonstrated that forest harvesting can result in a rise of the water table(Sun *et al*., 2000; Xu *et al*., 2002). This water table rise following harvesting is caused mainly by a reduction in evapotranspiration which itself is due to decreases in interception and leaf transpiration. The post-harvest water table rise is generally more significant during the first few years following harvesting, especially when compared to water tables of uncut treatments during dry growing seasons (Roy *et al*., 2000; Sun *et al*., 2000). However, this water table rise decreases by vegetation regrowth during the years after harvesting and the return of the water table level to its initial state lasts as long as 15 years(Verry, 1986) and depends on the site type, climate, and developing vegetation(Sun *et al*., 2001).

Experimental studies involving various harvesting intensities have rarely been conducted to assess the effects of treatments on the water table level in headwater streams. This study includes one year of pre- and two years of post-harvest observations documenting three potential management prescriptions for headwater areas. The objective of this study was to examine effects of forest harvesting on seasonal water table responses in small forested headwater riparian areas.

MATERIALS AND METHODS

1. Study Site

The study area is located in Webster County within the Sand-Clay Hills subsection of the Hilly Coastal Plain Province of Mississippi(Figure1). This physiographic region was selected because of the presence of numerous intermittent-flow channels within small-scale watersheds and soils which are conducive to interflow. Three first-order headwater catchments containing loblolly pine(*Pinus taeda* L.) stands of similar age class and near their final rotation age were selected for study. Four small watersheds were selected within each catchment(Choi *et al.*, 2012). The study area has a humid subtropical climate characterized by long, hot summers and short, mild winters. Precipitation is well distributed throughout the year with a 30 year mean of 1,451㎜. Mean winter temperature is 7℃; mean summer temperature is 26℃(U.S. National Weather Service station 222896 Eupora, MS)(Choi *et al.*, 2012).

Watershed size varied from 1.8 to 7.1㏊ among the 12 watersheds. Stream gradients and hillslope gradients ranged from 2 to 19% and 2 to 26%, respectively, but both were generally similar within catchments(Table 1). Soils were well drained, Fine, mixed, semiactive, thermic Typic Hapludults(Sweatman series) and were moderately well drained Fine-silty, mixed, active, thermic Oxyaquic

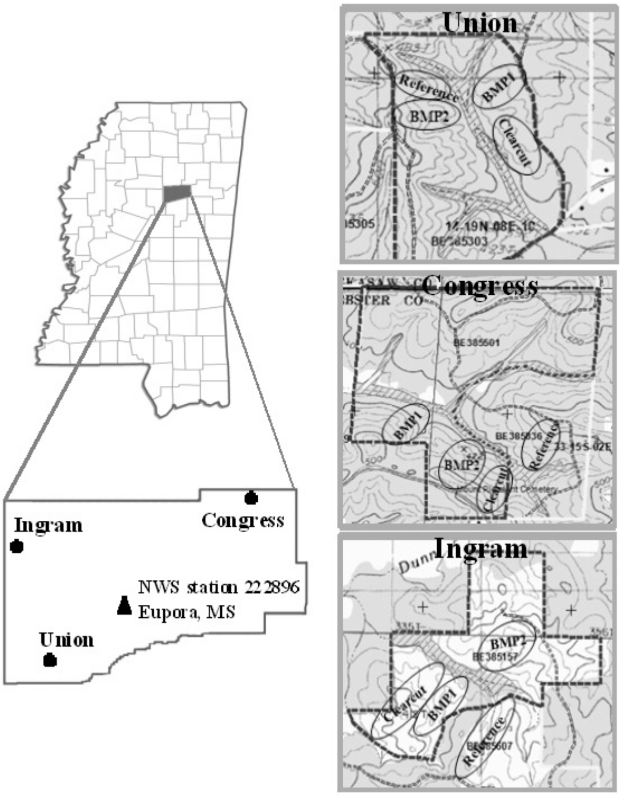

Figure 1. Location of study watersheds of Webster County, Mississippi

Table 1. Physical characteristics of the study small headwater areas in Webster County, Mississippi(Choi *et al.*, 2012)

Watershed	Treatment	Watershed area(ha)	Stream length(m)[a]	Stream gradient(%) Mean(min, max)[b]	Hillslope gradient(%) Mean(min, max)	Basal area removal(%)[c]
Union	BMP1	3.6	92	5(4, 6)	26(13, 39)	8.9
Union	BMP2	3.6	83	4(3, 5)	22(3, 42)	32.4
Union	Clearcut	1.8	81	4(3, 5)	26(14, 40)	70.1
Union	Reference	2.4	78	5(4, 5)	21(3, 39)	-
Congress	BMP1	2.4	117	5(4, 5)	15(2, 29)	28.1
Congress	BMP2	2.9	96	13(6, 9)	14(3, 31)	53.1
Congress	Clearcut	2.5	95	19(12, 22)	18(12, 30)	88.3
Congress	Reference	2.1	102	12(11, 13)	18(10, 40)	-
Ingram	BMP1	3.3	73	3(2, 4)	19(16, 24)	55.4
Ingram	BMP2	7.1	55	2(2, 3)	2(2, 3)	75.1
Ingram	Clearcut	5.2	85	5(4, 6)	16(10, 22)	95.2
Ingram	Reference	6.7	116	5(4, 6)	20(5, 29)	-

[a] Stream length was a distance from the center well of the first measurement transect to the center well of 5th measurement transect.

[b] Stream gradient was measured within measurement transects.

[c] Values were calculated approximately based on sub-sample within water table well transects.

Fragiudalfs(Providence series)(McMullen and Ford, 1978). Hillslope water table typically drops to >2m below the surface in the summer(Choi, 2011).

2. Methods

1) Study design and treatment

Twelve similar headwater streams were arranged in a completely randomized block design consisting of three blocks of four randomly assigned treatments(Table 1). The uppermost reaches(ephemeral streams) not governed by Mississippi's Forestry BMP guidelines(Mississippi Forestry Commission, 2000) received one of the following treatments: (1) clearcut- total harvest with no BMPs applied within the drainage channels. (2) BMP1- removal of all merchantable stems greater than 15.2㎝ diameter at breast height(DBH) leaving understory intact with minimum surface soil and forest floor disturbance. Logging debris was prohibited in the drainage channel. (3) BMP2- same as BMP1 with the addition of logging debris to the drainage channel in an attempt to decrease energy in the system and minimize head-cutting and continued channel development in the ephemeral area. The objective of logging debris addition in BMP2 were not part of this study; it was developed to test the effects of harvest residue on downstream water quality (most BMPs in the southeastern US prohibit logging debris within stream channels). Thus, the only effective difference between BMP1 and BMP2 was greater basal area removal in BMP2. (4) reference- left uncut as a control. Forest harvesting was conducted during October to December 2007(Choi *et al.*, 2012).

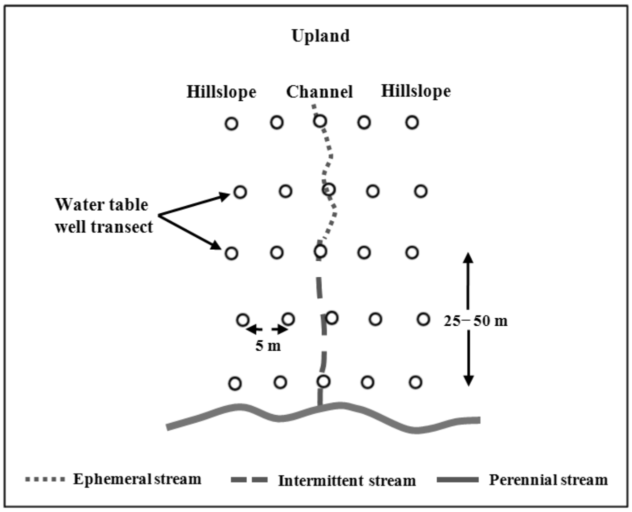

Figure 2. Schematic of approximate location of stream and water table well transects in small headwater areas of Webster County, Mississippi(Choi *et al.*, 2012)

2) Data collection

At the head of each intermittent stream, 5 transects were established perpendicular to the developed channel from the top of the ephemeral streams through the entire length of the intermittent stream(Figure 2). Spacing between transects was dependent on the length and slope of the drain as well as the areal extent of the watershed and ranged from 12 to 25m. Monitoring stations were located at 5m intervals along each transect(Figure 2). Three hundred screened wells with 1.5 to 2.5m in depth and 5㎝ internal diameter were constructed of 0.25㎝ thick polyvinyl chloride and installed in grids of 25 per sub-watershed to monitor water table depths(Choi *et al.*, 2012). Water table wells were monitored on a bi-monthly schedule from January 2007 to December 2009 using an electronic measuring tape. All measurements were referenced to the soil surface datum.

3) Data analysis

To detect timber harvesting effects on water table levels through time, the differences between pre- and post-harvest mean water table level were used to detect changes in water table responses to harvesting. Pre-harvest mean water table level was determined for January 2007 through November 2007. The difference between pre- and post-harvest water table level for each well was quantified as follows(Choi *et al.*, 2012):

$$DWT_{ij}=(Post\_WT_{ij}-Pre\_MWT_{ij})/Pre\_MWT_{ij}$$

where:

DWT_{ij} is difference in monthly water table level for each well in treatment j in block i.

Post_WT_{ij} is post-harvest monthly water table level for each well in treatment j in block i.

Pre_MWT_{ij} is pre-harvest mean water table level (January 2007 through November 2007) for each well in treatment j in block i.

i and j represent each block and treatment, respectively.

The difference in monthly water table levels for each well in a treatment was averaged for each period.

A randomized complete block(RCB) design was used to evaluate the effects of timber harvesting on seasonal water table level. The MIXED procedure of SAS(SAS Institute Inc., 2008) was used to fit a mixed linear model to water table data composed of the means of water table measurements taken bi-monthly within each treatment (Choi *et al.*, 2012).

$$Y_{ijk}=\mu+blk_i+trt_{ij}+t_{ijk}+trt_{ij}\times t_k+\varepsilon_{ijk}$$

$(i = 1,\cdots, 4;\ j = 1,\cdots, 4;\ k = 1, \cdots, 4)$

where:

Y_{ijk} is the mean *DWT* in treatment *j* in block *i* at time *k*.

μ is the grand mean.

blk_i is the random effect for block *i*.

trt_{ij} is the fixed effect for treatment *j* in block *i*.

t_k is a fixed factor for time *k*, where 1 and 2 represent wet and dry season measurements of 2008 and 3 and 4 represent wet and dry season measurements of 2009, respectively.

ε_{ijk} is the random error for treatment *j* in block *i* at time *k*.

The study objective was to evaluate the effects of forest harvesting on water table level among treatments. Therefore, when interactions among main effects were significant, planned comparisons were tested using the least square means for water table level within each treatment. Two sample t-tests also used to test differences between pre- and post-harvest observations on water table level. A significance level of α =0.05 was used for all statistical tests.

RESULTS

1. Hydrologic characteristic

This study encompassed three years(one pre- and two post-harvest) with distinct precipitation patterns. Total precipitation for 2007(pre-harvest) was below-average at 1001㎜(30-year mean=1,451㎜). Total precipitation for 2008(1^{st} year post-harvest) was roughly equal to the 30-year mean at 1498㎜. However, 28% of the total precipitation for 2008 fell during the months of August

Table 2. Wetness evaluation of monthly precipitation at Eupora 2E Station, Webster County, Mississippi, USA for the years, pre-harvest(2007), 1^{st} year post-harvest(2008) and 2^{nd} year post-harvest(2009)

Month	Lower Bound[1]	30-year Mean 1970~1999[2]	Upper Bound[3]	2007	2008	2009
			(mm)			
January	95	144	174	119(N)[4]	87(D)	149(N)
February	77	113	134	63(D)	144(W)	223(W)
March	125	169	198	19(D)	111(D)	195(N)
April	73	137	168	52(D)	172(W)	59(D)
May	73	133	162	33(D)	170(W)	361(W)
June	64	106	128	162(W)	41(D)	57(D)
July	66	103	124	160(W)	100(N)	317(W)
August	33	81	113	41(N)	198(W)	64(N)
September	57	96	117	166(W)	93(N)	239(W)
October	39	93	113	66(N)	78(W)	338(W)
November	85	127	155	59(D)	75(D)	52(D)
December	89	151	183	62(D)	23(W)	132(N)
Total	876	1,451	1,768	1,001	1,498	2,195

[1] Lower bound: 70% of all precipitation events in the month expected to exceed this value based on 30 years of data

[2] Data retrieved from National Water and Climate Center website(www.wcc.nrcs.usda.gov/climate/wetlands.html)

[3] Upper bound: 70% of all precipitation events in the month expected to be less than this value based on 30 years of data

[4] N: monthly precipitation between lower and upper bounds(Normal); D: monthly precipitation < lower bound(Drier than Normal); W: monthly precipitation > upperbound(Wetter than Normal)

and December(Table 2). The net result was that the study watersheds experienced a severe regional drought from February 2007 through December 2008(National Drought Mitigation Center, http://drought.unl.edu/dm/archive.html). Total precipitation for 2009(2nd year post-harvest) was 2195㎜, the highest in the 25-year record for Webster County, Mississippi. Wetness evaluations at the Eupora 2E Weather Station indicated that rainfall amounts during the 36 month period of water table observation were within the expected normal range for only nine months, wetter than the expected normal for 13 months and drier than the expected normal for 13 months based on long-term precipitation data(Table 2).

Mean water table level across all treatments ranged from 230㎝ below the surface during extreme drought conditions in 2007 to 73㎝ below the surface during the spring 2009 rainy season. Three-year mean water table level ranged from 138 to 230㎝, 92 to 218㎝, 73 to 221㎝, and 89 to 223㎝ for reference, BMP1, BMP2 and clearcut treatments, respectively(Figure 3). Patterns in rise and fall of water table were consistent across treatments. Water table remained lower in the reference watersheds than in all three treatments during the three years of study. Water table in the reference watersheds was lower than that of BMP1 pre-harvest, and higher than BMP1 post-harvest. BMP2 had the highest water table throughout the study except during the extreme drought of 2007(Figure 3).

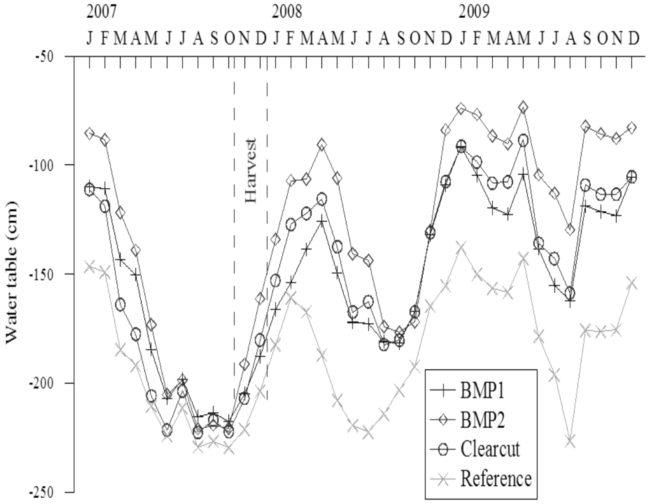

Figure 3. Monthly treatment means of water table levels in the study small headwater areas of Webster County, Mississippi

2. Effects of forest harvesting on seasonal water table dynamics

During the 2 years post-harvest, mean water table dynamics differed significantly among the treatments (p<0.001)(Figure 4). Increases in water table level was highest on BMP2(38.7%), followed in decreasing order by clearcut(36.6%), BMP1(24.9%), and reference(12.9%) treatments when compared to pre-harvest measurements. The BMP1 and BMP2 treatments showed different water table responses following harvest; mean water table level of BMP2 treatment was 14% higher than that of BMP1 treatment post-harvest. In all harvested treatments, water table level increased post-harvest; differences in mean water table level were lower each dry season than during the previous wet season(p<0.001)(Figure 4). However,

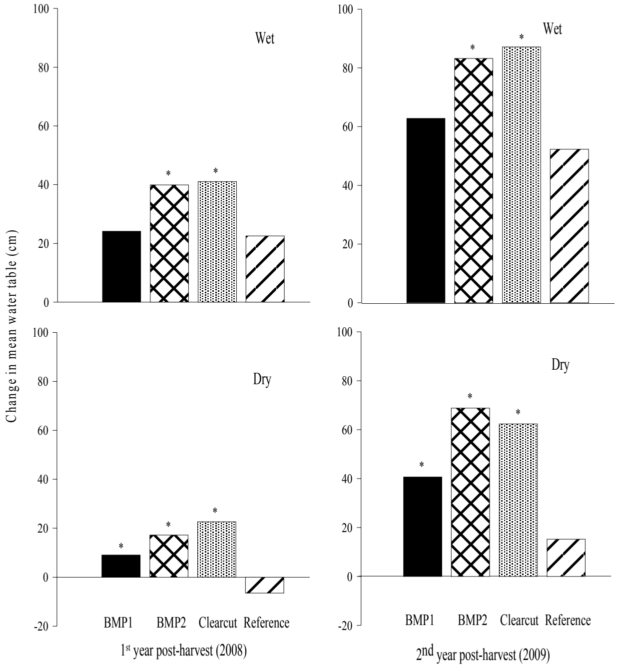

Figure 4. Changes in mean water table level by treatment over 2 years of post-harvest in the study small headwater riparian areas of Webster County, Mississippi; positive values indicate an increase in water table level relative to pre-harvest means; negative values indicate a decrease in water table level relative to pre-harvest means; *indicates significant differences between pre- and post-harvest values at α=0.05

water table responses may not be solely due to timber harvesting, but rather a function of changing precipitation patterns pre- and post-harvest in combination with forest harvesting(similar patterns were observed in reference). Therefore, mean water table level for each well within the reference was subtracted from the value for corresponding wells within the other treatments to account for differences caused by differing levels of precipitation.

Upon normalization, increases in water table level following timber harvesting ranged from 1.6㎝ in BMP1 to 18.5㎝ in BMP2 during wet season of 2008, from 15.6㎝ in BMP1 to 28.2㎝ in clearcuts during dry season of 2008, from 10.5㎝ in BMP1 to 34.9㎝ in clearcuts during wet season of 2009, and from 25.1㎝ in BMP1 to 54.2㎝ in BMP2 during dry season of 2009. Increases in water table level were greater during dry season(June through November) than during wet season(December through May). Post-harvest differences in mean water table level were significantly higher in 2009 than in 2008($p<0.001$) as a result of higher precipitation in 2009. Small decreases in the water table level during dry season of 2008 reflected prolonged drought conditions. Moreover, precipitation during this period (584.2㎜) was lower than pre-harvest precipitation(653.8㎜)(Table 2).

DISCUSSION

There was an increase in water yield in the treatment watersheds post-harvest, as has been reported in numerous other studies(e.g. those summarized in Brown *et al.* 2005) even in these small headwater areas. At the outset of the study, reference treatments had the lowest water tables followed in decreasing order by BMP1, clearcut and BMP2 treatments(Figure 3). Persistent drought during the pre-treatment year followed by higher than normal rainfall during the first and second years post-harvest made pre- and post-harvest comparisons difficult, however it is notable that during the extreme drought of 2007(pre-harvest), water tables in all treatments reached approximately the same low levels(>2m below the soil surface), whereas only the reference treatments had a comparable decreases in water table post-harvest. All treatment watersheds had water tables that were approximately 50㎝ higher than reference treatments during the summer of 2008, and 50 to 100㎝ higher than those of reference treatments during the summer of 2009. The most notable change occurred between BMP1 and clearcut treatments, in that prior to harvest clearcut treatments had lower water tables than BMP1 treatments, however post-harvest, water tables in clearcut treatments were elevated above those of the BMP2, and they remained elevated for the remainder of the study(Figure 3).

More basal area was removed in BMP2 than in BMP1 (Table 1) and this additional basal area removal resulted in a somewhat more elevated water table in BMP2 than in BMP1(Figure 4). Higher water tables in BMP2 was responsible for differences in operational implementation of harvest prescription between BMP1 and BMP2 treatments (Choi *et al.*, 2012). For example, more basal area was removed in BMP2 due to less operational restriction in terms of logging debris(Table 1). Stand heterogeneity may also be a factor, in that selective cuts preferentially remove more timber where there is a concentration of high-value timber.

In the present study, water table elevation in BMP2 and clearcut increased 38.7% and 36.6%, respectively over pre-harvest values. Despite considerable differences in basal area removed between BMP2 and clearcut treatments (Table 1), increase in water table elevation was not directly related to basal area removal in areas adjacent to monitoring grids. The consistently high water table in BMP2 watersheds is most likely a function of watershed size as BMP2 treatments were the largest in each of the three replicates(Table 1). Soils in this region have a high infiltration rate and tend to have numerous subsurface flow conduits, thus much of the rainfall accumulated in the catchment will move through the watershed as shallow subsurface flow rather than overland flow(Choi, 2011). The larger the watershed, the more water collected, thus the greater the contribution to subsurface flow. Shaman *et al.*(2004) in a study of spring-fed watersheds in the Catskill Mountains of New York reported a threshold watershed size of 8-21㎢(800-2100㏊) above which ground water contributions are independent of basin size, and below which contributions decrease with decreasing basin area. In a study of nine small(<3㏊) watersheds in East Texas, McBroom *et al.*(2003) reported that overland flow was rarely observed and that hydrologic response was the result of subsurface macro-channel flow. Where stormflow was measured, McBroom *et al.*(2008) reported significant increases in runoff following harvesting in small(<3㏊) watersheds and that a damping effect was observed in larger(>70㏊) basins. Uchida *et al.*(2005) also reported spatial variation in hydrologic response of small(0.59-9.5 ㏊) watersheds, both at hillslope and catchment scale, and attributed response to subsurface flow. While the studies in the Catskills(Shaman *et al.*, 2004) discuss the importance of ground water seeps discharging from bedrock in maintaining these low-flow headwater streams, subsurface flow at the study watersheds is governed by chains of interconnected macropores which may be oriented vertically and facilitate infiltration, or horizontally and facilitate exfiltration ('pipeflow' as described in Uchida *et al.*, 2001), especially during storm events and immediately thereafter. Discharge calculations were not included in this study, however it is expected that there will be a direct correlation between stream discharge, water table level and watershed area.

A number of studies have reported elevated water table as a response to timber harvesting(Williams and Lipscomb, 1981; Lockaby *et al.*, 1997; Xu *et al.*, 2002), as was the case in the present study. Elevated water tables are likely due to a reduction in evapotranspiration through the removal of overstory timber and consequent reduction in transpiration surface(a reduction in leaf area). Seasonal responses of water table post-harvest were apparent in that water table levels were more elevated during dry season (June through November) than during wet season (December through May). This may suggest that elevated water tables caused by forest harvesting are more pronounced during the growing season. A similar result was found in a study of seasonal responses of annual water yield at the Glenmorgan research farm in India(Sharda *et al.*, 1998) in which they observed that the major reduction in mean annual water yield occurring in blue gum(*Eucalyptus globulas*) plantations occurred during the months from July to October.

CONCLUSIONS

This study examined effects of forest harvesting on seasonal water table responses in small forested headwater areas. Following harvest, mean water table level increased significantly in all harvested treatments. The BMP1 and BMP2 treatments showed different water table responses because more timber was removed in BMP2. However, increase in water table elevation was not directly related to basal area removal in the study area despite considerable differences in basal area removed between BMP2 and clearcut treatments. When compared to reference treatments, seasonal responses of water table post-harvest were apparent in that water table levels were more elevated during dry season than during wet season. This may suggest that elevated water tables caused by forest harvesting are more pronounced during the growing season. These seasonal fluctuations were presumably driven by changes in evapotranspiration caused by differences in leaf area of overstory canopy and understory. Changes in water table following harvest may play a greater concern in water resources to downstream reaches during the growing season. Thus, understanding changes in water table is critical and should be considered in water resource management of headwater systems.

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